Exhibit H

IN THE UNITED STATES DISTRICT COURT
FOR THE SOUTHERN DISTRICT OF TEXAS
GALVESTON DIVISION

U.S. WELL SERVICES, LLC *Plaintiff*, v. TOPS WELL SERVICES, LLC and HONGHUA AMERICA, LLC, *Defendants*.	§ § § § § § § § § § §	Civil Action No. 3:19-cv-00237 **Jury Trial Demanded**

DECLARATION OF DR. ROBERT SCHAAF

1. My name is Robert Schaaf. I have been retained by counsel for Plaintiff U.S. Well Services, LLC ("USWS") as an independent technical expert in the matter listed above. I am being compensated at my usual rate and my compensation is not dependent on any opinions that I may render, any testimony, or any intermediate or final resolution in the matter.

2. I have been asked by USWS to review the following patents: U.S. Patent Nos. 8,789,601 (the "'601 Patent"), 9,410,410 (the "'410 Patent"), 9,611,728 (the "'728 Patent"), 9,970,278 (the "'278 Patent"), and 10,337,308 (the "'308 Patent") (collectively, "the Asserted Patents"), and to form opinions dealing with the manner in which one of ordinary skill in the technical art of those patents would understand those patents and the meaning of certain terms used in the claims of those patents. This declaration also provides my opinions about the person of ordinary skill in the art of those patents.

3. I have knowledge of the facts set forth in this declaration based on my review of these patents and my technical expertise. My review of these patents followed my ordinary practice. I began by reading the patents themselves and then reviewed their respective prosecution histories.

4. I graduated from the University of Southern California with a Bachelor of Science degree in Chemical Engineering. Since graduation, I have attended countless industry courses on oil field operations including classes on hydraulic fracturing. I have over 30 years of experience in the field of Petroleum Engineering with an emphasis on drilling and well completion operations including well stimulation. My experience includes an extensive background in hydraulic fracturing. I am currently a Petroleum Engineering consultant providing advice regarding the development and management of oil/gas wells and fields across the world.

5. I have presented papers at many industry gatherings and symposia. A listing of my publications is included as part of my curriculum vitae ("CV"), which is attached as Ex. 1.

6. I just completed serving as the Chair of the Los Angeles Basin Society of Petroleum Engineers where I have received awards in Projects and Service. I also was recognized with the Outstanding Engineering Merit Award for 2015 from the Orange County Engineering Council.

7. I have presented several papers on petroleum engineering topics at events including the Offshore West Africa Conference, the Prevention First 2014 Symposium, the

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SPE Middle East Oil Show, the SPE European Formation Damage Conference, the SPE Annual Technical Conference, and the Emerson Global Users Exchange.

8. Before I became a consultant, I was a senior project manager at Occidental Petroleum Corporation ("Occidental"). I was also project manager for the Los Angeles Basin at Aera Energy, LLC ("Aera"). For the 25 years before that, I worked for Chevron Corporation ("Chevron"), where I became Engineering and Drilling Manager for Chevron's Congo operations. During my time at Chevron, I also served in various roles for Chevron's operations in Kuwait, Angola, Zaire, Bakersfield, and the Los Angeles Basin.

9. During my over 30 years in the practice of petroleum engineering I have engaged in a number of operations and projects which have provided me with relevant experience and expertise to opine on this matter.

10. From 1979 to 1981, I was employed as a Reservoir Engineer for Chevron in Bakersfield, California. As part of my duties, I assembled development plans for such oil fields as Fruitvale, Yorba Linda, Midway Sunset, West Grimes, and Oak Canyon. All these fields are in California. The work included planning new wells, remediating existing wells, and bringing old wells back to production. All the work involved designing and executing well stimulations, including hydraulic fracturing.

11. From 1981 to 1983, I was employed as a drilling engineer for Chevron where I supervised drilling rigs for an ongoing development program. I had to both plan and supervise the work to get new wells drilled. This work included designing and implementing hydraulic fracturing work.

12. From 1983 to 1985, I was the lead engineer for Chevron for field operations in the Los Angeles Basin. There, I oversaw rig operations, new facilities installations, and production optimization. Among the projects that I supervised were placing new wells on production, maintaining existing wells, and developing ways to optimize oil production from various fields. One of my duties was to design and oversee hydraulic fracturing jobs to increase oil production from individual wells.

13. I was a production engineer from 1985 to 1987 where I worked in fields around the Los Angeles Basin. I developed drilling and workover programs for both onshore and offshore fields. The focus of my work was to find means to increase field oil production from idle or damaged wells. As part of the work, I would have to design well stimulations that included hydraulic fractures in order to increase oil production from non-performing wells.

14. Then, from 1989 to 1993 I was Chief Engineer in Zaire for Chevron. I oversaw the first horizontal well drilled in West Africa during my time there. My role was to develop programs for new wells as well as find means to increase production from existing wells. During my time in Zaire, I increased oil reserves by over 50%. To accomplish this increase, I designed and oversaw hydraulic fracturing projects that resulted in significant oil production increases.

15. From 1993 to 1997 I was a senior staff engineer in Angola. While in Angola, I designed development drilling programs to build on existing production, as well as oversaw expansion into new fields. The wells drilled required various means of stimulation in order to maximize oil recovery. Since the reservoirs were multi-layered, the

stimulation treatments needed diversion to treat all the various layers. I was responsible for the correct hydraulic treatment design for these complex reservoirs.

16. From 1997 to 1999, I was the planning manager for the Southern Africa Business Unit that oversaw the offshore operations in West Africa. From 1999 to 2001, I was the chief engineer for the Congo where I was in charge of drilling new wells, well completions, and increasing production of existing wells. All the designs included stimulation work where the stimulation technique (acidizing or fracturing) needed to be properly implemented.

17. I was a technical consultant for Chevron in Kuwait from 2001 to 2003, where I worked on the Burgan Oil Field. Burgan is the second largest field in the world. While there, I was in charge of developing the new water disposal project. I had to find means to safely and effectively inject the water produced with the Burgan oil. The drilling of these injection wells required the proper completion and stimulation techniques.

18. From 2003 to 2004, I was the drilling and engineering manager for Chevron in the Congo. There I oversaw the work to develop the various fields that Chevron managed in the Congo. Making sure that the hydraulic fracturing work was done properly during the well completions was a significant portion of this work.

19. From 2005 to 2011 I worked for Aera as a project manager. There I oversaw the design, construction, and start-up of all new wells and facilities. Included in my work responsibilities was to make sure new wells were brought on production successfully.

20. From 2011 to 2014, I was the Senior Project Manager for Occidental in the Los Angeles Basin. I was responsible for new and existing wells and facilities. The work

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included mixing and injecting completion fluids for well stimulation work including fracturing.

21. Further detail on my education, work experience, and the cases in which I have previously given testimony in the past five years is contained in my CV.

22. The methodology I have used in forming the opinions set forth herein was to review the patents identified above. I also reviewed the file histories of the patents to the extent necessary for forming the opinions set forth below.

Legal Understanding

23. I am not an attorney. Therefore, I have relied upon certain legal principles that have been explained to me.

24. I have been informed that when interpreting claim terms one must endeavor to employ the perspective of a person of ordinary skill in the relevant art at the time of invention. When interpreting the claims, I understand that the ordinary meaning of the language within the claims should be utilized unless the specification or prosecution history clearly provides reason for applying a different interpretation. In other words if a claim term has a well-known and understood meaning to a person of ordinary skill in the art that meaning should be applied to the claims unless the patentee states a clear and unambiguous alternative meaning that they intend to be in force.

25. I understand that a number of factors should be considered in determining the level of ordinary skill in the art, including: (1) the educational background of those actively working in the field at the time the invention was made (and particularly of any person(s) who may have independently made the invention(s) at about the same time as the

inventor(s)); (2) the type of problems encountered in the art; (3) the various ways that others sought to solve the existing problems; (4) the rapidity with which innovations were being made in the art at the time the invention was made; (5) the level of technological sophistication at the time the invention was made; (6) the educational level of the inventor; and (7) teachings and disclosures of any references that, while not prior art to the invention(s), nonetheless contain teachings or disclosures of what the level of ordinary skill in the field may have been at the time of the invention(s).

26. I have been informed that a patent is invalid for indefiniteness if its claims, read in light of the specification delineating the patent, and the prosecution history, fail to inform, with reasonable certainty, those of ordinary skill in the art about the scope of the invention.

27. I have further been informed that a claim element may be expressed as a means or step for performing a specified function without reciting the specific structure, material or acts in support thereof. I have also been informed that in such instances, the claim element is construed to cover the corresponding structure, material or acts described in the specification and equivalents thereof.

28. In determining the meaning of the claim terms addressed in this declaration, I have relied on the appropriate patent, including as appropriate the file history. I conducted my analysis from the perspective of one of ordinary skill in the art at the time of the invention.

29. For the ’601 Patent, ’410 Patent, ’278 Patent, and ’308 Patent, I have assumed the time of the invention is November 2012.

30. For the '728 Patent, I have assumed the time of the invention is May 2015.

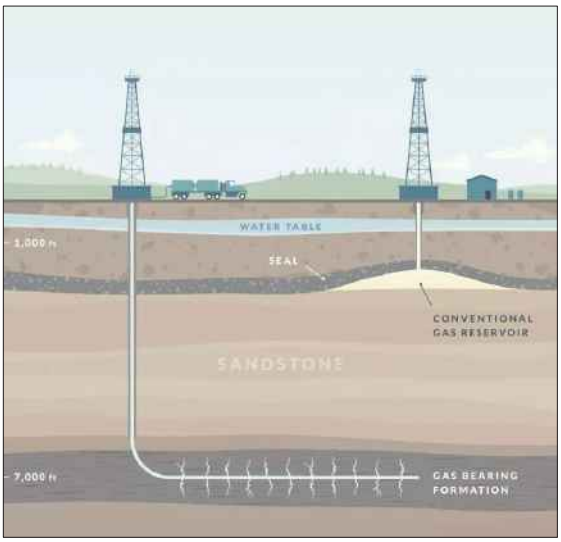
31.

One of Ordinary Skill in the Art

32. In my opinion, a person of ordinary skill in the art at the time of invention of each asserted patent would have had an accredited Bachelor's degree in Chemical, Electrical, Mechanical, or Petroleum Engineering; or other disciplines relevant to the design, engineering, and manufacture of hydraulic fracturing equipment; and approximately three years of experience in the field. In some cases a greater degree of education could compensate for a lesser degree of work experience. Similarly, in some cases a greater degree of work experience could compensate for a lesser degree of education. When I use the term "person of ordinary skill in the art," I am referring to such a person. I performed my analysis from the perspective of such a person.

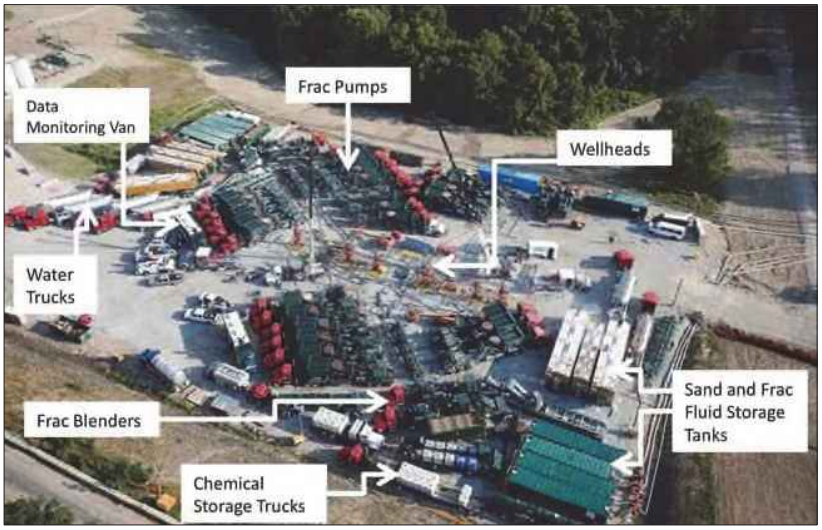
Technology Background

33. Hydraulic fracturing is a process that increases the amount of oil and gas produced from wells. The process involves pumping fluid into a wellbore at a high pressure. The fluid creates fractures in the rock formation below the wellbore, which stimulates the release of oil and gas from the formation:



(Schematic diagram of wellbore above gas bearing formation[1])

34. Many companies provide well services and perform operations at well sites owned by large exploration and production (E&P) companies. Providers of well services own and operate a variety of specialized equipment, which is transported to well sites on vehicles:



(Picture of hydraulic fracturing wellsite with diesel powered equipment on vehicles[2])

[1] https://www.thoughtco.com/fracking-hydrofracking-or-hydraulic-fracturing-1204048.
[2] http://www.kgs.ku.edu/Publications/PIC/pic32.html.

