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ENGINEERING DESIGN HANDBOOK

TIMING SYSTEMS

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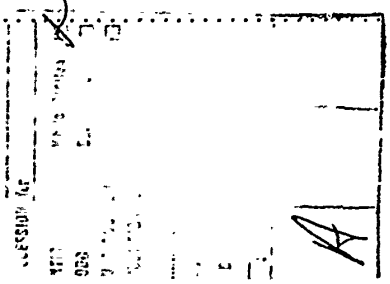
DEPARTMENT OF THE ARMY
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ENGINEERING DESIGN HANDBOOK
TIMING SYSTEMS AND COMPONENTS

Paragraph		Page
	LIST OF ILLUSTRATIONS	xviii
	LIST OF TABLES	xxviii
	LIST OF SYMBOLS	xxxi
	PREFACE	xxxv
	INTRODUCTION	
	CHAPTER 1. THE NATURE OF TIMING SYSTEMS	
1–1	Purposes and Factors Affecting Use	1–1
1–2	Timer Types	1–1
1–3	Relation of Accuracy, Output, Power, and Cost	1–2
1–4	Military Applications	1–3
	PART ONE – PRECISION REFERENCE TIMERS	
	CHAPTER 2. INTRODUCTION TO PRECISION REFERENCE TIMERS	
2–1	Time Standards	2–1
2–1.1	Apparent Solar Time	2–1
2–1.2	Mean Solar Time	2–1
2–1.3	Sidereal Time	2–2
2–1.4	Universal Time	2–2
2–1.5	Ephemeris Time	2–2
2–1.6	Atomic Time	2–3
2–1.7	U S Standard Time	2–3
2–2	Frequency Standards	2–3
2–3	Discussion of Required Parameters	2–4
2–4	Military Applications	2–5
2–4.1	Navigation, Position Finding	2–5
2–4.2	Air Traffic Control	2–7
2–4.3	Communications	2–7
2–4.4	IFF (Identification, Friend or Foe)	2–8
	References	2–9



SAMSUNG EXHIBIT 1028, Page 2

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TABLE OF CONTENTS (Con't.)

Paragraph		Page
	CHAPTER 3. SIGNAL GENERATION SYSTEMS	
3–1	Introduction	3–1
3–1.1	Definitions	3–1
3–1.1.1	Clocks	3–1
3–1.1.2	Frequency Standards	3–3
3–1.2	Primary Standards	3–3
3–1.3	Secondary Standards	3–3
3–1.4	Basic Operating Principles	3–3
3–1.4.1	Quartz-Crystal Clock	3–3
3–1.4.2	Atomic Clock	3–3
3–2	Quartz Crystal Oscillators	3–4
3–2.1	General Purpose Oscillator	3–4
3–2.2	Temperature Compensated Crystal Oscillator (TCXO)	3–4
3–2.3	Temperature Controlled Oscillator	3–6
3–2.4	Oscillator for Severe Environment	3–7
3–2.5	Precision Oscillators	3–8
3–3	Tuning Fork Oscillators	3–8
3–3.1	Application	3–8
3–3.2	Nontemperature Controlled Oscillator	3–9
3–3.3	Temperature Controlled/Compensated Oscillators	3–9
3–3.4	Effects of Other Environmental Factors on Stability	3–9
3–4	Atomic Resonance Devices	3–10
3–4.1	Atomic Action	3–10
3–4.2	Passive Resonators	3–11
3–4.2.1	Atomic Beam Resonators	3–11
3–4.2.2	Gas Cell Resonators	3–11
3–4.3	Active Resonators	3–11
3–4.3.1	Masers	3–11
3–4.3.2	RF Output of Masers	3–12
	References	3–13
	Bibliography, Temperature Compensated Quartz Oscillators (Par. 3–2.2)	3–14
	CHAPTER 4. BASIC DESIGN CRITERIA FOR SIGNAL GENERATION	
4–1	Introduction	4–1
4–1.1	General Theory	4–1
4–1.2	Components and Circuits	4–2
4–2	Quartz Crystal Oscillators	4–2
4–2.1	Quartz Crystal Units	4–2
4–2.1.1	Vibration Types	4–2
4–2.1.2	Enclosures	4–4

SAMSUNG EXHIBIT 1028, Page 3

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
4–2.1.3	Quartz Material	4–5
4–2.1.4	Design Considerations	4–7
4–2.2	Oscillator Circuitry	4–7
4–2.3	Ovens	4–9
4–3	Tuning Fork Oscillators	4–11
4–3.1	Tuning Forks	4–11
4–3.1.1	Dimensional Considerations	4–11
4–3.1.2	Quality Factor	4–11
4–3.1.3	Temperature Coefficient of Frequency	4–11
4–3.1.4	Shock and Vibration	4–12
4–3.2	Oscillator Circuitry	4–12
4–4	Atomic Frequency Standards	4–12
4–4.1	Passive Resonant Devices	4–12
4–4.1.1	System Considerations	4–12
4–4.1.2	Cesium Beam Standards	4–13
4–4.1.3	Rubidium Gas Cell Standards	4–14
4–4.2	Masers	4–14
4–4.2.1	System Considerations	4–14
4–4.2.2	Maser Devices	4–15
	References	4–16

CHAPTER 5. TIMING EQUIPMENT AND MEASUREMENT

5–1	Introduction	5–1
5–2	Time Measurement	5–1
5–2.1	Gated Counter	5–1
5–2.2	Vernier System Counter	5–2
5–2.3	Digital Interpolation Counter	5–3
5–2.4	Computing Counter	5–3
5–3	Synchronization Systems	5–3
5–3.1	Radio Transmission	5–3
5–3.1.1	Factors Affecting Radio Transmission	5–3
5–3.1.1.1	Great Circle Distance	5–3
5–3.1.1.2	Transmission Modes	5–4
5–3.1.1.3	Height of Ionsophere	5–4
5–3.1.2	Normal Radio Transmission	5–5
5–3.1.2.1	LF/VLF Radio Transmission	5–5
5–3.1.2.2	Loran-C Synchronization	5–8
5–3.1.2.3	Omega Synchronization	5–9
5–3.1.2.4	TV Network Broadcasts	5–11
5–3.1.3	Satellite	5–11
5–3.1.3.1	Teistar	5–11
5–3.1.3.2	Synchronization Via Relay II Satellite	5–13
5–3.1.3.3	Meteor Burst Clock Synchronization	5–13
5–3.2	Transfer Standard	5–14
	References	5–16

SAMSUNG EXHIBIT 1028, Page 4

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
	PART TWO – ELECTRONIC TIMERS	
	CHAPTER 6. INTRODUCTION	
6–1	Semiconductor Devices	6–1
6–1.1	Transistors	6–1
6–1.2	Integrated Circuits	6–2
6–1.2.1	Monolithic Circuits	6–2
6–1.2.2	Thin-film Circuits	6–2
6–1.2.3	Multichip (Hybrid) Integrated Circuits	6–3
6–2	General Timing Systems	6–3
6–2.1	The Analog System	6–3
6–2.2	The Digital System	6–4
6–3	Military Application	6–4
6–4	Requirements	6–5
6–4.1	Electrical Requirements	6–5
6–4.2	Mechanical and Environmental Requirements	6–5
6–5	Auxiliary Equipment	6–5
	CHAPTER 7. SYSTEM DESIGN CONSIDERATIONS	
7–1	Stationary Systems	7–1
7–1.1	General	7–1
7–1.2	Analysis of Requirements	7–1
7–1.3	Steps in Developing a System	7–1
7–1.3.1	Generalized Process	7–2
7–1.3.2	Trade-off Possibilities	7–3
7–1.3.3	Testing	7–3
7–1.4	Completion Criteria	7–3
7–2	Accelerated Systems	7–5
7–2.1	General	7–5
7–2.2	Component Selection and Qualification	7–6
7–2.2.1	Considerations	7–6
7–2.2.2	Resistors	7–6
7–2.2.3	Capacitors	7–6
7–2.2.4	Magnetic Cores	7–7
7–2.2.5	Tubes and Transistors	7–8
7–2.2.6	Power Supplies	7–9
7–2.3	Circuit Design and Breadboarding	7–9
7–2.4	Layout and Assembly Techniques	7–10
7–2.5	Performance Standards	7–12
7–2.6	External Interfaces	7–13
7–3	Radiation Hardening	7–13
7–3.1	Radiation from a Nuclear Explosion	7–14
7–3.1.1	X Rays	7–14
7–3.1.1.1	Nature of X Rays	7–14
7–3.1.1.2	Interaction With Materials	7–14

SAMSUNG EXHIBIT 1028, Page 5

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
7–3.1.2	Gamma Rays	7–14
7–3.1.3	Neutrons	7–16
7–3.2	Electromagnetic Pulses (EMP)	7–16
7–3.3	Components	7–18
7–3.3.1	Design Considerations	7–18
7–3.3.2	Hardened Components	7–18
7–3.3.3	Analysis	7–19
7–3.4	Circuit Techniques	7–19
7–3.5	Measurement and Simulation	7–19
7–4	Special Applications	7–20
7–4.1	Long Delay Stationary Systems	7–20
7–4.2	Satellite and Remotely Settable Timers	7–20
7–5	Timer Testing	7–21
7–5.1	General	7–21
7–5.2	Performance Tests	7–22
7–5.3	Safety Tests	7–22
7–5.4	Telemetry	7–22
7–5.5	Analysis of Data	7–23
7–6	Additional Factors in Design	7–23
7–6.1	Reliability and Maintainability	7–23
7–6.2	Human Factors Engineering	7–24
7–6.3	Cost Reduction	7–25
	References	7–25

CHAPTER 8. PRODUCTION TECHNIQUES

8–1	Production of Microelectronic Modules	8–1
8–1.1	General	8–1
8–1.2	Photoresist Masking	8–2
8–1.3	Thin-film Microelectronics	8–2
8–1.3.1	Screen-printing	8–3
8–1.3.2	Vacuum Deposition	8–3
8–1.3.3	Sputtering	8–3
8–1.3.4	Vapor-phase Deposition	8–4
8–1.3.5	Chemical Plating	8–4
8–1.4	Total Semiconductor Circuit	8–5
8–2	Integrated Circuits and Other Batch Fabrication Techniques	8–5
8–2.1	Semiconductor Monolithic Circuits	8–5
8–2.2	Thin-film Circuits	8–7
8–2.2.1	Components	8–7
8–2.2.2	Processing	8–8
8–2.2.3	Advantages and Limitations of Thin-film Circuits	8–9
8–2.3	Hybrid and Other Integrated Circuit Structures	8–9
8–2.3.1	Multichip Circuits	8–9

SAMSUNG EXHIBIT 1028, Page 6

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
8–2.3.2	Monobrid Circuits	8–9
8–2.3.3	Compatible Integrated Circuit	8–10
8–2.3.4	Insulated-substrate Circuits	8–10
8–2.4	Design Considerations	8–10
8–2.4.1	Type of Integrated Circuit	8–11
8–2.4.2	Packaging	8–11
8–2.4.3	Circuit Design	8–12
8–2.4.4	Available Component Values	8–12
8–2.5	Sealing	8–12
8–2.6	Encapsulation	8–14
8–2.7	Printed Circuits	8–14
8–2.7.1	Design Considerations	8–14
8–2.7.2	Taping the Artwork	8–16
8–2.7.3	Laminate Materials	8–17
8–2.7.4	Soldering Techniques	8–17
8–3	Requirements for Technical Documentation	8–18
	References	8–19

CHAPTER 9. PACKING, STORING, AND SHIPPING PROCEDURES

9–1	General	9–1
9–2	Devices Containing Explosives	9–1
9–3	Special Environmental Effects	9–1
9–3.1	RF Hardening	9–1
9–3.2	Lightning Discharge	9–2
9–3.3.	Static Electricity	9–2
	References	9–2

CHAPTER 10. ELECTRONIC ANALOG TIMERS

10–1	Introduction	10–1
10–2	Timing Circuits	10–1
10–2.1	RC Networks	10–1
10–2.2	RL Networks	10–6
10–2.3	Miller Integrators	10–7
10–2.4	Curpistor Timers	10–8
10–3	Level Detectors	10–9
10–3.1	Cold Gas Diodes	10–10
10–3.2	Heated Cathode Diodes and Triodes	10–10
10–3.3	Bipolar Transistors	10–10
10–3.4	Unijunction Transistor Detectors	10–11
10–3.5	Field Effect Transistors	10–11
10–4	Setting Methods	10–11
10–4.1	Setting Mechanism	10–11
10–4.2	Resistor Package	10–12

SAMSUNG EXHIBIT 1028, Page 7

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
10–5	Power Supplies	10–13
	References	10–13
	CHAPTER 11. ELECTRONIC DIGITAL TIMERS	
11–1	Introduction	11–1
11–2	Time Bases	11–2
11–2.1	Harmonic Oscillators	11–2
11–2.1.1	Oscillator Characteristics	11–2
11–2.1.2	Inductance-capacitance Oscillators	11–4
11–2.1.3	Resistance-capacitance Oscillators	11–6
11–2.1.4	Mechanical Resonator Oscillators	11–9
11–2.2	Relaxation and Pulse-type Oscillators	11–10
11–2.3	Present Oscillator Capabilities	11–12
11–3	Counters	11–13
11–3.1	General	11–13
11–3.2	Transistor Type Counters	11–14
11–3.3	Magnetic Core Types	11–15
11–3.4	Other Types	11–18
11–4	Output Circuits	11–19
11–4.1	General	11–19
11–4.2	Output Pulse Generation	11–19
11–4.3	Logical Interlock Functions	11–21
11–5	Setting Methods	11–21
11–5.1	General	11–21
11–5.2	Serial Methods	11–21
11–5.3	Parallel Methods	11–22
11–5.4	Combination Methods	11–22
11–6	Power Supplies	11–22
11–6.1	General	11–22
11–6.2	Power Supplies for Projectile Fuzing Applications	11–22
	References	11–27
	PART THREE -- MECHANICAL TIMERS	
	CHAPTER 12. INTRODUCTION	
12–1	General Systems	12–1
12–1.1	Basic Mechanical Timer Elements	12–1
12–1.2	Functions of Mechanical Timers	12–1
12–1.2.1	Interval Timers	12–1
12–1.2.2	Programmers and Sequencers	12–2
12–1.2.3	Clocks	12–2
12–1.3	Accuracy	12–2
12–1.4	Examples of Mechanical Timers	12–3
12–1.4.1	Interval Timers	12–3

SAMSUNG EXHIBIT 1028, Page 8

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
12–1.4.2	Fuzes	12–4
12–1.4.3	Programmers	12–5
12–1.4.4	Sequential Timers	12–6
12–2	Military Applications	12–6
12–2.1	Guided Missile Fuzes	12–6
12–2.2	Artillery Fuzes	12–7
12–2.3	Arming Delays	12–8
12–3	Requirements	12–9
12–4	Auxiliary Equipment	12–11
12–4.1	Torque Regulators To Compensate for Main Spring Run Down	12–11
12–4.2	Torque Regulators To Compensate for Variation in Output Loading	12–11
12–4.3	Automatic Dynamic Regulation Machine	12–12
	References	12–13

CHAPTER 13. MECHANICAL TIMER SYSTEMS

13–1	System Design Considerations	13–1
13–1.1	Design Specifications	13–1
13–1.2	Preliminary Considerations	13–1
13–1.3	Arming and Functioning Delays	13–3
13–1.4	Prototype Development	13–3
13–1.5	Testing	13–3
13–1.6	Final Acceptance	13–3
13–2	General Factors in Design	13–3
13–2.1	Reliability	13–4
13–2.2	Maintainability	13–4
13–2.3	Human Factors Engineering	13–5
13–2.4	Cost Reduction	13–5
13–2.4.1	Standard Parts	13–5
13–2.4.2	Manufacturing Tolerances	13–6
13–2.4.3	Mass Production	13–6
13–2.4.4	Material Substitution	13–6
13–2.4.5	Corrosion Preventive Finishes	13–6
13–2.4.6	Ease of Maintenance	13–6
13–2.4.7	Simplicity	13–6
13–2.4.8	Ruggedness vs Accuracy	13–6
13–3	Systems for High Acceleration	13–7
13–3.1	Setback	13–7
13–3.2	Forward and Sideways Acceleration	13–7
13–3.3	Centrifugal Force	13–7
13–3.4	Coriolis Force	13–8
13–3.5	Torque	13–8
13–3.6	Precessional Force	13–8
13–3.7	Effect of Spin on Timers	13–8

SAMSUNG EXHIBIT 1028, Page 9

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
13-4	Systems for Low Acceleration	13-9
13-4.1	Munition Classes	13-9
13-4.2	Timers for Guided Missile Fuzes	13-9
13-4.3	Timers for Bomb Fuzes	13-10
13-4.4	Timers for Grenade Fuzes	13-10
13-4.4.1	Launched Grenades	13-10
13-4.4.2	Rifle and Hand Grenades	13-10
13-5	Stationary and Long-delay Timers	13-10
13-5.1	Demolition Firing Device, XM70	13-10
13-5.2	Interval Timer, XM4	13-13
13-5.3	180-hr Airborne Timer	13-14
13-6	Timer System Testing	13-14
13-6.1	General	13-14
13-6.2	Performance Tests	13-15
13-6.3	Test Programming	13-16
13-6.4	Safety Tests	13-16
13-6.4.1	Destructive Tests	13-16
13-6.4.2	Nondestructive Tests	13-17
13-6.5	Analysis of Data	13-18
	References	13-18

CHAPTER 14. PRODUCTION TECHNIQUES

14-1	Designing for Production	14-1
14-1.1	The Production Process	14-1
14-1.2	Important Factors in Production	14-1
14-1.3	Steps Leading to Production	14-2
14-2	Designing for Mass Production	14-2
14-2.1	The Mass Production Process	14-2
14-2.2	Cooperation With the Production Engineer	14-2
14-2.3	Requirements for Mechanical Timers	14-3
14-2.4	Metals for Mechanical Timers	14-3
14-2.5	Lubrication	14-4
14-3	Manufacturing Methods for Timer Components	14-5
14-3.1	Escapement	14-5
14-3.2	Gears	14-5
14-3.3	Hairspring	14-5
14-3.4	Other Parts	14-5
14-3.5	Tolerances	14-5
14-4	Requirements for Technical Documentation	14-6
	References	14-7

CHAPTER 15. PACKING, STORING, AND SHIPPING PROCEDURES

15-1	Packing	15-1
15-1.1	Purpose	15-1

SAMSUNG EXHIBIT 1028, Page 10

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
15–1.2	Objectives	15–1
15–1.3	Packaging Engineer	15–1
15–1.4	Methods	15–1
15–1.5	Protection Levels	15–2
15–1.6	Packaging Steps	15–3
15–2	Storing	15–3
15–2.1	Types of Storage	15–3
15–2.2	Storage of Explosives	15–4
15–3	Shipping	15–4
15–3.1	Transportation Environments	15–4
15–3.2	Truck Transport	15–5
15–3.3	Rail Transport	15–5
15–3.4	Air Transport	15–6
15–3.5	Ship Transport	15–7
	References	15–10

CHAPTER 16. COMPONENT DESIGN

16–1	Introduction	16–1
16–1.1	Design Considerations	16–2
16–1.1.1	Tactical	16–2
16–1.1.2	Environmental	16–2
16–1.1.3	Safety	16–2
16–1.2	Timer Accuracy	16–3
16–2	Power Sources	16–3
16–2.1	Spring Motors	16–3
16–2.1.1	Torque	16–3
16–2.1.2	Efficiency	16–6
16–2.2	Negator Motors	16–6
16–2.3	Comparison of Spring Motors	16–7
16–2.4	Centrifugal Drive	16–8
16–2.5	AC Motors	16–8
16–2.6	DC Motors	16–11
16–2.7	Batteries	16–13
16–3	Gear Trains	16–14
16–3.1	Computing Systems	16–14
16–3.2	Types of Gear Train	16–14
16–3.2.1	Spur Gear Trains	16–14
16–3.2.2	Worm Gearing	16–14
16–3.2.3	Epicyclic Gearing	16–15
16–3.2.4	Hypocyclic Gear Trains	16–15
16–3.2.5	Harmonic Gear Drive	16–15
16–3.2.6	Synchronic Index Gear Train	16–16
16–3.3	Special Problems Associated With Small Mechanism Gearing	16–16
16–3.4	Friction Effects on Gear Train Efficiency	16–19

SAMSUNG EXHIBIT 1028, Page 11

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
16–3.5	Gear Theory and Tooth Design	16–21
16–3.6	Gear Ratios	16–23
16–3.6.1	Calculation With Continued Fractions	16–24
16–3.6.2	Brocot's Approximation Method	16–25
16–3.7	Gear Train Design	16–26
16–4	Escapements	16–26
16–4.1	Untuned Two-center Escapement	16–26
16–4.1.1	Factors Affecting Escapement Operation	16–27
16–4.1.2	Runaway Escapement Applied to Rocket Fuze	16–29
16–4.1.3	Dynamics of Runaway Escapement	16–30
16–4.2	Tuned Two-center Escapements	16–31
16–4.2.1	Junghans Escapement	16–32
16–4.2.2	Popovitch Escapement Modification	16–35
16–4.2.3	Dock Escapement Modification	16–36
16–4.2.4	Cylinder Escapements	16–36
16–4.2.5	Escapement Self-starting Capability	16–40
16–4.3	Tuned Three-center Escapements	16–41
16–4.3.1	Method of Increasing Torque Regulating Range of Detached Lever Escapements	16–43
16–4.3.2	Dynamic Analysis of Detached Lever Escapement	16–46
16–4.4	Spin Sensitivity of Tuned Escapements	16–49
16–4.5	Design Fundamentals	16–54
16–4.5.1	Untuned Two-center Escapements	16–54
16–4.5.2	Tuned Two-center Escapements	16–58
16–4.5.3	Tuned Three-center Escapements	16–60
16–4.5.4	Detached Lever Escapements With Pin Pallet	16–64
16–5	Setting	16–66
16–5.1	General	16–66
16–5.2	Improved Setting Method for Mechanical Time Fuzes	16–67
16–5.3	Linkage of Setter Components	16–69
16–5.4	Setting Mechanism for Mechanical Time Fuze, XM577	16–69
16–6	Output	16–71
16–6.1	Analog and Digital Outputs	16–71
16–6.2	Switches and Relays	16–72
16–6.3	Types of Switch	16–73
16–6.4	Cam Operated Outputs	16–74
16–6.5	Readouts	16–75
16–6.5.1	Scale Layout	16–75
16–6.5.2	Character Form	16–76
16–6.5.3	Grouping of Digits	16–76
16–6.5.4	Background	16–77
16–6.5.5	Illumination	16–77
16–7	Fluid Timers	16–77

SAMSUNG EXHIBIT 1028, Page 12

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
16–7.1	Pneumatic Dashpot	16–77
16–7.2	Silicone Grease Capsule	16–78
	References	16–79
	Bibliography, Gear and Tooth Design	16–81
	PART FOUR – PYROTECHNIC TIMERS	
	CHAPTER 17. INTRODUCTION	
17–1	General Systems	17–1
17–2	Military Applications	17–2
17–3	Requirements	17–2
	References	17–3
	CHAPTER 18. DELAY SYSTEM CHARACTERISTICS	
18–1	Space Limitations	18–1
18–1.1	Length	18–1
18–1.2	Diameter	18–2
18–1.3	Wall Thickness	18–2
18–2	Physical Characteristics of Body Material Housing	18–2
18–3	Vented Delays	18–3
18–3.1	Initiation Means	18–4
18–3.2	Output Mechanism	18–4
18–3.3	Baffles and Retainers	18–5
18–4	Obturated Delays	18–6
18–4.1	Initiation Means	18–7
18–4.2	Output Mechanism	18–7
18–4.3	Baffles and Retainers	18–7
18–4.4	Internal Free Volume	18–7
18–4.5	Seals and Closures	18–8
18–5	System Design and Performance	18–9
18–5.1	System Assembly Procedures	18–10
18–5.2	Performance Requirements	18–11
	References	18–12
	CHAPTER 19. PRODUCTION TECHNIQUES	
19–1	General	19–1
19–2	Designing for Mass Production	19–1
19–2.1	Measurement of Explosive Charges	19–2
19–2.2	Direct Pressing	19–2
19–2.3	Pelletizing	19–3
19–3	Requirements for Technical Documentation	19–3
	References	19–3

SAMSUNG EXHIBIT 1028, Page 13

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
	CHAPTER 20. PACKING, STORING, AND SHIPPING PROCEDURES	
20–1	General	20–1
20–2	Safety	20–1
20–3	Hazard Classification	20–2
20–4	Packing	20–2
20–5	Storing	20–3
20–6	Shipping	20–3
	References	20–5
	CHAPTER 21. PYROTECHNIC DELAY COMPONENTS	
21–1	Initiators	21–1
21–1.1	Stab Primer	21–1
21–1.1.1	Construction	21–1
21–1.1.2	Ignition Charge and Loading	21–1
21–1.2	Percussion Primer	21–2
21–1.2.1	Construction	21–2
21–1.2.2	Ignition Charge and Loading	21–2
21–1.3	Electric Initiator	21–2
21–1.3.1	Construction	21–2
21–1.3.2	Ignition Charge and Loading	21–3
21–2	Delay Elements	21–3
21–2.1	Basic Chemistry of Delay Compositions	21–3
21–2.1.1	Fuels	21–4
21–2.1.2	Oxidants	21–4
21–2.1.3	Binders	21–5
21–2.1.4	Lubricants	21–5
21–2.2	Delay Compositions	21–5
21–2.2.1	Early Compositions	21–5
21–2.2.2	Current Gasless Compositions	21–6
21–3	Relays	21–9
21–4	Sensitivity	21–9
21–4.1	Need for Characterization	21–9
21–4.2	Sensitivity to Initiation	21–10
21–4.2.1	Impact	21–10
21–4.2.2	Friction	21–11
21–4.2.3	Rifle Bullet Impact	21–11
21–4.3	Sensitivity to the Environment	21–11
21–4.3.1	Heat	21–11
21–4.3.2	Moisture (Hygroscopicity)	21–12
21–4.3.3	Electrostatic Discharge	21–12
21–4.4	Input and Output Sensitivity	21–12
21–4.4.1	Input	21–12
21–4.4.2	Output	21–13

SAMSUNG EXHIBIT 1028, Page 14

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
21–4.5	Analysis of Data	21–13
	References	21–14
	PART FIVE – FLUERIC TIMERS	
	CHAPTER 22. INTRODUCTION	
22–1	Advantages	22–1
22–2	Disadvantages	22–3
	References	22–4
	CHAPTER 23. FLUERIC SYSTEMS DESIGN	
23–1	Factors	23–1
23–2	Modular Components	23–2
23–3	Integrated Circuits	23–2
23–4	Matching Techniques	23–5
23–5	DC and AC Systems	23–7
23–6	Hybrid Systems	23–9
23–6.1	Coded Tape Valves	23–10
23–6.2	Tape Actuators	23–11
23–6.3	Vibrating Reed Frequency Sensors	23–12
23–6.4	Moving Part Detectors	23–12
23–6.5	Flow Control Devices	23–13
23–6.6	Pneumatic Switches	23–14
23–7	Test and Evaluation	23–15
23–7.1	Flow Meters	23–16
23–7.2	Velocity Meters	23–18
23–7.3	Pressure Meters	23–19
23–7.4	Flow Visualization	23–20
23–7.4.1	Water Table	23–20
23–7.4.2	Smoke	23–21
23–7.4.3	Optical Techniques	23–21
23–7.5	Frequency Meters	23–21
23–7.6	Signal Generators	23–21
	References	23–23
	CHAPTER 24. COMPONENT DESIGN	
24–1	Power Supplies	24–1
24–1.1	Ram Air Power	24–2
24–1.2	Packaged Pneumatic Power Supplies	24–4
24–1.3	Steady-state Supplies	24–4
24–1.3.1	General	24–4
24–1.3.2	Solid-propellant Gas Generators	24–5
24–1.3.3	Chemical Gas Generators	24–6

SAMSUNG EXHIBIT 1028, Page 15

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
24–1.4	Transient Supplies (Pressurized Bottles)	24–6
24–1.5	Storage Container Design	24–8
24–2	Oscillators	24–11
24–2.1	Feedback or Relaxation Oscillators	24–11
24–2.2	Torsion Bar Oscillator	24–12
24–2.3	Sonic Oscillators	24–12
24–2.4	Half-adder Oscillators	24–13
24–2.5	High-pressure, Low-flow Oscillators	24–14
24–2.6	Design of Oscillators from Theoretical Considerations	24–16
24–3	Flip-flops	24–16
24–3.1	General	24–16
24–3.2	Typical Performance Characteristics of a Bistable Flip-flop	24–18
24–3.3	Additional Refinements	24–20
24–4	Counters	24–21
24–4.1	Binary Counting	24–22
24–4.2	Binary Counters in Slow-responding Systems	24–23
24–4.3	Binary Counters in Fast-responding Systems	24–23
24–4.4	Decimal Counters	24–25
24–4.5	Nonsequential Counters	24–26
24–5	Logic Circuits	24–26
24–5.1	OR/NOR Elements	24–27
24–5.2	AND/NAND Elements	24–28
24–5.3	Combined Logic Elements	24–29
24–6	Resistance Elements	24–30
24–6.1	Tube Resistors	24–30
24–6.2	Orifice Resistors	24–31
24–6.3	Porous-metal Resistors	24–31
24–6.4	Variable Resistors	24–32
24–7	Capacitances	24–33
24–8	Turbulence Amplifiers	24–34
24–8.1	General	24–34
24–8.2	Disturbing the Main Jet	24–35
24–8.3	Inherent Acoustic Response	24–36
24–8.4	Cascading	24–36
24–8.5	Overdriving	24–37
24–8.6	Primary Uses and Typical Sizes of Turbulence Amplifiers	24–37
24–9	Outputs	24–38
24–9.1	Balanced Piston Output Device	24–38
24–9.2	Bellows-actuated Output Transducers	24–39
24–9.3	Thin Membrane	24–40
24–10	Setting Methods	24–41
	References	24–46

SAMSUNG EXHIBIT 1028, Page 16

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
	CHAPTER 25. PRODUCTION TECHNIQUES	
25–1	Materials	25–1
25–1.1	General Requirements	25–1
25–1.2	Suitable Materials	25–1
25–2	Fabrication	25–2
25–2.1	Plastics	25–2
25–2.1.1	Casting	25–2
25–2.1.2	Thermoforming	25–4
25–2.1.3	Photosensitive Plastics	25–4
25–2.1.4	Injection Molding	25–5
25–2.1.5	Jet Molding	25–6
25–2.1.6	Compression Molding	25–6
25–2.1.7	Transfer Molding	25–6
25–2.2	Metals	25–6
25–2.2.1	Conventional Machining	25–7
25–2.2.2	Powder Metallurgy	25–7
25–2.2.3	Die Casting	25–7
25–2.2.4	Chemical Machining	25–9
25–2.2.5	Electrical Discharge Machining (EDM)	25–10
25–2.2.6	Electrochemical Machining (ECM)	25–10
25–2.2.7	Electroforming	25–11
25–2.3	Ceramics	25–11
25–2.3.1	Photoetched Ceramics	25–11
25–2.3.2	Ultrasonic Machining	25–12
25–2.3.3	Electron Beam Machining	25–13
25–3	Summary	25–13
	References	25–15
	PART SIX – MISCELLANEOUS TIMING DEVICES	
	CHAPTER 26. ELECTROCHEMICAL TIMERS	
26–1	Basic Considerations	26–1
26–1.1	Electroplating Action	26–1
26–1.2	The Electroplating System	26–3
26–2	Electroplating Timer With Electrical Readout	26–3
26–2.1	Principle of Operation	26–3
26–2.2	Cell Construction	26–3
26–2.3	Timer Design	26–4
26–2.4	Advantages and Disadvantages	26–5
26–3	Electroplating Timer With Mechanical Readout	26–6
26–3.1	Principle of Operation	26–6
26–3.2	Cell Construction	26–6
26–3.3	Timer Design	26–8
26–3.4	Advantages and Disadvantages	26–8

SAMSUNG EXHIBIT 1028, Page 17

Downloaded from https://www.everyspec.com

TABLE OF CONTENTS (Con't.)

Paragraph		Page
26–4	Solion	26–8
26–4.1	Principle of Operation	26–8
26–4.2	Advantages and Disadvantages	26–9
26–5	Mercury Timer	26–10
26–5.1	Principle of Operation	26–10
26–5.2	Advantages and Disadvantages	26–10
	References	26–11
	CHAPTER 27. NUCLEAR DECAY TIMERS	
27–1	Radiation Source	27–1
27–1.1	Desirable Properties	27–1
27–1.2	Types of Radiation	27–2
27–1.3	Radioisotopes	27–3
27–2	Nuclear Particle Detector	27–3
27–2.1	Gas Tube Counters	27–3
27–2.2	Scintillation Counters	27–3
27–2.3	Semiconductor Radiation Detectors (SRD)	27–4
27–3	Associated Electronics	27–4
	References	27–5
	APPENDIX A. BOOLEAN ALGEBRA APPLIED TO LOGIC CIRCUITS	A–1
	GLOSSARY	G–1
	INDEX	I–1

SAMSUNG EXHIBIT 1028, Page 18

Downloaded from https://www.everyspec.com

LIST OF ILLUSTRATIONS

Fig. No.	Title	Page
2–1	Components of Airborne Air Traffic Control Equipment	2–7
2–2	Interrogation Pulse Modes Used on Secondary Surveillance Radar	2–9
2–3	Transponder Reply Codes Used on Secondary Surveillance Radar	2–9
3–1	General Purpose Crystal Controlled Oscillator	3–4
3–2	Temperature Compensated Crystal Oscillator (TCXO)	3–4
3–3	Temperature Compensation Circuit	3–5
3–4	Effect of Compensation on the Frequency of a 25-MHz Crystal Unit	3–5
3–5	Oscillator for Severe Environments	3–8
3–6	Precision Crystal Controlled Oscillator	3–8
3–7	Tuning Fork Vibrations	3–9
3–8	Cesium Atomic-beam Frequency-standard Apparatus	3–12
3–9	Schematic Diagram of the Hydrogen Maser	3–12
4–1	Crystal Oscillator Circuits for Frequency Standards	4–3
4–2	Basic Diagram of Atomic Resonator Controlled Oscillator	4–4
4–3	Complete Hydrogen Maser Frequency Standard	4–4
4–4	Basic Modes in Quartz Crystal Vibrators	4–5
4–5	Quartz Crystal Unit Holders	4–5
4–6	HC-6 Type Coldweld Unit	4–5
4–7	Round Transistor Type Coldweld Holder	4–6
4–8	Friction Losses in Quartz	4–6
4–9	Aging of Metal-enclosed and Glass-enclosed 5-MHz Crystal Units	4–7
4–10	Exploded View of Crystal Ovens	4–9
4–11	Basic Proportional Control System	4–10
4–12	Typical Control System Characteristics	4–10
4–13	Typical Tuning Fork	4–11
4–14	[illegible]	4–12
4–15	Cesium Atomic Beam Frequency Standard, [illegible]-III	4–14
4–16	Tactical Rubidium Gas Cell Frequency Standard	4–14
4–17	Satellite Maser With Bell Jar Removed	4–15
5–1	Gated Counter	5–2
5–2	Vernier Counting System	5–2
5–3	Great Circle Distance Calculation	5–3
5–4	Single-hop Sky-wave Paths	5–4
5–5	Multiple-hop Transmission Path	5–5
5–6	Transmission Delay Graph	5–6

SAMSUNG EXHIBIT 1028, Page 19

Downloaded from https://www.everyspec.com

LIST OF ILLUSTRATIONS (Con't.)

Fig. No.	Title	Page
5–7	Chart of Time Code Transmissions from NBS Station WWV	5–7
5–8	Indicated Propagation Delay, 20.0 vs 20.5 kHz	5–8
5–9	Indicated Propagation Delay, 19.9 vs 20.0 kHz	5–8
5–10	Residual Daily VLF Time Fluctuations	5–9
5–11	Simple Visual Timing System	5–9
5–12	Visual Timing System	5–9
5–13	Simplified Diagram of an Epoch Monitor System	5–10
5–14	Phase-tracking System	5–10
5–15	Automatic Receiver System	5–11
5–16	Pulse Generating and Measuring Arrangements at Andover, Me.	5–12
5–17	Interconnections of Generating and Measuring Equipment at Goonhilly Downs, Cornwall	5–12
5–18	Retransmission of Pulses from Mojave by Kashima and Injection of Pulses at Kashima	5–13
5–19	Pulses Photographed on February 20, 1965 at Mojave	5–13
5–20	Equipment Used at Mojave To Generate and Record Pulses	5–14
5–21	Equipment Used at Kashima To Generate and Record Pulses	5–14
5–22	Diagram of Meteor Burst Clock Synchronization System	5–15
6–1	Basic Small-signal Circuits	6–2
6–2	Block Diagram of Analog and Digital Timers	6–3
6–3	Simple Analog System	6–3
6–4	Simple Digital System	6–4
7–1	Basic Timer Diagram	7–2
7–2	Block Diagrams of Analog and Digital Timers	7–2
7–3	Control of Physical Variable	7–3
7–4	Square Hysteresis Loop Material	7–8
7–5	Methods of Driving the Core	7–8
7–6	Magnetic Core Driver	7–8
7–7	Summary of X-ray and Gamma Ray Interactions With Matter	7–16
7–8	Congruence Between Predicted and Measured Common-mode Output Voltage Offset	7–19
7–9	Long-interval Timer Block Diagram	7–21
7–10	Short-interval Timer Block Diagram	7–21
7–11	Typical VHF High-g Telemetry System	7–22
7–12	Sequence of Events	7–23
7–13	External System Building Blocks	7–24
8–1	Pellet or "Swiss Cheese" Package	8–1
8–2	Preparation of Pattern Using Photoresist	8–2

SAMSUNG EXHIBIT 1028, Page 20

Downloaded from https://www.everyspec.com

LIST OF ILLUSTRATIONS (Con't.)

Fig. No.	Title	Page
8–3	Uses of Photoresist in Various Processes	8–3
8–4	Vacuum Evaporation and Deposition Apparatus	8–4
8–5	Sputtering Apparatus	8–4
8–6	Chemically Plated Conductor and Resistor Pattern	8–5
8–7	Basic Structure of Integrated Circuit Wafer	8–6
8–8	Typical Integrated Circuit Components	8–6
8–9	Typical Diffused Integrated Circuit Components	8–7
8–10	Typical Thin Film Circuit	8–9
8–11	Typical Interconnected Multichip Circuit	8–9
8–12	Monobrid Circuit	8–10
8–13	Procedure for Parasitic-free Circuit Fabrication	8–11
8–14	Electrical Characteristics of Etched Copper Wiring	8–17
8–15	Annular Ring for an Unsupported Hole With Component Lead Soldered on One Side	8–18
8–16	Annular Ring for Swaged Terminals, Stand-offs, and Funnel Eyelets	8–18
8–17	Correct and Incorrect Conductor Patterns	8–18
10–1	Basic *RC* Network	10–2
10–2	Voltage-time Curve for Basic *RC* Network	10–2
10–3	Primitive *RC* Timer	10–3
10–4	A Practical Low Accuracy Timer	10–4
10–5	A Practical Timer Using a Single Semiconductor	10–4
10–6	Relaxation Oscillator	10–4
10–7	Voltage at the Detector	10–5
10–8	Block Diagram of Multiplier System	10–6
10–9	General Usage for Long Period *RC* Timer	10–6
10–10	Basic *RL* Network	10–7
10–11	Current-time Curve for Basic *RL* Network	10–7
10–12	Miller Integrator	10–8
10–13	Curpistor-diode Oscillator	10–8
10–14	Sawtooth Charge-discharge Curve	10–9
10–15	Relaxation Oscillator Using a Cold Gas Diode	10–10
10–16	Cold Gas Diode Detection Timer	10–10
10–17	Switching for Two-section Resistor Package	10–12
10–18	Binary Switching System for an Analog Resistor	10–12
11–1	Parallel Resonant Oscillators	11–4
11–2	Tuned-output Oscillator	11–5
11–3	Series-resonant Oscillator With Diode Limiting	11–6
11–4	Series-resonant Oscillator With Automatic Level Control	11–7
11–5	*RC* Frequency-selective Networks Used in Oscillators	11–8
11–6	Wien Bridge Oscillator	11–9
11–7	Twin-T, Unbalanced-network Oscillator	11–10
11–8	Saturable Core Oscillators	11–11
11–9	Primitive Counters	11–15
11–10	Typical Multivibrator	11–15
11–11	Block Diagram of Basic Timing Circuit	11–16

SAMSUNG EXHIBIT 1028, Page 21

Downloaded from https://www.everyspec.com

LIST OF ILLUSTRATIONS (Con't.)

Fig. No.	Title	Page
11–12	Schematic Diagram of Fuze, Electronic Time, XM587	11–17
11–13	Block Diagram of 10-Hz Clock	11–18
11–14	Ternary Divider	11–19
11–15	Magnetic Core Scaler	11–19
11–16	Two Phase Driver	11–20
11–17	Decade Frequency Divider	11–20
11–18	Typical Initiation Circuit	11–21
12–1	Military Timer Concept	12–2
12–2	Mechanical Interval Timer	12–3
12–3	Diagrammatic View of XM4 Interval Timer	12–3
12–4	Exploded View of a Mechanical Timer	12–4
12–5	Electromechanical Program Timer for Adaption Kit of Ballistic Missile	12–5
12–6	Schematic of Mechanical Timer With Electrical Rewind Circuit	12–5
12–7	Safing and Arming Mechanism	12–7
12–8	Safing and Arming Device, GM, M30A1	12–8
12–9	Timing Mechanism of Fuze, MTSQ, M564	12–9
12–10	Fuze, PD, M525	12–10
12–11	Capstan Torque Regulator	12–11
12–12	Effect of Capstan Regulator on Torque-Time Curves for Runaway Escapements	12–12
13–1	Coriolis Force	13–8
13–2	Fuze, Bomb Nose, M198	13–11
13–3	Fuze, Grenade, M551	13–12
13–4	Demolition Firing Device, XM70	13–12
13–5	Clockwork for Demolition Firing Device, XM70	13–13
13–6	Interval Timer, XM4	13–14
13–7	Clockwork of XM4 Timer	13–15
13–8	Cutaway View of 180-hr Timer	13–17
15–1	Role of Packaging Engineering	15–2
15–2	Basic Steps in Military Packaging and Their Normal Sequence	15–3
15–3	Markings for Boxes	15–4
15–4	Plot of Typical Shock Motion	15–5
15–5	Truck Transportation Vibration Data	15–5
15–6	Freight and Freight Car Shock Measurements	15–7/15–8
15–7	Impact Speed During Freight Car Switching Operations	15–9
15–8	Maximum Longitudinal Acceleration of Freight Car Body vs Switching Impact Speed	15–9
15–9	Maximum Shocks Recorded During Airline Test Shipment	15–9
16–1	Spiral Spring Power Motor	16–4
16–2	Negator Spring Motor	16–4

SAMSUNG EXHIBIT 1028, Page 22

Downloaded from https://www.everyspec.com

LIST OF ILLUSTRATIONS (Con't.)

Fig. No.	Title	Page
16–3	Average Maximum Solid Stress in Power Springs (for ℓ/h approximately 7000)	16–5
16–4	Typical Torque Curve for Power Spring	16–5
16–5	Input and Output Curves of a Conventional Spiral Power Spring	16–6
16–6	Input and Output Curves of a Prestressed (Spirator) Spring of the Same Weight as Power Spring in Fig. 16–5	16–7
16–7	Input and Output Curves of a B Type Negator Motor of the Same Weight as the Spiral Spring Motor in Fig. 16–5	16–7
16–8	Energy Comparison of Three Types of Motor Spring Having the Same Weight of Material	16–8
16–9	Centrifugal Drive Employed in the MTSQ, M502A1 Mechanical Time Fuze	16–10
16–10	Chronometric Governored DC Motor	16–12
16–11	Epicyclic Gearing	16–15
16–12	Hypocyclic Gearing	16–15
16–13	Harmonic Gear Drive	16–16
16–14	Principle of the Synchronic Index of a Gear Train	16–16
16–15	Comparison of Gear Tip Profiles	16–17
16–16	Direction of Resultant Effective Forces With Friction	16–20
16–17	Forces on Teeth With and Without Friction	16–21
16–18	Variations of Torque Output of Several Stages	16–21
16–19	Contact Action of Gear Teeth	16–22
16–20	Curves of Turning Error	16–23
16–21	Gear Trains	16–24
16–22	Runaway Escapement, Flat Pallet Faces	16–27
16–23	Runaway Escapement, Pin Pallet Type	16–28
16–24	Typical Rocket Accelerations	16–29
16–25	Variation in Rocket Arming Time	16–29
16–26	Runaway Escapement	16–30
16–27	Standard Junghans Type Escapement	16–33
16–28	Action of Junghans Escapement	16–34
16–29	Junghans Escapement, Frequency-torque Curve	16–35
16–30	Popovitch Modification of Junghans Escapement	16–36
16–31	Dock Modification of Junghans Escapement	16–37
16–32	Escapement Arbor and Adjusting Nut–Modified Configuration	16–38
16–33	Cylinder Escapement Assembly	16–38
16–34	Action Sequence of Cylinder Escapement	16–39
16–35	Pivot Friction Variation	16–40
16–36	Rebound Coefficient Variation	16–40
16–37	Pallet Friction Variation	16–40
16–38	Inertia Variation	16–41

SAMSUNG EXHIBIT 1028, Page 23

Downloaded from https://www.everyspec.com

LIST OF ILLUSTRATIONS (Con't.)

Fig. No.	Title	Page
16–39	Center Distance Variation	16–41
16–40	Variation of Lift	16–42
16–41	Alignment Error Variation	16–43
16–42	Detached Lever Escapement, Club Tooth Type	16–43
16–43	Detached Lever Escapement, Pin Pallet Type	16–44
16–44	Amplitude vs Torque Behavior	16–45
16–45	Balance Wheels	16–45
16–46	Effect of Varying Escape Wheel Inertia and Frequency	16–46
16–47	Beat Rate for a Detached Lever Escapement	16–47
16–48	Braking Fork	16–47
16–49	Effects of Braking Action	16–48
16–50	The Effects of Several Braking Surface Combinations	16–48
16–51	Modified Escapement	16–49
16–52	Escapement Spring Motion of Junghans Escapement	16–50
16–53	Escapement Spring Motion of E-K System	16–52
16–54	Escapement Spring Motion of PA System	16–52
16–55	Segmental Gear Compensator	16–53
16–56	Connected Mass Compensator	16–53
16–57	Operation of Runaway Escapement	16–54
16–58	Quantity Relationships for Pallet of Runaway Escapement	16–55
16–59	Runaway Escapement With Equal and Unequal Arms	16–56
16–60	Untuned Two-center Escapement With Equal-arm Pallet	16–57
16–61	Escapement Curves for Different Moments of Inertia	16–57
16–62	Rotating Drum Record of Escapement Motion	16–58
16–63	Operation Detached Lever Escapement	16–60
16–64	Escape Wheel Tooth Shapes	16–61
16–65	Determination of the Draw Angle	16–62
16–66	Lever With Safety Pin	16–63
16–67	Pin Pallet Escapement Geometry	16–64
16–68	Entrance and Exit Draw Dependence on Pallet Center	16–66
16–69	Simplified Lever	16–67
16–70	Setting Mechanism for Fuze, MT, XM571	16–68
16–71	Linkage of Setter Components	16–69
16–72	Mechanical Time Fuze, XM577	16–70
16–73	Setting Positions for Fuze, XM577	16–71
16–74	Two Types of Visual Output	16–71
16–75	Digital Counting Device	16–73
16–76	Adjustable Cam Timer	16–74
16–77	Cam Cycle Timer	16–74
16–78	Timing Chart for Cam-cycle Timer	16–75

SAMSUNG EXHIBIT 1028, Page 24

Downloaded from https://www.everyspec.com

LIST OF ILLUSTRATIONS (Con't.)

Fig. No.	Title	Page
16–79	Recommended Readout Display Scales	16–75
16–80	Multioriented Displays	16–76
16–81	Pneumatic Dashpot for Arming Delay	16–77
16–82	Delay Assembly of Fuze, XM218	16–78
17–1	Detonator, Delay, T65	17–3
18–1	Variation in Delay Time With Body Diameter	18–4
18–2	Sealing of Vented Delay Element	18–5
18–3	Charge Holders	18–5
18–4	Burning Time of Barium Delay Compositions (M112 Fuze)	18–6
18–5	Typical Baffled Delay Column	18–6
18–6	Delay Element, Obturated, M9	18–7
18–7	Characteristics of an Obturated Black Powder Delay Element	18–8
18–8	Stab Initiated Delay Actuator (MARK 14 MOD 0)	18–9
18–9	Electrically Initiated Delay Actuator (MARK 18 MOD 0)	18–10
18–10	Experimental Obturated Percussion Delay Detonator.	18–10
19–1	Scoop Loading	19–1
19–2	Charging Plate Loading	19–2
19–3	Tool for Direct Loading of Component	19–3
21–1	Typical Stab Primers	21–1
21–2	Percussion Primer, M39A1	21–2
21–3	Electric Squib, M2	21–3
21–4	Typical Relays	21–12
21–5	Picatinny Arsenal Impact Test Apparatus	21–13
22–1	Digital Interval Timer Block Diagram	22–2
23–1	Miniaturized Modular Circuit Elements	23–3
23–2	Fluid Timer Assembly Illustrating Modular Design	23–4
23–3	Characteristics of the Source	23–6
23–4	Characteristics of the Load	23–6
23–5	Matching Source and Load Characteristics	23–7
23–6	AC Rectification Flueric Device	23–8
23–7	Heterodyning a Flueric Signal	23–9
23–8	Monostable Coded-tape Valve	23–10
23–9	Bistable Coded-tape Valve	23–10
23–10	Displacement-Time Relationship for Tape-element Switching	23–11
23–11	Exclusive OR Coded-tape Element	23–11
23–12	Tape Actuator	23–12
23–13	Forces Acting on Tape Segment	23–12
23–14	Force-Displacement Relationship for Actuator	23–12
23–15	Wobble-plate Signal Generator With Out-of-phase Signal Outputs	23–13
23–16	Vibrating-reed Frequency Sensor	23–13
23–17	Double-reed Frequency Sensor	23–13

SAMSUNG EXHIBIT 1028, Page 25

Downloaded from https://www.everyspec.com

LIST OF ILLUSTRATIONS (Con't.)

Fig. No.	Title	Page
23–18	Test Results for Double-reed Frequency Sensor	23–14
13–19	Flueric Moving-part Detector	23–14
23–20	Temperature-sensitive Flueric Resistor	23–14
23–21	Flow-Temperature Characteristics for Resistor Shown in Fig. 23–20	23–15
23–22	Adjustable Laminar-flow Flueric Resistor	23–15
23–23	Temperature-sensitive Flueric Resistor	23–15
23–24	Output Pressure-Temperature Characteristics for Circuit Shown in Fig. 23–23	23–15
23–25	Flow Regions for Air and Water in Round Tubes	23–17
23–26	Air Power Expended in Typical Rectangular Nozzles	23–17
23–27	Indirectly Heated, Single-thermocouple Flow Meter	23–18
23–28	Three-thermocouple Compensated Type Flow Meter	23–18
23–29	Stretched-metal Diaphragm Pressure Meter	23–19
23–30	Calibration Curve of a Typical Pressure Gage	23–20
23–31	Wobble-plate Type Signal Generator	23–22
23–32	Circular Cam Signal Generator	23–22
23–33	Loudspeaker-actuated Signal Generator	23–22
24–1	Relation of Altitude and Air Speed to Pressure	24–3
24–2	Basic Gas Generator	24–5
24–3	Container Volume vs Required Flow for Air Bottle and Gas Generator	24–7
24–4	Two Examples of Idealized Container Designs	24–9
24–5	Weight-to-Volume Ratio vs Length-to-Diameter Ratio for Cylindrical Tanks With Hemispherical End Caps	24–11
24–6	Relaxation Oscillator	24–11
24–7	Torsion Bar Oscillator	24–12
24–8	Sonic Oscillator	24–13
24–9	Temperature Compensating Scheme for Sonic Oscillator	24–14
24–10	Development of an Oscillator from the Half-adder Element	24–15
24–11	HPLF Oscillator	24–16
24–12	Theoretical Performance Curve for Feedback Oscillator Employing Distributed Parameter Ducts	24–17
24–13	Performance of Experimental Oscillator	24–18
24–14	Bistable Flip-flop	24–19
24–15	Wall Interaction Fluid Flip-flop	24–19
24–16	Five Port Flip-flop Schematic	24–20
24–17	Typical Operating Curves	24–21
24–18	Typical Performance Curves	24–22
24–19	High-stability, High-pressure-recovery, Wall-attachment Amplifier	24–22

SAMSUNG EXHIBIT 1028, Page 26

Downloaded from https://www.everyspec.com

LIST OF ILLUSTRATIONS (Con't.)

Fig. No.	Title	Page
24–20	Edgetone Amplifier	24–23
24–21	Stages of Binary Counter	24–24
24–22	Details of Fluid Flow in a Counter	24–25
24–23	Flow Diagram for a Typical Sequential Control System	24–27
24–24	Symbolic Logic Representation	24–28
24–25	Circuit Arrangement for Comparison Circuit	24–29
24–26	Flueric Equivalent of Fig. 24–25	24–30
24–27	Pressure vs Flow for Etched-glass Resistors	24–30
24–28	Pressure vs Flow for Flattened-tube Resistors	24–31
24–29	Resistance of an Orifice	24–32
24–30	Flow of Water Through a Porous-metal Resistor	24–32
24–31	Flow of Hydraulic Fluid Through a Porous-metal Resistor	24–33
24–32	Needle Valve With 1-deg Taper Angle	24–33
24–33	Crimping Tool Placed Over Resistor Tube	24–34
24–34	Stages of Operation–Turbulence Amplifier	24–35
24–35	Input-Output Pressure Relationship for Turbulent Amplifier With Control Flow Off	24–35
24–36	Typical Output Pressure vs Control Input Pressure for a Turbulence Amplifier	24–36
24–37	Turbulence Created by Electrophoresis Effect	24–36
24–38	Output Pulse for a Positive Input Pulse	24–37
24–39	Output Pulse for a Negative Input Pulse	24–37
24–40	Output Mechanism–Balanced Piston Type	24–39
24–41	Bellows Transducer for Fluid Timer	24–40
24–42	Location of Transducers on Timer Body	24–41
24–43	Bellows Actuated Rotary Switch	24–41
24–44	Output Interface Circuit for Flueric Timer	24–42
24–45	Pressure Sensitive Switch Used in Fluid Timer	24–43
24–46	Flueric Timer Setting Device Using Intermittent Gearing	24–43
24–47	Housing Assembly–Flueric Timer Setting Device	24–44
24–48	Sleeve Hole Locations	24–44
24–49	Flueric Timer Packaged for Artillery Fuze	24–44
24–50	Fluid Timer With Card Preset	24–45
24–51	Preset Stage for an 18 Binary Field	24–46
25–1	Comparison of Plastic Forming Processes for Fabricating Economic Production Quantities	25–4
25–2	Photoetching of Photosensitive Plastic	25–4
25–3	The Screw Method of Injection Molding	25–5
25–4	Compression Molding	25–6
25–5	Transfer Molding	25–6
25–6	The Plunger Method of Die Casting	25–8
25–7	The Vacuum Method of Die Casting	25–8
25–8	Photoetching Process and Design Considerations	25–9

SAMSUNG EXHIBIT 1028, Page 27

Downloaded from https://www.everyspec.com

LIST OF ILLUSTRATIONS (Con't.)

Fig. No.	Title	Page
25–9	Chemical Milling, Showing the Effect Upon the Workpiece	25–10
25–10	Electrical Discharge Machining Arrangement	25–10
25–11	Electroforming	25–11
25–12	Cross Section of Typical Channel Etched in Photosensitive Glass	25–12
25–13	The Photoetching Process for Ceramics and Some Examples of Etched Photosensitive Ceramic	25–13
25–14	Ultrasonic Machining	25–13
25–15	Electron Beam Machining	25–15
26–1	Silver Plating Action	26–2
26–2	Bisset-Berman E-Cell	26–3
26–3	Operating Curve of Coulometer at Constant Current	26–4
26–4	Coulometer Detector Circuit	26–4
26–5	Typical Coulometer Voltage-current Characteristics	26–5
26–6	Electroplating Timer With Mechanical Readout	26–5
26–7	Interval Timer, MARK 24 MOD 3	26–7
26–8	Mechanical Readout Timer by Gibbs	26–8
26–9	Solion Timer	26–9
26–10	Typical Polarization Curves for the Solion	26–9
26–11	Mercury Timer	26–10
27–1	Elements of Nuclear Decay Timer	27–1
27–2	Decrease in Radioactivity as a Function of Use and Storage Period	27–2
27–3	Semiconductor Radiation Detectors	27–4
A–1	Symbol and Switch Analogy for AND Gate	A–1
A–2	Symbol and Switch Analogy for OR Gate	A–1
A–3	*not* Symbol is Bar Over Letter	A–2
A–4	Symbolic Representation of *not* A AND *not* B, also *not* (A AND B)	A–2
A–5	Venn Diagram for Fig. A–4	A–2
A–6	Symbols for the Basic Gates	A–3

SAMSUNG EXHIBIT 1028, Page 28

Downloaded from https://www.everyspec.com

LIST OF TABLES

Table No.	Title	Page
1–1	Timers Discussed in Handbook	1–2
1–2	General Characteristics of Timers	1–2
2–1	Loran-C Station Data	2–6
2–2	Reference Oscillator Requirements	2–8
3–1	Characteristics of Atomic and Quartz Crystal Frequency Standards	3–2
4–1	Designation of Quartz Vibrators	4–6
4–2	Summary of Characteristics of 5-MHz Crystal Unit	4–7
4–3	Analysis of Monometallic Type Fork	4–12
4–4	Physical Data Relating to Available Atomic Frequency Standards	4–16
5–1	Summary of HP Flying Clock Experiments	5–15
7–1	Comparison of Various Oscillators	7–4
7–2	Sampling Plan	7–5
7–3	Resistor Characteristics	7–7
7–4	Relative Performance of Various Oscillator Types	7–10
7–5	Comparison of Various Frequency Dividers and Counters	7–11
7–6	Operating Requirements	7–12
7–7	Electrical Requirements	7–13
7–8	Comparison of Radiation from Natural Substances	7–15
8–1	Types of Integrated Circuit	8–5
8–2	Compatible Thin-film Processes	8–7
8–3	Thin-film Resistor Materials	8–8
8–4	Typical Dielectric Materials	8–8
8–5	Values for Integrated Resistors	8–13
8–6	Values for Integrated Capacitors	8–13
8–7	Comparison of Properties of Typical Potting Materials	8–15
8–8	Copper-foil Thickness and Toierance	8–16
8–9	Clad-copper Thickness and Tolerance	8–16
8–10	Recommended Conductor Spacing	8–17
10–1	Changes in Timing Interval for Changes in Voltage	10–3
11–1	Relative Performance of Various Oscillator Types	11–14
11–2	Timer Power Supplies (Volume and Size)	11–23
11–3	Environmental Requirements	11–23
11–4	Electrical Requirements	11–23
11–5	Primary Power Supply Single Cells	11–25
11–6	Primary Power Supply Multicells	11–26
13–1	Comparison of Time Bases	13–2
13–2	Characteristics of XM4 Timer	13–16
13–3	Safety and Surveillance Tests	13–17

SAMSUNG EXHIBIT 1028, Page 29

Downloaded from https://www.everyspec.com

LIST OF TABLES (Con't.)

Table No.	Title	Page
14–1	Common Timer Lubricants	14–4
14–2	Supporting Data Package	14–6
15–1	Predominant Frequencies Measured in Cargo Spaces of Various Military Transport Vehicles	15–6
15–2	Percentage of Travel Time vs Speed Range for Fig. 15–6	15–10
16–1	Approximate Accuracies of Timepiece Types	16–4
16–2	Tabular Comparison of Motor Springs	16–9
16–3	Effect of Characteristics of Printed Matter on Legibility	16–76
18–1	Effect of Loading Pressure on $BaCrO_4$-B Compositions	18–2
18–2	Effect of Fuze Housing Material and Dimensions on Burning Time of Barium Chromate-Boron Compositions	18–3
20–1	Excerpt from Quantity-Distance Tables	20–4
21–1	Common Priming Compositions	21–2
21–2	Fuels for Delay Compositions	21–4
21–3	Oxidants for Delay Compositions	21–5
21–4	Heats of Reaction of Inorganic Mixtures Considered for Delays	21–7
21–5	Gasless Delay Compositions in Current Use	21–8
21–6	Effect of Ingredients on Burning Rate of Manganese Delay Compositions	21–9
21–7	Effect of Housing Material on Burning Rate of Manganese Delay Compositions	21–9
21–8	Effect of Dry Storage on Burning Time of Manganese Delay Compositions	21–10
21–9	Burning Rates of Various Tungsten Delay Compositions	21–10
21–10	Variations of Burning Rate Due to Change in Particle Size of Tungsten Delay Composition	21–10
21–11	Delay Characteristics for Various Percentages of Boron	21–11
21–12	Variation of Burning Rate With Loading Pressure of Barium Chromate/Boron Compositions	21–12
23–1	Characteristics of Digital Flueric Devices	23–2
24–1	Comparison of Fluid Power Supplies	24–2
24–2	Equations for Container Design	24–10
24–3	Truth Table for a Three Stage Binary Counter	24–23
24–4	BCD Truth Table	25–25
24–5	Excess Three BCD Truth Table	24–26
24–6	Excess Four BCD Truth Table	24–26
24–7	Truth Table for Gray Code Counter for Mechanizing Flow Diagram for the Typical Sequential Control System of Fig. 24–23	24–27

SAMSUNG EXHIBIT 1028, Page 30

Downloaded from https://www.everyspec.com

LIST OF TABLES (Con't.)

Table No.	Title	Page
24–8	Truth Table for a Single OR/NOR Element	24–28
24–9	Truth Table for a Single AND/NAND Element	24–29
25–1	Suitable Materials for Flueric Devices	25–2
25–2	General Characteristics of Materials and Consequent Application Considerations	25–3
25–3	Typical Surface Dimensional Tolerances in Photoetch Process	25–9
25–4	Comparisons of Various Fabrication Techniques for Flueric Devices	25–14
27–1	Radioisotopes Applicable to Nuclear Time Bases	27–3
A–1	Boolean Postulates and Equations	A–2

SAMSUNG EXHIBIT 1028, Page 31

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LIST OF SYMBOLS*

*Units and subscripts are defined where used

A	= area
a	= acceleration
AC	= alternating current
BR	= beat rate
b	= width
C	= capacitance
C	= Coulomb capacity
C	= viscous damping coefficient
c	= velocity of light
d	= diameter
DC	= direct current
E	= equivalent weight
E	= rebound coefficient
E	= Young's modulus of elasticity
F	= Faraday's constant
F	= force
f	= frequency
G	= gain
G	= shear modulus of elasticity
G	= torque

SAMSUNG EXHIBIT 1028, Page 32

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g = acceleration due to gravity

H = energy per cycle

H = power

h = thickness

I = current

I = moment of inertia

i = gear velocity ratio

J = ratio of moments of inertia

K = time magnification

k = proportionality constant

k = spring constant

L = inductance

L = latitude

Lo = longitude

ℓ = length

M = constant

m = mass

N = number of gear teeth

N = number of turns in a spring

n = factor

n = number of cycles

n = span of pallet

P = pressure

p = number of poles

SAMSUNG EXHIBIT 1028, Page 33

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Q = flow

Q = quality factor

R = recovery

R = resistance

R = sliding friction coefficient

R = universal gas constant

R_e = Reynolds number

r = burning rate

r = radius

S = length-to-diameter ratio

s = distance

T = period

T = temperature

T = tension

t = time

V = voltage

V = volume

v = velocity

W = weight

w = flow rate

X = forcing function

Z = impedance

α = escapement angle

α = temperature coefficient of the modulus of elasticity

SAMSUNG EXHIBIT 1028, Page 34

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β = current gain

β = temperature coefficient of frequency

γ = temperature coefficient of linear expansion

Δ = deflection

δ = change in voltage ratio

ϵ = gear ratio parameter

η = gear train efficiency

η = viscosity

θ = angle

θ = angular displacement

λ = length ratio

μ = coefficient of friction

ν = kinematic viscosity

ρ = density

σ = stress

σ = total pallet travel angle

τ = pitch

ϕ = angle through which gear turns

ϕ = escape wheel drop

ϕ = flux

χ = gear train ratio

χ = pallet and tooth lead

Ω = precessional angular velocity

ω = angular velocity

SAMSUNG EXHIBIT 1028, Page 35

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PREFACE

The Engineering Design Handbooks of the US Army Materiel Command have evolved over a number of years for the purpose of making readily available basic information, technical data, and practical guides for the development of military equipment. While aimed primarily at US Army materiel, the handbooks serve as authoritative references for needs of other branches of the Armed Services as well. The present handbook covers timing systems and components.

This handbook presents both theoretical and practical data pertaining to design methods and procedures for timing systems and devices. The subjects covered are precision reference timers, electronic timers, mechanical timers, pyrotechnic timers, flueric timers, and a few others.

Prepared as an aid to military designers, this handbook should also be of benefit to scientists and engineers engaged in other related research and development programs or who have the responsibility for the planning and interpretation of experiments and tests concerning the performance of materiel related to timers.

The handbook was prepared by The Franklin Institute Research Laboratories, Philadelphia, Pennsylvania. It was written for the Engineering Handbook Office of Duke University, prime contractor to the US Army Materiel Command. Its preparation was under the technical guidance and coordination of a special committee with representation from various agencies of the US Army Materiel Command.

The Engineering Design Handbooks fall into two basic categories, those approved for release and sale, and those classified for security reasons. The US Army Materiel Command policy is to release these Engineering Design Handbooks in accordance with current DOD Directive 7230.7, dated 18 September 1973. All unclassified Handbooks can be obtained from the National Technical Information Service (NTIS). Procedures for acquiring these Handbooks follow:

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SAMSUNG EXHIBIT 1028, Page 36

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TIMING SYSTEMS AND COMPONENTS

INTRODUCTION

CHAPTER 1

THE NATURE OF TIMING SYSTEMS*

A timer is a programming device; its purpose is to control the time interval between an input signal and an output event or events†. There are four essential components in all timers: (1) a start system that initiates the programming action, (2) a power supply that sustains the timing action, (3) a time base or regulator, and (4) an output system that performs the required operation at the end of the desired time interval.

1-1 PURPOSES AND FACTORS AFFECTING USE

In selecting the components of timing systems, the designer must first determine the purpose for which the system is to be used and the factors influencing the selection of components. Some of the factors to be considered in the choice of the basic mechanism are:

(1) Time Range. What timing intervals, time delays, sequencing, and programming are to be provided?

(2) Time Variation. Is the system to be designed to provide a fixed time interval, or is it to be variable? Is the time period to be adjustable locally or remotely; manually or automatically? What is the range of adjustment which will be required?

(3) Reliability. What reliability level is required?

(4) Accuracy. What timing accuracy or what repeatability is required?

(5) Safety. Must the timer be fail safe? Must it reset after interruption?

(6) Power Source. Will the timer be powered by a spring, g-weights, battery, AC mains, barometric pressure change, or other means?

(7) Input Signal. What is the input signal?

(8) Output Signal. What is the output signal? It is a mechanical motion; electronic, digital, or analog?

(9) Environment. What are the environmental extremes to which the timer will be exposed, and in which it must operate?

(10) Cost. Will the cost of the timer be compatible with the cost of the total system?

(11) Maintenance. Is maintenance or repair required? If so, how can it be facilitated?

1-2 TIMER TYPES

The types of timer discussed in this handbook are listed in Table 1-1. When discussing the various designs, timers are classified into one of the types shown depending upon the method used to generate the time base.

*Principal contributors to this handbook were Gunther Cohn, Joseph F. Heffron, Paul F. Mohrbach, Daniel J. Mullen, Raymond R. Raksnis, Melvin R. Smith, Ramie H. Thompson, and Robert F. Wood.

†Distinct terms for timing systems and components are defined in the Glossary.

SAMSUNG EXHIBIT 1028, Page 38

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TABLE 1-1

TIMERS DISCUSSED IN HANDBOOK

Timer Type	Handbook Organization: Part	Chapters	Introductory Chapter
Precision Reference Timers	One	2–5	2
Electronic Timers	Two	6–11	6
Mechanical Timers	Three	12–16	12
Pyrotechnic Timers	Four	17–21	17
Flueric Timers	Five	22–25	22
Miscellaneous Timing Devices (Electro-mechanical Timers, Nuclear Time Base Generators)	Six	26, 27	

Each part (One to Five) in this handbook begins with an introductory chapter that contains detailed definitions pertaining to the particular timer type, lists of advantages and disadvantages, and discussions of specific military applications, requirements, and auxiliary equipment used. This same information is contained in the two chapters comprising Part Six. Therefore, this general introductory material is not included in this chapter. Succeeding chapters in each Part discuss system design considerations, production techniques, packaging, storing, and shipping procedures, and component design details to the extent that those topics apply to the particular timer type.

1-3 RELATION OF ACCURACY, OUTPUT, POWER, AND COST

General timer characteristics are listed in Table 1-2. As a general rule, there is a direct relationship between the accuracy of a timing device and its output power and cost. Those timing devices that are most accurate, such as the quartz crystal controlled units and the cesium beam standards, are likely to have the least output power and to be the highest in cost. Those timers that have a lower order of accuracy, such as the pyrotechnic delays and the untuned-escapement mechanical timers, are likely to provide more output power and to be lower in cost.

TABLE 1-2

GENERAL CHARACTERISTICS OF TIMERS

Features	Precision Reference	Electronic	Mechanical	Pyrotechnic	Fluerie	Electro-chemical
Input to start	Voltage pulse	Voltage	Voltage or mechanical	Voltage, flame, or firing pin	Fluid pressure	Voltage, chemical release
Time ba	Crystal or atomic	Oscillator	Escapement, motor, tuning fork	Pyrotechnic burning rate	Oscillator	Rate of chemical reaction
Time range	10^{-9} sec to years	10^{-3} to 10^{3} sec	Seconds to days	10^{-3} to 10^{3} sec	1 to 10^{3} sec	Minutes to days
Accuracy	1 part in 10^{6} to 1 part in 10^{12}	±0.1%	±5% to 1 part in 10^{6}	±10%	±1%	±4-10%
Output	Voltage pulse or time interval	Voltage	Mechanical	Flame	Fluid pressure, voltage	Chemical reaction, voltage, chemical

SAMSUNG EXHIBIT 1028, Page 39

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1-4 MILITARY APPLICATIONS

All of the timing systems and components discussed in this handbook are of interest to the military. Many of the timers are components of ammunition, fuzing, or control devices. Particularly in fuzes where delays are crucial to safe and effective performance, timers are almost always present. Timers and time delay devices for various fuze types are covered in different chapters, depending on the type of timer used. Timers for most safing and arming devices, being mechanical, are discussed in Chapter 13. If information is sought about a particular fuze in this handbook, it is best located through the Index.

Since this is a timer handbook, fuzes and fuze explosive components are discussed herein only to the extent that knowledge of their operation aids the design of timing systems and components. For design details of fuzes and their components, see the following references:

(1) AMCP 706-179, Engineering Design Handbook, *Explosive Trains*.

(2) AMCP 706-210, Engineering Design Handbook, *Fuzes*.

(3) MIL-HDBK-137, *Fuze Catalog*, Department of Defense, 20 February 1970.
Vol. 1, *Current Fuzes (U)* (Confidential report).
Vol. 2, *Obsolete and Terminated Fuzes*.
Vol. 3, *Fuze Explosive Components (U)* (Confidential report).

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PART ONE – PRECISION REFERENCE TIMERS

CHAPTER 2

INTRODUCTION TO PRECISION REFERENCE TIMERS

2-1 TIME STANDARDS

Timekeeping has two distinct aspects: determination of date (or epoch) and determination of interval. Date is concerned with when an event occurred whereas interval is some fixed multiple or fraction of the unit of time and is independent of a starting point[1]*. For measurement purposes, an accurate time scale is set up so that, from a chosen origin point, a constant unit is laid off until the resulting scale extends over the interval of interest.

A system of time measurement requires regularly occurring, uniform, periodic phenomena as a reference base. Since man's earliest concern with time was linked with the passing of the days and nights, a system of time measurement evolved that was based on rotation of the earth. The rate of the rotation is determined by measuring the motion of some point on the earth's surface with respect to some celestial object or position. It was established that all time measurements based on the rotation of the earth are subject to nonuniformity due to periodic and irregular variations in the speed of rotation. These variations are detectable and compensatable, but the corrections, of necessity, must be made after the occurrence of the event. Time systems of this type are now known as rotational or nonuniform time whereas systems of measurement that are independent of the earthly day are called uniform time. A number of the time systems or standards of time which have been developed are described in the paragraphs that follow.

*Superscript numbers refer to References listed at the end of each chapter.

2-1.1 APPARENT SOLAR TIME

The apparent solar day is the interval of time between two successive lower transits of the sun's center over the same meridian, where a meridian is defined as a great circle passing through a given point and the two poles. Hence, a meridian is the intersection of a plane, through the poles and the given point, with the surface of the earth[2]. A system has been established of 24 standard meridians originating in Greenwich, England, and spaced every 15 deg about the surface of the earth. This system is used for navigational purposes and for time standardization. A lower transit occurs at apparent midnight. However, due in part to the fact that the earth's orbit is elliptical rather than circular and the orbital plane does not coincide with the plane of the equator, the apparent solar days vary in length.

2-1.2 MEAN SOLAR TIME

The system of mean solar time was devised to overcome the problem of variable day length. It is, however, actually based on sidereal time. Each day is of the same length, this length being equal to the average length of all the days in a solar year. The effect is the same as if the earth's orbit were circular and in the same plane as the equator. There is no means of observing mean solar time directly; nor can the apparent solar time be determined

SAMSUNG EXHIBIT 1028, Page 41

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directly with adequate accuracy. In practice sidereal time is observed, and mean and apparent solar times are calculated. The difference between apparent solar time, and mean solar time varies approximately ± 16 min in the course of a year. This difference is known as the equation of time. It should be noted that, while mean solar days are of uniform length, they are approximately 4 min longer than the period of the earth's rotation[3] with respect to a fixed star.

2-1.3 SIDEREAL TIME

The system of sidereal time avoids some of the problems caused by the earth revolving around the sun, seasonal and other changes, and provides a convenient method of locating celestial bodies. A sidereal day is defined as the interval between two successive upper transits of the vernal equinox over the same meridian[4]. The vernal equinox is formed by the intersection of the plane of the ecliptic with the plane of the earth's equator. This intersection is also called the "First Point of Aries" and is a fundamental reference point for locating celestial bodies[1]. However, due to the complex motion of the earth's poles, the vernal equinox does not remain fixed and consequently the sidereal day is not only somewhat shorter than the period of the earth's rotation but is also of variable length. These effects are small, and suitable corrections are possible.

2-1.4 UNIVERSAL TIME

Universal Time (UT) closely approximates mean solar time but in practice is derived from sidereal time which, in turn, is determined from the meridian transits of selected stars. Universal time is, therefore, a form of rotational time and is subject to the attendant irregularities. Over the years there have been improvements in detecting and predicting the variations in the earth's rotation, and universal time has been revised accordingly. Consequently there are now several subdivisions of this system[3]:

(1) UT_0 – Universal time calculated directly from observed sidereal time. This measure of universal time contains irregularities due to polar motions as well as rotational variations.

(2) UT_1 – Universal time derived by corrections of UT_0 for observed polar motion. However, irregularities due to variations in rotation remain.

(3) UT_2 – Universal time derived by correcting UT_0 for both observed polar motions and extrapolated seasonal variation in the rate of the earth's rotation. This measure of universal time is virtually free of nonuniformity due to periodic changes in rotation but irregularities caused by irregular variation in rotation are not wholly corrected.

(4) UTC – Internationally Coordinated Universal Time (UTC) approximates UT_2 and is used as the basis for all civil time keeping. As instituted on 1 Jan 1972, coordinated universal time proceeds at the same rate as atomic time (see par. 2-1.6) and differs from the latter by an exact multiple of one atomic second. Step changes in UTC of precisely one second (leap second) are introduced on 1 Jan and/or 1 July when required to keep the difference between UTC and UT_2 to less than ± 0.7 sec. The time signal emitted by the HF standard time and frequency transmitters (such as WWV) are coded to permit the users of these signals to determine the difference to UTC-UT, to within 0.1 sec.

2-1.5 EPHEMERIS TIME

Ephemeris time is based on the revolution of the earth around the sun. It is obtained in practice from observations of the motion of the moon about the earth. In October 1956, the International Committee of Weights and Measures defined the second of ephemeris time as the fraction 1/31,556,925.9747 of the tropical year for January 0, 1900 at 12 hours ephemeris time (January 0, 1900 = December 31, 1899)[1]. Since the unit of ephemeris time

SAMSUNG EXHIBIT 1028, Page 42

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is thus of constant length by definition, ephemeris time is a uniform time scale.

2-1.6 ATOMIC TIME

When an electron makes a transition from one energy state to another in an atom, it absorbs or emits energy. The amount of energy absorbed or emitted is equal to the difference in the energy of the two states. If the absorption or emission is in the form of electromagnetic energy (photons), its frequency is proportional to the change in electron energy. This means that an electron making a given transition in a given atom emits or absorbs a definite amount of energy at a specific frequency. It is this particular characteristic of atoms that serves as the basis for atomic clocks[4]. The most extensively developed atomic oscillator currently used as a time standard is the cesium beam resonator. This device utilizes a specific transition of the cesium atom. The frequency of oscillation has been *established*, in 1956, as 9,192,631,770 cycles per ephemeris second. Atomic time is the time based on this transition. The internationally coordinated atomic time scale is designated IAT. One second in the international systems of units has been *defined*, in 1967, as the duration of 9,192,631,770 cycles of this specific transition of the cesium atom. The IAT second is thus equal to the ephemeris second to within the errors in the determination of the latter. In the course of observations extending over many years, no difference in the rates of the atomic vs the ephemeris time scales has yet been found. Except for a (constant) difference in the origins of these two time scales, atomic time and ephemeris time are thus synonymous. From a practical standpoint, however, atomic time has all but replaced ephemeris time because of its vastly superior accessibility.

2-1.7 U S STANDARD TIME

U S Standard Time differs from the internationally coordinated universal time by an integral number of hours. The Master clock of the U S Naval Observatory, Washington, D.C., determines Standard Time for the United States. The master clock consists of an atomic resonator, a quartz crystal oscillator, and a clock movement. The Naval Observatory determines universal time and ephemeris time from astronomical observations, and publishes data that enable one to obtain the different kinds of time used in geodesy, navigation, and scientific work. The various clocks and frequency standards used in generation of signals for precision timers are discussed in par. 3-1.

2-2 FREQUENCY STANDARDS

Time standards and frequency standards are based upon dual aspects of the same phenomenon[5]. The reciprocal of time interval is frequency. As a practical matter, a standard of frequency can serve as the basis for time measurement. To avoid errors, when a frequency standard is used to maintain time (either interval or date) care must be taken to reference the frequency to the time scale of interest. If frequency is quoted in the units "hertz", the corresponding time interval will be in seconds, the unit of time in the international system of measure. The present international standard is based on the transition of the cesium (Cs) atom as discussed in par. 2-1.6. This Cs transition is also the fundamental reference for a frequency measurement. A Cs frequency standard consists basically of a quartz crystal oscillator, a synthesizer that translates the crystal frequency to the Cs frequency, a Cs beam tube, and a servo feedback loop that adjusts the crystal frequency so that the synthesizer output is always at the resonance frequency of the Cs atoms. If the standard is operating on the atomic time scale, one million cycles of the 1 MHz signal describe one second.

It is not necessary to have physical access to an atomic frequency standard to obtain a reference for accurate frequency measure-

SAMSUNG EXHIBIT 1028, Page 43

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ments. A local crystal oscillator can be controlled or monitored by suitable standard frequency and time signal emissions, provided these emissions are controlled by atomic clocks at the transmitter.

A local frequency standard can be maintained to within one part in 10^{10} or better by comparison of its relative phase or time difference to that of a received very low frequency (VLF) or high frequency (HF) carrier[4]. Any one of a number of monitoring systems may be chosen to make this comparison possible, depending on the degree of precision required for the relative phase measurement. For the greatest precision, the local standard must have a low drift that is predictable to within a few parts in 10^{10} over several days[1]. Averaging the time from days to months may be required to obtain very high accuracies.

Exceptions are the transmissions from the Loran-C system (see par. 2-4.1(2)) if received within about 1500 miles from the transmitter. It is possible to transfer the stability of the master clock that controls the transmission to the local oscillator to within 1×10^{-11} on a continuous basis, and averaging times are in the order of 100 sec. Anyone receiving these signals, which are controlled by the U S Naval Observatory frequency and time standards, has access to one of the most precise frequency standards available. (Previous frequency offsets – 3 parts in 10^8 from a nominal value of 100 kHz – in all standard transmissions were abolished on 1 Jan. 1972.)

2-3 DISCUSSION OF REQUIRED PARAMETERS

Several parameters are used to compare the performance qualities of precision reference timers. Any discussion of this subject requires a basic understanding of the following terms[6]:

(1) Accuracy. The degree to which the frequency of an oscillator is the same as the frequency of an accepted primary standard or the degree to which the frequency of an oscillator corresponds to the accepted definition of frequency. The particular reference standard or the particular definition of frequency must be included in the statement of accuracy.

(2) Reproducibility. The degree to which an oscillator of a given type will produce the same frequency from unit to unit and from one occasion of operation to another. In general, the degree to which the frequency of an oscillator may be set by a calibration procedure is included within this definition of reproducibility.