Equipment is deployed by operators on demand and often reconfigured at several well sites in the same day. Therefore, providers of well services try to minimize the downtime of equipment, which requires reconfiguring equipment at a new well site in an efficient manner.

35. The Asserted Patents generally describe solutions that use electric-powered equipment in a hydraulic fracturing system, including fracturing pumps driven by electric motors. Hydraulic fracturing operations have used diesel fuel as a primary source of power for decades.

36. Electric-powered pumps present specific challenges that are not pertinent in conventional hydraulic fracturing systems with diesel pumps. Accordingly, conventional systems were not equipped to use electric-powered pumps. For instance, conventional systems did not include a power source that provided useable power to operate electric pumps. *See, e.g.*, '278 Patent at 1:47-50 ("Fracturing fleets employing diesel-powered pumps [did] not use gas turbines, generators, switch-gear, or transformers, and lack gas compression."). Electric pumps also require specialized systems for control, such as a variable frequency drive ("VFD") which can control speed and torque for alternating current (A/C) motors.

37. Despite these necessary changes and redesigns, there are many conceivable benefits of using electric-powered fracturing pumps. For example, the specification notes that diesel-powered pumps are generally much heavier than electric-powered pumps. '601 Patent, 1:36-38. Therefore, electric pumps can decrease costs for transporting equipment

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and the physical footprint of equipment on site. These gains in efficiency can lead to significant cost savings and minimize equipment downtime.

Terms for Construction

38. Although it is my understanding that Defendants have also proposed other terms for construction, I have been asked to provide opinions on the meanings of the terms below, from the perspective of a person of ordinary skill in the art:

- "electric motor diagnostics"
- "attached"
- "electrically connected to the plurality of electric pumps to provide electrical power to the pumps"

"electric motor diagnostics"

39. I understand that the parties dispute the meaning of "electric motor diagnostics," as used in the '410 Patent, '601 Patent, and '728 Patent. In particular, it is my understanding that Defendants' position is that "electric motor diagnostics" means "the act of detecting a grounding or short in an electric motor," and USWS' position is that no construction is necessary.

40. For example, claim 1 of the '410 Patent[3] describes "the variable frequency drive frequently performs electric motor diagnostics to prevent damage to the at least one electric motor." '410 Patent, claim 1.

41. I agree with USWS' position that the term does not need any construction. The plain and ordinary meaning of the term "electric motor diagnostics" is consistent with

[3] Although my analysis focuses on independent claim 1 of the '410 Patent, the same reasoning is applicable to the remaining claims for which this term is in dispute.

the meaning that is well-understood by a person of ordinary skill in the art—i.e., tests performed on an electric motor to detect problems. It is my understanding that the term is consistently used in this broad sense in the fields of hydraulic fracturing, oilfield technology, and mechanical engineering in general.

42. I disagree with Defendants' proposed construction, which limits electric motor diagnostics to "the act of detecting a grounding or short in an electric motor." While detecting a grounding or a short in an electric motor may be an example of "electric motor diagnostics," a person of ordinary skill in the art would appreciate that the term is not limited as such.

43. I have reviewed the dictionary definitions that Defendants submit as extrinsic evidence, all of which support USWS' position. The definitions are broad and reflect how "diagnostics" are performed to detect problems in a system.

- Comprehensive Dictionary of Electrical Engineering: "diagnostic: (1) one set of tests to run through a system that ***determines whether the system is functioning correctly***. (2) pertaining to the ***detection and isolation of faults or failures***. For example, a diagnostic message, a diagnostic manual." HHUS00008865.
- McGraw-Hill Dictionary of Electrical and Computer Engineering: "diagnostics: information on ***what tests a device has failed and how they were failed; used to aid in troubleshooting***." HHUS00008868.
- Modern Dictionary of Electronics: "1. Having to do with the detection and isolation of a malfunction or error in a computer. 2. A message output by a

> compiler or assembler indicating that a computer program contains a mistake. 3. Software designed ***to locate either a fault in the equipment or an error in programming***." HHUS00008862.

Because electric motors are electromechanical systems, "diagnostics" for an electric motor should not be limited to detecting the electrical problems of ground faults ("grounding") or short circuits ("short"). Those of ordinary skill in the art would also recognize that motors may also suffer from mechanical problems that can cause them to malfunction, fail, or otherwise function incorrectly. Ground faults and short circuits are often beyond the scope of these mechanical problems in motors.

44. For instance, to ensure motor reliability, VFDs can be designed with instruments to detect vibrations in order to determine the health of motor bearings, identify misalignment and tension issues that could impact the performance of the motor, or perform other tests to assess the risk of mechanical failure. *See* Ex. 2 at 10, 17 (example of commercial medium voltage drive technology that can detect temperature conditions and vibration of bearings).

45. I further disagree with Defendants' proposed construction in light of the intrinsic evidence. For instance, the specification of the '410 Patent states:

> ***The VFD can be designed to maximize the flexibility, robustness, serviceability, and reliability required by oilfield applications, such as hydraulic fracturing. For example***, as far as hardware is concerned, the VFD can include packaging receiving a high rating by the National Electrical Manufacturers Association (such as nema 1 packaging), and power semiconductor heat sinks having one or more thermal sensors monitored by a microprocessor to prevent semiconductor damage caused by excessive heat. Furthermore, with respect to control capabilities, the VFD can provide complete monitoring and protection of drive internal operations while

> communicating with an operator via one or more user interfaces. ***For example*, *motor diagnostics can be performed frequently (e.g., on the application of power, or with each start), to prevent damage to a grounded or shorted electric motor 14.*** The electric motor diagnostics can be disabled, if desired, when using, for example, a low impedance or high-speed electric motor.

'410 Patent 3:54-4:4. A person of ordinary skill would recognize that "prevent[ing] damage to a grounded or shorted electric motor" is merely an illustrative example of a VFD design that serves "to maximize the flexibility, robustness, serviceability, and reliability" of the system. *See id.* Therefore, taken in relevant context, the specification indicates that the VFD can be designed to perform mechanical tests that are not captured by "detecting a ground or short in an electric motor."

"coupled to"

46. I understand that the parties dispute the meaning of "coupled to," as used in the '728 Patent. It is my understanding that Defendants' proposed construction for the term is "longitudinal connection for rotation," while USWS proposes no construction is necessary.

47. I agree with USWS that this term does not require a construction. In my opinion, the meaning of "coupled to" as used in the '728 Patent is consistent with the plain and ordinary meaning of the term. Specifically, the term "coupled to" is well-understood in the art to be a ***general*** term that describes connections between two components. While a person of ordinary skill in the art would appreciate that there are different ways of coupling one component to another, the meaning of the term "coupled to" is not limited to any particular coupling mechanism.

48. I disagree with Defendants' proposed construction of "longitudinal connection for rotation," which is not an understood concept to a person of ordinary skill in the art. I am unaware of any context which this definition would govern, in lieu of the ordinary meaning of the term.

49. Defendants have submitted examples of the term "coupling" used in the context of rotating components, which I have reviewed. While "coupling" commonly describes a specific mechanical component that connects two shafts that rotate on the same axis, this narrow application does not affect the meaning of "coupled to" as a general term. Even the term "coupling" is not limited to the context of rotating components, as shown by definitions submitted by Defendants:

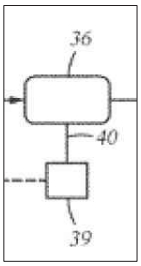
- Dictionary of Mechanical Engineering: "coupling (a) A device for connecting together two or more parts of a mechanism, (b) A device for connecting two vehicles." HHUS00009354, (c) A device for connecting railway coaches or trucks, consisting of two links united by a right-handed and left-handed screw." HHUS00009391.
- McGraw-Hill Dictionary of Scientific and Technical Terms: coupling . . . 1. Any device that serves to connect the ends of adjacent parts, as railroad cars. 2. A metal collar with internal threads used to connect two sections of threaded pipe." HHUS00009354.

Similarly, the term "couple" is not limited to the context of rotation:

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- McGraw-Hill Dictionary of Scientific and Technical Terms: "couple . . . [MECH] A system of two parallel forces of equal magnitude and opposite sense." HHUS00009354. *See also* HHUS00009357.
- Dictionary of Mechanical Engineering: "couple[:] A pair of forces, equal and parallel, but acting in opposite directions, which ***tend to*** rotate the body on which they act." HHUS00009391 (emphasis added).

50. To the extent the Defendants' proposed construction means that coupled components are able to axially rotate on the same axis, a person of ordinary skill in the art reading the specification of the Asserted Patents would understand there is no such requirement. For example, claim 7 of the '728 Patent describes "an electric motor coupled to and that drives the pump." '728 Patent, claim 7. The specification of the '728 Patent discloses "[a] motor 39, which connects to pump system 36 via connection 40, drives pump system 36 so that it can pressurize the slurry." '728 Patent, 4:44-46. This connection is illustrated in Figure 1 below.



'728 Patent, FIG. 1. Reading claim 7 of the '728 Patent in light of the specification, a person of ordinary skill in the art would understand that "coupled to" describes a connection between the electric motor and pump, which allows the electric motor to drive the pump. From the perspective of a person with ordinary skill in the art, this connection

is not limited to a connection on the same axis. For example, the connection between an electric motor and a pump is often accomplished by using a gearbox, belt, or chain, in which the motor rotates a component that is not on the same axis as the component used to drive the pump. *See* HHUS00008900; HHUS00008910; HHUS00008944.

51. Although I understand the use of the term "coupled to" in the '278 Patent is not disputed, the '278 Patent also uses "coupled to" in a general sense that is consistent with the plain and ordinary meaning of the term. For example, claim 1 of the '278 Patent provides:

> . . . a centralized control unit coupled to the plurality of electric pumps and the plurality of generators, wherein the centralized control unit is configured to:
>
> monitor at least one of pressure and temperature of the plurality of electric pumps and the plurality of generators.

'278 Patent, claim 1. Despite the electrical engineering context of claim 1, the term "coupled to" also denotes a general connection between a centralized control unit and pumps and generators. *See id.*; *see also id.* at claims 5, 7-8, 17-21; Abstract; 7:19-26. I am unaware of any principle that would narrow the meaning of the term in the mechanical engineering context of the '728 Patent. Accordingly, the same general definition is coherent across the Asserted Patents, and Defendants' proposed construction for "coupled to" is not appropriate.

"electrically connected to the plurality of electric pumps to provide electrical power to the pumps"

52. I understand that the parties dispute the meaning of "electrically connected to the plurality of electric pumps to provide electrical power to the pumps," as used in the

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'278 Patent, '410 Patent, and '601 Patent. Specifically, I understand that Defendants propose that the limitation means "on the same electrical circuit as the electric pumps, such that electricity flows from the generators to the pumps." I agree with USWS' position that no construction is necessary.

53. Claim 1 of the '601 Patent,[4] for example, provides:

> A system for hydraulically fracturing an underground formation in an oil or gas well to extract oil or gas from the formation . . ., the system comprising;
>
> > a plurality of pumps mounted on a trailer or truck and powered by electric motors and fluidly connected to the well . . .
> >
> > a plurality of generators electrically connected to the plurality of pumps to provide electrical power to the pumps.

'601 Patent, claim 1.

54. I disagree with Defendants' proposed construction, which requires that the plurality of generators be "on the same electrical circuit as the electric pumps, such that electricity flows from the generators to the pumps." Claim 1 of the '601 Patent distinguishes between the "plurality of pumps" and the "electric motors" that power the pumps. Therefore, in the context of this claim, Defendants' proposed construction incorrectly suggests that electricity flows to the pump itself, rather than the motor that powers the pump.

55. It is well-understood that the pump itself uses mechanical power, rather than electrical power. Since the motor is distinguished from the pump in claim 1 of the '601 Patent, electricity flows from the generators to the electric motors, not the pumps. The

[4] Although my analysis focuses on claim 1 of the '601 Patent, the same reasoning is applicable to the remaining claims for which this term is in dispute.

electric motors then convert this electrical power into mechanical power used by the pump. Therefore, Defendants' proposed construction is inappropriate because pumps always receive electrical power ***indirectly*** through a motor.

Limitations Subject to § 112(6)

56. I understand that Defendants propose that the following limitations are purely functional and thus subject to 35 U.S.C. § 112(6):

- "A/C console and a variable frequency drive that controls the speed of the pumps"
- "wherein the variable frequency drive has/includes . . . power semiconductor heat sinks having . . . thermal sensors monitored by a microprocessor to prevent [semiconductor] damage caused by excessive heat"
- "the centralized control unit is configured to: monitor at least one of pressure and temperature of the plurality of electric pumps and the plurality of generators"
- "[wherein the centralized control unit is] further [configured/comprising] [to reset/resetting] a fault occurring in the variable frequency drive"
- "wherein the centralized control unit is configured to: monitor one or more operating characteristics of the electric powered fracturing fleet"
- "wherein the centralized control unit is configured to: . . . control one or more operating characteristics of the electric powered fracturing fleet"

57. I also understand that alternatively, Defendants propose that each of the limitations above does not inform those skilled in the art about the scope of the invention with reasonable certainty.

"A/C console and a variable frequency drive that controls the speed of the pumps"

58. One of ordinary skill in the art would recognize that the "A/C console and a variable frequency drive" recited in claim 2 of the '410 Patent describes a structure that is widely used in industry for controlling the speed of electric pumps. Even without the

function recited by the claims, those knowledgeable in the art would understand that both terms refer to specific machinery.

59. A "variable frequency drive" ("VFD") is an electromechanical system that controls the speed of an electric alternating current ("A/C") motor by varying the input voltage and frequency of the electric motor that is connected to the VFD. Ex. 4 at 1-2. Although an "A/C console" may have multiple meanings without further context, the term clearly refers to specific equipment when used in conjunction with "variable frequency drive." Specifically, "A/C console" refers to a structure that can modify the A/C waveform (i.e., the voltage and frequency) of the alternating current supplied to the electric motor.

60. The specification describes the A/C console in connection with the VFD, disclosing that this configuration controls the speed of an electric motor—and hence the speed of the pump driven by the electric motor. '410 Patent 1:54-55, 3:34-42, 5:17-26, 5:38-41. Each of the descriptions for A/C console and VFD in the specification is consistent with the industry understanding for these devices, as described in Paragraph 58.

61. The claim language itself explicitly describes that the recited structure is used to control the speed of electric pumps, leaving no doubt that the terms describe the electromechanical systems familiar to those of ordinary skill in the art. For instance, claim 2 of the '410 Patent provides:

> The system of claim 1, further comprising an A/C console and a variable frequency drive that controls the speed of the pumps.

'410 Patent, claim 2. Independent claim 1, upon which claim 2 depends, explicitly describes that the "variable frequency drive [is] connected to the electric motor." '410

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Patent claim 1. One knowledgeable in the art would understand that this configuration enables speed control of an electric motor. Therefore, taken in context of the claims, both the "A/C console" and the "variable frequency drive" have structural meaning.

62. A person of ordinary skill in the art would understand the scope of the limitation, as used in '410 Patent, with reasonable certainty. Specifically, those knowledgeable in the art would readily understand A/C consoles and VFDs as specific equipment that can be used to control the speed of A/C motors and pumps, which is the exact purpose described in the claim.

"wherein the variable frequency drive has/includes . . . power semiconductor heat sinks having . . . thermal sensors monitored by a microprocessor to prevent [semiconductor] damage caused by excessive heat"

63. The claim limitation "wherein the variable frequency drive has/includes . . . power semiconductor heat sinks having . . . thermal sensors monitored by a microprocessor to prevent [semiconductor] damage caused by excessive heat" conveys to one knowledgeable in the art an arrangement of structures that prevents semiconductor damage caused by excessive heat. Each of the elements described in the claim limitation are familiar components in the industry that would have been readily recognized by a person of ordinary skill in the art at the time of the invention of the '410 Patent, '308 Patent, and '601 Patent:

- **VFD**: A "variable frequency drive" is well-known to one of ordinary skill in the art, as a specific electromechanical system that can control the speed of electric pumps. *See supra* ¶ 58. This understanding is consistent with how

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the term is used in the specification and claims of the '410 Patent, '308 Patent, and '601 Patent. *See supra* ¶¶ 60-61.

- **Power semiconductor**: One of ordinary skill in the art would understand that "power semiconductor[s]" are fundamental components in a VFD. The function of a VFD is to alter the characteristics of input power supplied to an electric motor, and power semiconductors are the touchstone of all modern systems that control and convert electric power. In fact, it is well-known that improvements in power semiconductor technology over time have increased the viability and performance of industry applications for VFDs. Ex. 5 at 9. Taken in context of the claim limitation, those knowledgeable in the art would recognize that "power semiconductor" describes the device that performs the power conversion required to fulfill the function of a VFD.
- **Heat sinks**: Those knowledgeable in the art would also be familiar with a "heat sink," which is a widely used heat exchanger that transfers heat from a device to a fluid medium. Heat sinks all share a distinctive physical design that extends a material that easily conducts heat (e.g., aluminum) away from a hot surface. *See* Ex. 6. Heat sinks are used throughout industry and are prevalent in electronic devices, such as the "power semiconductor" described in the claim limitation. *Id.* at 1.
- **Thermal sensors**: From the perspective of one of ordinary skill in the art, "thermal sensors" refers to devices used to monitor temperature.

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- **Microprocessor**: One of ordinary skill in the art would understand that the term "microprocessor" refers to a computing device that can communicate with other devices by sending and receiving signals. For example, one application of sending and receiving signals is monitoring temperature information from thermal sensors.

64. Those of ordinary skill in the art would recognize that the structural arrangement described in the claim is not purely functional, and denotes structure that prevents semiconductor damage caused by excessive heat. Included within the "variable frequency drive" are "power semiconductor[s]" that are critical to the functions of the VFD. Attached to the "power semiconductor[s]" are "heat sinks" for heat transfer. The "heat sinks" have "thermal sensors" to detect temperature conditions. The "microprocessor" monitors the temperature information from the "thermal sensors." From the perspective of a person of ordinary skill in the art, this specific arrangement of components can be used "to prevent damage caused by excessive heat."

65. Furthermore, the claim limitation, as used in the '410 Patent, '308 Patent, and '601 Patent, informs a person of ordinary skill in the art of the scope of invention with reasonable certainty. One of ordinary skill in the art would understand the scope of the claims, even without a specific procedure for preventing semiconductor damage. Instead, it is clear from the specific arrangement of components that the proposed solution is a specific physical design that can be used "to prevent damage caused by excessive heat" by detecting temperature conditions that can damage the power semiconductors. Therefore, a person of ordinary skill in the art would recognize that the claim is directed to the specific

configuration recited therein, rather than any algorithm or procedure used "to prevent damage caused by excessive heat."

"the centralized control unit is configured to: monitor at least one of pressure and temperature of the plurality of electric pumps and the plurality of generators"

66. The term "centralized control unit" as used in the '278 Patent has structural meaning in the context of hydraulic fracturing operations. Specifically, the term refers to a physical unit from which operators can control and monitor equipment that is distributed across a hydraulic fracturing site from a single location. Because hydraulic fracturing is a complex operation with multiple stages that require monitoring of myriad parameters, these control units were adopted throughout the industry long before the time of the invention. Although other industry terms are more often used to describe these structures (e.g., "data vans" or "frac vans"), a person of ordinary skill in the art would clearly understand that "centralized control unit" denotes such structure that allows communication with site equipment. The specification of the '278 Patent describes the "centralized control unit" in a context that is consistent with this understanding:

- "The system can also include a centralized control unit coupled to the plurality of electric pumps and the plurality of generators. The centralized control unit monitors at least one of pressure, temperature, fluid rate, fluid density, concentration, volts, amps, etc. of the plurality of electric pumps and the plurality of generators." '278 Patent at 1:3.
- "The centralized control unit is configured to monitor one or more operating characteristics of the electric powered fracturing fleet and control one or more operating characteristics of the electric powered fracturing fleet." '278 Patent 2:36-40.

In addition, the specification discloses that the preferred embodiment for the centralized control unit is "monitor/control data van 40," which reflects the term frequently used in

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industry. '278 Patent 5:7-62; Ex. 7 at 1 ('data vans" allow "[c]entralized monitoring and control of fracturing treatment").

67. The claims and specification also describe monitoring capabilities for "monitor/control data van 40" that are commonly provided in commercial "data vans." For example, claim 19 of the '278 Patent recites that the centralized control unit is "configured to monitor one or more operating characteristics of the electric powered fracturing fleet," with the electric powered fracturing fleet comprising one or more of ". . . blenders, sand silos, chemical storage units, conveyor belts, manifold trailers, [and] hydration units . . . ." '278 Patent, claim 19; *see also* 5:7-62, 7:54-8:20, 10:46-11:57. One of ordinary skill in the art would appreciate that a single structure frequently integrates monitoring and control for several or all of the equipment listed in claim 19. *See* Ex. 7 at 3. Therefore, the "centralized control unit" limitation describes a structure and is not purely functional in the context of the claim and specification, as understood by one of ordinary skill in the art.

68. One knowledgeable about the art at the time of the invention would have clearly understood the scope of the invention and appreciated that further specificity about the "centralized control unit" is not required to understand the scope of the invention in claim 1 of the '278 Patent. Specifically, a person of ordinary skill in the art would recognize that configuration of equipment is at issue, rather than additional technical details relating to the "centralized control unit" or its capabilities for monitoring such equipment. As the specification makes clear, the claimed invention relates to an electric-powered fracturing fleet that included equipment that previously was never used in conventional systems. '278 Patent at 1:47-50 ("Fracturing fleets employing diesel-powered pumps do

not use gas turbines, generators, switch-gear, or transformers, and lack gas compression, [and] therefore have no need to monitor such equipment."); *see also supra* ¶ 36. By describing the monitoring of "at least one of pressure and temperature of . . . the plurality of generators," claim 1 describes the arrangement of components in a system that did not previously exist. '278 Patent, claim 1. Therefore, a person of ordinary skill in the art would have understood the claim scope with reasonable certainty at the time of the invention.

"[wherein the centralized control unit is] further [configured/comprising] [to reset/resetting] a fault occurring in the variable frequency drive"

69. One of ordinary skill in the art would recognize that the "centralized control unit" recited in claims 6 and 15 of the '278 Patent describes a specific structure in hydraulic fracturing operations. Those of ordinary skill in the art would also appreciate that "resetting a fault" is a form of control that involves sending a command to the VFD. The specification in the '278 Patent consistently discusses controlling the VFD and resetting faults from the same "centralized control unit" as previously discussed. *See supra* ¶¶ 66-67. *E.g.*, '278 Patent at claim 6, claim 15, 5:7-20, 5:21-42. Therefore, the same functional meaning for "centralized control unit" in claim 1 applies in claims 6 and 15.

70. A person of ordinary skill in the art would have understood the claim scope with reasonable certainty at the time of the invention. Conventional hydraulic fracturing systems did not use electric fracturing pumps at the time of the invention, so a person of ordinary skill in the art would have recognized that further specificity is not necessary to understand the scope of the invention for claims 6 and 15 of the '278 Patent. *See supra*

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¶¶ 36, 68. Because VFDs are used to provide control for electric pumps, the scope of the claim is the arrangement of components in a system that did not previously exist, as in claim 1 of the '278 Patent. *See id.*

"wherein the centralized control unit is configured to: [monitor/control] one or more operating characteristics of the electric powered fracturing fleet"

71. One of ordinary skill in the art would recognize that the "centralized control unit" recited in the claim 19 of the '278 Patent describes a specific structure in hydraulic fracturing operations. Claim 19 and the specification describe the monitoring and control of equipment from both conventional and unconventional hydraulic fracturing systems. *See, e.g.*, '278 Patent, claim 19; 5:21-43. Monitoring and controlling both types of equipment is performed by the same "centralized control unit" as previously discussed. *See supra* ¶¶ 66-67. Therefore, the same functional meaning for "centralized control unit" in claims 1, 6 and 15 applies in claim 19.

72. A person of ordinary skill in the art would have understood that further specificity is not necessary to understand the scope of claim 19 of the '278 Patent. Conventional hydraulic fracturing systems at the time of the invention did not use "electric powered pumps, turbine generators, variable frequency drives, switchgear, [or] transformers." *See* '278 Patent at 1:47-50. Therefore, at the time of the invention, a person of ordinary skill in the art would have understood the claim scope, which involves the configuration of unconventional equipment in the hydraulic fracturing system. *See supra* ¶ 68-70.

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73. With respect to the aforementioned "centralized control unit" limitations, I understand that USWS has proposed, in the event that the Court construes said limitations as subject to 35 U.S.C. 112(f) or 112(6), that the structure which performs the claimed functions of said limitations to be "data van and equivalents thereof."

74. Based on my review of of the '278 Patent (including the claims, the specification, and the figures thereto), it is my opinion that one of ordinary skill in the art would understand that the '278 Patent to disclose at least a "data van" as the structure that performs the claimed functionality of various said "centralized control unit" limitations. For the same reasons as set forth in the foregoing paragraphs ¶¶ 66–72, it is my opinion that one of ordinary skill in the art would understand under the scope of invention, including with respect to the structure that performs the functions of said "centralized control unit" limitations, with reasonable certainty, according to USWS's proposed construction. In support of my opinion herein, I further note that Defendants' own relevant documents use the term "data van."[5]

Indefinite Limitations

75. I understand that Defendants contend that each of the following limitations does not inform those skilled in the art about the scope of the invention with reasonable certainty. I disagree.