(3) Intrinsic Reproducibility. The degree to which an oscillator will reproduce a given frequency without the need for calibrating adjustments either during manufacture or afterward. This quality is a characteristic of an apparatus design and not a characteristic of a resonance.

(4) Stability. The degree to which an oscillator will produce the same frequency over a period of time once continuous operation has been established. The specification of a stability value requires a statement of the time interval involved in the measurement, and the complete specification constitutes a functional relationship for which the measuring interval is the independent variable.

A frequency standard must provide a stable, spectrally pure signal if it is to yield a narrow spectrum after multiplication to the microwave region. The high signal-to-noise ratio requirements for quality communication systems have been met by the specification of narrow band widths, which in turn require stable narrow-band signals.

The quality of a precision quartz oscillator usually is expressed in terms of long-term and short-term stability. Long-term stability is sometimes called aging rate and usually is expressed in fractional parts per unit time, as

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"3 parts in 10^9 per day". It refers to slow changes with time in average frequency. arising usually from secular changes in the resonator or other elements of the oscillator. Short-term stability refers to changes in average frequency over a time span sufficiently short that long-term effects may be neglected.

(5) Spectral Purity. The spectral purity expresses the same information in the frequency domain as that expressed by stability in the time domain. A very crude oscillator will have a reasonably good spectrum at the frequency of oscillation; but, with frequency multiplication, the spectrum rapidly degrades. It is, therefore, necessary to have an extremely well-defined spectrum at the outset so that further multiplication into the microwave region will maintain acceptable quality. A simple way to improve spectral purity is to put the oscillator signal through a narrow band-pass filter before multiplication, or to phase lock a low noise oscillator to the multiplied signal.

2-4 MILITARY APPLICATIONS

2-4.1 NAVIGATION, POSITION FINDING

During peacetime the navigation of a military aircraft on a routine flight differs little from that of a similar nonmilitary aircraft. However, some military operations require high selective accuracy. Examples are a tanker seeking to rendezvous with an aircraft it is to replenish, a reconnaissance aircraft returning to its carrier, a fighter providing close support at front lines, an emergency supply aircraft, or one seeking survivors in a lifeboat. In addition, many military missions require a passive system to avoid betraying one's position, and vulnerability to manmade disturbances (jamming) must be considered. Similar conditions exist for a ship at sea.

Position finding or fixing is the determination of the position of the craft (a fix) without reference to any former position. To accomplish this with sufficient accuracy, one must depend on available precision reference signals:

(1) Loran. Loran (*LO*ng *RA*nge *N*avigation) was developed during World War II, at the MIT Radiation Laboratory, to provide ships and aircraft with a means of precise navigation. Basically, a Loran chain consists of a master and two or more slave stations. A pulse transmitted from the master station is received via ground wave by a slave station, which, in turn, transmits its pulse at a fixed time later. This fixed time, known as the coding delay, is kept constant by monitor stations that steer the chain. The time difference between reception of a master-slave pulse pair determines a hyperbolic line; the intersection of two such lines gives position.

Standard Loran, also known as Loran-A, operates in the 2-MHz band[7]. Each station transmits pulses of 45-μsec duration, which occupy a band width of 75 kHz.

(2) Loran-C. Loran-C was developed to extend Loran coverage with fewer stations. The Loran-C system, a pulsed radio navigation system is operated on a 100-kHz carrier by the U S Coast Guard, and offers a means for precision transfer of time. Clock synchronization to $\pm$ 1 μsec is possible within range of the east coast Loran-C chain. All Loran-C stations are now controlled by atomic clock standards and the emissions are monitored by the U S Naval Observatory[1]. Table 2-1[7] lists the locations of 30 Loran-C stations presently in operation. Loran-C signals are usable for ground wave reception to about 1500 km landward, 3000 km seaward, and about 10,000 km skyward at reduced accuracy[7].

Changes in Loran-C station emissions are published in "Time Service Announcements" published by the U S Naval Observatory. Ref. 8 is a discussion of the means of using Loran-C and includes the possible sources of error.

SAMSUNG EXHIBIT 1028, Page 45

TABLE 2-1. LORAN-C STATION DATA

Chain	Period, Rate μsec	Master[a]	Slaves[a,b] W	X	Y	Z
East Coast	SS-0 100 000	Cape Fear, N.C. ("T" slave sometimes broadcasts from Wildwood, N.J. at ED 84028.7 μsec)	Jupiter, Fla	Cape Race, Newfoundland (4 MW)	Nantucket Island, Mass.	Dana, Ind.
			13 695.5	36 389.6	52 542.5	68 564.2
Central Pacific (Hawaiian)	SH-4 59 600	Johnston Island		Upolo Point, Hawaii	Kure Island, Hawaii	
				15 971.8	35 252.4	
Mediterranean	SL-4 79 600	Simeri Chichi (Catanzaro), Italy		Matratin, Libya	Targabarun, Turkey	Estartit, Spain
				14 107.6	32 273.3	50 999.7
North Atlantic	SL-7 79 300	Angissoq, Greenland (500 kW)	Sandur, Iceland (4 MW)	Ejde, Faeroe Islands		Cape Race, Newfoundland (4 MW)
			15 068.2	27 803.9		48 212.3
Northern Pacific (Alaskan)	SL-2 79 800	St. Paul, Pribiloff Islands		Sitkinak, Alaska	Attu, Aleutian Islands	Port Clarence, Alaska (1850 kW)
				14 284.4	31 875.3	53 069.1
Norwegian Sea	SL-3 79 700	Ejde, Faeroe Islands	Sylt, Germany	Bo, Norway	Sandur, Iceland	Jan Mayen, Norway
			30 065.6	15 048.1	48 944.5	63 216.3
Northwest Pacific	SS-3 99 700	Iwo Jima (4 MW)	Marcus Island (4 MW)	Hokkaido, Japan	Gesashi, Okinawa	Yap Island (4 MW)
			15 283.3	36 685.2	59 463.0	80 746.5
Southeast Asia	S-3 49 700	Sattahip, Thailand		Lampang, Thailand	Con Son Island, South Vietnam	
				13 182.8 (computed)	29 522.1 (computed)	

[a]Power 250-400 kW, except where noted.
[b]Emission delay given with reference to master. Information current but subject to change.

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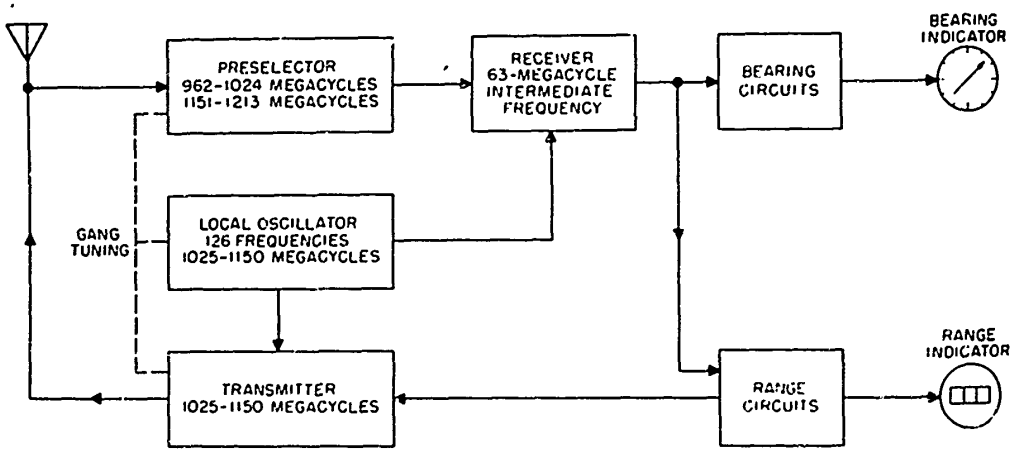


Figure 2-1. Components of Airborne Air Traffic Control Equipment[9,10]

2-4.2 AIR TRAFFIC CONTROL

In air traffic control, military aircraft may use TACAN (*Tac*tical *A*ircraft *N*avigation System) navigation equipment. TACAN is a military omnibearing and distance measurement system using the same pulses and frequencies for the distance measurement function as the Standard DME (Distance Measuring Equipment) system[9]. It is of the polar-coordinate type, i.e., there is a bearing facility that provides on the aircraft a meter indication of its direction in degrees of bearing from the ground beacon chosen by the pilot. There is also a distance facility that provides on the aircraft a meter indication in nautical miles of its distance from the ground beacon. Fig. 2-1[10] shows the components of airborne TACAN equipment such as the AN/ARN-21. A crystal-controlled 4044-Hz oscillator is used as a yardstick or time reference. In essence, the time interval between interrogation and reply is measured in terms of the corresponding number of cycles and fractions of a cycle of the 4044-Hz reference wave. The crystal controlled oscillator generates range markers that serve to measure microsecond intervals for the accurate measurement of distance[10].

2-4.3 COMMUNICATIONS

Modern military communication systems in which frequency stability of the transmitting and receiving equipment are supplied by a stable clock or precise interval control include synchronous digital transmission, switching, terminal, and security equipment[11].

Military applications require operation under severe environmental conditions, and usually impose restrictions on size and weight as well, particularly in airborne equipment. In mobile systems, Doppler shifts and time variations due to changing transmission path lengths must be compensated for by either automatic correction circuits or by manual readjustment of local equipment[12].

As an example, Table 2-2[13] summarizes the present and future frequency control requirements for SSB equipment. To obtain these requirements, a high degree of frequency-temperature stability must be obtained for the crystal oscillator along with low aging for the crystals and improvements in the frequency synthesizers.

The TRI-TAC communication system is planned to provide the Armed Forces with

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TABLE 2-2
REFERENCE OSCILLATOR REQUIREMENTS[13]

	Present SSB Voice	Future SSB Secure Voice
Δf (Total)	± 40 Hz	± 5 Hz
Δf/Equipment	± 20 Hz	± 2.5 Hz
$\frac{\Delta f}{f}$ (HF, 30 MHz)	6.7×10^{-7}	8.3×10^{-8}
$\frac{\Delta f}{f}$ (VHF, 76 MHz)	2.6×10^{-7}	3.3×10^{-8}
Temperature Range	−40° to +75°C	−40° to +75°C
Time (for frequency re-calibration)	26 wk	120 wk

the capability of a fully tactical, automatically switched, digital, secure communications network. Three methods for system synchronization other than the master-slave relationship are frequency averaging, independent atomic clocks, and bit stuffing[14].

A new multifunction avionic system based on the use of accurately synchronized clocks at each terminal of the system has been proposed[15]. The system must be synchronized to the order of 10 to 100 nsec if range accuracy of ±10 to 100 ft is required. These accuracies are currently achievable, both by atomic frequency standards and by less accurate crystal standards in systems where it is practical to resynchronize the remote station clocks to a common system time.

2-4.4 IFF (IDENTIFICATION, FRIEND OR FOE)

Secondary radar, originally used during World War II to identify friendly aircraft and ships, was known as IFF. Each vehicle was equipped with a pulse transponder that, upon receiving a radar pulse, replied with a specially coded group of pulses. These pulses, displayed on a radar screen next to the radar reply, indicated that the reply was from a friend. The pulse codes frequently were changed to guard against enemy use of captured equipment.

Secondary surveillance radar, or radar beacon, is an updated version of this system. Secondary surveillance radar uses equipment on the ground to transmit an interrogation signal to the aircraft that transmits a response back to the ground station. If the transponder in the aircraft is set to respond, it transmits a signal to the ground equipment that is processed and displayed on a radar screen. The interrogation pulse groups consist of several modes (Fig. 2-2[9]), the selection of which is either controlled by the ground operator or automatically selected in a mixed sequence. Before the transmitter of the airborne transponder will reply, the proper pulse pairs must be received and processed within the transponder. The transponder reply codes are shown in Fig. 2-3[9]. Two framing pulses spaced 20.3 μsec apart with 12 information pulses between them provide the basic reply code. Thus, the code system is capable of producing 4096 different coded identification replies. In addition to the information pulses, a special position identification (SPI) pulse may be used with any of the 4096 codes upon request[9].

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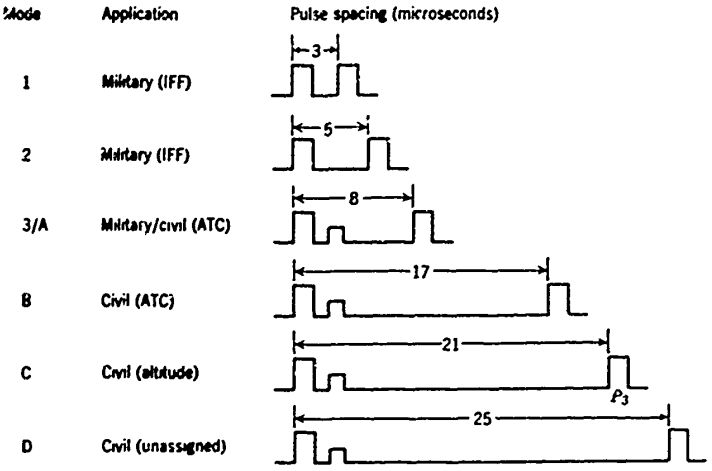


Figure 2-2. Interrogation Pulse Modes Used on Secondary Surveillance Radar[9,10]

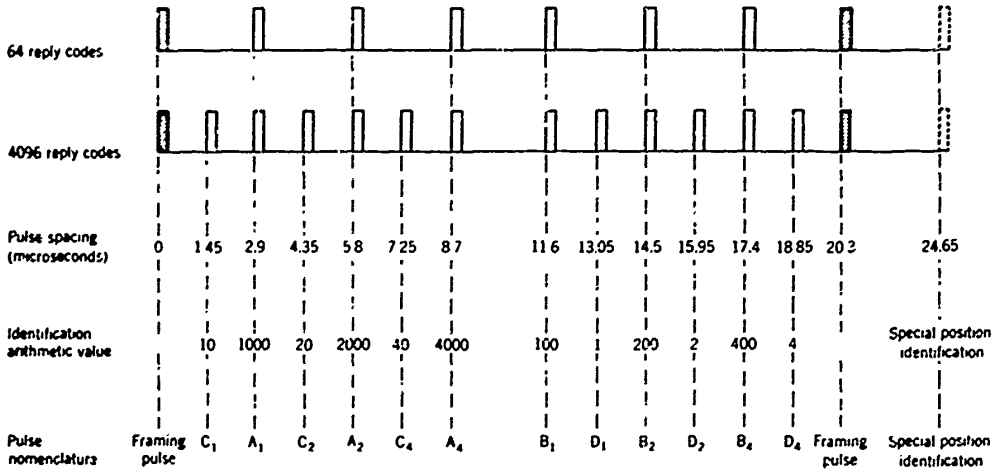


Figure 2-3. Transponder Reply Codes Used on Secondary Surveillance Radar[9]

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CHAPTER 3

SIGNAL GENERATION SYSTEMS

3-1 INTRODUCTION

Recent advances in the accuracy of time keeping have been due largely to the outstanding developments in precision clocks. The modern *quartz crystals* and *atomic clocks* attain a standard of precision considerably in advance of the best pendulum clocks, and their development has led to the elimination of the pendulum clock in major time-keeping observatories and in time service throughout the world. Two types of motion have been used to produce these clocks, viz., the mechanical vibrations of quartz and the oscillations of individual atoms[1].

The most stable frequency standards are the atomic clocks, specifically cesium beam, rubidium gas cell, or hydrogen maser. Their frequency stability is compared in Table 3-1. Since the comparison is at constant ambient conditions, it does not indicate at least one other important factor, namely that the stability of rubidium cells is affected much more by the temperature than is cesium. The cesium frequency standard has the highest intrinsic reproducibility and frequently serves as a primary standard.

The family of quartz crystal oscillators forms the secondary standards. The frequency stability of these oscillators varies, depending on temperature compensation or control features (see Table 3-1 state of the art as of 1971).

In addition to these frequency standards, the tuning fork is discussed in par. 3-3. Tuning forks can be made in a package of 0.7 in.[3] with a frequency stability of ± 0.001% when controlled in an oven.

3-1.1 DEFINITIONS

3-1.1.1 Clocks

The quartz-crystal clock and atomic clock are described:

(1) Quartz-crystal Clock. A standard quartz clock is a precision time piece that provides a series of electrical timing pulses at intervals of seconds or tenths of seconds; some applications require minutes to be marked, or to indicate the particular time of day. Most quartz clocks employ a crystal designed to operate at a nominal frequency of 5 MHz although frequencies of 1 MHz, 2.5 MHz, and 100 kHz are also much in use. Frequency division may be entirely electronic, or electronic in the first stages and then electromechanical[1].

(2) Atomic Clock: An atomic clock is a precision time piece controlled by an atomic or molecular spectral line[3]. These small electrical and magnetic vibrations are almost wholly independent of normal external conditions; and, because their frequencies are a property of the atoms themselves, they are identical for all atoms of the same kind.

In one of the most commonly used types of atomic clocks, the atoms used are those of cesium. However, many atomic clocks of several different kinds now have been made and are available commercially[3]. They enable time intervals to be measured with an accuracy approach 1 part in 10^{12} time units or 0.1 μsec per day. Clocks throughout the world can thus be synchronized to 1 μsec.

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TABLE 3-1

CHARACTERISTICS OF ATOMIC AND QUARTZ CRYSTAL FREQUENCY STANDARDS

Atomic Clocks	Frequency Stability (one day, constant ambient conditions)	Volume
Cesium beam	2×10^{-13}	800–2000 in.^{3}
Rubidium gas cell	10^{-12}	80–1500 in.^{3}
Hydrogen maser	2×10^{-14}	27 ft^3

Quartz Crystals[a]	Frequency Stability Over Temperature Range $\pm 10^{-6}$	Power Consumption, mW	Volume, in.^{3}
Crystal Oscillator	4 - 25	10–50[b]	0.25–3
Temperature Range			
–55° to + 105° C	25		
–40° to + 90° C	15		
0° to + 50° C	4		
Temperature Compensated Crystal Oscillator (TCXO)	0.1–10	35–100[b]	1–2.5
–55° to + 105°C	0.5–10		
–40° to + 75°C	0.3–10		
0° to + 50°C	0.1 – 1		
Temperature Controlled Crystal Oscillator (Single Oven)	0.005–0.1	1–10 W[c]	7–35
–55° to + 75°C	0.01–0.1		
–40° to + 75°C	0.01–0.1		
0° to + 50°C	0.005		
Temperature Controlled Crystal Oscillator (Double Oven)			
0° to +50°C	0.001–0.0001	5–15 W[c]	1000-2000

[a] from Ref. 2
[b] Output Power = 1 mW
[c] At lowest ambient temperature

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3-1.1.2 Frequency Standards

A frequency standard is an atomic clock that is used in frequency control because of its greater precision and accuracy. Basic to the choice of these atomic standards is their unprecedented frequency stability. For instance, the cesium and hydrogen atomic standards require no other reference for calibration. Three other devices that could be used as frequency standards are (1) thallium beam, (2) ammonia maser, and (3) rubidium maser. Atomic frequency standards operate by one of two means: (1) by determining the frequency corresponding to dipole inversion in a beam of atoms, or (2) by determining the frequency corresponding to a transition between the energy levels of atoms in a fixed sample.

3-1.2 PRIMARY STANDARDS

A primary frequency standard is one that provides a frequency that is well-defined without reference to any external standard. In all atomic frequency standards there are means for (1) selecting atoms in a certain energy state, (2) enabling long life times in that state, (3) exposing these atoms to microwave energy, and (4) detecting the results[4]. Two primary standards that have reached a high state of development are the hydrogen maser and the cesium beam. The cesium beam device uses passive atomic resonators to steer high quality quartz oscillators via feedback circuits. The hydrogen maser, an active device, derives its signal from stimulated emission of microwave energy amplified by electronic means to a useful power level.

3-1.3 SECONDARY STANDARDS

Secondary frequency standards are those that must be referenced to an accepted source such as a primary standard. Quartz crystal oscillators are used widely as high-quality secondary standards. The cesium beam device makes use of slaved quartz crystal oscillators. Another secondary standard is the rubidium vapor standard. It is a secondary standard because it must be calibrated against a primary standard during construction; it is not self-calibrating[4].

3-1.4 BASIC OPERATING PRINCIPLES

3-1.4.1 Quartz Crystal Clock

The resonant element of a quartz clock, usually called the crystal, is a bar, plate, or ring of quartz. To have it vibrate at a desired frequency in a particular mode, it is cut to certain dimensions and in a selected orientation to the various axes of the natural quartz crystal. The resonator assembly includes supports for the crystal and electrodes through which energy is supplied to the crystal to maintain the vibration using the piezoelectric property of crystalline quartz. The crystal is kept in oscillation by a maintaining amplifier connected to the electrodes of the resonator. The stability of the frequency of oscillation and the uniformity of the rate of the clock are primarily related to the quality of the quartz resonator and to characteristics of the maintaining amplifier, its power supply, and associated environmental control components. For more information on quartz crystal oscillators, see par. 3-2.

3-1.4.2 Atomic Clock

The cesium atomic beam uses the hyperfine transition of the cesium atom. The atoms pass through a system of magnets and are deflected away from a detector unless transitions are induced by an applied field derived from a quartz clock and alternating at the spectral line frequency. Any deviation from the spectral line frequency produces an error signal that is applied to the quartz oscillator to bring it back to its correct value. The nominal value of the quartz oscillator is usually 5 MHz and a fairly complex frequency converter is required between the clock and

SAMSUNG EXHIBIT 1028, Page 53

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the spectral line frequency[3]. Atomic resonance devices are discussed in more detail in par 3-4.

3-2 QUARTZ CRYSTAL OSCILLATORS

Crystalline quartz has great mechanical and chemical stability, and a high mechanical *Q* (which means that a small amount of energy is needed to sustain oscillation). The piezoelectric properties of quartz make it convenient for use in an oscillator circuit. Stressing of quartz and certain other crystals produces an electric potential at the electrodes. Conversely, placing each crystal in an electric field deforms them a small amount proportional to field strength and polarity. This property is known as the piezoelectric effect.

In practice, a quartz resonator is mounted between two electrodes, presently thin metallic coatings deposited directly on the crystal by evaporation. Mechanical support is provided at places on the crystal so chosen as to avoid, to the greatest extent possible, inhibition of the desired vibration while suppressing any unwanted vibrations. A correct alternating voltage applied across the crystal causes it to vibrate at a frequency such that mechanical resonance exists within the crystal. Details on the various shapes and their modes of vibration are discussed in par. 4-2. The various types of quartz crystal controlled oscillators are discussed in the paragraphs that follow. Oscillators for military equipment are covered by a military specification[5]. For frequency stabilities, see Table 3-1.

3-2.1 GENERAL PURPOSE OSCILLATOR

The simplest crystal oscillator uses neither temperature control nor temperature compensation techniques (see Fig. 3-1[6]). An amplifier, either vacuum tube or transistor type, is used with some degree of selectivity depending upon the type of crystal unit used. Degree of isolation from the load is dependent upon the output requirements and amount of stability required. In this case, the main cause of instability is temperature.

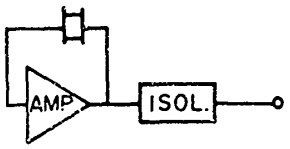


Figure 3-1. General Purpose Crystal Controlled Oscillator[6]

Crystal aging or drift is only a problem with this form of oscillator because it is small compared with changes due to temperature and can be absorbed by periodic adjustment of the circuit phase. For stability data, see Table 3-1. More information is contained in Ref. 7 and in a design handbook, Ref. 8.

3-2.2 TEMPERATURE COMPENSATED CRYSTAL OSCILLATOR (TCXO)

To obtain better stability than that possible with the basic crystal oscillator, TCXO can be used[2]. This principle is shown in Fig. 3-2[6]. The increased stability, however, is at the expense of added circuit complexity more volume, and higher power consumption. Fig. 3-3[6] shows a simple compensation circuit. Frequency deviation of 1 part in 10^6 over a temperature range of $-30°$ to 60°C has been shown possible with a 30 MHz overtone

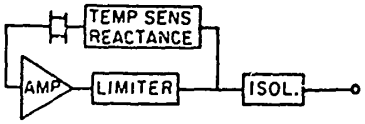


Figure 3-2. Temperature Compensated Crystal Oscillator (TCXO)[6]

SAMSUNG EXHIBIT 1028, Page 54

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AT-type unit. With more sophisticated design of the sensing network, 1 part in 10^7 in the temperature range -30^c to 50° at 3 MHz has been reported[9]. Fig. 3-4[6] shows the frequency-temperature curve for an uncompensated and, for comparison, a compensated 25 MHz crystal unit. A bibliography on TCXO's follows the references at the end of this chapter.

Added circuit complexity for temperature compensation consists of a varactor, a thermistor-resistor network, and a voltage regulator. The latter is added because regulation of 100 or 1000 to 1 is needed, depending on how good the voltage source is and the degree of frequency stability needed (see Fig. 4-1(B)).

The resistance of the thermistor-resistor network is temperature sensitive so that a voltage which is a function of temperature is supplied to the varactor. This voltage variation changes the capacitance value of the varactor and thus the load capacitance of the crystal. This load capacitance change varies the crystal oscillator frequency in a predetermined manner to compensate for the crystal frequency-temperature variation. Depending on the stability desired, the reactance change of the varactor also must compensate for temperature-induced changes of the voltage regulator, active device, circuit elements, and buffer amplifiers. The choice of values in the thermistor-resistor network is quite complicated and usually requires computer optimization techniques to determine the network parameters.

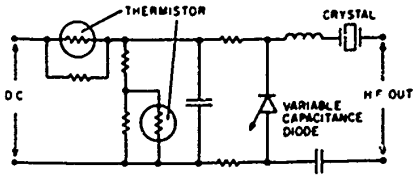


Figure 3-3. Temperature Compensation Circuit[6]

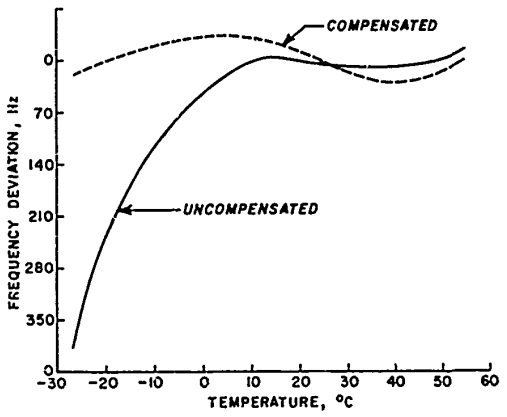


Figure 3-4. Effect of Compensation on the Frequency of a 25-MHz Crystal Unit[6]

The best angle of cut for the crystal depends on the stability needed and the temperature range. A compromise must be reached between the crystal with a more linear frequency-temperature slope between turning points with its greater frequency change and the crystal with a smaller frequency change but a more nonlinear slope. The more linear slope is easier to compensate but it must be compensated more precisely because of the larger frequency change. Another consideration is the location of the turnover points because synthesis of the compensating reactance is simplified when only one turn-over occurs in the temperature range of interest.

To obtain good frequency stability as a function of temperature, especially under temperature transient conditions, it is necessary that good thermal tracking exist among the crystal, varactor, and thermistors. If thermal gradients exist among these components, a large frequency change – on the order of a few parts in 10^6 – can take place under transient conditions. Also, the crystal unit exhibits transient behavior during temperature change, due to thermal gradients

SAMSUNG EXHIBIT 1028, Page 55

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within the quartz plate that can be as large as a few parts in 10^6 for rapid temperature changes.

The TCXO exhibits good frequency accuracy from turn-on because all components are at the same temperature whether power is being supplied or not and the slight temperature rise due to turn-on has only minimal effect on frequency. In certain applications this feature is of major importance.

The aging of a TCXO is dependent primarily on the crystal and presently is between 5×10^{-8}/wk to 5×10^{-10}/wk for the fundamental mode units used. When dealing with the TCXO, as with the oven crystal oscillator discussed in par. 3-2.3, the overall frequency tolerance that can be expected is arrived at by adding the aging, over whatever time period is applicable, to the frequency-temperature stability. For instance, the 5×10^{-7} frequency-temperature stability coupled with an aging of 1×10^{-8}/wk gives an overall frequency tolerance of 1×10^{-6} for 1 yr.

3-2.3 TEMPERATURE CONTROLLED OSCILLATOR

For applications calling for a stability better than that obtainable with a TCXO, a temperature controlled crystal oscillator (oven oscillator) must be used[2]. The ovens used are of two general types – thermostatically controlled and proportionally controlled. The thermostatically controlled oven uses a bimetallic or mercury thermostat to sense the temperature and supplies heat to the oven on an "on-off" basis. This gives simple control but normally is restricted to less precise frequency control and therefore is not covered here. The proportionally controlled type uses a resistance temperature sensor and by bridge circuitry supplies heat on a continuous basis. This results in better temperature control, thus higher precision frequency control.

The improved stability over the TCXO requires more space and considerably higher power consumption. In addition, there is added circuit complexity over the basic crystal oscillator (see Fig. 4-1(C)). The oven circuitry is composed of a resistance bridge, amplifier, transistor controller, and heater winding. A voltage regulator and multistage buffer amplifier are used and an automatic gain control circuit is needed to keep the crystal drive constant. One arm of the resistance bridge is the sensor, a specially wound resistor or a thermistor whose resistance value is a function of temperature. Any temperature change in the oven is detected by this sensor resulting in bridge unbalance. The bridge voltage output is amplified and operates on the transistor controller, causing more or less current to flow through the heater winding, thus regulating the temperature. There should be good thermal coupling between the sensor and the heater winding on the oven shell so that high loop gain may be employed. The oven structure should be well insulated, and possess large heat capacity, to keep the rate of change of temperature at a minimum. Without good thermal coupling the temperature at the crystal oscillator will vary considerably, due to heating of the control circuit, resulting in poor frequency stability. The operating temperature of the oven can be changed by varying the value of one resistor in the bridge circuit. This changes the balance point and thus the operating temperature. A well-designed single stage oven will give 0.1 deg to 1.0 deg C temperature stability over a wide ambient range.

Insulation is used in the oven around the components to keep heat loss low and to minimize temperature gradients within the chamber. Generally, the gradients are proportional to the power used in the heater. The best insulation is a vacuum and the normal way to achieve this is through use of a double wall dewar flask. A less expensive and more rugged method is the use of foam material;

SAMSUNG EXHIBIT 1028, Page 56

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however, heat loss is greater than in the evacuated case.

The operating temperature of the oven must be higher, usually by 10 deg to 15 deg C, than the highest ambient temperature expected. The actual operating temperature of the oven must be adjusted to correspond to the turn-over temperature of the crystal being used in that oven.

In order to realize the best frequency-stability performance possible with crystal-controlled oscillators, double-oven temperature stabilizing techniques are employed essentially to eliminate the effects of ambient temperature changes on the frequency of oscillation. A single, carefully-designed proportionally controlled oven can maintain an ambient ratio of the order of 500:1 (i.e., internal temperature change of 0.1 deg C for an ambient range of 50 deg C). Consequently, placing one such oven completely within another of similar capability will result in an overall ambient ratio of the order of 2.5×10^5:1 (about 0.0002 deg C variation for a 50 deg C change in ambient). As a result, frequency changes caused by ambient temperature changes are reduced to be of the order of 1×10^{-12}/deg C, or even less.

If the best available overtone-mode crystal units (i.e., fifth overtone, 5 MHz) are used in oscillators of this type, and corresponding care is observed in the design of a buffer amplifier, voltage regulator, etc., the effects of other ambient influences such as supply voltage and load impedance can be made to be of the same order as the effects of temperature, with the result that crystal-controlled oscillators are available whose output frequency will remain stable within 1×10^{-11} due to all causes – except shock vibration and static acceleration – for periods of a day or longer.

In order to achieve stability of this order, the temperature control and voltage regulator circuits usually are placed inside the first, or outer, temperature-stabilized enclosure along with the RF buffer amplifiers. The crystal unit and oscillator circuit are placed within the second, or inner, oven enclosure.

For proper operation of a two-stage oven system, the outer enclosure must be maintained at a temperature somewhat above the highest ambient temperature to be encountered, and then the inner enclosure must be held several degrees above the temperature of the outer oven. This necessarily requires that the turn-over temperature of the crystal unit used in such an oscillator be controlled carefully in manufacture since the operating point of the inner oven must be adjusted very accurately (within about 0.1 deg C) to the turn-over temperature of the crystal. For example, if an ambient range of 0° to 50°C is specified, the operating temperature of the outer oven would be chosen in the range of 60° to 65°C, and consequently the crystal units should be specified to have turn-over temperatures in the range of 70° to 75°C.

An oven stabilized oscillator is not on frequency immediately after turn-on because the oven must warm up to its operating temperature before the crystal can be stabilized at the turnover point. To obtain a fast warmup characteristic, a separate warmup heater and associated on-off thermostat are used. A large amount of power is used for a short time in the warmup heater, thus heating the chamber quickly. The thermostat will cut off a few degrees below the desired operating temperature where the proportional control takes over. Warmup times of 5 to 30 min, from lowest ambient, are normal with a power dissipation of 4-40 W during this warmup time.

3-2.4 OSCILLATOR FOR SEVERE ENVIRONMENT

Phase coherence and spectral purity are very important for stable frequency sources

SAMSUNG EXHIBIT 1028, Page 57

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subject to high shock and vibration in missile and space applications. Fig. 3-5[6] illustrates the use of an oven to obtain the thermal stability required. Particular attention is paid to the mounting material which is often foam. Since the environment requires a rather rigid support, the g forces are transmitted to the crystal vibrator which results in a frequency shift. The rigidity of the support relaxes with time and contributes to a high aging rate. For frequencies of 10 MHz and up, stability of the order of 1 part in 10^{10} per g is possible if the shock and vibration frequencies are less than the resonant resonance of the crystal mounting system. Static acceleration causes, as a rule of thumb, a relative frequency change of roughly 2×10^{-9} per g when the acceleration vector is in the worst case direction. Less than 1×10^{-10} per g is possible if the crystal unit can be oriented precisely in the acceleration field. It has been shown that the triple-ribbon supported vibrator in the TO-5 transistor enclosure has been found suitable for this class of service[6].

3-2.5 PRECISION OSCILLATORS

For the greatest stability and lowest drift rate, careful attention must be given to the oscillator circuit and the highest precision crystal unit must be used. Fig. 3-6[6] outlines the necessary controls that must be used and is typical of most precision oscillators on the market today. A double oven with proportional control is used to hold the temperature constant and to ensure that no gradients exist in the quartz plate (see par. 3-2.3). One factor governing the stability of a crystal unit is that

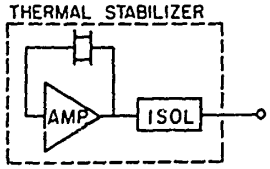


Figure 3-5. Oscillator for Severe Environments[6]

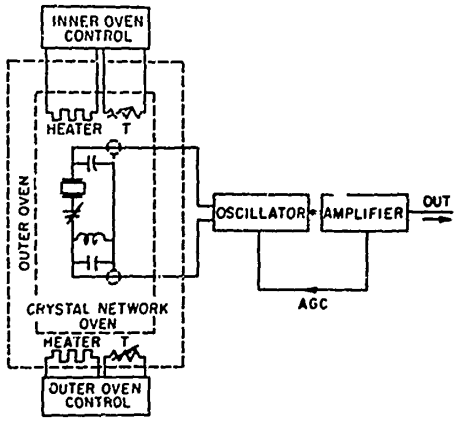


Figure 3-6. Precision Crystal Controlled Oscillator[6]

of amplitude of oscillation; therefore, a large amount of feedback is used in the amplifier and in the automatic gain control to maintain a constant level of the oscillator signal. An oscillator using the 2.5 MHz fifth overtone crystal unit design has an average daily drift rate as low as a few parts in 10^{10}, and after three weeks of operation, the aging is less than 10^{-9} Hz per wk[6]. Design criteria for the various crystal oscillators are discussed in par. 4-2.

3-3 TUNING FORK OSCILLATORS

3-3.1 APPLICATION

The tuning fork can be said to be one of the oldest vibrating devices used for frequency control. Tuning forks are not used in new military equipment because crystals are more stable. The only application is in situations where cost is of prime importance. Forks are much cheaper. They have been used in such devices as precision clocks, reference clocks in computers, navigation systems, satellite timers, and central timekeeping systems. One of the problems in its early application was keeping the fork vibrating. Ideally, the pickup and drive device for

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maintaining vibrations should be loosely coupled to the fork. Present practice uses a magnetic transducer for both pickup and drive functions.

The transducer consists of a magnet inside a coil located close to the tine of the fork. Changes in flux, due to the vibration, produce a signal in the pickup coil. Conversely, a signal applied to another transducer, also located near the tine, will maintain motion. An adequate amplifier connected between the two will cause the fork to vibrate at the proper frequency. Typical gains required of the amplifier are 10 to 50 dB depending on fork design[10].

3-3.2 NONTEMPERATURE CONTROLLED OSCILLATOR

As a standard oscillator, a fork vibrates at its fundamental, or lowest, resonant frequency. By the positioning of the drive and pickup coils, and by control of the oscillator amplifier phasing, a tuning fork can be made to oscillate at its second partial resonant frequency, about six times the fundamental frequency. At the higher mode, the tuning fork exhibits a Q and a frequency stability similar to those at its fundamental frequency. Present forks have Q's of 15,000 to 23,000 in vacuum, and a temperature coefficient of frequency in the range of 1/5 to 1/3 ppm/deg C from −20° to 50°C. Fig. 3-7[11] shows the modes of the fork motion when oscillating both in its fundamental and in its first partial mode.

3-3.3 TEMPERATURE CONTROLLED/ COMPENSATED OSCILLATORS

To help alleviate the effect of temperature on frequency, alloys such as Ni-Span, Vibraloy, Nivarox are used to produce low temperature coefficients. These alloys are heat-treated to adjust the coefficient. For close coefficients over wide temperature ranges, heat treating is not consistent enough

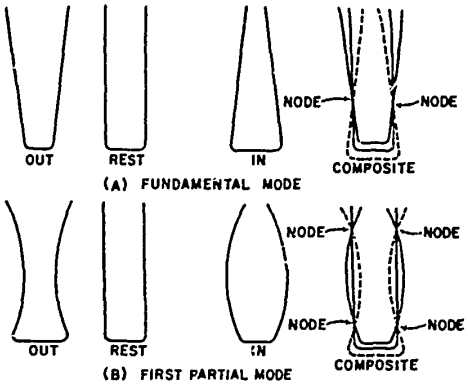


Figure 3-7. Tuning Fork Vibrations

to allow the use of alloy forks for general applications.

The most practical present method of compensation is the use of a bimetallic fork made of a laminate of a positive coefficient Elinvar alloy and a negative coefficient steel alloy. The coefficient then can be adjusted by grinding one laminate or the other.

Another method to correct the temperature coefficient problem is to use an oven. In this method, the fork is enclosed in a proportional oven controlled by vacuum tubes or transistors. At the present time, temperature versus frequency tolerances of ± 0.02% over the military temperature range and ± 0.001% in the room temperature range are readily achieved[10].

3-3.4 EFFECTS OF OTHER ENVIRONMENTAL FACTORS ON STABILITY

One of the environmental factors is fork attitude. A fork with tines down runs faster than one with tines up due to the effect of gravity. Of all frequency instruments, forks are the most susceptible to shock and vibration. Various methods to compensate for

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this include driving both tines with the coils between the tines, having an internal stud mounting in place of an external stud, and using foamed materials or damped springs.

Forks are subject to aging just as crystals are. Aged forks usually increase in frequency. Prescaking fork assemblies at moderately high temperatures provides a quick "aging" process so that a unit can be made compatible with its end use. In instances where precise adjustments are required, the frequency can be adjusted with a phase control. Variations up to 200 parts in 10^6 are practical and more than enough to compensate for future aging. For design details of tuning fork oscillators, see par. 4-3.

3-4 ATOMIC RESONANCE DEVICES

3-4.1 ATOMIC ACTION

Atoms are capable of existing in several different energy states that are the result of different energy relationships between the various components of the atom. The atom can switch about among the different energy states permitted to it, but to do so it must absorb or emit energy. The relationship of major interest, as far as atomic resonators are concerned, is that between the nucleus of the atom and its outermost or valence electrons. The magnetic moment of these electrons may be aligned either with or against the magnetic field of the nucleus depending upon the direction of spin of the electrons. It is these two possible alignments that constitute the hyperfine energy differences in the ground state of the atom of concern here.

If a magnetic field of proper frequency is applied to the atom, the magnetic moment of the electron can be induced to switch its alignment relative to the nuclear magnetic field. Electrons in the lower of the two energy states absorb energy and switch to the higher state; electrons in the higher states are stimulated to switch to the lower state by the applied field, but in doing so they emit rather than absorb energy. The emitted energy is of the same frequency as the stimulating field. The frequency of the magnetic field required to cause alignment transitions is related to the magnetic moment of the electron, the spin of the electron, and the magnetic field of the nucleus.

It should be noted that any quantity of atoms will have approximately equal numbers in each of the possible hyperfine levels of the ground state. If an RF magnetic field is applied, transitions from the lower level to the higher level will approximately equal those in the opposite direction. The RF energy absorbed will equal the energy emitted and there will be no sensible indication that the transitions have taken place. It is necessary, therefore, to work with a group of atoms that are preponderantly in only one of the two possible states. There are various means of achieving this condition; the means being suited to the particular type of resonator in question (see par. 3-4.2.1).

Transition frequencies are the same for all unperturbed atoms of a given substance, and the band width over which the transitions occur is quite narrow. It is this reproducibility of frequency from atom to atom, along with the extremely sharp resonance ($Q = 100$ million) that has led to the development of atomic resonators as precision time keeping devices.

There are basically two methods of using atomic resonators for time or frequency control: viz., as passive resonators or as active resonators. The passive resonator is used to determine and control the frequency of an applied RF magnetic field. Active resonators, on the other hand, actually generate an RF signal from the energy emitted by the atoms undergoing transition.

SAMSUNG EXHIBIT 1028, Page 60

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3-4.2 PASSIVE RESONATORS

3-4.2.1 Atomic Beam Resonators

Atomic beam resonators, as the name implies, make use of atoms or molecules of various substances in the form of a beam. This beam, under proper magnetic manipulation, is employed as an extremely precise frequency determining element. The most extensively developed form of beam resonator is the cesium beam, which is the international primary time standard. Considerable work also has been done on the thallium beam. The operation of the various atomic beams is quite similar and, therefore, only the cesium beam is discussed.

The cesium beam resonator consists essentially of a source of cesium^{133} atoms, focusing magnets, a transition chamber, and a detector. These components are enclosed in a magnetically-shielded vacuum envelope and are arranged as shown in Fig. 3-8[12]. There are two fundamental functions to be performed within the resonator: (1) isolation of the particular atoms that undergo the desired transition from one energy level to another, and (2) effecting and detecting the transition itself.

When the RF generator that supplies the energy to the transition chamber is tuned for maximum detector output, its frequency will be precisely the transition frequency. For a cesium beam the exact frequency is 9,192,631,770 Hz or, as the second is defined in terms of the cesium beam, it may be more correct to say that 9,192,631,770 cycles of the cesium beam oscillator equals one second of ephemeris time[13]. The band width of such a device is approximately 250 Hz.

3-4.2.2 Gas Cell Resonators

The operation of gas cell resonators, like that of atomic beam resonators, is based upon a hyperfine transition of atoms of certain alkali metals. The most extensively developed type of gas cell employs rubidium^{87}. However, gas cells have been constructed which use atomic hydrogen, sodium^{23} or cesium^{133}. Operation of these cells is similar to that of the rubidium cell. The means used for changing the energy states of the atoms in gas cells is called optical pumping[14].

A passive resonator generally employs a relatively low-frequency crystal oscillator as its primary source of RF energy. This oscillator is variable over a limited range, and the center frequency is usually a integral number of kilohertz or megahertz. Frequency multipliers and synthesizers are used to raise the oscillator frequency to that required to effect the desired transition. An alternate method is to operate the crystal oscillator at a submultiple of the transition frequency and use the synthesizer to obtain the desired standard frequency from the crystal oscillator. In either case, the signal applied to the atomic resonator usually is phase modulated, and a synchronous detection network is incorporated in the output circuit of the resonator. In this manner an error signal is generated which is applied as a correction to the crystal oscillator. The entire system is, in effect, a servo controlled oscillator with a highly specialized frequency determining element. Circuit parameters are such that for very short times the frequency stability is that of the crystal oscillator and for long times that of the atomic resonator. Time, in this case, is relative to the response time of the servo loop.

3-4.3 ACTIVE RESONATORS

3-4.3.1 Masers

A maser is an atomic or molecular device that is capable of coherent amplification or generation of electromagnetic waves. The masers employed in precision timing applications are generally of the gaseous type and are operated as oscillators. These oscillators depend for their operation upon the energy

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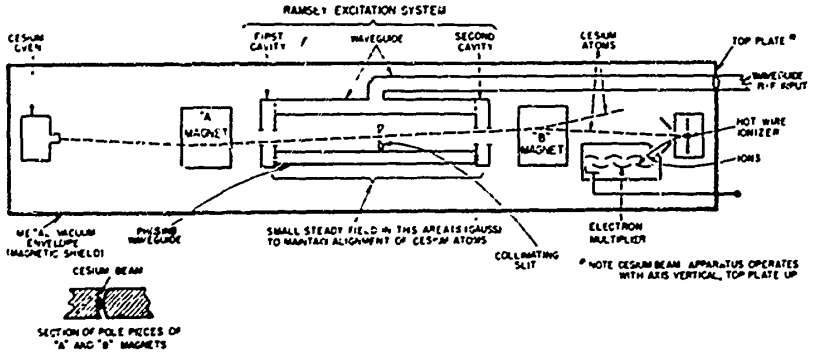


Figure 3-8. Cesium Atomic-beam Frequency-standard Apparatus

emitted by atoms or molecules undergoing transitions from a higher to a lower energy state. They, therefore, require a continuous supply of atoms or molecules in the desired energy state which may be provided either as a constant stream of selected atoms as in a beam resonator or by optical pumping as in a vapor cell.

The most extensively developed maser oscillator for timing or frequency control application is the atomic hydrogen maser. It consists essentially of a source of atomic hydrogen, a selecting magnet, a storage chamber, a resonant cavity, a vacuum envelope, and magnetic shields. The components are arranged as shown in Fig. 3-9[15].

The hydrogen maser requires a continuous stream of hydrogen atoms in the higher energy level of the hyperfine state. These are provided by passing molecular hydrogen through a dissociator that separates the molecules into atoms. The atoms then are passed through a focusing magnet that directs atoms in the desired state into a storage bulb while rejecting atoms in unwanted states.

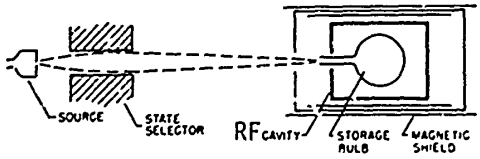


Figure 3-9. Schematic Diagram of the Hydrogen Maser[15]

Atoms entering the storage bulb are confined inside for a brief period before they can escape through the entrance. During this period some of them will emit energy spontaneously and make the transition to the lower energy state. The energy emitted will stimulate still more atoms to undergo transitions and these, in turn, will release more energy. When the resonant cavity is tuned to the frequency of the emitted energy, the occurrence of the transitions will be pulled into phase with the electromagnetic wave in the cavity. If enough transitions take place to provide sufficient energy to overcome the losses in the system, oscillation will occur at the transition frequency. A coupling loop in the cavity allows a small amount of power to be drawn from this oscillation without seriously disturbing the system. The resonant frequency of the cavity is adjustable over a small range so that it can be tuned precisely to the transition frequency.

3-4.3.2 RF Output of Masers

Masers of the type used for frequency

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control do not generate very large amounts of power. Also, to avoid shifting the frequency of the maser by variable loading, the output coupling must be kept low and isolation of the output circuitry must be provided. Useful output signal is thus reduced to a very low level. Higher level signals can be produced by phase locking the output of the maser to the signal from a precision crystal oscillator. Heterodyne circuits and frequency synthesizers are used to convert the maser output to the crystal frequency. In this manner an integral frequency at a power of several milliwatts is obtained.

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CHAPTER 4

BASIC DESIGN CRITERIA FOR SIGNAL GENERATION

4-1 INTRODUCTION

There is a continuous demand for increased precision and accuracy in frequency control. Today fast time pulses are used in radar, precision navigation systems, velocity measurement, guidance of fast-moving aircraft and missiles, and rating of ship and shore frequency standards. Microsecond synchronization of clocks for periods of 24 hr or more at a number of range stations is necessary for accurate determination of missile velocity. Standard oscillators that are used to control clocks at remote points must not vary in frequency more than 1 part in 10^{11} per day. Similarly, accurate synchronization of precision frequency standards ashore and afloat is essential to operation of single side band communication systems. The general theory of signal generation applicable to basic reference timers is described in the paragraphs that follow.

4-1.1 GENERAL THEORY

Three oscillator types used for the generation of frequency signals in basic reference timers are (1) quartz crystal oscillators, (2) tuning fork oscillators, and (3) atomic frequency standards. Each one has a special characteristic that is used for generating a constant frequency signal. In the quartz crystal oscillator, it is the mechanical vibration of the crystal; in the tuning fork oscillator, it is the mechanical vibration of the fork. Atomic frequency standards use transitions between states separated by energies corresponding to microwave frequencies (see pars. 3-2 to 3-4).

For a device to be used by a basic reference timer, its frequency must possess great stability and low drift rate. For a precision quartz crystal oscillator to possess these characteristics, detailed attention must be given to the design of the oscillator circuit and to the selection of a quartz resonator[1]. Tuning fork oscillators that are hermetically sealed and temperature compensated can be produced to operate in the frequency range of 400 to 1000 Hz and also at 50-60 Hz. With respect to atomic frequency standards, the controlled rubidium gas cell oscillator is the most compact, has a high degree of short-term stability, and a long-term stability sufficiently adequate for a wide range of applications. By virtue of the fact that cesium beam oscillators have a very high degree of long-term stability and the important property of intrinsic reproducibility, they qualify as primary frequency standards. Even though the size and weight of the cesium beam oscillators are greater than a rubidium gas cell, these instruments are portable. The atomic hydrogen maser has the highest degrees of short-term and long-term stability as well as intrinsic reproducibility when compared with available atomic oscillators. Its size, weight, and cost, however, are also greater[2].

Time standards and frequency standards are related. A standard of frequency can serve as the basis for time measurement, and vice versa, with certain restrictions. To avoid errors when a frequency standard is used to maintain time, either interval or epoch, care must be taken to identify the time scale of interest; i.e., atomic, UTC sidereal, etc.[3].

If a consistent local system of time and

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frequency standards is to be maintained, the standards must be intercompared. Further, if a local system is to be kept in correspondence with national standards, a reference must be established and maintained. Radio broadcasts from frequency and time standard stations are used most often as the link to keep this reference. The various systems that may be used for synchronization and the test methods used in these systems are discussed in par. 5-3.

4-1.2 COMPONENTS AND CIRCUITS

Most crystal-controlled frequency standards are composed of the following components[1]:

(1) A control element, i.e., the quartz crystal unit

(2) A negative resistance element, i.e., the oscillator circuit using vacuum tubes or transistors

(3) A thermostat or temperature-control device to keep the frequency control element and other circuit elements at constant temperature

(4) Suitable frequency dividers or other means for producing lower output frequencies

(5) Integrating devices, such as clock indicators

(6) A suitable power supply.

The circuits used in quartz crystal oscillators are shown in Fig. 4-1[4]. The basic circuit of Fig. 4-1(A) is relatively simple. For temperature compensation (Fig. 4-1(B)), the added circuit complexity is shown in heavy lines. Additions consist of a varactor, thermistor-resistor network, and voltage regulator (see par. 3-2.2). For temperature control, shown in Fig. 4-1(C), oven circuitry is added, again shown in heavy lines (see par. 3-2.3).

The atomic resonance of cesium and rubidium is used in a passive sense to control the frequency of quartz crystal oscillators through the action of electronic feedback circuits. Fig. 4-2[2] shows a basic block diagram of an atomic resonator-controlled oscillator while Fig. 4-3[2] shows a complete hydrogen maser standard. Design details of the components and circuits are covered in pars. 4-2 to 4-4.

4-2 QUARTZ CRYSTAL OSCILLATORS

4-2.1 QUARTZ CRYSTAL UNITS

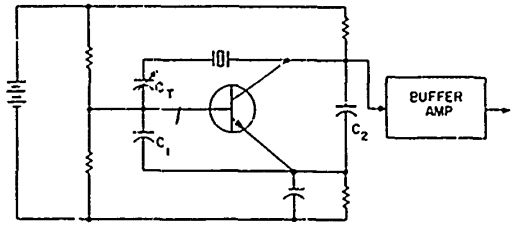
4.2.1.1 Vibration Types

It has been stated that the type of motion used in signal generation in the quartz crystal oscillator is the mechanical vibration of the quartz crystal itself. Fig. 4-4[5] illustrates the various modes of motion that are used in practically all crystal units on the market today. Quartz bars or plates are used in the flexural, extensional, and shear modes of motion to cover the frequency range from a few hundred hertz to over 200 MHz. In order to obtain the best characteristics, particularly as a function of temperature, certain orientations have been developed with respect to the crystallographic axes as shown in Table 4-1[5].

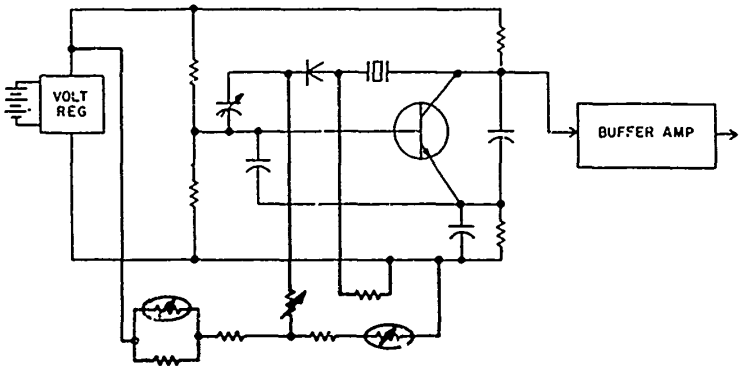
All of the high frequency units listed are excited by an electrical field that is perpendicular to the major surfaces of the crystal. In A and B vibrators, an electric field perpendicular to the major surface usually is used to couple to the thickness shear mode. To do so, the electrodes are deposited on the central portion that is the principal frequency determining part of the quartz plate. When the resulting two-terminal resonator is connected into a circuit, it behaves as though it were an electrical network. It is so located in the oscillator circuit that its equivalent electrical network becomes a major part of the resonant circuit that controls oscillator frequency. At present, AT-cut plates vibrating either in their fundamental mode or in one of

SAMSUNG EXHIBIT 1028, Page 69

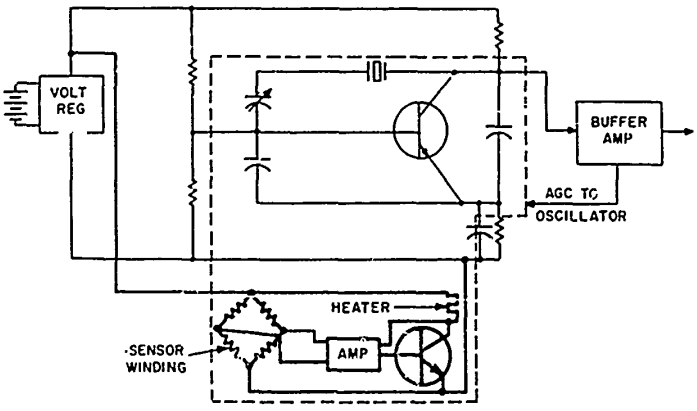
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(A) Basic Circuit



(B) Temperature Compensated Circuit



(C) Temperature Controlled Circuit

Figure 4-1. Crystal Oscillator Circuits for Frequency Standards[1]

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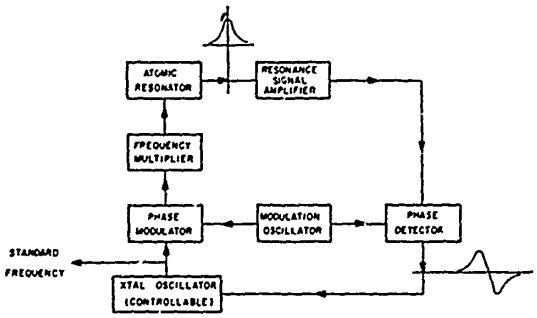


Figure 4-2. Basic Diagram of Atomic Resonator Controlled Oscillator[2]

their mechanical overtones are being used almost exclusively for frequency standards[5]. The quartz plates have a plano-convex shape, are polished, and carry electrodes that are applied by vapor deposition.

The attainment of a high Q and low aging is possible by use of meticulous care in the preparation of the crystal unit[6]. Aging rates of 2×10^{-9} per wk and less, and Q values of 1.5×10^{6} to 2×10^{6} for 5-MHz fifth overtone plano-convex units are attained commercially in reasonable quantities for oven controlled use. (For a definition of Q, see par. 4-3.1.2.)

4-2.1.2 Enclosures

The performance of crystal vibrators is controlled largely by the type of mounting system used and its enclosure. Types of holders in current use are shown in Fig. 4-5[5]. Holders HC-6, HC-13, and HC-18, with crystal vibrators listed in Table 4-1, can be used to cover the frequency range from a few kHz to 200 MHz. This type of holder is sealed to the base by soldering. To eliminate the resulting contamination, all-glass holders of the HC-6 and HC-18 dimensions were developed. Designated as HC-26 and HC-27, they are used principally in the high-frequency, thick-

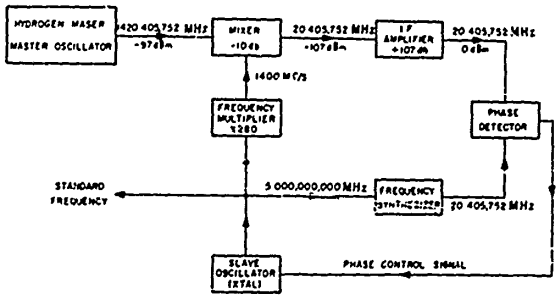


Figure 4-3. Complete Hydrogen Maser Frequency Standard[2]

SAMSUNG EXHIBIT 1028, Page 71

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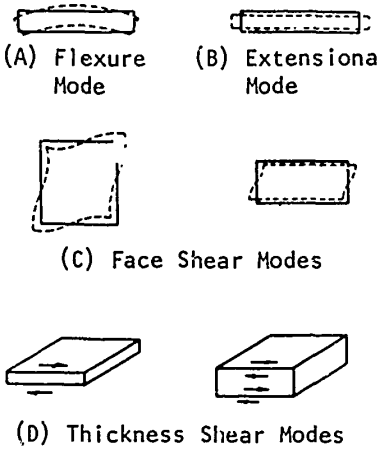


Figure 4-4. Basic Modes in Quartz Crystal Vibrators[5]

ness shear crystal units[7]. For high frequency overtone precision crystal units, HC-30 and T-11 all-glass holders are used[8]. They are of the drop seal type and eutectic solder may be used in the mounting system. However, in the HC-26 and HC-27 enclosures, high temperature bonding agents such as silver paste and cements must be used. The principal advantage of glass holders is that they are easier to clean, and with normal processing, there should be less contamination inside the enclosures.

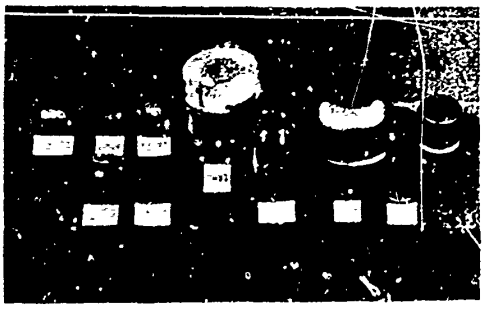


Figure 4-5. Quartz Crystal Unit Holders[5]

A new sealing machine has been reported for use with HC-26 and HC-27 glass holders[9]. This machine has a production capability of 10,000 units per month with high reliability. A 5-MHz fundamental resonator in evacuated coldweld HC-6/U and round transistor configurations has been developed for use in temperature compensated oscillators. Specific goals were long-term aging of no more than 2 parts in 10^9 per wk, high Q (500,000 min), good frequency stability of 35 ± 2 parts per 10^6 between turning points, and ability to withstand bakeout temperatures of 450°C. Figs. 4-6[10] and 4-7[10] depict the HC-6 type coldweld unit and the round transistor type coldweld holder. Materials used for the enclosures included copper-clad kovar bases, compatible glass-to-metal seals, and covers of high purity nickel. In attempts to miniaturize the enclosure as much as possible, there have been recent developments to produce holders similar to the TO-5 transistor enclosure, but having a height of 0.070 in. and a diameter of 0.250 in. The seal is made by an electron beam welding process[11].

4-2.1.3 Quartz Material

Synthetic quartz is now available from commercial sources, and recently attempts have been made to improve the Q-value. Internal friction limits Q as shown in Fig. 4-8[12]. This is a plot of the internal friction of natural quartz over a wide temperature range

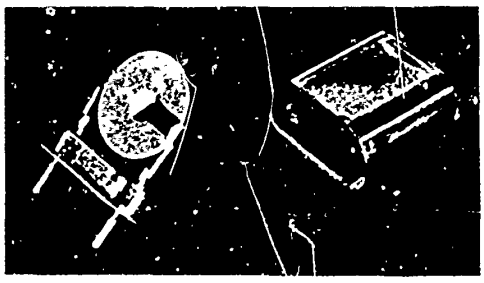


Figure 4-6. HC-6 Type Coldweld Unit

SAMSUNG EXHIBIT 1028, Page 72

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TABLE 4-1

DESIGNATION OF QUARTZ VIBRATORS[5]

Vibrator Designation	Usual Reference	Mode of Vibration	Frequency Range
A	AT Cut	Thickness Shear	0.5 to 250 MHz
B	BT	Thickness Shear	1 to 30 MHz
C	CT	Face Shear	300 to 1000 kHz
D	DT	Face or Width Shear	200 to 750 kHz
E	+5°X	Extentional	60 to 300 kHz
F	−18°X	Extensional	60 to 300 kHz
G	GT	Extensional	100 to 500 kHz
H	+5°X	Length-Width Flexure	10 to 100 kHz
J	+5°X (2 plates)	Duplex Length-Thickness Flexure	1 to 10 kHz
M	MT	Extensional	60 to 300 kHz
N	NT	Length-Width Flexure	10 to 100 kHz
K	X-Y bar	Length-Width Flexure or Length-Thickness Flexure	2 to 20 kHz

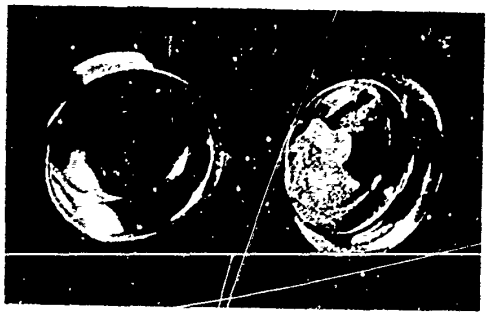


Figure 4-7. Round Transistor Type Coldweld Holder

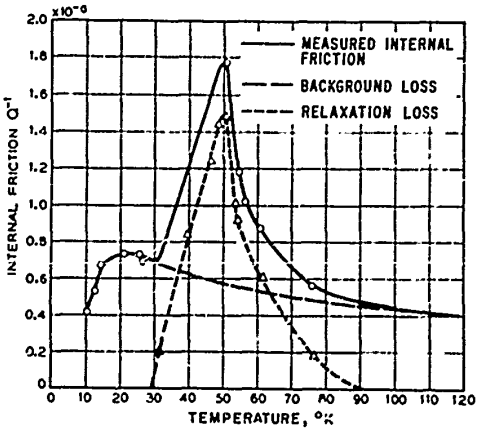


Figure 4-8. Friction Losses in Quartz[12]

obtained by determining the Q of a 5-MHz fifth-overtone glass-enclosed AT-cut vibrator[13,14].

This crystal unit construction has been used for measuring the Q of both synthetic and natural quartz because it is felt that most of the measurable loss is in the vibrating material and not in the mounting system. It

SAMSUNG EXHIBIT 1028, Page 73

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has been demonstrated that the Q of synthetic quartz can be improved to a value equal to natural quartz by appropriate control of the growth solution and growth rate[15]. The background relaxation shown in Fig. 4-8 has been explained as a direct conversion of acoustic waves into thermal energy[14]. The sodium carbonate method of quartz growth leads to crystals of very small hydrogen content with a Q in the order of 2×10^6 at the 5-MHz level[13]. A BT-cut vibrator whose elastic constant is twice as high as an AT-cut vibrator offers higher Q values[16].

4-2.1.4 Design Considerations

Oscillator crystal design primarily is concerned with obtaining high Q units that have low resistance and exhibit good temperature behavior. The presence of unwanted modes at certain frequency ranges of conventionally used crystal designs can cause serious application difficulties. A study has been made in which the techniques of energy trapping used to design filter crystals can control the mode spectrum[17]. The latest issue of the *Military Crystal Specifications* states that the resistance of the unwanted modes should be at least double the resistance of the main mode[18]. Table 4-2[19] summarizes the characteristics of new crystal unit design of the 5-MHz fifth overtone type. Techniques for processing crystals to meet requirements of military and satellite applications have been developed[20]. Stabilities in the 10^{-11} range per month and recoverability to within 2 parts per 10^{10} after temperature interruption were realized in isolated cases.

Aging rates of thickness-shear AT-cut vibrators have been reduced in the past few years by the use of glass holders or cold-welded metal holders that allow high temperature bakeout prior to sealing. Fig. 4-9[12] illustrates how the change in frequency has been reduced by these means.

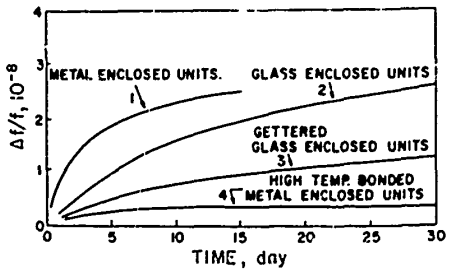


Figure 4-9. Aging of Metal-enclosed and Glass-enclosed 5-MHz Crystal Units[12]

4-2.2 OSCILLATOR CIRCUITRY

In very general terms, a crystal-controlled oscillator may be described as consisting of an amplifier, or gain circuit, together with a feedback network that contains a piezoelectric crystal unit[4]. A typical oscillator circuit is

TABLE 4-2

SUMMARY OF CHARACTERISTICS OF 5-MHz CRYSTAL UNIT

Frequency: 5000.000 kHz (5th overtone mode)
Tolerance: ± 1 part per 10^6 at optimum operating temp. (in range 70° to 80°C)
Average Q: 2,500,000
Maximum effective resistance:
Series = 140 ohm; parallel = 185 ohm
Offset and retrace characteristics:
Freq. offset: $< 1 \times 10^{-9}$ 24 hr after restart
Aging retrace: $< 5 \times 10^{-10}$ 72 hr after restart
Temperature coefficient:
0.1 part per 10^6/deg C within ± 0.5 deg C of operating temp.
Aging: $< 5 \times 10^{-10}$/day after 3 days
$< 7 \times 10^{-10}$/wk after 30 days
Level of drive: 70 μA ± 20%
Typical parameters: L = 9.2 H
C_m = 0.0001 pF
C_o = 4.3 pF

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shown in Fig. 4-1(A). Self-oscillation of such a circuit will occur provided that the loop gain exceeds unity at some frequency for which the total loop phase is $2n\pi (n = 0, 1, 2...)$. The stable level of oscillating signal will be determined either by the self-limiting characteristics of the loop, or by the action of an external automatic-gain-control loop acting on the circuit.

When the desired frequency of oscillation corresponds to the lowest resistance vibrational mode of the controlling crystal unit (i.e., fundamental-mode operation of a thickness-shear type resonator), additional band-limiting networks generally are not required in the oscillator loop. However, such is not always the case. For example, a low-frequency oscillator may be designed to use a flexure-mode crystal that could exhibit lower resistance at a higher frequency corresponding to an extensional or width-shear mode of vibration. In this instance, a simple low-pass network would be required in the oscillator loop to insure operation at the desired flexure-mode frequency. Similarly, a band-pass network would be needed in order to assure operation of an oscillator circuit at one of the overtone-modes of a thickness-shear-resonator (i.e., the resistance of the desired fifth overtone mode of a VHF crystal unit could be greater than that of either the fundamental, third, or seventh-overtone modes).

The output signal spectrum of a crystal-controlled oscillator will depend upon the oscillating level, the electrical noise introduced by circuit elements, and by the bandwidths of the circuits. Generally, the spectral width is extremely small; and, for a majority of applications, only the center or average frequency behavior need be considered. Disregarding for the moment the corruption of signal purity by electrical noise, the average frequency of oscillation always will be determined by the loop phase requirement. Deviations in frequency from a constant value will result whenever any perturbation of loop phase occurs. These perturbations generally may be considered to be of two classes, namely:

(1) Deviations in electrical circuit parameters

(2) Deviations in the crystal unit characteristics.

In class (1) are included such factors as the temperature coefficients of capacitors, inductors, resistors, and transistors; the aging of these devices; their voltage and current characteristics; and their susceptibility to mechanical disturbance. Whatever the cause, a phase perturbation in the circuit transfer phase will cause a change in the average frequency of oscillation, assuming that the crystal unit characteristics remain unperturbed.

Class (2) deviations include changes in crystal unit characteristics caused by temperature, temperature gradient, drive level, "frequency aging", and mechanical disturbances (shock, acceleration, and vibration).

The crystal oscillator circuit generally is designed to use a gain circuit having as broad a band as practicable consistent with operation of the desired crystal modes in order to reduce the network effect on frequency stability. The crystal feedback network, on the other hand, usually is designed to have as narrow a transmission band as can be obtained so as to make the frequency of oscillation depend essentially only on the crystal unit characteristics. When frequency adjustment is required, it is accomplished preferably by introducing a variable reactance that changes the transmission frequency of the crystal network without widening the transmission band. When these general practices are followed, the oscillator frequency stability will depend primarily upon the characteristics of the crystal unit, which

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should be chosen to have (1) a high *Q*-factor; (2) a low temperature coefficient of frequency over the intended operating temperature range; (3) a low drive-level coefficient of frequency; (4) low sensitivity to mechanical shock, acceleration, and vibration; and (5) low frequency aging. More information on oscillator circuitry is contained in Refs. 21-23.

4-2.3 OVENS

The design of ovens for crystal oscillators should consider requirements of the specific application. Two examples of prototype ovens developed for portable communications and satellite instrumentation – ovens A and B, Fig. 4-10, respectively -- are presented. Fig. 4-10[24] shows an exploded view of the ovens while Fig. 4-11[24] presents the basic circuit diagram of the control system. Oven A was designed to maintain a single HC-6/U crystal at a preset temperature between 80° and 90°C over an ambient temperature range of −50° to 75°C. The entire package measured 3.2 in.^{3}. Oven B was designed to maintain a compensated crystal oscillator at a temperature of 0° to 5°C to a stability of 50 millidegrees short term and an objective of 100 millidegrees over the variation in ambient temperature of −55° to −15°C. This package measured 5.2 in,^{3}. See also par. 3-2.3.

One major factor in design is to control the heat produced at a "hot spot" such as a resistor or transistor. Sources of such heat (see Fig. 4-11) are the integrated circuit, the oven control transistors, and the bridge resistors. The transistor was sunk into the oven shell to distribute its heat to the shell and aid the heater in its functions. Fig. 4-12[24] is a plot of the typical control system with a maximum power of 3 W for quick warm-up.

The circular printed circuit board in the oven (Fig. 4-10) contains the bridge resistors, temperature adjusting potentiometer, and the differential amplifier housed in a standard TO-5 transistor case. Insulation of the entire assembly was achieved by a microfiber type of glass wool.

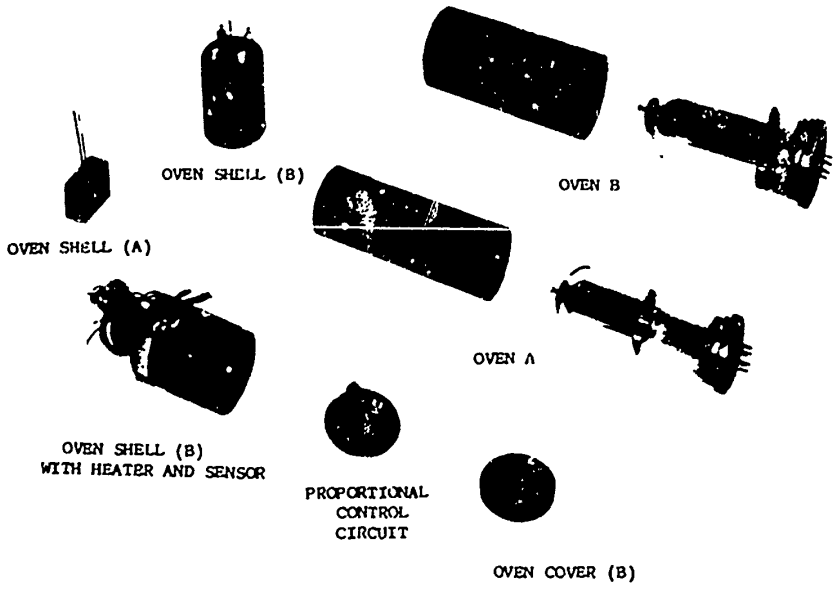


Figure 4-10. Exploded View of Crystal Ovens

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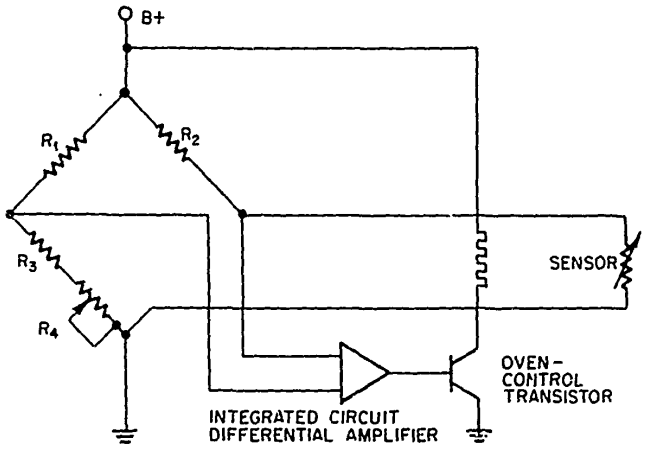


Figure 4-11. Basic Proportional Control System

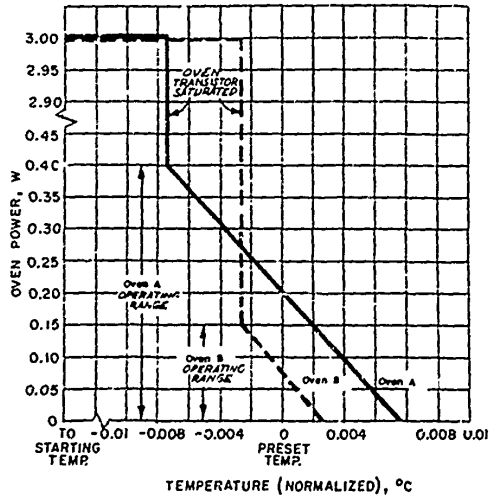


Figure 4-12. Typical Control System Characteristics

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4-3 TUNING FORK OSCILLATORS

4-3.1 TUNING FORKS

4-3.1.1 Dimensional Considerations

The frequency f of a fork is determined by the tine dimensions. Frequency is directly proportional to tine thickness and inversely proportional to the square of tine length

$$f = k\left(\frac{h}{\ell^2}\right), \text{Hz} \qquad (4\text{-}1)$$

where

k = proportionality constant, dimensionless

h = tine thickness, in.

ℓ = tine length, in.

The remaining dimension (b) has no relation to frequency (Fig. 4-13[25]). Usually a low-frequency fork is long and a high-frequency fork is short, but this is not mandatory. Although most forks are driven so that they vibrate in a fundamental mode, higher frequencies sometimes are produced by driving a fork in an overtone mode.

4-3.1.2 Quality Factor

The quality factor Q of the fork is related to its material, dimensional relationships, and the method of driving the fork. Q also can be determined from the spacing of the half power points or by the vibration decay characteristics. Forks made of certain aluminum alloys can attain twice the Q of nickel alloy forks but have very poor frequency versus temperature coefficients. The Q of a resonator (electrical, mechanical, or any other) is[26]

$$Q = 2\pi\left(\frac{H_s}{H_d}\right), \text{ dimensionless} \qquad (4\text{-}2)$$

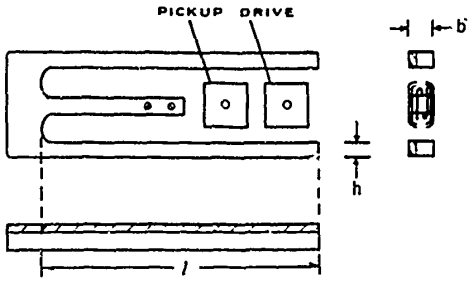


Figure 4-13. Typical Tuning Fork

where

H_s = energy stored per cycle, ft-lb

H_d = energy dissipated per cycle, ft-lb

4-3.1.3 Temperature Coefficient of Frequency

Temperature variation is the largest single factor affecting frequency stability. The temperature coefficient of frequency β is[27]

$$\beta = (\alpha + \gamma)/2, (\text{deg C})^{-1} \qquad (4\text{-}3)$$

where

α = temperature coefficient of the modulus of elasticity, $(\text{deg C})^{-1}$

γ = temperature coefficient of linear expansion, $(\text{deg C})^{-1}$

By suitable selection of materials, β can be made to approach zero. This was the basis for development of the constant modulus alloys. The metal used for mono-metallic types has a composition as shown in Table 4-3[27]. Fork manufacturers may vary the composition to suit certain requirements of stability, temperature limits, etc.

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TABLE 4-3

ANALYSIS OF MONOMETALLIC TYPE FORK

Metal	Composition, %
Nickel	30-38
Chromium	5-13
Iron	48-61
Manganese	0.5-2
Silicon	0.5-1
Cobalt	0.5-1
Tungsten	1-3

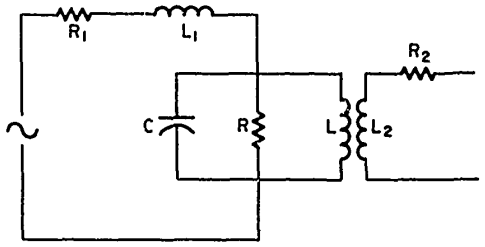
Bimetallic construction uses a block of constant modulus alloy and a strip of carbon steel, silver soldered together. The ratio of nickel alloy to carbon strip thickness determines the temperature coefficient of the tuning fork and will be in the range of 4-6 to 1 with the nickel alloy being the largest quantity[27].

4-3.1.4 Shock and Vibration

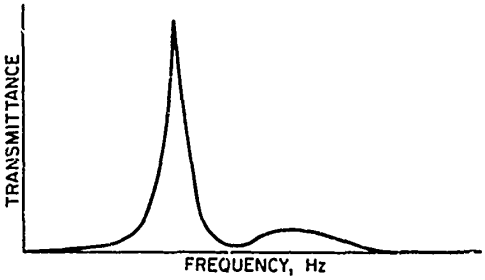
Both tines of a fork can be forced to vibrate parasitically in phase, in addition to the normal out-of-phase vibration under disturbance of shock or vibration. However, if the coils are placed between the tines, see Fig. 4-13, the pick-up coil will tend to cancel pick-up voltage due to in-phase tine motions and thus reduce this component in the output. Use of an internal stud to mount the fork at its center of moment reduces the shock and vibration effects by approximately 5 times in the internal stud configuration[25].

4-3.2 OSCILLATOR CIRCUITRY

A simplified equivalent circuit of the fork assembly in the form of a two-terminal pair network is shown in Fig. 4-14(A)[27]. As with the crystal, the fork parameter values are dependent on amplitude of vibration. In the figure, the representation is that of an electromagnetic transducer or resonator in which an output coupling is placed to produce an output that is proportional to the



(A) Simplified Equivalent Circuit



(B) Transmittance vs Frequency

Figure 4-14. Oscillator Circuit

amplitude of oscillation. Transmittance (ratio of generalized output to input) is shown as a function of frequency in Fig. 4-14(B). Peak response corresponds to antiresonance of the motional parameters, and the secondary response corresponds to series resonance of the motional equivalent capacity with the coupling coil inductance. The latter is typically one or two percent higher in frequency than the primary response and is sufficiently low in amplitude compared with the main response that oscillation will still occur at the primary response[27].

4-4 ATOMIC FREQUENCY STANDARDS

4-4.1 PASSIVE RESONANT DEVICES

4-4.1.1 System Considerations

The atomic resonances of cesium and

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rubidium are used passively to control the frequency of quartz crystal oscillators through the action of electronic feedback circuits. The basic system arrangement is shown in Fig. 4-2. In this system, the frequency of the controlled crystal oscillator is an integral submultiple of the atomic resonance frequency. To provide standard frequency signals on the basis of the commonly defined time intervals, a frequency synthesizer is included as a part of the resonance controlled oscillator. The synthesizer may either be (1) included within the frequency control loop to relate the rational frequency of the crystal oscillator to a submultiple of the atomic resonance, or (2) part of a secondary system phase locked to the primary loop as shown in Fig. 4-2. Note that the feedback control loop attempts to match the multiplied frequency of the controlled oscillator to the frequency of the atomic resonance. The response time of the control loop determines the length of time that errors in the crystal oscillator continue before correction is made in terms of atomic resonance. In time intervals short compared with loop response period, the oscillator stability is that of the crystal oscillator, while in the case of time intervals that are long compared with the loop response period, the stability is that of atomic resonance.

An important consideration in the design of the control system is the noise associated with the atomic resonance signal. This noise will modulate the crystal oscillator frequency and degrade the short-term stability performance. To combat this, the control loop response speed may be limited by the designer and thus effectively filter the noise before it reaches the oscillator. However, disturbances caused by the environment can introduce errors that are not corrected as quickly and effectively as may be required. Compromises are, therefore, necessary to best match the application. Another frequency modulation noise may arise from the frequency multiplication process but in most practical devices, the resonance signal noise dominates[2].

The larger signal-to-noise ratio of the rubidium resonance controlled oscillators makes them more effective for short-term control of frequency errors induced by shock and vibration than those controlled by cesium resonance. Other design factors include phase control of the modulation signals, harmonic distortion of these signals, and the spectral purity of the microwave signal applied to the atomic resonator[28].

4-4.1.2 Cesium Beam Standards

Cesium beam standards are maintained at the National Bureau of Standards (NBS) and at the U S Naval Observatory (USNO), the two organizations chiefly involved in distributing accurate and precise time and frequency information within the U.S. NBS is responsible for the custody, maintenance, and development of the national standards of frequency and time (interval) as well as their dissemination to the general public. This mission of USNO includes the provision of accurate time as an integral part of its work associated with the publication of ephemerides in support of navigation and in the establishment of a fundamental reference system in space[29].

The National Bureau of Standards has developed several cesium standards and one thallium standard. NBS-I, the oldest machine, was originally operated using cesium but was converted to thallium in 1962. NBS-II provides a line width of 110 Hz, while NBS-III, the longest machine, provides a spectral line width of 48 Hz (see Fig. 4-15[30]). NBS-5 has an accuracy of better than 1 part in 10^{12}.

All of the NBS devices use the Ramsey-type excitation instead of the Rabi-type. The original Rabi method of exciting the atomic transitions in an atomic beam resonance experiment uses a single oscillating field[31]. Ramsey introduced a method by which the transitions are excited by two separated oscillating fields. Advantages of this method

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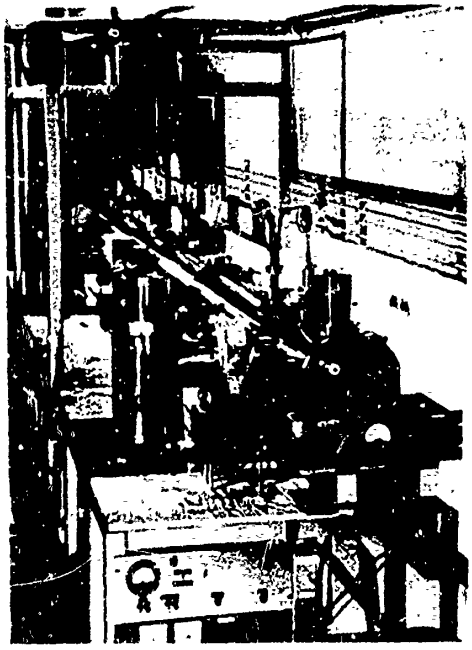


Figure 4-15. Cesium Atomic Beam Frequency Standard, NBS-III

are[32]: (1) improved resolution of the spectrometer, (2) a high degree of uniformity of the magnetic fields not required, and (3) a higher resolution than a single field when observing very high frequency transitions. This latter advantage is gained at the expense of a reduction in the signal-to-noise ratio.

Examples of commercial cesium atomic beam frequency standards are Hewlett-Packard Models 5061A and 5062A. The former is available with two different beam tubes, standard and high performance.

4-4.1.3 Rubidium Gas Cell Standards

Rubidium gas cell standards require, as a component of the gas cell mixture, an inert buffer gas that interacts with the rubidium gas to cause a pressure shift. Commercial development of rubidium gas cell controlled oscillators has led to refined designs entirely based upon solid-state electronic circuits. The rubidium instrument is compact and operates reliably. A militarized version designed for U S Army tactical applications is illustrated in Fig. 4-16[2]. Capable of surviving rough handling and the problems involved in a wet environment, these units have been designed for operation in guided missiles and aircraft as well as in general applications for which they can be installed in a relay rack[2].

4-4.2 MASERS

4-4.2.1 System Considerations

Atomic hydrogen masers and rubidium gas cell masers are active oscillators that provide output signals directly from the quantum transitions within the atomic particles. For practical applications, it is necessary to make maser signals available at millivolt power

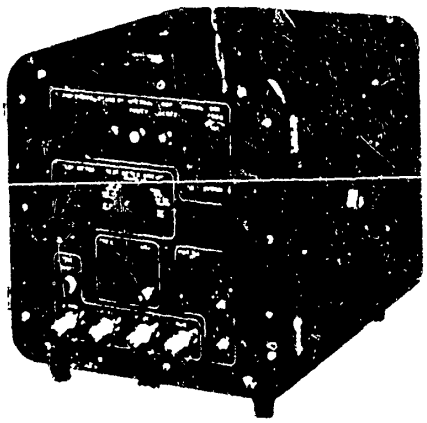


Figure 4-16. Tactical Rubidium Gas Cell Frequency Standard[2]

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levels and synthesized to convenient frequencies. For the hydrogen maser, accessories are available to phase lock high quality crystal oscillators to the maser signal by using commercial synthesizers. The basic block arrangement is shown in Fig. 4-3.

Noise is a fundamental factor that limits stability and the spectral purity of the signal in maser frequency standards. The internal noise of the oscillator includes thermal noise and noise characteristics of the maser type and design. External circuits also contribute additional noise. The mixers are the sources of most of the noise and where very short term stability or high spectral purity are important, low noise preamplifiers are used ahead of the mixers[2].

4-4.2.2 Maser Devices

Techniques and design principles relevant to the construction and operation of hydrogen masers are well documented[33]. An atomic hydrogen maser clock system for installation in a satellite to be used for measuring the gravitational red shift has been developed, and performance data presented for the operation of a laboratory model, see Fig. 4-17[34]. Prototype atomic hydrogen standards for field use at tracking stations have been developed[35]. Designed for minimal operator attention, the unit contains a hydrogen maser, receiver-synthesizer, automatic cavity tuner, clock, standard output frequencies and time signals, and other system electronics.

Another type of maser that has been developed is the optically pumped rubidium maser oscillator[36]. It is considerably smaller than hydrogen maser, but affected by the same factors that limit the long term stability of the rubidium gas cell standard. Short-term stability is expected to be one part in 10^{12} for observation times of 1 sec and long-term stability to be about one part in 10^{11} per month. Table 4-4[2] compares physical data of three types of atomic frequency standards.

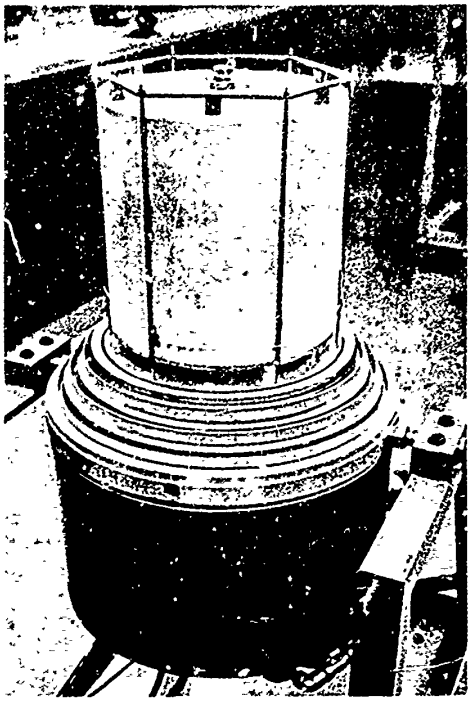


Figure 4-17. Satellite Maser With Bell Jar Removed

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TABLE 4-4

PHYSICAL DATA RELATING TO AVAILABLE ATOMIC FREQUENCY STANDARDS[2]

Characteristic		Atomic Hydrogen Maser	Rubidium Gas Cell Controlled Oscillator	Cesium Atomic Beam (24-in.) Controlled Oscillator
Nominal Resonance Frequency		1420.405751 MHz	6834.682608 MHz	9192.631770 MHz
Resonance Width		1 Hz	200 Hz (typical)	250 Hz
Atomic Interaction Time τ_A		0.5 sec	2×10^{-3} sec (typical)	2.5×10^{-3} sec Interaction length, L = 25 cm (typical)
Atomic Resonance Events per Second		10^{12}	10^{12}	10^{6}
Principal Frequency Offsets	Magnetic	$f - f_0 = 2750\ B^2$ (gauss) 5×10^{-13} (typical	$f - f_0 = 574\ B^2$ (gauss) 1×10^{-9} (typical)	$f - f_0 = 427\ B^2$ (gauss) 1×10^{-10} (typical)
	2nd Order Doppler	4×10^{-11} ($\partial f/\partial T$ = 1.4×10^{-13}/°K)	8×10^{-13}	3×10^{-13}
	Collisions	2×10^{-11}	3×10^{-7} (typical)	none
State Selection Method		Atomic Beam Deflection in Hexapole Magnets	Optical Pumping	Atomic Beam Deflection in Dipole or Multipole Magnets
Resonance Detection Method		Atomic Microwave Radiation (active maser oscillation)	Optical Absorption	Surface Ionization of Deflected Atoms
Temperature of Resonating Atoms		300°K	330°K	360°K

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CHAPTER 5

TIMING EQUIPMENT AND MEASUREMENT

5-1 INTRODUCTION

Chapters 2, 3, and 4 are concerned with the basic considerations of setting up precision reference timing systems. In this chapter we deal with the equipment and techniques available to the local user who must solve problems requiring accurate knowledge of time. For accurate time keeping – regardless of whether the required time scale is atomic time, universal time, or any other (see par. 2-1) – the local system should (1) provide a consistent time interval, (2) be initially synchronized with the master time, and (3) be checked periodically against the master time to ensure that the scales remain in correspondence. In other words, accurate time keeping requires an accurate and stable measuring system and effective means of synchronizing this system with the master. The equipment, techniques, and resources available to the local user to achieve these ends are discussed in the paragraphs that follow.

5-2 TIME MEASUREMENT

Precision time keeping or time indication usually requires the use of a very stable oscillator such as a quartz crystal oscillator (see pars. 3-2 and 4-2) or one that depends on the frequency corresponding to a particular energy-level transition (see pars. 3-4 and 4-4). Military Specifications for the cesium beam frequency standard are listed as Refs. 1-4.

Unless very long time intervals are being measured, the full stability inherent in these oscillators cannot be obtained with ordinary techniques. By use of the most basic method of time interval measurement, the number of complete oscillator cycles which elapse between start and stop of an interval are counted electronically. If, for example, the oscillator frequency were 100 MHz and its short-term instability were one part in 10^{10}, then oscillator stability would be the limiting factor in the measurement accuracy only for time intervals greater than a hundred seconds. To make full use of oscillator stability for shorter time intervals, measurements can be made of the fractional cycles that occur during the time interval[5]. To measure the number of oscillations in an interval, use is made of electronic counters. The basic elements of counters include (1) decade counting assemblies, (2) a main gate that controls the time interval during which the input signal is measured, (3) a time base which supplies a reference of time for the main gate, (4) decade divider assemblies, and (5) a means of shaping the input signal to provide for proper operation of the gate. Numerical readouts are used to display the count.

5-2.1 GATED COUNTER

Transient or repeated time intervals often are measured using a gated counter to count the cycles of an oscillator. In its simplest form, a gated counter (Fig. 5-1[5]) forms a pulse from the input sinusoid and this pulse train is "gated" into a counter. Referring to the figure, the crystal oscillator is free-running and thus can be highly stable. Before the initiation of a time measurement, the reset multivibrator sets the counter to zero. Transmission of the crystal-controlled train to the counter is prevented by the gate. When a start pulse arrives, the gate binary switches

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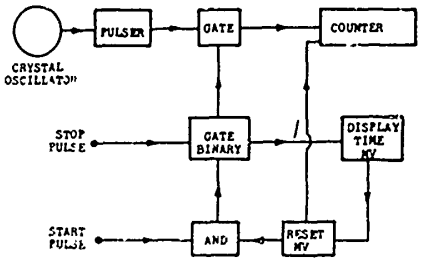


Figure 5-1. Gated Counter[5]

and opens the gate that allows subsequent time pulses to pass through to the counter. These are counted until a stop pulse arrives, and then the gate binary returns to its original state and the passage of timing pulses to the counter is stopped. The display-time multivibrator deactivates the gate binary so that the accumulated count can be viewed[5].

For transient measurements, the accuracy obviously is limited to ± 1 cycle of oscillation in a system using a simple polarized threshold detector. The accuracy of this "gated counter" system would be doubled if a bipolar threshold detection system were employed. However, any increases in order of magnitude are not assured and the counter has to operate at higher speeds. Present technology sets a counting rate limit on binary counters at approximately 100 MHz and, consequently, accuracies greater than 10 nsec cannot be obtained by the brute force application of this method[5].

A somewhat better accuracy can be obtained from the gated counter approach when doing repetitive measurements. Results of an extensive analysis indicate that 100 measurements are required for an accuracy of 1 nsec with 90% confidence with a 100-MHz counter[5]. Recycle and display typically requires several milliseconds, and thus 100 measurements might require 1 sec (Ref. 6).

5-2.2 VERNIER SYSTEM COUNTER

The next level of improvement in accuracy has been achieved by the use of "vernier systems"[7]. Essentially, the principle of operation is that a coarse counter counts the whole number of crystal clock oscillations while vernier counters indicate the correction due to fractional clock cycles. A block diagram of the system is shown in Fig. 5-2[6]. The correction is measured by causing a vernier oscillator to commence pulsing at the start of the time interval. The vernier oscillator frequency is slightly higher than that of the clock oscillator, and vernier oscillations are counted until the vernier oscillator comes into phase with the clock generator. A measure of this phase of the clock generator then can be obtained. This phase determination at the end of the time interval is made by another vernier actuated by the stop signal[5]. Two restrictions on this method are (1) there are stringent stability requirements for the vernier generators, and (2) there is a "dead time" because the vernier measurement is not available until the vernier and the clock coincide.

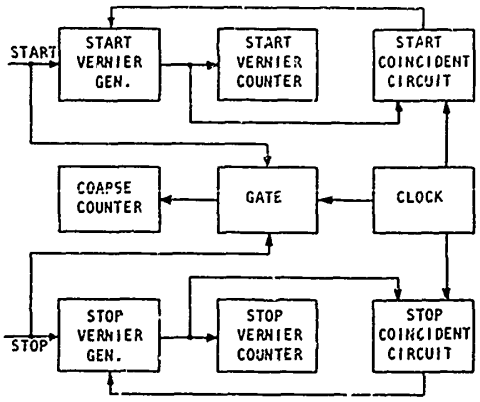


Figure 5-2. Vernier Counting System[6]

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5-2.3 DIGITAL INTERPOLATION COUNTER

Another technique that does not have the restrictions of the vernier is the digital interpolation technique[5]. In this method, a pulse train derived from and synchronous with the clock oscillator is fed into a delay line. At the start of a time interval to be measured, a pulse is developed that is applied to the opposite end of the line. If the line has the proper length, there will be a superposition of pulses at only one point on the line. By tapping the line at regular intervals and connecting threshold detectors to each tap, the detector at or near a point of superposition will be triggered. Since the location of the detector is a measure of the time by which the start of a given time interval and a particular clock pulse differ, the detector at that point can be used to drive an indicator as in a time interval measurement. It has been shown that this method makes possible the improvement in accuracy of a conventional gated-counter time measuring system by a factor of 5 (exclusive of crystal accuracy)[5].

5-2.4 COMPUTING COUNTER

Computing counters combine the most precise electronic counter with a built-in arithmetic capability. With this combined system, the raw data from the measurement section can be treated mathematically to produce the desired form. For example, the computer section can be programmed to correct for fractional frequency deviation of the source. At present these counter systems can measure fractional frequency divisions as small as 5×10^{-10} for 1 sec averaging time.

5-3 SYNCHRONIZATION SYSTEMS

5-3.1 RADIO TRANSMISSION

Time synchronization accuracy to ± 1 msec can be achieved with presently available standard time signals such as those transmitted by station WWV[7]. The method used here requires the determination of the propagation delay between the transmitter and the clock station. This delay then is applied as a correction to the clock reading[8]. In addition, HF services broadcast time of day information. Time ticks of these broadcasts may be used in much the same way. With present LF/VLF time services and the receiving equipment now available, time synchronization accuracy is a few milliseconds[9].

5-3.1.1 Factors Affecting Radio Transmission

The principal factors that affect the propagation delay for HF signals are (1) the great circle distance between transmitter and receiver, (2) the transmission mode, and (3) the virtual height of the ionosphere reflection layers. How these parameters are determined and how the propagation delay is calculated are discussed in the paragraphs that follow.

5-3.1.1.1 Great Circle Distance

A straightforward way to compute the great circle distance between two points makes use of haversines. Refer to Fig. 5-3[9],



Figure 5-3. Great Circle Distance Calculation[6]

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suppose A and B are two points on the earth for which the latitude and longitude are known. The following relationships must then be found:

(1) For longitude

$$Lo_{AB} = Lo_A - Lo_B \text{, deg} \qquad (5\text{-}1)$$

where

Lo_A = longitude of Point A, deg

Lo_B = longitude of Point B, deg

(2) For latitude, if the two points are on the same side of the equator

$$L_{AB} = L_A - L_B \text{, deg} \qquad (5\text{-}2)$$

where

L_A = latitude of Point A, deg

L_B = latitude of Point B, deg

If the two points are on opposite sides of the equator,

$$L_{AB} = L_A + L_B \qquad (5\text{-}3)$$

The haversine of the great circle distance, in degrees of arc, is given by[9]

$$\text{hav } D = (\cos L_A)(\cos L_B)(\text{hav } Lo_{AB}) + \text{hav } L_{AB} \qquad (5\text{-}4)$$

Note that the haversine of an angle $\theta = (1 - \cos \theta)/2 = \sin^2 (\theta/2)$. Great circle distance can be determined by reference to a table of haversines versus angles[10].

5-3.1.1.2 Transmission Modes

The propagation path is a groundwave path for most LF/VLF transmissions. Short distance HF transmissions closely follow the great circle route from transmitter to receiver. For HF transmission over a distance of more than about 160 km, the propagation path is a sky-wave.

The maximum distance that can be spanned by a single hop (i.e., one reflection from the ionosphere) via the F2 layer is about 4000 km (see Fig. 5-4[9]). It follows then that the fewest number of hops between transmitter and receiver is the next integer greater than the great circle distance divided by 4000. Transmission modes with one or more hops greater than the minimum number of hops occur frequently as shown in Fig. 5-5[9].

5-3.1.1.3 Height of Ionosphere

Long distance HF transmissions usually are reflected from the F2 layer that varies in height from about 250 to 450 km. It has been determined from experience that the virtual height of the F2 layer averages about 350 km (see Fig. 5-4). This height can be used for delay estimation.

Once the transmission modes and layer heights have been determined, the transmission delay can be determined graphically by reference to Fig. 5-6[9]. This graph is plotted for a single hop, but it can be used to determine the distance for multiple hops. The

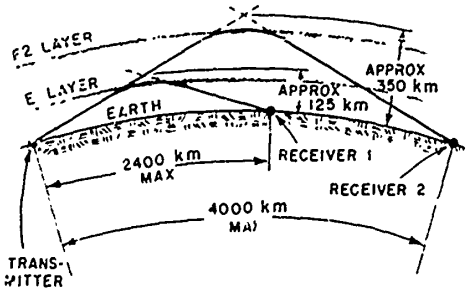


Figure 5-4. Single-hop Sky-wave Paths

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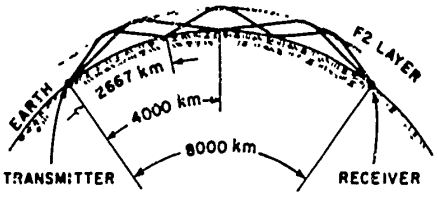


Figure 5-5. Multiple-hop Transmission Path

distance covered by a single hop and the delay for a single hop is determined, and this delay is then multiplied by the total number of hops to obtain the total delay.

This propagation delay is applied as a correction to the clock reading, and the clock ticks are then produced in synchronism with the transmitted master timing signal (i.e., WWV). WWV is a high-frequency station operated by the U S National Bureau of Standards at Ft. Collins, Colorado. Its time code transmission is made for one minute out of five, ten times per hour, and is produced at a 100 parts per second rate carried on a 1000-Hz modulation. Fig. 5-7[8] shows time code transmission from station WWV.

5-3.1.2 Normal Radio Transmission

5-3.1.2.1 LF/VLF Radio Transmission

Low frequency and very low frequency signals follow the earth's curvature, and are in effect guided by the ionosphere acting as a boundary. The high phase stability and long range coverage of the lower frequencies make them valuable for standard frequency transmissions. Time synchronization with the present LF/VLF services, as with HF, must include the factors of propagation and receiving system delay except for the simplification of all ground wave transmission. VLF waves propagate at about 292,000 km/sec as compared with 278,000 km/sec for HF waves[9]. Since LF and VLF transmissions are propagated for relatively great distances by ground wave, propagation delay for these frequencies usually can be found directly, after the great circle distance is calculated.

Whereas time synchronization with LF/VLF could be accomplished to no better than a few milliseconds before, there is a new method, using dual VLF transmissions, in which the synchronization can be accomplished to an accuracy of 2 or 3 μsec or better[10]. In this method, the Dual Frequency Transmissions of Radio Station WWVL at Fort Collins, Colorado, were used as a means of time synchronization of remote clocks. A special receiving system was designed and fabricated for the simultaneous reception of either 19.9 and 20.0 kHz or 20.0 and 20.5 kHz. The system automatically combines the received signals to produce a timing pulse train with a repetition rate equal to the difference frequency and with a phase determined by the instantaneous phase coincidence of the received signals. Two receiving systems were operated simultaneously, one at NASA, Greenbelt, Maryland, and one at RMS Engineering, Inc., Atlanta, Georgia. Adequate data were obtained with the 100-Hz separation to confirm a received time accuracy of better than a few microseconds during certain hours of uninterrupted data[10].

Another system similar in concept is the NBS-NASA system[11]. The frequencies used here are the 20.0-kHz standard frequency carrier, with either 20.5 or 19.9 kHz as the single auxiliary frequency for a given test period. These frequencies were all synthesized and phase locked to the USFS. Carrier period ambiguities were 50 μsec; difference frequency signal ambiguities of the period were either 2 or 10 msec. The single transmitter and antenna at Fort Collins, Colorado was used because frequency shift keying was used. This procedure allowed 10-sec transmission time alternately for each frequency. To relate these transmissions to UTC, the phases of the two frequencies being broadcast were adjust-

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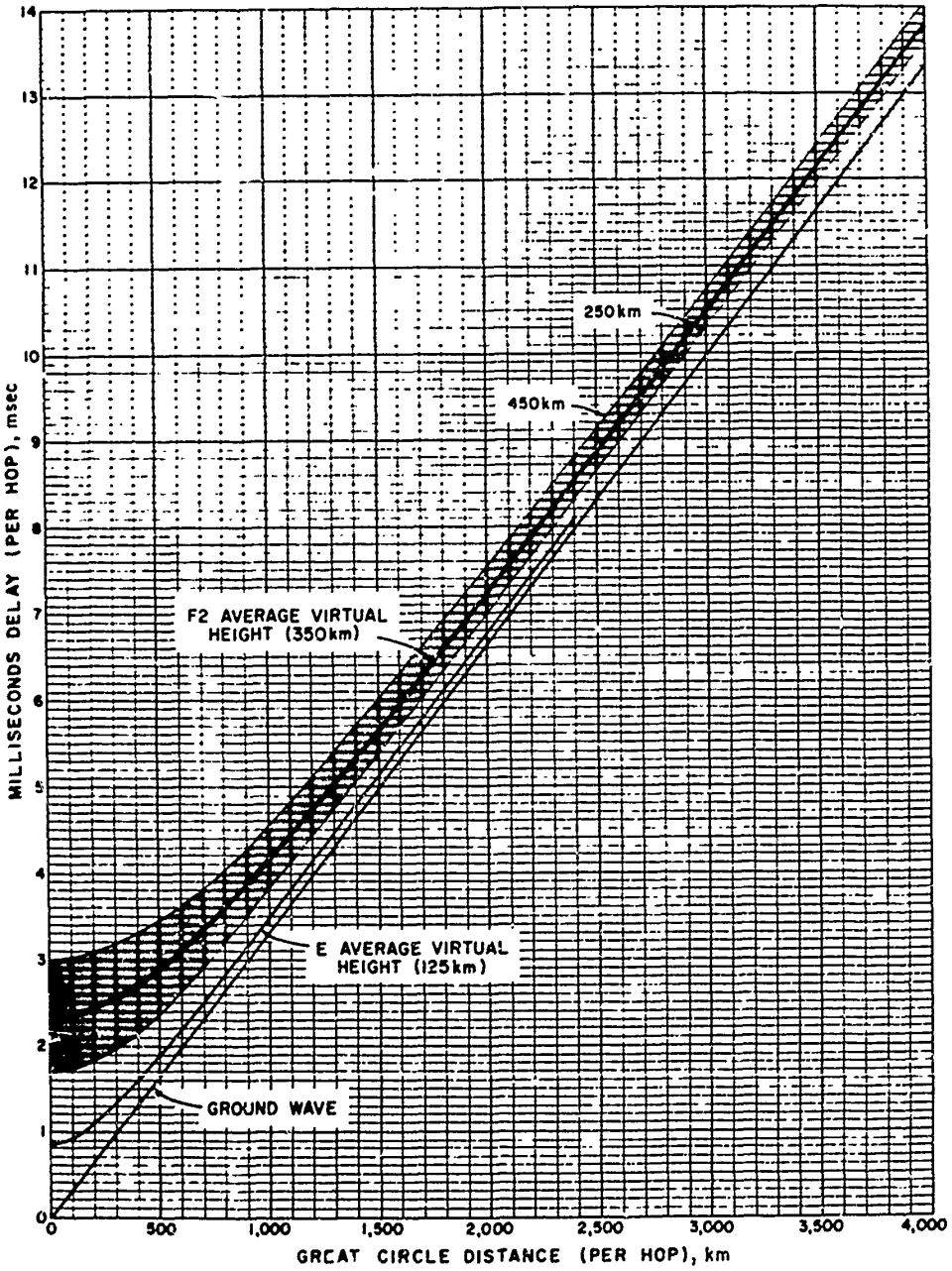


Figure 5-6. Transmission Delay Graph

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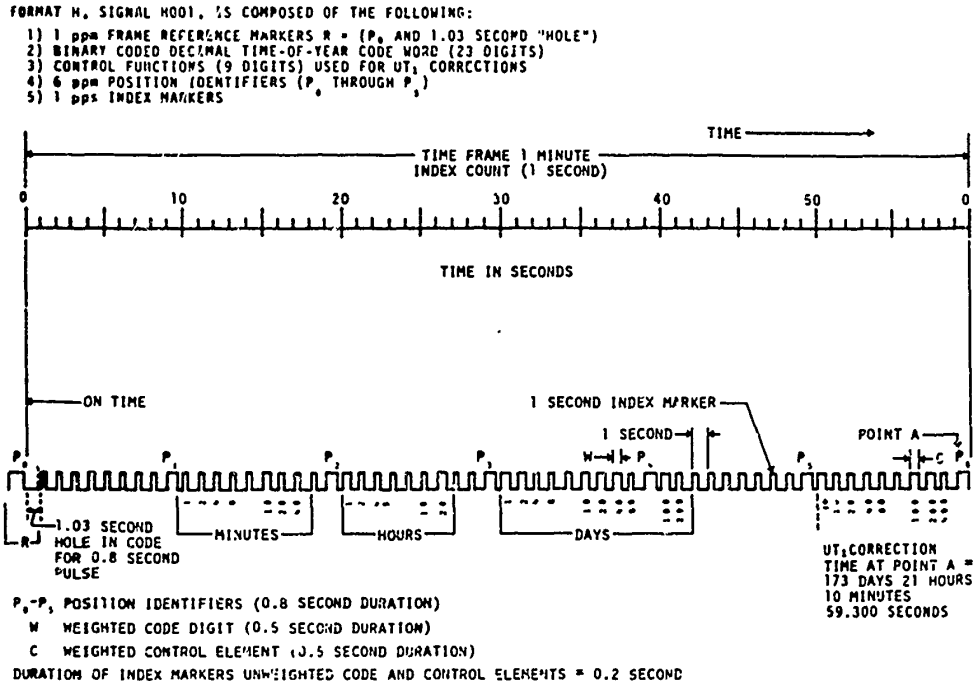


Figure 5-7. Chart of Time Code Transmissions from NBS Station WWV[9]

ed at the transmitter to go through zero simultaneously in a positive direction coincident with a second's tick of UTC. Phase relations are maintained, upon reception, with the time of simultaneous phase agreement with a delay the amount of which depends upon the phase velocity of the signals and the distance between receiver and transmitter.

To extract timing information from the signals, one or two conventional phase tracking VLF receivers can be used. To relate the phases of the received signals to the time scale operating at the receiving site for time synchronization, a calibrator was used to generate the same two frequencies as transmitted from the local time scale, with the same simultaneous phase relationship conditions. The calibrator consists of a sawtooth waveform generator that is synchronized by a 100 pulse per second rate taken from the local time scale divider chain. An interchange of signals from the receiving antenna and the calibrator output permits a measurement to be made of the pair of phase differences. From the two measured quantities, the relation between transmitter time scale and receiver time scale may be calculated, provided that the carrier propagation delays are known. Propagation fluctuations on the path from Fort Collins, Colorado, to the Goddard Space Flight Center at Greenbelt, Maryland were studied by keeping the clocks at the two locations synchronized using portable clocks. Results are shown in Figs. 5-8[11] and 5-9[11] that indicate the propagation delay as derived from the difference frequency measurements. To evaluate the maximum stability of synchronization of the system, the day-to-day

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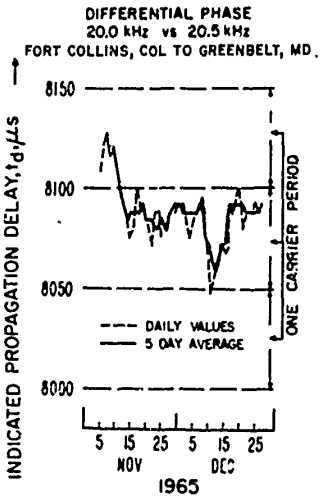


Figure 5-8. Indicated Propagation Delay, 20.0 vs 20.5 kHz[9]

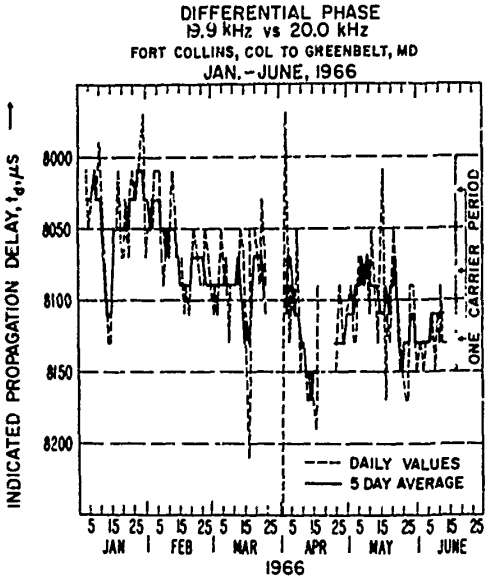


Figure 5-9. Indicated Propagation Delay, 19.9 vs 20.0 kHz[9]

time variation of the received carrier was plotted as shown in Fig. 5-10[11]. If the same cycle of the carrier had been identified each day, this figure would indicate the system capability of synchronization.

5-3.1.2.2 Loran-C Synchronization

A pulsed radio navigation system, operated by the U S Coast Guard, called the Loran-C system, uses a 100-kHz carrier and offers a means for precision transfers of time. Clock synchronization to ± 1 μsec is possible within the range of any station of the East Coast Loran-C chain. The master Station of the East Coast Chain, at Cape Fear, N.C., is controlled with respect to the U S Naval Observatory master clock[9].

The mechanics of station clock synchronization to Loran-C transmissions depend on the type of receiver being used and the required timing precision. Fig. 5-11[12] shows a simple visual timing system. This system can be used within a few hundred kilometers of a master chain transmitting 1 part per sec identifiers or within that range of any station on the East Coast chain. Useful range may be expanded by photographic integration, and accuracies up to ± 20 μsec for ground waves can be achieved. Fig. 5-12[12] shows a visual timing system for use with any skywave situation and for ground waves not requiring automatic receiver accuracies. An epoch monitor system (Fig. 5-13[12]) produces a pulse rate that is reset to the delayed 1 part per sec. The phase decodes the signal. Accuracies are limited by ability to cycle-select and may be improved by photographic integration.

A phase tracking system is shown in Fig. 5-14[12]. This system provides a record of the local oscillator phase drift with respect to Loran-C. Used within the ground range of a Loran-C station, the resulting record, which is free of diurnal shift, can be used to compare the station oscillator with the cesium reference at the Loran-C station to within one or two parts in 10^{12} per 24-hr period.

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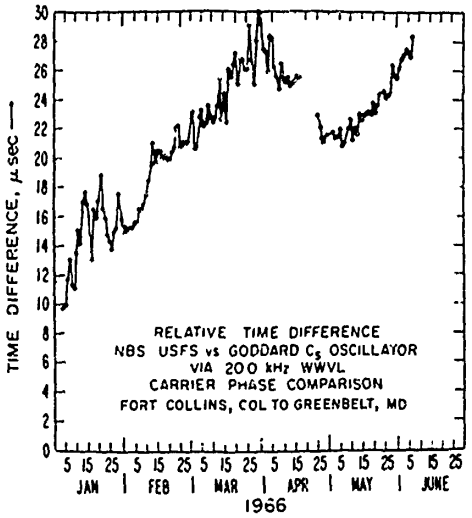


Figure 5-10. Residual Daily VLF Time Fluctuations[9]

Accuracies are generally in the range of ± 20 μsec. An automatic receiver system, Fig. 5-15[12], is used depending on the particular chain to be monitored. An automatic receiver has the capability of cycle-selection, and accuracies up to 0.1 μsec have been attained. The system can be calibrated by a Loran-C simulator.

A recent comparison among three precise timing centers in the United States was conducted for over one year[13]. These data involved a 3500-km ground wave path, and the long term precision achieved between the three remote stations was 2 μsec.

5-3.1.2.3 Omega Synchronization

Omega is a very low frequency navigation system. The basic navigational frequency of Omega is 10.2 kHz. In addition, navigational

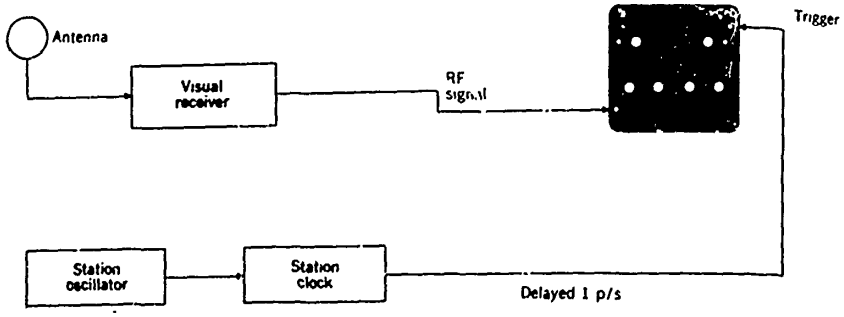


Figure 5-11. Simple Visual Timing System[9]

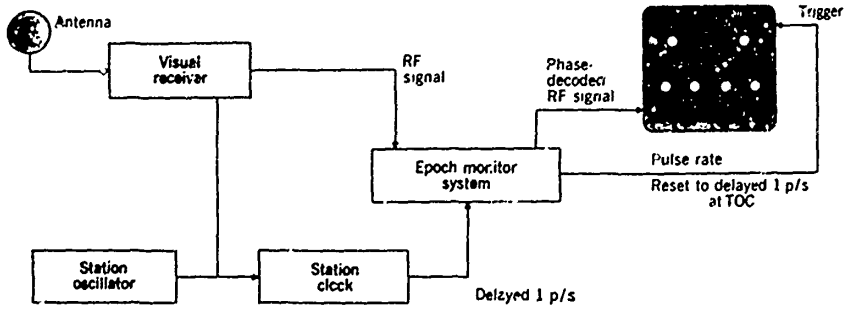


Figure 5-12. Visual Timing System[11]

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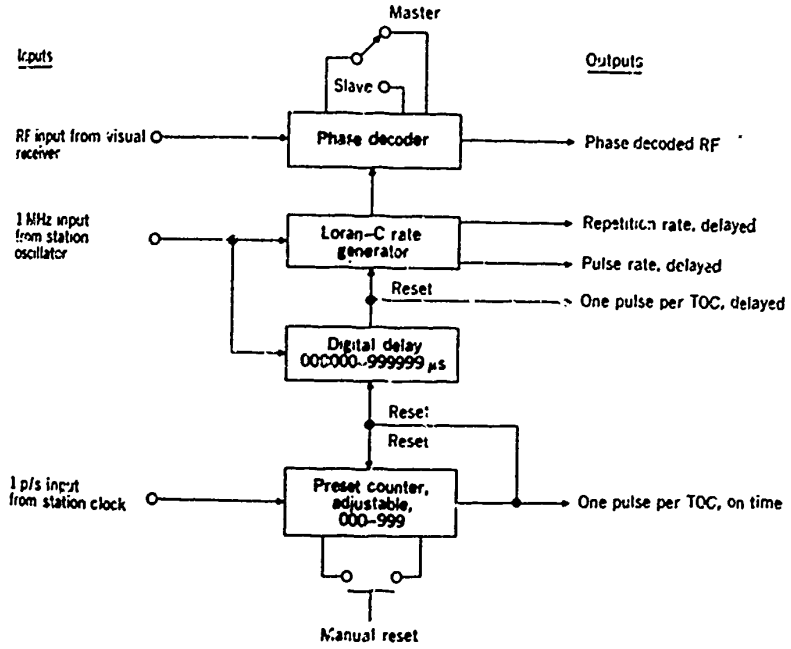


Figure 5-13. Simplified Diagram of an Epoch Monitor System

frequencies of 13.6 kHz and 11-1/3 kHz also are broadcast[14]. Epoch at timing sites may be deduced and maintained to better than 3 μsec, and frequency can be maintained to one part in 10^{12}. Long bursts of continuous wave are transmitted (on the order of 1 sec or more) and repeated every 10 sec. All stations go off and on together, with 0.2 sec off between transmissions. There is no master-slave relationship, all stations being equal.

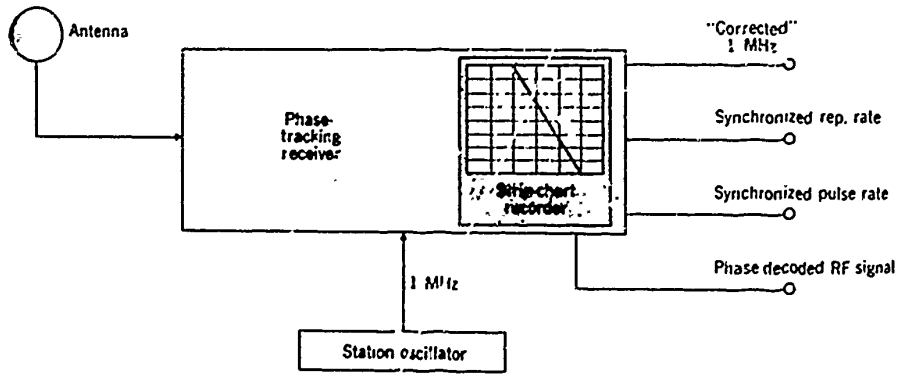


Figure 5-14. Phase-tracking System[11]

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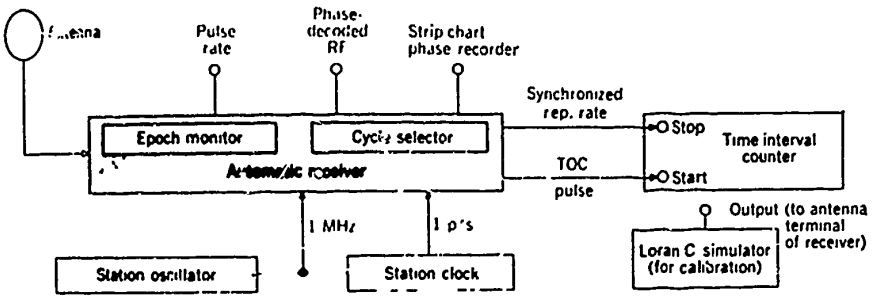


Figure 5-15. Automatic Receiver System[12]

5-3.1.2.4 TV Network Broadcasts

This method is readily available, inexpensive, and a common source for many users within the continental United States. In essence the time comparison is between the "read" from counters that are located near different clocks[13]. The counters are started by the clocks with the same tick from the local reference clocks. The counters are stopped by a "sync" pulse broadcast from a TV transmitter. The difference between any pairs of counter readings remains constant.

A system developed by NBS for use in the continental United States uses line-10 of the odd field in the 525-line system M as a passive transfer pulse. The broadcasts originate from the New York City studios of any or all of the three commercial TV networks. Carried through the TD-2 relay system, the received microwave signal is converted at a terminating station to a video signal and retransmitted by VHF or UHF to local service areas.

NBS distributes the line-10 daily measurements in terms of UTC (NBS) in the Monthly NBS Time Service Bulletin. The USNO distributes line-10 data in terms of UTC (USNO-MC) in the weekly Series 4 Time Services Bulletin. These publications also cover future changes, modifications to the TV system, or other factors affecting users in the field.

Advantages of line-10 timing include (1) simplicity, (2) low cost of comparison equipment, (3) low cost of maintaining synchronization with long range precision of 10 μsec, and (4) a method for simultaneous maintenance of microsecond synchronization of several clocks within the service area of one transmitter.

5-3.1.3 Satellite

Experiments in time transfers by use of satellites have shown that clocks can be synchronized to high precision at facilities equipped with satellite tracking antennas. Pulsed signals were transmitted simultaneously from ground stations over the satellite circuit with correlations to time kept by a master clock at the U S Naval Observatory[9]. Accuracy was within ± 1 μsec.

5-3.1.3.1 Telstar

By using narrow band signals between ground stations in the U S and the United Kingdom, a one-way transmission was achieved by means of Echo I (a passive reflector) in August 1960. The successful operation of Telstar 1 (an active relay satellite) provided an essentially symmetrical circuit for simultaneous, two-way transmission and reception having a high signal-to-noise ratio of 40 dB. The purpose of this experiment was to determine the time

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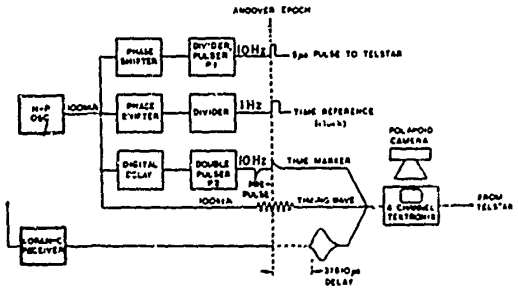


Figure 5-16. Pulse Generating and Measuring Arrangements at Andover, Me.[12]

difference between the master clocks of the U S Naval Observatory and the Royal Greenwich Observatory at Herstmonceux, U.K. Signals were transmitted simultaneously over the satellite circuit from the ground stations at Andover, Maine, and Goonhilly Downs, Cornwall, U.K. These signals were pulsed and were of a 5-μsec duration. The difference in time between the transmitted and received pulses was measured at each station, and the relative setting of the station clocks was obtained directly. The equipment used at Andover, Maine, (see Fig. 5-16[15]) included the following[15]:

(1) Hewlett-Packard (HP) quartz crystal oscillator and clock

(2) Pulser (P1) that initiated pulses to Telstar

(3) Pulser (P2) to provide two sets of pulses, one to trigger a 4-channel oscilloscope and one to provide time markers

(4) An oscilloscope camera

(5) Receivers for time signals transmitted on HF, VLF, and Loran-C.

Pulses were emitted using the Loran-C station on Nantucket Island, in groups of 8, spaced 1 msec apart, at a repetition rate of 20 groups/sec. The cycles within a pulse had a period of 10 μsec. The equipment at Goonhilly is indicated in Fig. 5-17[15]. The Post Office oscillator was a 100-kHz Essen-ring oscillator. Along with a chain of dividers, it gave an output signal of 1 Hz which provided the time reference. The 60-kHz transmission at MSF, Rugby, was used to relate Goonhilly to Herstmonceux. It was demonstrated by the use of Telstar that clocks at satellite ground stations on either side of the Atlantic could be synchronized with an accuracy of ± 1 μsec.

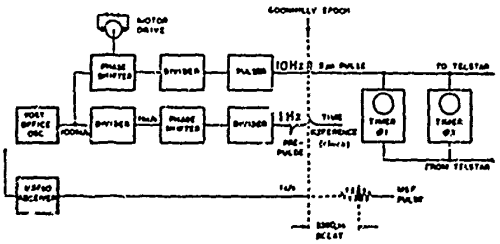


Figure 5-17. Interconnections of Generating and Measuring Equipment at Goonhiily Downs, Cornwall[12]

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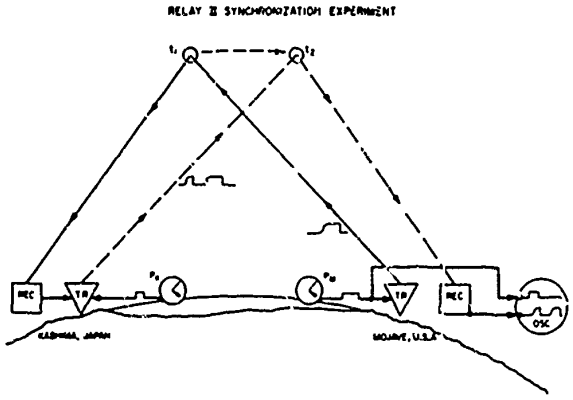


Figure 5-18. Retransmission of Pulses from Mojave by Kashima and Injection of Pulses at Kashima[12]

5-3.1.3.2 Synchronization Via Relay II Satellite

Experiments were carried out to synchronize clocks via the NASA Communications satellite Relay II between Mojave, U S., and Kashima, Japan in 1965. Pulses 11 μsec long were emitted from a pulse generator (Pm) at Mojave and pulses 5 μsec long were emitted from a pulse generator (Pk) at Kashima, at rates of 100, 1000, and 10,000 pulses per sec. Fig. 5-18[16] illustrates the determination of the time difference in clocks between Mojave and Kashima when the Pm and Pk pulsers were operating at 10,000 pulses per sec rate. Fig. 5-19[16] shows the pulses photographed on February 20, 1965 at Mojave. The first and fourth traces are 1-μsec time markers. The Mojave-transmitted pulse is shown in the second trace. The third trace shows the Kashima pulse transmitted on the left and the Mojave pulse retransmitted at the right. Figs. 5-20[16] and 5-21[16] indicate the oscilloscopes, pulsers, and oscillators used for generating and recording the pulses at Mojave and Kashima, respectively. By using this system, it was estimated that the clocks were related to ± 0.1 μsec on each part with a probable error, obtained independently at the two stations for each part, of about ± 0.01 μsec.

5-3.1.3.3 Meteor Burst Clock Synchronization

An experimental system has been developed in which the frequency offset between two remote frequency standards was determined through an exchange of timing information over a meteor burst radio propagation channel[17]. In this experiment, forward scatter propagation at VHF frequencies from a meteor burst provides a phase-stable, broadband propagation made for the transmission of timing information over

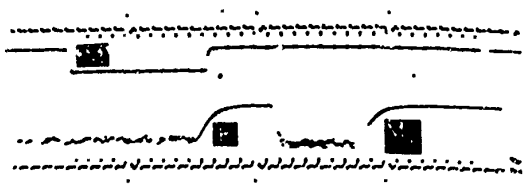


Figure 5-19. Pulses Photographed on February 20, 1965 at Mojave[12]

SAMSUNG EXHIBIT 1028, Page 99

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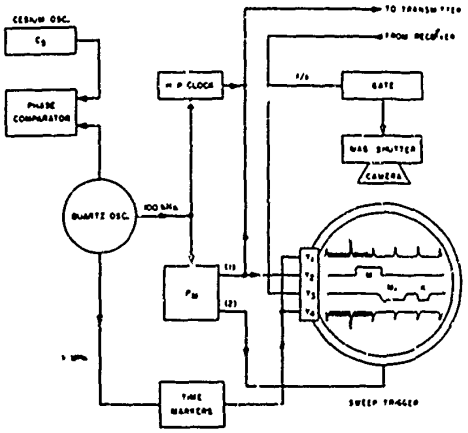


Figure 5-20. Equipment Used at Mojave To Generate and Record Pulses[5]

ranges up to 2000 km. A trail of electrons is used as a reflector to transmit information. The electron trail is created from the collision of the meteor with air particles in the lower E-region of the ionosphere. Techniques employed to measure instantaneous time offset were similar to those used in the Telstar experiment. Fig. 5-22[17] is a block diagram of the system used to synchronize clocks at Seattle, Washington, and Boseman, Montana. Values of $\Delta f/f$ measured by this meteor burst system, obtained by computer results, compare to within 4 parts in 10^{10} to the values measured by standard phase comparison methods.

5-3.2 TRANSFER STANDARD

To compare frequency and time between places far removed, a very satisfactory

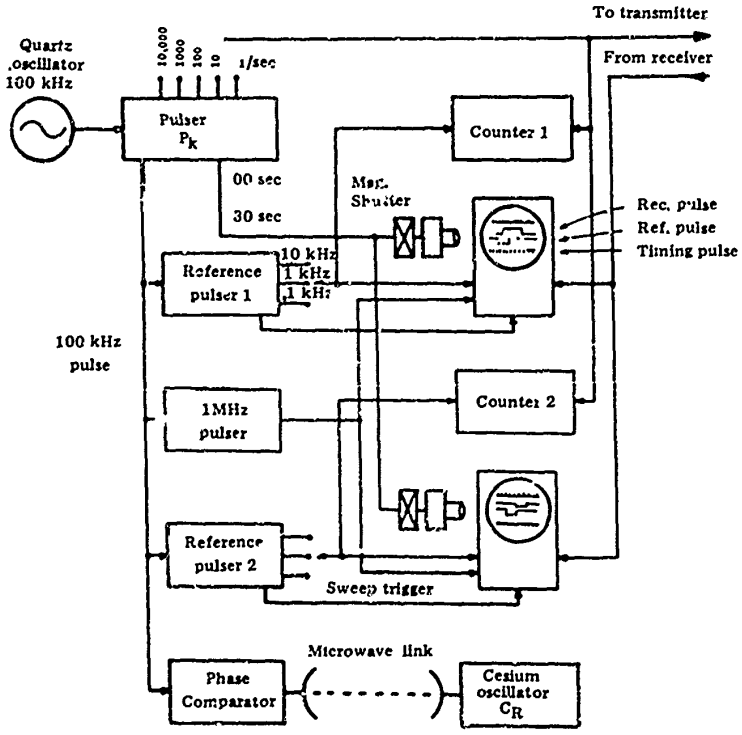


Figure 5-21. Equipment Used at Kashima To Generate and Record Pulses[5]

SAMSUNG EXHIBIT 1028, Page 100

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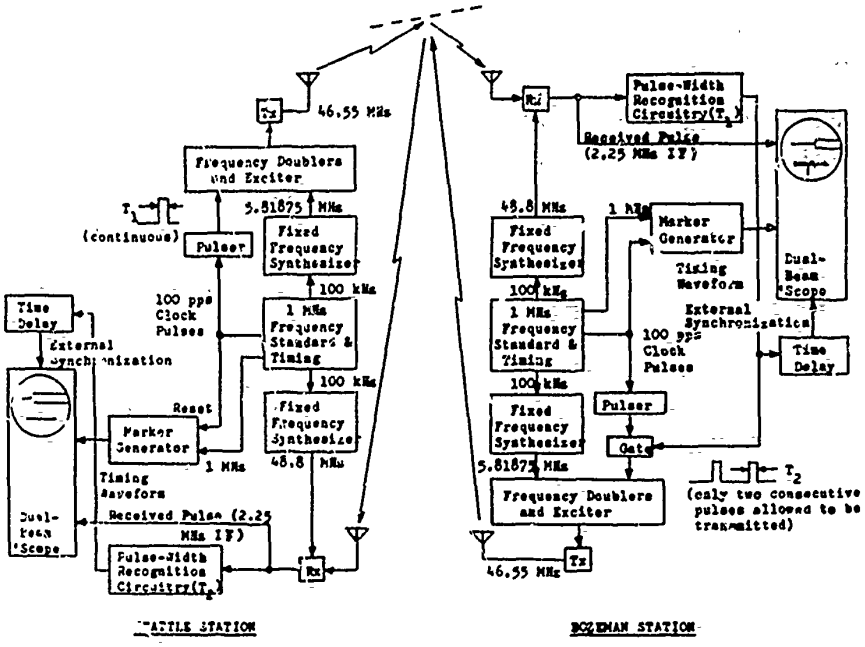


Figure 5-22. Diagram of Meteor Burst Clock Synchronization System[17]

TABLE 5-1

SUMMARY OF HP FLYING CLOCK EXPERIMENTS

Date	Description
April, 1964	Time correlated between U S and Switzerland to about 1 microsec. RF propagation time established within about 200 microsec. Two clocks (#1 and 2) operated within a few parts in 10^{12} of one another and within a few parts in 10^{12} of "long beam" cesium standards at Neuchatel, Switzerland, and NBS at Boulder, Colorado.
Feb./Mar., 1965	Time (or frequency) correlated between 21 places in 11 countries to within 1 microsec. One clock (#3) accumulated less than 6 microsec time difference and the other (#4) less than 1 microsec in 23 days (compared against NBS UA).
May/June, 1966	Time (or frequency) correlated within about 0.1 microsec between 25 places in 12 countries. Two clocks (#8 and 9) agreed with each other within 1 microsec after 31 days with an average frequency difference of less than 1.6 parts in 10^{13}.
Sept/Oct., 1967	Time (or frequency) correlated between 53 places in 18 countries to about 0.1 microsec. Two clocks (#51 and 52) exhibited time differentials of 1.7 and 3.5 microsec over 41 days (compared to HP house standard), corresponding to average frequency differences of 5×10^{-13} and 10×10^{-13}, respectively.

SAMSUNG EXHIBIT 1028, Page 101

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method is to carry an accurate clock, usually by airplane, between them. Such a "flying clock" experiment has been conducted several times by Hewlett-Packard, the fourth of which was conducted in 1967[18]. The time span for the experiment was 41 days and the clocks traveled a total of 100,000 km. Two HP clocks were used. By comparing these clocks to the HP house standard at the beginning and end of the 41-day period, the time differences were found to be only 1.7 and 3.5 μsec. This corresponds to offsets of 5 and 10 parts in 10^{13} in the frequency standards that actuate the clocks. Time correlations were made to 0.1 μsec. Table 5-1[18] is a summary of the four HP flying clock experiments to date. The clock used was an atomic-controlled cesium beam standard and clock assembly that had its own standby battery power supply. The frequency in the standard of the portable clock as well as the time kept initially was compared with the national standards at the National Bureau of Standards and the U S Naval Observatory. After the trip, the portable clock was again compared with these same standards so that any slight changes could be referred back on previous measurements as a tolerance.

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SAMSUNG EXHIBIT 1028, Page 102

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SAMSUNG EXHIBIT 1028, Page 103

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PART TWO – ELECTRONIC TIMERS

CHAPTER 6

INTRODUCTION

The last decade saw a gradual evolution in the field of electronics. First came the development of the semiconductor devices (transistors and diodes) and second, a technology known as *integrated circuits*. The combination of these two had a great impact on the design of electronic circuits, especially in regards to miniaturization. Moreover, this advance has changed the design of military timers.

Research and development in all phases of the technology is continuing at an ever increasing rate; consequently, new developments are arriving rapidly. This influx of new information presents a problem in writing a handbook that is supposed to contain the latest circuits and techniques because the procedures will be superseded by newer ones by the time the handbook is printed. The best that can be done is to give the designer background information and impress on him the need for reviewing the current literature before selecting a given circuit.

6-1 SEMICONDUCTOR DEVICES

6-1.1 TRANSISTORS

Like the triode vacuum tube, its semiconductor counterpart, the transistor is a three-terminal electronic device that performs many of the same functions as the vacuum tube. The transistor has replaced the vacuum tube in most areas of electronics. There are several reasons for this wide acceptance:

(1) Transistors, being small and light, are the logical choice when size and weight are important factors.

(2) They require no filament supply, which means that their power requirement is much less than that for a vacuum tube.

(3) They have a longer useful life than vacuum tubes.

(4) As long as transistors are operated in a nondestructive environment, their operating characteristics do not deteriorate with time. A nondestructive environment is one wherein temperature, humidity, and radiation levels are such that the electrical properties of the semiconductor materials are not destroyed. Vacuum tubes have a limited operating life, because of cathode deterioration with use.

(5) Finally, transistors are physically more rugged than tubes because they are solid state.

During the early development of transistors, vacuum tubes were superior to transistors but with the advance of semiconductor technology their advantages soon disappeared. Some of the advantages of vacuum devices were that they could be designed with a higher input impedance and that they could operate at higher voltage levels than semiconductor devices. For the unijunction transistor that is used as a level detector, the input impedances are now comparable. Silicon transistors have made the use of higher voltages possible, although still not as large as those for vacuum tubes.

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Fig. 6-1 compares three basic transistor circuits with the equivalent vacuum tube circuits. Most of the electronic timing circuits discussed in this handbook use semiconductors rather than vacuum tubes. However, the designer should keep in mind that circuits can be constructed using either component.

6-1.2 INTEGRATED CIRCUITS

An ideally integrated circuit completely eliminates individual electronic parts – such as resistors, capacitors, and transistors – as the building blocks of the electronic circuit. In the place of these parts are tiny chips of semiconductor material which serve the functions of several transistors, resistors, capacitors, and other electronic elements. The elements are interconnected to perform the task of a complex circuit, often comprising a number of complete conventional circuit stages. Within or on top of these tiny silicon chips are microscopically small depositions or growths of material layers which serve the functions of the individual discrete parts. Thus, multistage amplifiers, complex flip-flops, and dozens of other functional circuits are becoming the basic components of electronic circuits.

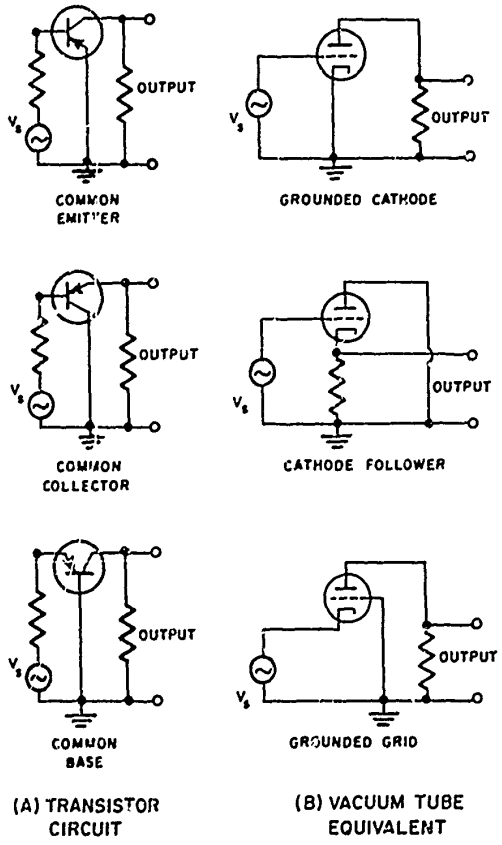


Figure 6-1. Basic Small-signal Circuits

Basically, there are two general classifications of integrated circuits – the semiconductor monolithic integrated circuit and the thin-film integrated circuit. Each of the basic circuits can have a variety of structures with specific advantages or disadvantages for a particular application. Thin-film component arrays also have been added to semiconductor circuits in networks that promise to combine various features of the individual devices in a single configuration of maximum utility.

6-1.2.1 Monolithic Circuits

The basic semiconductor integrated circuit is a monolithic device; i.e., the circuit elements are fabricated on a silicon substrate. In today's circuits, this material is silicon, which serves the monolithic device as the chassis, called a substrate.

6-1.2.2 Thin-film Circuits

The basic thin-film circuit begins with a substrate, made of an insulating material such as glass or ceramic. Upon this substrate is deposited a pattern of the passive elements of the circuit (i.e., resistors, capacitors) as well as an interconnecting pattern of metal. Deposition is by various techniques, such as vacuum evaporation, sputtering, and silk screening. The active elements (i.e., transistors, diodes) are added separately to the thin-film pattern.

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6-1.2.3 Multichip (Hybrid) Integrated Circuits

The multichip circuit is not a monolithic device. Rather, it is composed of individual parts, made either by film or diffusion processes. These parts are attached to a ceramic substrate and interconnected by a combination of metalization processes and wire bonding techniques. The completed circuit may be housed in packages identical to those used for monolithic circuits.

6-2 GENERAL TIMING SYSTEMS

Electronic timers can be classified into two general types – analog and digital – distinguished in Fig. 6-2. The circuits are discussed in detail in pars. 10-2 and 11-2 to 11-4, respectively; however, a brief description is given here to illustrate the basic difference.

6-2.1 THE ANALOG SYSTEM

In engineering language, the term analog usually connotes a continuous stimulus as opposed to discrete pulses that typify a digital system. The factor that determines the classification is how the time interval is generated. In an analog system, the time interval is generated by a continuous circuit action as typified by Fig. 6-3(A). In this circuit, when switch S is closed, capacitor C charges through resistor R and the voltage across C increases with time as shown in Fig. 6-3(B).

The voltage developed across the capacitor V_c at any given time is a function of the series resistor and capacitor, the voltage of the power supply, and time

$$V_c = V_b \left[1 - e^{-t/(RC)}\right], \text{ V} \qquad (6\text{-}1)$$

Eq. 6-1 can be arranged to solve for time

$$t = RC \ln \left(\frac{V_b}{V_b - V_c}\right), \text{ sec} \qquad (6\text{-}2)$$

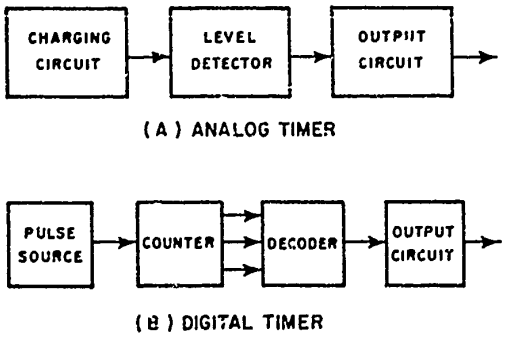


Figure 6-2. Block Diagrams of Analog and Digital Timers

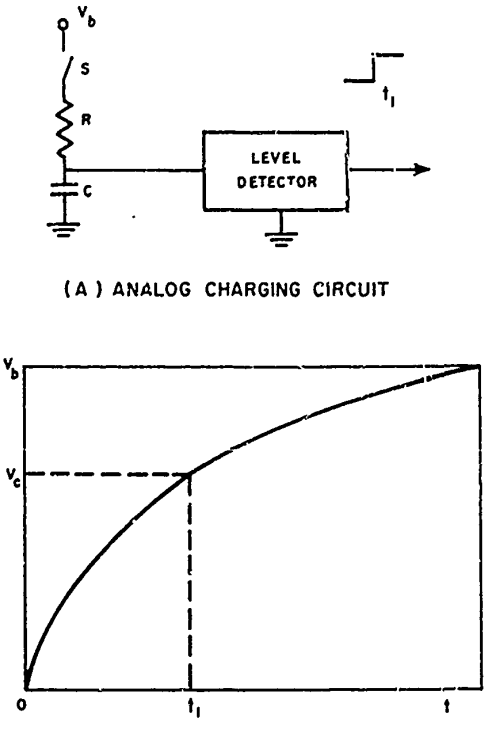


Figure 6-3. Simple Analog System

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where

V_c = voltage across capacitor, V

V_b = power supply voltage, V

C = capacitance, F

R = resistance, ohm

t = time, sec

The level detector is quiescent until V_c reaches a value that causes the detector to trigger. The time delay is determined by V_b, R, C, and the value of V_c at which triggering occurs. The simplified analog circuit illustrated in Fig. 6-3(A) is an example of a one-shot device. Modifications to this circuit which permit it to recycle and generate a succession of timing pulses are presented in par. 10-2.

The main advantage of this type of system is simplicity. Only a capacitor, a resistor, a voltage source, and a level detector are required. On the detriment side is its inaccuracy and instability. From Eq. 6-2 it can be seen that the error is a direct function of R and C. For example, if R and C drift by 10%, the time will change by 10%. The error due to small changes in source and bias voltages is a function of the change in the ratio of bias to source voltage and the value of that ratio. The smaller the ratio, the smaller the error for equal percentage change in the ratio. For applications where the ratio is approximately 0.5, a 10% change in the ratio can give a time error of up to 16%.

6-2.2 THE DIGITAL SYSTEM

Even very simple digital timing circuits require many more individual components than analog timers. Thus, digital timing systems have benefited greatly from integrated circuit technology.

Fig. 6-4 illustrates a simple digital timing circuit. The pulse source is typically an oscillator and pulse shaper that supplies uniform time-spaced pulses to the counter when S_1 is closed. The counter is composed of the discrete state elements D_1, D_2, and D_3. The discrete state of these elements (L_1, L_2, and L_3) is monitored by the decoder that has a pulsed output F when some predetermined combination of the outputs occurs. The sequence of these outputs is a function of the number of pulses supplied to the counter. The decoder pulse output is converted to a continuous output signal by the output circuit.

6-3 MILITARY APPLICATION

This handbook emphasizes the military application of electronic timers. The main categories for these timers are

(1) High-acceleration systems (artillery)

(2) Low-acceleration systems (rockets, bombs, guided missiles)

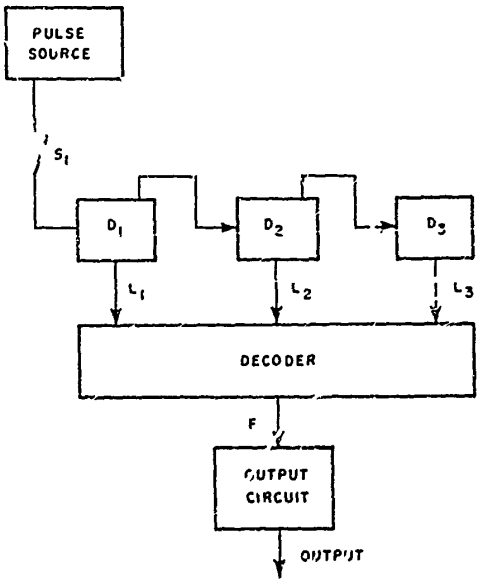


Figure 6-4. Simple Digital System

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(3) Stationary timers (demolition, controls).

Each of these uses represents a peculiar environment that the timer must endure. None of these applications, however, would use what is considered to be a high-precision timer.

Electronic timers can be used to provide delay for (1) arming, (2) functioning, or (3) self-destruction or sterilization.

6-4 REQUIREMENTS

Timers used for military application must meet electrical, mechanical, and environmental requirements. Electronic timers are similar to other pieces of military equipment in that they must operate in all types of environment.

6-4.1 ELECTRICAL REQUIREMENTS

Since most of the electronic timers for military purposes are portable, the power sources are restricted to batteries. Much work has been done on trying to develop batteries that have a long shelf life, high regulation, and small size. The types of power sources available are discussed in pars. 10-5 and 11-5. Like other military timers, it is desirable that electronic timers be simple, compact, rugged, accurate, reliable and have low power consumption.

6-4.2 MECHANICAL AND ENVIRONMENTAL REQUIREMENTS

While these timers have an electronic time base, they are nonetheless components of mechanical systems that must withstand storage, shock, and vibration over the military temperature range. Ammunition timers may be subjected to high acceleration and spin forces. See par. 16-1.1 for a listing of typical military conditions that may be required.

Since the components of electronic timers have no moving parts, they can be encapsulated or potted in a plastic material; many ammunition timers are so packaged. Potting provides many desirable attributes: (1) increased shock and vibration resistance, (2) protection against moisture and other contaminants, (3) increased thermal resistance, and (4) handling protection. Potting, then, makes it easier to achieve the required ruggedness.

Electronic timers are more susceptible than other timers to electromagnetic radiation in the environment. See par. 7-3 for methods of radiation hardening.

6-5 AUXILIARY EQUIPMENT

Auxiliary equipment for military timers ranges from the calibration and maintenance equipment usually associated with any military electronic equipment to the field operated time-to-action setting devices (fuze setters) used in conjunction with ammunition timers. Auxiliary equipment usually is subject to less stringent mechanical and environmental requirements than the timers themselves; however, time-to-action setting devices for ammunition timers must be rugged and capable of working in the field. Space and power requirements for auxiliary timer equipment are also less stringent.

Ammunition timing systems usually require an integral timer plus a time-to-action setting device that introduces the desired time setting into the ammunition timer. Since only the ammunition timer is expended, considerable effort is made to incorporate all self-checking features and components necessary for setting in the non-expended and reusable setting device. Thus timers themselves in an overall ammunition timing system are likely to be of less complexity than the timer auxiliary equipment. Time-to-action setting devices for analog and digital timers are covered in pars. 10-4 and 11-5, respectively. Timer testing and calibration are treated in par. 7-5.

SAMSUNG EXHIBIT 1028, Page 108

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CHAPTER 7

SYSTEM DESIGN CONSIDERATIONS

7-1 STATIONARY SYSTEMS

7-1.1 GENERAL

Design goals are determined at the outset when any new military system is being developed. These goals, which are defined for each major component of the system, provide that the total system will result in a product that is safe, reliable, combines maximum accuracy with design simplicity, is constructed ruggedly for successful operation in a military environment, and has a reasonable life cost cycle.

7-1.2 ANALYSIS OF REQUIREMENTS

In the development of a military item, an analysis of requirements is mandatory when planning either a new concept or a modification of an existing unit. These requirements, after defining the limits within which a designer may operate, usually contain: (1) performance factors that must be met, (2) a description of associated equipment with which the item must interface, (3) approximate cost to manufacture, (4) operating parameters, and (5) probable environments.

In particular, the requirements for an electronic timer might include the following:

(1) Delay time range with ability to set in predetermined increments

(2) Accuracy given as plus or minus an allowed percentage of timing error

(3) Operating temperature range

(4) Military transportation, vibration, environmental, and storage requirements

(5) Maximum space allowable for the unit including the electrical power supply

(6) Cost goals

(7) Setting considerations. including method and resolution.

The designer must be thoroughly familiar with the stated requirements so that he is in a position to evaluate them. Should any of the requirements be too difficult, time consuming, or costly to achieve, a judgment can then be made whether or not to request relaxation of one or more requirements to reduce development time and cost risk. This judgment process is called trade-off. It is quite possible that the most economical approach would be to use an existing timer, perhaps with modifications. However, if a new design is called for, then the timer development should follow a series of logical steps.

7-1.3 STEPS IN DEVELOPING A SYSTEM

Stationary electronic timers are essentially of two types:

(1) Precision reference timers, typified by a precise crystal controlled oscillator followed by a binary divider network. This timer can be extended to any desired time period at the expense of providing more divider stages and the additional power to drive them.

(2) Electronic timers having an *RC* time

SAMSUNG EXHIBIT 1028, Page 109

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base used in relaxation oscillator circuits. These devices can be relatively simple.

Details of precision reference timers are covered in Chapters 4 and 5, while those of electronic timers are located in Chapters 10 and 11. Stationary timer systems must fulfill all of the requirements listed in par. 7-1.2, except perhaps for the following:

(1) Size and weight restrictions are not as stringent.

(2) Shock requirements, such as operability under setback and acceleration forces, are not specified.

The development of a timer used in a stationary system or one used in a mobile system (see par. 7-2) is considered successful and complete only when pilot lots have passed all tests and the timer has been accepted as a standard item ready for mass production. There are many steps between the first preliminary schematic and the final production of the standard timer. Throughout development, the designer must consider a great many details at each of the four basic stages: (1) preliminary schematics, (2) bread boarding, (3) testing and revision of model, and (4) final acceptance.

7-1.3.1 Generalized Process

The generalized process of time delay is illustrated in Fig. 7-1[1]. The output is triggered when the physical variable coincides with the preset reference value. Two important design factors are the repeatability of the characteristic curve, including hysteresis and independence of changing operating conditions, and the accuracy of the detector. Linearity is desired at times when a convenient readout dial is needed. In many applications, the ability to reset to zero is also of major importance. Another important physical variable in many time delay devices is temperature because of the large variations in

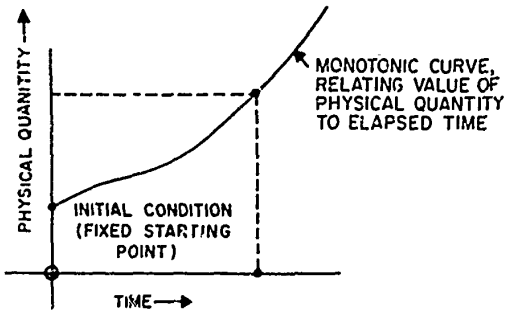


Figure 7-1. Basic Timer Diagram[1]

ambient conditions from place to place[1].

Figs. 7-2[1] and 7-3[1] show generalized behavior of a physical variable in a timing mechanism. The value of the physical variable is changed by a source of driving energy. When the timing cycle is initiated by an external signal, the change begins. Change then proceeds at a controlled rate that depends on the design and adjustment of the mechanism. The detector delivers an output signal when the value of the physical variable matches the built-in reference signal. Electrical power is used in electronic timers as the driving power that is modulated to change the physical variable[1].

The elements to be considered for use in an electronic timer are[2]:

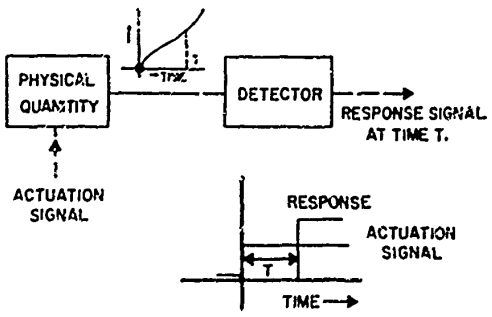


Figure 7-2. Block Diagram of an Elementary Timer[1]

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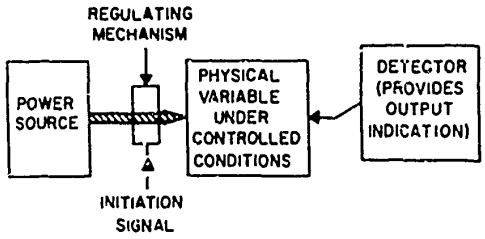


Figure 7-3. Control of Physical Variable[1]

(1) Power Supplies. Batteries using alkaline zinc and silver oxide, a solid-state battery, existing ground power, etc.

(2) Time base. *LC* oscillator, *RC* oscillator with gas-diode trigger, magnetic core oscillator, nuclear time base, etc.

(3) Frequency Dividers and Counters. Transistor flip-flop binary divider, transistor flip-flop ring counter, magnetic core flip-flop, magnetic core ring counter, etc.

(4) Output Circuits. To produce a signal that initiates the first element in an explosive train, for instance, or to delay the application of high voltage to a radar set in order to allow the acquisition magnetron to reach operating temperature.

7-1.3.2 Trade-off Possibilities

An excellent way to evaluate the various alternatives is to tabulate each class of component and then estimate the relative suitability of each factor to meet the design requirements. Such a tabulation is shown in Table 7-1[2] in which the oscillator type and accuracy, voltage and current requirements, power available, frequency, and approximate size are given for various oscillators.

Better than marginal improvements over old systems are required to justify a new design. These improvements should include such features as increased reliability, reduced cost, or greater accuracy. Production or shelf-item components that are introduced into a system must still be checked out by electrically testing the assembled item. This must be done because (1) component shelf life usually must be known or estimated, (2) mating components may introduce incompatibility, and (3) the performance of the new design may be degraded by coupling effects between old and new items.

After a review of the timer requirements has been made and trade-offs decided upon, the electronic timer designer can begin preliminary designs. At this phase of development it is quite possible that the choices of the various components of the system have been narrowed so that either available data or prototype hardware development can be used to eliminate all but one of the approaches. The prototypes can then be fabricated and prepared for testing.

7-1.3.3 Testing

The prototypes are subjected to tests that simulate or duplicate the forces and environments which the final version will have to survive. Most of the parameters can be measured with standard measuring equipment. The tests include[3]:

(1) Electrical Tests. Conformance of the timer with circuit requirements, dielectric strength, insulation resistance, and continuity.

(2) Environmental Tests. Vibration, operating temperatures, storage temperatures, and drop tests.

(3) Timer Performance and Accuracy. Checking after exposure to each of the preceding test groups.

7-1.4 COMPLETION CRITERIA

After the prototype is proven to be capable of satisfying all requirements, a testing

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TABLE 7-1

COMPARISON OF VARIOUS OSCILLATORS

Oscillator type and accuracy	Voltage, V	Current, A	Power Level, mW	Frequency, Hz	Size, $in.^3$
LC (Including amplifier) 0.1 to 1.0%	4 to 6	4×10^{-4}	1.6 to 2.4	1000	1
RC Feedback oscillator 0.01 to 0.1%	120 to 280	10^{-3}	12 to 28	1k to 10k	<0.5
Magnetic core 0.1 to 1.0%	15	1×10^{-2} to 2×10^{-2}	150 to 300	10 to 100	1
RC unijunction transistor 1 to 3%	10 to 20	2×10^{-3}	20 to 40	1 to 100	1 to 2
RC (SCR as trigger device; initial negative voltage on capacitor) 3%	50	2×10^{-4}	10	1	2.5
Multivibrator 2 to 4%	10	2×10^{-5}	0.2	1 to 10	2
RC Four-layer diode 5% (questionable)	60	15×10^{-5}	9	1 to 100	2
RC Gas diode 5% (questionable)	300	4×10^{-5}	12	1	5

program is initiated which is based on statistical sampling. See Table 7-2[3] for a sampling plan for a typical electronic timer. The proven timer then can be produced in quantity and integrated into the weapon system. Perhaps the most important criterion is reliability.

Reliability is the probability that material will perform its intended function for a specified period under stated conditions[4]. With respect to the design of electrical timers, several important considerations have a direct bearing on device reliability:

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TABLE 7-2

SAMPLING PLAN

Lot size inclusive	Sample size	Accept lot	Reject lot
0–25	Use 100% Inspection		
26–35	20	0	1
36–50	25	0	1
51–150	30	0	1
151–300	30	1	2
301–over	60	2	3

(1) The number of component parts should be a minimum.

(2) If discrete components are used, the reliability of each should be as high as is commensurate with total circuit reliability and cost.

(3) Parts must withstand extreme environmental conditions and still operate successfully.

(4) Components should be used whose important properties are known and reproducible.

(5) Timers should be designed so that factors that affect reliability can be detected by means of nondestructive tests or inspection.

From the reliability measurements point of view, two kinds of systems can be distinguished[5]: (1) The repairable or recoverable system designed to perform for a long time in a large number of operations, and (2) the nonrepairable or nonrecoverable system designed to perform only once. Stationary systems can be put in the former category and mobile systems in the latter. See par. 7-2 for reliability consideration for mobile systems.

The reliability of stationary systems depends on maintenance policy, i.e., on schedules for overhaul, parts replacement, and inspection. Repair maintenance is not used until parts fail during system operation. In this case, component wearout becomes the dominant factor and the system failure rate becomes much higher than it originally was. A newly built system that has been debugged is essentially free from wearout failures and its reliability is governed by the frequency of chance failures. During this period, components are replaced as they fail. After this period, wearout failures begin to show up and if only repair maintenance is used, the system failure rate would rise. However, when high reliability is required, preventive maintenance is used to prevent wearout failures from appreciably affecting system operation[5]. In other words, long-life systems must be maintained preventively if long failure-free operating periods are required, and the system chance failure rate must be very low. In regard to the probability of the first failure of the system, whether it be chance or wearout, the answer can be given only by means of a system probability analysis when the component parameters are known and not by means of system tests. For more details about system reliability measurements and testing, see Ref. 5.

7-2 ACCELERATED SYSTEMS

7-2.1 GENERAL

Timers and programmers are used by the military in virtually every type of munition from low g missiles to high g projectiles. The use of electronic timers, used in fuzes, began during and after World War II when system requirements called for more versatile and sophisticated equipment. In particular, electronic digital timers have been used extensively in more expensive large-scale weapons after many problems of size, power supply, and shock which are inherent in vacuum tubes were eliminated by the introduction of the transistor.

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The use of electronic timers in accelerated ammunition requires a low-cost rugged time base. An error of less than 0.1% under all conditions of use and operating temperatures range from −50° to 125°F are typical. The use of temperature control is not feasible in applications that require an oscillator output to be available a few milliseconds after initiation. Timers must operate under high spins, after high setback accelerations during firing, and sometimes under severe deceleration forces imposed by target impact. Other requirements for the time fuze are small size (e.g., about 1 in.^{3}) and a low power drain[6]. The paragraphs that follow discuss various design considerations for this type of electronic timer.

7-2.2 COMPONENT SELECTION AND QUALIFICATION

7-2.2.1 Considerations

The electric components used in the circuits of electronic timers consist of capacitors, resistors, magnetic cores, tubes and transistors, and power supplies. The accelerated environment puts stringent requirements on their ruggedness, aging, and temperature characteristics. Factors working against fuze component reliability vary with the type of fuze in which the components are used. Requirements for long inactive shelf life, extreme environmental conditions while in operation, and the limited ability to pretest for functioning just before use add to the difficulties in selection of components. For these reasons, the designer should use standard components wherever possible.