- "performs / performing / further performing electric motor diagnostics"
- "to prevent damage to the . . . electric motor"
- "if [it/they] become grounded or shorted"

[5] *See, e.g.*, TOPS's website at http://topswellservices.com/overview, USWS00002597 (Honghua equipment presentation), HHUS00000813 (Annex 1, Lease Equipment Lease, to TOPS-Honghua Lease Agreement).

- "frequently"
- "can be ported from one well to another"
- "excessive heat"
- "pumps are moveable"
- "mobile platforms"
- "at least one of pressure and temperature of the [plurality of electric pumps and the plurality of generators]/[electrically powered pump and the generator]"
- "an [underground/rock/subterranean] formation
- "capable of pumping the hydraulic fracturing fluid at high pressure to crack the formation / so that the fracturing fluid enters and cracks the formation / configured to pump fluid [at high pressure] into [the/a] wellbore [at high pressure] [that intersects the formation] so that the fluid passes from the wellbore into the formation, and fractures the formation"
- "high-strength steel or steel alloy"

"performs / performing / further performing electric motor diagnostics"

76. The limitation "performs / performing / further performing electric motor diagnostics" as used in the claims of the '410 Patent, '601 Patent, and '728 Patent informs a person of skill in the art of the scope of the claims with reasonable certainty.

77. "Electric motor diagnostics" is a well-understood term to a person of ordinary skill in the art. *See supra* ¶¶ 41-43. This understanding is consistent with the specification's use of the term "electric motor diagnostics." *See supra* ¶ 45. Additionally, one of ordinary skill in the art would have understood during the time of the inventions that a "variable frequency drive" could be designed with instruments to "perform electric motor diagnostics" on an electric motor. *See* Ex. 2 at 10, 17 (example of commercial medium voltage drive technology that provide "[m]otor supervision" functions).

78. A person of ordinary skill in the art would recognize from the context of the inventions that further clarification is not necessary for "electric motor diagnostics" in

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order to understand the scope of the claims with reasonable certainty. For instance, claim 1[6] of the '410 Patent, for example, recites:

> A system for hydraulically fracturing an underground formation in an oil or gas well to extract oil or gas from the formation, the oil or gas well having a wellbore that permits passage of fluid from the wellbore into the formation, the system comprising:
>
> > a plurality of electric pumps fluidly connected to the well and powered by at least one electric motor, and configured to pump fluid into the wellbore at high pressure so that the fluid passes from the wellbore into the formation, and fractures the formation; and
> >
> > a variable frequency drive connected to the electric motor to control the speed of the motor, wherein the variable frequency drive frequently performs electric motor diagnostics to prevent damage to the at least one electric motor.

'410 Patent, claim 1. Read in light of the specification, the claim describes an arrangement of electric-powered fracturing equipment that did not exist in conventional diesel-powered hydraulic fracturing systems. *See, e.g.*, '410 Patent at 1:13-37; 6:13-31. A person of ordinary skill in the art would therefore understand that the "electric motor diagnostics" limitation is used to define the function of the VFD in the system, as well as its interface with the electric motor. Under this context, it is sufficient to refer to "electric motor diagnostics" in the general sense because the pertinent detail is that the claims describe the ***VFD*** performing these diagnostics (rather than some other element within the system). *See* '410 Patent 3:54-4:4 ("The VFD can be designed to maximize the flexibility, robustness, serviceability, and reliability required by oilfield applications, such as hydraulic fracturing.").

[6] Although my analysis focuses on claim 1 of the '410 Patent, the same reasoning is applicable to the remaining claims for which this term is in dispute.

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79. In addition, even though the term "electric motor diagnostics" alone would be sufficient to understand the scope of the invention, claim 1 of the '410 Patent further recites that the "electric motor diagnostics" are performed "to prevent damage to the at least one electric motor." This limitation further explicitly provides that the "electric motor diagnostics" are used for a particular purpose—to prevent damage to the electric motor. One of ordinary skill in the art would recognize that this purpose is consistent with the benefit of performing tests to detect problems in an electric motor (i.e., "electric motor diagnostics").

80. In the context of the claims, one of ordinary skill in the art would understand that it would be unreasonable to provide further specificity for "electric motor diagnostics" (e.g., by specifying the exact electric motor diagnostics performed). Instead, those of ordinary skill in the art would recognize that the implementation of "electric motor diagnostics" will depend on design preferences and constraints. For example, one design for "electric motor diagnostics" may measure certain variables, while another design may measure a different set of variables, even if both designs share the same objective (e.g., predicting mechanical failure in an electric motor, detecting misalignment, or identifying the presence of a ground or short). The discretion in design is evident, for example, in the following:

- U.S. Patent No. 6,330,525 (Title: "Method and apparatus for diagnosing a pump system") ("Several manufacturers provide partial solutions for the off-line diagnosis of electric motors. Framatome and Liberty Technologies both provide for PC based ***electric motor diagnostics systems*** consisting of vibration sensors

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to detect motor bearing failure, a measurement of motor voltage wherein current and phase are coupled to an FFT for the calculation of a motor signature, and temperature sensors to sense elevated motor winding temperatures and, ***in some cases,*** flux analysis, and insulation characteristics of the motor windings and shaft alignment sensors to measure motor-to-coupler alignment." at 3:20-32) (attached as Ex. 8);

- U.S. Patent No. 5,917,428 ("Integrated motor and diagnostic apparatus and method of operating same") ("A method and apparatus for real-time ***electric motor diagnostics*** and condition monitoring. While the motor is energized, ***dynamic operating parameters are determined and a notification signed is generated if predetermined criterion are satisfied***. The diagnostic apparatus is integrated with the motor and ***includes a set of sensors, a processing unit, a memory and an output interface for communicating alarms, warnings and calculated operating parameter values or the like*** to a display device and to an external supervisor having wireless paging capability to alert a remote operator or maintenance personnel." at Abstract) (attached as Ex. 9).

Therefore, a person of ordinary skill in the art at the time of the inventions would have understood the scope recited by a "[VFD] . . . performing electric motor diagnostics" with reasonable certainty, even without further detail about specific diagnostics performed which are provided by the claims.

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"to prevent damage to the . . . electric motor"

81. The limitation "to prevent damage to the . . . electric motor" as used in the claims of the '410 Patent, '601 Patent, and '728 Patent informs those skilled in the art of the claim scope with reasonable certainty.

82. The limitation "the variable frequency drive frequently performs electric motor diagnostics to prevent damage to the electric motor" describes concepts that are well-understood to those knowledgeable about the art. '410 Patent, claim 10.[7] The limitation describes a specific piece of machinery, specific tests performed by the machinery, and the specific function of those tests. One of ordinary skill in the art would have understood during the time of the inventions that a "variable frequency drive" could be designed with instruments to "perform[] electric motor diagnostics" on an electric motor. Ex. 2 at 10, 17 (example of commercial medium voltage drive technology that provide "[m]otor supervision" functions). Those knowledgeable in the art would further recognize that the very benefit of performing these electric motor diagnostics is "to prevent damage to the . . . electric motor."

83. A person of ordinary skill in the art would understand from the context of the claims that further specificity about any steps performed "to prevent damage to the . . . electric motor" is not necessary in order to understand the scope of the claims with reasonable certainty. Specifically, a person of ordinary skill in the art would have been aware that the VFD's function is to control the speed and torque of the electric motor,

[7] Although my analysis focuses on claim 10 of the '410 Patent, the same reasoning is applicable to the remaining claims for which this term is in dispute.

which allows the VFD to reduce the motor load to prevent damage. *See, e.g.*, Ex. 4 at 1, 4 ("If a centrifugal pump surges, or has lost prime, or a part has broken, the system should be able to shut down without causing further damage."). Because the invention describes a configuration of equipment in a hydraulic fracturing system, the limitation is used to define the function of the VFD, and its interface with the electric motor. *See supra* ¶ 78. Therefore, the pertinent detail is that the claims describe the ***VFD*** incorporating measures to prevent motor damage (rather than some other element within the system). *See id.*

84. In addition, a person of ordinary skill in the art would recognize that the implementation of specific motor diagnostics "to prevent damage to the . . . electric motor" will depend on design preferences constraints. *See supra* ¶ 80. Because there is discretion in implementation, it would not be reasonable to provide further specificity under the context of the claims. *See id.* Therefore, a person of ordinary skill in the art at the time of the inventions would have understood the claim scope with reasonable certainty.

"if [it/they] become grounded or shorted"

85. The limitation "to prevent damage to the . . . electric motor" as used in the claims of the '601 Patent informs those skilled in the art of the claim scope with reasonable certainty.

86. A person of ordinary skill in the art would understand the terms "grounded" and "shorted" to refer to a "ground fault" and "short circuit," respectively. Both ground faults and short circuits are electrical problems relating to the flow of current in an electrical circuit. USW00006730; USW00006748-9. The terms "grounded" and "shorted" are also commonly used to describe ground faults and short circuits in electrical circuits within

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machinery or equipment. This understanding for "grounded" and "shorted" is a basic concept that is familiar to those of ordinary skill in the art, as well as those who have introductory knowledge or experience relating to electrical circuits. Therefore, in the context of the claims, "if [the electric motor] becomes grounded or shorted" describes a ground fault or short circuit in an electrical circuit within an electric motor. *See, e.g.*, '601 Patent, claim 8.[8]

87. In addition, a person of ordinary skill in the art would recognize that further specificity for the limitation "if [it/they] become grounded or shorted" is not reasonable. Rather, both ground faults and short circuits tend to produce the same effect of uncontrolled electrical flow leading to the shutdown of equipment, even though they can result from a number of reasons known to those of ordinary skill of the art. For example, conditions that may cause ground faults and short circuits may include loose connection of wires, worn wire insulation, frayed electrical components, etc. Therefore, it is sufficient to describe an electric motor as "becom[ing] grounded or shorted" which specifies a type of problem that thwarts the proper operation of equipment. A person of ordinary skill in the art during the time of the invention would have understood the claim scope with reasonable certainty.

"frequently"

88. The term "frequently" as used in the claims of the '410 Patent, '601 Patent, and '728 Patent informs a person of skill in the art of the scope of the claims with

[8] The same reasoning is applicable to the remaining claims for which this term is in dispute.

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reasonable certainty. For example, claim 1 of the '410 Patent[9] states in relevant part: "the variable frequency drive frequently performs electric motor diagnostics to prevent damage to the at least one electric motor." '410 Patent, claim 1.

89. Although the term "frequently" can depend on context, a person of ordinary skill in the art would understand what "frequently" denotes in the context of electric motor diagnostics for hydraulic fracturing pumps. Because hydraulic fracturing operations require operators to shut down and restart equipment at multiple well sites during a short period of time, *see supra* ¶ 34, motor diagnostics would be performed "frequently" if they occur at least once from startup to shutdown. Performing diagnostics at this frequency would be sufficient to detect mechanical or electrical issues that result from transporting equipment from one well site to another, for example.

90. The specification confirms the understanding that motor diagnostics are performed "frequently" if they are performed at least once from startup to shutdown:

> "For example, motor diagnostics can be performed ***frequently (e.g., on the application of power, or with each start)***, to prevent damage to a shorted electric motor 14. The electric motor diagnostics can be disabled, if desired, when using, for example, a low impedance or high-speed electric motor."

'410 Patent, 3:66-4:4 (describing motor diagnostics performed by the VFD). In addition, those knowledgeable in the art would understand that "electric motor diagnostics" (and more generally, "diagnostics") can refer to tests performed discretely (e.g., manually, upon a decision made by an operator), or according to a set routine (e.g., a computer program).

[9] Although my analysis focuses on claim 1 of the '410 Patent, the same reasoning is applicable to the remaining claims for which this term is in dispute.

In light of the specification, the term "frequently" precludes the former, and is consistent with the latter. Therefore, the example of performing motor diagnostics "on the application of power, or with each start" indicates a set routine that would occur at least once from startup to shutdown, instead of an isolated decision to perform diagnostics. Furthermore, it would not make sense to refer to "disabl[ing]" motor diagnostics that are performed manually.

91. Therefore, from the perspective of a person of ordinary skill in the art, the metes and bounds of "frequently" is clearly defined in light of the specification and the claims, and informs a person of ordinary skill in the art of the claim scope with reasonable certainty.

"can be ported from one well to another"

92. The limitation "can be ported from one well to another" as used in the claims of the '601 Patent, '410 Patent, and '308 Patent informs a person of skill in the art of the scope of the claims with reasonable certainty. For example, claim 3 of the '410 Patent[10] provides: "wherein the electric pumps are mounted on vehicles, and can be ported from one well to another." '410 Patent, claim 3. In the context of the claim language alone, "ported" is synonymous with "transported." The specification supports this understanding:

> Alternatively, and as shown in FIG. 2, trailers 112 can be used to transport the pumps 110 and electric motors 114, with two or more pumps 110 carried on a single trailer 112. Thus, the same number of pumps 110 can be transported on fewer trailers 112

[10] Although my analysis focuses on claim 3 of the '410 Patent, the same reasoning is applicable to the remaining claims for which this term is in dispute.

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'410 Patent, 6:23-28.

93. A person of ordinary skill in the art would be familiar with the practice of mounting hydraulic fracturing equipment on vehicles, as well as transporting (i.e. "porting") equipment between well sites. *See supra* ¶ 34. As the specification describes, the same practice was used for conventional diesel hydraulic fracturing operations. *See* '410 Patent, 1:27-30. The specification has many other descriptions of this practice for the disclosed invention. *See, e.g.*, *id.* at 1:55-59, 3:18-23, 4:60-64, 6:4-7, FIGS. 1-2. Therefore, based on the claims and disclosures in specification, a person of ordinary skill in the art during the time of the invention would understand the scope of the invention with reasonable certainty.

"excessive heat"

94. The term "excessive heat" as used in the claims of the '410 Patent, '601 Patent, and '308 Patent informs a person of skill in the art of the scope of the claims with reasonable certainty.[11] For example, claim 9 of the '410 Patent provides: "wherein the variable frequency drive has one or more power semiconductor heat sinks having thermal sensors monitored by a microprocessor to prevent damage caused by excessive heat." '410 Patent, claim 9.

95. While the amount of heat that is deemed "excessive" may be a function of system's design constraints and operating conditions, a person of ordinary skill in the art would readily recognize that the term "excessive heat" refers to an amount of heat that

[11] Although my analysis focuses on claim 9 of the '410 Patent, the same reasoning is applicable to the remaining claims for which this term is in dispute.

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exceeds the threshold heat level suitable for the particular system under the given operating conditions. Accordingly, such excessive heat would damage the power semiconductors. The claims provide a specific arrangement of components that allows the variable frequency drive to prevent semiconductor damage caused by such excessive heat. *See supra* ¶¶ 64-65. Given the full context and structure recited in the claims, a person of ordinary skill in the art would understand the term "excessive heat" to mean "heat that damages the power semiconductors." *See supra* ¶¶ 64-65. Therefore, a person of ordinary skill in the art during the time of the invention would understand the scope of the invention with reasonable certainty.

"pumps are moveable"

96. The limitation "pumps are moveable" as used in the claims of the '728 Patent informs a person of skill in the art of the scope of the claims with reasonable certainty. For instance claim 6 of the '728 Patent provides: "wherein the pumps are moveable to different locations on mobile platforms." '728 Patent, claim 6. In the full context of the claim, "moveable to different locations" refers to the common practice of mounting hydraulic fracturing equipment on vehicles for transport to different well sites. *See supra* ¶ 34, 92-93. The specification of the '728 Patent supports this understanding. *See, e.g.*, 1:45-48 ("Heavy duty trailers, skids, or trucks are required for transporting the large and heavy pumps and engines to sites where wellbores are being fractured"). Therefore, based on the claims and disclosures in specification, a person of ordinary skill in the art during the time of the invention would understand the scope of the invention with reasonable certainty.

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"mobile platforms"

97. The limitation "mobile platforms" as used in the claims of the '728 Patent informs a person of skill in the art of the scope of the claims with reasonable certainty. For instance, claim 6 of the '728 Patent provides: "wherein the pumps are moveable to different locations on mobile platforms." '728 Patent, claim 6. In the full context of the claim, the limitation refers to the common practice of mounting hydraulic fracturing equipment on vehicles having platforms for transport to different well sites. *See supra* ¶ 34, 92-93. The specification of the '728 Patent supports this understanding. *See, e.g.*, 1:45-48 ("Heavy duty trailers, skids, or trucks are required for transporting the large and heavy pumps and engines to sites where wellbores are being fractured"). Therefore, based on the claims and disclosures in specification, a person of ordinary skill in the art would understand the scope of the invention with reasonable certainty.

"at least one of pressure and temperature of the [plurality of electric pumps and the plurality of generators] / [electrically powered pump and the generator]"

98. Claim 1 of the '278 Patent describes that the "centralized control unit is configured to monitor at least one of pressure and temperature of the plurality of electric pumps and the plurality of generators." A person of ordinary skill in the art would understand this limitation, as it is used in the '278 Patent, with reasonable certainty. Specifically, data vans (i.e., centralized control units) were used to monitor operating parameters for certain equipment at a well site. *See supra* ¶ 66. Therefore, a person of ordinary skill of the art would understand that the limitation describes a configuration that uses a centralized control unit to monitor operating parameters for electric pumps and

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generators, which are two types of equipment absent from conventional diesel-powered systems. '278 Patent at 1:47-50 ("Fracturing fleets employing diesel-powered pumps do not use gas turbines, generators, switch-gear, or transformers, and lack gas compression, [and] therefore have no need to monitor such equipment."); *see also supra* ¶ 35-36. Based on this understanding, a person of ordinary skill in the art at the time of the invention would have understood the scope of the claim with reasonable certainty.

"an [underground/rock/subterranean] formation"

99. The limitation "an [underground/rock/subterranean] formation" as used in the claims of the '601 Patent, '410 Patent, '278 Patent, '308 Patent, and '728 Patent informs a person of skill in the art of the scope of the claims with reasonable certainty.

100. For example, claim 1 of the '410 Patent describes a "system for hydraulically fracturing an underground formation." '410 Patent, claim 1.[12]

101. Hydraulic fracturing is a widely practiced "method of enhancing oil and gas recovery from wells by injecting water, sand, and chemicals into rock formations." *See* Ex. 10 at 1. The claims and specification make clear that the inventions claim systems for practicing this method:

> Hydraulic fracturing has been used for decades to stimulate production from conventional oil and gas wells. The practice consists of pumping fluid into a wellbore at high pressure. Inside the wellbore, the fluid is forced into the formation being produced. When the fluid enters the formation, it fractures, or creates fissures, in the formation. Water, as well as other fluids, and some solid proppants, are then pumped into the fissures to stimulate the release of oil and gas from the formation.

[12] Although my analysis focuses on claim 1 of the '410 Patent, the same reasoning is applicable to the remaining claims for which this term is in dispute.

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'410 Patent, 1:13-20. *See id.* at 1:21-37. Therefore, a person of ordinary skill in the art at the time of the invention would have understood the claim scope with reasonable certainty.

"capable of pumping the hydraulic fracturing fluid at high pressure to crack the formation / so that the fracturing fluid enters and cracks the formation / configured to pump fluid [at high pressure] into [the/a] wellbore [at high pressure] [that intersects the formation] so that the fluid passes from the wellbore into the formation, and fractures the formation"

102. The limitation "capable of pumping the hydraulic fracturing fluid at high pressure to crack the formation / so that the fracturing fluid enters and cracks the formation / configured to pump fluid [at high pressure] into [the/a] wellbore [at high pressure] [that intersects the formation] so that the fluid passes from the wellbore into the formation, and fractures the formation" as used in the claims of the '601 Patent, '410 Patent, '278 Patent, '308 Patent, and '728 Patent informs a person of skill in the art of the scope of the claims with reasonable certainty.

103. For example, claim 10 of the '410 Patent describes a "a pump for pumping the hydraulic fracturing fluid into the well, and then from the well into the formation., the pump capable of pumping the hydraulic fracturing fluid at high pressure to crack the formation." '410 Patent, claim 10.[13]

104. Hydraulic fracturing is a well-known technique to those of ordinary skill in the art, which involves pumping hydraulic fracturing fluid at high pressure to crack the formation:

> Water containing sand and chemical agents is then pumped at very high pressures, typically thousands of pounds per square inch, through the perforations into the surrounding rock. The intense pressure exerted by the

[13] Although my analysis focuses on claim 10 of the '410 Patent, the same reasoning is applicable to the remaining claims for which this term is in dispute.

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> water cracks the rock, creating minute fractures that propagate sometimes hundreds of feet away from the wellbore.

Ex. 10 at 3. The specification and claims make clear that this same technique is described by the disputed limitation. *See, e.g.*, '410 Patent, 1:13-37. Therefore, a person of ordinary skill in the art at the time of the invention would have understood the claim scope with reasonable certainty.

"high-strength steel or steel alloy"

105. The limitation "high-strength steel or steel alloy" as used in the claims of the '410 Patent and '601 Patent informs a person of skill in the art of the scope of the claims with reasonable certainty.

106. Specifically, the term "high-strength steel or steel alloy" is well-understood and refers to a "steel or steel alloy designed to provide better mechanical properties than standard steel." From the perspective of a person of ordinary skill in the art, this understanding is evident from parsing the language in the limitation:

- **"Steel or steel alloy"**: An alloy is a basic concept that refers to the combination of metals. "Steel" refers to a wide range of alloys that are composed of iron and carbon, and sometimes other elements such as chromium. "Steel alloy" is a combination of steel and other alloying elements.
- **"High-strength"**: Those knowledgeable in the art would be familiar with methods for increasing the strength of steel and other metals. *See* Ex. 11. For example, various methods of heat treatment for steel are an introductory

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topic in materials science. Likewise, it is well known that adjusting the metal composition in alloys can improve the mechanical properties of a metal.

107. From the perspective of a person of ordinary skill in the art, the phrase "high-strength" does not define a specific threshold for mechanical strength. Instead, it merely denotes that methods (e.g., heat treatment) have been applied to improve the mechanical properties of standard carbon steel. Furthermore, those knowledgeable in the art would also be aware of situations where these methods are not applied to strengthen steel (e.g., where standard steel is deemed sufficient for low-strength applications). Accordingly, it is common to refer to "high-strength" steel or steel alloys without identifying a specific threshold for mechanical strength.

108. Indeed, those knowledgeable in the art would recognize that it would be unreasonable to identify a specific threshold for mechanical strength without further information about the application for which a metal is used. For example, a certain level of strength may be sufficient for one pump design, but inadequate in another.

109. Dictionary definitions for similar terms support the understanding that "high-strength steel or steel alloy" is not defined by a specific threshold for strength:

- A Dictionary for the Oil and Gas Industry: "high-strength steel *n*: low carbon steel with very small amounts of molybdenum, niobium, titanium, or vanadium. Also called high alloy steel, high-strength alloy steel or high-strength, low-alloy steel." USW00006720.
- McGraw-Hill Dictionary of Scientific and Technical Terms: "high-strength low-alloy steel . . . Steel containing small amounts of niobium or vanadium

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> and having higher strength, better low-temperature impact toughness, and, in some grades, better atmospheric corrosion resistance than carbon steel." USW00006733.

110. The intrinsic record supports the position that "high-strength" does not denote a specific degree of mechanical strength. For instance, claim 10 of the '410 Patent[14] describes "an electric motor having a high-strength steel or steel alloy shaft attached to the pump and configured to drive the pump." '410 Patent, claim 10. Similarly, the specification discloses that "the electric motor 14 can include . . . a high strength 4340 alloy steel shaft, although other suitable materials can also be used." '410 Patent, 3:50-54. A person of ordinary skill in the art would recognize that "4340 alloy steel" is a specific material that adheres to standards well-known to those knowledgeable in the art. Ex. 12. Yet the mechanical strength of 4340 alloy steel can vary based on heat treatment:

> AISI 4340 is a heat treatable, low alloy steel containing nickel, chromium and molybdenum. It is known for its toughness and capability of developing high strength in the heat treated condition while retaining good fatigue strength.

Id. at 2.

111. Therefore, a person of ordinary skill in the art would understand with reasonable certainty that the term refers to a specific classification of materials that is widely used throughout industry, rather than a "steel or steel alloy" with a sufficient level of mechanical strength.

[14] Although my analysis focuses on claim 10 of the '410 Patent, the same reasoning is applicable to the remaining claims for which this term is in dispute.

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Additional Disclosures

112. It is my understanding that Defendants have not yet submitted an expert declaration regarding the issues discussed in this declaration. Further, it is my understanding that the Defendants have not yet submitted a brief to the court explaining the basis for their positions with respect to the various claim terms. Accordingly, I reserve the right to supplement this declaration or otherwise address any arguments that may be raised by any expert retained by the Defendants or by the Defendants in their briefs.

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I declare under penalty of perjury that the foregoing is true and correct.