When selecting timer components, the designer may take advantage of the fact that components which are inadequate for long time applications may be entirely suitable for use in fuzing systems. Possibilities include components with a relatively short operating life or with failure rates that rise sharply with cycling. Even though some fuzes undergo many tests prior to actual use, their total operating life expectancy is normally much less than that of stationary system components. Tolerances of some components may prohibit their use in certain types of electronic equipment, but they may be used in an electronic time fuze.

Mounting of components in a preferred orientation along with potting to strengthen the entire configuration will help the component survive the severe environment. To eliminate the effects of aging and thermal changes, three solutions can be used[7]:

(1) Use components whose original properties are adequate.

(2) Use hermetic sealing to protect components from damage due to environmental conditions.

(3) Choose components so that the variation of one component property is compensated by another component.

7-2.2.2 Resistors

The types and characteristics of resistors that are available for military use in an electronic timer are shown in Table 7-3[8]. Available resistance varies widely. The units are capable of withstanding the required environment and have a minimum change of values under operating conditions. For additional information about resistors, see par. 10-4.2.

7-2.2.3 Capacitors

Capacitors currently produced that will meet the temperature and stability requirements for electronic timers are porcelain capacitors (a ceramic capacitor with a temperature coefficient of 15 ± 5 parts per million/deg C is presently in production). The porcelain capacitor is stable during storage life and is readily available with a 0 ± 25 parts per

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TABLE 7-3

RESISTOR CHARACTERISTICS

	Wire Wound	Carbon Film	Metal Film
Nominal Value, ohm	0.1 Ω – 1 Meg Ω	1 Ω – 1000 Meg Ω (10^{14} ohm avail.)	30 Ω – 15 Meg Ω
Initial Tolerance, %	0.002%	0.1	0.1 (0.05 avail.)
Wattage Rating, W	0.05 – 250	0.1–5	0.1–4
Temp. at which derating starts, °C	125 Typ.	70–120	70–125
Zero Wattage Temp, °C	250 Typ.	150 Typ.	175 Typ.
Temp. Coefficient of Resistance, ppm/deg C	± 10 stand. ± 2 avail. –80 to +6000 avail.	–250 to ± 500	10–250
Range over which TCR holds, °C	various –65 to +150 for stand. ± 10 ppm	–65 to +150	–65 to +150 Typ.
Maximum Working Voltage, V	100–1200	200–15,000	200–750
Dielectric Withstanding Voltage, V	100–2500	200–1000	200–1000
Current Noise, μV/V	– – – – – – –	0.1–1	0.05–0.2
Distributed Inductance, μH	⩾ 1	⩽ 10 GHz	⩽ 10 GHz
Distributed Capacitance, pF	⩾ 0.8	⩽ 10 GHz	⩽ 10 GHz
Voltage Coefficient of Resistance, ppm/V		2–20 Typ.	1–5
Load Life, Max. change, %	0.05–1.0	0.1–1.0	0.1–1.0
Short-time Overload, Max. change, %	0.01–0.1	0.01–0.5	0.1–0.5
Moisture Resistance, Max. change, %	0.005–5	0.03–1.5	0.1–1.5
Temp. Cycling, Max. change, %	0.07–0.2	0.02–0.5	0.05–0.5
Terminal Strength, Max. change, %	0.00–0.05	–0.2	–0.2
Low Temp. Operation, Max. change, %	0.02–0.25	0.05–0.5	0.005–0.5
Soldering, Max. change, %		0.01–0.5	0.05–0.5
Shelf-life, Max. change, %	0.002–0.1	0.05–0.2	0.05
Shock, Max. change, %	0.00–0.2	0.1–0.5	0.01–0.5
Vibration, Max. change, %	0.01–0.2	0.1–0.5	0.01–0.5

million/deg C temperature characteristic. The capacity shifts a maximum of 0.1% over a ten-year period with most of the drift occurring during the first few months. Temperature characteristics within ± 5 parts per million/deg C are available. To achieve 0.1% accuracy in the design of oscillators, a calibration capacitor is used. For a basic oscillator frequency of 1000 Hz, a calibration capacitor must have a tolerance of ± 2% up to 300 pF and ± 1% on values above this. High spin and shock should have no adverse effects on the capacitors[9].

7-2.2.4 Magnetic Cores

Magnetic cores are used in electronic counters because of their ability to maintain memory with no power. The core is made of ferromagnetic material that exhibits a square hysteresis loop. Fig. 7-4[10] shows an idealized version of this material. The fluxes shown in the figure are

ϕ_r = remanent flux

ϕ_s = saturation flux

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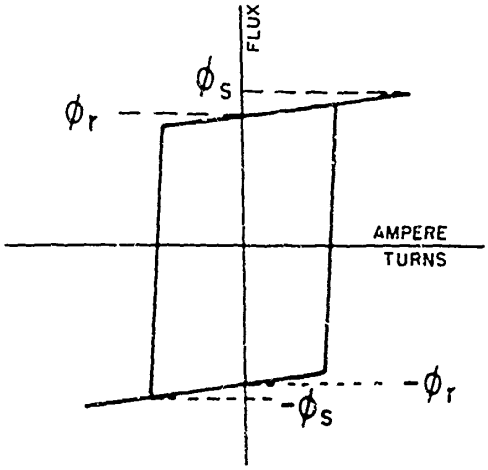


Figure 7-4. Square Hysteresis Loop Material

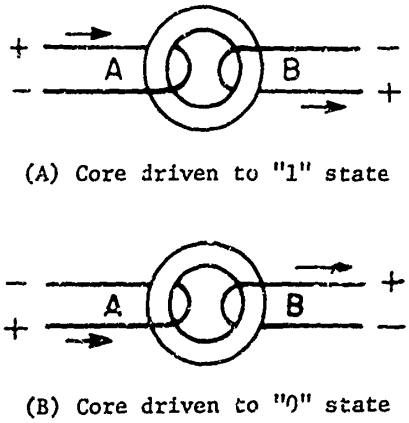


Figure 7-5. Methods of Driving the Core

The squareness ratio is equal to ϕ_r/ϕ_s, which, for the cores used in military timers, is a minimum of 0.9. With no drive applied, the core is normally in either the ϕ_r or the $-\phi_r$ state. When sufficient drive is applied in the proper direction, the core switches to the opposite ϕ_s state; when the drive is removed, the flux changes to ϕ_r. Fig. 7-5[10] illustrates the method of driving the core to the "0" and "1" states. The $-\phi_r$ state is designated "0" and the ϕ_r state is designated "1". Further information on magnetic cores and core circuits is given in Ref. 11. Fig. 7-6[2] shows the diagram of a typical magnetic core driver.

7-2.2.5 Tubes and Transistors

Rugged tubes are commercially available for accelerated military items. Cold cathode diodes and triodes depend on light to provide initial ionization. This problem has been solved by placing a band of radioactive material around the tube which helps to provide a consistent breakdown voltage. The choice between a diode and a triode often is made on the basis of available energy because a triode, while slightly more complicated, has more efficient energy transfer characteristics[7]

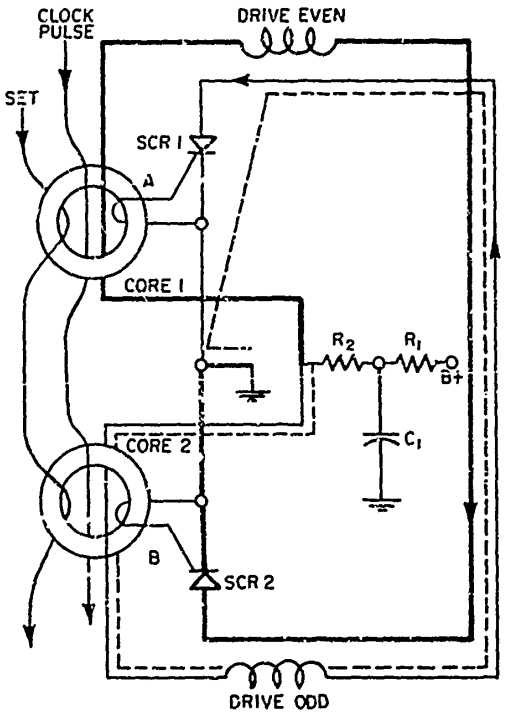


Figure 7-6. Magnetic Core Driver

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Transistors at first were too expensive to use in one-shot devices such as electronic fuzes. However, with improvements in the state of the art, cost has been reduced so that more and more transistors now are being used in osciliators for electronic timers. A unijunction transistor is used as the trigger device in an *RC*-oscillator[2]. Transistors with high-gain bandwidth products, high voltage, and a guaranteed beta over three current decades are available commercially for use in amplifiers, oscillators, mixers, and other signal processing applications. They provide maximum reliability and heat transfer, and are designed to meet rugged military specifications. They are encapsulated by a welded hermetic seal and can be mounted in any position[2]. Storage and operating range is −65° to +200°F.

7-2.2.6 Power Supplies

Several types of batteries are used in electronic timers. One type is the alkaline zinc and silver oxide battery. Voltage rating is 1.5 V per cell. It can be fabricated with the cells free of the electrolyte for reserve action. The electrolyte is stored in a container adjacent to cells and forced out into the cells, for example, by firing an electric squib[2]. See par. 11-6 for more information on power supplies.

7-2.3 CIRCUIT DESIGN AND BREADBOARDING

Circuit design begins with the synthesis of a circuit that meets the performance objectives. In the interest of cost and time savings, such a circuit is developed initially within the component constraints imposed by the system requirements indicated in par. 7-1.2. Since integrated circuits are being used more and more because of their packaging and reproducibility attributes, the designer also should keep in mind several present monolithic component limitations. Generally, large values of resistors and capacitors, as well as close absolute component tolerances, are to be avoided. The number of capacitors should be held to a minimum because they occupy valuable die space. Inductors should be eliminated entirely in a monolithic design because at present they are not fabricated adequately in integrated form. If a hybrid construction is planned, then discrete components are used along with the integrated circuit elements. See par. 8-2 for more information about integrated circuit techniques.

To synthesize the circuit design, a decision must be made as to the power supply, the frequency divider and counter type, and the output circuit that will attain the desired accuracy.

Compilations such as shown in Tables 7-1 and 7-4[12] show the various oscillators and their relative performance capability. Accuracy obtainable, voltage and current requirements, frequency stability, and approximate size are listed. Table 7-5[2] gives the same data for frequency dividers and counters.

Once the circuit is synthesized, a breadboard model can be built. Its performance can be evaluated with well known test procedures. Reasons for discrepancies in the anticipated performance usually can be pin-pointed by taking stage-by-stage measurements. This emphasizes the value of breadboarding because theoretical analysis cannot localize problem areas. Initial problems sometimes can be eliminated by part changes. At other times, a new circuit must be synthesized to remove the limitations of the first attempt.

Once a satisfactory breadboard model has been developed and the interconnection requirements of the system have been satisfied, the designer's initial task is ended[13]. The next step is the development of a prototype.

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TABLE 7-4

RELATIVE PERFORMANCE OF VARIOUS OSCILLATOR TYPES

Oscillator type	Frequency stability*	Resistance to shock and spin	Power drain	Complexity
LC parallel tuned	good	fair	low	low
LC series tuned	very good	fair	low	med
RC wien bridge	very good	good	low	med
RC parallel-T	very good	good	low	med to high
RC bridged-T	very good	good	low	med
RC phase shift	fair to good	good	low	med
multivibrator	fair to good	good	low to med	med to high
magnetic square loop	good	fair to poor	med to high	high
pulse RC discharge	fair	good	low	med
pulse curpistor-C	fair to good	good	very low	med
mechanical resonator	excellent	poor	low	med to high

*Frequency stability, variation: excellent $< 1 \times 10^{-4}$; very good 10^{-4} to 10^{-3}; good 10^{-3} to 10^{-2}; fair $> 10^{-2}$.

7-2.4 LAYOUT AND ASSEMBLY TECHNIQUES

With the circuit breadboard performing as required, a suitable layout can be considered. The first basic rule that insures reliable circuit operation involves packaging. The circuit should be compatible with the thermal limitations of a standard package whenever possible. Since the package provides a conductive path that dissipates the heat generated internally, circuit power dissipation must be limited so that the internal operating temperature does not exceed allowable limits.

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TABLE 7-5

COMPARISON OF VARICUS FREQUENCY DIVIDERS AND COUNTERS

Type of counter or frequency divider	Voltage, V	Current, A	Power Level, mW	Size, $in.^3$
Magnetic core decade Input frequency- 1 Hz max.	10	5×10^{-5}	0.5	0.3
Magnetic core decade Input frequency- 10 Hz	10	7×10^{-5}	0.7	0.3
Magnetic core decade Input frequency- 10 Hz	10	2.5×10^{-4}	2.5	0.3
Magnetic core decade Input frequency- 1000 Hz	10	2.1×10^{-3}	2.1	0.3
Magnetic core ring counters or feed-back shift register- Arbitrary number of stages	10	Depends on input frequency as given above	Depends on input frequency as given above	Maximum size: 1/3 $in.^3$ per decade of frequency reduction
Transistor decade (flip-flops) Input frequency- 1000 Hz max.	6	5×10^{-5}	0.3	0.3 0.01
Transistor decade (flip-flop ring counter) 1000 Hz max.	6	3×10^{-5}	0.2	0.7 0.03
Complementary metal oxide semiconductor	10 to 15	$<10^{-3}$	<15	0.02

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The maximum number of permissible leads depends on package limitations. By use of integrated circuits, standard transistor can-packages are limited to 12 leads while flat and dual in-line packages will accommodate 14 leads.

A second fundamental layout objective is the size of the ultimate monolithic die. With properly designed circuits produced with high packaging yields, die size is often the controlling factor in the manufacturing cost of integrated circuits.

The circuit designer has no control over the size and geometry of active components. These are fixed by the types and specifications used in the final breadboard. In the light of the variations in manufacture components, it is advisable that the circuit designer work in close cooperation with the part supplier.

A modern aid for integrated circuit design is the computer. If the circuit design is known well enough to provide complete characterization electrically and topographically, it can be optimized by computer methods. A manufacturer's off-the-shelf circuits can be specified completely and stored in a computer library[13].

All printed circuit assemblies, even for small production quantities, are dip soldered. This method saves labor, and results in greater reliability. Generally, all conventional components are mounted on the side of the circuit board opposite the pattern, so that they are not immersed in the solder during the dipping operation. With two-sided circuits, the components are mounted on the side opposite the one to be dipped. Components mounted on the dip side are assembled after dipping and soldered in place by hand.

Preforming and precutting of axial lead components greatly increase the speed and efficiency of assembly of printed circuit boards. Other efficient methods of assembly are flow soldering, wave soldering, and cascade soldering. The simplest way to assemble components to a printed circuit board is to bend the leads of the components and insert them through holes in the printed wiring board, hand solder the connections between the component pigtail tips and the printed conductor, and then cut off the excess lead lengths. Care should be exercised in the hand-soldering operation to avoid cold-solder joints and resin joints[14].

7-2.5 PERFORMANCE STANDARDS

Performance standards that an electronic timer is expected to meet for accelerated systems usually are determined by the end use of the timer. Timers can be used in missile, rocket, bomb, or projectile fuzes. Existing off-the-shelf power supplies, for instance, usually will not meet the requirements for projectile fuze timers.

Setback and spin requirements vary widely. Table 7-6[15] is a general summary of these operating requirements. Electrical requirements are comparatively uniform, typical requirements being listed in Table 7-7[13]. In electronic time fuzes, accuracy is dependent upon the time error in starting as well as the running error.

TABLE 7-6

OPERATING REQUIREMENTS

Fuze	Setback, g	Spin, rps
Missile	25	5
Rocket		
"Nonspin"	100	5
Spin	100	100
Projectile	27,000	500

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TABLE 7-7

ELECTRICAL REQUIREMENTS

Projectile Fuze	Voltage, V	Current, mA
Missile	12–15	30–50
Rocket	6.7 ± 0.7	100
Projectile*	6–15	30–100

*Summary of three developments.

Typical performance standards for a long-delay bomb fuze include[2]:

(1) Delay time from 15 min to 100 hr settable in 15-min steps

(2) Accuracy within ± 5%

(3) Operating temperature range --65° to +160°F

(4) Operation after an impact deceleration of 20,000 g for 5 msec in any direction

(5) Usual military, vibration, and environmental requirements

(6) Maximum size: 3 in. in diameter by 2-5/8 in. long including power supply.

Oscillator frequencies of interest fall in the range of 10 to 10,000 Hz. Frequency choice is determined mainly by the incremental setting resolution desired and the technical limitations of the particular type of oscillator chosen. Setback at launch or firing will occur momentarily and will require continuity of signal, with recovery to the original signal. Spin may persist throughout the useful life of the timer. Since some rounds do not spin, it may be desirable to develop separate oscillators for spin and nonspin applications. The oscillator frequencies must remain within specification tolerances for (1) variations of supply voltage of ± 20% from the nominal design value and (2) variations of other parameters to their extreme values[1,2].

In most applications, protection will be required against catastrophic failures that would increase the frequency and shorten arming or firing time, thus creating a safety hazard. To minimize timing error, most uses require a rapid buildup and stabilization of the energizing power.

A final requirement for electronic timers is accuracy after prolonged storage at temperature extremes. Crystallization, cold flow, and other deteriorating effects in the frequency determining elements must be minimized. Effects of irradiation from nuclear detonations may be of importance. To be confident that the timer will perform as required, it is necessary to subject it to extensive tests (see par. 7-5).

7-2.6 EXTERNAL INTERFACES

The primary external interface for electronic timers used in accelerated systems is remote selection of the time delay. Electronic setting in its simplest form eliminates the need for circuit power while the selection is being done. For information on time setting methods see par. 10-4.

Provisions for external interfaces should insure electrical, mechanical, and environmental compatibility between the timer and any external cabling and selecting system. Mating connectors should pass MIL-STD specifications[16]. The connector in the timer should be capped when the cabling from the selection system is removed. A cap should act as an environmental shield to protect the timer[17].

7-3 RADIATION HARDENING

It is necessary for some types of timers to survive the radiation environment of a nuclear

SAMSUNG EXHIBIT 1028, Page 121

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burst. The radiated energy will destroy the average electronic circuit within several miles of the burst unless radiation hardening is employed. Before discussing the techniques used to harden electronic circuits, it would be well to examine the environment that is generated by a nuclear explosion.

7-3.1 RADIATION FROM A NUCLEAR EXPLOSION

A nuclear explosion resembles a blackbody at a temperature of several tens of millions degrees and, in accordance with Planck's radiation formula, radiates most of its energy as soft X rays. Almost all of the energy, approximately one billion kilowatts per megaton, is released in the first microsecond in the form of X rays, gamma rays, alpha rays, beta rays, and neutrons. Note that the first two are electromagnetic while the three remaining are corpuscular. Table 7-8[18] compares four of these components.

7-3.1.1 X Rays

7-3.1.1.1 Nature of X Rays

X rays are produced in a nuclear burst by high-velocity electrons colliding with electrons attached to an atom. When a charged body—such as an electron—is decelerated, a pulse of electromagnetic radiation is produced. For convenience, the acceleration or deceleration of an electron is measured in electron volts (eV). A 500-eV electron, for example, refers to one that has been accelerated by a potential difference of 500 V. The energy required to ionize an atom by removing an outer electron is much less than 100 eV while that required for an inner electron may be as high as 70,000 eV. X rays produced by collision with outer electrons are called soft X rays while those produced by displacement of inner electrons are called hard X rays. The main difference between these emanations is the wavelength: soft X rays range from ten to one angstrom, hard X rays cover one to 0.1 angstrom.

7-3.1.1.2 Interaction With Materials

Ionization, the production of hole-electron pairs in a material, results from the absorption of photons (soft and hard X rays). Photons, which comprise up to 75% of the energy in a nuclear explosion, interact with matter in any of three ways: (1) Compton scattering, (2) photoelectric effect, and (3) pair production (see Fig. 7-7[19]).

The results of these processes are the production of hole-electron pairs that migrate to oppositely charged junctions under the influence of the applied electric field. This photocurrent in proximity to the junctions causes minority carriers to be swept across, creating an amplified secondary photocurrent due to the current gain of the device. The momentary effect is saturation of the device with a high current surge and a resultant voltage transient. Among the subsequent effects in this chain of events are transistor latchup, circuit ringing, junction breakdown and, in integrated circuits, even lead melting because current surges can range from 1 mA to 1 A. Spurious triggering is common with even small photocurrents and can disrupt the most carefully designed circuit. Photocurrents short out capacitors, turn nominal insulators into conductors, and are especially harmful in integrated circuits because they appear in the base material as well as at the site of active devices and thus form coupling and shorting paths throughout the chip.

7-3.1.2 Gamma Rays

Approximately 3.5% of the energy radiated from a nuclear burst occurs in the first 50 μsec as gamma rays. These rays, with a wavelength of 0.1 to 0.01 angstrom, are similar to X rays generated by several million volts.

Gamma rays are similar to X rays in that they ionize the material into which they penetrate; i.e., they remove electrons from neutral atoms. In most situations this effect is

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TABLE 7-8

COMPARISON OF RADIATION FROM NATURAL SUBSTANCES[18]

	X rays	Alpha rays	Beta rays	Gamma rays
Character	Quanta $h\nu$ (governed by waves of length c/ν)	He^{++} ions = He nuclei	Electrons	Same as X rays, same or shorter wavelength
Velocity	Velocity of light c	Up to 1/15 c	Up to 99.8/100 c	Velocity of light c
Energy of particle or quantum	Visible light: several eV. Technical X rays: $10^4 - 10^6$ eV	Up to 8.8×10^6 eV	Up to 2×10^6 eV	Up to several 10^6 eV
Penetrating power		1/100 mm aluminum	Several /10 mm aluminum	Several cm lead
Absorption, observed	$I = I_0 e^{-\mu x}$	Limited range; dense ionization over the full length of range; straight paths except very rare sharp deflections	Limited, not sharply defined range; less dense ionization than by α rays; crooked paths	$I = I_0 e^{-\mu x}$ good approximation
Absorption, theory	Each quantum when absorbed gives away total energy in one process; fraction of energy lost per cm path is constant	Each particle spends its energy on many ionization processes; no deflection in collisions with electrons because of large mass of α particle; very rare sharp deflection in collision with nuclei	Each particle spends its energy on many ionization processes; deflection occurs since β particle is light	Each quantum when absorbed gives away its energy in one or a few processes: ionization (photo-electric effect), Compton effect, or pair production
Relation to emitting atom	Wavelength sharply defined characteristic of electronic structure of emitting atom	Energy of α particle sharply defined, characteristic of emitting nucleus	*Continuous* β-ray spectra with sharp high-energy limit are characteristic of emitting nucleus; *sharp-line* β-ray spectra represent emission of K or L . . . electrons	Wavelength of γ ray sharply defined characteristic of emitting nucleus

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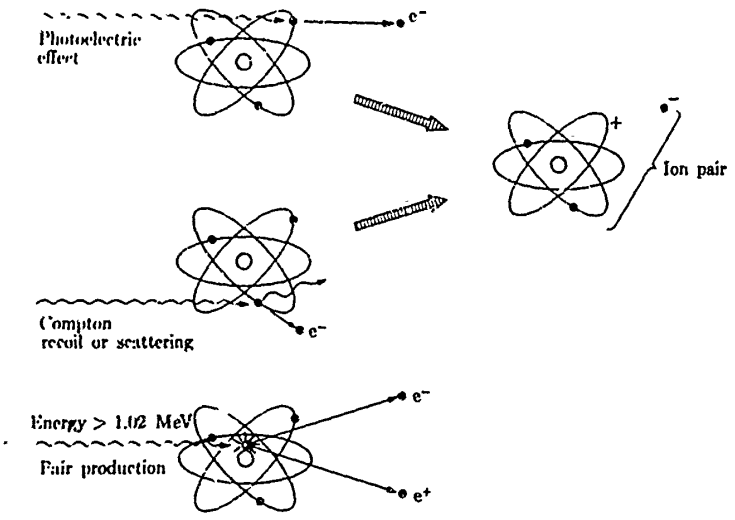


Figure 7-7. Summary of X-ray and Gamma Ray Interactions With Matter[19]

temporary so that the device returns to its original state when the radiation is discontinued. The time lapse is referred to as recovery time.

7-3.1.3 Neutrons

The effects of neutrons—although they are particles of appreciable mass—are similar in character to gamma rays. Neutrons can penetrate a considerable distance through the air and constitute a great hazard.

7-3.2 ELECTROMAGNETIC PULSES (EMP)

Under the proper circumstances a significant portion of the energy released during a nuclear detonation can be made to appear as an ElectroMagnetic Pulse (hence, EMP) having the same frequencies or wavelengths as those employed by most commercial radios and military systems[20]. Two unique properties of EMP are of crucial significance--(1) its extremely great range, EMP being capable of disabling electrical and electronic systems as far as 3000 miles from the site of the detonation, and (2) the fact that EMP can cause severe disruption and sometimes damage when other weapon effects such as nuclear radiation blast, thermal effects, dust, debris, and biological effects are all absent. This means that a high-yield nuclear weapon, burst above the atmosphere, could be used to knock out improperly designed electrical and electronic systems over a large area of the earth's surface without doing any other significant damage. The range of EMP is diminished greatly if the weapon is detonated within the atmosphere.

An idea of the amplitude of EMP can be gained when we compare it with fields from man-made sources. A typical high-level EMP pulse could have an intensity of 100,000 V/m. This is a thousand times more intense than a radar beam of sufficient power to cause biological damage such as blindness or sterilization. It is ten million times as intense as fields created by sources in a typical metropolitan area. Recently two factors have

SAMSUNG EXHIBIT 1028, Page 124

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greatly increased the significance of the EMP threat: (1) increased sophistication in nuclear strategy and weapons, and (2) increased susceptibility of electronic systems due to the broad introduction of semiconductors and the ever-greater dependence on complex operational hardware.

EMP differs from the electromagnetic environment usually encountered. The very intense EMP fields are distributed widely, whereas intense natural (lightning) or man-made fields are localized. Further, EMP occupies the spectrum through the lower microwave band. Most man-made fields are confined to only a narrow part of the spectrum. It follows, therefore, that protection practices and components for non-EMP environments–radio-frequency interference, lightning, radar, etc.–are not directly applicable for EMP problems.

The asymmetrical flow of charges caused by a nuclear explosion causes electromagnetic fields to be radiated away from the burst point. These fields cause a corresponding flow of charges, or electrical currents, in distant metallic conductors. This is comparable to the way the electromagnetic fields from a TV transmitter set up currents in a rooftop TV antenna. Any metallic object exposed to electromagnetic fields can be a collector of electromagnetic energy; i.e., act like an antenna, even though it was never intended to be that. Generally, the larger the metallic structure, the greater is the amount of intercepted EMP energy.

The level of the EMP environment can be reduced by shielding, geometric arrangement, geographic relocation, or grounding. Good shielding design is the best practice. It usually centers on pragmatic compromises related to the realities of construction and fabrication, economics, and applicational requirements. The dominant principle in circuit geometry is the avoidance of coupling configurations–most notably inductive loops. Good circuit layout practices apply equally to large cable systems or to printed circuit packages. It is generally independent of circuit dimensions. Grounding is not a panacea. If it is not applied realistically, it may make matters worse. In some systems controlled resistive grounds are used purposely to promote energy dissipation and to suppress ground loop currents.

The fraction of the collected energy which is applied to a sensitive component may be reduced by introducing an amplitude limiting device, such as a spark-gap, a filter, or a disconnect mechanism between the energy collector and the component. Protection against EMP also may be achieved by choosing less sensitive components or subsystems. For instance, vacuum tubes are more damage-resistant than transistors. Their incorporation, however, might create other problems. Increasing or selecting digital logic circuits having digital voltages and switching thresholds is preferable. Coding signals sent via long interconnecting wiring will minimize EMP "fooling" the system.

Testing is as important as planning and implementation of hardware protection. The balances between laboratory tests and full-scale simulations, and between component and full-system tests, depend on many factors, such as system size, probable threat situations, and unavoidable susceptibilities. Both analytical and empirical approaches are required to realize a hardened system. Neither can be relied upon exclusively. The number of uncertainties and unknowns is so large that one approach often is used to confirm the results of the other approach.

Today, it is considered to be sufficient to permit the design and implementation of most military hardware with high assurance of acceptable EMP hardness. But it does cost some money and effort, and the indications are that this hardness will never come "free". Typical EMP hardening costs (if incorporated early) for strategic systems can be on the order of a few percent of the system cost[20].

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7-3.3 COMPONENTS

7-3.3 1 Design Considerations

The hardening of a timing system that must operate during irradiation has two major problem areas[21]. The system must not lose its capability to perform due to permanent damage to its components, primarily from neutron irradiation. In addition, timing accuracy will be affected directly by any temporary disabling due to transient response of system circuitry to ionizing radiation, primarily photons.

Hardening the time system against permanent damage by neutron irradiation can be accomplished mainly by choosing the "hardest" components and allowing for their degradation to a level to which the weakest components can be raised by proper shielding. To minimize the transient response of the system would require extensive circuit redesign.

The degree of overdesign depends on specification level and system complexity. For example, at 10^{12} n/cm^2 with energies greater than 10 keV, an overdesign factor of 20 is reasonable; at 10^{13} n/cm^2 a reasonable overdesign factor could be 5. At 5×10^{14} n/cm^2, however, an overdesign factor for safety margin is hard to obtain[22]. Some of the most sensitive semiconductor components begin to show radiation effects at about 10^{11} n/cm^2. The upper end of the range is about 10^{15} n/cm^2. See Refs. 23-26 for detailed information on hardening.

7-3.3.2 Hardened Components

Hardened components are the foundation for a survivable system. Advances in semiconductor device technology have produced dielectrically isolated integrated circuits of high-gain bandwidth product with thin-film passive components for use in radiation environments. Computer aided analysis and design have been made possible by the development of codes like SCEPTRE and TRAC that use large-signal radiation equivalent circuits for semiconductor components. Reliability engineering and quality control have evolved new techniques for minimizing structural defects that might limit semiconductor performance.

The most important failure mechanism due to neutrons is the degradation of semiconductor device operating characteristics. The main aspect of this problem is β degradation, where β is the current gain. Various studies have shown that control of base width is needed in order to control β degradation. This can be done more directly by controlling gain bandwidth product which is inversely proportional to the square of the base width. Selection of a gain bandwidth product that ensures the largest overdesign factor consistent with the present state of art and market availability is now possible for small signal devices. For power transistors, overdesign must be supplemented by circuit design techniques that minimize the dependence of circuit functional parameters on the gain of the power transistor. Devices such as SCR's and unijunction transistors should not be used unless a verified source of hardened devices has been established. Microcircuits, including p-n-p transistors, should be avoided if possible due to the difficulty of controlling base width in such structures[22]. Several methods have been developed to produce films that are insensitive to a radiation-induced space charge buildup. These are the silicon oxynitride films[27] and the silicon-on-sapphire isolation techniques[28]. For additional details on component hardening techniques, see Ref. 29.

While surface properties of semiconductor devices also are changed by the ionizing dose, the parameters of most transistors and modern diodes are relatively independent of changes in surface properties. The net result is that these components can be used up to total doses of 10^6 rad. Surface field-effect transistors suffer large changes in turn-on voltage due to total dose effects and have

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thresholds as low as 5000 rad. These transistors should be avoided in radiation hardened systems[22]. Surface dose effects can be controlled to a degree by imposing stringent specification limits on junction leakage currents.

7-3.3.3 Analysis

In the design and analysis of electronics in the radiation environment, it is necessary to describe the electrical effects of radiation on semiconductor devices quantitatively. The Ebers and Moll Model[30], the simplest large signal model, can be readily modified to include radiation effects. The devices must be characterized and predictions--nominal and worst case--of device response to the nuclear environment must be made. The device must then be measured in radiation facilities. Predicted and measured responses are then compared, and any significant differences must be resolved. Analysis must cover all of the current and voltage regions that the device encounters in the system. In no case should circuit analysis be performed until satisfactory device models are defined.

7-3.4 CIRCUIT TECHNIQUES

Current transients from photons create noise pulses, a change of state in digital circuits, and other transient phenomena. The two main elements of a circuit hardening approach are[22]:

(1) Shielding to limit radiation levels in the electronic circuits

(2) Special circuit design techniques to minimize circuit functional response characteristics to radiation effects.

Shielding can effectively reduce X ray flux but it usually is ruled out for use with neutron and gamma flux because of severe weight penalties. When shielding is not feasible, the circuit must be redesigned.

The most cost effective way to analyze a circuit is to use a computer to predict system operating parameters as functions of radiation exposure. Proof tests can then be performed at radiation facilities and compared with the computer predictions. Agreement between predicted and measured results provides confidence in the hardened design.

A typical comparison of measured and predicted response for the microcircuit of a general purpose amplifier is shown in Fig. 7-8[22]. For further information on circuit hardening techniques, see Refs. 29 and 31.

7-3.5 MEASUREMENT AND SIMULATION

In order to simulate exposures and to measure their effects, a radiation facility is required. Facilities such as a TRIGA Mark F reactor at the radiation facility of the US Army Harry Diamond Laboratories can be used to irradiate components. Neutron dosimetry is used for energies greater than 10 KeV with dosimetry accuracy being 20-25%[21].

Among the results found at this facility was that reset circuitry need not be hardened against permanent neutron damage but that it

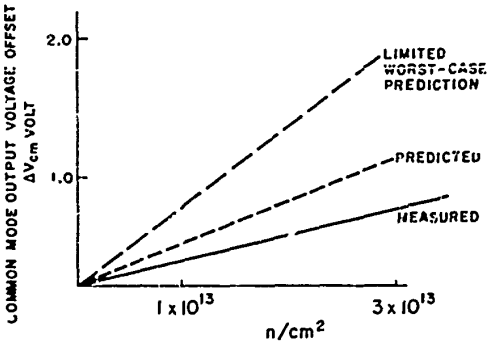


Figure 7-8. Congruence Between Predicted and Measured Common-mode Output Voltage Offset[22]

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must remain inactive after the timing sequence has started. A burst of ionizing radiation could produce photocurrents in transistors which would act as a reset signal, thus resetting all flip-flops and magnetic circuitry. Photocurrents due to ionizing radiation in microcircuits fabricated with p-n junction isolation were almost an order of magnitude greater than those fabricated with dielectric isolation. Performance degradation of the latter type of microcircuit can be expected to follow closely the degradation of its discrete components. Thermistors irradiated at the facility were found to indicate lower temperatures after irradiation (i.e., their resistance increased); each thermistor had its own characteristic pattern of change[21].

Magnetic core dividers contained three types of component: diodes, SCR's, and magnetic cores. The SCR's failed to operate after relatively low dosages. Their principle of operation makes them extremely vulnerable to ionizing radiation even if they are built to withstand permanent damage. However, a two-transistor equivalent of the SCR is radiation resistant. Damage to the diodes of the magnetic divider showed some decrease in core switching time and loop current because of increased forward voltage drop across the diodes. Magnetic cores were not damaged. Output circuits were also vulnerable because of the presence of SCR's in the system and indicated that substantial redesign would be necessary.

Simulation of timer circuits can be done by computer. The basic information needed to model a timer circuit is the circuit schematic and its electrical performance characteristics. Gamma dose rate modeling is accomplished by the addition of a current generator and, in neutron effects modeling, the gain of the transistor is altered to simulate progressive degradation[32].

7-4 SPECIAL APPLICATIONS

7-4.1 LONG DELAY STATIONARY SYSTEMS

Electronic timers are used in mine fuzes and demolition devices. Mine fuze timers are now used for:

(1) Opening of a missile or artillery round containing a set of scatterable mines

(2) Arming of mines after ejection from the round

(3) Self-destruction of the mine after a time ranging from hours to weeks

(4) The signature analysis circuitry to help determine the functioning time against the target and to assist in resisting counter measures. These timers are made from COSMOS chips.

Examples of long-range timers are described in Refs. 33 and 34.

7-4.2 SATELLITE AND REMOTELY SETTABLE TIMERS

In the design of a timer for a satellite separation system, provision usually is made to provide outputs anywhere within long and short intervals by adjusting a single resistor per interval. Each interval timer is independent and may be connected in series or parallel with any number of other interval timers in any order. The timer should be able to operate reliably under normal and space temperature and pressure conditions, and also under vibration of 10 to 5000 Hz (at maximum acceleration of 54 g)[35]. Off-the-shelf components with no compensation can yield accuracies of ± 10% or better over the temperature range of −4° to 158°F. Selection of timing capacitors having a low temperature

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coefficient and low-leakage can yield ± 5% accuracies in this temperature range. With combinations of bias and timing current compensation, accuracies of ± 2% can be obtained. Redundancy can be accomplished easily because of the independence of the circuits that produce the timing interval and fire the explosive charge, and the fact that the oscillator for each interval is normally off. Figs. 7-9[35] and 7-10[35] show diagrams of long-interval and short-interval timers.

A remotely settable timer is an electronic system consisting of a 2-channel timer and a setting unit connected together either by a 2-wire or 3-wire link or by a 2-way radio link[10]. A typical timer system is settable from 1 to 20,000 sec in 1-msec increments. The frequency source is a crystal controlled oscillator, accurate to ± 2.5 parts in 10^7 over a range of 21 to 31 V DC, a temperature range of 32° to 140°F, and shock and vibration environment of a missile launch[10].

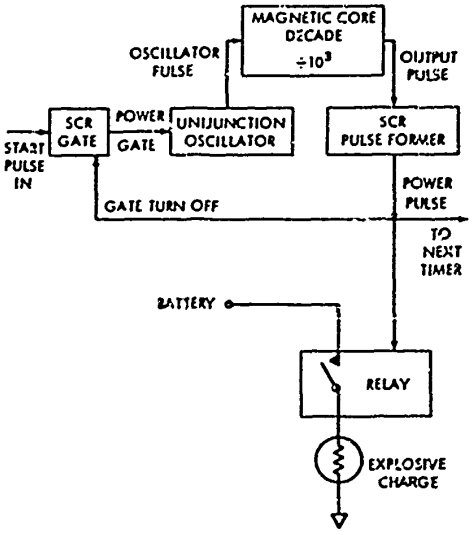


Figure 7-9. Long-interval Timer Block Diagram

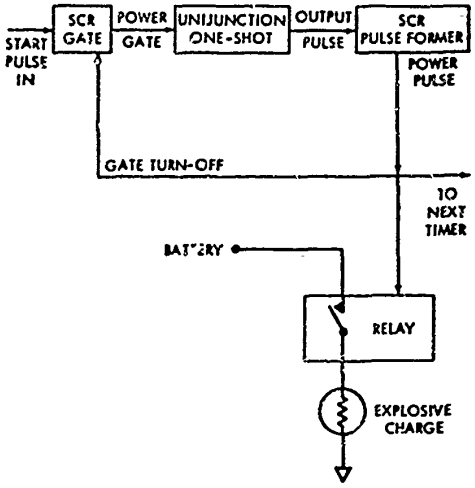


Figure 7-10. Short-interval Timer Block Diagram

Another type of remotely settable magnetic core electronic timer is shown in Fig. 7-6. This timer consists of a temperature-stabilized 1000-cycle *LC* oscillator accurate to 0.1%, a magnetic core counter in double line register mode, and a remote selection unit. Time delays from 1 to 200 sec can be obtained with a setting resolution to 0.1 sec. The remote selection system eliminates the need for circuit power while the time delay is being selected. The time delay selected can be stored indefinitely in the magnetic cores of the timer.

7-5 TIMER TESTING

7-5.1 GENERAL

During the design and development of an electronic timer, as with any other timer system, each component is subjected to a number of tests to determine if it performs in the manner expected. When the prototype is

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built, it is subjected to performance and proof tests to see if the prototype satisfies the requirements. Since some of these tests damage the item and since the available number of items is limited, it is desirable to use special tests and it is necessary to apply special methods of data analysis.

7-5.2 PERFORMANCE TESTS

The components of a timer as well as the complete timer assembly must undergo tests to establish that the system functions properly. For a discussion of development and acceptance tests that are used to check out new timer designs, see par. 13-6.2.

7-5.3 SAFETY TESTS

Safety tests are used to determine whether performance meets safe handling requirements. There are two types: (1) destructive tests where operability after the test is not required and (2) nondestructive tests where operability is required. For a discussion of these tests, see pars. 13-6.4.1 and 13-6.4.2.

7-5.4 TELEMETRY

Telemetering in the broad sense is the transmission of data by any means from a remote and usually inaccessible point to an accessible location. Usually telemetering refers to electrical methods of acquiring and transmitting data, especially for transmission by an RF link from the munition to a ground station[36]. The requirement for telemetering data from fuzes using electronic timers may be quite severe, e.g., in an artillery fuze where survival of the telemetering transmitter, power source, and antenna may be necessary under accelerations in excess of 50,000 g during setback. A typical system meeting these requirements is shown in Fig. 7-11[7]. Transducers in the device being tested convert the variable being measured into an electrical signal that subsequently is used to modulate the carrier of an RF transmitter. The signal is received, amplified, and demodulated on the ground and recorded on magnetic tape or on an oscillograph for subsequent analysis.

Fig. 7-12[37] shows the sequence of events

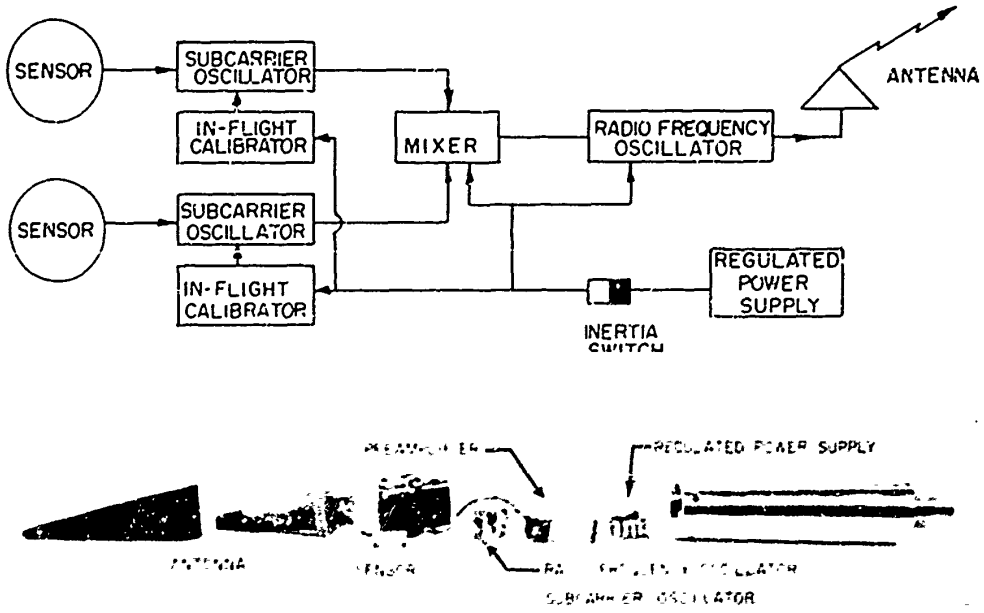


Figure 7-11. Typical VHF High-g Telemetry System

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of an electronic programmer system for a projectile. The projectile was equipped with a telemetry unit that transmitted the frequency of both oscillators and the outputs from both channels. The outputs occurred at T-7, T-6, T-4, and T-0 sec. The purpose of the test was primarily to determine if the decade dividers, output logic, and firing circuit would operate properly after being subjected to gun-fired environments[37].

7-5.5 ANALYSIS OF DATA

It is important that the timer system designer use statistical procedures to re-enforce his conclusions. Timers may be manufactured in large lots and only a few items will be tested. These are selected randomly so that the sample will represent the lot. For more information about the analysis of data, see par. 13-6.5.

7-6 ADDITIONAL FACTORS IN DESIGN

In order to design a timer for use in severe environments so that it will function within the limits set forth in the specifications, a number of general design factors must be considered. These include reliability, human factors engineering, and cost.

7-6.1 RELIABILITY AND MAINTAINABILITY

In designing for reliability, the designer has two powerful tools at his disposal at all stages of the design. They are: (1) derating of components and (2) reliability analysis. Derating of components means operating them at substantially less than their rated values of voltage, wattage, temperature, etc. Reliability analysis is the calculation of system or equipment reliability from the failure rates of the components used. If these techniques do not reduce the component failure rate sufficiently, then redundancy or standby systems can be used. In the case of electronic timers—where high reliability, small space, and low weight are specified—redundancy and standby systems cannot always be used and therefore the first two methods commonly are employed. Techniques for reliable design are[5]:

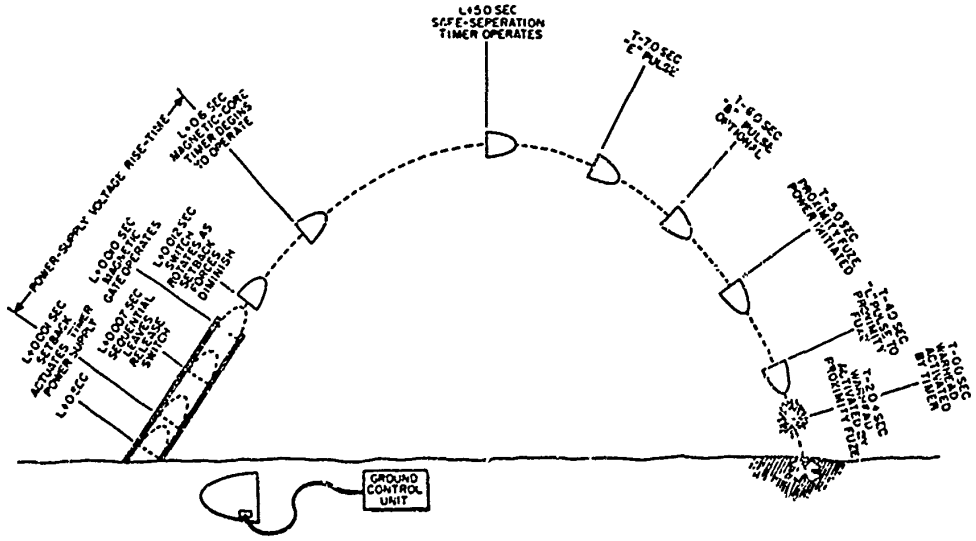


Figure 7-12. Sequence of Events

SAMSUNG EXHIBIT 1028, Page 131

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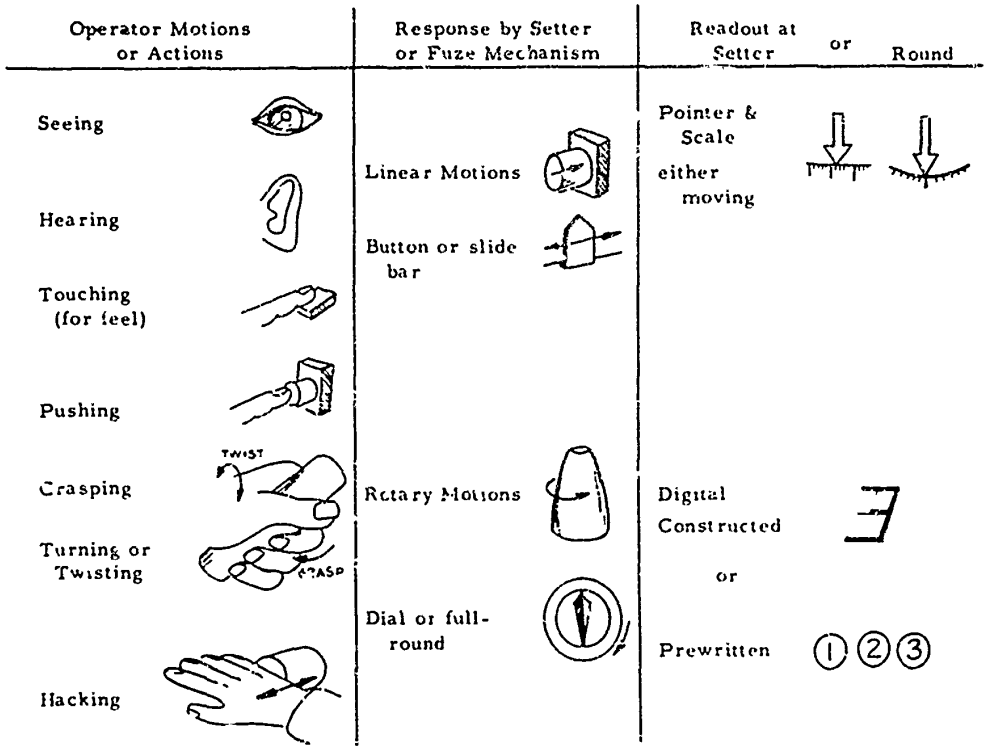


Figure 7-13. External System Building Blocks

(1) Design to a minimum of parts without degrading performance.

(2) Perform design reliability reviews by means of reliability analyses.

(3) Apply derating techniques.

(4) Reduce operating temperatures by providing heat sinks, good packaging, and good cooling.

(5) Eliminate vibrations by good isolation and protect against shock, humidity, corrosion, etc.

(6) Specify component reliability and burn-in requirements.

(7) Specify prototype tests and production debugging procedures.

In regard to maintainability, the design engineer should keep in mind the principles discussed in par. 13-2.2. Improved reliability will reduce the need for maintenance. Full use should be made of standard parts, components, tools, and test equipment. Interchangeable parts, components, and assemblies are essential to good maintainability and should be an important part of the design philosophy.

7-6.2 HUMAN FACTORS ENGINEERING

Human factors engineering is the scientific union of men with machines so as to enhance

SAMSUNG EXHIBIT 1028, Page 132

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the man-machine system. A knowledge of the performance of both man and timer parts is required for an efficient union. An example of the use of human factors engineering is the evaluation of a setting mechanism for analog electronic timers[8]. In this study, a handbook of information and data was developed that would be useful to a designer of resistor setting switches for an electronic timer used in artillery fuzes. It contains a detailed treatment of the operator and his relations to the function of setting internal mechanisms.

A designer uses his ability to synthesize a concept from a series of known elements. An illustration of the general nature of various input mechanisms is shown in Fig. 7-13[8]. In a man-machine situation, man is considered the variable with the machine being constant. The human factors engineer is concerned primarily with machine or product design to improve the overall efficiency. See par. 13-2.3 for further details.

7-6.3 COST REDUCTION

The production of electronic timers at reduced cost is subject to the same considerations as those of any other timers. The factors that the designer must keep in mind are listed in par. 13-2.4. Statements about tolerancing, as applied to electronic timers, refer to tolerances of voltage, current, or power ratings which are required to keep the final design working according to specifications and to permit the most economical manufacturing procedure.

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SAMSUNG EXHIBIT 1028, Page 135

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CHAPTER 8

PRODUCTION TECHNIQUES

8-1 PRODUCTION OF MICROELECTRONIC MODULES

8-1.1 GENERAL

Microelectronic digital modules are being fabricated today by a wide variety of techniques. Since each technique has strengths and weaknesses, the circuit designer should be aware of the many ways to solve a specific design problem. As in all military applications, reliability is of key importance. After reliability, the next consideration is the timer type. It can be either a control device or an ammunition component. Control devices, such as precision timers, are used repeatedly, and normally kept on the bench where they are carefully handled and can be made accessible for repair. On the other hand, ammunition components, such as fuze timers, are one-shot, low cost devices, are often subject to large forces, and must have a long storage life.

Based on the concept of packaging, the field of microelectronics may be divided into three areas[1]:

(1) Packaging of discrete, miniature component parts

(2) Printing of component parts and their interconnection pathways, *in situ*, as a series of thin films on flat wafer substrates

(3) Modification of a block of semiconductor material to obtain the varied resistive, dielectric, conductive, and junction characteristics of interconnected components.

Hybrid approaches can be employed in which combinations of two or three of the preceding techniques are used in the fabrication of a single circuit. Miniature parts are available of more or less conventional construction that can be packaged into tiny modules and subsequently into larger assemblies. A different approach, still using individual parts, involves fabrication of a component of nearly flat configuration, such as a ceramic wafer. Required wafers of a prescribed area then are connected together by means of riser wires, soldered to metallized notches at the edges of the wafers to yield a package of prescribed dimensions. This technique and another in which component parts are manufactured in the shape of tiny cylinders of predetermined dimensions and inserted into holes in a printed circuit board are designed to expedite assembly. However, they offer little size reduction over that obtained by small conventional parts. An example of this pellet or "Swiss-cheese" package is shown in Fig. 8-1[1].

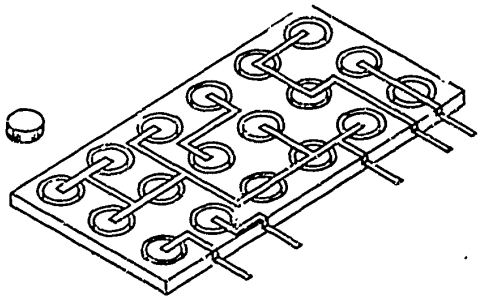


Figure 8-1. Pellet or "Swiss Cheese" Package

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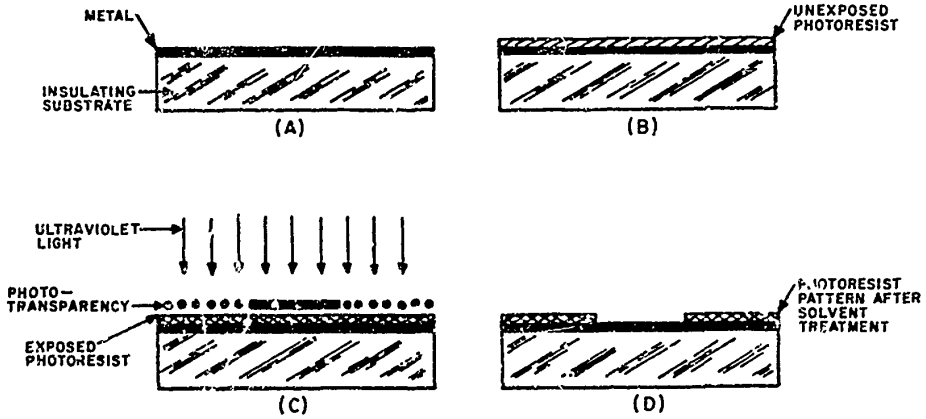


Figure 8-2. Preparation of Pattern Using Photoresist

8-1.2 PHOTORESIST MASKING

The photoresist masking technique is used extensively in thin-film and solid circuit packaging approaches. The required steps in the preparation of a pattern on a substrate are illustrated in Fig. 8-2[1]:

(1) The metal clad substrate is coated by spin-coating, dip-coating, and air brush spraying or painting.

(2) The substrate is coated with photoresist and allowed to dry.

(3) The photoresist is exposed to ultraviolet light through a negative or positive of the pattern.

(4) The pattern is developed by dissolving away the unexposed areas with organic solvent vapors, such as trichloroethylene.

The result is a resist coating on the substrate surface of the desired configuration. Equipment necessary includes a light source, an exposure frame, and fixtures to align the pattern on the substrate.

Microcircuits can be made using photoresist in a number of different ways. The photoresist can be formed into an accurate detailed mask on the surface of the metal-clad substrate. Thin layers then either can be added or subtracted from the exposed surface of the base metal. To add metallic materials, methods such as sputtering, vacuum evaporation, screen printing, electro-deposition, or chemical deposition can be used, while electroetching or chemical etching can be used to remove metal. Following the use of any of these processes, the protective photoresist can be stripped off the surface of the base material. Excellent stripping solvents include methylene chloride or hot chloroform. Fig. 8-3(A)[1] shows how photoresist protects the underlying material during an etching process. In Fig. 8-3(B) photoresist prevents the underlying metal on another plate from being electroplated. In Fig. 8-3(C), photoresist is used as a disposable mask during chemical deposition; when the photoresist is removed by solvent, the overlying deposit is also removed.

8-1.3 THIN-FILM MICROELECTRONICS

The more important techniques for placing conductive, resistive, and insulating thin films upon substrates include (1) screen-printing, (2) vacuum deposition, (3) sputtering, (4) vapor-phase deposition, and (5) chemical plating[1].

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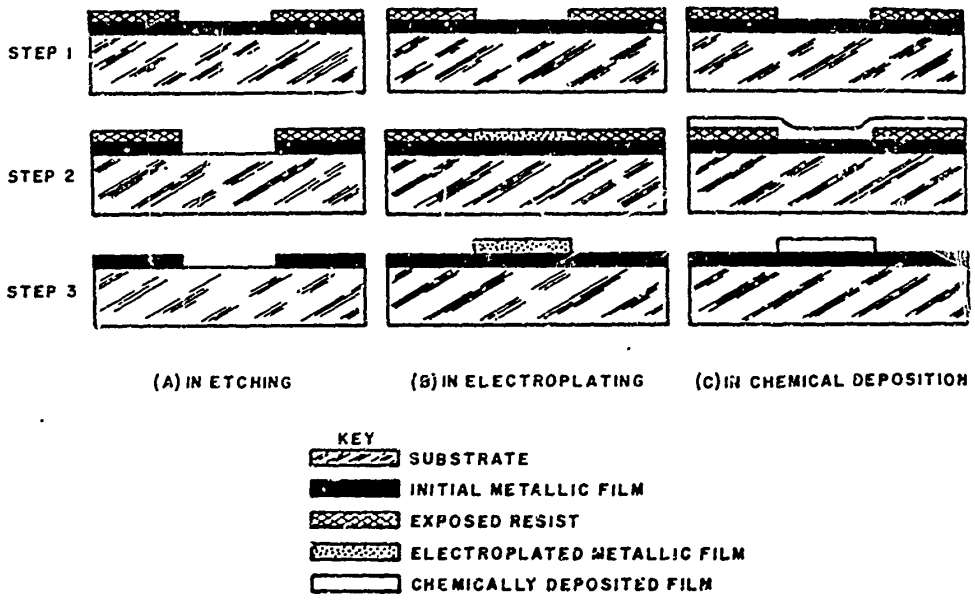


Figure 8-3. Uses of Photoresist in Various Processes

8-1.3.1 Screen-printing

Screen-printing commonly is used to apply ink in order to form geometric patterns on substrates. The process consists of three steps[2]:

(1) Prepare a patterned screen so that some areas of mesh are open for ink to pass while others are closed or masked.

(2) Accurately position the pattern on the substrate.

(3) Push ink down into and across the mesh of the screen with a squeegee.

While the stencil-like patterns may be prepared by both cutting and photographic methods, photography is required in micro-miniature circuit work because of the fine lines and intricate patterns.

8-1.3.2 Vacuum Deposition

In vacuum deposition, a solid material (the charge) is converted into a gas, either by evaporation or sublimation, and condensed onto a cool substrate elsewhere in the vacuum system[3]. Fig. 8-4[1] is a diagram of a typical apparatus for vacuum evaporation and deposition. Electric-resistance heating provides the energy for vaporization; other methods are inductidn-heating, electron bombardment, and concentrated solar radiation. A vacuum of 10^{-4} mm of Hg pressure or less is required to insure that the distance an atom can travel before colliding with another atom is large compared with the distance between charge and substrate.

8-1.3.3 Sputtering

The process in which a metal is bombarded by an ionized gas and atoms or in which

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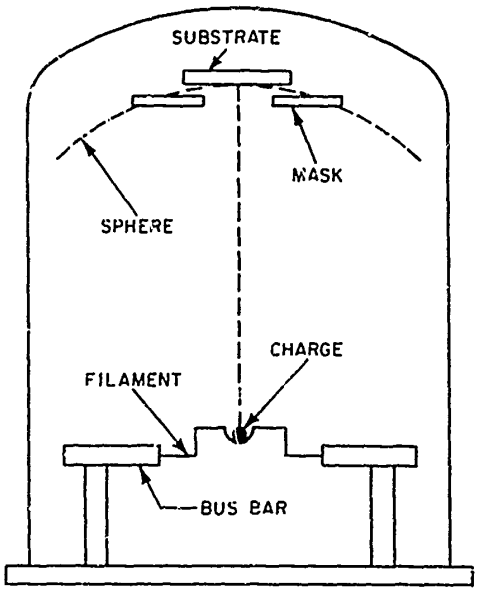


Figure 8-4. Vacuum Evaporation and Deposition Apparatus

groups of atoms are driven from the metal surface because of the impact is known as sputtering. Metal deposition by sputtering requires pressures as low as 10^{-2} to 10^{-6} mm of Hg and an electric field of several hundred to several thousand volts. Fig. 8-5[1] shows a typical arrangement. The metal to be sputtered is made the cathode, and the substrate is placed on a tray or rack within 1-2 in. of the cathode. The gas used (usually argon) is ionized by the electrons from the cathode. These ions are accelerated toward the cathode, which they strike, and to which they transfer kinetic energy so that surface atoms are vaporized. Some of this metal condenses on any object in its path and coats it, while some returns to the cathode after collision with gas molecules. Sputtering is slow and difficult to control but is especially useful in the deposition of refractory metals such as tungsten, tantalum, and molybdenum. Arc-melted tantalum has been sputtered in argon at a pressure of 10-20 microns and a potential of 3500 V between electrodes with

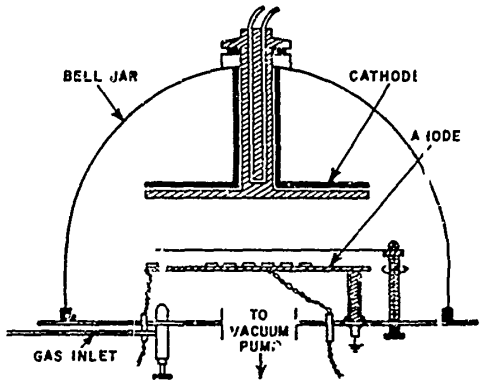


Figure 8-5. Sputtering Apparatus

2.5-in. spacing. The sputtering rate, under these conditions, was 100 Å per min[4].

8-1.3.4 Vapor-phase Deposition

The process in which a substrate is coated by heating it to a high temperature in the presence of a gaseous metallic compound is called vapor-phase deposition or pyrolysis. The temperature of the substrate is high enough to decompose the metallic compound but not high enough to vaporize the deposited metal. By this means, the heated substrate decomposes the compound and the metal is deposited on the substrate. Vapor phase deposition has been used to make thin-film resistors by coating glass with tin-oxide film[5].

8-1.3.5 Chemical Plating

In chemical plating, metallic ions in solution are reduced by an agent absorbed on the surface of a substrate and are deposited on the substrate. The "electroless nickel" process is the most common method and is used to deposit a very adherent Ni-Ni_3P alloy for electrical resistance elements[6]. The deposited nickel alloy is electroplated with copper and solder, masked with a photoresist, and thus etched in unmasked areas to yield conductor and resistor patterns for thin-film microcircuits. Fig. 8-6[1] shows a conductor and resistor pattern made in this manner.

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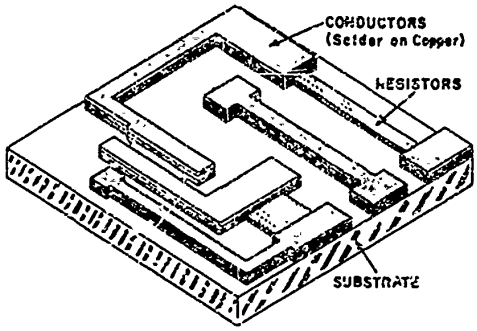


Figure 8-6. Chemically Plated Conductor and Resistor Pattern

8-1.4 TOTAL SEMICONDUCTOR CIRCUIT

The third major approach to microelectronics is that of fabricating all component parts, both passive and active, from a single block of semiconductor material. Various areas of a slice of semiconductor material are selectively exposed for diffusion by a process known as oxide-masking. An oxide is grown on the silicon slice and selectively etched away using photoresist masking. Subsequent diffusion processes then allow selected impurity atoms to enter the material at specific exposed surfaces and to continue to penetrate for a distance determined by time and temperature. This is the so-called "planar process", and is used by most of the transistor manufacturers[1]. This approach generally is classed among integrated circuits and is discussed in par. 8-2.

8-2 INTEGRATED CIRCUITS AND OTHER BATCH FABRICATION TECHNIQUES

The term *integrated circuits* refers to a family of devices related by advantages they have over conventionally wired circuits rather than by common design or manufacturing methods. These advantages include: (1) drastic reduction in size and weight, (2) a substantial increase in reliability, (3) promise of substantial cost reductions, and (4) improved circuit performance. Further, the integrated circuit normally is composed of closely associated parts so that repair becomes difficult, if not impossible. In the event of trouble, the entire circuit is replaced as a single component. There are essentially two general classifications of integrated circuits: (1) semiconductor monolithic, and (2) thin-film. There are also combinations of these that could combine all of the various features of the individual devices in a complex configuration affording maximum utility. Table 8-1[7] lists the present most commonly used structures as well as those that show promise of implementation in the future.

8-2.1 SEMICONDUCTOR MONOLITHIC CIRCUITS

The basic structure of a monolithic circuit consists of three distinct layers of different materials, see Fig. 8-7[7]. The thick bottom layer is p-type silicon, and a thin epitaxial layer of n-type silicon is grown upon it. This p-n structure then is topped with a film of silicon dioxide. All of the component parts are built within the n-type semiconductor region. The primary function of the p-region is to act as a substrate for circuit elements formed within the n-region. The silicon dioxide film protects the semiconductor surface against contamination by external impurities and provides the means for selectively depositing various components into the n-region beneath.

Components that normally are associated with a monolithic circuit are resistors, diodes,

TABLE 8-1

TYPES OF INTEGRATED CIRCUIT

Basic Group	Variations
Semiconductor monolithic circuits	Multichip (hybrid) circuits
Thin-film circuits	Monobrid circuits
	Compatible monolithic circuits
	Insulated-substrate monolithic circuits

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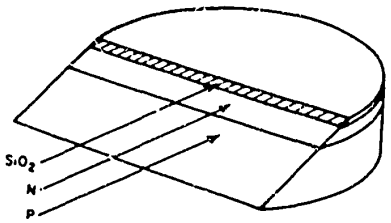


Figure 8-7. Basic Structure of Integrated Circuit Wafer[7]

transistors, and capacitors. Fig. 8-8[7] illustrates typical cross section of these components. If a number of components are to be fabricated in the n-region, means must be provided to insulate components from each other. This is done as shown in Fig. 8-9[7] where each component is bounded by a region of n-type material in contact with the p-type substrate. When the substrate is at a negative potential with respect to the n region, this p-n junction is reverse-biased and little or no current will flow through the substrate between one component and another. This form of insulation is known as diode isolation. Diffusion is used to form the isolation regions, the transistor base region, the diode anodes, and the resistor. The diffusion processes are described:

(1) Diffusion. Impurity atoms are introduced into a semiconductor wafer by diffusion to change the electrical characteristics of the wafer material. Certain types of impurity atoms will create p-type silicon while others will create n-type silicon. This substitution process is called doping. To diffuse impurity atoms, the silicon wafer is placed in a furnace and its temperature is raised to a point between 1000° and 1200°C. The heated wafer is then subjected to a gas flow containing a heavy concentration of impurity atoms. The doping level and the depth of diffusion are controlled closely by adjusting temperature, diffusion time, and the concentration of impurity atoms in the gas stream. However, to fabricate an integrated circuit, selective diffusion must be used.

(2) Selective Diffusion. Selective diffusion is used to distribute impurities only into precisely defined regions of a wafer. Selectivity is accomplished by using a series of masks that protect portions of the wafer against penetration of impurities. The masking material, silicon dioxide, easily is formed on the silicon wafer by maintaining it in an oxygen atmosphere. To diffuse the various components of an integrated circuit into the wafer of Si-O_2-coated silicon, areas where diffusion is to take place must be etched away. However, in order to accomplish selective etching, the SiO_2 layer must be masked by photoresist (see par. 8-1.2), which is used to coat one surface of the three layer wafer. A mask, which is usually glass that has an opaque printed pattern of the areas into which impurities are to be diffused, is held firmly over the wafer and the assembly is exposed to ultraviolet light. This fixes the photoresist in those areas not covered by the pattern. The wafer then is subjected to an etching solution that removes the SiO_2 film.

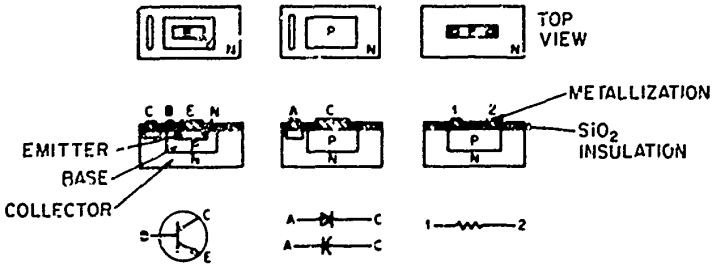


Figure 8-8. Typical Integrated Circuit Components[7,13]

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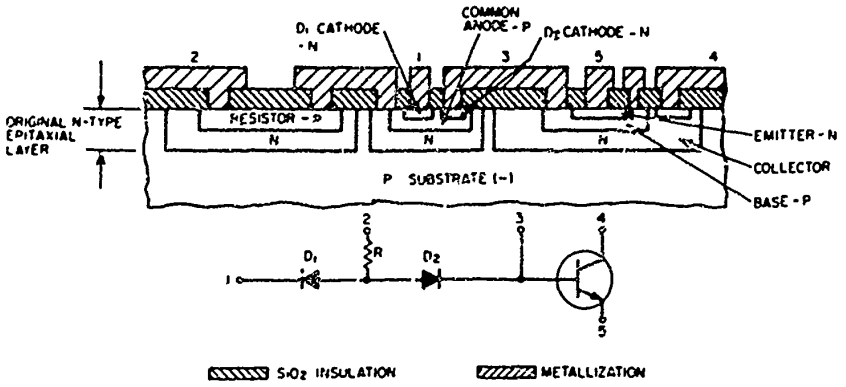


Figure 8-9. Typical Diffused Integrated Circuit Components[7,13]

After etching, the photoresist is removed. The wafer is then ready for the diffusion cycle. For more details on this process, see Refs. 7 and 8.

8-2.2 THIN-FILM CIRCUITS

The thin-film circuit substrate is made of a passive, insulating material such as glass or ceramic. The passive components of the eventual circuit are deposited and interconnected on this insulating surface. A large number of metallic and metal-dielectric materials (cermets), having a wide variety of electrical characteristics, are employed in these depositions. A serious drawback of present thin-film circuits is the fact that technology is unable to fabricate active components using processes that are compatible with thin-film depositions. See Table 8-2[7] for passive processes that are compatible. As a result, the cost of thin-film circuits which require a large number of active components is relatively high compared with monolithic semiconductor circuit cost.

8-2.2.1 Components

Properties of resistors made by thin-film methods depend on the resistivity of the material, the thickness of the deposit, and the length-to-width ratio. Some of the more important thin-film materials for resistors are shown in Table 8-3[7]. The principal electrical characteristics of capacitors are determined by the type and thickness of the dielectric and the area of the plates. For a listing of typical dielectric materials and characteristics that can be achieved, see Table 8-4[7].

TABLE 8-2

COMPATIBLE THIN-FILM PROCESSES[7]

Deposition Process	Material
Metals	
Vacuum Evaporation	Nichrome, aluminum, chromium, gold, nickel
Cathode Sputtering	Tantalum
Vapor Plating	Copper, gold, nickel, tin oxide
Dielectrics	
Vacuum Evaporation	Silicon monoxide, silicon dioxide
Anodization	Tantalum oxide
Vapor Plating	Silica, alumina, glass

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TABLE 8-3

THIN-FILM RESISTOR MATERIALS[7]

Material	Suitable Process	Ohms/Sq. Range	Temperature Coefficient	Characteristics
Nickel-Chromium (nichrome)	Vacuum evaporation	50–400	± 50–100	Good temperature coefficient, good adhesion
Tin-Oxide	Vapor plating	100–5000	± 100–300	High sheet resistance, good adhesion
Tantalum	Sputtering	50–500	± 100–200	Good process control and temperature coefficient, good adhesion, high stability
Cermets	Silk screen	10–100,000	± 100–300	Wide range of resistivity, process not suitable for close tolerances

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TABLE 8-4

TYPICAL DIELECTRIC MATERIALS[7]

Dielectric	Deposition Process	Capacitance at 6 Volts	Q at 10 MHz	Temperature Coefficient*	Accuracy (before trimming)
Silicon Monoxide	Vacuum evaporation	0.013 pF/mil^2 at 30V	200	200–250	± 15%
Alumina	Vapor plating	0.3 pF/mil^2 at 12V	10–100	150–400	± 10%
Tantalum	Anodic oxidation	1.55 pF/mil^2 at 12V	good	150–350	± 20%
Silicon Dioxide	Vapor oxidation	0.25–0.4 pF/mil^2	10–100	100	

*Parts per million/deg C

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8-2.2.2 Processing

An example of a typical thin-film circuit is shown in Fig. 8-10[7]. A typical sequence in the fabrication of a thin-film circuit includes the following steps (for more detailed information about this process, see Refs. 7 and 8):

(1) Clean substrate thoroughly to remove all contaminants.

(2) Store in a dust-free atmosphere until ready to use.

(3) Deposit the resistive pattern, usually using tin oxide.

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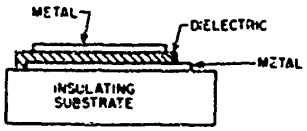


Figure 8-10. Typical Thin Film Circuit[7,13]

(4) Deposit the bottom plates of the capacitors.

(5) Deposit the interconnecting strips.

(6) Deposit the capacitor dielectric.

(7) Deposit a conductive film over the structure to form the top capacitor plates and the final interconnecting pattern.

8-2.2.3 Advantages and Limitations of Thin-film Circuits

The advantages of thin-film circuits over monolithic semiconductor circuits are[7]:

(1) Thin-film passive components can be made with a wider range of values, to closer tolerances, and have better electrical characteristics.

(2) Practically any active component, made in a discrete form, can be used in a thin-film circuit.

(3) Design of circuits for conversion to thin-film assemblies is greatly simplified.

The disadvantages are[7]:

(1) Circuits are larger.

(2) Circuits are more expensive (even in large quantities).

(3) Circuits are less reliable.

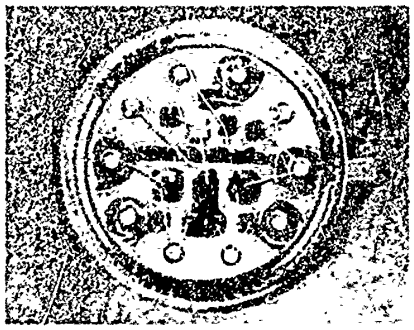


Figure 8-11. Typical Interconnected Multichip Circuit[7]

8-2.3 HYBRID AND OTHER INTEGRATED CIRCUIT STRUCTURES

Structures that may use both semiconductor and thin-film technologies are called hybrid and may include multichip circuits, monobrid circuits, compatible circuits, and insulated-substrate circuits.

8-2.3.1 Multichip Circuits

Multichip circuits consist of components that are interconnected on a common substrate. Basically, they are more like discrete component circuits than integrated circuits; but since they possess some of the advantages of the latter, they are put in the integrated circuit family. They are practical to use in applications requiring small quantities of identical microminiature devices, or where monolithic devices cannot meet necessary performance requirements. Batch processing can be employed in multichip circuits for the various components which make up the circuit. Fig. 8-11[7] shows a typical interconnected multichip circuit.

8-2.3.2 Monobrid Circuits

A monobrid circuit combines two or more

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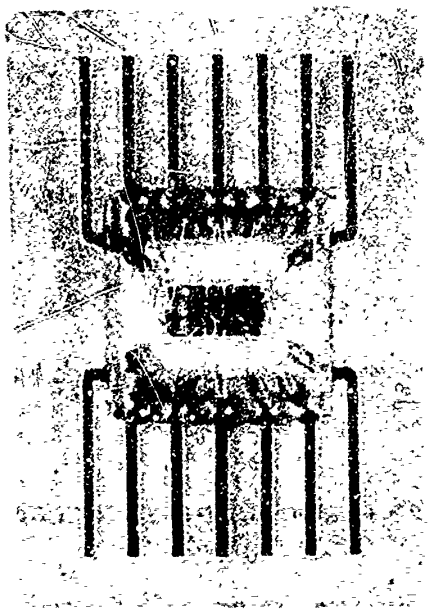


Figure 8-12. Monobrid Circuit[7]

monolithic circuits in a single package (see Fig. 8-12[7]). It is used when a monolithic structure cannot be employed because of complexity and large chip size. For example, transistors, which require different electrical characteristics, make processing in monolithic form difficult. Monobrid circuits are therefore used to[7]:

(1) Economically package complex circuits in a single package

(2) Optimize performance of complex circuits

(3) Use a wider range of components.

8-2.3.3 Compatible Integrated Circuit

The compatible integrated circuit has a basic semiconductor substrate in which diffused semiconductor components provide the basic circuit function. A pattern of thin-film passive components is placed over the monolithic substrate and insulated from it by a thin layer of silicon dioxide. Interconnections between the thin-film components and the semiconductor circuits are made through etched windows in the silicon dioxide layer. A compatible circuit requires the process steps for a monolithic circuit plus additional steps to form the thin-film components. It is, therefore, more expensive to manufacture but is a true monolithic circuit combining advantages of both monolithic and thin-film circuits[7].

8-2.3.4 Insulated-substrate Circuits

In order to eliminate the parasitics associated with various semiconductor junctions, a method has been developed for the construction of a parasitic-free structure that retains all the advantages of a basic monolithic structure[7]. The parasitics give rise to capacitances, diodes, and transistors that are not part of the original circuit design but are associated with the fabrication processes. Fig. 8-13[7] illustrates the following steps in the fabrication of a parasitic-free circuit:

(1) Basic substrate is prepared for insulated substrate circuit.

(2) SiO_2 layer is etched selectively, leaving raised SiO_2-covered islands.

(3) A new layer of SiO_2 is grown over top surface.

(4) A thick layer of polycrystal silicon is grown on top of the wafer and portions of top and bottom surfaces are removed along the dashed lines.

(5) Wafer is turned upside down, and SiO_2 film is grown over the surface leaving single-crystal islands completely isolated from polycrystal substrate.

8-2.4 DESIGN CONSIDERATIONS

Beginning either with the schematic dia-

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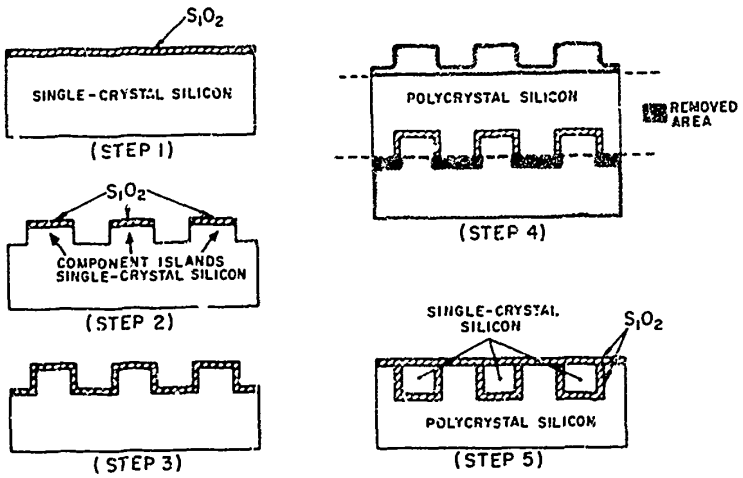


Figure 8-13. Procedure for Parasitic-free Circuit Fabrication[7]

grams of an existing system, or a block diagram of a proposed system, the following questions should be considered, each being discussed in the paragraphs that follow:

(1) What is the most economical integrated circuit that is suitable for a particular condition?

(2) What portion of a system could use the advantages of an integrated circuit?

(3) What type of packaging is best suited for a system, and how many packages are needed to house the integrated portion of a system?

(4) What are the circuit design latitudes and limitations?

8-2.4.1 Type of Integrated Circuit

Most off-the-shelf integrated circuits are limited to medium or low power devices. This is mainly because of the large present demand in the logic area where power requirements are minimal. Amplifiers with power dissipation of 1.8 W have been built by using integrated circuit packages[7]. If the devices were to be mounted on a heat-dissipating surface, the power could be increased but the power limitations of the integrated elements tend to restrict the maximum limits. Integrated circuits can be made using power transistors and larger packages but the possible benefits of circuit integration must be weighed against the high development costs. Of course, in the field of low power circuits, there are few technical limitations that cannot be overcome.

8-2.4.2 Packaging

The type of package and how much circuit can be placed in a single package are circuit design decisions when considering layout and interconnection. Two standard types of hermetically sealed packages have been developed by the industry, a transistor-type package and a flat package. The transistor type is more compatible with component assemblies of existing equipment, while the flat pack permits a greater packing density in subsystem assemblies. Another type is the dual in-line plastic package that is less expensive but has a narrower temperature range. Special considerations include die size because manufacturing yield of integrated

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circuits is very dependent on it. Smaller die sizes result in more circuits per wafer, less waste material, and smaller loss because of wafer imperfections[7].

The number of components that can be placed on a given size of die depends upon the type of components needed, their composition (diffused or film), the resistivity of the material, and the value of the parts. Actual space requirements must be augmented by a 0.5-mil minimum spacing between adjacent elements within a single isolation island, and a minimum space of 2 mils between each isolation island[7]. All available die space cannot be used because of circuit layout but, with careful design, this wasted space can be kept to a minimum. Component density of a silicon chip is always a function of process refinement and is subject to improvement. Hence it behooves the designer to stay abreast of the latest techniques. See Refs. 9 and 10 for details on packaging.