ROBERT SCHAAF

Executed on March 6, 2020

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EXHIBIT 1

ForensisGroup®

301 North Lake Avenue, Suite 420, Pasadena, CA 91101-5119
626/795-5000 TEL 626/795-1950 FAX 800/555-5422 (Toll Free)
www.ForensisGroup.com

ROBERT SCHAAF
Curriculum Vitae

Petroleum and Drilling Engineering Expert

PROFESSIONAL EXPERIENCE

Consultant / Expert Witness 2014-Present

- Expert witness for over 60 oil/gas drilling & operation cases including patent litigation
- Instructor for industry classes on oil and gas drilling and operations
- Provided technical advice and background information to investment advisors
- Performed the reservoir and economic analysis of property acquisitions
- Project Manager for international drilling and construction projects

Occidental Petroleum 2011-2014

Senior Project Manager, Los Angeles Basin

- Project manager for the re-development of the Dominguez Hills Oil Field
- Designed and led the refurbishment of the Platform Emmy drilling rig
- Led the development of new oil/gas wells and workovers of existing wells
- Supervised the new well installations of both onshore and offshore wells

Aera Energy, LLC 2005-2011

Project Manager, Los Angeles Basin

- Managed all engineering and implementation aspects for new projects
- Delivered 30+ projects annually on-time and on-budget
- Oversaw the drilling of new onshore and offshore wells

Chevron 1979-2004

Engineering and Drilling Manager, Congo

- In charge of all engineering, drilling, and construction functions
- Supervised drilling and completion program for all new wells
- Implemented multi-stage acid jobs and hydraulic fracturing projects that optimized production from multiple reservoir zones

Sr. Technical Consultant, Kuwait

- In charge of the $1.5B Kuwait's Burgan effluent water project development
- Developed new well completion and stimulation program for new water injection wells that included hydraulic fracture stimulations in multiple zones
- Led team to review, design, procure and install new artificial lift equipment

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Chief Engineer, Congo

- Ran Chevron Oil Congo's engineering department that included reservoir/production/drilling engineering, budgeting/planning, and facilities design
- Designed and implemented drilling program in the Congo that reduced per well drilling costs by 25%
- Oversaw all well completions and stimulation work that included multi-stage hydraulic fracturing of horizontal wells

Planning Manager, Southern Africa Business Unit

- Managed business unit's $500 MM annual capital budget that adequately balanced short-term cash requirements with long-term earnings improvement
- Developed unique scheme to secure project funds for under-financed partner.
- Assembled innovative financing technique to move forward internal projects when capital was non-existent
- Performed the economic analysis for various offshore Angola concessions

Sr. Staff Engineer, Angola

- Coordinated the planning of the $450 MM North Nemba offshore oil rig that set new standards for the interaction of multi-disciplined teams
- Led the development and implementation of the $38 MM Northeast Numbi offshore oil rig that was on budget and put on line in 50% of the average time
- In charge of well completions and stimulation work that included multi-stage acid stimulations, gravel packs, and hydraulic fracturing
- Developed the reservoir simulation model that led to a new water injection strategy in the Vermelha reservoir of the Numbi Field. The realignment stabilized the reservoir pressure & reduced the oil decline from over 30% to fewer than 10%.

Chief Engineer, Zaire

- In charge of all reservoir/production/drilling engineering for Zaire Gulf Oil
- Developed new exploitation strategy that added 5.5 MM barrels of reserves to the Mibale field
- Applied horizontal drilling and multi-stage fracturing to develop the Libwa Field

Area Engineer, Los Angeles Basin

- Led the 10 production engineers overseeing Chevron's fields
- Led operations review that reduced annual costs by over $1,000,000 at the Whittier and Huntington Beach fields
- Maintained a production decline of less than 6% at the Yorba Linda steam project by careful monitoring of reservoir energy and temperature
- Increased production by expanding water injection to reservoirs that were previously thought to be unsuitable for secondary recovery
- Led the effort to sell various small California leases. Obtained almost twice the anticipated transaction price by utilizing a coordinated marketing effort focusing on potential value of under-exploited resources

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Production Engineer, Los Angeles Basin

- Increased oil production 68% in the Montebello Field (LA Basin) waterflood by identifying unseen fault blocks and the realignment of water injection patterns
- Developed multi-stage stimulation projects using both mechanical and chemical diverters at Montebello that raised oil production of various wells from under 10 BPD to 20-80 BPD
- Expanded pumping unit system to increase and optimize production

Lead Engineer, Los Angeles Basin

- Led team of 4 engineers on field operations including planning/supervising rig operations, new facilities installations, and production optimization
- Supervised well completions including perforating, acid stimulations, and multi-stage hydraulic fracturing
- Re-established economic viability to the aging Beverly Hills Field by optimizing hydraulic lift system at three drill sites

Drilling Engineer, Bakersfield

- Supervised drilling rigs for ongoing development program
- Designed, assembled, and coordinated drilling programs for a wide variety of development and exploration wells
- Oversaw well completions that included acid jobs and fracturing jobs

Reservoir Engineer, Bakersfield

- Designed and implemented deep cyclic steam project in the Fruitvale Field to recover an additional 10% of oil in place
- Implement well stimulus programs (acidizing and hydraulic fractures) for multi-layer reservoirs in the Fruitvale and Lost Hills Fields
- Significantly increased gas production from the West Grimes (Sacramento Valley) Field by discovering and exploiting bypassed gas zones

EDUCATION

Bachelor of Science, Chemical Engineering, University of Southern California

Graduate Business Classes, California State College Bakersfield

- Project Management Professional (Certified by Project Mgmt. Institute)
- Six Sigma Black Belt
- Chairman LA Basin Society of Petroleum Engineers (SPE)
- SPE Project, Facilities, and Construction Award – 2019
- SPE Service Award - 2019
- Received R&A Award for the development of a company Toastmaster Club
- Outstanding Engineering Merit Award 2015 – Orange County Engineering Council

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PAPERS

"Platform Emmy Deck Extension Project" presented at the Prevention First 2014 Symposium – October 2014

"Engineered Severe Service Valve Solution" presented at the Emerson Global Users Exchange – September 2010

"Advanced Wireless Application for Critical Service Valves" presented at the Emerson Global Users Exchange – September 2010

"Alternative Economic Criteria for Superior Project Analysis" presented at the SPE Middle East Oil Show in Bahrain – June 2003

"Stimulation of a Producing Horizontal Well Using Enzymes that Generate Acid In-Situ Case History" presented at the SPE European Formation Damage Conference held in The Hague, The Netherlands – May 2001

"An Innovative Technique of Obtaining Project Financing for the Equity Share of a Developing Country's National Oil Company" presented at the SPE Annual Technical Conference in New Orleans, Louisiana – September 1998 and published in the Journal of Petroleum Technology – January 1999

"Calculated Risk Taking for Fast-Track Development" presented at the Offshore West Africa conference in Accra, Ghana – November 1997

"Adapting a Reservoir-Management Strategy to Changing Reservoir Conditions" presented at the SPE Annual Technical Conference in San Antonio, Texas – Oct. 1997 and published in the Journal of Petroleum Technology – December 1997

"Changing Reservoir Management Strategy in the Numbi Field" presented at the Offshore West Africa conference in Libreville, Gabon – November 1996

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Date: July 2019
Case: Sand Revolution LLC v. Continental Intermodal Group –Trucking LLC, U.S. Patent and Trademark Office Before the Patent Trial and Appeal Board: Patent No. 8,944,740. Declaration.

Date: April 2019
Case: Arrows Up, LLC v. Oren Technologies, LLC, U.S. Patent and Trademark Office Before the Patent Trial and Appeal Board: Patent Nos. 9,682,815, 9,248,772, 9,914,602, and 9,617,066. Deposition.

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Date: March 2019
Case: Schlumberger Technology Corporation v. Integrated Drive Systems LLC, U.S. Patent and Trademark Office Before the Patent Trial and Appeal Board: Cases IPR2018-00603/IPR2018-00604 for Patent No. 9,644,431. Rebuttal Declarations.

Date: March 2019
Case: Continental Intermodal Group-Trucking LLC v. Sand Revolution LLC, Sand Revolution II, LLC, U.S. District Court Western District of Texas, Midland/Odessa Division: Case No. 7:18-cv-00147-DC for Patent No. 8,944,740. Declaration.

Date: January 2019
Case: Roxane I. Beeman v. Art McAdams, San Mateo County, Superior Court of the State of California: Case No. 17CIV05278. Trial Testimony.

Date: December 2018
Case: Hunting Titan, Inc. v. DynaEnergentics GMBH & Co. KG, U.S. Patent and Trademark Office Before the Patent Trial and Appeal Board: Case IPR2018-00600 for Patent No. 9,581,422. Declaration.

Date: December 2018
Case: Billy Petty v. Chevron Corporation, Kern County, Superior Court of the State of California, County of Kern: Case No. BCV-16-103012 TSC. Deposition.

Date: November 2018
Case: Armstrong Oil Inc. v. Pieco, Inc. and Athnassia, LLC, Orange County, Superior Court of California: Case No. 30-2016-00881376-CU-PO-CJC. Deposition.

Date: November 2018
Case: Schlumberger Technology Corporation v. Integrated Drive Systems LLC, U.S. Patent and Trademark Office Before the Patent Trial and Appeal Board: Cases IPR2018-00603 and IPR2018-00604 for Patent No. 9,644,431. Deposition.

Date: May 2018
Case: Arrows Up, LLC v. Oren Technologies, LLC, U.S. Patent and Trademark Office Before the Patent Trial and Appeal Board: Patent Nos. 9,682,815, 9,248,772, 9,914,602, and 9,617,066. Declarations.

Date: April 2018
Case: Halliburton Energy Services, Inc. v. Schlumberger Technology Corporation, U.S. Patent and Trademark Office Before the Patent Trial and Appeal Board: Cases IPR2017-01579 and IPR2017-01580 for Patent No. 8,905,133. Declarations.

Date: March 2018
Case: Halliburton Energy Services, Inc. v. Schlumberger Technology Corporation, U.S. Patent and Trademark Office Before the Patent Trial and Appeal Board: Cases IPR2017-01575 and IPR2017-01577 for Patent No. 8,905,133. Declarations.

Date: February 2018
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HALLIBURTON EXHIBIT 1050
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Date: July 2016
Case: Seadrill v. Transocean: U.S. Patent and Trademark Office Before the Patent Trial and Appeal Board; Case IPR2015-01929. Deposition.

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Case: Crescent Terminals v. ExxonMobil Oil Corp. and Saybolt, LP: Civil Action Number: D194,189, District Court of Jefferson County, Texas 136th Judicial District. Deposition.

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Date: June 2015
Case: Larry Gilman, et al. v Mannon L. Walters, et al: AAA; Case No. 52-198-Y-00012-12 FED INSD No. 3:12-cv-00114-SEB-WGH. Deposition.

Date: March 2015
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Date: September 2014
Case: Macpherson Oil Company, et al. v Pace Diversified Corporation: Kern County, California Superior Court; Case No. S-1500-CV-274945-DRL. Deposition.

Date: June 2014
Case: Hayward Industries, Inc. v. Pentair Water Pool and Spa, Inc.: U.S. Patent and Trademark Office Before the Patent Trial and Appeal Board; Case IPR2013-00285. Deposition.

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EXHIBIT 2



Product brochure

Medium voltage AC drive
ACS 5000, 1.5 MW – 36 MW, 6.0 – 6.9 kV

Power and productivity
for a better world™









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ACS 5000 – powerful motor control

The ACS 5000 provides powerful and reliable control for induction, synchronous and permanent magnet motors.

The ACS 5000 provides speed or torque control for motor-driven applications in the medium and high power range from 1.5 to 36 MW at motor voltages from 6.0 to 6.9 kV. It is available with air cooling in the lower power range and with water cooling in the medium to high power range.

The compact air-cooled ACS 5000 is a general purpose drive designed to control standard motors, typically used for applications such as pumps, fans, compressors, mixers, mills and conveyors. The high-power water-cooled ACS 5000 provides reliable motor control for high power, high speed or special performance applications such as large pumps, fans, extruders, compressors and SAG and ball mills.

The ACS 5000 is supplied with separate or integrated input isolation transformer.

Proven solution for a wide range of industries

Since its market introduction in 2005 the ACS 5000 has provided reliable and efficient control of medium voltage applications in a wide range of industries.

Key product features

- High system efficiency due to multilevel-fuseless topology, IGCTs and Direct Torque Control (DTC)
- High reliability due to low parts count
- Optimal network friendliness due to 36-pulse configuration
- Modular design for optimum configurations
- High level of personal safety and drive availability due to superior arc protection
- Low cost of ownership due to high efficiency and simplified installation, commissioning and maintenance
- Fast and accurate control performance due to DTC
- Suitable for standard induction, synchronous and permanent magnet motors

Fields of application

Industries	Applications
Cement, mining and minerals	Grinding mills, conveyors, fans and pumps
Chemical, oil and gas	Compressors, extruders and pumps
Metals	Blast furnace blowers, fans and pumps
Pulp and paper	Fans and pumps
Power generation	Gas turbine starters, ID/FD fans and pumps
Water	Pumps
Other applications	Test stands and wind tunnels

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ACS 5000 – High performance and low cost of ownership

The ACS 5000 is designed for maximum reliability, efficiency and versatility – features that have a direct impact on the customer's cost of ownership.

Reliable and efficient

The combination of well-proven components and an innovative topology results in a reliable and efficient drive.

IGCT semiconductors

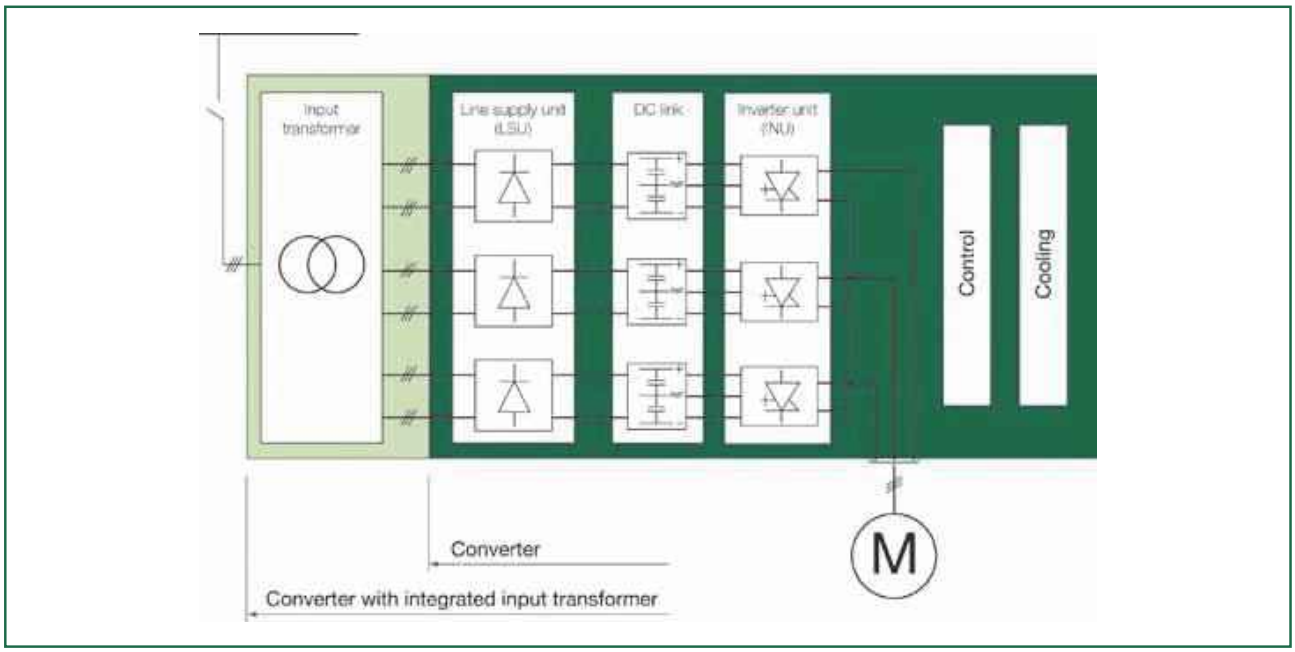
The ACS 5000 uses a power semiconductor known as IGCT (Integrated Gate Commutated Thyristor), which is an ideal switch for high-powered medium voltage applications. The use of IGCTs results in low parts count, providing an efficient and reliable drive.

Long-life DC-link capacitors

Advanced, self-healing, environmentally friendly foil capacitors, designed for a long lifetime, are used in the DC-link. ABB has clearly distinguished itself with this technology compared to unreliable and maintenance-intensive designs based on electrolytic DC-link capacitors.

Fuseless

The converter design does not require any medium voltage power fuses, which are known to be unreliable, costly and subject to aging. Instead of fuses the ACS 5000 uses IGCTs/thyristors, which provide faster and more reliable protection for the power components. The ACS 5000 protection scheme responds in less than 25 µsec, about two hundred times faster than fuses.



ACS 5000 Voltage Source Inverter Multilevel-Fuseless (VSI-MF) topology

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Powerful and application-friendly

During development of the ACS 5000, special attention was given to the entire drive system to provide highest configuration flexibility and ensure powerful and application-friendly performance.

Powerful performance

Fast, reliable and accurate process control in combination with low energy consumption results in top performance. The ACS drive control platform is ABB's award-winning Direct Torque Control (DTC), resulting in the highest torque and speed performance as well as the lowest losses ever achieved in medium voltage drives. Control of the drive is immediate and smooth under all conditions, even during high supply voltage and frequency variations.

Motor friendly

The ACS 5000 topology has an optimum number of switching levels, which provides a multilevel output waveform. This allows the use of standard motors up to 6.9 kV without compromising reliability.

Network friendly

The ACS 5000 is equipped with a 36-pulse rectifier to minimize harmonic distortion. It meets the most stringent requirements for current and voltage harmonic distortion as defined by IEEE, IEC and EN. This eliminates the need for costly harmonics analysis or installation of network filters when applying a new drive.

Flexible

Modular design

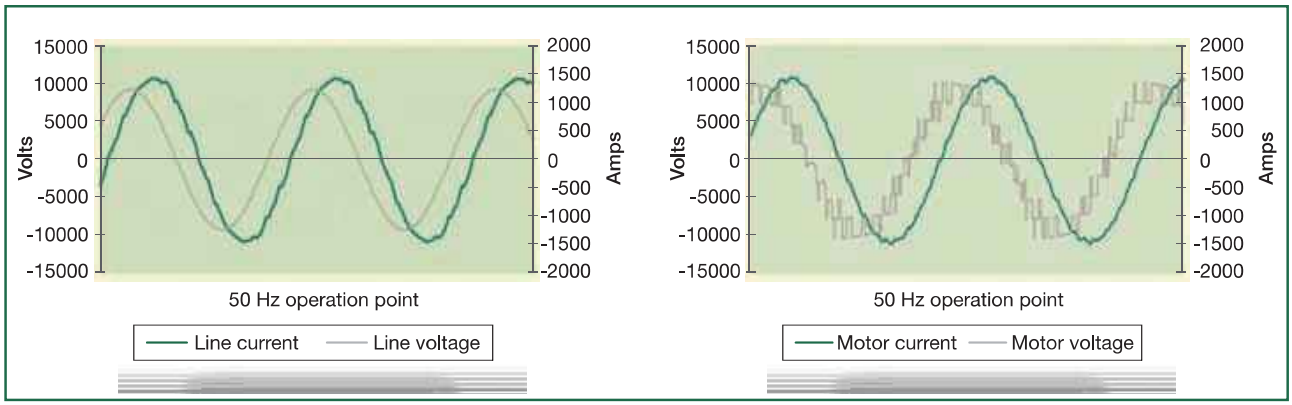
The modular design of the water-cooled ACS 5000 allows the optimum configuration of any drive system. Each configuration, consisting of well-proven and certified modules, fits exactly the customer's requirements.

Transformer flexibility

For highest transformer flexibility, the ACS 5000 is available for connection to an external input isolation transformer or with an integrated input isolation transformer.

High level of personal safety

Electric arcs represent a hazard source for people and goods. For systems where large and dangerous arc fault currents can occur, special attention is required. Therefore, the high-power water-cooled ACS 5000 is equipped with a superior protection function and ABB's Arc Guard System™. This IAC classified solution assures very fast arc detection and elimination (less than 6 ms) to protect people and equipment and eliminate unnecessary production stops.



Line and motor current and voltage

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ACS 5000 air cooled – The general purpose drive

2 – 7 MW



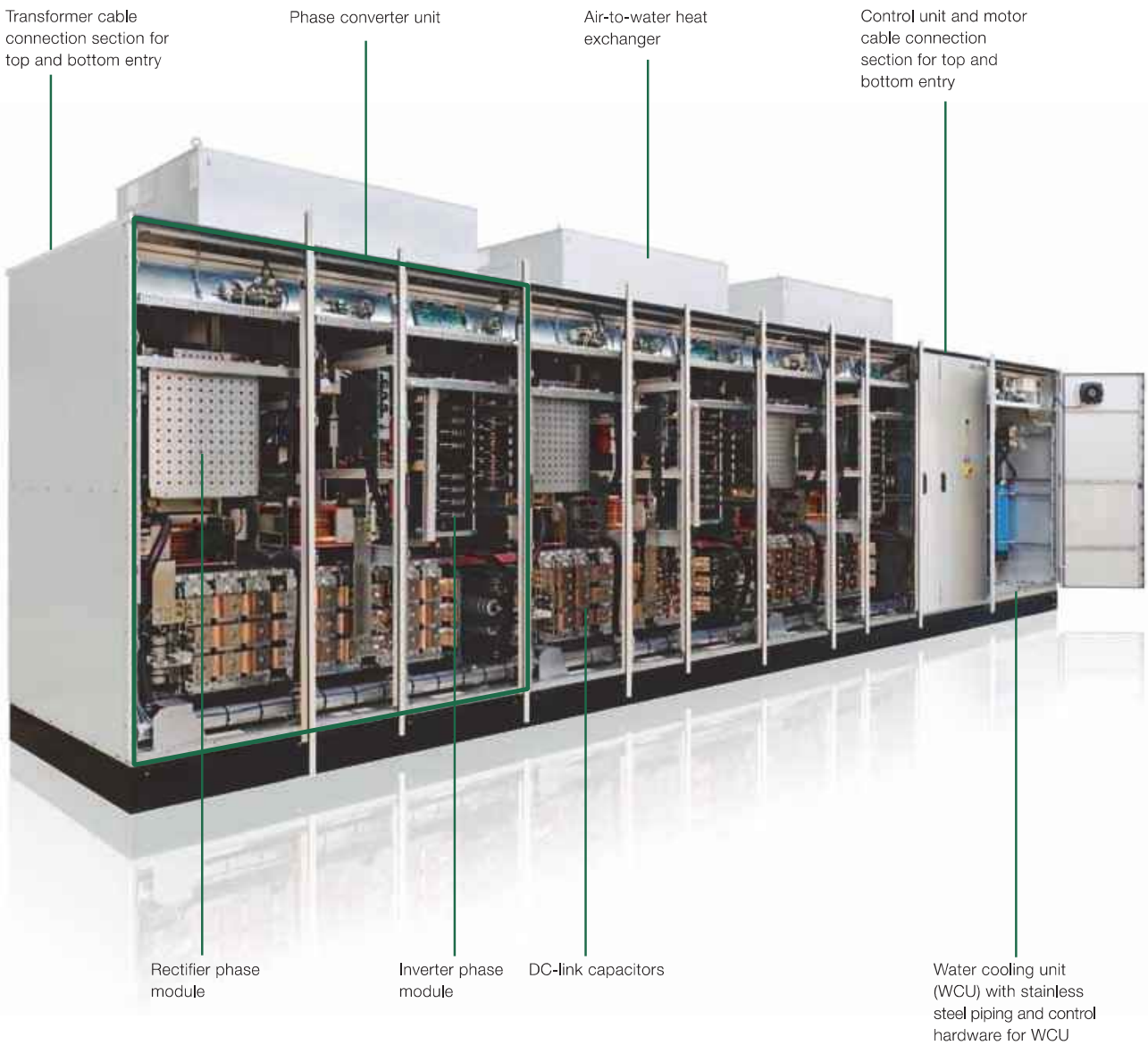
User-friendly drive control panel for local operation
- Keypad with multi-language display
- Main supply on/off pushbuttons
- Emergency off pushbutton

Air-cooled ACS 5000 for operation with separate input isolation transformer, 7 MVA, 6.9 kV

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ACS 5000 water cooled – The special purpose drive

5 – 36 MW (higher on request)



Water-cooled ACS 5000, 18 MVA, 6.9 kV

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ACS 5000 – features and benefits

The ACS 5000 is designed to deliver value through reliable process control and low cost of ownership.