8-2.4.3 Circuit Design

A reorientation of circuit design philosophy must be made when a change to an integrated circuit is contemplated. While it is true that many circuits can be converted part-for-part from discrete form to integrated form, it is more economical and better performance results when the circuit is designed by using integrated circuit technology. For instance, it is less expensive to fabricate integrated transistors than passive elements such as resistors and capacitors. As a result, transistors can be used freely but since passive elements are relatively large and difficult to control to close tolerances, the latter are likely to determine ultimate cost. Large values of resistors and capacitors should be avoided because the smaller values are more easily produced and more economical. Resistive and capacitive tolerances should be as open as possible to produce higher yields and lower costs.

A severe limitation in integrated circuit technology is the non-availability of inductors as integrated circuit elements. Some components have been fabricated but resulting inductance and Q values have been too low. Therefore circuits requiring inductors must be externally added to an integrated circuit. A partial solution is to use extremely small toroids[7].

8-2.4.4 Available Component Values

There is more restriction on the range of component values for integrated circuits than for discrete components. These restrictions often prevent direct conversion of discrete circuits to integrated circuits. Tables 8-5[7] and 8-6[7] summarize integrated component values.

8-2.5 SEALING

All integrated circuit packages require permanent sealing. For reasons of reliability, hermetic sealing generally is required to prevent the intrusion of moisture and corrosive atmospheres that could cause an operational failure. Even when the package is encapsulated, a good hermetic seal is advisable to prevent contamination by cleaning solvents, solder flux, out-gassing of packaging, and packing material that may be forced into the package. Package sealing methods include (1) welding, (2) solder sealing, (3) glass-to-glass sealing, and (4) plastic sealing[8]. The sealing method should be established before package selection, which means that the thermal limitations of the device being packaged must be considered in light of the package sealing requirements. A discussion of the sealing methods follows:

(1) Welding. Automatic or semiautomatic production equipment is used in weld sealing. It is fast, efficient, and the internal device is subjected to the least thermal punishment. Both round can and flat packages are welded by spot stitching or continuous seam welds.

(2) Solder Sealing. Soldering is the most popular method of sealing flat packages.

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TABLE 8-5

VALUES FOR INTEGRATED RESISTORS[7]

	Diffused		
	Mono	Multichip	Thin Film
Usable Resistivity (ohms/sq.)	2.5 (emitter) 100–300 (base)	2.5–300	100–400
Temperature Coefficient	500–2000 ppm/deg C	500–2000 ppm/deg C	30–60 ppm/deg C
Maximum Power	0.1 W	0.25 W	0.1 W
Tolerance	± 10%	±5%	± 5%
Range of Values	15 Ω 30 kΩ	15 Ω 30 kΩ	40 Ω 100 kΩ

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TABLE 8-6

VALUES FOR INTEGRATED CAPACITORS

	Diffused		Thin Film
	Mono	Multichip	(Oxide)
Maximum Capacitance	0.2 pF/mil^2 for collector-base junction	1 pF/mil^2	0.25–0.40 pF/mil^2
Breakdown Voltage	5 or 20 VDC	5–50 VDC	50 VDC
Q (at 10 MHz)	1–10	10–50	10–1000
Tolerance	± 20%	± 10%	± 10%

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Packages, lids, and solder preforms are available in various configurations. Separate solder preforms should match the dimensions of the particular packages used. They are available in thicknesses ranging from 0.0005 to 0.005 in. and in several material combinations, the most typical of which is 80% gold/20% tin.

(3) Glass-to-glass Sealing. Glass-to-glass sealing has several advantages. It eliminates several glass-to-metal interfaces, and also eliminates the separate solder preform and associated gold-plating requirements. The disadvantages are limited availability of various package sizes and the need for specialized equipment to make the seal and to protect the internal circuitry from damage at high sealing temperatures (approx. 600°C)[8].

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(4) Plastic Sealing. Plastics are poor sealants because they are porous and a good hermetic seal is difficult to attain with them. However, plastics are ideal for shock and vibration resistance packaging (see par. 8-2.6).

8-2.6 ENCAPSULATION

Potting compounds are used to encapsulate electronic parts for protection against shock, pressure, temperature, moisture, dirt, corrosion, fungus, vibration, and arcing between components. Electronic components, such as those used in fuzes, are more reliable and have longer life when properly encapsulated.

Circuits to be plastically encapsulated usually are made with chips eutectically mounted and bonded on a skeleton lead frame. These frames are gold-plated Kovar. They are made in strips or matrices so that they can be adapted to automatic, multiple unit molding. A protective resin is applied to the lead frames to protect the chip surface and to hold the gold wire leads in place. The final package is formed by the transfer molding process, and the resulting matrix of completed packages is sheared to produce the individual packaged components[8].

Potting of electronic components, however, has these disadvantages[11]:

(1) Replacement of wires of components is almost impossible.

(2) Potting compounds generally do not withstand very high or very low temperatures.

(3) Potting adds weight.

(4) Circuit design must be compatible with potting.

(5) Components must be cleaned and protected before encapsulation.

(6) Electrical circuit characteristics may be affected adversely.

The most common types of packing compounds are epoxies, polyurethanes, polyesters, and silicones. Table 8-7[11] shows characteristics typical of these materials. One major consideration is the compatibility of any packing formulation with explosives[12].

8-2.7 PRINTED CIRCUITS

One of the greatest benefits from the proper application of printed circuitry is product uniformity. Once procedures and processes are set up, a printed circuit from the assembly line will be the same as the previous one. This result establishes an ease of testing and inspection which is not possible with hand wiring. Design decisions are a result of trade-off studies of complexity of design versus manufacturing costs, simplicity of design versus weight, complexity of design versus skill required, and necessary tolerances versus facilities available. Factors affecting printed circuits are covered in the paragraphs that follow.

8-2.7.1 Design Considerations

To permit maximum efficiency of part or module placement and to facilitate the production of printed circuit boards, standard grids have been devised for the location of mounting holes. The modular units of location are based on 0.100, 0.050, or 0.025 in. and are applied to both axes of rectangular coordinates[13].

The thickness of copper foil usually is given in terms of its weight per square foot. The equivalent thickness in inches equals 0.0014 in. per oz/ft^2. Tables 8-8[13] and 8-9[13] give thicknesses and tolerances of copper foil and clad copper. Fig. 8-4[13] can be used to compute minimum conductor width and thickness. The estimated temperature rise above ambient temperature versus current for various cross-sectional areas of etched copper conductors is illustrated in this figure. The amount of possible undercut should be included when designing for minimum con-

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TABLE 8-7

COMPARISON OF PROPERTIES OF TYPICAL POTTING MATERIALS

Material	Linear Shrinkage	Thermal Expansion	Thermal Conductivity	Volume Resistivity	Dielectric Strength
Epoxy					
Unfilled	very low-med.	low-high	low-medium	good-excel.	very good
Filled (rigid)	very low-low	low	high	very good-excel.	very good-excel.
Filled (flexible)	low-high	low-high	medium	good-very good	very good
Syntatic	very low-low	very low	very low-low	very good	good
Polyurethane					
Foam	very low	low-high	very low	very good	(not avail.)
Cast	very low-high	high	very low	good-very good	good-very good
Polyester					
Filled (rigid)	med.-very high	low-high	medium	good-very good	very good
Filled (flexible)	med.-very high	high	medium	good	good-very good
Silicone					
Cast (filled)	low	high	very high	excellent	good
RTV rubber	high	very high	medium	very good	very good
Gel	very low	very high	medium	excellent	excellent

Key to Ranges

LINEAR SHRINKAGE, in./in.: very low 0.002; low 0.0021–0.004; medium 0.0041–0.010; high 0.0101–0.010; very high 0.0201.
THERMAL EXPANSION, (in./in. deg C) X 10^{-5}: very low 2.0; low 2.1–5.0; high 5.1–10; very high 10.1 (figures referenced against aluminum).
THERMAL CONDUCTIVITY, (cal/sec/cm^2/deg C per cm) X 10^{-4}: very low 1.5; low 1.6–4.0; medium 4.1–9.0; high 9.1–20; very high 20.1.
VOLUME RESISTIVITY, ohm-cm: good 10^{11}–10^{12}; very good 10^{13}–10^{14}, excellent 10^{15}–10^{17}.
DIELECTRIC STRENGTH, V/mil: good 225--399; very good 400–500; excellent 500.

ductor width. This normally is computed as 0.001-in. undercut per ounce of copper per side. In computing conductor spacings of either coated or uncoated boards for altitudes below 10,000 ft, use Table 8-10[13].

To increase the rigidity of the board and forestall any possible plate resonances, several practices are available. Boards between 0.031 and 0.062 in. thick should be supported at intervals of not more than 4 in. Boards greater than 0.093 in. thick should be supported at not more than 5-in. intervals. Finally, all boards should be supported within 1 in. of the board edge on at least three sides.

Moisture that enters insulating board material can greatly affect dielectric strength, dielectric constant, and the dissipation factor of the material. Conductors should not be allowed to approach the board edge within 1/8 in. If conductors are used as a board edge plug-in, the edge should be chamfered. This avoids delamination or lifting of conductors by giving the board the proper lead-in.

Terminal area annular rings should have a width of 0.020 in. for unsupported holes (Fig.

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TABLE 8-8

COPPER-FOIL THICKNESS AND TOLERANCE

Thickness		Tolerance, in.
oz/ft²*	in.	
1	0.0014	+0.0004 −0.0002
2	0.0028	+0.0007 −0.0003
3	0.0042	±0.0006
4	0.0056	±0.0006
5	0.0070	±0.0007

*In industry, thickness of copper foil is given in terms of its weight per square foot. Thus, 1-oz copper weighs 1 oz/ft²

8-15[13]) and 0.010 in. for plated-through holes (Fig. 8-16[13]). Fig. 8-16 shows that the ring for swaged holes should extend 0.010 in. beyond the swaged flange of a terminal or stand-off. To provide a satisfactory drill lead-in, the inside diameter of the terminal area should not exceed 0.020 in. To eliminate many soldering defects, the drill diameter should exceed the minimum inside diameter of the terminal area by at least 0.010 in.

8-2.7.2 Taping the Artwork

The conversion of any circuit design from schematic to a completed, printed-wiring board is a critical process for several reasons. First, no amount of touch-up can correct an inferior job of taping. Extreme accuracy and cleanliness are essential during this operation. All conductor paths and interconnections should be made with free flowing lines and rounded corners. Fig. 8-17[13] illustrates some correct and incorrect conductor patterns. In the application of the tape on the artwork, great care is necessary when forming a free-flowing bend. Tape breakage or an uneven width of a taped conductor can result if undue pressure or pull is used. No more than two layers of tape in any one area should be used because inaccuracies can result in reproduction during the photographic process. Since a static charge that attracts foreign particles is likely to build up on the polyester-film master, cleanliness should be rigorously maintained.

TABLE 8-9

CLAD-COPPER THICKNESS AND TOLERANCE

Nominal Thickness, in.	Tolerance, ±in.			
	Class I		Class II	Class III
	Paper	Glass		
1/32 (0.031)	0.0045*	0.0065	0.004	0.003
1/16 (0.062)	0.0060*	0.0075	0.005	0.003
3/32 (0.093)	0.0075*	0.0090	0.007	0.004
1/8 (0.125)	0.0090*	0.0120	0.009	0.005
1/4 (0.250)	0.0120	0.0220	0.012	0.006

*For 1-oz copper on one side, tolerance is 0.0005 in. less than value shown.
For nominal thicknesses not shown in this table, the tolerance for the next greater thickness shown applies.

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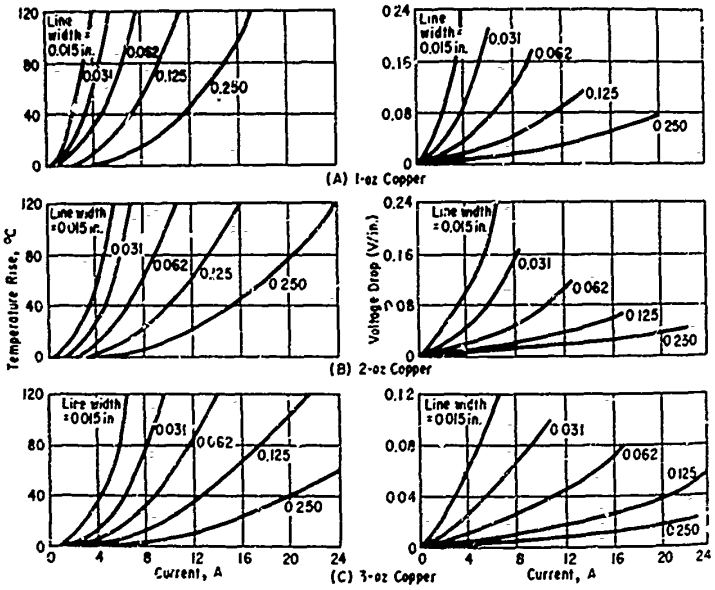


Figure 8-14. Electrical Characteristics of Etched Copper Wiring[13]

8-2.7.3 Laminate Materials

Printed-wiring board laminates fall into two broad categories: (1) paper-based phenolics, and (2) glass based epoxies. The phenolics are numbered x, xx, and xxx and these numbers signify that the laminate contains phenolic resin by weight of at least 35, 45, or 55%, respectively. A phenolic designated xxxp indicates that the laminate has been plasticized for punching. Phenolics have good mechanical and electrical properties, and are used except where good dimensional stability, high impact strength, arc resistance, or high insulation at high humidity are required. The most commonly used glass laminates, G-10 and G-11, exhibit good mechanical and dimensional stability at high temperature, good insulation and heat resistance, and low moisture absorption. Two disadvantages of these types are: (1) they cause excessive tool wear, and (2) they have poor punchability. A paper based epoxy (FR-3) is a compromise material. It is flame resistant, can be punched cold, and its properties are similar to the better phenolics[13].

8-2.7.4 Soldering Techniques

Packaging densities often make it necessary to use a double-sided board with conductors and electrical connections on both sides.

TABLE 8 10

RECOMMENDED CONDUCTOR SPACING

Voltage Between Conductors, VDC or AC peak	Minimum Spacing Coated	Minimum Spacing Uncoated
0 to 30	0.010 in.	0.025 in.
31 to 50	0.015 in.	0.025 in.
51 to 150	0.020 in.	0.025 in.
151 to 300	0.030 in.	0.050 in.
301 to 500	0.060 in.	0.100 in.
Over 500	0.00012 in./V	0.00012 in./V

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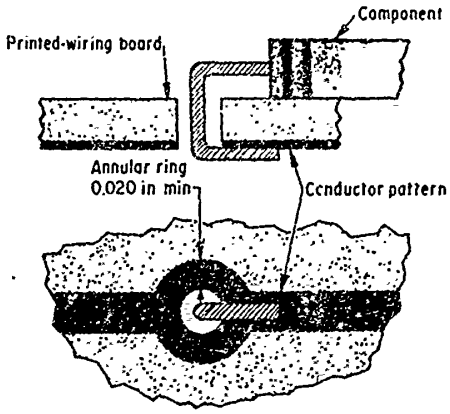


Figure 8-15. Annular Ring for an Unsupported Hole With Component Lead Soldered on One Side[13]

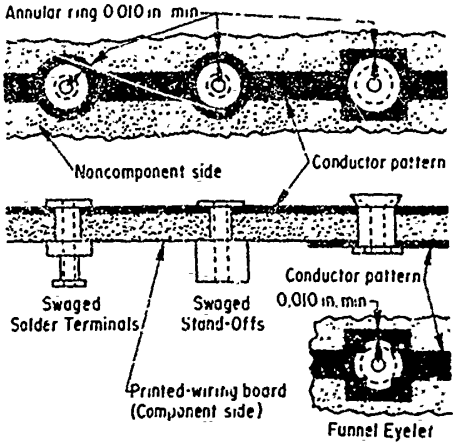


Figure 8-16. Annular Ring for Swaged Terminals, Stand-offs, and Funnel Eyelets[13]

Electrical, soldered connections between both sides of the board are made in one of four fundamental ways[13]:

(1) Plated-through holes

(2) Eyelets as an interface connection only

(3) Eyelets in component holes

(4) Bare holes with a terminal area on a noncomponent side, or if an electrical connection is needed on the component side, terminal areas on both sides.

For the first three methods, the board is subjected to an automatically controlled wave solder operation. Capillary action is used for the plated-through holes or eyelets when the board comes in contact with the solder wave, and this action solders the connection on the component side. The correct temperature of the solder bath and having a clean solderable surface at the right temperature are very important. For more detailed information about soldering techniques, see Refs. 15 and 16.

8-3 REQUIREMENTS FOR TECHNICAL DOCUMENTATION

Production requires a complete technical data package. This documentation is to ensure that military items are capable of reliable performance. See par. 14-4 for detailed information on the contents of a technical data package.

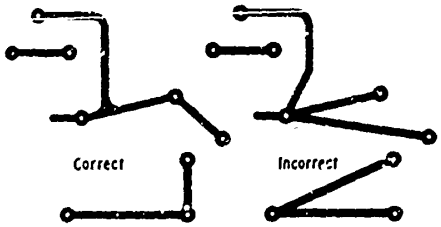


Figure 8-17. Correct and Incorrect Conductor Patterns[13]

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CHAPTER 9

PACKING, STORING, AND SHIPPING PROCEDURES

9-1 GENERAL

Military materiel is packaged to protect it from harmful environments, including transportation. Packaging will protect the item after production, during storage, during transport, and until delivery to its ultimate user[1]. During the transportation phase, which includes both handling and carriage, the Department of Transportation (DoT) regulations must be strictly observed for movement within the U S. Since items must be stored for long periods, they must be protected against physical damage and deterioration; it also may be necessary to conduct periodic inspections of stored materiel.

From the military standpoint, good packaging methods protect the item through all phases and environments, with minimum cost. Items must be protected for one of three required levels: overseas shipment (Level A), long-term storage (Level B), or interplant shipment (Level C).

The most damaging environments during transportation by truck, rail, ship, or aircraft are usually shock and vibration. However, temperature extremes and other potentially harmful environmental factors should be considered as relevant to damage assessment or prevention.

These subjects are treated in more detail in Chapter 15; see par. 15-1 for packing, par. 15-2 for storing, and par. 15-3 for shipping.

9-2 DEVICES CONTAINING EXPLOSIVES

When electronic timers contain explosive charges, they must be given the special handling required to assure safety during packing, storing, and shipping. The basic reference for safety is the *Safety Manual*[2]. The applicable hazard class must be established, the device must be packed and labeled correctly, stored in magazines in accordance with quantity-distance requirements, and shipped according to transportation regulations. These topics are discussed in detail in Chapter 20; see par. 20-4 for packing, par. 20-5 for storing, and par. 20-6 for shipping.

9-3 SPECIAL ENVIRONMENTAL EFFECTS

In the packaging, storing, and shipping of electronic timers, particularly those containing electroexplosive devices (EED's), several environmental effects must be considered. These include stray RF energy, lightning discharge, and static electricity. It should be pointed out that packaging to reduce or eliminate these effects is possible but costly. Further, since the hazard cannot be defined precisely during all storing and shipping phases, no standard military timer makes provision for these effects in its packaging assembly. The paragraphs that follow discuss methods by which these effects can be minimized.

9-3.1 RF HARDENING

RF energy is particularly hazardous to EED's and to solid-state devices that are found in most modern weapon systems. This energy is limited effectively by the use of a complete Faraday shield. In general, there is a relatively large loss associated with copper and iron containers. Reflection losses account for most of the elimination of energy at the

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lower frequencies. Copper appears to be superior to iron for high reflection losses but the reverse is true for absorption losses[3]. Hence, a copper-flashed iron would provide an ideal material for a shielded container. Containers for sensitive devices need good electromagnetic seals at the closure junction. Gasket materials are currently manufactured that provide good contact under pressure.

Current safety practices for EED's require (1) input leads be shortcircuited, and (2) twisting together of long lead wires. For a more detailed discussion of combatting stray RF energy see Ref. 3.

9-3.2 LIGHTNING DISCHARGE

With respect to packaging, the safest way to take care of lightning hazard is to place the device in a steel container. However, it is much less expensive not to load and unload during storms. Storage areas are protected by lightning rods and arresters, and vehicles used to ship the devices are protected by grounding straps[2].

9-3.3 STATIC ELECTRICITY

Packages that tend to generate static electricity are to be avoided. Generally of the plastic film type, they are sometimes difficult to recognize because the film is deposited on the inside of a metal foil bag. The safe approach is to wrap the devices in metal foil and enclose them in a moisture resistant container if desired or necessary.

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2. AMCR 385-100, *Safety Manual,* Army Materiel Command, April 1970.

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CHAPTER 10

ELECTRONIC ANALOG TIMERS

10-1 INTRODUCTION

An analog timer derives its time base from the time interval generated by the motion of a measurable parameter between two predetermined values. An hourglass is a classical example. Electronic analog timers characteristically depend on changes in voltage or current. Their major virtues are simplicity of design and fabrication coupled with moderate accuracy and stability in military environments.

Fundamentally, all types of electronic timers are analog timers. Digital electronic timers, which are covered in Chapter 11, count the number of cycles through which an analog timer progresses. The distinction that is made in this handbook is that we will treat as analog timers those timers which are concerned primarily with a single cycle or a small number of cycles of the overall analog timing process. The distinction does not completely resolve the classification problem because some of the analog timers can and have been used as time bases for digital timers. However, most digital timing systems currently use linear oscillators as time bases. These are covered in Chapter 11.

Military electronic analog timers are designed to meet a variety of accuracy specifications, environments, and power supply conditions. Severe environmental conditions arise in projectile fuzes where analog timers may be exposed to a wide temperature range, spins of 500 revolutions per second, and setback forces of 35,000 g for 10 msec. When these environmental conditions are coupled with design requirements of ±20% supply voltage variability, 5 to 10 $in.^3$ total volume available for the timer plus power supply, and a 0.1% error limit; the design problem is difficult. A large portion of the material that follows is directed toward timer applications in projectile fuzing.

10-2 TIMING CIRCUITS

Many military applications require a small electronic timer or time base in the 0.5-10% stability region. The paragraphs that follow discuss networks and circuits that fulfill these requirements.

In most military high-volume timer applications, the primary engineering problem is production of a timer that meets the environmental and space requirements at minimum cost. Since high-volume applications may have widely differing environmental and space requirements, no single timer design can be a minimum cost solution for all applications. Thus, engineering design time may be considered as a good investment for high-volume applications. This contrasts with low-volume or single-usage applications where direct procurement of an overdesigned and high-cost timer may be the most economical solution of a timing problem.

10-2.1 RC NETWORKS

RC networks are probably the most commonly used delay networks. The *RC* timer typically uses a transistor detecting element and a silicon controlled rectifier as an output driver. A basic *RC* network is shown in Fig. 10-1. When switch S is closed, an electrical charge builds up exponentially on the capacitor, thereby increasing the voltage across the capacitor as shown in Fig. 10-2.

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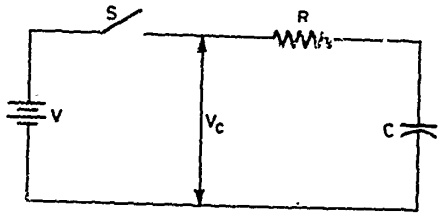


Figure 10-1. Basic RC Network

Specifically,

$$V_c = V\left[1-e^{-t/(RC)}\right] + V_{co}e^{-t/(RC)} \quad (10\text{-}1)$$

where

V_c = voltage across the capacitor, V

V = applied voltage, volt

V_{co} = voltage on the capacitor at $t = 0$, V

t = time, sec

R = resistance, ohm

C = capacitance, F

The basic timing interval, assuming the switch closes at t_o and the capacitor is charged to V_{co} at this time, is

$$t_1 - t_o = RC \ln\left(\frac{V - V_{co}}{V - V_1}\right), \text{ sec} \quad (10\text{-}2)$$

where V_1 = value of V_c at time t_1

The accuracy of the timing interval is related directly to the values of R and C but the dependence of the timing interval on changes in V, V_{co}, and V_1 is more complicated. Table 10-1 gives the percentage change in the interval for a ± 10% change in the ratio of V_1 to V for various values of the ratio. Voltage V_{co} is assumed to be zero. More detailed tables can be computed from

$$\Delta t = \left\{ \frac{\ln\left[\dfrac{1}{1-\dfrac{V_1}{V}\left(1+\dfrac{\delta}{100}\right)}\right]}{\ln\left[\dfrac{1}{1-\dfrac{V_1}{V}}\right]} - 1 \right\} 100, \% \quad (10\text{-}3)$$

where

Δt = change in the timing interval, %

δ = change in V_1/V, %

For example, $\delta = +10$, a 10% increase in the voltage ratio, corresponds to a Δt value of +15.2% for a ratio of 1/2 (Table 10-1). Eq. 10-3 assumes that V_{co} is zero. An extensive analysis of the accuracy of RC timers is given in Ref. 1 where capacitor leakage currents; detector circuitry leakage currents; and other secondary, accuracy determining parameters are considered.

Adjustment of the timing interval is, within limits, normally provided by varying V, R, or both. A linear relationship between V_1 and time may be approximated by using a large R,

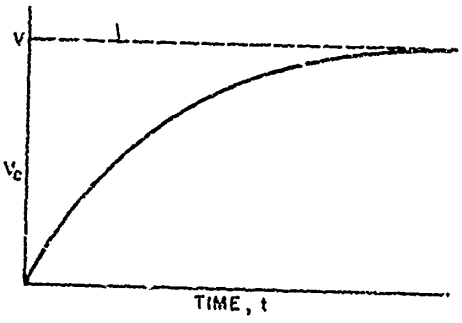


Figure 10-2. Voltage-time Curve for Basic RC Network

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TABLE 10-1

CHANGES IN TIMING INTERVAL FOR CHANGES IN VOLTAGE

Voltage Ratio V_1/V	Change in Timing Interval, % +10% change in the ratio	−10% change in the ratio
0.1	+ 10.6	−10.5
0.2	+ 11.3	−11.1
0.25	+ 11.8	−11.4
0.3	+ 12.2	−11.8
0.333	+ 12.7	−12.0
0.4	+ 13.5	−12.6
0.5	+ 15.2	−13.8
0.6	+ 17.7	−15.3
0.666	+ 20.3	−16.6
0.7	+ 22.1	−17.4
0.75	+ 25.7	−18.9
0.8	+ 31.7	−20.9
0.9	+100.0	−27.9

i.e., a very long time constant circuit compared with the required range of delays. The limit to the length of time delay is established by leakage of the capacitor, which in most cases makes the *RC* arrangement inadequate for delays above several minutes. Delays of several milliseconds are attained at the lower extreme. When resetting, S must be opened and the capacitor completely discharged.

Fig. 10-3[2] shows an *RC* network incorporated in a primitive timer. The basic timing interval is the same as that given in Eq. 10-3. The voltage *V* is applied to the emitter of a unijunction transistor (UJT). The UJT does not turn on until the voltage at the emitter exceeds the emitter peak point voltage V_1. When the UJT does turn on, the timing capacitor discharges rapidly through resistor R_1 and the emitter-to-base-one junction of the UJT. The silicon-controlled rectifier (SCR) is turned on by the conducting UJT. As the discharge current of capacitor C flowing through the UJT decreases, the UJT stops conducting. Capacitor C starts to charge again and the entire cycle is repeated, except that the silicon-controlled rectifier stays on unless deliberately unlatched, e.g., by removing the anode voltage. The load is not energized as long as the SCR is off.

A practical timer of the type described is shown in Fig. 10-4[3]. Time delays from 0.4 msec to about 4 min can be obtained with the component values shown in the figure. The timing interval is determined before a timing run by setting resistor R_t and capacitor C_t. The timing interval is initiated by the application of the 28-V DC power supply.

A simpler example of a practical timer is shown in Fig. 10-5[3]. This single, active element circuit does not use a SCR as a load driver; instead, the UJT drives a microminiature relay directly. Time delays from 0.5 sec to approximately 3 min can be obtained with the values of R_t and C_t shown. The timing interval starts with the application of the DC power supply.

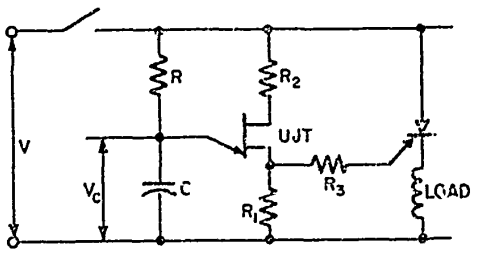


Figure 10-3. Primitive RC Timer

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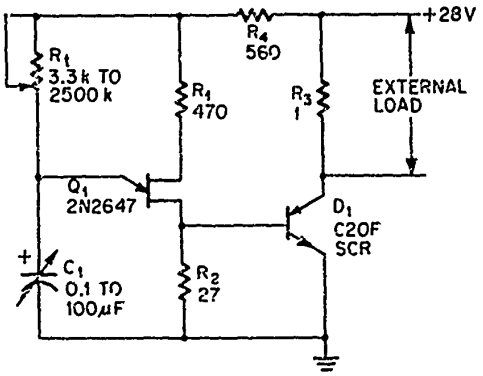


Figure 10-4. A Practical Low Accuracy Timer

The *RC* timers discussed have used the basic *RC* relaxation oscillator scheme of Fig. 10-6[4]. When switch S is closed, the voltage across capacitor C_t increases exponentially until the trigger point of the voltage detector is reached. At this point, the input impedance of the voltage detector suddenly decreases from megohms to several ohms. The capacitor discharges through this low impedance. At the end of the discharge, the detector again assumes a high input impedance and the cycle repeats. This simple scheme is adequate for time delays up to hundreds of seconds but the values of the components that determine the primary timing interval become quite large. For example, periods of about 100 sec require capacitors of approximately 1 to 10 μF and resistors of approximately 10 to 100 megohms. For good accuracy these values must be quite stable.

The requirements for highly stable, high value resistors and capacitors normally limit the choice of components to those of large physical dimensions which are often prohibited by other design requirements, particularly in military fuzing applications. One way to solve this problem is to have a relaxation oscillator of fairly small period continue cycling, and then count the number of cycles with a digital counter. When the number of cycles equals the number desired, the counter "times out" and provides an output pulse. Practical digital systems of this type using *RC* relaxation oscillators have been designed, although linear oscillators now are preferred as the time base of such systems. (Digital timers are described in Chapter 11.) Another way to avoid using large components for long period *RC* relaxation oscillators is to open and close switch S in Fig. 10-6 at a fixed rate. The voltage seen by the detector V_{ct} is shown in Fig. 10-7[4]. S is now an electronic switch that is assumed to change voltage levels by short duration ramps. Then

$$\frac{a_1}{b_1} = \frac{a_2}{b_2} = \frac{a_n}{b_n} = M, \text{ dimensionless} \quad (10\text{-}4)$$

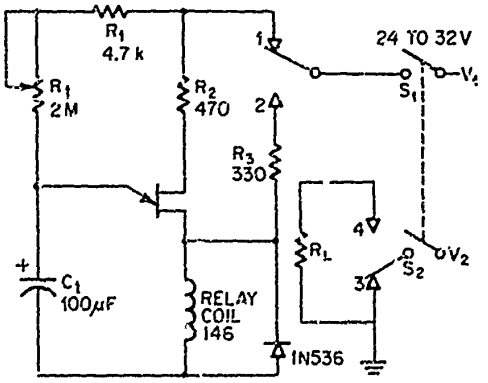


Figure 10-5. A Practical Timer Using a Single Semiconductor

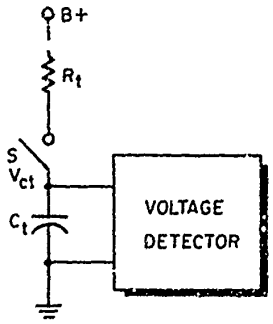


Figure 10-6. Relaxation Oscillator

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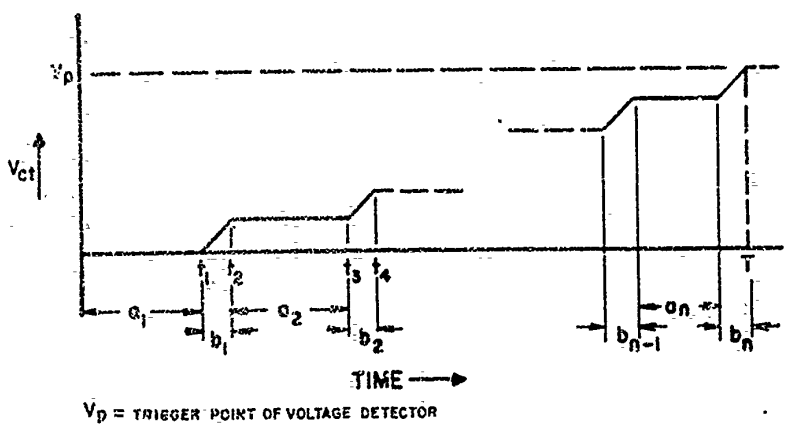


Figure 10-7. Voltage at the Dectector

where

a = time between closures of S as defined in Fig. 10-7, sec

b = time S is closed as defined in Fig. 10-7, sec

n = number of "on-off" cycles during time T

M = constant

t = time of $C_t R_t$ to change to V_p, sec

then

$$T = (M + 1)t = \text{total timing interval, sec} \qquad (10\text{-}5)$$

Thus the *RC* time constant of the original *RC* relaxation oscillator has been multiplied by $(M + 1)$. Fig. 10-8[4] is a block diagram of one system that has been used to achieve this multiplying effect. A complete description of this system is given in Ref. 4. Note that this system uses another *RC* relaxation timer in the triggering circuit to control the period of the flip flops that switch the electronic switch formed by diodes D_1 and D_2; therefore, the overall circuit can be recognized as one that allows one *RC* timer to control the total time interval in which the charging path of another *RC* timer is complete.

Long period *RC* timers that use unijunction transistors as detection elements, either with large value resistors and capacitors or using a time constant multiplying scheme, have a characteristic problem. The UJT usually requires that a current of about 1 μA flow into the unijunction emitter before the trigger voltage is reached. This characteristic becomes a serious problem when the charging current for the capacitor that determines the timing interval—at the end of the time interval—is of the same order of magnitude as the emitter current required before triggering. Under these conditions, the timer will function erratically, if at all. The common solution is to provide a sampling pulse that lowers the trigger voltage of the UJT. The sync circuit of Fig. 10-8 performs this function. Fig. 10-9[3] shows a general usage, long timing interval *RC* timer. The basic timing interval is determined by R_1 and C_1. If high quality, low leakage capacitors and a low leakage diode are used, intervals up to 2 hr can be obtained from this timer. Transistor Q_2 and R_2, C_2, and R_5 form a free running *RC* oscillator whose period is less than 2% of the basic timing interval of the timer. This free running oscillator supplies negative pulses to the upper base of voltage detector Q_1 to lower the triggering voltage and bypass the triggering current/UJT problem. The timing interval is started by application of the 28-V DC power supply.

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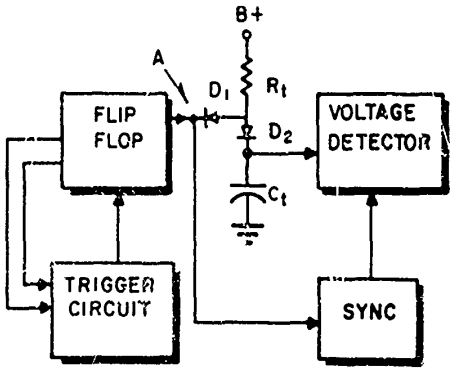


Figure 10-8. Block Diagram of Multiplier System

10-2.2 RL NETWORKS

Fig. 10-10 shows the basic RL network. When the switch is closed (assumed at $t = 0$), the current increases as shown in Fig. 10-11. Specifically

$$I = \frac{V}{R}\left(1 - e^{-tr/L}\right), \text{A} \qquad (10\text{-}6)$$

where

I = current, A

L = inductance, H

The detector, which is frequently the coil of an ordinary relay inserted in series with the RL components, responds to current. Therefore, when the current builds up to a predetermined value, the relay actuates. By varying R or V the delay time can be adjusted. However, R directly affects the steady-state dissipation in the circuit. Several variables make this delay mechanism (which can be low-cost) incapable of very high accuracy. The copper coils of the inductor are sensitive to ambient temperature changes as well as the resistance R. Friction in relay pivots depends on wear as well as ambient temperature; differential expansion can change the friction by changing the fit on the pivots. Lastly, spring-supported relay elements suffer changes in spring constant over a temperature range.

Time delays may be increased by intentionally introducing eddy currents. A conducting slug or shading coil will link a significant portion of the magnetic flux. As the flux builds up, a current is generated in the shading coil that generates a bucking flux. The bucking flux slows down the buildup of the magnetic field and the coil current. Shading coils are temperature sensitive, which is a disadvantage. The build-up in inductance, coinciding with the closing of a relay, causes a momentary drop in current, thus producing arcing due to inductive energy buildup when switch S is opened. Time delays vary from milliseconds to several seconds. In suitable applications, this economical circuitry operates output contacts in a simple and direct

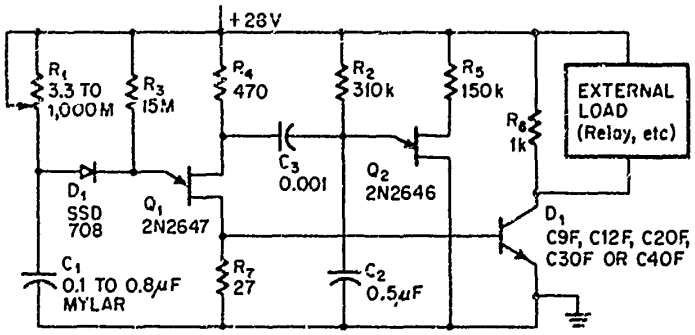


Figure 10-9. General Usage for Long Period RC Timer

SAMSUNG EXHIBIT 1028, Page 162

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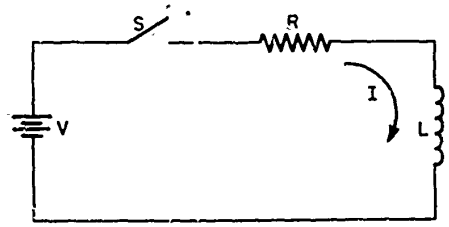


Figure 10-10. Basic RL Network

manner. Instantaneous resetting is possible by bringing the current to zero.

10-2.3 MILLER INTEGRATORS

The Miller integrator circuit, shown in Fig. 10-12[5], can attain longer time delays than a single RC circuit because it provides a timing voltage that varies essentially linearly with time. The standard timing formula for the circuit of Fig. 10-12 is

$$t_1 - t_o = CR_2\,(1+\beta)\ln\left\{1+\left[\frac{V_o}{V_1}\left(\frac{R_1}{R_2}\right)\left(\frac{1}{\beta}\right)\right]\right\}, \text{sec} \qquad (10\text{-}7)$$

where

C = timing capacitor value, F

R_1, R_2 = resistor values, ohm

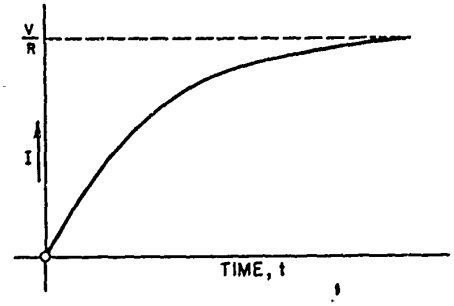


Figure 10-11. Current-time Curve for Basic RL Network

V_s = DC supply voltage, V

V_1 = applied input voltage, V

V_o = resulting final amplitude of the output ramp,

β = large signal current gain of transistor Q, dimensionless

The equation simplifies to

$$t_1 - t_o \approx CR_1\left(\frac{V_o}{V_1}\right), \text{sec} \qquad (10\text{-}8)$$

if $\beta \gg 1$ so that $1 + \beta \approx \beta$ and if the natural logarithm argument is much smaller than one so that

$$\ln(1+a) \approx a \qquad (10\text{-}9)$$

The standard timing equations, Eqs. 10-7 and 10-8, ignore transistor leakage current, transistor input impedance, and capacitor leakage current. Detailed analysis of these variables place limitations on the usefulness of the timing equations. Stable timing to within a few percent error as predicted by the standard timing equations is possible under the following conditions:

(1) Silicon transistors are used exclusively.

(2) Circuit resistances are kept approximately equal, and large (in excess of 50 k ohms).

(3) Transistor current gain is as high as possible, and in any case not less than 20.

(4) Time magnification K (achieved by making $V_o = KV_i$) is no more than 3.

(5) Timing capacitor leakage resistance (in ohm) is greater than 10 times the quantity given by $\frac{R_1R_2(1+\beta)V_o}{R_1V_o + \beta R_2 V_i}$ (refer to Fig. 10-12 for identification of voltages and resistances).

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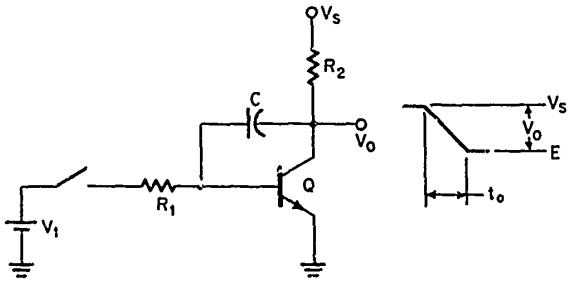


Figure 10-12. Miller Integrator

Temperature compensation for timing stability is difficult. The most important parameters are:

(1) Transistor leakage current is, within limits, associated with a negative temperature coefficient, i.e., time delay decreases with increasing temperature.

(2) Capacitor leakage current is associated with a positive temperature coefficient.

(3) Capacitor variation can produce either a positive or negative temperature coefficient depending on capacitor type. These parameters can be used together to obtain some measure of compensation. A ± 2% stability has been obtained in this manner for a temperature range of 0° to 40°C.

10-2.4 CURPISTOR TIMERS

Long term single cycle *RC* analog timers can be constructed from constant current sources that have small output currents. The curpistor is a constant-current ion chamber that will pass constant currents from 1 X 10^{-12} to 5 X 10^{-9} A, depending upon the degree of ionization in the chamber. The constant current is obtained by collection of all the ions produced by the radium foil cathode when a potential from 50 to 300 V is applied. This current is determined mainly by the activity of the cylindrical radium foil (cathode), its distance from the center rod (anode), and the nature of the gas inclosed in the tube.

Fig. 10-13[6] shows an experimental configuration using a curpistor and XD-1C cold cathode diode. The capacitor C is charged by the curpistor current at a rate *dq/dt* and the resulting "perfect" time integral of the charging current, assuming ideal components, is defined by

$$E = \frac{1}{C}\int I\,dt \qquad (10\text{-}10)$$

in differential form $I = C\left(\frac{dE}{dt}\right)$

for a linear voltage increase $I = C\left(\frac{\Delta E}{\Delta t}\right)$

where

E = voltage, V

I = constant curpistor current, A

C = capacitance, F

t = pulse time, sec

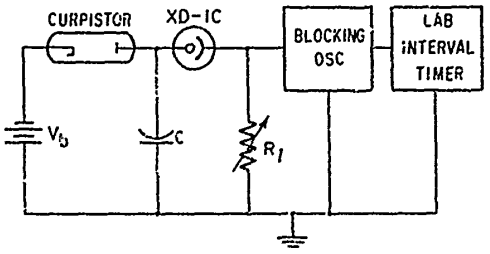


Figure 10-13. Curpistor-diode Oscillator

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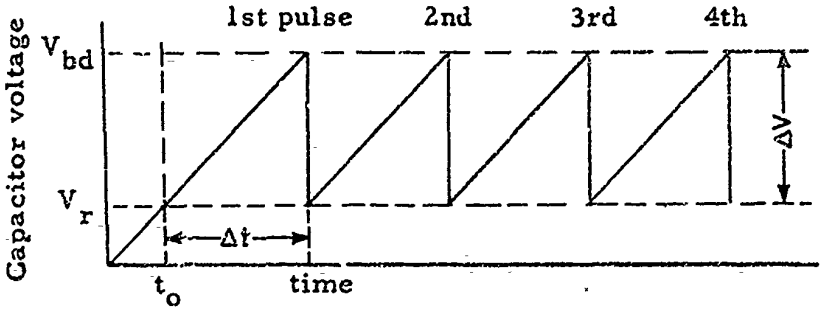


Figure 10-14. Sawtooth Charge-discharge Curve

The capacitor voltage V_C rises linearly until it reaches diode breakdown voltage V_{bd} at which time there is an arc discharge and about 25 percent of the energy $CV^2/2$ stored in C is transferred to the load resistance R_L. If C initially has zero charge, then $\Delta E = V_{bd}$. However, after the initial pulse, there is a residual voltage V_r on the capacitor C which is used as a reference in all of the succeeding pulses. In this case, $\Delta E = V_{bd} - V_r$, as is illustrated in Fig. 10-14[6]. Hence V_r is dependent largely upon the impedance of the diode during the time of discharge plus the load resistance. It is not significant for single cycle operation.

The primary advantage of the curpistor timer over conventional *RC* timers is the length of delay that can be achieved easily. A serious disadvantage is the relatively high voltage necessary for curpistor operation. For example, the experimental configuration of Fig. 10-13 requires a source of at least 165 V. This is balanced partially by the fact that the regulation of the source is not a problem. Any source of 165 to 300 V that can supply 10^{-8} A is adequate. The use of nuclear batteries for curpistor voltage sources is possible, and this in itself is an advantage.

Other disadvantages of the curpistor timer are those associated with any long period *RC* timer. The leakage current through the capacitor, capacitor mounting, and detector must be very small in relation to the constant charging current. Ref. 6 describes the evaluation of experimental curpistor timers.

10-3 LEVEL DETECTORS

Electronic analog timers require a device to detect the arrival of the analog parameter (voltage or current) at the predetermined level that indicates the end of the timing interval of the timer. In the examples of *RC* timers shown in Figs. 10-3, 10-4 and 10-5, the level detecting function is performed by a unijunction transistor. In the *RL* timer described in par. 10.2-2, the detection function is accomplished by means of the magnetic flux sensitivity of the relay. The Milier integrator of Fig. 10-12 uses an N-P-N transistor as a voltage detector.

The ideal characteristics of a level detector are that: (1) it impose no load on the circuit it monitors, at least until the analog parameter being monitored has reached the predetermined level, and (2) it provide a high level output instantaneously at that time. In addition, it also should be repeatable in a given circuit, inexpensive, identical from item to item, and unaffected by environmental changes.

Various voltage level detectors for *RC* timing circuits have been used including cold gas diodes, conventional heated cathode diodes and triode vacuum tubes, conventional silicon and germanium transistors, silicon-controlled rectifiers, UJT's, and field effect transistors.

SAMSUNG EXHIBIT 1028, Page 165

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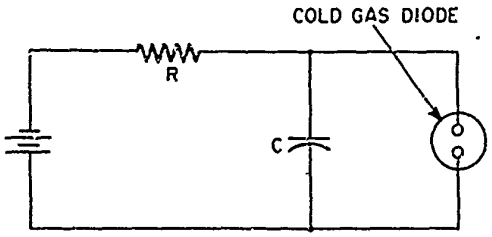


Figure 10-15. Relaxation Oscillator Using a Cold Gas Diode

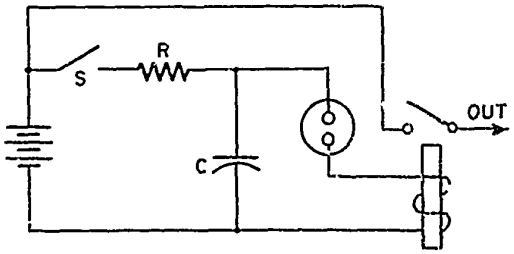


Figure 10-16. Cold Gas Diode Detection Timer

10-3.1 COLD GAS DIODES

Perhaps the earliest and most used voltage level detector for electronic analog timers is the cold gas diode. The diode itself is usually a hermetically sealed envelope containing two electrodes and an inert gas such as neon or argon. Glass is the usual envelope material. Fig. 10-15 shows a primitive relaxation oscillator using a cold gas diode. Capacitor C charges through the resistance R until the diode breaks down and discharges the capacitor to some low voltage at which the diode turns off and the cycle repeats. This is essentially the circuit of many "winking" light strings for Christmas trees. Fig. 10-16 shows the same circuit adapted as a timer. The capacitor charges, after switch S is closed, until the diode breaks down and activates the relay. The relay, of course, can be replaced with a low-value resistor, and the voltage drop across the resistor can perform other output functions. Ref. 7 describes the overall behavior of cold gas diode relaxation oscillators. Cold gas diode voltage detectors have very low loading characteristics for *RC* timer applications and, since breakdown time is very short, the output of the detector can be considered for most applications to be instantaneous. The disadvantages of cold gas diode detectors are:

(1) Variation from item to item in breakdown voltage is high.

(2) Glass envelopes usually used in cold gas diode construction allow ambient light to impinge on the gas. The varying intensity of ambient light thus causes changes in the breakdown voltage.

(3) The breakdown voltages usually obtainable are too high to be compatible with solid-state circuitry.

10-3.2 HEATED CATHODE DIODES AND TRIODES

Standard vacuum tube detectors normally are not used. Their primary disadvantage is the need of a filament power supply and the relatively high voltages necessary for vacuum tube operation. Loading of the *RC* timing circuit is usually very small. If large voltages were used in the *RC* charging circuit, relatively quick repeatable output response could be obtained.

10-3.3 BIPOLAR TRANSISTORS

Bipolar transistors were used widely as voltage detectors for *RC* circuits in spite of the considerable loading effect on the *RC* changing circuit. Variation from transistor to transistor, however, sharply influenced timer period. The appearance of unijunction transistors (UJT) and field effect transistors (FET), with their very high input impedance characteristics, makes the use of bipolar transistors in high accuracy voltage detectors a rarity except in special purpose designs.

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10-3.4 UNIJUNCTION TRANSISTOR DETECTORS

The UJT is a three-terminal, solid-state device having a single P-N junction. This fact leads to characteristics that are quite different from those of conventional transistors. The primary characteristic of the UJT for application as a voltage detector for *RC* timer circuits is its relatively high input impedance. Ref. 8 summarizes the theory and characteristics of the UJT while Ref. 9 describes in detail its use in typical relaxation oscillators and timing circuits.

The primary disadvantage of the UJT as a detector occurs with long period timers. The UJT requires a small current before trigger voltage can be reached. This current, for long period *RC* networks, can be a significant part of the capacitor charging current. Hence, the UJT loads the *RC* circuit just before time out of the timer. A sampling pulse applied to the UJT to momentarily lower the triggering voltage is the common solution to the loading problem. See par. 10-2.1 for additional detail.

UJT's are available from many manufacturers at reasonable prices. It is recommended that a designer specifically consult the manufacturers' literature on any device to be used because specifications vary widely.

10-3.5 FIELD EFFECT TRANSISTORS

Field effect transistors are available in two types: (1) the junction field effect transistor (JFET), and (2) the metal-oxide semiconductor field effect transistor (MOSFET). For long period *RC* timer voltage-level detector functions, the difference of concern is that the leakage current of the MOSFET is considerably lower than that of the JFET so that the MOSFET can be used as a normally "off" device.

Since the leakage current of the MOSFET can be typically as low as 0.5 pA, the device is suitable for long period *RC* timer application. Further, the MOSFET does not have the UJT characteristic current requirement previous to triggering. The primary disadvantage for voltage level detection of the MOSFET is temperature compensation and price (compared with UJT's).

10-4 SETTING METHODS

For analog timers, the basic timing interval of the analog process is the parameter that is to be "set". This contrasts with digital timer setting in that digital counters are usually "set" by changing the number of basic analog intervals which must occur before output.

Electronic analog timers usually initiate the timing process upon application of voltage to the timer or on the closing of a contact pair. The contact pair closing itself often applies a specific voltage to a portion of the timer which influences the basic timing interval. Thus timers often can be considered to be voltage controlled, and the basic timing interval also can be considered to be voltage controlled. However, setting of the timing interval by controlling a voltage applied to the timer from a device external to the timer is difficult, inconvenient, and perhaps, in some applications, hazardous. In practical applications analog timers usually are set by varying a resistive element. The voltage applied to the timer to initiate the timing sequence is obtained ideally from a well regulated supply.

10-4.1 SETTING MECHANISM

The internal setting mechanism of a time setting system is that portion which responds to the operator's input motion and translates it into a single, discrete, electrical configuration of the internal resistor package The resistor package design, however, has a marked influence upon the internal setting mechanism. Analog resistors (potentiometers) may, for certain reasons, be limited to subranges below the total required resistance range. Here, a switching arrangement would be required in order to tie subrange resistance

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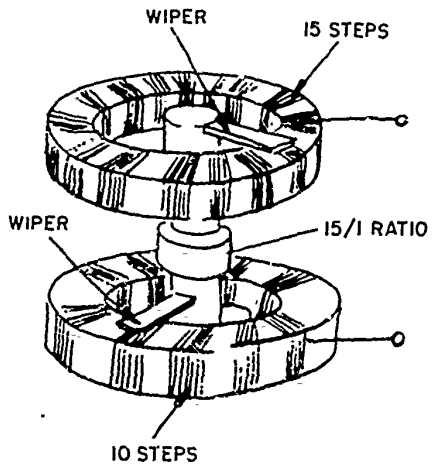


Figure 10-17. Switching for Two-section Resistor Package

together as required. Fig. 10-17[10] depicts a resistor package for use over a 150-bit range. It has two analog resistor subranges, one of 1–9 ohms in 1-ohm steps and a second resistor range of 10–150 ohms in 10-ohm steps.

If a binary count form of analog resistor package is desired (i.e., 1-, 2-, 4-, 8-, 16-, 32-, 64- and 128-ohm step values), the logic switching pattern would have to be provided either at the wiper or at the contact point resistor interface. A schematic representation of such a system is presented in Fig. 10-18[10]. Other setting schemes are described in Ref. 10.

10-4.2 RESISTOR PACKAGE

The selection of a resistor package is, like the external and internal mechanism, dependent upon a series of input and output requirements or characteristics. The inputs are comprised of environmental loads or conditions coupled with the form of the internal switching and the space available. The output requirements dictate resistor accuracy, linearity, base and range of values, capacity (wattage), voltage rating, operational drift, and inductive/capacitance impedance.

The primary division of resistors into types is based on the resistance element. If the element is a metallic wire, wound on a form, the resistor is a "wire-wound" type; if the resistive element is a conducting film deposited on a nonconducting base, the resistor is a "film" type. High cost and a low upper limit of resistance have restricted wire wound resistor usage. The film resistor is a newcomer, and uses less expensive materials and processes. It is capable of extreme upper values of resistance. A reference chart that shows the general ranges of parameters for each major type of conventional resistor is shown in Table 7-3.

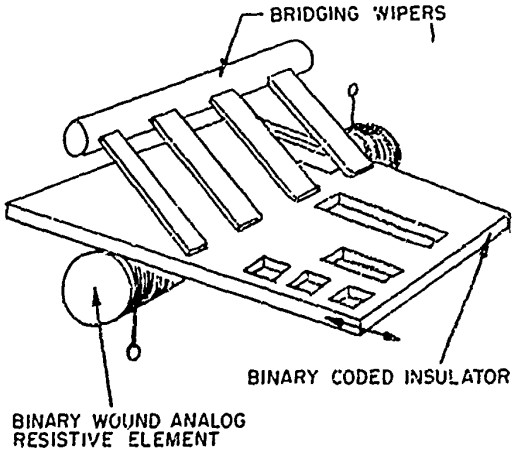


Figure 10-18. Binary Switching System for an Analog Resistor

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There are distinct advantages to the selection of thin film networks as the resistor package for analog electronic timers. With respect to separate components, these prepackaged networks are superior for the following reasons:

(1) Size. The package density is greater than available with individual components.

(2) Performance. The capacitive coupling is constant from network to network.

(3) Reliability. The number of external connections is reduced, and internal connections are stronger. The single package concept reduces the probability of mislocated components. The rugged construction is well suited to gun launch environment.

(4) Cost. Assembly and inspection time are reduced, and inventory control is simpler.

With respect to potentiometer type resistive elements, the prepackaged network offers the advantages of lower cost and smaller size. Wire wound potentiometers have an upper resistance limit below the capability of the network approach. Further, discrete valued resistances allow additional leeway on position control of the input while maintaining any specific set resistance value.

10-5 POWER SUPPLIES

Unless internal voltage regulation is incorporated in an analog timer, timing error usually is affected by power supply variation. Since digital timers rely on a form of analog timer for their counting time interval, they too usually are subject to error as a result of poor voltage regulation. For general usage of most timers, a regulated supply is recommended. Power supply design problems for analog timers under general usage conditions differ little from those of other electronic equipment. Off-the-shelf power supplies usually can be incorporated to solve regulation, environmental, space, and weight constraints. The special problems of projectile fuzing design, however, present difficulties of power supply design which are seemingly unique to this application. Since these problems are common to both analog and digital projectile fuzing timers and, in addition, are usually more complex for digital timing systems, power supply selection for these applications is covered in par. 11-6.

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CHAPTER 11

ELECTRONIC DIGITAL TIMERS

11-1 INTRODUCTION

Electronic digital timers establish time delays by counting how often an analog timer has cycled. Their chief advantage for general application is that their accuracy for extremely long time delays can approach that of the analog timer that drives them. Their general application to military systems has paralleled their commercial use, and virtually every large-scale weapon system uses them in some form of programming application. The application of electronic digital timers to projectile fuzing presents a special set of stringent environmental, weight, and volume restrictions on such timers. The latter applications are the principal concern in this chapter.

Although any analog timer can be used as a time base for digital timers, harmonic oscillators are particularly well suited for this use. Hence, they are thus covered in this chapter rather than in Chapter 10.

Electronic digital timer systems for projectile fuzing applications can be divided into several subsystems:

(1) Power supply

(2) Time base

(3) Counter

(4) Output circuit

(5) Internal setting and checkout equipment.

In operation, a particular timing interval is selected by the user and set into the output circuit by means of the interval setting and checkout equipment. The power supply usually is activated also at this time. At the first motion of the projectile, the time base is activated or enabled and begins stepping the counter. As the counter steps, it advances the count previously set into the counter toward the counter's maximum possible count. When this count is reached, the output circuit produces the proper output for fuze activation.

The overall accuracy of any digital timing system is limited by the accuracy of the time base, and system accuracy is close to that of the base. Hence the selection of the time base is of considerable importance. Therefore, the subject of time bases for projectile fuzing is covered in detail in par. 11-2. This subject has received considerable study at the U S Army Harry Diamond Laboratories from which the information is excerpted at length. Each of the oscillator types used has certain advantages and capabilities and may be used over a wide range of operating parameters. Highly stable *LC*, *RC*, and saturable core oscillators can be fabricated to perform satisfactorily over the military temperature range with variations of ± 20% in supply voltage.

In general, the setting and checkout equipment is reusable while the power supply, time base, counter, and output circuit are expended. Therefore, efforts are made to include as much as possible of the necessary sophistication in the setting and checkout equipment.

The particular advantages of electronic digital timers for projectile fuzing applications, in contrast with other types of timers, lie in the possibility of mass producing a very small number of projectile digital electronic timer types that will cover practically all

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projectiles and applications at costs far below those attainable with other timers. Integrated circuits with their high quality control, physical ruggedness, and small number of required connections make the electronic digital timer the best candidate for such a major cost reduction approach. Another, and from past experience more likely, consequence of the availability of electronic digital timers is the possibility of increased sophistication of fuze missions and functions. This is due to the relative ease with which more logic circuitry could be incorporated into the integrated circuits of the timer.

11-2 TIME BASES[1]

Oscillators may be grouped under two general types: (1) linear, or quasilinear type, having essentially a sine-wave output; and (2) relaxation, or pulse type, having a discontinuous recurring waveform. Most precision oscillators are of the first type, although some types of pulse oscillator have achieved comparable accuracy. For additional information about oscillators, see also Ref. 2.

To obtain high accuracy and to permit precise calibration, it is necessary to isolate the oscillating circuit from changes in power-supply voltage and impedance and also from impedance changes in the load or output circuit. Dependent on the type of circuit and environment, it may also be necessary to shield against electromagnetic and electrostatic interference or proximity effects. Where the highest accuracy is required, thermal control or isolation and calibration at the time of use may be necessary.

11-2.1 HARMONIC OSCILLATORS

11-2.1.1 Oscillator Characteristics

Harmonic, or sine-wave oscillators, are composed of an amplifier to provide power gain and a resonator, or filter network, to determine the frequency of oscillation. The amplifier must be provided with a positive feedback path so that enough of the output power can be returned to the input in proper phase to sustain oscillation. The resonator must be connected at some point in the feedback loop, or in the amplifier, to control the frequency of oscillation by its phase and attenuation properties. For a nearly linear system, the gain around the loop will be unity and the total phase shift will be zero, or a multiple of 360 deg. If gain of greater than unity exists, the output will increase until the loop gain is reduced to unity because of limiting in the amplifier or other controlling element which is often provided. It can be seen that the phase shift around the loop must add up to zero if a single coherent frequency is being generated. If a phase change takes place in any part of the amplifier or feedback loop, the frequency of the oscillator will shift so that the resonator will generate an equal but opposite phase shift.

Hence, the phase properties of the resonator with respect to frequency determine the frequency of oscillation. The amplitude response characteristics are also important in suppressing spurious modes of oscillation and in reducing the amount of noise amplification at other frequencies. It is desirable to have a maximum $d\theta/df$ for the resonator which maintains the frequency stability, but a minimum $d\theta/df$ for the amplifier and coupling networks which are inherently unstable.

Transistor amplifiers are characterized by rather large changes in input and output resistance and capacitance with changes in temperature and operating power levels. To minimize the effects of these impedance changes with respect to amplifier phase shift, the input and output coupling impedances should be kept as low as possible consistent with required gain. Changes in transit time within the transistors will cause a variation in phase shift. This effect can be reduced by using high-frequency transistors, which will also have less input and output capacitance

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and, therefore, less change in capacitance.

The reactive elements of the resonator should be loaded by the amplifier as lightly as possible to achieve a maximum phase change versus frequency. The optimum coupling impedances should be achieved by tapped reactive elements or by an impedance transformer to avoid unnecessary dissipative loading of the resonator. The oscillator should be isolated by a buffer or output stage and not designed to supply appreciable load power, as this will result in additional resonator loading and degradation of frequency stability.

The amplitude of oscillation in simple transistor oscillators is limited by hard clipping or rectification at the collector as its voltage swings beyond zero and forward biases the collector junction, or by a shift in the conduction angle toward a condition of increased cutoff as the result of base-emitter rectification. The latter condition generally is avoided in linear amplifiers by eliminating the base circuit capacitor. A resistor of several thousand ohms in series with the base usually improves the wave form and, in some cases, the frequency stability of low-frequency oscillators, where more precise amplitude limiting is not used.

An excessive amount of positive feedback usually produces considerable distortion, while only slightly more than unity feedback, required for oscillation, may result in sudden stoppage under adverse temperature, voltage, or loading conditions.

The distortion resulting from even an adequate drive signal can cause a tendency toward less stable frequency output. This results from a change in phase shift at the fundamental frequency as more or less of the fundamental component is made available from the intermodulation with the harmonic frequencies present. It is thus desirable, when highest stability is required, to provide an external limiting circuit to regulate the loop gain to unity automatically and maintain the amplifier in the linear operative region. In laboratory equipment, this usually is accomplished by a thermistor or lamp, which is heated by the output power, and is coupled into a bridge or attenuator circuit to control the loop gain.

To avoid distortion, these limiting devices must have a time constant long in comparison with the period ($1/f$) of the oscillator. Lamps and thermistors are not suitable for use as amplitude-sensing regulators where high shock, wide temperature range, and rapid stabilization must be considered; the filaments or thermistor beads must be isolated thermally to function properly, which makes them vulnerable to shock. Also, these devices stabilize too slowly for short-interval timers requiring rapid start-up and functioning. A thermistor, however, is useful to help stabilize gain as the temperature varies, thus reducing the dynamic range required in the automatic level control.

Transistors and diodes, having nonlinear properties when operated with large control voltages, but performing as variable linear resistors with small signal voltage may be used as amplitude limiters with a small increase in distortion. In such use, the oscillator amplitude is sampled by a rectifier-filter arrangement having a rapid charging time constant to achieve rapid stabilization and a much longer discharging time constant to achieve maximum signal filtering. The output of the filter is applied to the nonlinear control device, which adjusts to keep the amplifier operating at a constant level in the linear region.

Field-effect transistors also may be used as low-distortion voltage-controlled resistors by applying the signal between source and drain, and the control voltage between source and gate.

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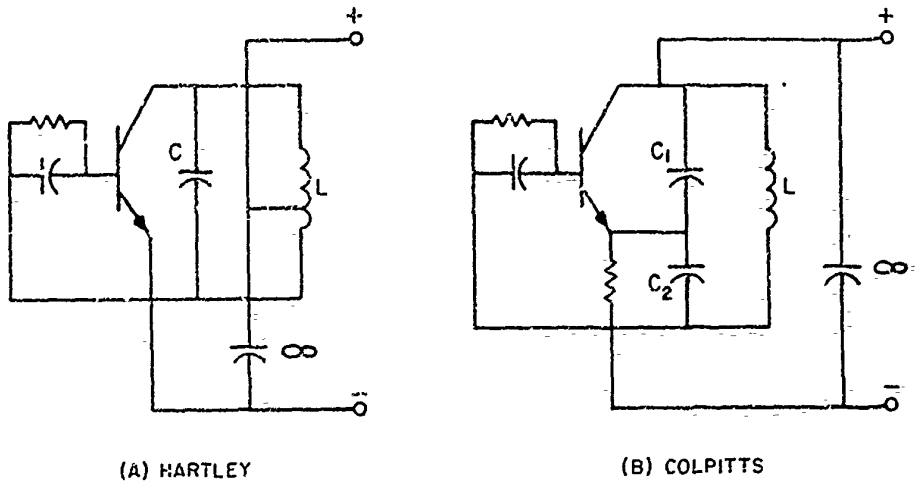


Figure 11-1. Parallel Resonant Oscillators

11-2.1.2 Inductance-capacitance Oscillators

This type of oscillator is perhaps the oldest and most widely used. In most cases the inductor and capacitor are connected in parallel to give a maximum impedance and zero phase angle at the resonant frequency. In considering a simple transistor oscillator (Fig. 11-1[1]), the emitter usually is connected to a tap on the coil (Fig. 11-1(A)) or a tap between two capacitors used in series across the coil (Fig. 11-1(B)). The base and collector are connected at opposite ends of the LC parallel combination through appropriate coupling elements to permit application of DC biases to the transistor. A great variety of connection configurations are possible, which may be treated analytically as one of these two basic circuits.

The two most important considerations are preservation of as high a resonator Q as possible and adjustment of the amount of positive feedback for optimum performance. To minimize resonator loading by the amplifier, the collector as well as the emitter may be connected to a tap on the inductor. This permits a larger inductor and a smaller capacitor for a given frequency and usually results in a higher operating Q value. An equivalent approach, known as the Clapp circuit, makes use of three capacitors in series across a two-terminal inductor with the transistor connected across the capacitive divider. At the lower frequencies, the larger of these capacitors, for a proper impedance match, becomes somewhat bulky if of high quality.

The inductor, for use in the audio-frequency range, must contain a permeable core to be of reasonable size and Q value. Molybdenum permalloy powdered cores are most suitable although powdered iron and ferrite cores also are used. These cores have an appreciable temperature coefficient of permeability, and must be specially designed and stabilized for use over a wide temperature range. Specially treated molyperm cores having a permeability of about 200 have been fabricated, which have a temperature coefficient about equal and of opposite sign to the temperature coefficient of polystyrene capacitors. By a matching technique, it is possible to achieve a near zero temperature coefficient for the resonator over a wide temperature range. A lower permeability core and polycarbonate

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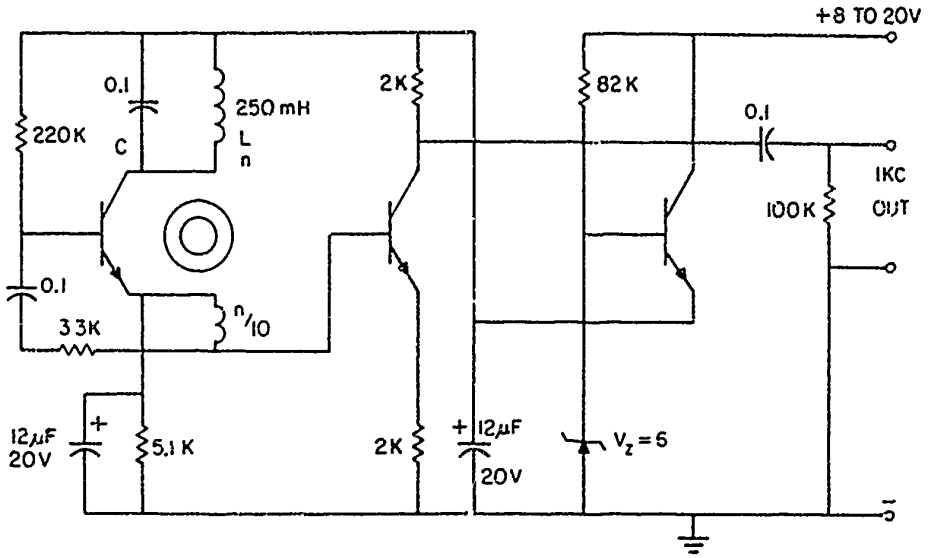


Figure 11-2. Tuned-output Oscillator

capacitor combination has also been used with good results, although generally the polycarbonate-dielectric capacitor has a more S-shaped temperature coefficient, making a wide range match more difficult.

The value of inductance is also a function of the magnitude of the direct and alternating currents present. It is, therefore, important to keep these currents very constant or at very low amplitude to maintain a stable frequency. For circuits working over an appreciable range of supply voltage, it is best to keep the direct current out of the inductor by use of a shunt-feeding resistor and capacitor. The shunt-feeding resistor, however, should not load the inductor heavily, and the coupling capacitor should be large enough to have very low phase shift if maximum frequency stability is to be preserved. Series feeding of the direct current through the inductor and operation on a low, zener-stabilized voltage seem preferable to the difficulties of maintaining a high Q with shunt feed of the supply current. Such a circuit diagram is shown in Fig. 11-2[1], including voltage-regulating and output amplifiers. The regulator stage shown is useful in that it maintains a fairly constant current drain over a large voltage range. Shunt regulators using only zener diodes draw excessively high current at the higher voltages unless the regulated voltage is low in comparison with the supply voltage. A push-pull circuit with a center-tapped primary may be used to eliminate the DC component in the inductor and reduce distortion if the stability of the resonator elements is good enough to warrant the additional complexity.

An alternate circuit arrangement makes use of a series LC resonator, which has a minimum impedance and zero phase shift at the resonant frequency. When used as a series element in the positive feedback loop, it may be used to control the frequency of an oscillator. To preserve resonator Q, in this case, it is necessary to couple into and out of the circuit with amplifier impedances, which are low compared with the series resistance of the resonator. The series resonator capacitor conveniently isolates the DC bias voltages of the amplifier. This circuit is readily adaptable to bridge feedback arrangements permitting negative feedback for DC, which aids bias

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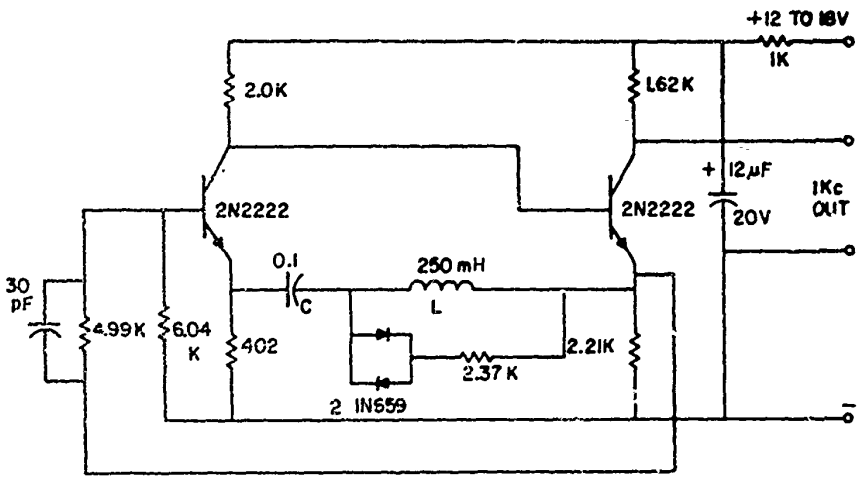


Figure 11-3. Series-resonant Oscillator With Diode Limiting

stabilization and also provides a magnification of the phase characteristic of the resonator proportional to amplifier gain. Maximum bridge phase change occurs with a unity ratio in the bridge arm pairs, although the curve is rather broad and deviations in ratio for biasing convenience up to three to one cause only a slight loss in overall stability.

Fig. 11-3[1] shows a circuit diagram of a series *LC* bridge oscillator with limiting diodes connected across the inductor. The silicon diodes and resistor shown limit the peak-to-peak voltage across the inductor to about 1 V for supply voltages between 10 and 20 V. With some matching in the temperature coefficients of the polystyrene capacitor and the molyperm inductor, a stability of better than ± 0.1 percent has been obtained from −55° to +71°C with these voltage variations. As shown, the resonator *Q* is degraded from about 50 to 8 by the limiting diodes, but the measured phase magnification in the bridge of 3.3 brings the equivalent *Q* back to about 25.

A somewhat similar arrangement using an automatic level control (ALC) is shown in Fig. 11-4[1]. The series impedance of the resonant circuit will change about 40% over the temperature range because of the temperature coefficient of the inductor wire. If the emitter resistor in the bridge is made of copper wire (noninductively wound), the bridge will stay nearly balanced over the temperature range, thus reducing the dynamic range required of the ALC transistor. A field effect transistor is used as a voltage-variable resistor to achieve the bridge balance. This transistor is controlled by a peak-detection diode connected to the amplifier output. The frequency constancy of this oscillator is determined almost entirely by the stability of the *LC* resonator components.

11-2.1.3 Resistance-capacitance Oscillators

The most popular *RC* oscillator type, which has been used in a variety of audio-frequency signal generators, is known as the Wien-bridge circuit. The two *RC* sections forming the positive feedback arms of the bridge (Fig. 11-5(A)[1]) perform equivalent to a high-pass and a low-pass section in cascade and give maximum output with zero phase shift at a common cutoff frequency. At this frequency, the output at the center lead of the *RC* bridge arms is about one-third of the

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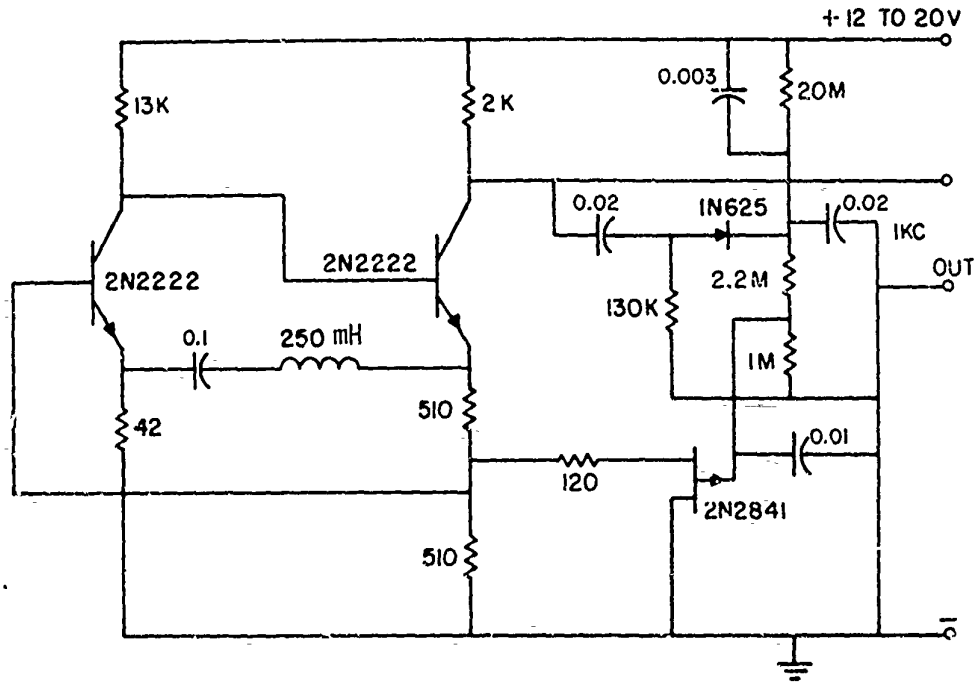


Figure 11-4. Series-resonant Oscillator With Automatic Level Control

input, and the amplitude and phase response are roughly equivalent to those of an *LC* resonator with a *Q* of one-third. When used with a high-gain amplifier coupled to the bridge to form an oscillator, the phase-versus-frequency response can be enhanced by a large amount. The Wien bridge requires, however, extremely high or extremely constant input resistance and extremely low or extremely constant output resistance for the amplifier. Both of these conditions are difficult to realize with transistor amplifiers. By optimum choice of *RC* impedance and special amplifier design, a highly stable oscillator can be achieved.

Another *RC* oscillator circuit in wide use employs a parallel-T null network as the frequency-determining element. This network, shown in Fig. 11-5(B), has a high value of $d\theta/df$ near balance and is in this manner similar to the Wien bridge. Much confusion exists in the literature because of its many possible methods of use in oscillator circuits. The parallel-T, or twin-T as it is often called, may be symmetrical as shown, or may have the input and output sides dissimilar. The shunt arms may bear the impedance ratios of 1/2 with respect to the series arms, or may be varied by allowing the factor n of Fig. 11-5(B) to vary and readjusting the series arms to obtain f_o. Maximum phase sensitivity results with n equal to 1/2. In this case, as with the Wien bridge, the null frequency is given by $W = 1/(RC)$ (where R and C are the values for the series elements). At null, with all elements in the proper ratio, the phase shift through the network approaches 180 deg. If the shunt resistance is now reduced by a small amount, the phase shift at minimum transmission will be 180 deg and will be of positive and high slope versus frequency in a symmetrical manner for about ± 80 deg. However, if the shunt resistance is made larger than the balance value, a somewhat similar but negative slope in the transfer characteristic will occur centered around 0 deg.

An oscillator may thus be made by using a single-stage amplifier with high gain and 180

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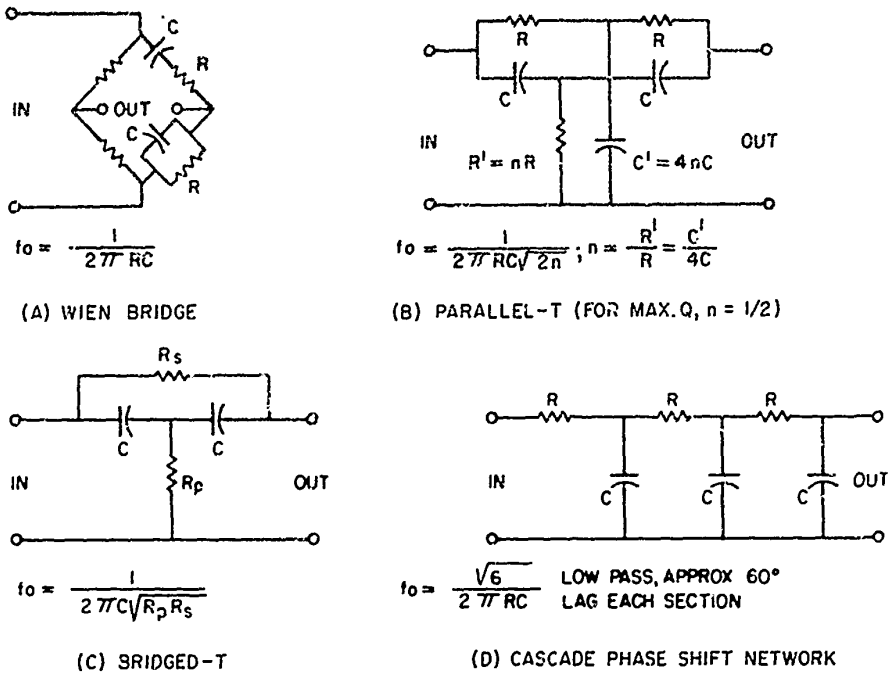


Figure 11-5. RC Frequency-selective Networks Used in Oscillators

deg of phase shift along with a network phase shift of 180 deg, or by using a zero phase shift amplifier along with a zero phase shift network in a single feedback loop. Two-loop feedback oscillators have been built with a precisely nulled network in the negative feedback loop and an amplitude control device in the positive feedback loop which maintains the total loop gain at unity.

Still another twin-T arrangement makes use of the network in which the common and output terminals are reversed. The new output terminal is worked into a common-base transistor stage (ideally a short circuit), and oscillation occurs by having zero phase shift in both the network and amplifier. An interesting property of this network is that it has an input-to-output voltage gain of slightly greater than unity, with a maximum occurring when n (defined in Fig. 11-5(B)), is about 5. In this case any transistor having a β greater than 11 will sustain oscillation. The network R should be much larger than the emitter input impedance, and the network C should be much larger than the transistor capacitance.

Other oscillator circuits using the bridged-T, or the phase shift network shown in Fig. 11-5(C), or variations of these networks, are possible. For the bridged-T, a high ratio (5 to 25) of R-series to R-parallel is desirable to give a high phase shift factor in the network, which makes the oscillator insensitive to transistor changes with temperature and voltage.

The L-section phase shift networks of Fig. 11-5(D) frequently are tapered (increased in impedance toward the output end) to reduce loading between sections. A three-section filter with R and C elements reversed also will oscillate, but the high-pass type is likely to give increased distortion and therefore may

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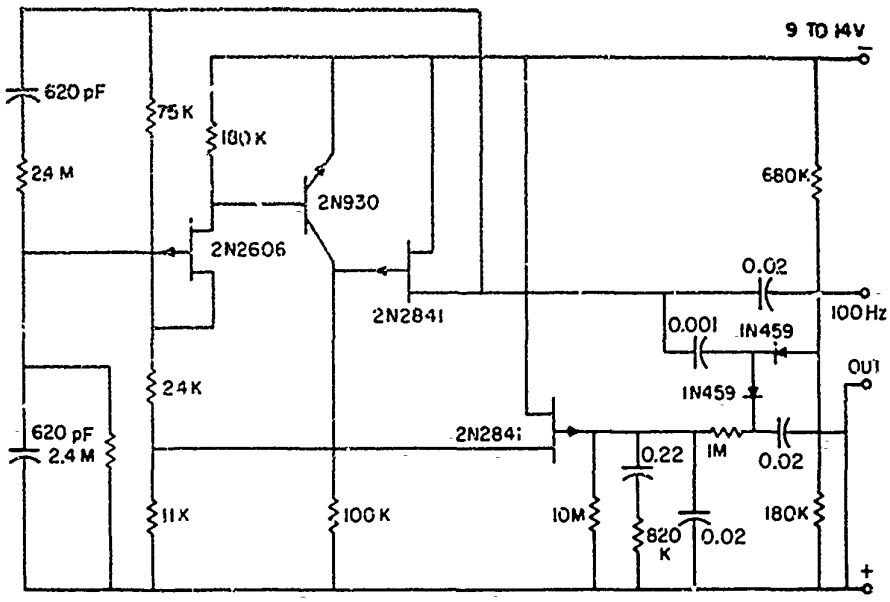


Figure 11-6. Wien Bridge Oscillator

not be so stable. Oscillators using these networks have been reported giving stabilities comparable to those of the other types discussed. This circuit is sensitive to changes in amplifier input and output impedances. A three-phase oscillator using three field-effect transistors (located between the L-network) has given good results.

Fig. 11-6[1] shows a 100-Hz Wien-bridge oscillator developed by Sann of U S Army Harry Diamond Laboratories. Field-effect transistors are used in the amplifier input to obtain a very high input impedance and in the ALC circuit to obtain a linear resistor that is controlled by a peak-to-peak rectifier on the output. This circuit has been tested from −55° to 80°C with supply voltage from 9 to 14 V. Combined frequency deviations were ± 2 parts in 10^4 for the amplifier alone. Wirewound precision resistors and monolithic ceramic capacitors were used, but these were kept at room temperature to evaluate the amplifier. Compensation to 1 part in 10^3 (0.1%) is not difficult, although the shock stability and long term drift are not evaluated so easily.

Fig. 11-7[1] shows the circuit diagram of an oscillator using a phase inverting parallel-T network in the positive feedback loop. A thermistor is used across the negative feedback resistor to stabilize the gain over the temperature range. The thermistor may be replaced with a controllable resistor as part of an ALC circuit similar to the one used in Fig. 11-4, to give better amplitude control and frequency stability. The shunt resistor in the parallel-T network is reduced by shunting with a much larger resistor, to obtain a network loss slightly less than the gain of the amplifier. Amplifier limiting (or an ALC circuit) maintains the oscillation amplitude constant. A circuit of this type has performed over the temperature range of −55° to 80°C and ± 30% variation in supply voltage with frequency changes of ± 55 parts in 10^4. The frequency determining network consisted of monolithic ceramic capacitors and metal film resistors with near zero temperature coefficients.

11-2.1.4 Mechanical Resonator Oscillators

Electromechanical resonators have been

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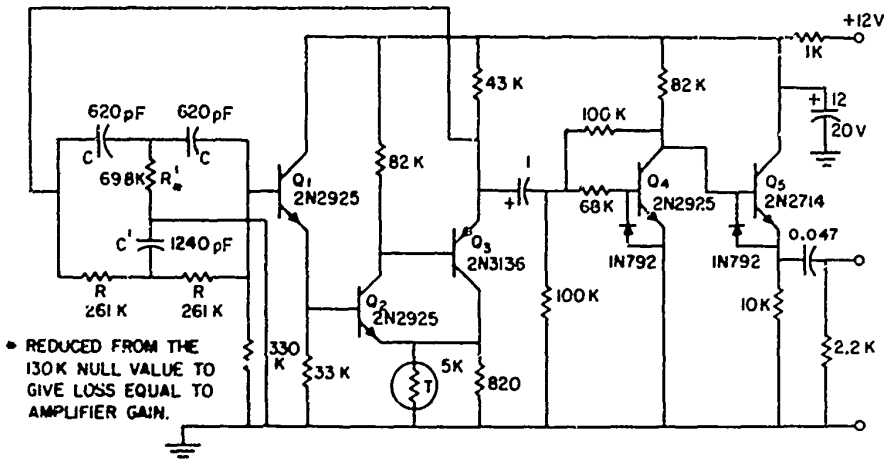


Figure 11-7. Twin-T, Unbalanced-network Oscillator

used in oscillators for a number of years, especially where highest accuracy is required. Electrically driven tuning forks have achieved accuracies of 1 part in 10^6, and quartz crystals can be obtained with a daily stability of 1 part in 10^9. Lower-precision resonators, operating on magnetostrictive or torsional modes, are also available. These devices are sensitive to shock and vibration and to temperature variations. High-frequency quartz crystals of the overtone types have been used under conditions of fairly heavy shock. Transistor-driven balance wheels are also operable under occasional high-shock conditions but are not considered reliable under conditions of continuous severe vibration.

11-2.2 RELAXATION AND PULSE-TYPE OSCILLATORS

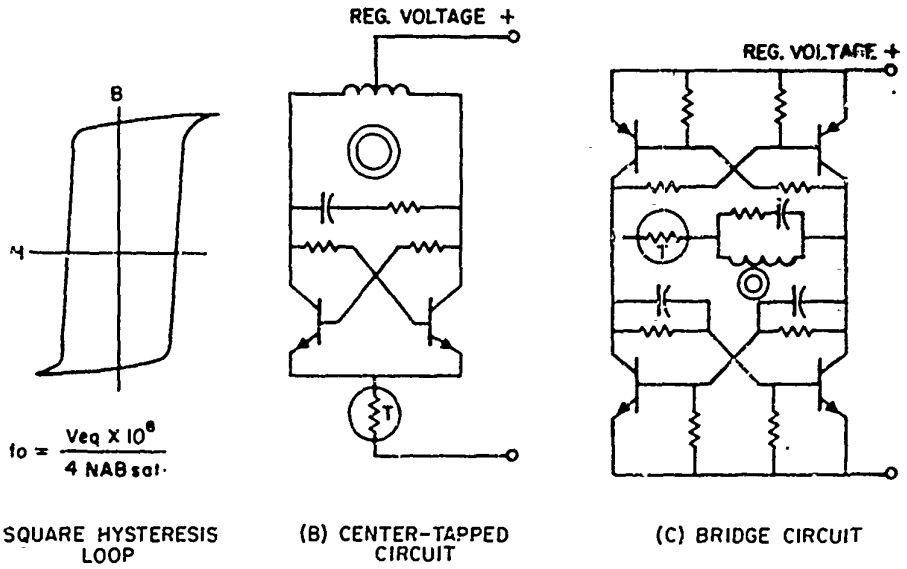
Nonsinusoidal oscillators of a variety of types have been used in timing applications of moderate precision. The most common of these is the free-running multivibrator. A compensated unit of this type has been built that was constant to 0.1% from −55° to 75°C. Similar laboratory precision has been obtained using unijunction transistors or pnpn switches. The extremely high input impedance of the insulated-gate, field-effect transistors may increase the capabilities of this type of relaxation oscillator.

Another type of relaxation oscillator makes use of a resistor, or a small ion chamber or curpistor, which contains a controlled amount of radium compound, and serves as a very low-current source for charging a capacitor. A special gas diode and sensitive counting relay are connected in series across the capacitor, which partially discharge the capacitor each time it reaches the diode breakdown voltage. The ion chamber eliminates the need for regulating the supply voltage, but requires about 75 V above diode breakdown. Principal causes of error are variations in the diode firing voltage and in the residual voltage left on the capacitor after each pulse. Accuracies of 1% have been achieved. The system is suited to very long-period timers because of the extremely small average current drawn. The radioactivity associated with the ion chamber is a slight disadvantage.

Saturable-reactor oscillators have become increasingly popular in recent years as timing devices. These oscillators make use of the sudden change in impedance or voltage of the

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(A) SQUARE HYSTERESIS LOOP

(B) CENTER-TAPPED CIRCUIT

(C) BRIDGE CIRCUIT

Figure 11-8. Saturable Core Oscillators

winding on a square loop core to trigger flux reversing and readout functions as the core reaches saturation. The timing action of this device with its abrupt discontinuity is much more favorable to precise timing than the slowly changing exponential waveform of an *RC* circuit (see Fig. 11-8[1]).

Fig. 11-8(A) shows a hysteresis loop for a typical square-loop inductor. In use in an oscillator, the inductor is connected into a multi-vibrator-type circuit that switches the flux continuously from a condition of positive saturation to negative saturation and back again each time the core saturates. Fig. 11-8(B) shows a push-pull circuit for use with a center-tapped coil while Fig. 11-8(C) shows a complementary flip-flop circuit for use with a two-terminal coil. The latter has an advantage where low-frequency operation is required, since the period of oscillation is proportional to the number of turns on the coil. The center-tapped coil uses only one-half of the turns during each half cycle. Frequencies as low as a few hertz have been obtained, but the inductors become large for frequencies below 100 Hz. Other circuit arrangements also have been employed, using multiple feedback windings to achieve oscillation.

It is necessary to regulate precisely the switching voltage applied to the core winding because frequency is directly proportional to applied voltage. Total flux change of a typical core may vary as much as 10% over a temperature range of −55° to 75°C, decreasing with increasing temperature. This variation is compensated partially by the positive temperature coefficient of the coil winding since the effective driving voltage is equal to the input voltage minus the *IR* coil drop. During the cycle a low current is drawn while the core is switching, with high current flowing as the core saturates. The residual temperature coefficient of frequency may be further reduced by use of a positive temperature coefficient thermistor in series with the inductor, or thermistor, or diode compensation of the voltage regulator. In this manner, accuracies of better than 0.1% have been achieved over the usual military temperature range.

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The square-loop cores usually are made of very thin grain-oriented material, such as Orthonol or Supermendur tape wound in toroidal form, and supported by a nonmagnetic metallic spool. These cores are sensitive to shock and must be specially packaged and treated to avoid permanent frequency shifts resulting from shock. They are also sensitive to spin accelerations and may shift frequency several percent under high spin.

11-2.3 PRESENT OSCILLATOR CAPABILITIES

Laboratory models of all of the types of oscillators shown have been built which gave better than 0.1% accuracy over ± 20% supply voltage variation and a temperature range of −55° to 75°C.

A number of military-type, saturable-core oscillators have been produced and are commercially available from several sources. These items perform well over the temperature range and under typical missile shock environment. They are, at present, not so accurate under the high accelerations associated with gun-fired rounds. Spin accelerations of 6000 g may shift the frequency as much as 5% Specially designed cores have reduced this variation to as low as 1%. Firing shocks of about 15,000 g have introduced permanent changes up to 1%. Operation in strong magnetic fields is to be avoided. A large bar magnet 6 in. away shifted the frequency 0.4%. When brought within 1 in., the frequency increased 14%. Residual shift in frequency was very slight when the field was removed.

A limited number of inductance-capacitance oscillators of ruggedized type have been shock and centrifuge tested. In the shock tests, permanent changes from 0.1 to 1% have been observed for accelerations of 15,000 g. The units were of a potted type but not specifically designed for high shock. Newer units presently under development are expected to show improved shock resistance. Two units of improved type recently fired at 20,000 g showed permanent changes of 0.05 and 0.2%.

In the centrifuge tests, *LC* oscillators were spun up to 10,000 g, and showed frequency increases of 0.05 to 0.4% with the force perpendicular to the toroidal axis. Another unit with the force along the toroidal axis showed a decrease of 0.06%. If the toroidal core can be kept within less than 1 in. of the spin axis of the projectile, it is believed that frequency changes of less than 0.1% can be obtained in most uses.

The toroidal core of a 1-kHz *LC* oscillator was exposed to the same magnetic fields as were applied to the saturable-core oscillator. At 6 in., the change in frequency was about 0.05% and at 1 in., about 2%. Residual shift on removal of field was negligible.

Shock and spin tests are planned for the several types of *RC* oscillators that have been laboratory tested. It is believed that *RC* circuits are likely to prove more stable in high spin and shock environments than those circuits containing inductors because of the inherent shift in the permeability of magnetic cores when under stress. Resistors and capacitors also can be expected to change in value when subjected to force fields but it is believed that improved packaging and construction techniques can be used to reduce these changes considerably.

The problems of temperature stability and aging of the frequency-determining components must be considered. From a production standpoint it is better, insofar as possible, to place the burden of obtaining low temperature coefficient upon the component suppliers where quality control can be more closely and precisely monitored. Aging control must be placed in the area of component design. At present, wire-wound resistors with temperature coefficients as low as 10 parts per million per deg C (ppm/deg C) are readily available and 2 ppm/deg C can be

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obtained. They also may be obtained with specified nonzero temperature coefficients which may be used to compensate for variations in other components. Metal-film precision resistors are available from a number of sources with coefficients of ± 25 ppm/deg C.

Of the various film-dielectric capacitors, polystyrene film units offer the more nearly linear temperature coefficients, the nominal value being −120 ppm/deg C. Variations of ± 15 ppm/deg C in this value may be expected. Stability of the polystyrene capacitors under high shock at 70°C is expected to be a problem. These capacitors usually are not used above 85°C. Polycarbonate dielectric capacitors, which have a lower but less linear temperature coefficient, may be more useful at these temperatures. Monolithic glass-in-cased capacitors are available with a coefficient of 115 to 165 ppm/deg C. Also, monolithic ceramic capacitors are available with coefficients of ± 25 ppm/deg C. The monolithic types are said to have excellent retrace and aging properties, and are expected to be highly shock resistant. Silvered mica capacitors have excellent stability and retrace characteristics, and temperature coefficients of 40 to 70 ppm/deg C. Their shock stability depends, to a large extent, on how they are fabricated and packaged.

Permalloy powder cores are now available for which inductance will vary less than ± 0.25% from −65° to +125°C. Cores of this type are also available that have coefficients of approximately 120 ppm/deg C and give a near-zero *LC* coefficient when used with polystyrene capacitors.

The flux storage capacity of the square-loop inductors decreases with temperature, but this is partially compensated by an increase in wire resistance with temperature when used in a saturable-core oscillator. All magnetic cores are stress sensitive and, for stability, must be packaged to keep mechanical stress to a minimum.

To obtain highest thermal frequency stability, it is likely that the resonators of any of the oscillator types will require some temperature-coefficient adjustment or parts matching on individual oscillators after performance over the temperature range has been observed. A final frequency calibration adjustment probably will be required after partial assembly and temperature cycling tests. A comparison of the relative performance capabilities of the various oscillator types is given in Table 11-1[1].

11-3 COUNTERS

11-3.1 GENERAL

Most counting circuits use an electronic or magnetic circuit having two stable states as their basic logical element. While schemes using multistable basic elements are being investigated, binary basic elements and binary logic elements are those generally available. The basic logical element function is that of a scaler or divider. The element has an output after a predetermined number of input pulses are supplied. If it has an output for every two inputs, it is a binary scaler or binary logical element and usually is termed a flip-flop. If the basic element requires three input pulses for one output, it is called a ternary scaler; one output for ten inputs is the characteristic of a denary scaler. Fig. 11-9 shows a basic binary element (Fig. 11-9(A)) and three of these elements connected to make a three-stage counter (Fig. 11-9(B)). Note that for binary counters, the scaling factor between input and output is 2^n where n equals the number of stages.

Fig. 11-10[3] shows a typical transistor binary flip-flop constructed of discrete elements. A semiconductor integrated circuit can be used to perform the same function as the discrete elements shown.

Fig. 11-11[3] shows a block diagram of a complete electronic digital timer system and indicates how the counting stages fit into the

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TABLE 11-1

RELATIVE PERFORMANCE OF VARIOUS OSCILLATOR TYPES

Oscillator Type	Frequency Stability*	Resistance to Shock and Spin	Power Drain	Complexity
LC parallel tuned	good	fair	low	low
LC series tuned	very good	fair	low	medium
RC Wien bridge	very good	good	low	medium
RC parallel–T	very good	good	low	med. to high
RC bridged–T	very good	good	low	medium
RC phase shift	fair to good	good	low	medium
multivibrator	fair to good	good	low to med.	med. to high
magnetic square loop	good	fair to poor	med. to high	high
pulse RC discharge	fair	good	low	medium
pulse curpistor–C	fair to good	good	very low	medium
mechanical resonator	excellent	poor	low	med. to high

*Frequency stability, variation: excellent $< 1 \times 10^{-4}$; very good 10^{-4} to 10^{-3}; good 10^{-3} to 10^{-2}; fair $> 10^{-2}$.

overall function of the timer. A 1280-Hz *LC* oscillator is inhibited by an initiate gate. On receiving an initiation signal, a simple 7-stage ripple-through counter provides the basic time base of 10 Hz. Divide-by-ten circuits are used in the time accumulator for tenths of seconds, units of seconds, and tens of seconds. A single binary divider serves as the 100-sec accumulator. A negative-going signal from the 100-sec binary will latch a controlled rectifier in the firing circuit and energize a detonator. Varying time delays are selected by setting the counter stages to a preselected count before the initiate gate is enabled.

Electronic digital timers have been constructed using both transistor flip-flops and transistor driven magnetic core flip-flops. Each has its particular advantages. Examples are given in the paragraphs that follow. Other types of multistable basic elements are being investigated in relation to projectile fuzing environment, and these also are discussed.

11-3.1 TRANSISTOR TYPE COUNTERS

Almost all types of counter use transistor junctions or discrete transistors as the active elements to perform the electronic functions of the timer and, in that sense, all electronic digital timers for projectile fuzing are transistor counters. However, in those coun-

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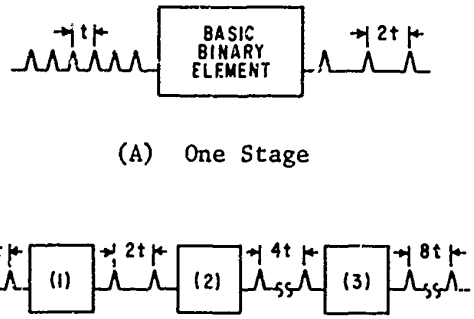


Figure 11-9. Primitive Counters

ters referred to as transistor type counters, only transistors are used as information storage in the basic logical element. Thus the basic logical stage of this type counter is similar in electrical configuration to that shown in Fig. 11-10.

This type of basic logical element suffers from a practical drawback because the element must be supplied with power throughout the complete time that it must preserve the count. This can be a serious disadvantage. Hence, this type of counter seldom is used. Fig. 11-12[4] is a schematic diagram of an electronic digital timer that uses basic logic elements of the magnetic core type. Note, however, the four binary divider stages, A4 through A7, in the center of the figure. These stages are used purely as dividers, and the time interval selection information does not concern them. Thus the timer uses a transistor counter as a divider, and memory core logic to store the set time interval.

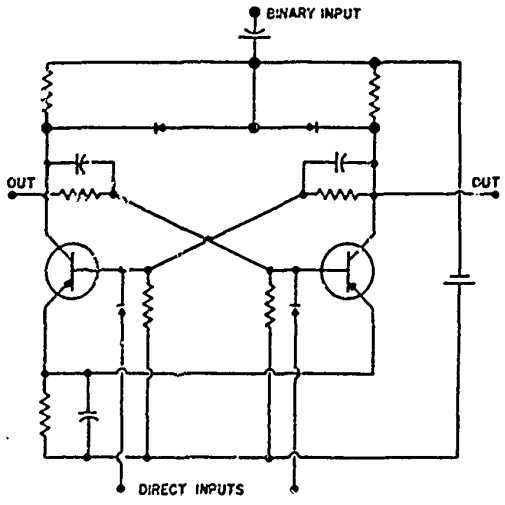


Figure 11-10. Typical Multivibrator

Some experimental digital timers for projectile fuzing were developed in early research using transistor counters exclusively. Fig. 11-13[5] shows the block diagram of such a system. Note that the basic logical elements are ternary dividers of all transistor construction. A schematic of one of the dividers is shown in Fig. 11-14[5].

Although pure transistor counters are not preferred at present due to their power drain during the interval from set to launch time, they do present the best prospects for miniaturization. With sufficient advance in miniaturization, power demands are sure to decrease radically so that transistor junction counters must be considered as possibly and probably desirable components for projectile fuzing applications.

11-3.3 MAGNETIC CORE TYPES

Cores have many advantages over strict electronic counters for military application. Aside from the ability to store information without power expenditure, they are resistant to nuclear radiation, relatively inexpensive, and have volumes comparable with discrete electronic components. Their principal disadvantage—from a long-range viewpoint—is the fact that they are relatively difficult to miniaturize and they require multiple connections. The magnetic cores used for memory operation are discussed in par. 7-2.2.4. Additional information on magnetic cores and core circuitry is contained in Ref. 6. Their important property is, of course, that

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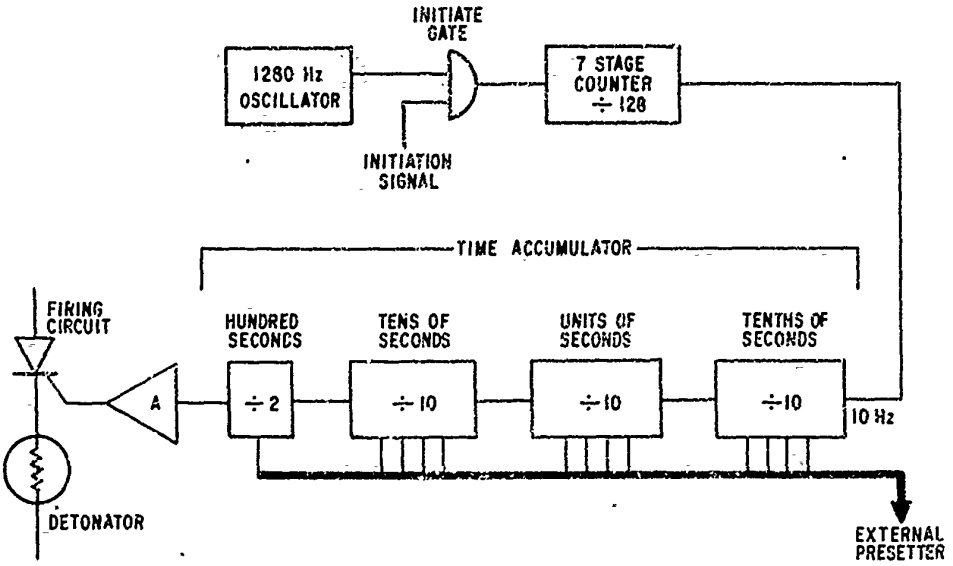


Figure 11-11. Block Diagram of Basic Timing Circuit

the core "remembers" the direction of the last significant change in the applied magnetic field.

There are many different configurations of cores and drivers that can perform counting, scaling, and memory functions. Fig. 11-15[7] shows cores connected to form a scaler that could have an output pulse for every fourth clock pulse. The odd and even drive pulses are generated from the clock pulses by the circuit of Fig. 11-16[7].

Suppose core "0" of Fig. 11-15 were put into the "1" state and cores 2, 3, and 4 were put into the "0" state. Now, a drive current of sufficient magnitude and duration is applied to the even drive winding as shown. Core 2, in the "0" state and being driven to the "0" state, does not switch (but a small voltage is generated due to the $\phi_s - \phi_r$ flux change). Core 0 in the "1" state switches to the "0" state. The output of core 0 drives core 1 to the "1" state. The diode in the 1-2 loop isolates core 2 from core 1, so that core 1 is unloaded when it switches to the "1" state and it is completely switched before core 0 is completely switched to the "0" state. The next drive pulse appears in the odd drive line, driving cores 1 and 3 to the "0" state. This transfers the "1" from core 1 to core 2. In this manner the "1" is transferred from core to core, and since core 3 is connected to core 0, the "1" will circulate. If an output were taken from the loop joining cores 3 and 0, the output would appear once for every four clock pulses.

In Fig. 11-16, core A is initially set to the "1" state and core B is set to the "0" state. The clock pulse is derived from an oscillator or from a previous decade, and drives both cores A and B to the "0" state. Core A switches to the "0" state, turning on SCR A, which allows capacitor C to discharge through the even-drive winding and core B, putting a "1" into core B. Resistance R is large enough so that (B+)/R is less than the holding current of SCR A and SCR B. The second clock pulse from the oscillator again drives cores A and B to the "0" state; now core B switches, and C discharges through the odd-drive winding and core A, putting a "1" into core A. In this manner, the clock pulses generate alternate drive pulses to the scaler.

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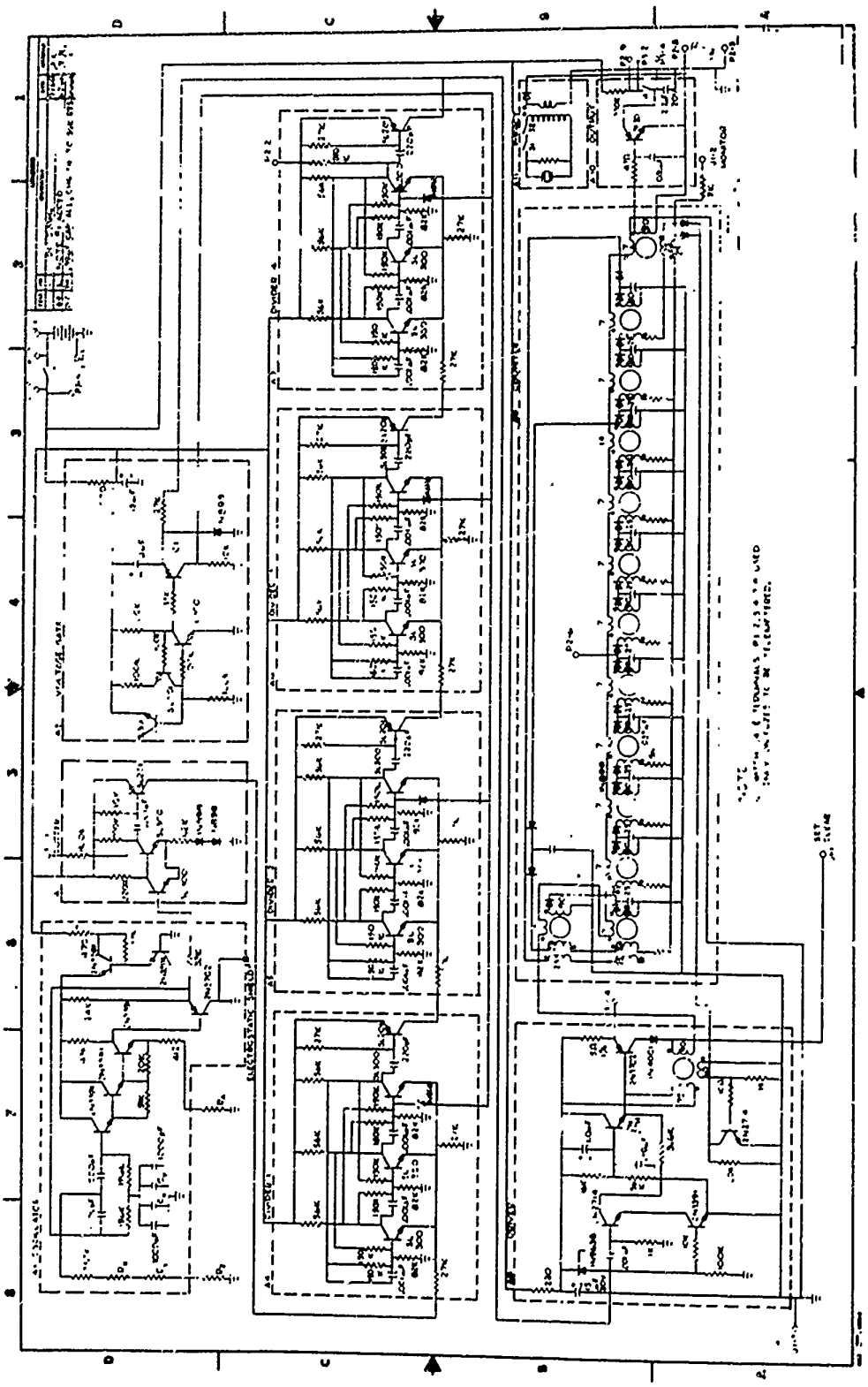


Figure 11-12. Schematic Diagram of Fuze, Electronic Time, XM587

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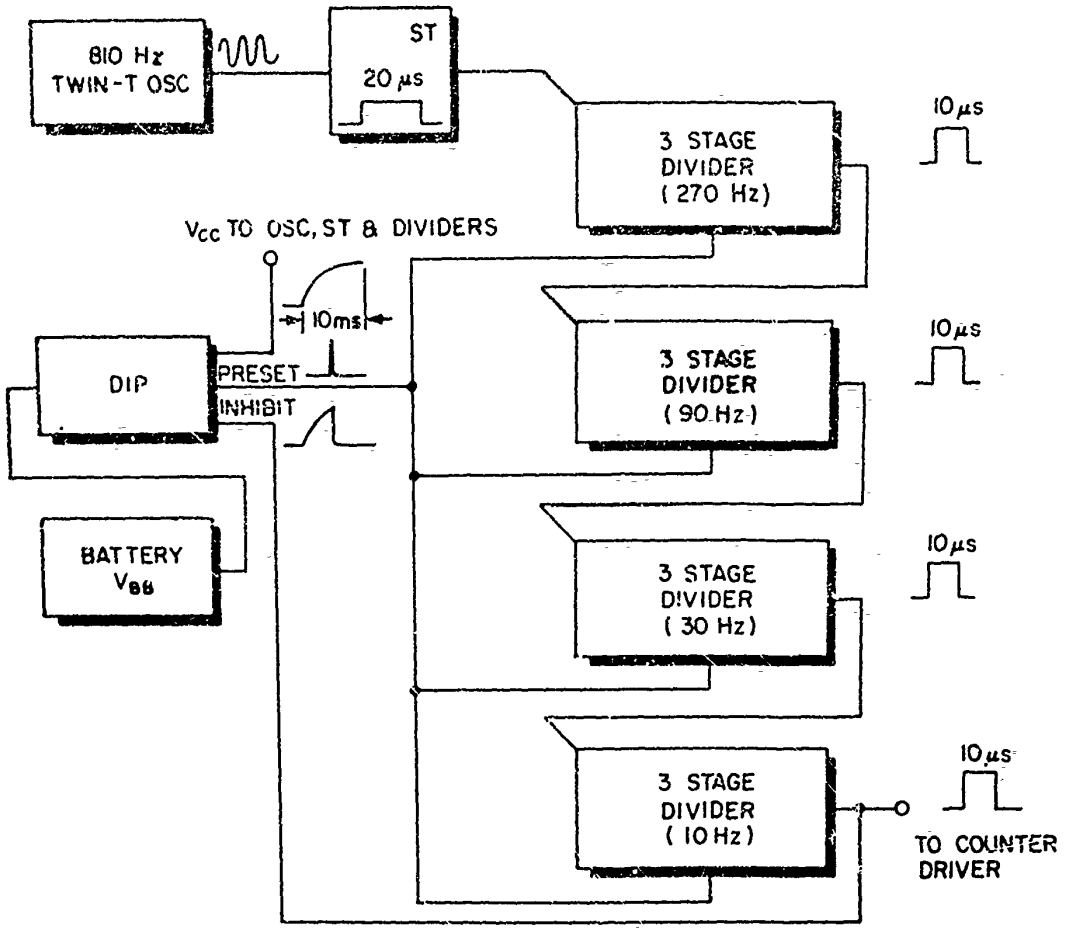


Figure 11-13. Block Diagram of 10-Hz Clock

Fig. 11-17[8] shows a complete decade core scaler for an experimental timer. Note the similarity between the simple example of the scaler given by Figs. 11-15 and 11-16, and the completed operational item.

11-3.4 OTHER TYPES

There are a number of other devices and phenomena that have been used to develop counters or scalers. Vacuum tubes and cold gas diodes were perhaps the first with sufficient frequency response to be considered for projectile fuzing. Solid-state devices seem to have most of their advantages (barring radiation resistance) and require less power.

Investigation is continuing on several other methods. Incremental flux switching as applied to projectile fuzing is discussed in Ref. 9. Dielectric polarization memories with nondestructive readouts are discussed in Ref. 10. Plated wire memories, deposited magnetic memories, and magnetic domain propagation also have been considered.

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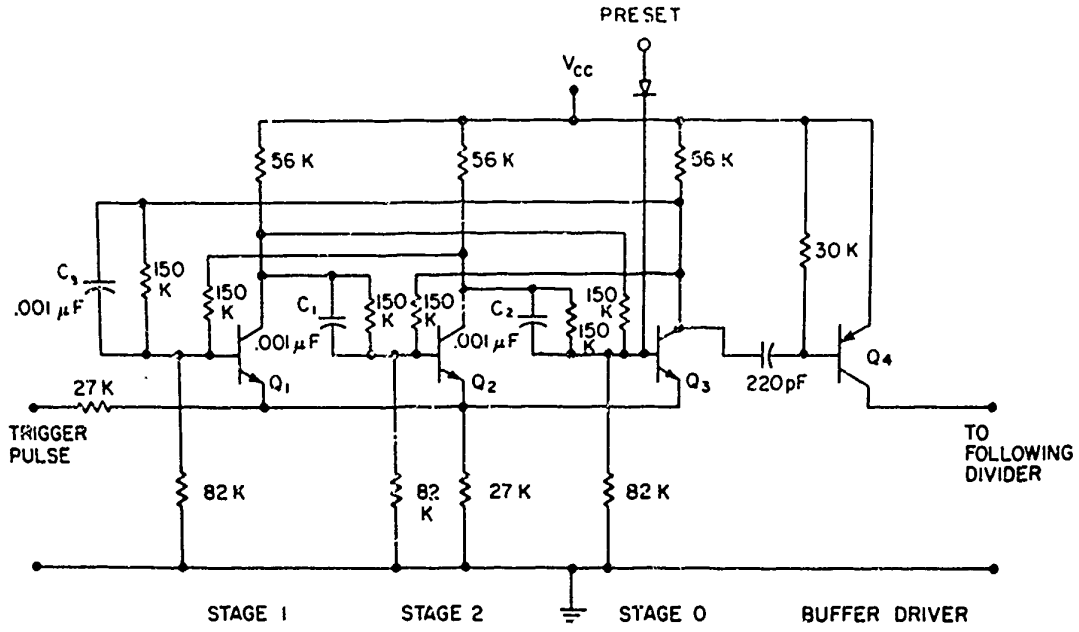


Figure 11-14. Ternary Divider

11-4 OUTPUT CIRCUITS

11-4.1 GENERAL

The primary function of the output circuits of digital electronic timers used for projectile fuzing applications is to produce an electrical signal on occurrence of the "timing out" of the counter circuitry which will cause detonation of the projectile warhead. The secondary function—of almost equal importance—is the positive prevention of electrical initiation of the warhead under any circumstances except when functioning is desired. In particular, the output circuits must not produce an electrical initiation stimulus on counter "time out" unless the projectile is armed.

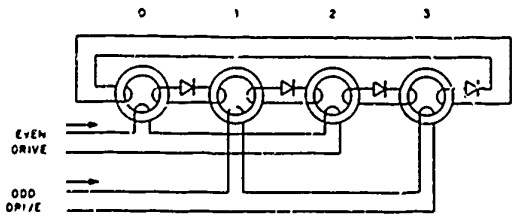


Figure 11-15. Magnetic Core Scaler

In missile and rocket applications, the output circuits of the timer may produce a relatively low power signal that is transmitted to sophisticated decision making electronics in the warhead. In contrast, the output circuits for electronic timers used in artillery projectiles must provide a relatively high energy output and provide all electrical logical interlock functions. The output circuit design is heavily dependent on the system mission in the case of projectile fuzing applications. Refs. 3, 11, and 12 provide examples of output circuits for particular electronic digital timers.

11-4.2 OUTPUT PULSE GENERATION

Since output circuits for electrical timers used in missile and rockets need only supply an electrical signal to warhead logic circuits, they generally use a solid-state active element

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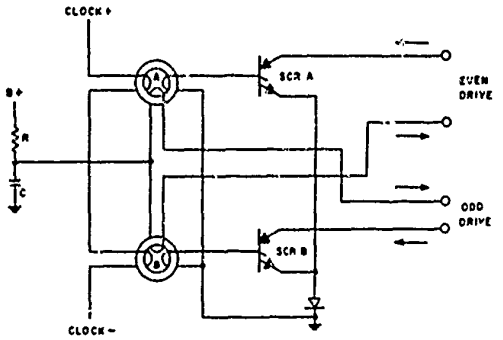


Figure 11-16. Two Phase Driver

for output pulse generation. The electrical requirements are seldom severe. Hence, a transistor, silicon-controlled rectifier (SCR), or unijunction transistor that is identical with those used in the counter circuits often is employed to reduce the number of different components in the overall timer and thereby reduce overall cost.

In artillery projectile fuzing and in other instances where the output circuits must directly initiate detonation, special means are employed to insure reliable functioning. Detonation initiation usually requires the output circuits to function an electroexplosive device (EED). The DC resistance of the bridgewires commonly used in hot wire EED's varies from a few tenths of an ohm to a few ohms. Currents of fractions of an ampere to several amperes are required to provide reliable initiation which usually occurs within 10 or 20 msec from application of the current. Especially sensitive EED's—requiring currents as low as 100 mA—sometimes are used in artillery projectile fuzing to minimize output circuit current requirements. Such sensitive items require special safety precautions during assembly and handling.

The basic problems for output circuit design are the relatively high power required by the EED and the impedance mismatch between the EED's resistance wire of a few ohms and the operating impedance level of solid-state circuitry which in general is much larger than 50 ohms. A typical solution to the output circuit/EED interface problem is shown in Fig. 11-18. The +12 V DC is not applied to the initiation circuit until after the rocket or missile has been launched or, in the case of artillery applications, the projectile has been fired. At this time the 150 μF capacitor charges rapidly through the transistor and the 1.5 k ohm resistor. The transistor acts as a self-biasing device to maintain the capacitor charge. If the timer "times out" and the logic decision circuits provide a positive "initiate signal" to the SCR, the 150 μF capacitor discharges through the SCR and the EED resistance wire providing initiation of

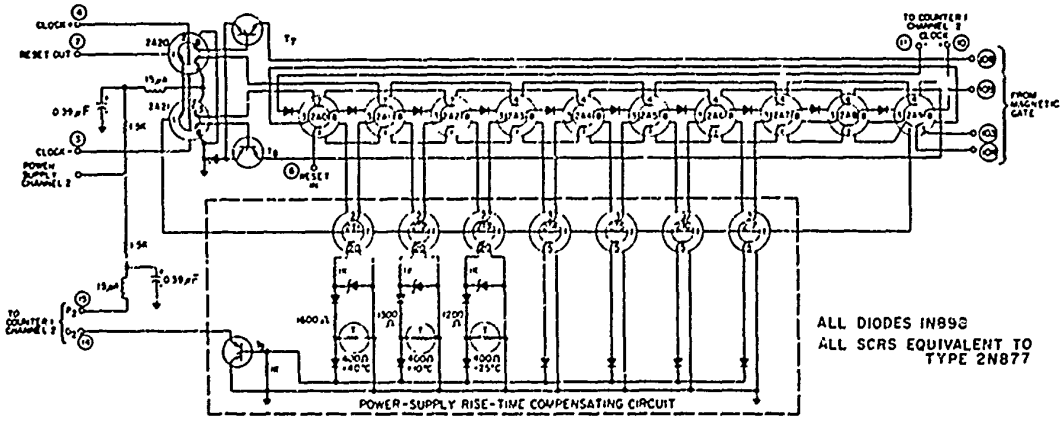


Figure 11-17. Decade Frequency Divider

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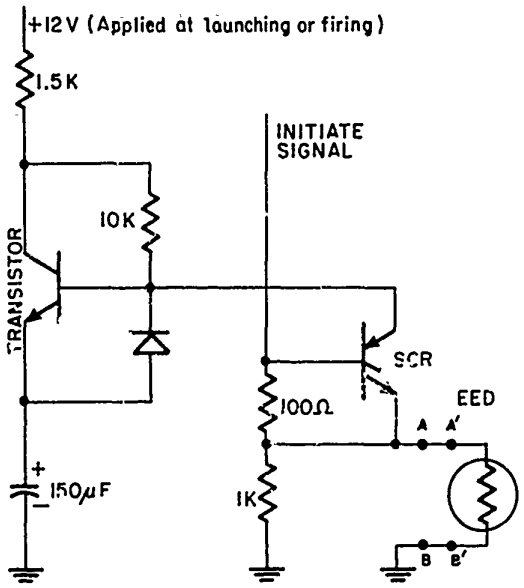


Figure 11-18. Typical Initiation Circuit

the explosive charge. Many output circuits are designed along these general lines. In many applications, however, a set of switch contacts are inserted between the SCR output and the EED (AA′ or BB′ in Fig. 11-18). The switch often is closed by a mechanical arming function in missiles and rockets, and by centrifugal force in spinning projectiles.

11-4.3 LOGICAL INTERLOCK FUNCTIONS

In missile and rocket application, the electronic timer output circuits may have little to do except pass on the signal from the last stage of the counter to the elaborate warhead electronic decision making circuits. These circuits, which may have inputs from elaborate sensors, make the detonation decision. The artillery projectile, in contrast, usually requires that all the electronic decision making capability be incorporated directly into the output circuitry of the electronic digital timers. The primary safe and arm function for artillery projectile fuzing applications, however, is accomplished mechanically.

11-5 SETTING METHODS

11-5.1 GENERAL

The most common method of setting a digital timer for fuzes is to preset a count into the counter such that the counter reaches its maximum count after the desired number of input pulses from the time base. When the counter has reached this maximum count, detonation occurs. Thus, if we desire detonation after 593 clock pulses have stepped in a counter with a maximum count of 1000, we would preset the counter to 407. Presetting of the counter can be accomplished by setting the counter to zero and stepping it to the correct setting by inserting single pulses or by "jamming" the stages to the desired setting. The first of these methods is called serial setting, the second parallel setting. Refs. 3, 11, and 13 provide examples of both methods.

11-5.2 SERIAL METHODS

Using a serial set method for counters involves:

(1) Applying power. External power is supplied if the counter can retain its reading without power. The fuze power supply must be actuated for counters that cannot do so.

(2) Clearing the counter to zero

(3) Counting the required number of pulses supplied to the counter input

(4) Checking the operation of the counter, if necessary.

Serial setting usually can be accomplished with few electrical contacts with the fuze, and this is a decided advantage. The primary disadvantage of serial setting arises when the number of setting pulses supplied must be large; for, then setting time can become intolerable. The setting pulses can be supplied at a rate much greater than those normally

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supplied by the time base to overcome the disadvantage but this approach is limited by the ability of the counter to respond to the higher repetition rate pulses. In general, high response rate for the counter means a more costly counter. Hence, this approach is limited by economics.

11-5.3 PARALLEL METHODS

Using a parallel set method for counters involves:

(1) Applying power. External power is supplied if the counter can retain its reading without power. The fuze power supply must be actuated for counters that cannot do so.

(2) Applying the correct pulse to every stage of the counter

(3) Checking the operation of the counter, if necessary.

Parallel setting can be accomplished in very short times. The primary disadvantage is that many electrical contacts must be made with the fuze. Electrical contacts are particularly troublesome in rugged military equipment.

11-5.4 COMBINATION METHODS

Compromises between the serial and parallel methods involve treating the counter as if it were several smaller counters and setting each by the serial method. The disadvantages of more electrical contacts are not as serious because (1) there are less contacts than in the parallel method, and (2) the setting time will not be overly high because a much smaller number of pulses can be applied simultaneously to the smaller counters than would be necessary for the undivided counter.

11-6 POWER SUPPLIES

11-6.1 GENERAL

Digital timers rely on some form of analog timer as a time base and hence the overall accuracy of the digital system can be no better than that of the analog timer base count. Although the electronic digital counting methods employed in digital timers are relatively insensitive to voltage fluctuations, the overall system—which includes the voltage sensitive analog timer—is thus still subject to error due to poor voltage regulation.

For general application timers, the design problems for the power supply are essentially the same as those of other electronic logic circuits. Off-the-shelf power supplies are recommended for these applications because they are available in great variety and can be obtained economically to provide well regulated voltage for the analog time base, and less well regulated outputs for the remaining, less critical portions of the system. Study of the specifications for off-the-shelf supplies from several manufacturers before selecting a final unit can be very helpful to the timing system designer if he does not have an intimate knowledge of power supply design. The specifications may point out problem areas—such as transient protection or radio frequency interference vulnerability, which the off-the-shelf power supply manufacturers have solved—which are directly applicable to the timing system problem under consideration.

Special problems arise in power supply design for projectile fuzing systems. The remainder of this discussion is aimed at these more stringent applications.

11-6.2 POWER SUPPLIES FOR PROJECTILE FUZING APPLICATIONS

In projectile fuzing design it appears that oscillators, timing circuits, safing and arming mechanisms, and arming switches sometimes are considered first and laid out. Then, almost as an afterthought, the remaining space is allocated to the power supply with a catch-all form factor. We here enter a strong plea to give the power supply more consideration during development. Designers rely on manufacturers' claims and theoretical values for

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TABLE 11-2

TIMER POWER SUPPLIES (VOLUME AND SIZE)

Fuze	Max. Volume, in.^{3}	Typical Dimensions, in.
Missile	45	2.5 X 3.0 X 6.0
Rocket	21	3 diam. X 3 long
Projectile	4	1-5/8 diam. X 2 long

power per unit weight or per unit size without giving adequate consideration to the overdesign needed to insure operation at temperature extremes, and ruggedization at high setback and spin forces. Most existing off-the-shelf power supplies will not meet the requirements for projectile fuze timers.

Projectile fuzing design timers can be divided into the following categories:

(1) Timers for missile fuzes (approximately 300-mile range)

(2) Timers for rocket fuzes

(3) Timers for projectile fuze

Maximum flight times of the fuzes are 3 min. The volume available for the power supply depends on the size of the military item. Based on past requirements for proximity fuzes, Table 11-2[14] lists these sizes and presents typical power supply dimensions. The setback and spin requirements vary widely for these vehicles, while the range of temperatures for operation and storage is the common military range. Table 11-3[14] summarizes these environmental requirements while Table 11-4[14] shows the typical electrical requirements and indicates that the power requirements are relatively uniform.

Most power supplies for fuzing applications are activated on fuze setting. It would appear

TABLE 11-3

ENVIRONMENTAL REQUIREMENTS

Fuze	Setback, g	Spin, rps	Temperature Range, °F
Missile	25	5	−65 to +160
Rocket			
"Nonspin"	100	5	−65 to +160
Spin	100	100	−65 to +160
Projectile	27,000	500	−65 to +160

sensible to lighten the load on the power supply by activating it at the time of launch or firing, thus requiring a shorter life. However, typical supplies do not have well controlled turn-on times, and they would thus influence accuracy of the overall fuze timer. For a very slow missile with a velocity of 200 fps, a 50-msec uncertainty in turn-on time would amount to a 10-ft uncertainty in position. With higher velocity projectiles the problem gets worse.

The required active life of the power supply is of major concern. Two major types of digital timer are in use or under development, each having different life requirements for power supplies. One type requires that power be supplied continuously to the timer from the time of fuze setting until projectile detonation. Integrated flip-flop circuit timers have this requirement. The other type, principally timers of the memory core type, requires power only from firing or

TABLE 11-4

ELECTRICAL REQUIREMENTS

Fuze	Voltage, V	Current, mA
Missile	12–15	30–50
Rocket	6.7 ± 0.7	100
Projectile*	6–15	30–100

*Summary of three developments.

SAMSUNG EXHIBIT 1028, Page 193

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launch time until detonation. Between setting time and launch or firing time, the only requirement on the power supply is open circuit voltage.

Thus timers using memory cores instead of flip-flop circuits are preferred because power supply requirements are less stringent. In addition, electronic timer systems that require power from time of fuze setting until projectile detonation are not compatible with several types of artillery missions in which time from fuze setting until firing is not well controlled, e.g., sustained barrage and surveillance firing at specific targets. Missions of this type often lead to the problem of determining when the power supply has adequate power to provide detonation on target. Fuzes usually are designed to permit ready replacement of the power supply thus providing a means of insuring adequate power if a low power condition is suspected or indicated.

The power supplies for projectile fuze timers are single electrochemical or stacks of such cells. In practice, the number of stacked cells required for a given electronic timer depended, in the past, on the electrochemical potential difference of the individual cell type and the voltage required to operate the electronic timer. For instance, an electronic timer requiring 5.5 V for operation would need at least four stacked cells for a 1.5-V cell and at least five cells for a 1.1-V cell. The recent development of transistorized DC to DC converters makes a second approach to the problem possible. With such a converter, a single cell can supply the total required power at the correct voltage. Although this approach is presently more expensive, it is considered superior from a reliability viewpoint because, in general, it has fewer parts and is comparatively easy to construct.

Electrochemical systems for power supplies usually are subdivided into two groups, active and reserve. The active group includes the common flashlight battery and the common automobile battery. The distinguishing characteristic is that the electrochemical system of the battery is assembled or mixed during manufacture. In the reserve systems, in contrast, the mixing of assembling of the necessary components is accomplished at the time when voltage is required. The reserve system is best represented by thermal batteries in which the heat necessary for the proper electrochemical reaction is provided by a pyrotechnic mix at battery activation time. Another good example of the reserve system is the available car battery in which the electrolyte is not added until the battery is sold and placed in the customer's car. The primary advantage of the reserve systems is long shelf life.

A composite of manufacturers' literature and laboratory data is shown in Tables 11-5[14] and 11-6[14] giving the characteristics of various electrochemical systems.

As a note of caution it should be observed that although recent development in printed circuits, transistors, solid-state junctions and components, and integrated circuitry has allowed performance of fuzing functions with less and less power per component, added sophistication of fuzes and the tasks they are called upon to perform have resulted in keeping the power requirements the same. Hence, the power supply specification problem is as important as ever and seems destined to remain so.

SAMSUNG EXHIBIT 1028, Page 194

TABLE 11-5

PRIMARY POWER SUPPLY SINGLE CELLS

Electrochemical System	Temperature Range, °F	Size		Volume, $in.^3$	Commercial Designation	Setback, g	Spin, rps	Remarks	Shelf Life at 70°F, yr
		L, in.	*D*, in.						
Leclanche (carbon-zinc)	35 to 140	1.83	1.03	1.56	C	Unknown	Unknown	Marginal at high extreme	1
Alkaline-MnO_2-Zinc	0 to 140	1.83	1.03	1.56	C	Unknown	Unknown	Marginal at extremes	1
Mercury	0 to 160	–	–	2	None available	ca 20,000	Probably 250	Marginal at low extremes	2
Thermal (molten-electrolyte) (Reserve)	–65 to 160	3	3	21	None available	15,000	100	Life marginal	20
Pb-PbO_2-Fluoboric Acid (Reserve)	–20 to 160	–	–	2	None available	20,000	400	–	10

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TABLE 11-6

PRIMARY POWER SUPPLY MULTICELLS

Electrochemical System	Temperature Range, °F	Size, in.^{3}	Commercial Designation	Setback, g	Spin, rps	Remarks	Shelf Life at 70°F, yr
Mercury	−20 to 140	2	None Available	20,000	probably 250	Marginal at extremes	2
Pb-PbO_2-Fluoboric Acid	−20 to 160	2	None Available	20,000	400	—	10
Ag_2O-Zn-KOH (commercially available)	0 to 160	2	None Available	20,000	250	Marginal at high extremes	2

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PART THREE – MECHANICAL TIMERS

CHAPTER 12

INTRODUCTION

12-1 GENERAL SYSTEMS

Mechanical timing systems are used extensively in military applications in the function of programmers, sequencers, clocks, and fuzes. These military systems use timers in two forms: (1) the purely mechanical systems in which the time base is a mechanical device such as a tuned or untuned escapement; and (2) hybrid systems that use crystals, tuning forks, or electronic circuits as the time base to control the beat rate of the escapement. It is a basic premise of this handbook that timing systems be classified according to the functional nature of their time base; therefore, the latter hybrid systems are discussed elsewhere in this handbook, and this chapter will limit its discussion to those systems having a mechanically operated time base.

12-1.1 BASIC MECHANICAL TIMER ELEMENTS

The basic mechanical timer systems are comprised typically of various combinations of four components:

(1) The power supply or source of energy

(2) An escapement (the time base) that periodically releases the energy, maintains oscillations, and in some systems actuates the computing elements

(3) The computer or counting element which totals the oscillations of the escapement and provides an output signal when a predetermined number of counts has been received

(4) An output such as a settable readout, a switch which closes, a cam which rotates, or a means of producing a firing signal.

Fig. 12-1 diagrams a typical example of a military timer containing these four components.

12-1.2 FUNCTIONS OF MECHANICAL TIMERS

Mechanical timers perform control functions in many military applications, and methods of performing these control functions are almost as varied as the requirements themselves.

12-1.2.1 Interval Timers

Interval timers are the class of timers which control the time that elapses before an event takes place. An example of this type is an escapement timer as shown in Fig. 12-2[1]. The power supply is a mainspring driving the output shaft; the time base is a tuned two-center escapement; the counter is a gear train; the output is a cam-operated switch; the activator holds the escapement until removed.

A specialized group of interval timers are mechanical time fuzes. Mechanical time fuzes are placed in a separate category because they represent a major usage class, and because they are required to operate under a much more severe set of environmental conditions than are the other types of mechanical timers. Examples of these types of timer are shown in Figs. 12-3[2] and 12-4[3].

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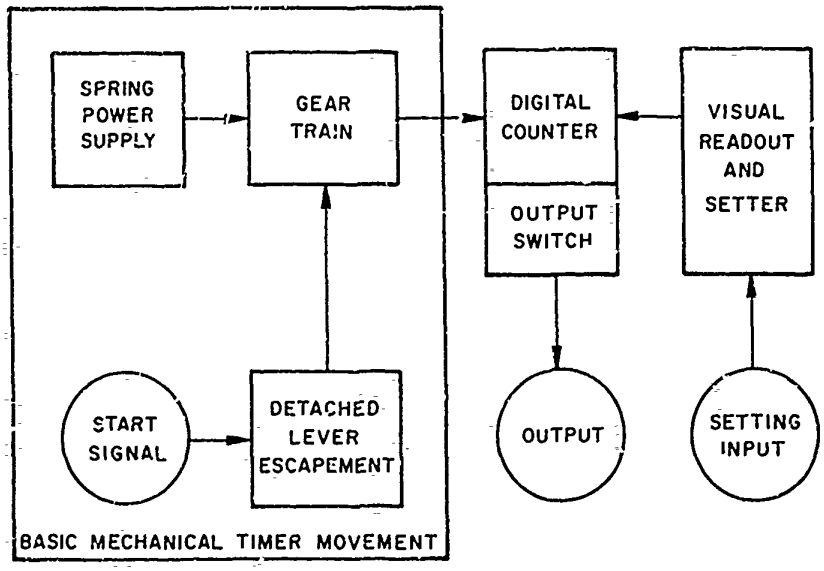


Figure 12-1. Military Timer Concept

12-1.2.2 Programmers and Sequencers

Programmers and sequencers are mechanical timers that control the time interval relating a series of events, control the sequence of events, or control the duration of the events. The typical function of these timers is to provide for the completion or interruption of electrical circuits at a predetermined time or for a predetermined interval.

12-1.2.3 Clocks

Clocks are a class of timing devices which are operated so as to have some absolute reference to time. As a general rule, the mechanical clocks that are used by the U.S. Army have as their output some type of read-out device. The clock may be used to relate to absolute time, to indicate elapsed time, or to control electrical circuits with relation to absolute time.

12-1.3 ACCURACY

In the use of an interval timer for a military or space application, accuracy is an important characteristic that must be given serious consideration. For field use the highest accuracy (± 0.1%) is achieved by the crystal, the *LC* or the tuning fork oscillators. Some mechanical timers (the spring-mass systems) provide better than ± 0.5% accuracy. The mechanical verge and the *RC* oscillator provide accuracies of ± 5% in common applications. Mechanical systems under the proper conditions will supply fairly good accuracy. Electronic timers have a reputation for accuracy, usually based on the use of crystal controlled oscillators for the time base or on the *LC* oscillator (in which higher accuracies than are possible with the common spring-balance are obtained). The spring balance, however, frequently approaches the accuracy of the *LC* oscillator in actual use because drift in diode discharge devices degrades the *LC* accuracy.

Increased accuracy generally costs more due to the need for precise components.

Errors in mechanical timers which contribute to lack of accuracy are those of the escapement, counter, setter, and output.

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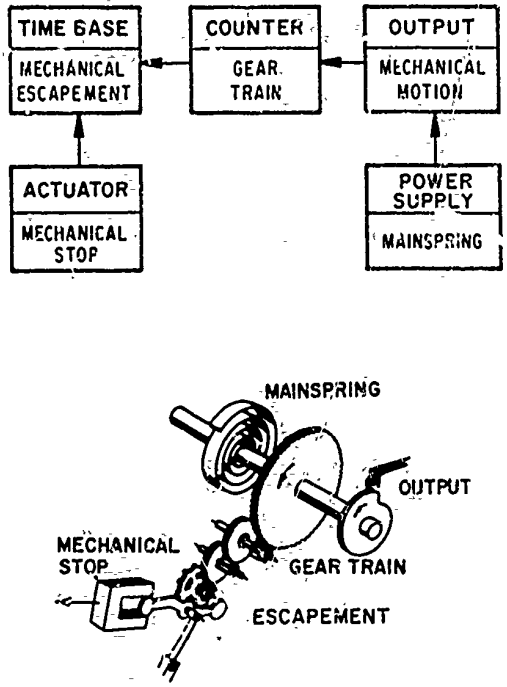


Figure 12-2. Mechanical Interval Timer[1]

Overall accuracy of the escapement will depend upon the sum of the effects that tend to destroy isochronism.

One of the principal sources of error is the interaction between the spring-mass and the ratchet during the period when energy is transferred between them to maintain oscillation. The disturbance should be as small as possible, should occur at the point of maximum kinetic energy, and should take place as quickly as possible in order not to impair accuracy.

Environmental conditions also affect timer accuracy. Special modifications must be made when the timer is to operate at extremely low or high temperatures, or under vibration or shock. Generally, operation over a temperature range of −10° to 120°F is no problem; however, a much wider operating range often is required.

Fluid timers, wherein the motion is regulated by a gas or liquid (see par. 16-7), are not as accurate as clockworks but have found application in arming delays of fuzes.

12-1.4 EXAMPLES OF MECHANICAL TIMERS

12-1.4.1 Interval Timers

Interval timers are mechanical timers in which the escapement is used to provide for measurement or control of a single time interval. A diagram illustrating this type of timer is shown in Fig. 12-2. The mechanism may be arranged so that the interval to be measured is variable. The timer may be one-shot or resettable.

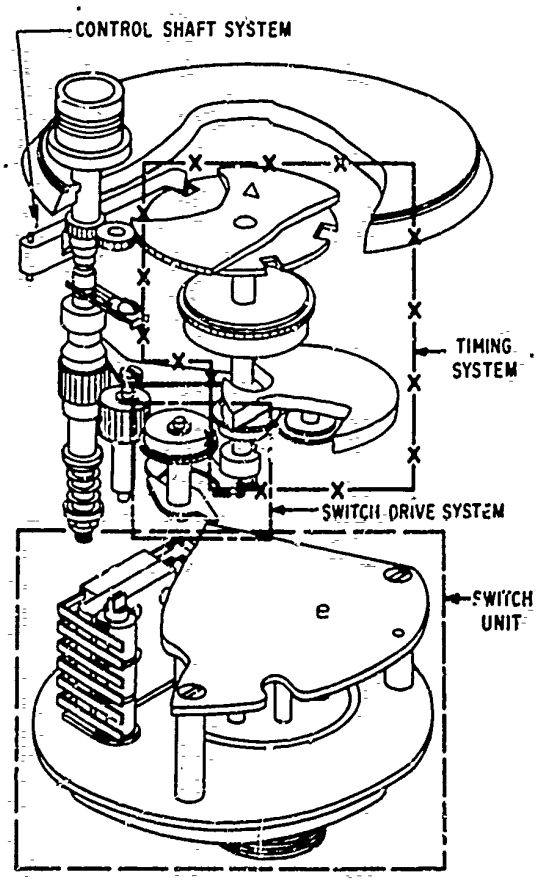


Figure 12-3. Diagrammatic View of XM4 Interval Timer

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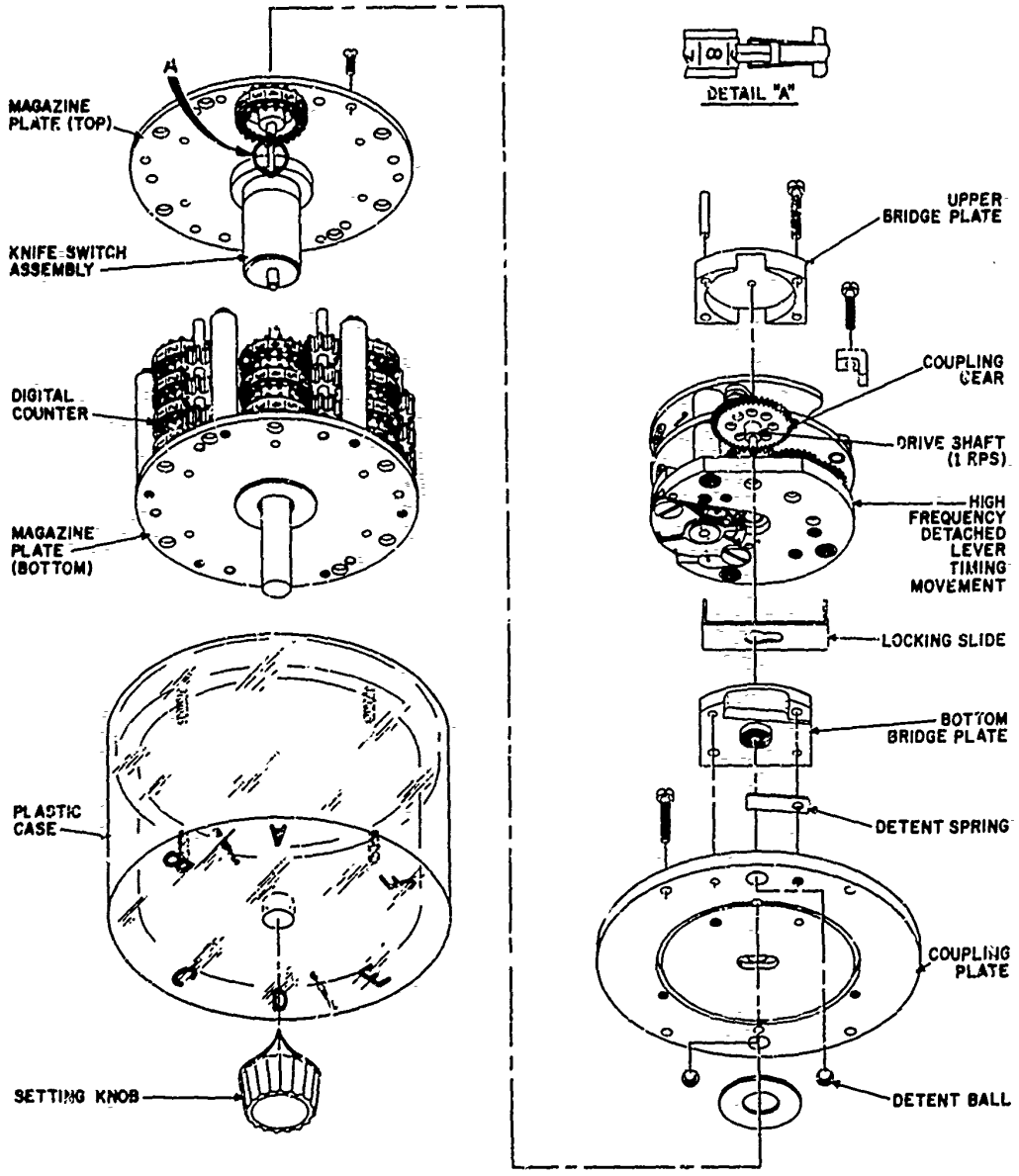


Figure 12-4. Exploded View of a Mechanical Timer

12-1.4.2 Fuzes

A fuze is a device with explosive components designed to initiate a train of detonation and to function an item of ammunition at the time and under the circumstances desired. A mechanical time fuze is activated by a clocklike mechanism preset to the desired time. It performs this mission when attached to ammunition that may be traveling towards a target or that may be awaiting the approach of a target. In either case, a stimulus is required to trigger the operation of the fuze.

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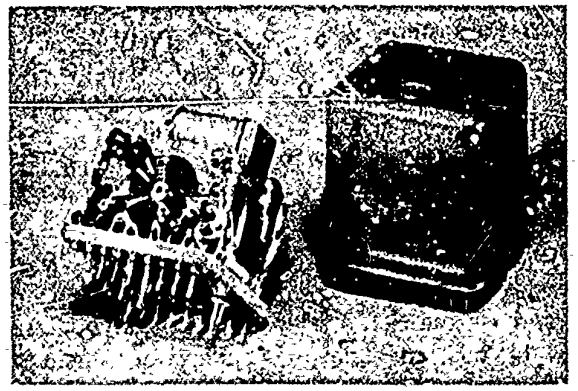


Figure 12-5. Electromechanical Program Timer for Adaption Kit of Ballistic Missile[4]

It is obvious that the foundation of the mechanical time fuze system is the accurate measure of time. Timing mechanisms used in fuzes are predominantly tuned two-center escapement and gear-train combinations. An example of a mechanical time fuze is shown in schematic form in Fig. 12-9.

12-1.4.3 Programmers

An example of a mechanical programmer is shown in Fig. 12-5[4],* with a schematic shown in Fig. 12-6[4]*. It originally was developed for U S Naval Ordnance Laboratory as part of a ballistic missile adaption kit. Once triggered by a momentary electrical pulse at an appropriate point in the missile trajectory, this device runs for approximately 1 min, operating electrical switches in accordance with a predetermined program. Once initiated, the timer requires no further external power, performing its function with considerable accuracy through all anticipated flight environments.

The mechanism consists of a tuned two-center escapement and gear train which controls the rate of a spring-driven output shaft to which electrical circuit disks are secured.

Most mechanical timers have a major disadvantage; if they are to be tested, some sort of physical access must be provided during component and system test to allow for rewinding of the power spring. Such a requirement is not only inconvenient, but it also prevents the device from being hermetically sealed against humidity and external contamination.

To overcome this problem, a unique

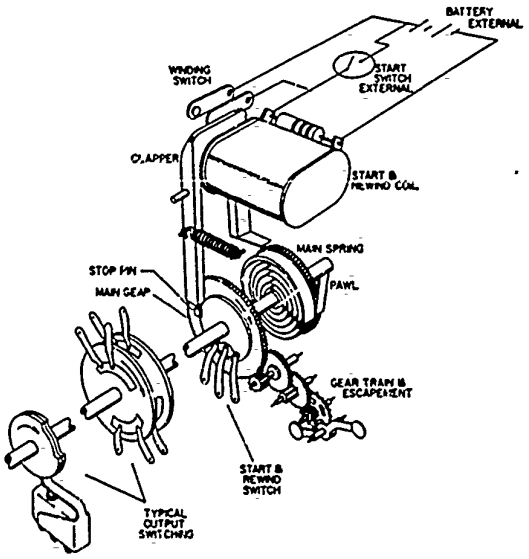


Figure 12-6. Schematic of Mechanical Timer With Electrical Rewind Circuit[4]

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feature was developed. The timer is started by electrically activating an integral solenoid that releases the main shaft. Power for testing is supplied through a rewind circuit to this same coil through an internal flip-flop switch. During the timer duty cycle, one of the circuits programs this power to the solenoid for several seconds, rewinding the spring for the following cycle. The power spring has enough energy for several successive cycles without such rewinding and with no loss of accuracy. Other features of this timer are typical of most military timers:

(1) Exceptionally rugged, having a high tolerance for shock, vibration, and acceleration

(2) Almost totally unaffected by large doses of nuclear radiation

(3) Unaffected by temperature or pressure variations

(4) Small, light and inexpensive.

12-1.4.4 Sequential Timers

In sequential timers a mechanism is provided which will permit a time controlled series of events to occur after a specified time delay. Most sequential timers provide a series of outputs with independently adjustable time intervals from one output to the next. The initiation of each succeeding time element is dependent upon completion of the preceding output. Length of the total cycle is the sum of the individual elements.

Accuracy of short intervals following long delays can be increased by connecting timers in tandem. For example, suppose a 30 ± 3 sec interval once every 24 hr ± 15 min is required. By using a mechanical timer with 1/2% accuracy, the delay specification can be satisfied within 8 min, comfortably below the requirement. To generate with the 24 hr timer 30 ± 3 sec requires a minimum interval accuracy of 0.035%. A simpler way to achieve this accuracy is to actuate a 30-sec interval timer of 10% accuracy. The load switch of the 24-hr delay timer is used to start the motor of the 30-sec interval timer that in turn activates the load.

12-2 MILITARY APPLICATIONS

Mechanical timer systems are used extensively by the US Army in fuzes for various weapons. They are used to accomplish the following functions in a fuze:

(1) Provide an arming delay; where the arming process is controlled so that the fuze cannot function until the projectile is a safe distance from the launching site.

(2) Provide an impact delay; where it is required that the fuze function within a specified time interval after striking a target.

(3) Provide a functioning delay; where it is required that the fuze function a given time interval after launching or emplacement.

(4) Provide self-destruction or sterilization; where the end of the useful life of a munition can be recognized by the time interval after launching or after some other signature.

In most fuze applications, the final action of a timing mechanism will either release another mechanism, or line up an explosive train, and set off a detonator. For details on the design of fuzes see Ref. 5 and for details on mechanical timers, Chapter 13.

12-2.1 GUIDED MISSILE FUZES

Another application of a mechanical timer is in guided missile application where fuzes perform an arming function and a firing function as do other fuzes. The term for the separable arming device is the Safing and Arming (S&A) mechanism.

Since a guided missile is a large, expensive item, a high probability of functioning is

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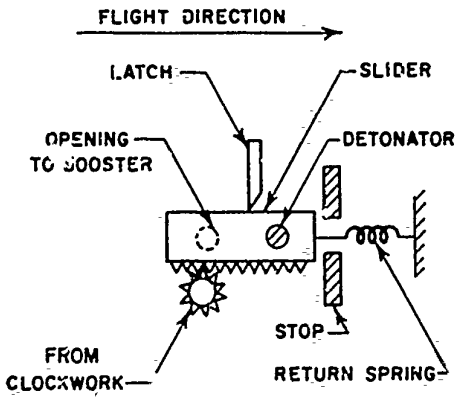


Figure 12-7. Safing and Arming Mechanism

required. Accordingly, multiple fuzing often is employed. The advantage of the multiple units is that the probability of functioning (success) increases exponentially.

The environmental and operational conditions found in guided missiles require the design of fuzes, S&A mechanisms, power supplies, and other components which are peculiar to missile applications. For example, the acceleration of missile upon firing is limited to a value of about 60 g; therefore, the arming mechanism must be designed to operate with this acceleration. Although a wound spring might be used as a source of power to provide for arming a fixed time after launch, as a general rule, any arming system that uses stored energy is considered undesirable from the safety standpoint. Perhaps the best type of arming mechanism for these low accelerations involves a time-acceleration integrator that senses the true launching environment.

Suppose an arming device is required for a hypothetical missile that has the following characteristics: (1) it will arm when under an acceleration of 11 g if this acceleration lasts for 5 sec, and (2) it will not arm when under an acceleration less than 7 g for a period of 1 sec. Consider the arming device shown in Fig. 12-7[6]. Setback forces encountered during acceleration of the missile apply an inertial force to the slider. Thus after a specified time, the detonator will be aligned with the booster and the latch will drop down to lock the slider in the armed position. If at any time during this process the acceleration drops below 7 g, the slider will be returned to its initial position by a return spring. Because of its weight (if not damped), the slider would move too fast under these accelerations; hence, a restraining force is necessary. Therefore, an untuned escapement is used to regulate the motion of the slider. It turns out that this arrangement results in a double integrating accelerometer; i.e., the displacement of the slider is related to the distance the missile has travelled.

An example of this type of mechanism is the Safing and Arming Device, GM. M30A1 shown in Fig. 12-8[5]. This device is, of course, much more refined than the example cited, although the performance parameters for the example were taken from this device.

12-2.2 ARTILLERY FUZES

The mechanical time fuze provides a preset functioning time for an artillery projectile. Fig. 12-9[6] shows the complete timing movement for Fuze, MTSQ, M564. This fuze can be used only in spin-stabilized projectiles because centrifugal force is used to release the escapement lever and permit operation of the timing mechanism. The fuze could be used, for example, on a projectile fired from a 105 mm howitzer.

When a projectile with the M564 Fuze is fired, setback force resulting from the acceleration of the projectile drives the hammer weights of the hammer spring assembly back against the setting lug on the timing disk of the movement. This frees the timing mechanism from the setting pin. Centrifugal force, caused by rotation of the projectile in the weapon, moves the arbor-stop lever outward and unlocks the arbor of the timing mechanism. Simultaneously, the detents move to free the escapement lever.

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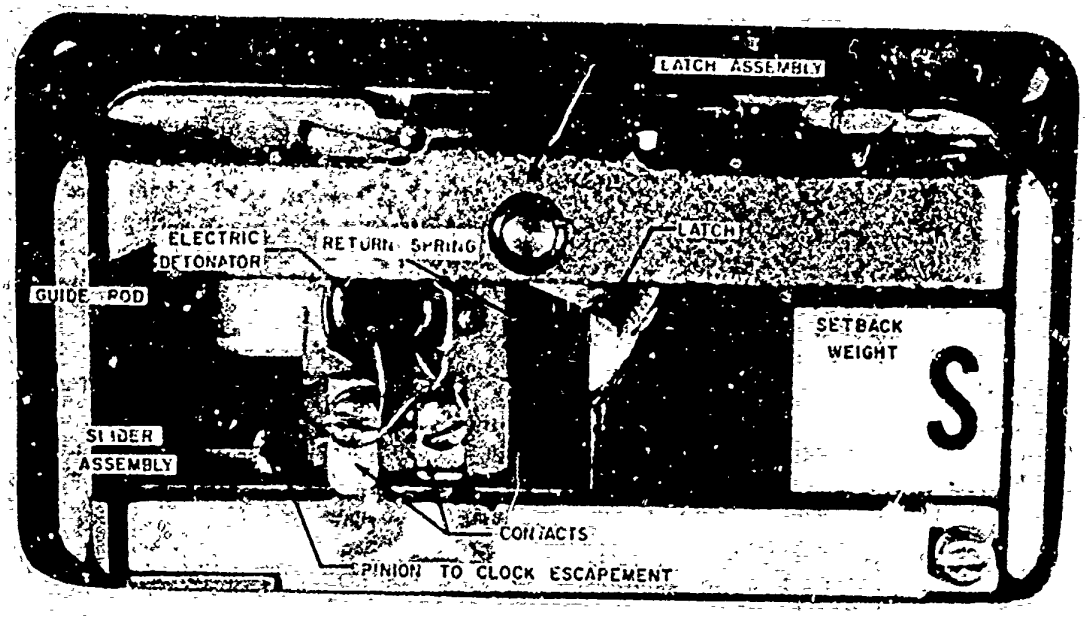


Figure 12-8. Safing and Arming Device, GM, M30A1

The timing movement begins to operate.

The movement is a spring-driven clockwork, which can be set to control a mechanism for releasing the firing pin. When the clockwork is assembled and stored, the driving spring is locked in the wound position by a spring-loaded arbor-stop lever that swings outward against the resistance of its spring when acted upon by sufficient centrifugal force. With the stop lever in the outward position, the arbor is free to turn, and the spring can unwind to drive the gear train. At the set time, the firing arm drops into the firing notch on the timing disk, releasing the firing pin that strikes the detonator. The detonator fires, igniting the explosive train.

12-2.3 ARMING DELAYS

A typical fuze for 81 mm mortar ammunition is Fuze, PD, M525, as shown in Fig. 12-10[5]. The M525 is a superquick, point-detonating fuze that has been quite successful because of its relative simplicity. It consists of two major parts:

1. A head assembly that contains a striker, firing pin, and a clockwork for delayed arming. The striker with tapered striker spring is designed especially to permit the fuze to be fully effective when impact is at low angles.

2. A body that contains the arming mechanism (a slider), detonator, lead, and booster pellet.

The fuze has two pull wires, connected by a cord for easy withdrawal, that remove two setback pins that lock the fuze in the unarmed position to insure safety during storage, transportation, and handling. The wire is pulled with the round immediately over the mortar tube and just ready for release.

Operation is as follows: upon firing, acceleration of the projectile produces setback forces that cause the setback pin to move to the rear. The safety pin is released as

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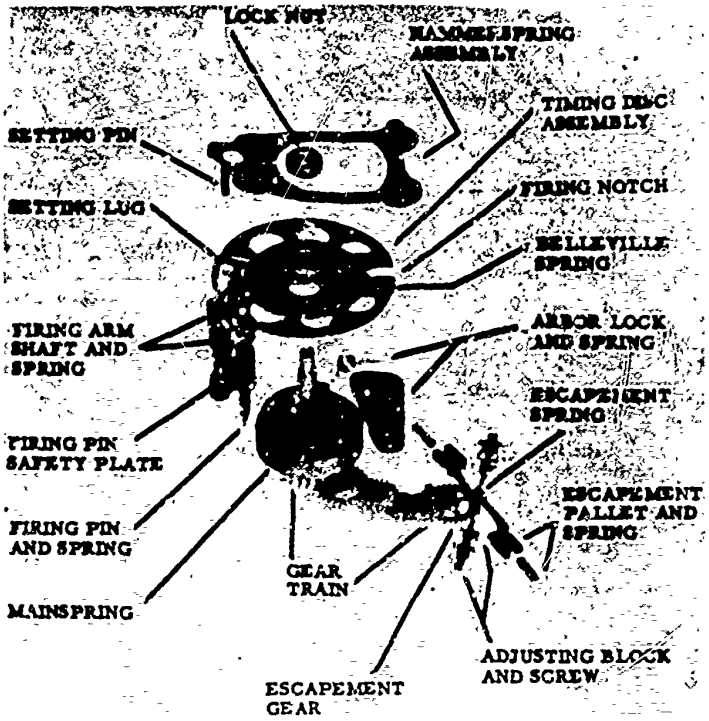


Figure 12-9. Timing Mechanism of Fuze, MTSQ, M564

a result of this motion so that the spring on the safety pin pushes it outward. Provided the projectile is within the mortar tube, the pin rides on the bore. Since the slider therefore still is retained from moving, the fuze is bore safe. The pin is thrown clear of the fuze when the projectile emerges from the muzzle. The firing pin in its rearward position is in the blank hole of the slider so as to act as a second detent on the slider.

Setback also frees the escapement to start the clockwork in the head assembly. At the end of the 3-sec arming delay, a spring causes forward motion of the firing pin, causing it to withdraw from the slider. The slider, then, is prevented from moving until both (1) the projectile clears the tube, and (2) the clockwork runs down.

When the slider is free to move, the detonator in the slide is aligned with firing pin and lead. Upon target impact, the stricker pushes the firing pin into the detonator. The detonation sets off the lead and booster.

12-3 REQUIREMENTS

Some of the basic requirements for a military timer are compactness, low power consumption, low cost, high accuracy, and resistance to shock. Other related factors include simplicity, ruggedness, reliability, environmental compatibility, and resistance to vibration.

Simplicity and ruggedness are really subheadings under the factor of reliability. Simplicity means nonintricate and few components parts, and a minimum need for precision assembly and adjustment. Ruggedness usually follows from simplicity. It means

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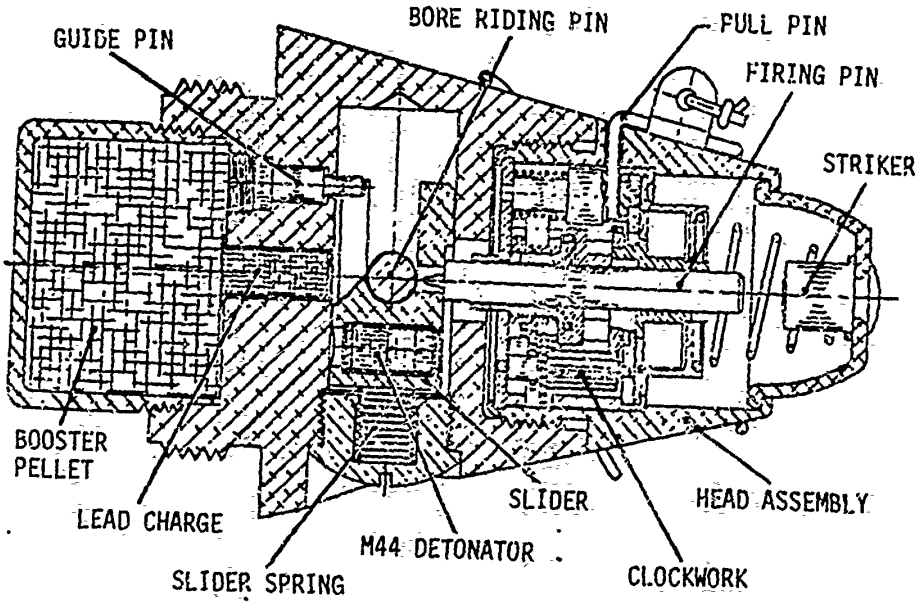


Figure 12-10. Fuze, PD, M525

the ability to withstand and still operate successfully after prolonged storage and exposure to extremes of temperature, humidity, shock, vibration, etc. without the need for periodic maintenance. In this respect, a rugged timer would also be a reliable timer. In regard to ruggedness, the detached lever (tuned three-center) escapement—with its delicate pivots and precision jeweled bearings (if used) that require periodic lubrication, and dirt-free environments and the fine hairspring—does not tend to be very rugged. Shock-mounted bearings and dry lubricants can make this type of escapement more adaptable to military requirements and it has been used with moderate success in bomb fuze timers. In addition, in order to survive high shock loadings, components having a high strength-to-weight ratio often are used.

Actual performance requirements that the various mechanical timers must meet vary with the system in which the timer must operate. A typical set of requirements for an experimental mechanical interval timer are:

(1) Unit to be designed to provide output with an accuracy of ± 0.2 sec

(2) Output selected from six possible firing intervals between 40 and 120 sec with one-knob control

(3) All-mechanical system with volume approximately 6 in.^{3}

(4) Operate over a temperature range –40° to +160°F.

Requirements for a typical time fuze (M564) are:

(1) The unit is to be designed to provide an output between 2 and 100 sec. Timing error is not to exceed 0.18% while spinning at the specified rpm.

(2) Time Range Setting:

Method fuze setter or wrench

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Maximum	100 sec
Minimum (prescribed)	2.0 sec
Divisions	1.0 sec
Setting accuracy	0.1 sec
Setting torque	90-110 lb-in.
Setting direction	clockwise

(3) System: all mechanical

(4) Temperature Limits: −40° and 52°C

12-4 AUXILIARY EQUIPMENT

12-4.1 TORQUE REGULATORS TO COMPENSATE FOR MAIN SPRING RUN DOWN

The beat rate of mechanical timing mechanisms varies to some degree with input torque. This effect is known as torque sensitivity[7]. Because of this torque sensitivity, inherent to some degree in all mechanical escapements, many devices for regulating the torque delivered to the escapement have been developed. Among them are the gravity escapement, the fuzee, and the remointoire or constant-force device. They are attempts to improve on accuracy by minimizing inherent torque variation in the power supply.

A gravity escapement is an accurate clock escapement in which the mainspring or driving weight lifts a small lever, which drops to give an impulse to the pendulum or balance, and is thus independent of the driving force. The fuzee is a conical, spirally-grooved pulley in a time piece from which a cord or chain unwinds onto a barrel containing the spring, and which by its increasing diameter compensates for the lessening power of the spring. The remointoire is a device by which the clock train does not drive the escape wheel directly but rather through an auxiliary mechanism—such as a small spring, or weight, or a DC motor which drives the wheel of the ordinary escapement. Except for the remointoire, these regulators are attempts to compensate for the torque variation due to mainspring run-down.

12-4.2 TORQUE REGULATORS TO COMPENSATE FOR VARIATION IN OUPUT LOADING

In many military applications, instead of having a small fixed load (such as minute and second hands), the timer is asked to throw switches, to turn cams, or to bring rotors into alignment. These functions not only impose relatively large loads on the timing movement but also the loads are often variable throughout the cycle and from one timer operation to another. Therefore, the escapement sees a relatively large variation in torque resulting from the difference between the torque available and the torque applied to the load.

An example of a torque regulator that allows the power supply to deliver varying amounts of torque for external work while maintaining a constant torque to the escapement is the remointoire. The principle of operation is based on the age-old capstan (Fig. 12-11[7]). The input torque is applied to one

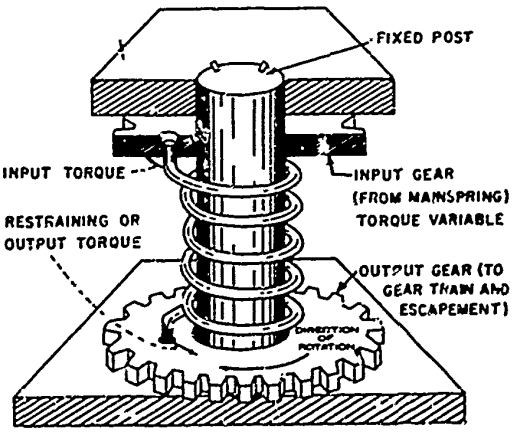


Figure 12-11. Capstan Torque Regulator

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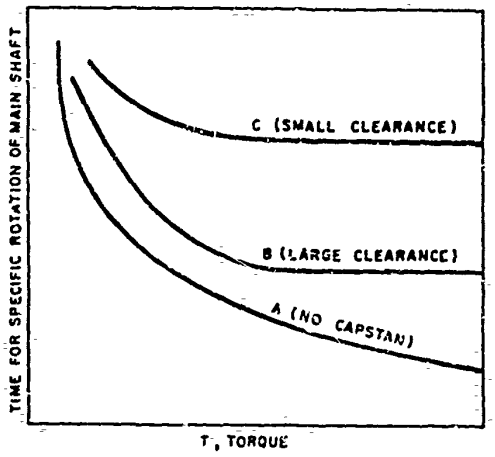


Figure 12-12. Effect of Capstan Regulator on Torque-Time Curves for Runaway Escapements

end of the torsion spring, and the output is obtained from the other end. The ID of the coil is only slightly larger than the OD of the fixed shaft. If the output gear is restrained by an increased load, the input torque causes the coil to deflect angularly, thereby decreasing the ID until contact is made on the fixed shaft, at which time the difference between output and input force follows the torque amplification behavior characteristic of the capstan. For example, in a runaway escapement the time t required for a specific angular rotation of the main shaft is approximately inversely proportional to the square root of the torque, or

$$t \approx \sqrt{\frac{1}{G}}, \text{sec} \qquad (12\text{-}1)$$

where

G = torque, oz-in.

This is plotted as curve A of Fig. 12-12[7] and represents the case when no torque regulation is used. If a capstan regulator were added with large clearance between coil ID and shaft OD, the curve marked B would result. If a small initial clearance were used, curve C would result. The flat ranges of both B and C indicate those portions where the capstan coil is tightly wrapped about the fixed shaft. These curves show that the running rate is constant for relatively large ranges of torque. The capstan regulator is simple, rugged, and inexpensive, and thus is suitable for military applications.

12-4.3 AUTOMATIC DYNAMIC REGULATION MACHINE

Some form of escapement adjustment is required to correct for escapement beat rate variations due to small construction differences. In the pallet type escapement (shown in Fig. 16-27) the stiffness of the escapement spring can be changed by movement of the adjusting nut along the spring. This is done by turning small adjusting screws. Another possible complication is that a particular beat rate is required not at zero spin, but at some rpm close to what the escapement will have when operating in a spin-stabilized projectile. To speed up this adjustment operation of the production phase, an automatic dynamic regulating machine has been designed and is presently in operation at Frankford Arsenal. The equipment works in the following manner[8]:

(1) The fuze movement is held securely in a suitable chuck and allowed to run while being rotated about its geometric center at a rotational velocity simulating free flight conditions.

(2) As the movement is being rotated at constant speed, a beam of light is intercepted by the escapement lever. This beam of light emanates from a light source located directly above the chuck and on the same center line. The light passes through an opening in the movement, is reflected from an inclined surface on one of the movement plates, and leaves in a radial direction. In passing through the movement, the beam is interrupted by one wing of the escapement lever as the lever oscillates. The light leaving the movement

SAMSUNG EXHIBIT 1028, Page 209

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becomes a blinking signal that is pulsating at exactly the same frequency as the escapement. This radial beam then strikes an annular mirror that surrounds the rotating chuck and is reflected to a photoelectric cell. The signal generated by the photocell has a frequency identical to the movement frequency.

(3) The photocell signal is amplified and sent to the printer where it is electromechanically compared with a signal received from a crystal controlled frequency standard. When the movement frequency is correct, the printer records a straight vertical line of dots on a paper tape.

The automatic dynamic regulation machine provides for adjustment of the movement while it is rotating in the chuck. In this sense the automatic machine is a true regulator because it both performs the operation and gives a visual indication of the result. The automatic dynamic regulator is basically the same as the standard machine, except for the addition of a servo control and a special chuck.

The machine operates at spin speeds up to 13,500 rpm and has been tested safely up to 26,000 rpm.

Some advantages of this regulating process are:

(1) Increased output with fewer machines

(2) Increased output with less labor

(3) Improved quality through elimination of human bias

(4) Lower level of skill required because the machine performs the adjustment

(5) Increased capability with substantially lower capital investment.

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SAMSUNG EXHIBIT 1028, Page 210

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CHAPTER 13

MECHANICAL TIMER SYSTEMS

13-1 SYSTEM DESIGN CONSIDERATIONS

When a new military system is being developed, various design goals are determined at the outset. These goals then are defined for each component so that the total system will result in a product that is reliable, combines maximum accuracy with design simplicity, is ruggedly constructed for successful operation in a military environment, and has a reasonable life cost cycle.

13-1.1 DESIGN SPECIFICATIONS

The design specifications are the basis for all development work, whether they relate to an entirely new concept or a modification of an existing unit. By defining the limits within which a product designer may operate, these specifications usually contain: (1) performance factors that must be met, (2) description of associated equipment with which the product must interface, (3) approximate cost to manufacture, (4) operating parameters, and (5) probable environments.

In particular, the requirements for a timer might include:

(1) Delay time range with ability to set in predetermined increments

(2) Accuracy within plus or minus a certain percentage

(3) Operating temperature range −50° to 125°F

(4) Ruggedness, including required operation after impact deceleration of a given number of g's for a given duration in any direction

(5) Military transportation, vibration, environmental, and storage requirements

(6) Maximum space allowable for the unit including the mechanical power supply

(7) Cost goals

(8) Setting considerations, including methods and resolutions.

13-1.2 PRELIMINARY CONSIDERATIONS

The designer of a timer must be thoroughly familiar with the bases for the stated requirements. He then is in a position to evaluate the requirements. Should any of the requirements be too difficult, time-consuming, or costly to achieve, he could then give an intelligent proposal to relax one or more of them in order to reduce the development time and cost risk.

Often the most economical approach to the problem would be to use an existing timer—with perhaps slight modifications—to satisfy the present requirements. Failing this, the next step would be to review various types of timer (literature search, patents, in-house designs, etc.) so that a decision could be made as to which type holds the most promise for the design goals.

Many elements can be considered for use in a mechanical timer:

(1) The time base types include balance

SAMSUNG EXHIBIT 1028, Page 211

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wheel and hair spring, pallet mass and reed spring, inertial governor, tuning fork, counter oscillating rims, and vibrating beam (wire).

(2) Escapements including detached lever and escape wheel; nondetached lever and escape wheel; runaway escapement; crank and cam; cylinder type, nonlinear gear train; and, for electromechanical timers, mechanical switch and electronic armature, and electronic switch and armature.

(3) Power supplies include the mainspring (either spiral power spring or Negator B type spring motor); the remointoire (a means of rewinding the mainspring to regulate torque to the escapement); and, for electromechanical timers, the battery.

(4) Computing systems include gear train counters that can be either straight spur and pinion sets, epicyclic or hypocyclic train, and the harmonic drive and stepping wheel counter.

(5) The outputs (for display or activation of another device) can be either analog or digital.

An excellent way to evaluate the various alternatives is to tabulate each class of component and then estimate the relative suitability of each factor to meet the design requirements. Such a table for the comparison of time bases is shown in Table 13-1[1]. This table was prepared for the development of a long-delay timer for a bomb fuze, and includes electromechanical and electronic time basis. In that study, each of the timer elements was rated by a weighting factor to aid in judgment. This method will give a clear picture of which type of time base, escapement, etc. most likely will fit the design requirements.

Obviously, new designs must provide more than marginal improvements over old systems or they are economically not worth the effort. These improvements would include increased accuracy, higher reliability, greater capability, decreased cost, greater ease of handling, improved safety, etc.

Even though production or shelf-item components are phased into the design, a good designer will conduct all necessary development tests on the assembled item.

TABLE 13-1

COMPARISON OF TIME BASES

				Reliability					
Time base	Weighting Factor, %	Frequency range 15	Accuracy 15	Simplicity 25	Ruggedness 25	Size 5	Cost 10	State of development 5	Total 100
Balance wheel & hairspring		85	70	70	60	80	60	90	70.3
Pallet mass & reed spring		70	60	75	65	75	65	75	68.5
Inertial governor		70	30	85	70	75	80	70	69.0
Tuning fork		50	90	80	75	65	70	80	71.5
Counter-oscillating rims		60	80	80	75	70	70	85	72.0
Vibrating beam (wire)		50	70	40	75	40	40	40	53.3
RC circuit		100	60	70	85	50	60	90	75.8
LC circuit		45	70	70	85	40	55	90	68.0
Crystal oscillator		20	90	30	75	30	30	85	51.5

SAMSUNG EXHIBIT 1028, Page 212

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This should be done for several reasons:

(1) Different components have different shelf lives.

(2) Mating components may possibly be incompatible.

(3) Coupling effects between old and new items may degrade the performance of the new assembly.

13-1.3 ARMING AND FUNCTIONING DELAYS

One of the basic decisions the designer must make is whether to use similar or different methods for arming and functioning. Arming is the changing from the safe condition (that of storage, transportation, and handling) to that of readiness for functioning. Functioning is the succession of normal actions from initiation of the first element to delivery of an impulse from the last element of the explosive train.

The selection is based on the same considerations discussed in par. 13-1.2. For some applications, a combination of mechanical arming and electrical functioning may be optimum and has in fact been used. As far as timers are concerned, the combination of an arming clock and impact functioning is common where no functioning delay is desired.

Timing accuracy is the important characteristic that distinguishes these two applications. For functioning, timing must be precise or else the terminal effects of the munition will be degraded.

The usual tolerance on functioning delay timers is usually less than ± 3%. Arming delays are far less critical, provided they insure safety before and functioning after arming. Common arming delay tolerances are usually greater than ± 10%.

13-1.4 PROTOTYPE DEVELOPMENT

After a review of the requirements has been conducted and decisions as to trade-offs completed, the designer is ready to begin preliminary designs. The choices might typically be narrowed down to two approaches by this time. When available data are not sufficient to eliminate one of the approaches, prototype hardware development could be tested to aid in the selection of the best approach. The prototypes then can be fabricated and made ready for testing.

13-1.5 TESTING

The tests that the prototypes are subjected to simulate or duplicate the forces and environments that the final version will have to survive. The test program is described in par. 13-5.

The failure of either of the two prototypes in any of the tests will entail its elimination from the program. If the performance of either type is marginal, rework or possible complete redesign may be required. The tests then are rerun and, if successful, the design then is reviewed for production methods and tooling requirements.

13-1.6 FINAL ACCEPTANCE

After the prototype is proven to be capable of satisfying all requirements, a testing program is initiated which is based on statistical sampling. The proven timer now will be produced in quantity and integrated into the weapon system.

13-2 GENERAL FACTORS IN DESIGN

The timer used in military applications is a complex device. Certainly, engineering knowledge is required to design the timer so that it will function within the limits set forth in the specifications while working under severe environmental conditions. There are a number

SAMSUNG EXHIBIT 1028, Page 213

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of general design factors that must be considered including reliability, maintainability, human factors engineering, and methods of cost reduction.

13-2.1 RELIABILITY

Reliability is the probability that materiel will perform its intended function for a specified period under stated conditions[2]. It is generally defined as a statistical probability at some confidence level. For example, a system may be described as having a reliability of 99 percent with a confidence level of 95 percent. This means that for a specified period of time we would be 95 percent confident that there would be no more than one failure out of 100.

With respect to the design of mechanical timers, several important considerations have a direct bearing on the reliability of the device. These are:

(1) The escapement system has a self-starting capability.

(2) The number of components parts is minimum.

(3) Parts are simple in design and manufacture.

(4) The need for precision assembly and adjustment is minimum.

(5) Parts must withstand and still operate successfully under extreme environmental conditions.

(6) Materials should be used whose important properties are reproducible and well known to the designer.

(7) As far as possible, timers should be designed so that factors which affect reliability can be detected by means of nondestructive tests or inspection.

The usual practice of providing redundant components to increase overall reliability is not always practical, particularly in military applications. Hence, when the overall system reliability is specified, the components must have higher reliabilities because the overall system reliability normally is the product of the individual component reliabilities. Designers of timers should be aware of the characteristics of the system in which the timers will be used and the desired system reliability so that they can determine the limits in which the timer must perform. Tests to determine reliability sometimes are carried out by a group independent of the design organization. Difficulties in interpreting results can be more easily resolved if the designer is familiar with the techniques used by evaluators, uses similar techniques to assure himself that his designs are reliable, and designs devices in which reliability is as nearly inherent in the design as possible.

13-2.2 MAINTAINABILITY

In regard to maintainability the design engineer should keep the following objectives in mind[3]:

(1) Improve reliability to reduce the need for maintenance.

(2) Reduce the frequency of preventive (cyclic) maintenance.

(3) Improve maintainability to reduce downtime.

(4) Reduce the logistic burden by making full use of standard parts, components, tools, and test equipment.

(5) Make parts, components, and assemblies interchangeable.

(6) Consider modular replacements.

(7) Reduce the requirements for highly trained specialists.

SAMSUNG EXHIBIT 1028, Page 214

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Maintainability must be designed into a system; it just doesn't happen. This places the burden of solving a large part of the maintenance problem squarely on the shoulders of the design engineer. Every designer should attempt to view the maintainability requirements from the standpoint of the maintenance technician.

In selecting components, the designer first should consider the use of proven parts in order to reduce development time and cost.

Current procedure in regard to handling a defective clockwork in a timer is to remove the defective unit, and substitute a new one; thus design for ease of removal of the clockwork is of paramount importance. In many instances, it does not pay to repair a defective clockwork. Interchangeability then becomes significantly important.

13-2.3 HUMAN FACTORS ENGINEERING

Human factors engineering is the scientific union of men with machines so as to enhance the man-machine system. An efficient union requires a knowledge of the performance of both man and the timer parts. The first attempt at understanding a man-machine relationship was made about 1880 and became the "time and motion study" branch of industrial engineering. In a man-machine situation, man is considered the variable with the machine constant. The human factors engineer primarily is concerned with machine or product design to improve the overall efficiency.

When properly applied, human factors engineering reduces the cost of the final product, makes it easier to use in the field, and often means the difference between success and failure. Guidelines for such factors as maximum torque settings, minimum visibility requirements, and other physiological properties have been compiled in reference handbooks[4,5].

For an illustration of human factors engineering applied to time fuzes in tank-fired ammunition, see par. 16-5.2.

13-2.4 COST REDUCTION

There are a number of factors which must be considered in the continuing effort to reduce the cost of manufacture of mechanical timers. These include:

(1) Standard parts

(2) Manufacturing tolerances

(3) Mass production

(4) Material substitution

(5) Corrosion preventive finishes

(6) Ease of maintenance

(7) Simplicity

(8) Ruggedness vs accuracy.

The paragraphs that follow review these factors and are aimed to pinpoint the philosophies involved.

13-2.4.1 Standard Parts

The decision as to whether to adopt an existing timer to a system design or to design a new timer is often one of the most difficult decisions a designer has to make. A new item often has been developed because, in the layout stage, it took less effort to sketch in something that fit the dimensions than to learn what was available. On the other hand, the hard and fast resolution to use only shelf items often has resulted in systems that are appreciably inferior to the best obtainable with regard to reliability, effectiveness, or compactness, and in the perpetration of obsolete items.

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As a general rule, the standard item always must be given first preference and must be considered carefully.

13-2.4.2 Manufacturing Tolerances

All timer parts must be properly toleranced following good design practice. Every length, diameter, angle, and location dimension must be given and defined in tolerances as broad as the performance of the part can tolerate to permit the most economical manufacturing procedure. Particularly in high-volume parts, costs rise rapidly as tolerances are made tighter. All fits must be stipulated. These fits should be chosen with primary concern for function and accuracy. Tolerance stackups indicate whether parts can be assembled properly and whether an assembly will operate as expected. Expected user environments, temperature extremes, and their effects upon critical interference and clearance fits must be considered. It is imperative in the development of mechanical timers that tolerance stackup determinations be complete before manufacture of hardware is begun.

Tolerancing affects the interchangeability of parts. Complete interchangeability is desirable whenever feasible. However, in complex mechanisms, such as timers, where components are small and tolerances are critical, complete interchangeability is often impractical. Selective assembly may be used to conform to the tolerance specifications.

13-2.4.3 Mass Production

Design for mass production using modern machines, tools, jigs, and fixtures has definite advantages in cost reduction. This, in combination with streamlined methods, have proven to be the greatest factor in making it possible to produce large quantities of parts at substantial savings (see par. 14-2).

13-2.4.4 Material Substitution

New material technology is increasing all the time, and the possibilities of substituting materials such as plastics for metals in gear design (i.e., molded gears) warrants continuing review. It must be borne in mind, however, that requirements of ruggedness in timer parts to resist setback and acceleration forces will be difficult to meet with plastics unless through good design these forces are resisted in a manner such that the gearing is not affected adversely. Savings also can be affected by purchasing materials in large quantities.

13-2.4.5 Corrosion Preventive Finishes

The use of corrosion preventive finishes is very important, particularly, for timer assemblies that are stored for future use. If these assemblies are stored for any period of time, the possibility of rust or corrosion build-up can inhibit free running of the timer so that additional work is required to make them ready for use. This increased time and money is prohibitive, and can be avoided by adequate finish specifications.

Closely associated with corrosion prevention is the subject of lubrication. This is discussed in par. 14-2.5.

13-2.4.6 Ease of Maintenance

If the timer assemblies are so designed that they can easily be maintained, a great saving will result (see par. 13-2.2).

13-2.4.7 Simplicity

Simplicity means nonintricate design, few component parts, and a minimum need for precision assembly and adjustment. Overall cost is a function of simplicity and, of course, of the materials used.

13-2.4.8 Ruggedness vs Accuracy

There are a number of accurate timing movements that are manufactured by various clock and watch manufacturers. However, to

SAMSUNG EXHIBIT 1028, Page 216

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adapt these to the stringent environmental conditions that military timers require means that various components have to be strengthened, tolerances have to be reduced for cost savings, etc. These decisions require a series of design trade-offs that must be made by the designer so that the timer will perform at the required accuracy. Only through thorough analysis and testing can these problems be resolved.

13-3 SYSTEMS FOR HIGH ACCELERATION

A timer used in an artillery projectile experiences high forces due to projectile acceleration. Maximum acceleration occurs while the projectile is still in the gun tube. Setback acceleration can be large, up to 50,000 g, and rotation in spin-stabilized rounds reaches 100,000 rpm. Spin introduces centrifugal, Coriolis, and precessional forces. In addition to setback, the projectile also is subjected to linear accelerations in forward and sideways directions.

A typical time fuze designed to operate under setback and spin forces is the Artillery Fuze M564 (Fig. 12-9). Mortar Fuze M525 (Fig. 12-10) is subjected primarily to setback forces.

13-3.1 SETBACK

The force of setback F_s is expressed as[6]

$$F_s = \left(\frac{W_p}{g}\right) a, \text{ lb} \qquad (13\text{-}1)$$

where

W_p = weight of the part, lb

g = acceleration due to gravity, ft/sec^2

a = linear acceleration of the projectile, ft/sec^2

The high setback accelerations (occurring in the gun tube) affect the clock mechanism by causing a "stamping" action in the region near the bearings; this may introduce added friction in the clock mechanism. To overcome this, some clockwork manufacturers subject new mechanisms to very high accelerations to "prestamp" the mechanism beforehand. Since clockworks used in fuzes are not started until the linear acceleration is reduced considerably, the effect of high g forces on the escapement and mainspring need not be considered, assuming of course that the setback did not cause any permanent deformation in either the mainspring or escapement spring.

13-3.2 FORWARD AND SIDEWAYS ACCELERATION

Setforward—a negative setback—is an acceleration in the direction of projectile travel[6]. It occurs when projectiles are rammed into an automatic weapon and after firing. Present time fuzes will withstand about 1000 g setforward.

A sideways acceleration occurs when, upon firing, the projectile aligns itself with the gun tube. For example, the 175-mm field gun and the 120 mm tank gun have such high lateral forces that fuze ogives have broken off[6]. These forces have not been measured; however, the damage was simulated in drop tests by accelerations of 10,000 g.

13-3.3 CENTRIFUGAL FORCE

The centrifugal force vector F_c is directed on a radial line orthogonal to the spin axis[6]

$$F_c = \left(\frac{W_p}{g}\right) r\,\omega^2, \text{ lb} \qquad (13\text{-}2)$$

where

r = radial distance from the spin axis to the center of gravity of the part, ft

ω = angular velocity, rad/sec

SAMSUNG EXHIBIT 1028, Page 217

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Since F_s and F_c are forces applied at the center of gravity of the part that experiences both types of acceleration and since they act at 90 deg to each other, the maximum force F_{max} occurs when the quantity $(F_s^2 + F_c^2)^{1/2}$ is a maximum.

13-3.4 CORIOLIS FORCE

If a part within the timer has a radial component of velocity as the unit spins, it experiences a Coriolis force. The condition is illustrated in Fig. 13-1[6], where a part within a radial slot is allowed to move outward as the body is subjected to a constant angular velocity. The Coriolis force F_{co} is determined by [6]

$$F_{co} = 2v\left(\frac{W_p}{g}\right)\omega, \text{lb} \qquad (13\text{-}3)$$

where

v = radial component of velocity of the part, ft/sec

13-3.5 TORQUE

Torque, the product of a force times its lever arm, occurs within the projectile. If the projectile is increasing or decreasing its spin rate (i.e., an angular acceleration is present), a torque G will be produced on every internal part such that[6]

$$G = I_p \alpha, \text{lb-in.} \qquad (13\text{-}4)$$

where

I_p = moment of inertia of the part, slug-in.^{2}

α = angular acceleration, rad/sec^2

Torque also may be produced from centrifugal effects when the pivot point of the part does not coincide with its center of gravity. Under this condition both a force and a lever arm are present.

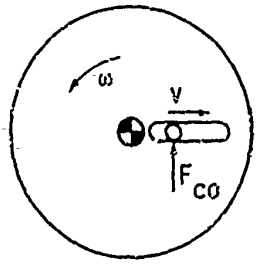
13-3.6 PRECESSIONAL FORCE

If a part experiences a torque about any axis other than its spin axis, it will precess, i.e., it will turn about still another axis. It can be shown (from the equation governing rotating bodies) that the part will turn about an axis perpendicular to both the spin axis of the projectile and the torque direction. The precessional angular velocity Ω is expressed as

$$\Omega = \frac{G}{I\omega}, \text{rad/sec} \qquad (13\text{-}5)$$

13-3.7 EFFECT OF SPIN ON TIMERS

In general, spin will affect a spring-mass clock mechanism so that the timer will run fast. Centrifugal forces acting on the ends of the escapement spring tend to stiffen the spring, thus resulting in a higher escapement-lever frequency as spin speed increases.



F_{cc} = Coriolis Force
V = Velocity
ω = Spin Velocity

Figure 13-1. Coriolis Force

SAMSUNG EXHIBIT 1028, Page 218

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Effects of spin on two types of cylinder escapement are discussed in Ref. 7.

In a study at Frankford Arsenal, the clockwork movements of 56 mechanical time fuzes (T316) were spun at various rates on a production type regulation machine and their rate variation was noted[8]. The movement center was concentric with the center of rotation. Thirty fuzes were initially regulated dynamically to 77.52 Hz (the natural frequency of this movement) at 6000 rpm. The remaining group of 26 was regulated to 77.52 Hz at 12,000 rpm.

Operation of the movement at spin speeds other than their regulation speed caused deviations in timing accuracy. High spin speeds caused the movements to run on the fast side whereas low spin speeds resulted in slow running times. A movement of the type tested regulated at 12,000 rpm and set for 20 sec would have the following errors in running time:

(1) Fired from a 155 mm howitzer in Zone 7 (11,700 rpm), the movement would run approximately 0.025 sec slow.

(2) Fired from a 90 mm gun (17,000 rpm), the movement would have a timing error of approximately 0.500 sec fast.

(3) Fired from the 155 mm howitzer in Zone 1 (5400 rpm), regulated at 6,000 rpm and set for 20 sec, the movement would produce an error of approximately 0.0242 sec slow.

13-4 SYSTEMS FOR LOW ACCELERATION

13-4.1 MUNITION CLASSES

In this category we are dealing with such military items as rockets, guided missiles, grenades, and some mortar projectiles. The components of these munitions experience much lower forces from acceleration, being exposed to about 10,000 g as an upper limit. Setback forces may be calculated from Eq. 13-1. The magnitude of the acceleration is often relatively low, and its duration is much longer than that for high acceleration systems. For some rockets, the duration may be as long as 2 to 4 sec. Arming and functioning of the fuze system by ballistic forces must, therefore, be dependent on this different acceleration-time profile (low acceleration-long time).

A second important characteristic of the munitions in this low-acceleration category is that the munitions usually are fin-stabilized; thus spin forces are negligible.

Bomb fuzes are a special class in this category. Being dropped from aircraft, bombs do not experience setback forces. Like the other munitions in this category, bombs usually have negligible spin.

13-4.2 TIMERS FOR GUIDED MISSILE FUZES

Consider the following typical requirement for a guided missile fuze:

(1) It shall arm when under an acceleration of 11 g, or higher if this acceleration continues for a minimum of 5 sec.

(2) It shall not arm when under an acceleration less than 7 g for a period of 1 sec or more.

A schematic drawing of a possible arming mechanism is shown in Fig. 12-7. The slider can move to the left after overcoming the force of the return spring. After the slider has moved a certain distance, the detonator will be aligned with the booster and the latch will drop to prevent return of the slider. The mechanism is then "armed". If the latch is not permitted to drop in back of the slider, the slider will return to its initial starting

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position when the acceleration is removed. This would be the case when an acceleration of 7 g or less is applied. Note the presence of the clockwork gear which restricts the slider movement. It has been found that the clockwork can provide the time-dependent restraint on the slider to satisfy the given condition (1).

Clockwork devices, in addition to being used for arming, can be used for self-destruct mechanisms. Self-destruction devices are added to rockets and guided missiles to prevent armed ammunition from causing damage if they impact on friendly territory and to prevent capture by the enemy. Mechanical time devices may be used to detonate the bursting charge if the target is missed—i.e., a firing stimulus is not received—and a certain delay time has been exceeded.

The guided missile Safing and Arming Device, GM, M30A1 is shown in Fig. 12-8.

13-4.3 TIMERS FOR BOMB FUZES

A bomb fuze, like other fuzes, must arm at an appropriate time after release and function at or near the target. Time fuzes are used when an air burst is desired. Timing devices for both arming and functioning are used in some of the newer bomb fuzes.

Fig. 13-2[6] illustrates Fuze, Bomb Nose, M198 that contains a timer for both arming and firing processes. See Ref. 6 for a description of its action.

13-4.4 TIMERS FOR GRENADE FUZES

13-4.4.1 Launched Grenades

Grenade launchers, designed to propel grenades farther than they can be thrown by hand, have a range of about 400 m. Since they impart spin to the grenade, both spin and setback forces can be used for arming.

Fuze, PD, M551 (Fig. 13-3[6]) is used for grenades launched from the 40 mm XM79 Grenade Launcher. It functions by impact or graze action. See Ref. 6 for a description of its action. The timer permits arming times of 66 to 132 msec, corresponding to 60 to 120 ft in range of the temperature extremes.

13-4.4.2 Rifle and Hand Grenades

The current standard service rifle is not designed to accommodate a rifle grenade. However, if a rifle grenade is desired, the required timer would be designed like any other low-acceleration system. Rifle grenades are not spun but subjected to setback accelerations of 500 to 1000 g. This setback force in combination with an escapement timer can serve for arming safety. The setback forces may be calculated from Eq. 13-1.

Hand grenades commonly use a pyrotechnic delay element, see par. 21-2.

13-5 STATIONARY AND LONG-DELAY TIMERS

Stationary timers perform in essentially fixed locations; hence, they need not withstand acceleration or spin forces. Very often, the delay desired of stationary timers is long (minutes to hours) compared with that of other military timing systems. Most stationary timers are used for demolition purposes. They occasionally may be used for mines although most mines are triggered by foot or vehicle impact. If the timer output is a switch closing or if the timer is located remotely from the explosive charge, the timer may be used for repeated operations.

There is an occasional need for long-delay timers that can be delivered by a projectile. Naturally, these timers must withstand the acceleration and spin forces imparted by the particular ammunition, and the setback forces upon impact with the ground.

13-5.1 DEMOLITION FIRING DEVICE, XM70

The XM70 (Fig. 13-4[9]) is a mechanical

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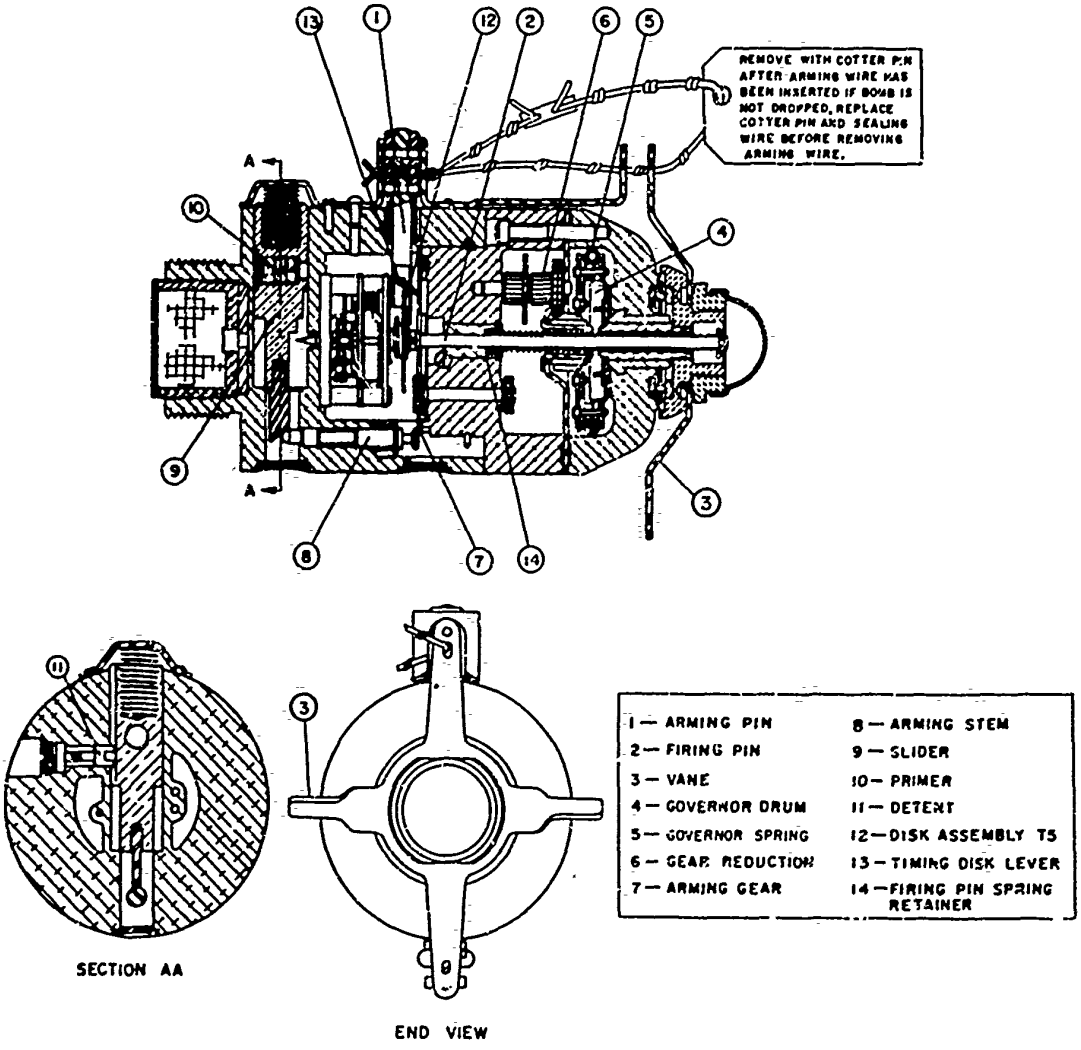


Figure 13-2. Fuze, Bomb Nose, M158

timer. It releases a spring-loaded firing pin after any desired time interval between 5 min and 24 hr. While the timer does not contain explosives, it permits access to its firing pin through a tapped hole in the case (not shown). This hole fits a standard coupling for attachment of primacord, RDX, or other demolition charge. If desired, the firing pin motion can be used to operate a switch in an electric circuit.

The power source for the XM70 is a constant-torque spring motor (negator). The spring also provides two other functions. To set the unit, the spring must be transferred from the storage spool to the output spool. Thus, the amount of spring transferred is an indication of the time interval desired, obviating a separate setting indicator. The constant-torque spring is printed with graduations that represent 5-min intervals when the

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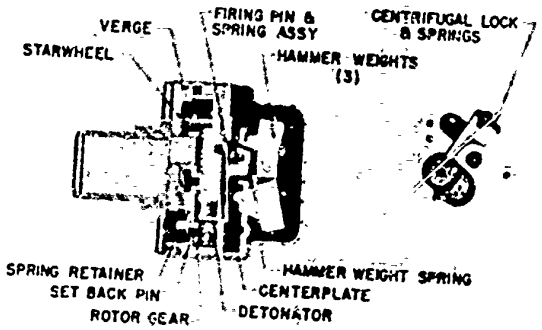


Figure 13-3. Fuze, Grenade, M551

spring is permitted to return to the storage spool at the controlled rate. These graduations are visible through a window in the case. The other function performed by the spring is to serve as a safety latch. A notch in the output spool of the spring serves as the release point for the firing pin. In the unarmed condition the release is held off the spool by the arming mechanism. In setting the XM70, the spring is wound onto the output spool covering the notch. The notch is not uncovered again until the end of the elapsed time at which time the spring-loaded release will drop and permit firing pin motion.

The clockwork of the XM70 is an

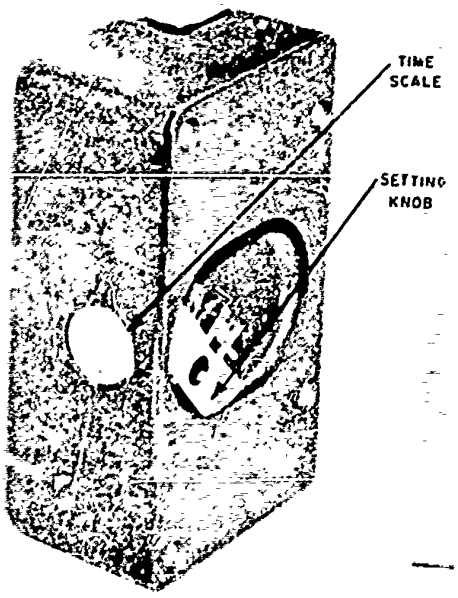


Figure 13-4. Demolition Firing Device, XM70

SAMSUNG EXHIBIT 1028, Page 222

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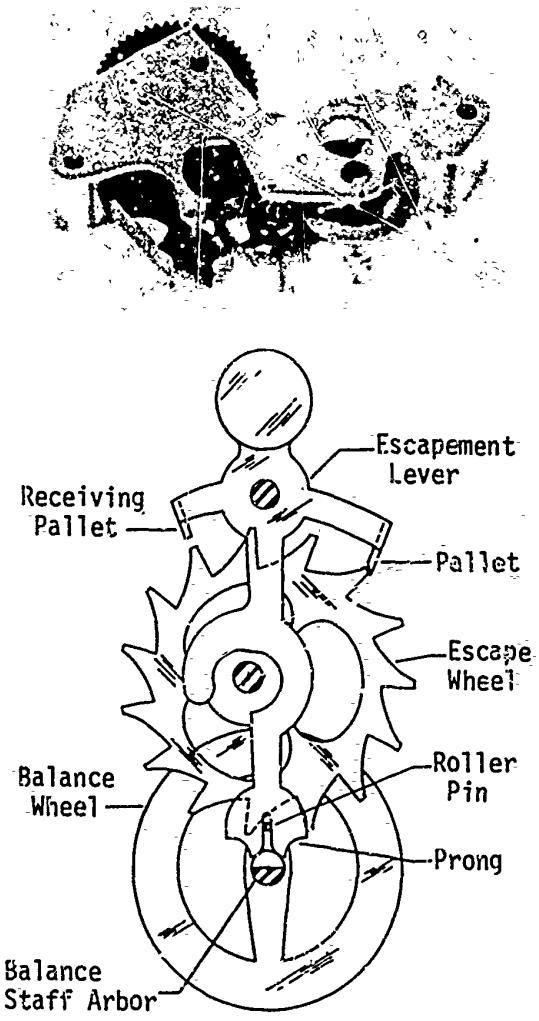


Figure 13-5. Clockwork for Demolition Firing Device, XM70

inexpensive, self-starting detached-lever escapement (Fig. 13-5[9]). The assembly includes –in addition to those linkages required for arming, disarming, and recocking–linkages that prevent the unit from being reset to a different time until it is disarmed. These interlocks insure user safety.

13-5.2 INTERVAL TIMER, XM4

The XM4 is a 30-min delay timer designed to switch three circuits at any time that is set from 5 to 30 min, in intervals of 5 min each. With a luminous dial, it can be set either in daylight or darkness. It is sealed in an olive-drab cylindrical case. A small threaded electric connector extends downward from the lower end of the case while the knob for winding and setting the timer extends upward from the top of the flange. After the case is sealed, the XM4 is completely waterproof. The timer is shown in Fig. 13-6[10] and the

SAMSUNG EXHIBIT 1028, Page 223

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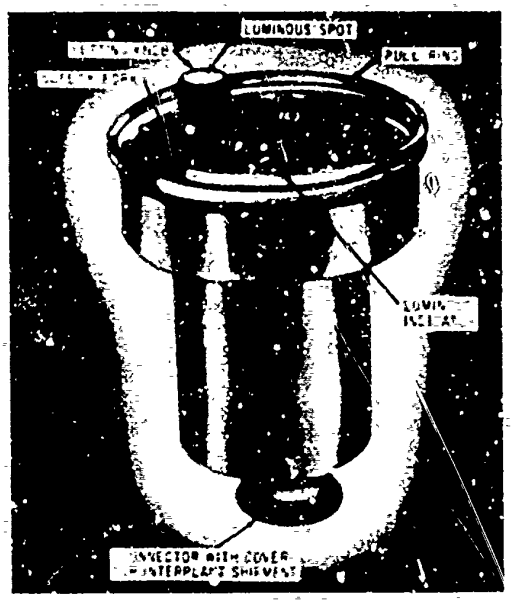


Figure 13-6. Interval Timer, XM4

clockwork in Fig. 13-7[10]. The clockwork is a modified, standard, 15-jewel watch movement. A small torque, supplied by the timing mainspring, is transmitted through the main timing shaft to a release mechanism that controls a switch drive system. The switch drive system is powered by a separate mainspring that gives the larger torque needed to turn the drum of switch. Both clockwork and switch are powered by Dynavar mainsprings that are wound when the timer is set. This makes the XM4 a self-contained unit requiring no external power source.

The XM4 passed all required tests and performs with a standard deviation in timing error of less than ± 1% at all delay settings. Its principal characteristics are shown in Table 13-2[10].

13-5.3 180-HR AIRBORNE TIMER

As an example of a long-delay timer consider the 180-hr airborne timer shown in Fig. 13-8[11]. This timer was developed for use in the Army lunar-probe missile. The chassis of the timer is made up of four plates, and is enclosed in a cylindrical cover measuring 2.75 in. in diameter by 2.06 in. in length. A T787 bomb-fuze clockwork is mounted on the third plate. The mainspring panel is mounted on top of the clock. Since the T787 clockwork only provides a 78-hr running time, the requirement for a 180-hr timer was met by use of the mainspring from the T908 Bomb Fuze.

Three separate electronic switches are controlled by the programmer which is made up of two concentrically mounted commutators. The programmer is suspended between the top and second plates. A dimple motor is mounted in a housing on the third plate. The motor actuates a switch that closes the first circuit and gives a starting kick to the clock mechanism.

Suspended under the third plate is a restarting clock with a free-running verge escapement. It runs during the acceleration period of the first stage of the rocket and gives the main clock a restarting kick if it has been stopped by the acceleration forces. The restarting clock is released under an acceleration of 40 g by the motion of a g-weight that travels on two shafts fixed between the second and bottom plates.

13-6 TIMER SYSTEM TESTING

13-6.1 GENERAL

During the design and development of a timer system, each component is subjected to a number of tests to determine if it performs in the manner for which it was designed. When the prototype is built, it is subjected to performance and proof tests to determine if the prototype satisfies its requirements. Since some of these tests damage the item and, since the available number of items is limited, it is desirable to use special tests and necessary to apply special methods of data

SAMSUNG EXHIBIT 1028, Page 224

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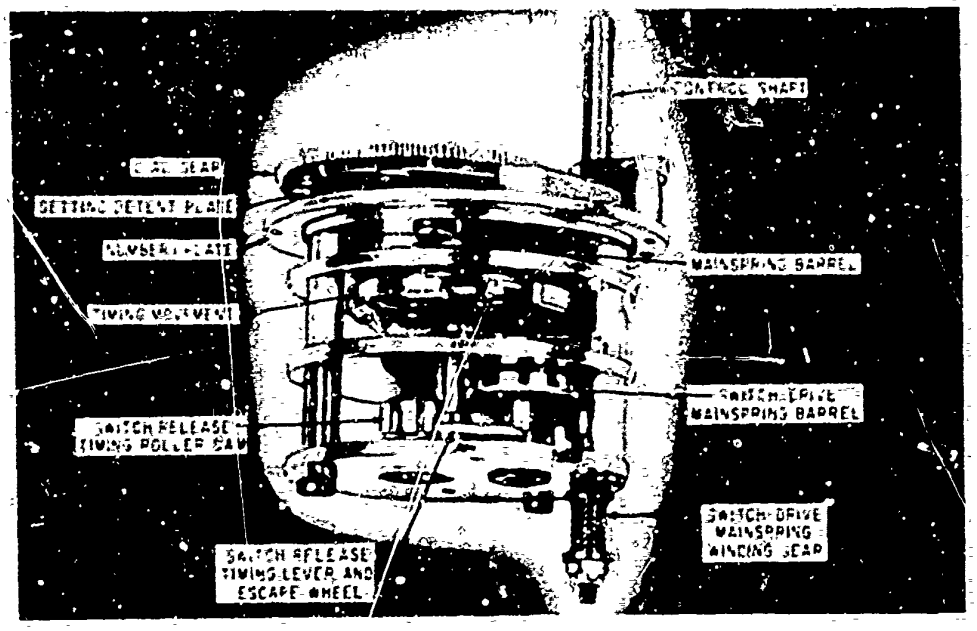


Figure 13-7. Clockwork of XM4 Timer

analysis. There is a definite trend toward test standardization. The pertinent standard tests are indicated in the paragraphs that follow.

13-6.2 PERFORMANCE TESTS

The components of a timer as well as the complete timer assembly must undergo tests to establish that the unit functions properly and does its intended job. *Development* tests are performed to evaluate the designer's latest effort; *acceptance* tests are performed to evaluate the final design and often are called approval tests or evaluation tests. Development tests seek an answer, while acceptance tests confirm it. The tests differ in three respects:

(1) Development tests are applied to individual components; acceptance tests are applied to the entire timer only.

(2) Development tests are severe and run until failure; acceptance tests stop at a predetermined acceptance level.

(3) Development tests are specified by the designer; acceptance tests are specified by a Service Board.

Timers are tested to determine timing accuracy by comparing performance with a timing instrument that is accurate enough to assure compliance with the accuracy requirements in the specification.

If the timer is to be used in a spin-stabilized projectile, the effects of spin upon the timing rate must be investigated to determine the extent of the error. In this test, timers are mounted in a production-type regulation machine that simulates the spin of the projectile. Movements first are regulated dynamically at predetermined frequencies and speeds. Then the movements are spun at various speeds, and timing deviations are recorded.

An important characteristic of many timers is the ability to start or restart by themselves. This feature is tested by subjecting the timer

SAMSUNG EXHIBIT 1028, Page 225

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TABLE 13-2

CHARACTERISTICS OF XM4 TIMER

Type	Interval timer
Materials	
Case	aluminum
Setting system	aluminum, steel, stainless steel
Clockwork	aluminum, steel, stainless steel, 12% nickel silver, Dynavar, gold-plated brass, drill rod, red ruby, commercial watch parts
Switch drive	steel, Dynavar
Switch	aluminum, rhodium-plated beryllium copper, glass-filled diallyl-phthalate plastic, solid-gold contacts, lead
Diameter of case	1.5 in.
Diameter of flange	2.2 in.
Length below flange	2.1 in.
Weight	161 g
Time range	5-30 min
Time intervals	5 min
Temperature limits	−55° and 75°C

to accelerations or other forces and noting the starting performance of the timer.

13-6.3 TEST PROGRAMMING

It is important to plan a test schedule ahead of time. Planning will avoid wasting units in overtesting, and will permit sequential and combined testing when desired. A typical test plan that covers safety and surveillance is shown in Table 13-3[6]. For a given timer design, some of these tests may be omitted while other more appropriate ones may be added—i.e., tests should be consistent with the intended use of the timer. It is important to use enough samples, so that valid conclusions may be drawn, i.e., establish an acceptable confidence level.

The order of testing should be considered carefully. It often is desired to perform sequential tests where the same timer is subjected first to one test, then to another. In this way, cumulative effects, but not synergistic effects, may be evaluated. It also must be remembered that a timer never encounters a simple isolated environment during its service life. Temperature, humidity, and pressure are always present in the atmosphere, and each alters and is altered by the others; it is almost certain the timers will experience rough handling. The JANAF Fuze Committee has suggested a series of tests which evaluates the fuze design under conditions closely simulating combinations of environments as they actually are encountered[1,2].

Timers for fuzes are required to meet a number of environmental and performance tests, described in MIL-STD-331[3]. Tests are either destructive (see par. 13-6.4.1) or nondestructive (see par. 13-6.4.2).

13-6.4 SAFETY TESTS

Safety tests are designed to investigate the requirements for safe handling. There are two types:

(1) Destructive tests where operability after the test is not required.

(2) Nondestructive tests where operability is required.

13-6.4.1 Destructive Tests

In destructive tests, the timer assembly usually is installed in its end item such as a fuze. Forty-foot drop, jolt, and jumble tests are designed to test the ruggedness of the fuze[3]. It is advisable also to conduct these tests at extreme temperature (−50° to 125°F) in order to find out whether the materials or components are vulnerable at these temperatures.

Safing and arming devices for projectile fuzes must pass muzzle impact and impact safe distance tests; for bomb fuzes they must withstand a number of jettison and accidental

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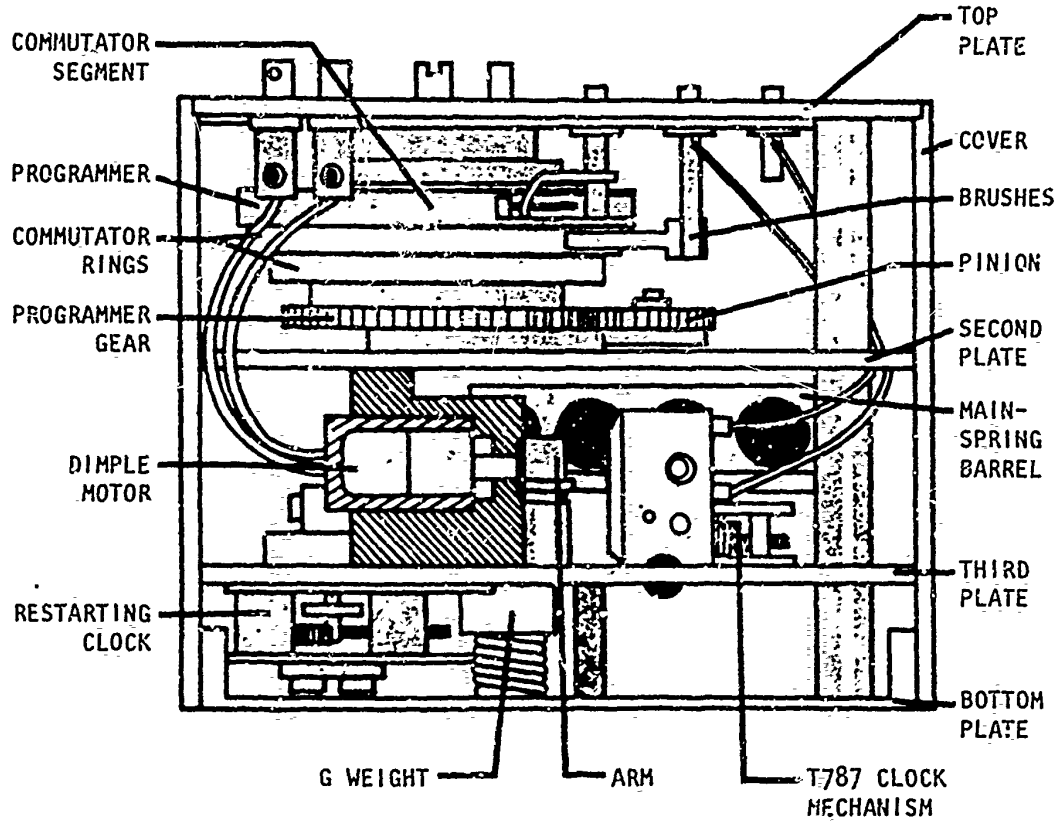


Figure 13-8. Cutaway View of 180-hr Timer

release tests; and for air delivery the devices must be safe in parachute delivery and arrested landing tests[3].

13-6.4.2 Nondestructive Tests

These tests check the performance, ruggedness, and reliability of the timer assembly by simulating actual conditions in which the timer will be expected to perform.

A large group of environmental tests has been standardized to evaluate the performance of timers under various conditions that simulate handling, transportation, and atmospheric conditions. Applicable tests for fuze timers are selected from among transportation-vibration, temperature-humidity cycling, salt spray, five-foot drop, thermal shock, extreme temperature storage, rough handling (packaged), sand and dust, and fungus resistance[3].

TABLE 13-3

SAFETY AND SURVEILLANCE TESTS

Test	MIL-STD-331 Test No.	Typical Quantity
Jolt	101	6*
Jumble	102	6
Five-foot drop	111	10
Forty-foot drop	103	10
Transportation vibration	104	10
Temperature and humidity	105	5
Vacuum-steam pressure	106	5
Waterproofness	108	5
Salt spray	107	2

*Sequential in 3 positions

SAMSUNG EXHIBIT 1028, Page 227

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To check the effect of acceleration upon the timing movement, units are placed in a centrifuge, air gun, or shock machine and subjected to simulated accelerations of the prescribed magnitude[6].

13-6.5 ANALYSIS OF DATA

It is important that the timer system designer use statistical procedures to make certain that his conclusions are valid.

Timers are manufactured in huge lots and only a few are chosen to be tested from the lots. These are selected carefully "at random" so that the sample will represent the lot faithfully. Costs of procuring timers and running tests will limit the sample size. Since economy requires that a small sample be tested, confidence in high reliability cannot be assured. However, statistical principles make it possible to attribute a certain degree of confidence to the results obtained with a given sample size. The designer must determine what compromise between accuracy and economy should be adapted to his particular case.

The concepts of random sampling, frequency distributions, measures of reliability, statistical significance, and practical significance should all be understood by the designer so that he can at least recognize the need for a professional statistician when it arises. The subject of military application of statistics is covered in other handbooks[14-16].

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SAMSUNG EXHIBIT 1028, Page 228

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SAMSUNG EXHIBIT 1028, Page 229

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CHAPTER 14

PRODUCTION TECHNIQUES

14-1 DESIGNING FOR PRODUCTION

A knowledge of production tools, machines, and processes is imperative in working toward the goals of improved production methods and lower manufacturing costs. Manufacturing processes are the primary processes used in the fabrication of engineering materials, and must be kept in mind when considering alternative production procedures and attempts to optimize the production process.

In general, the quantities involved in the manufacture of timer components for military use are large, and hence the philosophy of production is based primarily on the mass production process. In designing for mass production, the designer should be aware of how mass production techniques are applied and the manufacturing methods that are available in modern machine shops. In addition, production of these large quantities must be carefully documented and controlled to assure quality production.

14-1.1 THE PRODUCTION PROCESS

The totality of operations that transform raw materials and blanks that enter the plant into finished products is known as the production process.

The selection of a process for a given operation is influenced by several factors, including the product quality desired, the cost of labor needed, the number of units to be produced, and the materials of construction. When an item can be produced by one of several methods, there is often one best method for a given set of requirements[1].

There are three types of production: (1) unit production, (2) series production, and (3) mass production, namely:

(1) **Unit Production** is the production of single products or of small batches of products with large time intervals between successive runs. Since parts of various dimensions and diverse configurations may be required, universal equipment and general-purpose tools are used. Because of the diversity of the operations, personnel engaged in unit production must have high qualifications. As one might expect, costs may be high and production slow but unit production is optimum for small quantities.

(2) **Series Production** is the manufacture of several products in small batches. One or several operations are carried out at each workplace, and either the entire batch or a smaller group of parts moves together from operation to operation.

(3) **Mass Production** is the steady production of uniform products. The elements of work are of specialized character, and wide use is made of automatic and mechanized tools and devices. For details, see par. 14-2.

14-1.2 IMPORTANT FACTORS IN PRODUCTION

Accuracy as well as reliability are of utmost importance in the production of mechanical timers for military use. Making the parts rugged helps to meet both of these requirements. Processing accuracy is understood to refer to the degree to which the finished parts correspond to the form and dimensions specified in the drawings. Variations in the dimensions of parts produced can result from

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many factors that influence the manufacturing process. A few of these are tool wear, inaccuracy in the machine or cutting tools, nonuniformity of the material being processed, and deformations in the machine tool or part during processing.

14-1.3 STEPS LEADING TO PRODUCTION

During the development of a timer for military use, successful testing of prototypes is necessary before production of the timer. This may require several stages of development, leading to full-scale field tests. At the other extreme, there may be a product improvement and limited testing because the item may be based on a previously successful timer design. The design engineer should collaborate with the production engineer while the timer is still in the design phase to insure that the timer can be mass produced with readily available materials.

14-2 DESIGNING FOR MASS PRODUCTION

14-2.1 THE MASS PRODUCTION PROCESS

Mass production has as its aim the steady production of uniform products. Each workplace is assigned a specific operation, and the elements of work have a narrowly specialized character. In mass production, wide use is made of specialized and automatic machinery, special cutting tools, measuring instruments, and a variety of automatic and mechanized instruments and devices. The product design, technological process study, and equipment design should be complete and thorough because of the large investments required in the preparation for mass production. Details of production are well documented in the literature[2].

The materials, the processes for forming and protecting them, and the skilled hands to use them are available but it is up to the production engineer to integrate these into the optimum combination, not only for a reliable product but also for efficient and economic production. The problem is to establish—for each component of a mechanical timer—the optimum combination of materials and processes to meet the functional requirements of shape, strength, and resistance to chemical and physical hazards.

Other considerations are: (1) timer components must be chemically compatible over the military temperature range with other metals, plastics, lubricants, explosives, or other materials with which they may be exposed, particularly in storage[3]; and (2) the production process must not adversely affect ease of maintenance (see par. 13-2.2).

The choice of the manufacturing process is influenced by the material chosen, the quantity of parts involved, and the compatibility of the parts with the process. Each component is considered as an individual design, with alternate methods of manufacture being assessed on the basis of the processes and materials involved to obtain an effective assembly. Decisions such as the use of punch and shave techniques rather than milling is an example of this weighing of alternatives with respect to economy. Materials and processes also must be considered together because of the possible effect upon each other.

One method that can aid in the choice among different solutions is value engineering analysis. In this method, ways of achieving the objectives are defined and cost or resource consequences are estimated for each way. Basically, a choice must be made between maximizing product capability for a given cost or minimizing the cost for achieving a given objective[4].

14-2.2 COOPERATION WITH THE PRODUCTION ENGINEER

The designer must have a working knowledge of the aspects of production but need

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not be an expert in detailed production techniques. The designer should consult with the production engineer. This should be done at the stage when the mechanical principles have been established and coordinated to meet the specifications but before the design is consolidated to the point where all details are frozen. The production engineer's knowledge of the various processes for forming and fabrication is invaluable to the designer, and his suggestions often can improve the design or its cost-effectiveness.

14-2.3 REQUIREMENTS FOR MECHANICAL TIMERS

The materials, parts, and assemblies used in timers must comply with the requirements stated in the applicable drawings, referenced standards, and specifications. Those for Fuze, MTSQ, M564E3 (see Fig. 12-9) are typical of the requirements for mechanical time fuzes and therefore can serve as an example. (For further details on the data package, see par. 14-4.) The M564E3 is required to

(1) Be made as shown on assembly drawing F10 543 194

(2) Meet all conditions stated in its specification, MIL-F-60802 (MU)

(3) Pass the specified fuze, fuze component, environmental, and performance tests of MIL-STD-331

(4) Be manufactured within the quality assurance provisions of MIL-STD-109, with critical, major, and minor defects as defined

(5) Have surfaces with roughness values according to MIL-STD-63?

(6) Be accompanied by a data card according to MIL-STD-1167

(7) Be packaged as specified

(8) Meet the following requirements for workmanship:

(a) Metal Defects. All components shall be free from cracks, splits, cold shuts, inclusions, porosity, or any similar defect.

(b) Threads. All threads shall be full and undamaged for the length required by the applicable drawing.

(c) Burrs. No parts shall have a burr that might interfere with the assembly or function of the item or that might be injurious to personnel handling the item.

(d) Foreign Matter. No part or assembly shall contain dirt, chips, grease, rust, corrosion, or other foreign matter.

When the assembly to be manufactured contains explosive components, proper safety precautions must be taken, see par. 19-2.

14-2.4 METALS FOR MECHANICAL TIMERS

Part uniformity, tool wear, and manufacturing economy are all affected by the material being used in mass production. It is therefore important that all materials, particularly metals, be uniform in composition. The mechanical properties of metals used in the production of timer components must satisfy the applicable specifications. It is expedient for the designer to use qualified materials when at all possible.

All metals should be either corrosion-resistant or protected against corrosion by appropriate application of coatings[5]. Corrosion due to galvanic action resulting from dissimilar metals also must be considered. General properties and characteristics of the metals used for components of mechanical timers are covered in the following Military Handbooks:

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TABLE 14-1

COMMON TIMER LUBRICANTS

Type	MIL. Spec.	Composition	Comments
Oil	MIL-L-3916[7]	Specified synthetic ester mixture and additives	Low temperature (–40°F) non-spreading lubricating oil
Oil	MIL-L-11734[8]	Specified mixture of C9-C10 dibasic acid esters and additives	Standard fuze oil; used in many mechanical time fuzes over military temp. range
Solid film	MIL-L-8937[9]	MoS_2, graphite, etc. in resin binder	Bonded solid-film lubricant; resin cures at 300°F for 1 hr
Solid film	–	Same as above	Same as above except resin cures at 400°F
Solid film	MIL-M-7866[10]	Powdered MoS_2 min. purity 98.5%	Unbonded; applied by tumbling or burnishing
Solid film	–	TFE Teiomer	Introduced recently

(1) MIL-HDBK-723(MR), *Steel and Wrought Iron Products*

(2) MIL-HDBK-693(MR), *Magnesium and Magnesium Alloys*

(3) MIL-HDBK-694A(MR), *Aluminum and Aluminum Alloys*

(4) MIL-HDBK-697(MR), *Titanium and Titanium Alloys*

(5) MIL-HDBK-698(MR), *Copper and Copper Alloys.*

For example, the metals used in the timing movement of the M564E3 Fuze are aluminum, stainless steel, and brass, in addition to an alloy steel mainspring.

14-2.5 LUBRICATION

A lubricant is expected to perform the jobs of minimizing friction, wear, and galling between sliding or rolling parts. It must do these jobs under two types of condition: (1) those which are inherent in the component element itself – such as load, speed, geometry, and frictional heat; and (2) those which are imposed from external sources – such as temperature and composition of the surrounding atmosphere, nuclear radiation, inactive storage, vibration, and mechanical shock. The imposed conditions are usually the more restrictive ones for lubricant selection[6]; low temperature is particularly significant.

Lubrication itself as well as the selection of the proper lubricant is critical because it affects timer reliability. For example, improper lubrication will prevent parts from moving as intended. A proven lubricant should be selected and employed at the time of material and part design.

A wide variety of lubricants with proven military properties are available. The most commonly used lubricants for escapements, gears, bearings, and linkages are listed in Table 14-1[6]. Modern timer lubrication trends may be summarized as follows:

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(1) Timer components have been successfully lubricated with various oils and dry solids.

(2) Of the oils, the most commonly used is the standard fuze oil (MIL-L-11734). This is as expected since the oil has been standardized for over twenty years.

(3) Solid film lubricants now predominate over the oils because they have better storage characteristics.

(4) The TFE telomer solid lubricant, introduced only a few years ago, appears to have proven itself as an effective and versatile lubricant for timers.

14-3 MANUFACTURING METHODS FOR TIMER COMPONENTS

14-3.1 ESCAPEMENT

The escapement consists of a number of small parts (see Fig. 13-5) that are produced by conventional production techniques[2,11]. In manufacturing the escape wheel the following operations may be used: blanking, tooth milling, punching and shaving, hardening and tempering, face grinding and polishing. Similar operations, used for pallets and levers, are blanking and shaving, milling, piercing, deburring, grinding, and polishing.

The escape wheel must satisfy the following requirements[12]:

(1) Surface finish of at least 63 rms on the working surfaces of the tooth

(2) Accurate geometrical tooth form

(3) Minimum run-out with respect to outside diameter.

14-3.2 GEARS

Production methods for the gears used in the gear train include milling, hobbing, piercing, and blanking. Both involute and epicyloid tooth shapes are used, the selection depending on the factors discussed in par. 16-3.5. The Wickenberg gear tooth design allows greater radial tolerances because of the larger root depth. A minimum of six teeth is used on small pinions in current practice[3].

14-3.3 HAIRSPRING

The hairspring is manufactured by repeatedly drawing wire, flattening it, cutting it to blanks of the required length, coiling the blanks in a barrel to give them the shape of an Archimedean spiral, followed by heat treatment of the coiled springs in order to stabilize their shape (form fixing), and lastly separation of the stabilized hairsprings[12]. Special machines used for these operations are a drawing machine, a rolling mill, a coiling machine, and heat treatment furnaces.

In military timers that use the tuned two-center escapement (see par. 16-4.2), the coiled hairspring is replaced by a straight metal bar that acts as a flexing beam. Manufacturing method is similar except for coiling.

14-3.4 OTHER PARTS

The balance wheel is made by blanking and shaving followed by stress relief using heat treatment furnaces.

Pins and shafts usually are made on automatic screw machines. The plates to complete the assembly are drilled on an automatic jig-borer or the holes can be punched, depending upon the accuracy of dimensions required between holes.

14-3.5 TOLERANCES

Most military components are toleranced to permit complete interchangeability of parts over the entire temperature range. However, in timers, where components are small and tolerances critical, complete interchangeability is not practical. Hence, selective assembly methods are used (see par. 13-2.4.2).

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TABLE 14-2

SUPPORTING DATA PACKAGE

Military Specifications	
MIL-I-45208	Inspection System Requirements including Appendix A, Supplemental General Quality Assurance Provisions
MIL-HDBK-204	Inspection Equipment Design
Purchase Descriptions	
TL-PD-18	Purchase Description for Manufacturing Process Report
TL-PD-37	Purchase Description for Drawing Package
TL-PD-124	Purchase Description for Evincive Data Reports
TL-PD-125	Purchase Description for Preparation of Item Purchase Description
TL-PD-328	Purchase Description for Inspection Equipment Lists
Other Documents	
AR 380-32	Security Classification Guide for Proximity Fuzes and Components
AR 380-130	Armed Forces Industrial Security Regulations
AR 754-10	Conservation of Materials
HDLR 380-10	Thermal Batteries, Security Classification and Controls

14-4 REQUIREMENTS FOR TECHNICAL DOCUMENTATION

Production requires complete documentation. The required documents should be comprehensive and carefully written, and then assembled into a technical data package. A technical data package should comprise the documentation needed to ensure (1) that military items are capable of reliably performing the functions for which they were designed, and that (2) they can be produced promptly and economically by commercial contractors[13].

The content of the technical data package varies depending on the nature of the item being manufactured. A purchase description or specification always is included as are drawings of the item to be constructed. The only exception to the requirements for a drawing is for items that do not commonly require one, such as a can of lubricant. A manufacturing process report is included for the production of items that are unique or require special instructions beyond common manufacturing techniques. A typical data package may contain the following documents:

(1) Specification or purchase description

(2) Drawings and parts lists

(3) Manufacturing process report

(4) Test equipment manuals and drawings

(5) Gage drawings and inspection equipment list

(6) Instructions for preparing a data report.

Other documents sometimes used include security requirements check list, and depot maintenance work requirements. A typical supporting data package used by US Army Harry Diamond Laboratories is shown in Table 14-2[13].

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7. MIL-L-3918, *Lubricating Oil, Instrument, Jewel Bearing, Nonspreading, Low Temperature,* Dept. of Defense.

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CHAPTER 15

PACKING, STORING, AND SHIPPING PROCEDURES

15-1 PACKING

15-1.1 PURPOSE

The basic purpose of military packaging is to insure that items are fit to perform their intended functions when the time comes for their use. Packaging will protect the item after production, during storage, during transport, and until delivery to its ultimate user. During the transportation phase, which includes both handling and carriage, the Department of Transportation (DoT) regulations must be strictly observed. Since items must be stored for long periods in protected or unprotected storage areas, they must be protected against physical damage and deterioration; means also may be required to conduct periodic inspections of the stored material.

15-1.2 OBJECTIVES

The objective of military packaging include: (1) uniform, efficient, and economical packaging; (2) similar items packaged and marked in a similar way; and (3) packaging requirements and materials kept to a minimum.

15-1.3 PACKAGING ENGINEER

The preceding objectives are the responsibility of the packaging engineer. In addition, the packaging engineer is responsible for the development and engineering execution of all aspects pertaining to the preservation, packaging, packing, processing, and marking. His functions and responsibilities are related closely to activities of supply management, field service maintenance, procurement, and production. The role of the packaging engineer and his relation to the design engineer are shown in Fig. 15-1[1].

15-1.4 METHODS

From the military standpoint, good packing methods are those that protect the item through all phases and environments, with a minimum cost. Some questions to be answered as a guide to the packing problem are:

(1) Does the method afford the required protection?

(2) Does the method result in the lowest cost consistent with required protection?

(3) Does the method use noncritical materials?

(4) Are materials readily available?

(5) Does the method require special facilities and equipment?

(6) Does the method permit minimum depreservation effort at time of use?

(7) Does the method result in the least cube and weight, consistent with required protection?

(8) Can the method be easily adapted for mechanization, when conditions such as quantity to be procured warrant?

(9) Does the method provide for reuse of containers for recoverable, repairable items?

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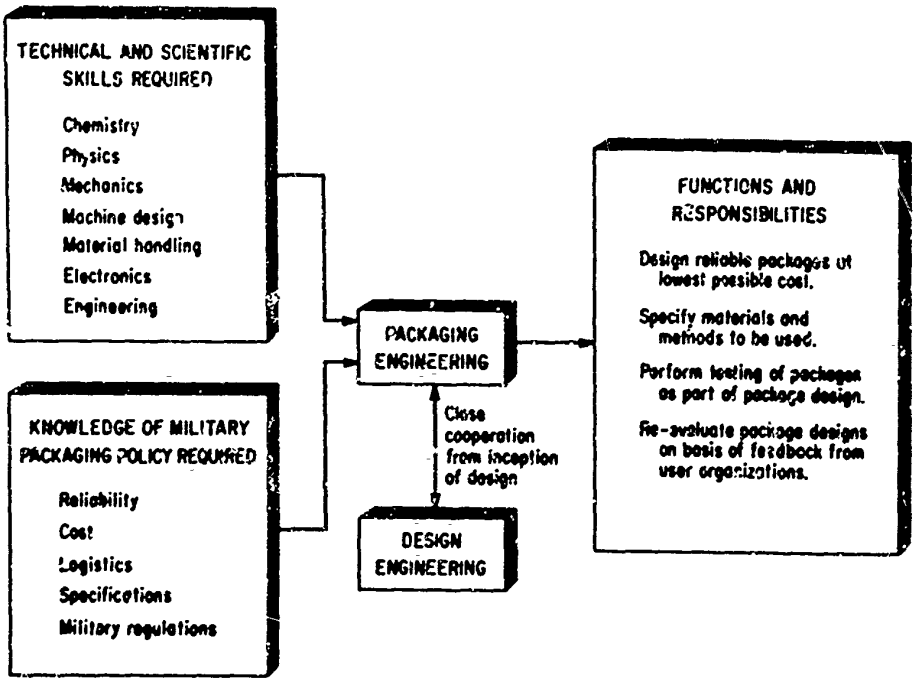


Figure 15-1. Role of Packaging Engineering

(10) Is the method consistent with quantity end-use?

(11) Does the method provide continued protection for more than one like item in a unit pack until the contents are depleted?

(12) Does the method promote uniformity in the application of packaging methods?

(13) Does the method meet statutory requirements?

15-1.5 PROTECTION LEVELS

There are three levels of military protection. The levels of protection are described in terms of the performance expected of the package and must be translated into specific technical or design requirements for individual items or categories of items. The performance criteria are:

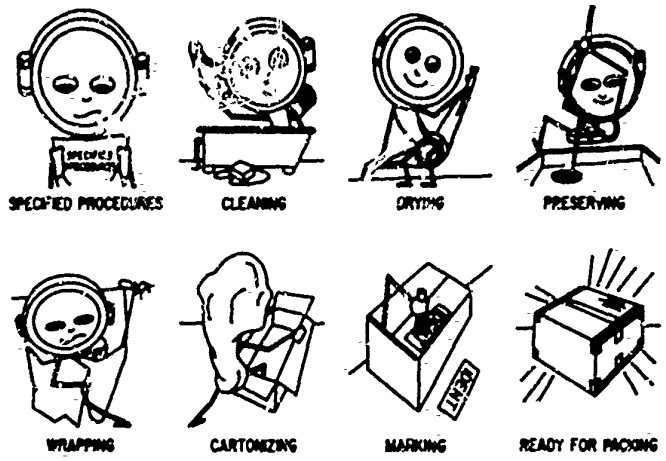
(1) *Level A, Military Package.* Preservation and packaging which will afford adequate protection against corrosion, deterioration, and damage during world-wide shipment, handling, and open storage.

(2) *Level B, Limited Military Package.* Preservation and packaging which will afford adequate protection against known conditions that are less hazardous than Level A is designed to meet. This level provides a higher degree of protection than afforded by Level C. The design of Level B is based on firmly established knowledge of the shipment, handling, and storage conditions to be encountered and on the determination that the costs of preparation are less than Level A.

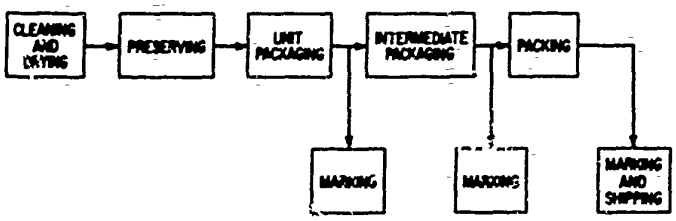
(3) *Level C, Minimum Military Package.* Preservation and packaging which will afford adequate protection against corrosion, deterioration, and damage during shipment from

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(A) BASIC STEPS IN MILITARY PACKAGING



(B) NORMAL SEQUENCE OF PACKAGING STEPS

Figure 15-2. Basic Steps in Military Packaging and Their Normal Sequence

supply source to the first receiving activity for immediate use or for controlled humidity storage.

15-1.6 PACKAGING STEPS

The normal sequence of packaging and the steps which may be followed are shown in Fig. 15-2[1]. The materials and methods which can be used in carrying out each of the basic steps are well documented in specifications and standards.

For cleaning, drying, preserving, and unit packaging the basic governing specification is MIL-P-116.

Standard markings (an example is given in Fig. 15-3[1]) for use on military supplies and equipment to be shipped or stored are given in MIL-STD-129C.

15-2 STORING

All military material must be packaged so that it is capable of withstanding the effects of extreme environmental conditions during storage. The various classes and types of storage for which the packaging engineer must provide are given in par. 15-2.1.

15-2.1 TYPES OF STORAGE

(1) *Class A, Dormant Storage.* The packaged item is protected against the elements by preservation, sealing, covering, or placing in shelter and buildings, either dehumidified or nondehumidified. Items in dormant storage

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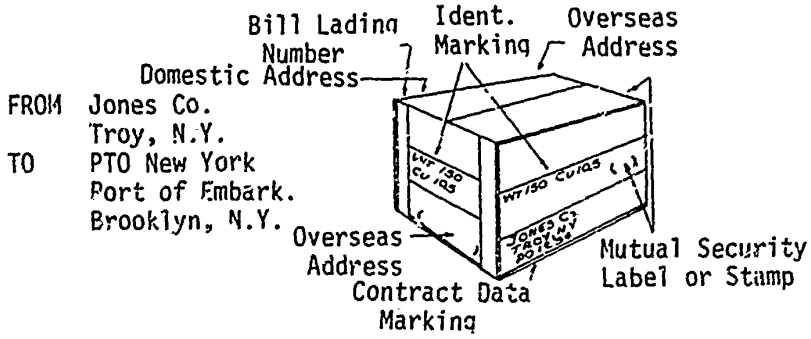


Figure 15-3. Markings for Boxes

are not operated between reprocessing cycles.

(2) *Class B, Active Storage.* The packaged item is protected by the same basic measures as dormant storage except that certain preservation requirements are replaced or supplemented by specific pe- dic exercising, either by running the equipment or by operating the equipment with an external power or driving source.

(3) *Type 1, Outside Storage.* The storage area is exposed to the extremes of local, natural environments. The stored item must be protected from all weather elements as well as fungus, pests, dust, pilferage, and the unpredictable results of idle curiosity. For open storage, maximum use of known packaging methods and materials is specified to insure the protection of the material. Surveillance and maintenance are required to minimize deterioration.

(4) *Type 2, Sheltered Storage.* The material is stored in ventilated or unventilated, heated or unheated buildings and shelters. The stored material is not protected from atmospheric changes of temperature and humidity. Surveillance and maintenance are required to keep deterioration to a minimum.

(5) *Type 3, Dehumidified Structural Storage.* The material is stored in structures in which the atmosphere is maintained at a relative humidity of 40% or less. Controlled humidity provides the highest degree of protection, and little surveillance and maintenance are required.

(6) *Type 5, Dehumidified Nonstructural Storage.* The material is stored in completely or partially sealed packages with a mechanical or static dehumidification of each item, single or in series, with the relative humidity of the atmosphere within the interior areas not exceeding 40%. Inspection and surveillance are required to ensure constant protection.

15-2.2 STORAGE OF EXPLOSIVES

The storage of devices containing explosive material is controlled by the potential hazards of the explosive. Explosives must be stored in standard ammunition magazines designed for this purpose and in special areas. These areas generally are not heated nor wired for electricity. The package must be labeled to identify the contents as explosives and to indicate the explosive classification. Periodic surveillance and inspection are required. For additional details, see par. 20-5.

15-3 SHIPPING

15-3.1 TRANSPORTATION ENVIRONMENTS

During transportation the most damaging

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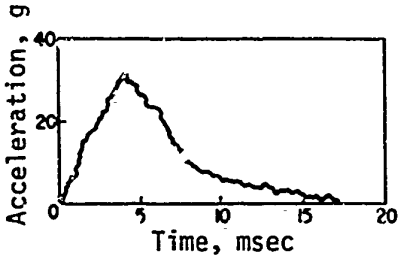


Figure 15-4. Plot of Typical Shock Motion

environments are from shock and vibration. Vibration is an oscillating motion which can be either repetitive or transient. Shock connotes impact, collision, or a blow, usually caused by physical contact. It denotes a rapid change of loading or a rapid change of acceleration with a resultant change of loading.

Although an equation may be developed to define a particular shock motion, actual shock motions are usually complex and can best be described graphically. A typical example is given in Fig. 15-4[1] where acceleration is used as the parameter. Velocity or displacement also could have been used as the parameter. There are a variety of possible shock motions because pulse shape, duration, and peak acceleration may vary[2,3].

15-3.2 TRUCK TRANSPORT

When considering truck transport, we are concerned mainly with the effect of vibration on the cargo. Vibration frequencies in motor trucks are determined by:

(1) The natural frequency of the unsprung mass on the tires

(2) The natural frequency of the spring system

(3) The natural frequency of the body structure.

The amplitude of vibration depends on

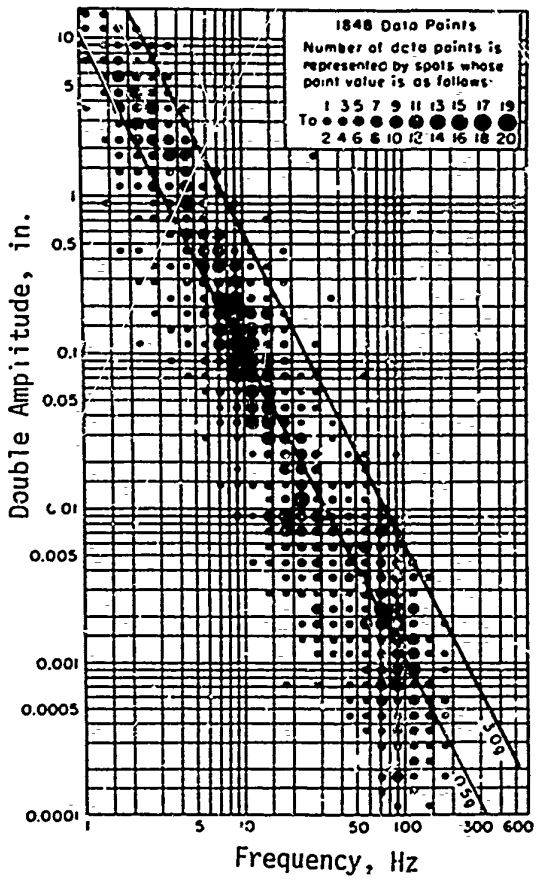


Figure 15-5. Truck Transportation Vibration Data

road conditions and vehicle speed. Intermittent road shocks of high magnitude can occur, with resultant extreme truck body displacements. If the cargo is not secured, it may be severely damaged. The predominant natural frequencies of various military transport vehicles, as measured in the cargo space, are given in Table 15-1[1]. Fig. 15-5[1] presents vibration data measured in the cargo space of trucks and trailers.

15-3.3 RAIL TRANSPORT

Freight car vibrations are caused by track and wheel irregularities, and occur principally in the lateral and vertical directions. The most damaging phases of rail shipment are those

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TABLE 15-1

PREDOMINANT FREQUENCIES MEASURED IN CARGO SPACES OF VARIOUS MILITARY TRANSPORT VEHICLES

Type of Vehicle	Direction of Acceleration	Predominant Frequencies, Hz		
		Springs	Tires	Body
Truck (2-½ tons)	Vertical	2 to 4	8 to 13	70 to 180
	Longitudinal	–	10 to 20	70 to 100
	Lateral	2	10 to 20	100 to 200
Truck (3/4 ton)	Vertical	2 to 3	5 to 10	60 to 110
	Longitudinal	–	–	70 to 100
	Lateral	–	–	60 to 70
Trailer (1 ton)	Vertical	3 to 5	8 to 10	50 to 100
	Longitudinal	–	–	50 to 100
	Lateral	2	–	50 to 120
M-14 Trailer	Vertical	1 to 4	7 to 10	50 to 70
	Longitudinal	3 to 4	8 to 10	200 and greater
	Lateral	2 to 4	–	–
M1, 2T Trailer	Vertical	2.5 to 5	7.75 to 10.5	100 to 150

shock and transient vibrations that occur during coupling, starting, and stopping[4].

Fig. 15-6[1] presents data on the number of occurrences of shock of various levels recorded on the floor of a freight car during a 700-mile trip. Lateral and vertical shock occurrences are plotted against car speed. Table 15-2[1] shows the percentage of travel time in each speed range during the 700-mile trip. The duration of the shock impulses was estimated to be between 10 and 50 msec.

By observing a representative number of railroad operations, Fig. 15-7[1] was constructed. It shows the velocity of impact during switching versus the percentage of occurrence at each velocity. From this figure, 7 mph is obtained as the approximate mean speed of impact. This is above the 5-mph limit for which the switching gear provides cushioning protection. The maximum longitudinal acceleration at various impact velocities from 1 to 7 mph is plotted in Fig. 15-8[1].

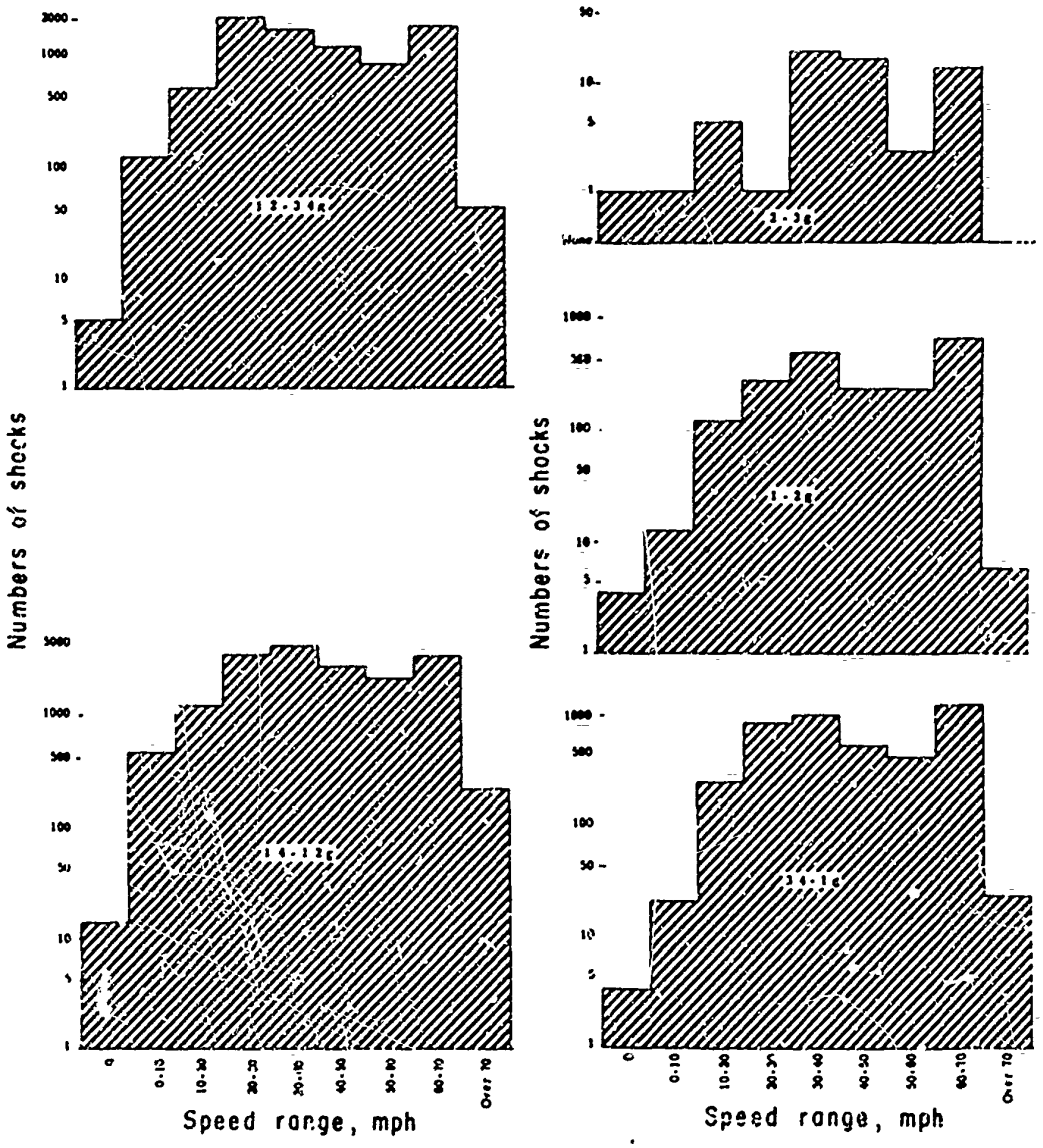
15-3.4 AIR TRANSPORT

The loadings that are important during air transport are those that occur during flight in rough air. The in-flight shock and vibration environment is generally not too severe. The dynamic loadings are differentiated from shock loadings in that they consist of fairly high magnitude acceleration imposed for a prolonged period of time. These accelerations can be as high as 2 to 3 g during normal operation of large transport aircraft.

The most damaging conditions encountered during air shipment are the shocks resulting from handling operations. This is shown in Fig. 15-9[1] which is a plot of the maximum shocks recorded during a test shipment by a major airline. For the test, two impact recorders were placed in a wooden box whose total weight was 73 lb. Both longitudinal and vertical shocks were recorded.

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(A) VERTICAL SHOCKS MEASURED ON FREIGHT

Figure 15-6. Freight and Freight Car Shock Measurements

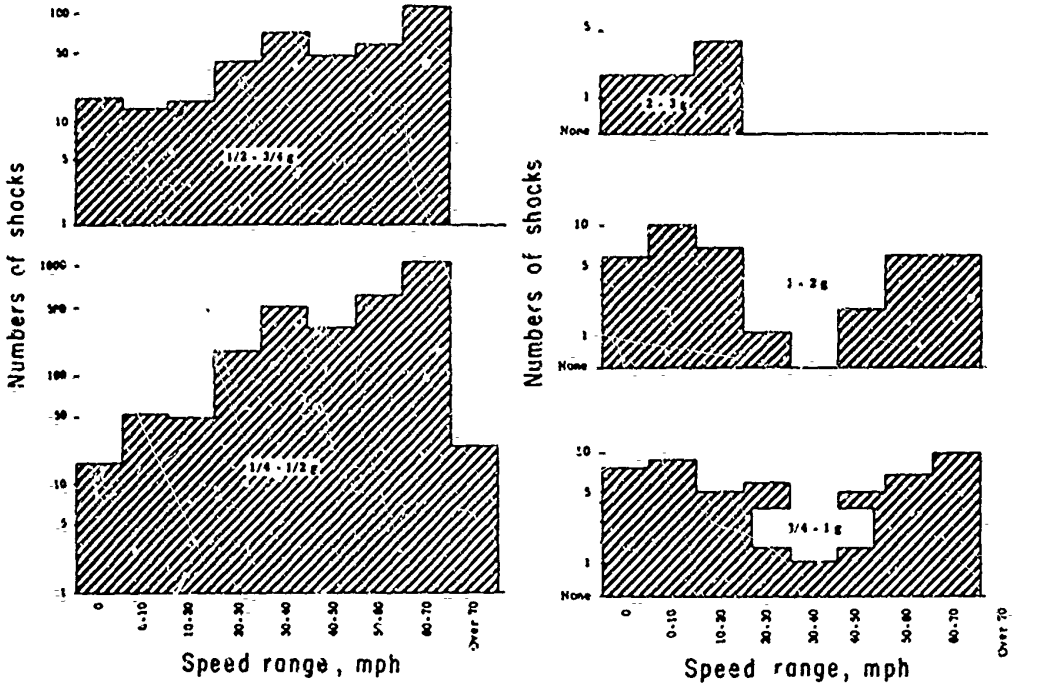
15-3.5 SHIP TRANSPORT

Vibrations are produced in ship structures from an imbalance or misalignment of the propeller shaft system and the flow of water from the propellers around the ships' hull. The frequency range of these vibrations is about 5 to 25 Hz, with acceleration reaching a maximum of about 1 g.

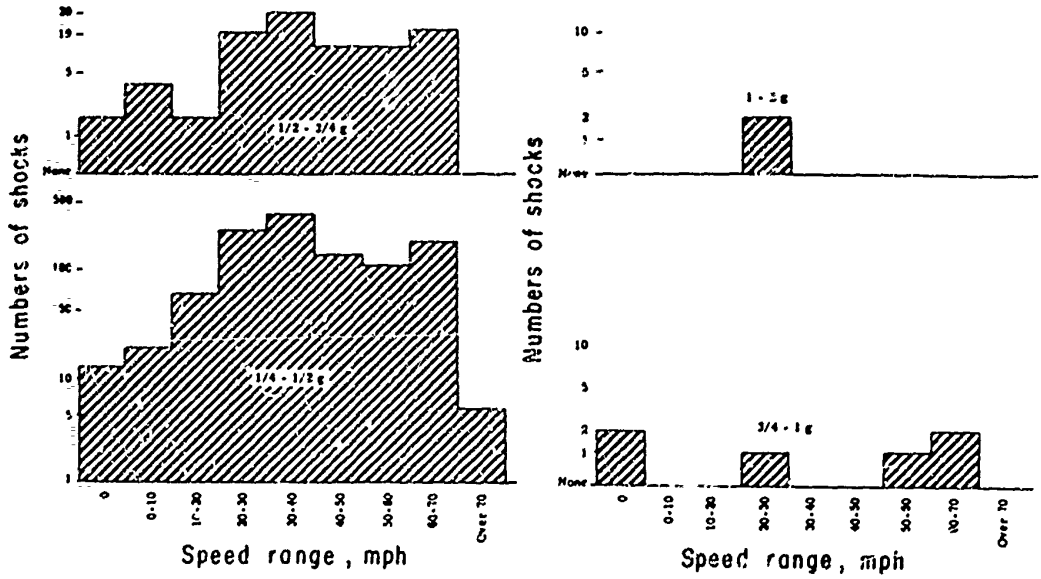
During normal voyages ship cargos do not experience damaging shocks. The highest shocks occur during loading and unloading operations.

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(B) LONGITUDINAL SHOCKS MEASURED ON FREIGHT CAR FLOOR



(C) LATERAL SHOCKS RECORDED ON FREIGHT CAR FLOOR

Figure 15-6. Freight and Freight Car Shock Measurements (Cont'd)

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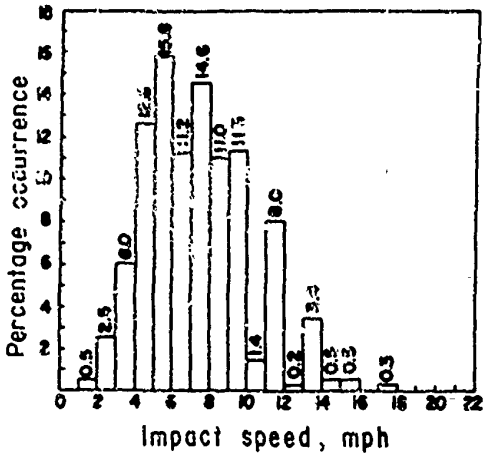


Figure 15-7. Impact Speed During Freight Car Switching Operations

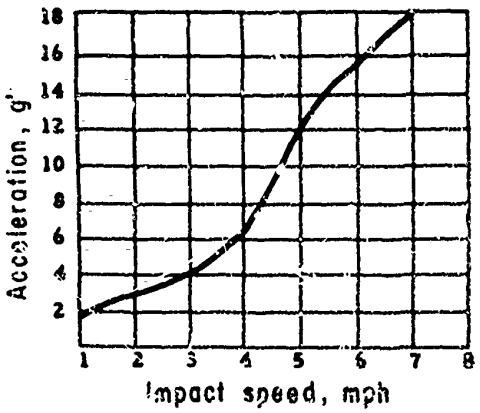


Figure 15-8. Maximum Longitudinal Acceleration of Freight Car Body vs Switching Impact Speed

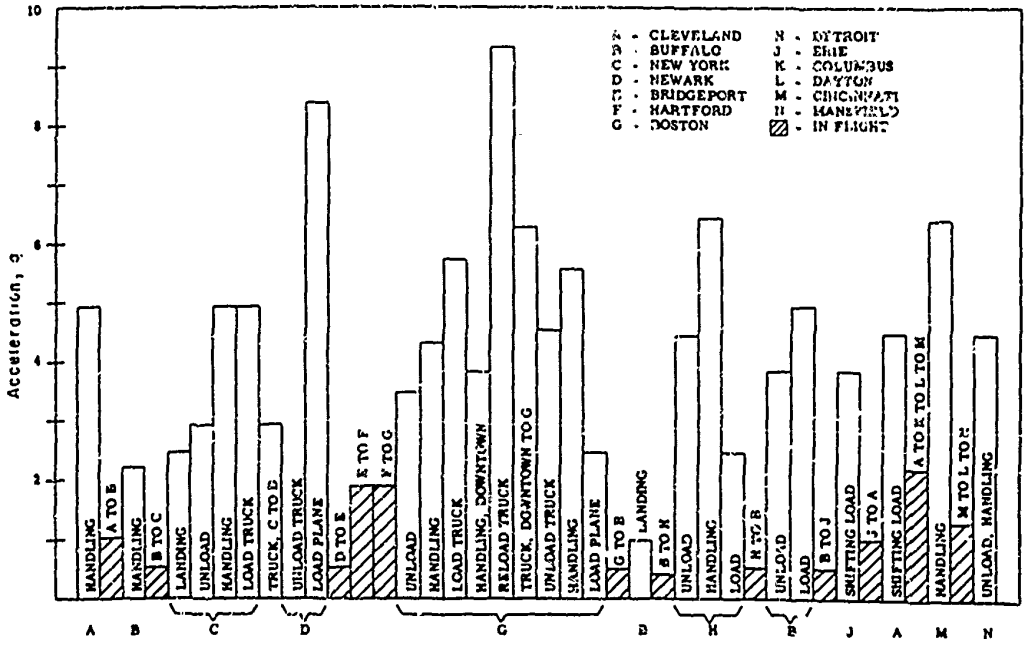


Figure 15-9. Maximum Shocks Recorded During Airline Test Shipment

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TABLE 15-2

PERCENTAGE OF TRAVEL TIME VS SPEED RANGE FOR FIG. 15-6

Speed Range, mph	Travel and Recording Time, %
0	9.3
0-10	14.3
10-20	9.4
20-30	20.3
30-40	21.2
40-50	10.8
50-60	6.1
60-70	8.3
over 70	0.3

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CHAPTER 16

COMPONENT DESIGN

16-1 INTRODUCTION

All timers can be considered to be composed of 5 separate components:

(1) An *Actuator* to start the timer

(2) A *Power Supply* or source of energy

(3) An *Escapement* (Frequency Converter) that serves as the time base, periodically releases energy, maintains the oscillations, and in some movements activates the counting system

(4) A *Counting System* that counts a predetermined number of oscillations

(5) An *Output* such as a settable readout, or switch closure, or cam rotation which provides an output pulse.

Using different combinations of these components, many types of timers can be constructed. Some of the factors that must be considered in the design of a mechanical timer are:

(1) Timing accuracy required

(2) Duty cycle required

(3) Spin environment (max rpm)

(4) Acceleration environment (max g's)

(5) Allowable gross weight

(6) Allowable gross volume

(7) Temperature extremes (operational and storage)

(8) Number and type of outputs required

(9) Pressure environment

(10) Allowable impact shock (direction and amplitude)

(11) Allowable vibration.

A good timer design has the following features:

(1) Reliability of action

(2) Resistance to damage in handling and use

(3) Resistance to deterioration in storage

(4) Simplicity of construction

(5) Adequate strength in use

(6) Compactness

(7) Ease of manufacture

(8) Economy of manufacture.

The last item, economy of manufacture, deserves special note because it affects each of the preceding features. The best way to achieve economic mass production is to use as many as possible proven components from previous timer designs. The designer therefore should be acquainted with the characteristics of military timers. New designs require extensive tests before economy can be assured.

The most common military usage of mechanical timers is in the mechanical time

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fuze. The timer clockwork is an integral part of a mechanical time (MT) fuze, and thus is subjected to and must pass all tests that fuzes are subjected to. The development of the clockwork will occur concurrently with the development of the fuze. The clockwork for MT fuzes used in projectiles may be called upon to operate in the time interval between the instant of firing to the initiation of the primer. Thus the forces existing within the realm of interior ballistics, exterior ballistics, and terminal ballistics must be considered. Disturbing forces are created on delicate clockwork mechanisms from setback, spin, temperature variations and extremes, and impact decelerations. These forces will cause the timepiece to deviate from its at rest behavior. Therefore, materials used for the clockworks should be strong, light as possible, and properly lubricated.

Fig. 12-2 shows a mechanical timer and a block diagram of its five basic components. The *Time Base* is a mechanical escapement; the *Counter* is a gear train; the *Output* is a cam operated switch. The *Power Supply* is a mainspring driving the output shaft; the *Actuator* holds the escapement until removed.

16-1.1 DESIGN CONSIDERATIONS

16-1.1.1 Tactical (Fuze Timers)

Mechanical fuze timers are designed for different tactical situations[1]. They may be used with various ammunition items such as artillery projectiles, aircraft bombs, sea mines, small arms projectiles, rockets, and guided missiles. Each series has its own tactical requirements and will experience different environmental forces during operation and storage. A mechanical timer may be designed for one specific round or it may be functional and applicable to a given series of one type of projectile. For example, it may be used with all HE projectiles that can be fired from howitzers and guns ranging from 75 mm to 155 mm. The latter type timer will experience muzzle velocities ranging from 420 to 3000 fps. Some of the tactical situations that the timer will be subjected to are: ground detonation (surface or after penetration), or air burst.

16-1.1.2 Environmental

Environmental conditions will influence type of materials, method of sealing, design of component parts, and method of packaging.

(1) Operating Temperature. The timer must withstand temperatures ranging from an air temperature of 125°F (ground temperature of 145°F) in hot-dry climates to an air temperature of −50°F (ground temperature of −65°F) in cold climates. Temperatures can drop to −80°F in bomb bays of high-flying aircraft, and aerodynamic heating can raise the temperature of missiles launched from high speed planes above 145°F[2].

(2) Storage Temperature. −70° to 160°F, operable after removal from storage.

(3) Relative Humidity. 0 to 100%.

(4) Water Immersion. For certain applications the timer may be required to be waterproof. For this test, the timer must be operable after immersion in water at 70°F ± 10 deg F under a pressure of 15 ± 5 psi for one hour.

(5) Rough Treatment. The timer must withstand the rigors of transportation and rough handling.

(6) Fungus. The timer must not support fungus growth.

(7) Surveillance. Operable after 10-20 yr storage.

16-1.1.3 Safety

Another of the designer's important consid-

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erations is safety in manufacture, in loading, in transportation, in storage, and in assembly to the operating system. This applies to timers in fuzes which initiate an explosive train.

16-1.2 TIMER ACCURACY

It has been reported that accuracies under 0.1% can be achieved with mechanical timers employing tuning forks or crystals for their time base. The best spring-mass systems can approach 0.5% in timer accuracy. Increased accuracy generally costs more.

Spring-mass systems are best employed for long time durations where the frequency of the spring-mass can be 5 Hz or lower. For time intervals of fractions of seconds, the tuning fork or crystal time base operating at 1000 Hz or higher may be used. Spring-mass systems operating at high frequency (above 100 Hz) can provide for good timer accuracy for short time intervals[3].

All timers have some inherent error in their operation. Proper adjustment can reduce this error to a lower limit depending on the type of mechanism. Spring-mass timers commonly available may have errors ranging from 30 sec per day to 0.1 sec per day, with the cost of the timer increasing as the inherent error decreases[4].

Environment also will affect timer accuracy. Special modifications must be made when the timer is to operate at extremely low or high temperatures, or under vibration or shock. Operation in the military range of −50° to 125°F requires special design and assembly techniques. Table 16-1[4] shows environmental temperature effects on various types of timepieces.

16-2 POWER SOURCES

The power supply provides the torque required to operate a mechanical timer. The five types of power supplies which may be applied are spring motors, centrifugal drives, AC motors, DC motors, and ram air.

16-2.1 SPRING MOTORS

There are basically two types of mainspring motors*, the spiral spring and the "constant-force" negator. These are shown in Figs. 16-1 and 16-2, respectively. The spiral spring can be made more compact for small outputs because only one spring panel is required, whereas the negator spring must use a storage drum and a separate output drum. The negator spring is capable of producing more usable energy from a spring of equal dimension, because it supplies a constant usable torque throughout its entire length. Another advantage of the negator spring is that no interleaf friction is present since the spring uncoils with a rolling motion. The constant torque negator is especially desirable with torque-sensitive escapements. Compared with battery supplies, mainsprings generally have the advantage of lower cost, greater ruggedness, larger storage life, and better low-temperature operating capability.

16-2.1.1 Torque

For the spiral spring the factors of torque, stress, width and thickness are related to each other

$$G = \frac{\sigma b h^2}{6}, \text{ lb-in.} \qquad (16\text{-}1)$$

where

G = torque, lb-in.

σ = stress, psi

b = width, in.

h = thickness, in.

*When a strip of spring steel is wound around itself so that each turn touches the next, these are known as power or motor springs. Small spiral springs when wound with space between the coils are called hairsprings. Hairsprings can be analyzed theoretically more easily than power springs because the disrupting factor of surface friction between coils is not present.

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TABLE 16-1

APPROXIMATE ACCURACIES OF TIMEPIECE TYPES

Timekeeper	Temperature Range, °F					
	−30° 150°	0° 120°	30° 120°	50° 90°	72°	Constant Temp
Chronometer	D	C	B	A	A	A
Chronometer Watch	D	D	C	B	A	A
Balance-Driven Clock (adjusted)*	D	D	C	B	B	B
Balance-Driven Watch (adjusted)	D	D	D	C	C	C
Balance-Driven Clock (unadjusted)	E	E	D	D	C	C
Balance-Driven Watch (unadjusted)	E	E	D	D	C	C
Spring-Wound Watch (adjusted)	D	D	D	C	C	C
Spring-Wound Clock (adjusted)	D	D	D	C	C	C
Spring-Wound Watch (unadjusted)	F	F	E	E	D	D
Spring-Wound Clock (unadjusted)	G	G	F	F	F	F
Electric-Rewind Clock	F	F	E	D	D	D
Stalled-Motor Clock	G	G	F	E	E	E

A ± 1 sec/day
B ± 5 sec/day
C ± 10 sec/day
D ± 30 sec/day
E ± 1 min/day
F ± 2 min/day
G ± 5 min/day

*Adjusted means timed in more than one position for 24 hr or more. Rate of watch in all positions is equal.

In Eq. 16-1 G and σ are the maximum values attainable with any particular spring, taken with the spring let back one revolution from fully wound. Stress has a fairly definite relation to thickness (as shown in Fig. 16-3[5]). This figure is valid for springs with a length ℓ to thickness h ratio of about 7000. With higher ratios the curve would shift downward; with lower, upward. Also as the ratio of arbor diameter d_1 (Fig. 16-1) to thickness h increases, the curve would shift downward.

Example: Find the maximum torque delivered by a spring 0.5 in. × 0.05 in. × 30 ft wound on a 1 in. arbor. From Fig. 16-3 the stress corresponding to a thickness of 0.05 in. is about 210,000 psi. Substituting in Eq. 16-1 yields

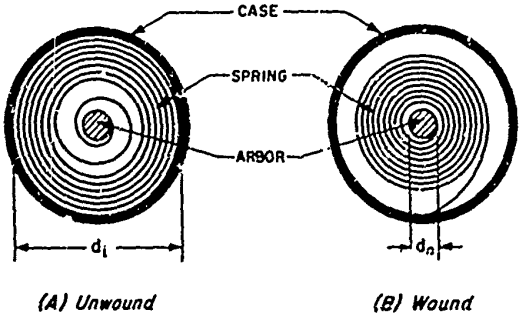


Figure 16-1. Spiral Spring Power Motor[4]

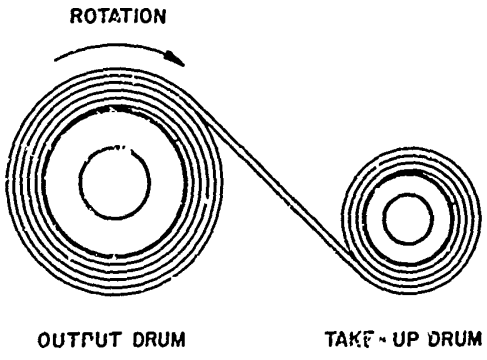


Figure 16-2. Negator Spring Motor

SAMSUNG EXHIBIT 1028, Page 250

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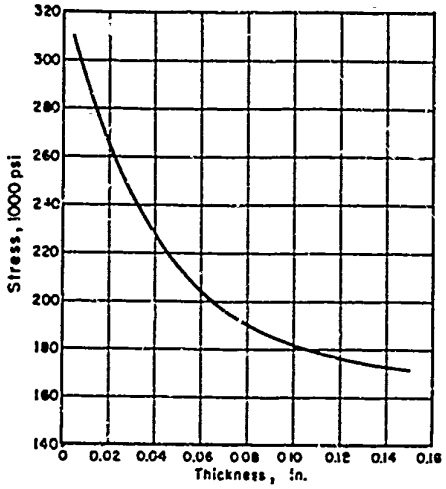


Figure 16-3. Average Maximum Solid Stress in Power Springs (for ℓ/h approximately 7000)[5]
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$$G = \frac{210{,}000 \times 0.5 \times 0.05^2}{6} = 43.7 \text{ lb-in.}$$

In order for a spring to contain the maximum number of turns in a given volume, the value ($\ell \times h$) should equal 1/2 the available volume (drum volume minus arbor volume). Expressed mathematically in two dimensions, (the spring width b being constant)

$$\ell h = \frac{1}{2}\left(\frac{\pi d_2^2}{4} - \frac{\pi d_1^2}{4}\right) \qquad (16\text{-}2)$$

$$\text{or } \ell = \frac{d_2^2 - d_1^2}{2.55h} \qquad (16\text{-}3)$$

$$\text{or } d_2 = (2.55\ell h + d_1^2)^{1/2} \qquad (16\text{-}4)$$

where

ℓ = length, in.

h = thickness, in.

d_2 = case drum diameter, in.

d_1 = arbor diameter, in.

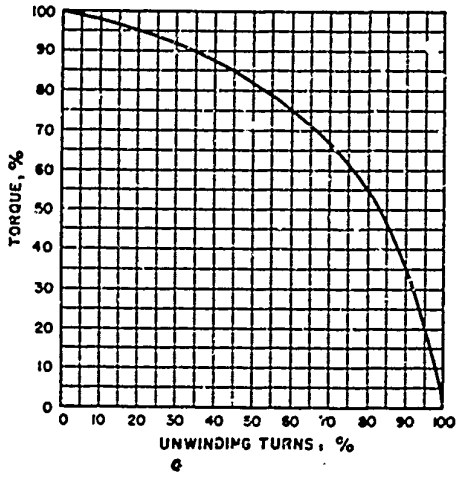


Figure 16-4. Typical Torque Curve for Power Spring[5]
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With reference to the arbor size, it has been found, both experimentally and practically, that the arbor diameter should be from fifteen to twenty-five times the spring thickness h.

The number of turns N can be expressed by the equation

$$N = \sqrt{\frac{2(d_1^2 + d_2^2) - (d_1 + d_2)}{2h}} \qquad (16\text{-}5)$$

In the foregoing paragraph the torque and stress are at a maximum. In order to determine the torque at any intermediate position of the spring from solid to free, the curve of Fig. 16-4[5] may be used. The shape of this curve is typical and fairly constant for springs of well proportioned design.

Example: A 15-turn spring has a maximum torque of 20 lb-in. Find the torque when 6 turns are let out. From Fig. 16-4 at 40%, the torque is 88%. Thus 88% of 20 is 17.6 lb-in.

SAMSUNG EXHIBIT 1028, Page 251

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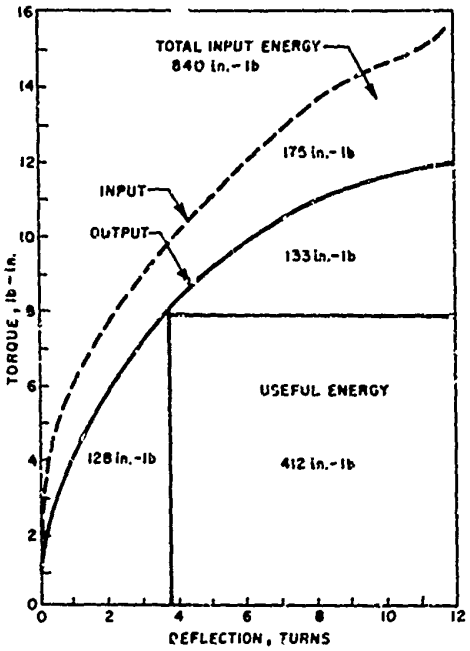


Figure 16-5. Input and Output Curves of a Conventional Spiral Power Spring[6]

The spiral spring motor is relatively inexpensive, compact, and convenient. The moment delivered by the spring decreases as it unwinds--from maximum at release, to zero at full rundown. The spiral spring can produce a specific torque at only one point; at other times it is either too great or too small. Further, all associated components--transmission elements, escapements, governors, etc.--must be designed to take the maximum full wind torque. Most spiral springs operate through a maximum of only about 17 useful revolutions. One way to increase the number of turns is to lengthen the spring and use thinner material. The practical length-to-thickness ratio (ℓ/h) is about 15,000:1. Additional length always increases intercoil friction. Gearing will be needed if the driven mechanism must operate through more revolutions than the spring.

16-2.1.2 Efficiency

The useful output of a spiral spring is about 1/2 of the input as shown in Fig. 16-5[6]. The number of turns at high torque also is limited. To increase total output, it is necessary to design for higher torque and use gearing to obtain the required length of run.

A special form of the spiral spring is the prestressed spiral spring (spirator). The spirator--a compact, single-axis mechanism--resembles a spiral spring in appearance, but contains a *prestressed* spring. The spirator is prestressed to form a tight coil. After forming, the spiral is turned inside out; the outer end is reverse bent, and fastened to the arbor; and the inner end is secured to the case. This action results in:

(1) High resisting moment at the start of winding

(2) Gradual increase in stress and torque during winding

(3) Use of thinner material and greater length of prestressed material

(4) Activity of a greater proportion of length during run-down.

The outstanding characteristic of the spirator is its ability to sustain delivery of useful torque through many turns. The input-output curves for a typical spirator is shown in Fig. 16-6[6]. The spirator is obviously superior to the conventional spiral spring. Furthermore, the spirator produces more total useful energy for the same weight of material, making it much more efficient in terms of useful energy compared with the energy potential of the material.

16-2.2 NEGATOR MOTORS

With the constant-torque negator motor (also known as a negator B motor) the motor is wound from drum B to A (Fig. 16-2). On unwinding as indicated by the arrow, almost constant torque is developed due to the tension produced by the spring plus the

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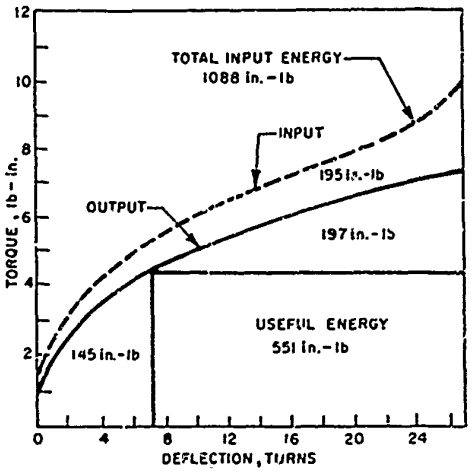


Figure 16-6. Input and Output Curves of a Prestressed (Spirator) Spring of the Same Weight as Power Spring in Fig. 16-5[6]

moment developed due to reverse bending of the strip as it is unwound from the output drum. Normally the strip is attached to the A drum, but is merely allowed to wind about the B drum. Besides constant torque, the B motor has the advantage of no intercoil friction.

About 60 revolutions is the upper practical limit for the B type motor if constant torque is required. If a slight linear gradient can be tolerated, type B motors can be made up to 100 turns. The B type motor can be designed to deliver the exact number of turns required, and thus eliminate or reduce required gearing.

The constant torque or low linear gradient of the B motor makes it easy to control the output. Constant torque often is misinterpreted as constant speed, which it is not. Constant speed requires a governor, the complexity of which can be reduced greatly by coupling to a B motor.

Since there is no intercoil friction, there is no need for lubrication. Optimum B motor design to produce maximum total energy in a given space, accepting a slight torque variation, should be considered unless there is no need for requiring absolutely constant output torque.

Fatigue should be considered in a B type motor use due to high repetitive stresses. A motor rating should consider both torque required and required life. Fig. 16-7[6] shows the input-output curve for a B-type negator.

16-2.3 COMPARISON OF SPRING MOTORS

An energy comparison of the three types of motor–spiral, spirator, negator–for the same material weight as shown in Fig. 16-8[6]. A tabular comparison is given in Table 16-2[6].

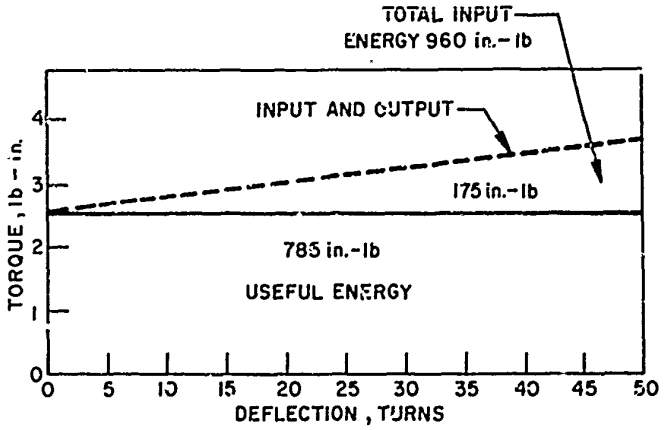


Figure 16-7. Input and Output Curves of a B Type Negator Motor of the Same Weight as the Spiral Spring Motor in Fig. 16-5[6]

SAMSUNG EXHIBIT 1028, Page 253

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TABLE 16-2

TABULAR COMPARISON OF MOTOR SPRINGS[6]

	Spirator (Spiral)	Prestressed Spiral	Negator (Noncumulative Force)
	Physical Characteristics		
Mounting	On a single arbor with restraining ring or case.	Same as spiral spring.	On two spindles: one output, one take-up.
Relaxed Configuration	Coils expanded against retaining case.	Same as spiral spring.	Tightly coiled spiral on take-up spool.
Wound Configuration	Tight coil on arbor.	Same as spiral spring.	Tightly coiled on output drum.
Number of Rotations	Seldom greater than 15.	Readily, 20 turns. As many as 50 turns possible at reduced energy storage efficiency.	Limited only by space available (100 turns present practical limit).
Forming Process	Wound directly on arbor, or some reverse winding of longer springs.	Prestressed through sequential bending and thermal processing then reverse wound and fastened to arbor.	Prestressed through sequential bending and thermal processing.
	Performance		
Charging	Stressed cumulatively as a unit by winding to a tight spiral.	Same as spiral spring.	Stressed uniformly by reverse wrapping onto second drum.
Useful Energy Storage	Limited by number of effective revolutions, moderate nonuniform working stresses.	More useful energy because of high working stresses.	Highest energy storage because of higher working stresses, nearly uniform stress distribution throughout material.
Torque Output	Optimum value available only momentarily. Diminishes rapidly from maximum throughout cycle.	Diminishes on delivery stroke less rapidly than power spring from a beginning maximum.	Initial torque maintained throughout cycle.*
Efficiency	Energy wasted by friction and in compensating for nonuniform rate of release.	Same as spiral spring except much lower percentage of input energy need usually be wasted.	Negligible friction loss and little energy wasted because it is released at uniform rate.*
Input Torque	Effort increases during winding. Torque input required to fully wind reaches a high peak.	Effort also increases but less rapidly. Lower input required to fully wind.	Winding effort remains low because restraining torque does not build-up.

*For constant-torque B motor. Low-gradient J motor produces very slight torque increase which decreases gradually at a constant rate during rundown.

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TABLE 16-2

TABULAR COMPARISON OF MOTOR SPRINGS[6] (Cont'd.)

	Spirator (Spiral)	Prestressed Spiral	Negator (Noncumulative Force)
	Application Characteristics		
As a Drive Unit	Limited number of turns. Gearing usually required.	More turns usually possible. Simplification of associated gearing possible.	Greatest number of turns. Sometimes applied without gearing.
To Deliver Linear Force	Requires gearing and linkage to provide linear displacement.	Can provide longer linear displacement, with less linkage than power spring.	Large number of turns available for conversion to long-displacement linear force.
Adjustability	Wide output torque range available for output adjustment.	Narrow output torque range available for adjustment.	Output nonadjustable once mounted unless bands are specially formed.
Associated Components	Must be able to handle high maximum output torque.	Lower maximum torque allows use of lighter duty parts.	Constant output allows use of light-duty parts.
Output Control	Governor escapement must operate over wide torque range.	Governor operates over narrower torque range.	Governor required only for very close control.

where

ω = motor shaft speed, rpm

f = frequency of electric supply, Hz

p = number of poles

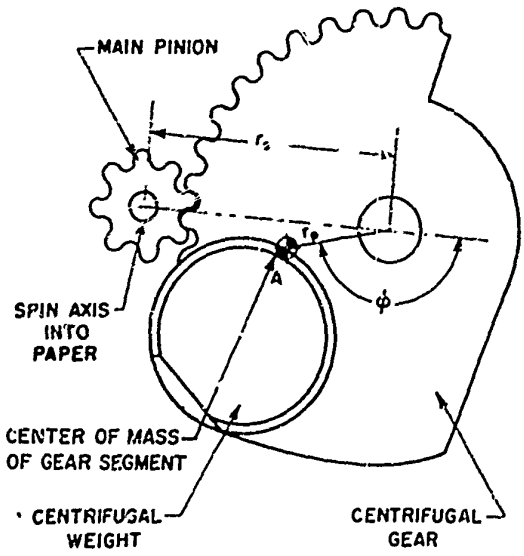


Figure 16-9. Centrifugal Drive Employed in the MTSQ, M502A1 Mechanical Time Fuze

A synchronous motor will, on the average, be exactly as correct as the line frequency, rotating through an angle corresponding to a pair of poles during each cycle. Instantaneous speed variation of a synchronous motor is called "hunting".

Some of the more salient features of the synchronous motor are:

(1) Exact relation exists between speed and line frequency.

(2) Speed is independent of line voltage and wave form distortion as long as synchronism is maintained.

(3) Pull-out torque and starting torque vary as the square of the applied voltage.

(4) Input power increases as square of applied voltage where shaft load is negligible.

(5) Hunting is a superimposed low frequency modulation of instantaneous speed, with average speed held constant. Hunting may be important where output is driven at high speed.

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(6) Very special designs are available where it is economical to produce a unit with a large number of poles (low synchronous speed) in a small size. These units are at their best where load demand for shaft power is almost negligible. Low speed means fewer gear reduction stages and longer bearing life.

(7) Most economical starting means is generally by a shading coil, which does not have high starting torque. Thus bearing friction must be very low, even at low temperatures. Capacitor starting provides more starting torque in larger units.

(8) Hysteresis motors employing a motor of permanent magnet material commonly are employed to develop synchronous torque.

(9) Reluctance motors using a notched rotor often are used as synchronous drives. These develop relatively poor starting torque that can be boosted by providing a small amount of induction motor action on top of the synchronous behavior.

(10) With very many poles, synchronous speed is so low that the motor readily synchronizes with a minimum of starting torque.

(11) Extremely high accuracy can be obtained from synchronous motors driven from a temperature controlled crystal oscillator source. Somewhat lesser accuracy is obtainable from a tuning fork supply. However, these supplies are often cumbersome.

The electrical drive, as compared with weight and spring drives, has the great advantage of obviating the winding and running time limitation. Also the motor can be kept small since the speed of the working shaft or shafts usually is smaller than the motor speed, as a result of which the torque reduced to the motor shaft also becomes small. Although the electric motor represents the ideal form of drive, since the need for a regulator is also obviated, its applications are limited. When constructed as an asynchronous motor, it responds to voltage variations, and when designed as a synchronous motor, it responds to frequency variations (disadvantage of synchronous clocks that are connected to a nonfrequency-stabilized line). If frequency stability is assumed, the synchronous motor is an ideal driver.

16-2.6 DC MOTORS

Governor controlled DC motors can provide timer accuracies to 0.1%. A means for speed control, however, must be provided because the speed of DC motors is usually voltage dependent. A convenient method is to provide a set of centrifugally operated contacts on a plate fixed to the DC motor shaft, with a pair of slip ring brush contacts. The centrifugally operated contacts make and break armature current. When the required speed is reached, the contacts open, which may open the armature circuit thereby slowing down the motor or introduce a dropping resistor that also will decrease armature current. A dropping resistor is more common and can result in finer speed control.

For good accuracy the springs associated with the centrifugal governor must be free of internal strains that may gradually shift the governing point. The design must take into account such environmental factors as shock, vibration, and acoustic noise which may cause faulty operation. Contact ratings must be adequate for the life of the unit and protection must be provided against salt spray and humidity in service environments.

An example of a commercial timing motor manufactured by the A. W. Haydon Co. is the chronometric governor shown in Fig. 16-10(A)[8]. The motor rate is independent of load, line voltage, and temperature variations. The principle of operation is shown in Fig. 16-10(B).

The motor is geared directly to a cam-operated lever extending between a pair of leaf-spring contacts and so arranged that its

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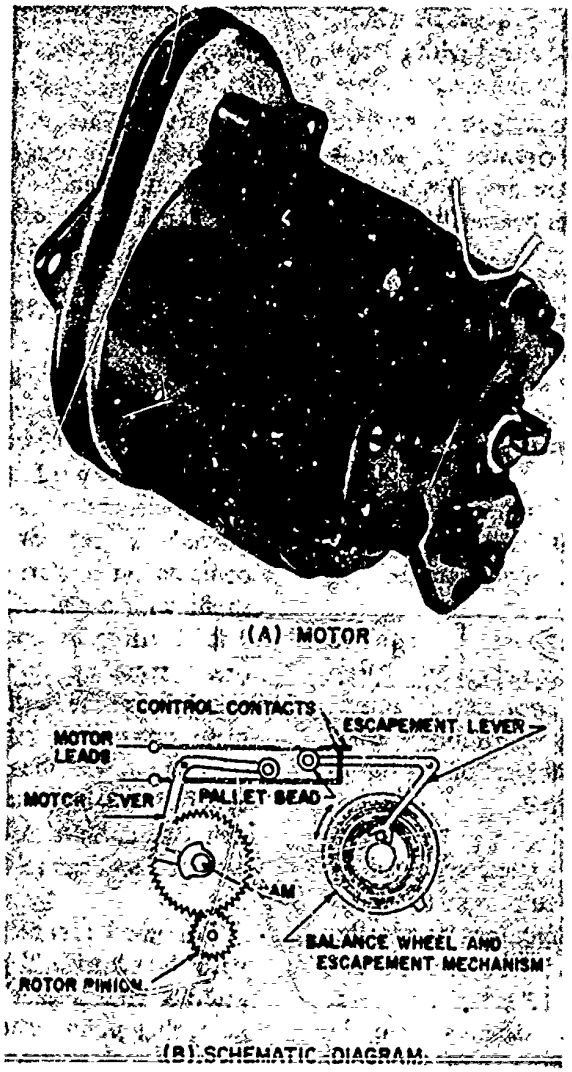


Figure 16-10. Chronometric Governored DC Motor

motion in either direction opens the contacts. Also located between the contacts is a pallet bead. insulated by mechanical attachment to the clock escapement lever in such a manner that the clock escapement merely releases these contacts allowing them to close while the motor-operated cam does the work of opening the contacts. The contacts are connected directly in series with the motor so that the faster the motor tries to go, the quicker the contacts are opened; yet they close at regular intervals as released by the escapement.

Thus pulses of full line voltage are applied to the motor at regular intervals, controlled by the escapement, and the duration of these pulses is determined by the travel of the motor. This results in a uniform travel of the motor during each time interval and, consequently, a constant rotor speed is obtained. The motor is designed to deliver maximum torque at slightly below minimum voltage under the least favorable temperature conditions. The motor, therefore, tends to overspeed but in doing so opens the governor contacts more quickly, thus shortening the duration of power pulses delivered to the motor. This results in a consequent reduction in motor speed.

SAMSUNG EXHIBIT 1028, Page 257

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Since the motor-driven cam transmits the same oscillating motion regardless of its direction of rotation, the motor is reversible. Further, when the clock balance wheel stops, it always tends to find its center position under the influence of the hairspring. Contacts always revert to a closed position when the current is turned off, and, consequently, the unit is reliably self-starting.

For power to keep the balance wheel oscillating, uniform mechanical impulses are delivered to the clock escapement through the contact springs that bear on the pallet bead, previously described, which is connected directly to the escapement lever. Uniformity of these mechanical pulses is assured since the contact springs are lifted a uniform distance by the oscillating motion of the cam-operated lever. Driving power for the balance wheel, therefore, is constant and independent of the motor speed or load and voltage variations applied to the motor.

The standard escapements are 300-beat and 900-beat types giving 150 or 450 complete oscillations per minute. The arrangement of the escapement and contact mechanism is such that the contacts are allowed to close at each half oscillation, and at this instant the escapement derives its energy from the contact springs. Thus the escapement mechanism is not called upon to perform any more work than when running free in an ordinary clock. Energy is stored in one contact spring just preceding the release of energy from the opposite spring, and the balance wheel thus gets its impulse at a time when the contact spring is not connected to the motor.

Some typical performance figures achieved by means of this governor are:

Voltage, ± 20%	Speed ± 0.1%
Temperature, −65° to + 165°F	Speed ± 0.3%
Vibration, 5-300 Hz, 10 g max.	Speed ± 0.5%

As in the case of AC motors, the power source for DC motors must be considered. Often the source of DC power is a battery.

16-2.7 BATTERIES

The electrical battery has advantages by a large margin over a mainspring particularly in power density. This margin is claimed to be anywhere between 100 and 1500 times larger, depending upon the type of battery and the operating conditions. However, there is a restriction that the energy must be withdrawn at a relatively slow rate if all of it is to be made available for work. Other disadvantages of the electrical power supply include its change in output with temperature, its relatively short unattended storage life (1 or 2 yr for most batteries) and its inability to operate satisfactorily at temperatures below −40°F.

A battery that overcomes the last two disadvantages is the "reserve" battery that is inactive until ready for use. One method of making a reserve battery is to store the electrolyte in a glass ampule that is broken to activate the battery. Reserve zinc and silver oxide cells were in common use in World War II proximity fuzes.

Modern reserve batteries may be of the thermal type. A thermal battery uses electrolytes of various inorganic salts which are solid and nonconducting at normal military temperatures. Upon application of sufficient heat, the electrolyte melts and becomes conductive. A typical electrochemical system consists of calcium or magnesium anodes with various reducible cathodes, such as calcium chromate. The inorganic salts used as the electrolyte are generally potassium chloride and lithium chloride. Battery output from 2.5 to 450 V is available over the temperature range of −65° to 200°F.

Thermal cells typically are constructed either as a pellet or as a closed cup. The cells are then stacked into a cylindrical configuration with the diameter and the number of cells being varied to provide various capacities

SAMSUNG EXHIBIT 1028, Page 258

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and voltages. The cell stacks then are insulated electrically and thermally, and encased in a metal container that is hermetically sealed. The container also includes, as heat source, an electric squib or mechanical primer. Thermal batteries range from 0.5 in. diameter by 0.5 in. length to 4 in. diameter and 5 in. length. Typical voltage tolerance is ± 10%.

Compared with other batteries then, the thermal battery has an acceptable shelf life. It has a versatile electrical output and is readily activated remotely. However, it shares the disadvantage with all batteries of a shortness of life, once activated. Also, thermal batteries are expensive, costing at least five times the amount of a good mainspring.

16-3 GEAR TRAINS

16-3.1 COMPUTING SYSTEMS

One of the basic components of a mechanical timer is the computing system. The computing system is essentially a counter that counts each of the periodic oscillations of the time base. For any given time interval, the system must be capable of registering the total number of oscillations which have occurred since time zero.

The most common type of computer is the gear train in which a set number of degrees of revolution of an output shaft represent a specific number of oscillations and, therefore, an interval of time. The output shaft is constrained to a constant rate of rotation by the oscillator or escapement.

16-3.2 TYPES OF GEAR TRAIN

There are several types of gear train which can be used to do the counting. These include straight spur gear and pinion sets (as found on ordinary clocks and watches), worm gear pairs, epicyclic trains, hypocyclic trains, harmonic drive, and synchronic index train.

16-3.2.1 Spur Gear Trains

Straight spur gear and pinion sets are used for the counting train in most timers. In small timing movements, the gears are about 0.3 to 0.4 in. in diameter, and pinions are about 0.06 in. in diameter and have as few as six teeth. The ratio per mesh is usually between 4:1 and 10:1 with the latter being a general upper limit.

There are two types of straight spur gear train: speed increasing and speed reducing. In the speed increasing type, a multiple stage train might be used to drive a fast moving escape wheel from a slow-moving mainspring barrel. This type is less efficient than the speed reducing train obtained when the input energy is supplied directly to the oscillator at the fast-moving end of the train. Torque variation and efficiency loss especially are pronounced when small pinions having six or seven teeth are used.

The overall efficiency of a typical five-stage timer gear train having a ratio of approximately 8600:1 is about 30 to 40 percent at best; and this can vary widely during operation due to gear eccentricities, tooth-to-tooth tolerance variations, engagement action, etc. Since the torques involved in driving the oscillator are very small, these gear trains can be a source of difficulty, especially when the speed increasing type is used, because the torque transmitted to the fast moving end becomes very irregular.

Angular errors in output shaft position as great as 1 or 2 percent can result from errors in gear concentricity, roundness, and tooth-to-tooth spacing since timer gears are not, in general, precision gears. A partial solution to these problems can be obtained if precision gear sets are used having at least 12 teeth on the pinions and using the involute form.

16-3.2.2 Worm Gearing

Worm gearing can provide high reduction

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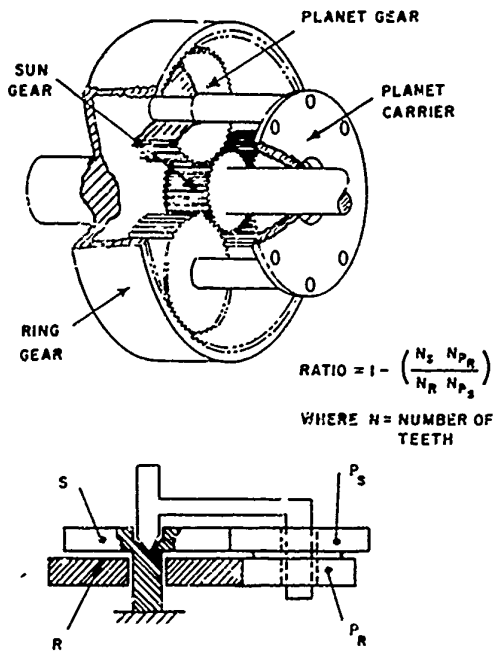


Figure 16-11. Epicyclic Gearing

per stage (about 100:1) but the efficiency is lower because of the sliding contact. Worm gears have not been used to any extent in timers probably because of large effects on performance caused by frictional variations, greater cost to manufacture, and less position al accuracy than spur gear sets.

16-3.2.3 Epicyclic Gearing

Epicyclic gearing is a planetary arrangement of several gears in which one or more of the gears is constrained to move bodily around the circumference of coaxial gears that may be either fixed or rotating. The motion of the constrained gear is composed of a rotation about its own axis and a rotation about the axis of the coaxial gear. This form of gearing is used most often where a speed-changing device is required; it has not found application as a timer computer. For an epicyclic form that provides the highest ratios per stage obtainable, gears having a diametral pitch of approximately 600 would have to be used in order to fit a 100:1 stage with a 1 in. diameter inclosure. Such gears are not obtainable, and the complexity of the epicyclic system rules it out for ratios that are much less than 100:1. Fig. 16-11[9] is an example of epicyclic gearing.

16-3.2.4 Hypocyclic Gear Trains

In this system, a relatively large-diameter gear rolls on or meshes with a slightly larger internal gear having two or three more teeth, Fig. 16-12[9]. As a result of this action, a wobbling motion is generated which can be converted to a rotary output. The advantages of this type of gearing are a large ratio per stage (50:1 to 150:1 for nominal 1-in. gears depending on diametral pitch) and the elimination of problems associated with very small pinions. Hypocyclic gear-train systems have not been used in timer-sized devices and, as a consequence, little can be said about limitations or merit in such an application.

16-3.2.5 Harmonic Gear Drive

The harmonic gear-drive mechanism is a relatively new invention introduced by The United Shoe Machinery Company in 1957 (see Fig. 16-13[9]). It consists of a flexible gear or spline having a large number of teeth which meshes with a rigid gear or spline having slightly fewer teeth. Very high ratios per stage are obtainable. They may be between 100:1 and 1000:1, depending on the size of the

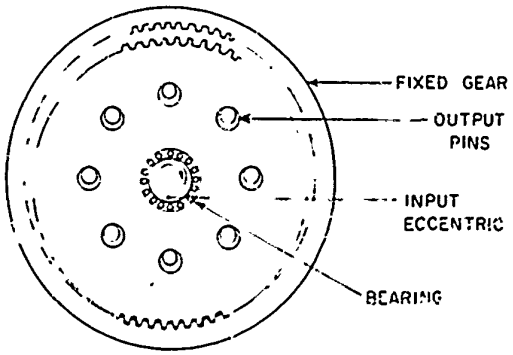


Figure 16-12. Hypocyclic Gearing

SAMSUNG EXHIBIT 1028, Page 260

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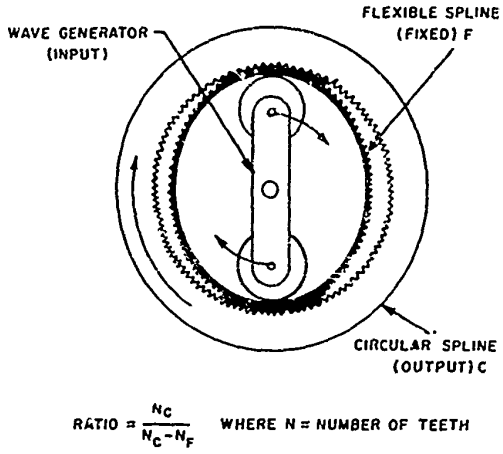


Figure 16-13. Harmonic Gear Drive

mechanism and the number of teeth which can be used. It has a high positional accuracy and high torque loading capacity. This type of gearing has not been produced in miniature size suitable for timer applications.

16-3.2.6 Synchronic Index Gear Train

An accurate gear-train computing system can be designed by using the synchronic index of a gear train. For example, two concentric coplanar spur gears, one having 103 teeth and the other 100 teeth and both driven by a single pinion having 11 teeth (see Fig. 16-14[9]) will require 10,300 revolutions of the pinion to return the three gears simultaneously to their original positions. This coincidence of position could be used to close an electrical switch that would complete a firing circuit or release a mechanical latch. The counter would be set by rotating the pinion the desired number of revolutions (less than 10,300) in the reverse direction. Different setting methods and mechanical outputs could be devised. Various turn ratios can be achieved with relatively few gears and with good resolution of the readout or output function.

16-3.3 SPECIAL PROBLEMS ASSOCIATED WITH SMALL MECHANISM GEARING

When gears are applied to small mechanisms as clocks and timers, special problems arise. First, tooth profiles of small mechanism gears are widely different from those of power gearing. While almost all power gearing is used for a step-down in velocity ratio between the driver and the driven gear, in a clock or timer mechanism the prime mover—the mainspring barrel—may move a small number of revolutions per unit time and the escapement wheel several orders of magnitude faster.

The wheels are so tiny, that, in order to avoid using excessively small teeth, it is necessary to use driven gears having as few as 6 or 7 teeth. The tooth profiles of these gears must be those which permit operation over 60 deg of rotation of the driven gear. For this purpose, tradition has long dictated the use of the cycloidal based design for speed increasing trains. However, in the area of speed-increasing gear trains for timer mechanisms, much of the available data tends to disprove use of the cycloidal configuration and greatly favors the use of involute design.

The very small size and low power transmitted by timer gearing introduces special problems. It is inevitable that manufacturing errors are relatively large in tiny gearing, and rolling curves demanded by strict

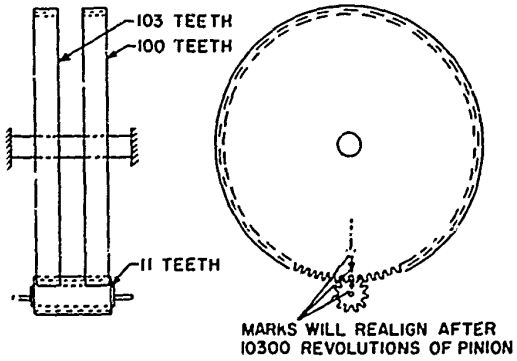


Figure 16-14. Principle of the Synchronic Index of a Gear Train

SAMSUNG EXHIBIT 1028, Page 261

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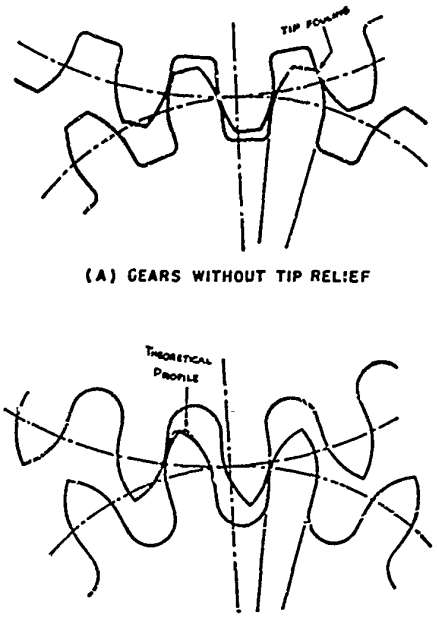


Figure 16-15. Comparison of Gear Tip Profiles[10]

theory need to be modified by a generous tip relief so that no contact can take place on the edges or tops in spite of errors of tooth form, spacing, or depth of engagement. Fig. 16-15(A)[10] shows the interference between two tooth surfaces caused by errors of form and spacing while Fig. 16-15(B) shows the relieved tip which avoids the effect. Generous clearance between flanks and between tips and roots are used on fine involute gears in all cases where the energy available to turn the gears is small.

The characteristics of gearing in timing mechanisms for ordnance are unique in comparison to most small gear applications. The more important ones are:

(1) The system is a step-up (or speed increasing) train, in which the pinions are driven by the gears.

(2) In order to conserve weight and space, the gears are relatively small and the gear train employs large gear ratios per mesh, necessitating pinions with rather few teeth.

(3) Rotation usually is restricted to a single direction, thus a large backlash is not a particularly important disadvantage.

(4) The gears are subject to extreme shock, vibration, and acceleration and the teeth may be subject to high impulsive loads.

Any useful gear design should, therefore, meet the following requirements:

(1) The gear teeth, especially those of the pinions, must be rugged enough to withstand large shock loads, dictating thick teeth with little or no undercut.

(2) The mesh should have as high an efficiency as possible since two inherent flaws of a step up train—decreasing torque and tendency toward increased friction from driving a small pinion—combine to promote eventual self-locking for high ratios with several meshes. Although nothing can be done for torque loss, friction can be reduced by smooth, accurate mating surfaces; by continuous action and a high contact ratio to smooth transmission and distribute the load; and by placing the action largely in the arc of recess.

(3) The gears must achieve efficient action without extreme tolerance limitations on tooth profile or center distance.

(4) The design should be such that uniform accuracy in mass production is easily achievable.

(5) Adequate backlash is necessary to allow for center distance variations.

(6) Consideration of time, money, and equipment requires a degree of ease in manufacture of such designs, preferably in a variety of methods, without necessitating special tooling.

SAMSUNG EXHIBIT 1028, Page 262

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The design of the various gearing systems (involute, cycloidal, clock-tooth) are well documented in the literature (see Bibliography at the end of this chapter). However, it remains with the designer of military timers to make a choice as to which system or combination of systems will best approach or equal the useful gear-design requirements as outlined.

In order to facilitate the choice between gear systems, a comparison of the relevant features of each should be made. Advantages and disadvantages follow:

a. Cycloidal Gears:

(1) Advantages:

(a) Most contact tends to occur on the arc of recess.

(b) Train efficiency is high.

(c) They are in common use.

(2) Disadvantages:

(a) Teeth on small pinions are tapered to extremely thin roots.

(b) Tolerance requirements on tooth profile and center distance are rather small, and often critical.

(c) Cutter design for the cycloidal curve is complicated, being another cycloidal curve, and therefore prone to inaccuracy.

(d) Neither the cutters nor the gears are completely interchangeable.

(e) Contact ratios are usually less than unity.

b. Involute Gears:

(1) Advantages:

(a) Stronger tooth profiles are possible through versatility of design with standard equipment.

(b) Tolerance requirements on tooth profile and center distance are more liberal.

(c) Involute cutter design is quite simple, consisting of straight lines.

(d) Both cutters and gears are extremely versatile and interchangeable.

(e) Contact ratios are usually greater than unity.

(2) Disadvantages:

(a) Standard designs applied to pinions with few teeth result in rather large undercutting that weakens the teeth.

(b) Train efficiency is low.

(c) Standard designs tend toward greater approach action.

c. Clock Tooth Gear:

(1) Advantages:

(a) Minimum obliquity of thrust if largest possible generating circle is used.

(b) Minimum sensitivity to errors of diameter and center distance.

(c) Standard designs of teeth for certain numbers of teeth and gear ratios are available.

(2) Disadvantages:

(a) Highly specialized gearing for going trains.

(b) Standard design for the addendum of the driving gear varies with the number of

SAMSUNG EXHIBIT 1028, Page 263

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teeth in driven pinion and the gear ratio. This system does not lead to easy standardization of tool stocks.

(c) It is desirable from friction considerations to have more recess contact than approach contact, so that special tooth forms must be employed rather than true epicycloidal curves.

From the standpoint of simple cutter design, interchangeability and higher allowance on tooth profile and center distance, a preference for involute gears can be justified with possible combination with clock tooth gear sets in the train.

16-3.4 FRICTION EFFECTS ON GEAR TRAIN EFFICIENCY

It is a well established fact that when two surfaces are in contact, and friction is completely absent, the line of thrust between the surfaces lies on the common normal. If sliding friction is present, the line of thrust is inclined to the common normal at an angle whose tangent equals the coefficient of friction.

Further, if two surfaces are shaped similar to a shaft and bearing, there exists an imaginary circle, called the friction circle, within the shaft whose radius is equal to the radius of the shaft multiplied by the sine of the angle of friction. If the line of thrust applied to the shaft passes inside the friction circle, the shaft will become friction locked and fail to rotate. If the line of thrust passes near to the friction circle, the shaft will rotate but at a low efficiency.

By using these facts, various phases of gear engagement can be studied, and variations of output torque and efficiencies can be determined. Fig. 16-16(A)[11] shows the locations of the normal force when two gears run together in the absence of friction. Fig. 16-16(B) indicates the location and direction of the sliding friction forces both before and after the line of centers. The direction of the friction force will oppose the motion of the driver relative to the driven surface and be perpendicular to the common normal. Fig. 16-16(C) shows the gear mesh with the normal force applied to the drive in presence of frictson. The effective output under these conditions is then the vector sum of the normal force and the friction force. The angle of inclination of the resultant thrust to the normal thrust is the friction angle. Where brass and steel are in sliding contact, this angle is assumed to be 11°19′. Fig. 16-17(A)[11] shows a gear and pinion in contact before the line of centers. When the torque is applied to the driver, a normal force F_n will pass through point C in a direction normal to both tooth profiles. The moment arm of the normal force of the gear is a and the moment arm of the pinion is b. Fig. 16-17(B) shows the same gear and pinion in contact before the line of centers with sliding friction present. The resultant force F_t passes through the contact point C. The moment arm of F_t for the gear is c and the moment arm of the pinion is d. In order to evaluate gear mesh performance, the torque output with friction ($G_{driven}\ (F_R)$) is compared to torque output with no friction ($G_{driven}\ (F_o)$), where the same input torque is applied in both cases. Their ratio, termed instantaneous efficiency, is determined by

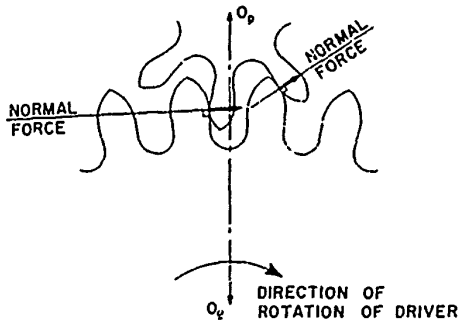
$$\text{Instantaneous Efficiency} = \frac{G_{driven}\ (F_R)}{G_{driven}\ (F_o)} = \frac{da}{cb} \qquad (16\text{-}8)$$

Even though the friction force is reversed after the line of center, the equation for efficiency is the same. Eq. 16-8 is a general one which applies to both involute profiles and variations of the cycloidal form.

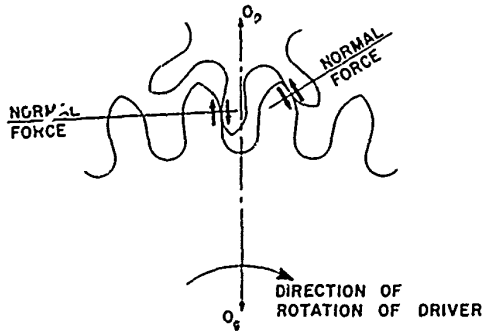
To determine the efficiency curve for a pair of gears in contact, the force diagram must be determined for each increment of the angle of action and the moment arms measured. By using Eq. 16-8 the efficiency can be

SAMSUNG EXHIBIT 1028, Page 264

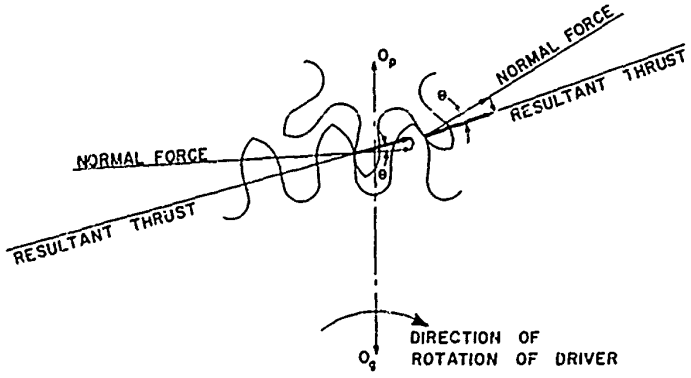
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(A) DIRECTION OF NORMAL FORCE IN ABSENCE OF FRICTION BEFORE AND AFTER CENTER



(B) FRICTION FORCES BEFORE AND AFTER CENTER

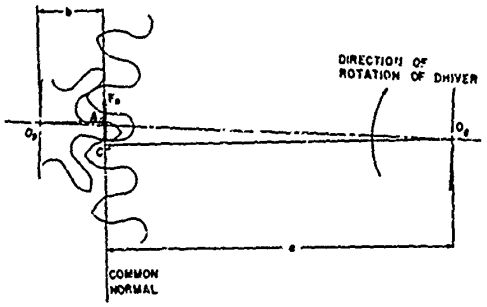


(C) NORMAL FORCE APPLIED IN DIRECTION OF FRICTION

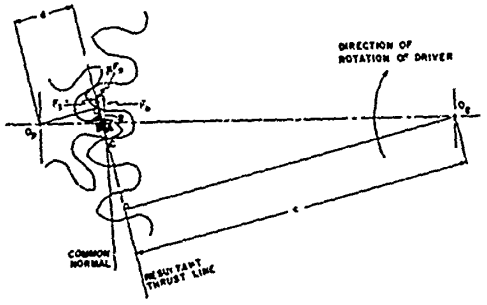
Figure 16-16. Direction of Resultant Effective Forces With Friction

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(A) NORMAL FORCE F_n BEFORE CENTERS WITH MOMENT ARMS *a* and *b*



(B) EFFECTIVE RESULTANT THRUST BEFORE CENTERS WITH MOMENT ARMS *c* and *d*

Figure 16-17. Forces on Teeth With and Without Friction

calculated. A graphic technique has been developed for plotting torque fluctuations that are contributed by the tooth form of a gear and pinion set when going in and out of mesh[11]. Other effects such as gear eccentricities and mainspring torque are not considered.

Fig. 16-18[10] shows the cumulative effect on efficiency of three stages of gears with the individual efficiencies plotted on the same graph. It can be shown that step-down gear trains are more efficient than step-up trains and that incorrectly designed gear trains can be self-locking due to friction[10].

By referring to the direction of the friction force in Fig. 16-16(B) it is evident why recess action is desirable. The transmitted forces and friction combine during approach action and tend to separate the gears while during recess action they oppose each other and exert less net radial force on the gears.

A study has been performed to justify the use of involute gearing over the traditional cycloidal form. The parameters studied include different pressure angles, different center distances, different gear blank sizes, different cutter feed depths, and combinations of these.

16-3.5 GEAR THEORY AND TOOTH DESIGN

The forms of the teeth of gears are based on either of two types of curves—the cycloid and the involute. A cycloid is the curve traced by a point on the circumference of a circle when the circle rolls without slipping along a straight line. Two variants of this curve are used in gearing: the epicycloid (used in clock gear trains) in which the circle rolls on the outside of another circle; and the hypocycloid, in which the circle rolls on the inside of another circle.

An involute is the curve traced by the end

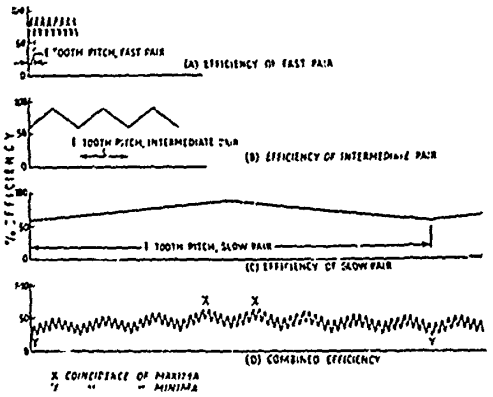


Figure 16-18. Variations of Torque Output of Several Stages[10]

SAMSUNG EXHIBIT 1028, Page 266

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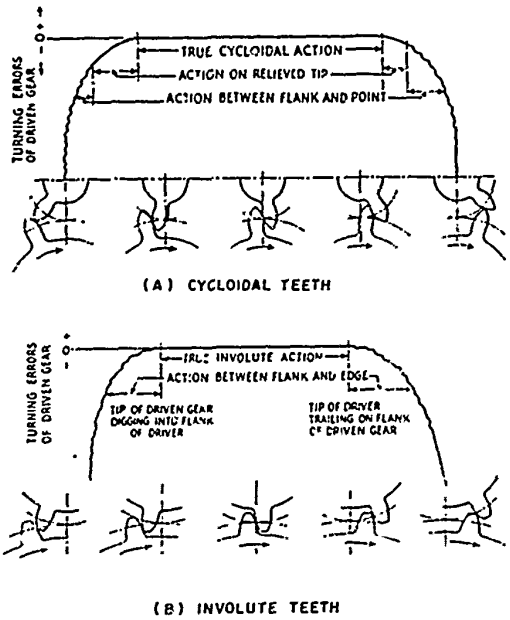


Figure 16-19. Contact Action of Gear Teeth[10]

of a string when it is held taut, as it is unwound from a drum. Involute gearing was developed more recently than cycloidal gearing. The theory of both types of gearing depends on geometrical principles, the fundamentals of which are available in a number of texts (see Bibliography at the end of this chapter).

These theories of involute and cycloidal curves have as their basis the requirement that the shape of the tooth profiles in contact must be such that the normals to the profiles at all points of contact shall all pass through the pitch point thereby insuring that the pair of engaging teeth transmit a constant velocity ratio. However, it is impossible to form the teeth with mathematical precision. As a result, within limits depending on the accuracy attained in practice, variations of velocity ratio take place, and successive engaging pairs of teeth sometimes enter into load-bearing contact more abruptly than they should. Fig. 16-19(A)[10] shows a cycloidal gear pair from which all of the teeth except one on each wheel have been removed. Fig. 16-19(B) shows a similar pair, but with involute teeth. In each figure, a diagram of turning errors is shown which illustrates the sharp acceleration of the driven gear from rest, until true involute or cycloidal action is arrived at, with contact between the designed working faces of the teeth. Following this, there is a slowing down action until the driving tooth passes out of engagement, leaving the driven tooth stationary. The important fact to be noted here is the lead in and lead out on the turning error curves. If there is any kind of error of tooth form or spacing, part of the lead-in or lead-out curve has load bearing action.

In Fig. 16-19(B) the irregular rough lines, which represent contact upon an edge, are as a result of no tip relief, and there is an abrupt change from tip contact to true involute contact. Fig. 16-19(A) shows the lead-in and lead-out curves to be smooth, because the theoretical curves are blended into the relieved tips.

If several such curves, spaced at intervals of one circular pitch, are drawn in succession, the resulting diagram (see Fig. 16-20[10] will show the take-up of load bearing contact of the teeth The parts of the curves which protrude above their preceding or succeeding curves represent load bearing contact. Since none of these curves can be exactly perfect in practice, it should be realized that contact on any given pair of teeth must in general always begin at a point of change over from retarded motion to accelerated motion. To minimize the reduction of output torque in step-up gear trains, special tooth profiles are designed. These variations cause a hump to occur in the turning error curve which indicates that most of the load bearing contact occurs after the point of contact has passed the line of centers (Fig. 16-20(A)). For gears in less particular applications than clocks or timers, the turning error is caused to be slightly humped (Fig. 16-20(B)). If by any combination of inaccura-

SAMSUNG EXHIBIT 1028, Page 267

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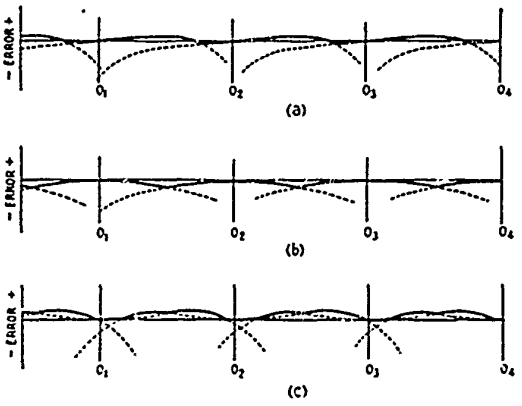


Figure 16-20. Curves of Turning Error[10]

cies the curve becomes double humped, (Fig. 16-20(C)), the load bearing contact would occur when the point of contact was remote from the line of centers and friction would be at its greatest value.

The single humped condition can be affected by arranging the tolerances on the tooth profile so that the curvatures are greater than dictated by rolling curve theory, never less.

16-3.6 GEAR RATIOS

In the design of gear trains, it is important to design the individual gear meshes so that a minimum of spur gear sets are used in order to avoid friction losses. In practice, gear ratio per gear mesh should not exceed 10/1 or go below 1/10, otherwise the large gear would have too many teeth (which is equivalent to having a large pitch diameter) or the small gear would have too few teeth.

One gear mesh is required for each decade of gear ratios, thus:

Gear Ratio	No. Meshes
10:1 or 1:10	1
100:1 or 1:100	2
1000:1 or 1:1000	3, etc.

The ordinary gear velocity ratio i is determined by

$$i = \frac{\omega_1}{\omega_2} = \frac{N_2}{N_1} \qquad (16\text{-}9)$$

where

ω_1 = speed of first gear in mesh (driver), rpm

ω_2 = speed of second gear in mesh (driven), rpm

N_1 = number of teeth in first gear (driver)

N_2 = number of teeth in second gear (driven)

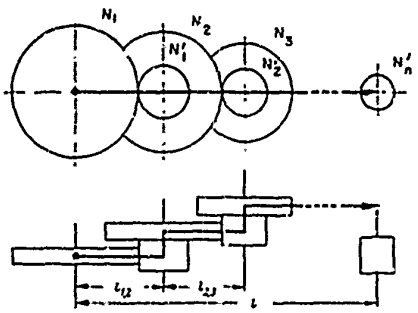
For decreasing speeds, $i > 1$ and for step up gearing, $i < 1$. It must be remembered that the torque transmitted decreases as the speed is increased and vice versa.

If rotational speeds are to be changed significantly, particularly in a limited space, the transformation can be accomplished by introducing a second gear on the shaft of the driven gear of the first mesh, which in turn drives a gear on a third shaft, then introducing a second gear on the third shaft and driving a gear on a fourth shaft. This method can be carried on until the desired gear ratio is obtained. Fig. 16-21(A)[7] is an illustration of a speed increasing train ($i < 1$), and Fig. 16-21(B) shows a speed decreasing train ($i > 1$).

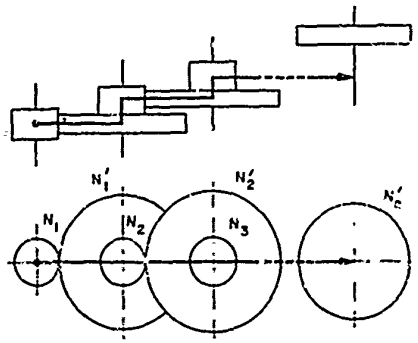
For a given gear ratio, the small wheels generally are determined first. Their selection usually is made according to desired degree of quality. Wheels with smaller numbers of teeth are usually cheaper to produce whereas wheels with higher teeth numbers provide a better degree of overlap and thus smoother running. By using the recommended number of meshes for a particular gear ratio, it remains the designer's job to provide a

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(A) SPEED INCREASING



(B) SPEED DECREASING

Figure 16-21. Gear Trains[7]

combination that will fulfill the ratio requirements.

There are several methods for solving gear ratios whose numerators or denominators are higher-place prime numbers. Since it is not always necessary to maintain exactly the specified gear ratio, a good approximation to the solution can be made by the following two methods:

(1) Calculating with continued fractions. The originally specified gear ratio is reduced to a fraction with lower teeth numbers.

(2) Using Brocot's approximation method which yields considerably better results but which requires an auxiliary table[1,2].

16-3.6.1 Calculation With Continued Fractions

Theory will not be discussed here; it may be found in the appropriate mathematical literature. The procedure in the example that follows clearly shows the computation.

Given a gear ratio $i = 347/439 = N_2/N_1$.

The computation process is:

439:347 = 1 = a
-347
92 347:92 = 3 = b
-276
71 92:71 = 1 = c
-71
21 71:21 = 3 = d
-63
8 21:8 = 2 = e
-16
5 8:5 = 1 = f
5:3 = 1 = g
3:2 = 1 = h
2:1 = 2 = i.

From the coefficients a to i thus found, associated teeth numbers are obtained which become increasingly greater and whose quotient continually approaches the true value:

$N_1 = A' = a\,1 + 0 = 1$ $\quad N_2 = A = a\,0 + 1 = 1$

$B' = b\,A' + 1 = 4$ $\quad B = b\,A + 0 = 3$

$C' = c\,B' + A' = 5$ $\quad C = c\,B + A = 4$

$D' = d\,C' + B' = 19$ $\quad D = d\,C + B = 15$

$E' = e\,D' + C' = 43$ $\quad E = e\,D + C = 34$

$F' = f\,E' + D' = 62$ $\quad F = f\,E + D = 49$

$G' = g\,F' + E' = 105$ $\quad G = g\,F + E = 83$

$H' = h\,G' + F' = 167$ $\quad H = h\,G + F = 132$

$I' = i\,H' + G' = 439$ $\quad I = i\,H + G = 347$

SAMSUNG EXHIBIT 1028, Page 269