Features	Advantages	Benefits
Flexible input transformer configuration		
	The ACS 5000 is available with an integrated or a separate input isolation transformer, which can be placed outside the electrical room.	– Integrated transformer for quick installation and commissioning. – Separate transformer for minimum air-conditioning. The losses from the transformer do not dissipate into the electrical room.
Reliable and efficient components		
	ABB's IGCT power switching device results in low parts count, providing an efficient and reliable converter.	Highest reliability for minimum down-time
	The ACS 5000 multilevel-fuseless topology results in a drive with unmatched efficiency.	Highest efficiency leads to energy saving and improved productivity
Network and motor friendliness		
	The ACS 5000 36-pulse rectifier meets the most stringent requirements of inter-national standards for current and voltage harmonic distortion.	Elimination of network harmonics to avoid penalties and system interfer-ences. Costly harmonic analysis or network filters are not required.
	The ACS 5000 provides a multilevel output waveform for increased motor friendliness.	Suitable for standard motors
Direct Torque Control (DTC)		
	The fast control provided by DTC allows optimum process control and exact motor performance with minimum torque ripple and lowest energy consumption.	Fast, accurate and robust process control for constant product quality, minimum raw material waste and minimum machinery wear.
Maintenance		
	The modular design of the ACS 5000 simplifies maintenance. It allows easy front access to the drive's components. The cooling equipment is available with redun-dant fans or pumps.	Faster and easier maintenance which lowers maintenance costs.
Arc protection		
	The ACS 5000 is equipped with a superior system for arc protection.	High level of personal safety and drive availability. Unnecessary production stops are eliminated.
DriveMonitor™ (optional)		
	DriveMonitor™ provides monitoring access to the drive even from remote locations.	User-friendly drive monitoring and remote diagnostics
Service and support		
	ABB, the largest drives supplier world-wide, has a global support network, which provides assistance and spare parts 24 hours/day, 365 days/year	Around the clock access to drive spe-cialists and spare parts

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Simple drive system integration

The ACS 5000 allows smooth and simple system integration into the customer's industrial environment.

Open control system
ABB offers an open communication strategy, enabling connection to higher-level process controllers. The ACS 5000 can be installed with all major fieldbus adapters for smooth integration, monitoring and controlling of different processes, according to customer requirements.

DriveOPC
DriveOPC is a software package, which allows communication between ABB drives and the customer's Windows®-based applications.

Benefits
– Standard interface
– Remote connection via LAN (Local Area Network)
– Access to:
  – drive control
  – signals and parameters
  – data and fault loggers

Maintenance

Simple and efficient maintenance is an important factor in lowering operating costs. The modular concept of the ACS 5000 implies minimal maintenance.

Reliable components
ABB drive technologies, such as IGCT power semiconductors and the multilevel-fuseless topology, provide a low parts count, which increases reliability, extends Mean Time Between Failures (MTBF) and improves availability.

Easy access
The ACS 5000 is designed to allow easy front access to the drive's components.

Redundant cooling
The cooling equipment is available with redundant fans or pumps, which increases availability.



Phase converter unit of the water-cooled ACS 5000

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Monitoring and diagnostics

The ACS 5000 is available with an intelligent monitoring and diagnostics system, which allows secure access to the drive from any location in the world.



Benefits

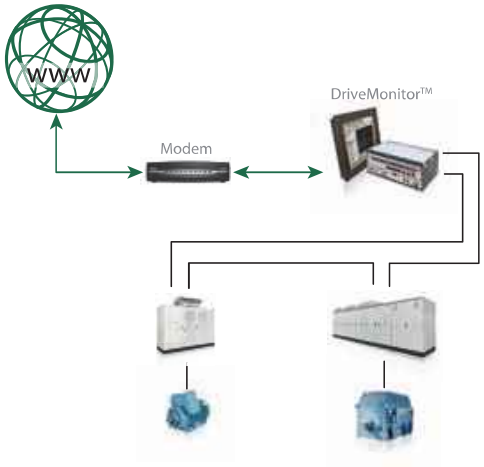
- Early detection to avoid costly repairs
- Reduction of process-critical faults
- Optimization of maintenance cost and schedule over the product life cycle
- Long-term statistics for optimization of process performance
- Easier root cause analysis – reduced Mean Time To Repair (MTTR)

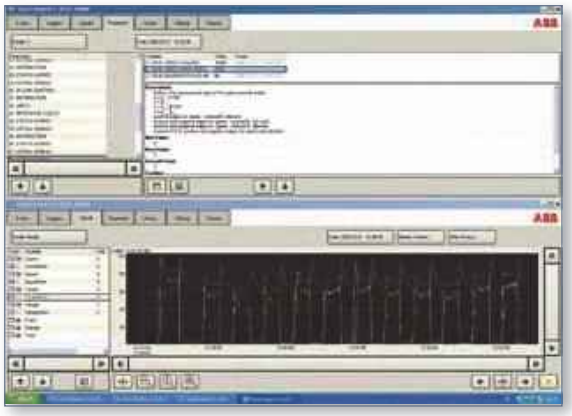
DriveMonitor™ allows real-time access to the drive. It supports monitoring and diagnostics of ABB drives for new and existing installations.

The optional tool consists of a hardware module inside the drive, as well as a software layer that automatically collects and analyzes selected drive signals and parameters.

Long-term monitoring functions deliver important information on equipment status, maintenance tasks needed and possible performance improvements. As experts can gain access to the drive remotely, DriveMonitor™ also helps cut maintenance costs by reducing on-site work.

With extra diagnostic packages, DriveMonitor™ can also monitor other drive system components, such as main circuit breaker, transformer and the driven machine. Special packages related to the application, such as rolling mills, water pumps and compressors, can be integrated into the system.





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ACS 5000 for induction or synchronous motors

Depending on the power rating and the application characteristics, the ACS 5000 can be used with induction, synchronous or permanent magnet motors.

ACS 5000 for induction motors

Squirrel cage induction motors are the workhorses of industry due to their versatility, reliability and simplicity.

The ACS 5000 can be applied to induction motors up to 23 MW. It is typically used with induction motors for applications such as pumps, fans, compressors and conveyors.

ACS 5000 for synchronous motors

Alternatively, the ACS 5000 can be used with synchronous motors. Synchronous motors are typically considered for higher power ratings. In addition to their high power capabilities, synchronous motors offer a wide field weakening range as well as the benefits of high efficiency and high performance.

Permanent magnet motors

The ACS 5000 can also be used with permanent magnet motors for low-speed or high-speed applications.



ABB's AMI induction motors



ABB's AMS synchronous motors

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Testing

Thorough testing ensures proven functionality and performance and reduces commissioning time.



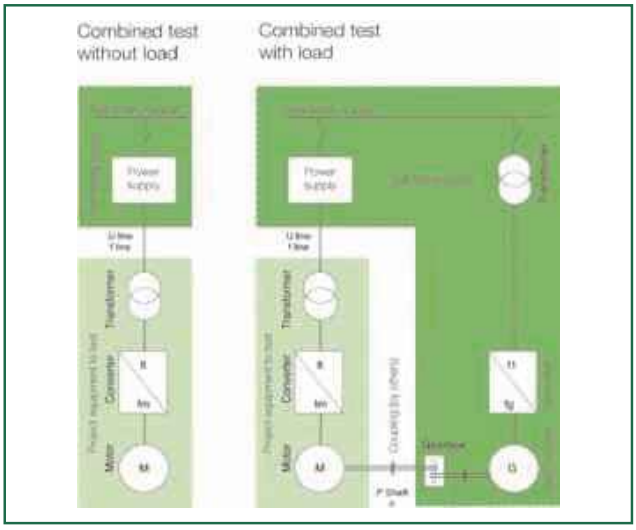
ABB is committed to ensuring the reliability of every drive it delivers. To ensure that quality standards and customer requirements are fully met, every component of a drive is subjected to thorough testing in ABB's test facilities.

Routine test

Routine tests and functional tests form an integral part of the scope of supply of ABB's medium voltage drives. The tests are performed in accordance with international standards and ABB quality assurance procedures.

Combined test

Additionally, ABB can perform a combined test with the complete drive system – including transformer, converter and motor – to verify the performance and to ensure a smooth integration into the customer's facility.



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Service and support

The ACS 5000 is backed by unrivalled service and support from the customer's initial inquiry throughout the entire life cycle of the drive system.

Installation and commissioning

Proper installation and commissioning of the equipment, done by qualified and certified commissioning engineers, reduces start-up time, increases safety and reliability and decreases life cycle costs. In addition, operators can be given practical training by experienced specialists on site.

Training

ABB provides extensive training for its medium voltage drives. A range of training programs is offered from basic tutorials to programs tailored to the customer's specific needs.

Life cycle management

ABB's drive life cycle management model maximizes the value of the equipment and maintenance investment by maintaining high availability, eliminating unplanned repair costs and extending the lifetime of the drive.

Life cycle management includes:
- Providing spare parts and expertise throughout the life cycle
- Ensuring efficient product support and maintenance for improved reliability
- Adding functionality to the initial product
- Enabling a smooth transition to a new technology at the end of the life cycle

Services for ABB's medium voltage drives

- Supervision of installation and commissioning
- Training
- Remote diagnostics
- Customized maintenance contracts
- Local support
- 24 x 365 support line
- Spare parts and logistics network
- Worldwide service network

Global network, local presence

Aftersales service is an integral part of providing the customer with a reliable and efficient drive system. The ABB Group of companies operates in more than 100 countries and has a worldwide network of service operations.



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Data sheet ACS 5000 air cooled with integrated transformer

Motor data			Converter	Converter data			
Voltage	Shaft power *		Type code	Power	Current	Length	Weight **
kV	kW	hp		kVA	A	mm	kg
6,000 V							
6.0	1500	2010	ACS 5060-A1A-M5	1800	170	5700	7700
6.0	1800	2410	ACS 5060-A1B-M5	2200	210	5700	7700
6.0	2000	2680	ACS 5060-A1C-M5	2500	240	5700	7700
6.0	2500	3350	ACS 5060-A1D-M5	3000	290	6000	9200
6.0	2800	3750	ACS 5060-A2A-M5	3300	315	6400	10200
6.0	3150	4220	ACS 5060-A2B-M5	3700	355	6700	11200
6.0	3550	4760	ACS 5060-A2C-M5	4200	400	6700	11200
6.0	4000	5360	ACS 5060-A2D-M5	4600	440	6700	11200
6.0	4500	6030	ACS 5060-A2E-M5	5300	510	6700	15500
6.0	5000	6700	ACS 5060-A2F-M5	6000	585	6700	15500
6,600 V							
6.6	1600	2140	ACS 5066-A1A-M5	1900	170	5700	7700
6.6	2000	2680	ACS 5066-A1B-M5	2400	210	5700	7700
6.6	2250	3020	ACS 5066-A1C-M5	2800	240	6000	9200
6.6	2500	3350	ACS 5066-A1D-M5	3300	290	6000	9200
6.6	2800	3750	ACS 5066-A2A-M5	3600	315	6400	10200
6.6	3150	4220	ACS 5066-A2B-M5	4100	355	6700	11200
6.6	3550	4760	ACS 5066-A2C-M5	4600	400	6700	11200
6.6	4000	5360	ACS 5066-A2D-M5	5000	440	6700	15500
6.6	4500	6030	ACS 5066-A2E-M5	5800	510	6700	15500
6.6	5600	7500	ACS 5066-A2F-M5	6700	585	6700	15500
6,900 V							
6.9	1600	2140	ACS 5069-A1A-M5	2000	170	5700	7700
6.9	2000	2680	ACS 5069-A1B-M5	2500	210	5700	7700
6.9	2250	3020	ACS 5069-A1C-M5	2900	240	6000	9200
6.9	2800	3750	ACS 5069-A1D-M5	3500	290	6000	9200
6.9	3150	4220	ACS 5069-A2A-M5	3700	315	6700	10200
6.9	3550	4760	ACS 5069-A2B-M5	4200	355	6700	11200
6.9	4000	5360	ACS 5069-A2C-M5	4800	400	6700	11200
6.9	4500	6030	ACS 5069-A2D-M5	5200	440	6700	15500
6.9	5000	6700	ACS 5069-A2E-M5	6100	510	6700	15500
6.9	6000	8040	ACS 5069-A2F-M5	7000	585	6700	15500

Notes:

* Indicative information referring to a typical 4-pole induction motor under nominal supply voltage conditions.

** Weight indications are approximate; listed without excitation unit (for synchronous motors)

General dimensions ACS 5000 air cooled with integrated transformer

Cabinet height: 2360 mm excl. cooling fans
2863 mm incl. cooling fans
2963 mm with redundant cooling fans

Cabinet depth: 1100 mm (up to 1300 mm for subframe 2D, 2E, 2F)

Excitation unit for synchronous motor drives (stand-alone cabinet)

Dimensions: 800 x 1000 x 2360 mm (L x D x H)

Weight: approx. 700 kg

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Data sheet ACS 5000 air cooled for operation with external transformer

Motor data			Converter	Converter data			
Voltage	Shaft power *		Type code	Power	Current	Length	Weight **
kV	kW	hp		kVA	A	mm	kg
6,000 V							
6.0	1500	2010	ACS 5060-A1A-D5	1800	170	3300	3000
6.0	1800	2410	ACS 5060-A1B-D5	2200	210	3300	3000
6.0	2000	2680	ACS 5060-A1C-D5	2500	240	3300	3000
6.0	2500	3350	ACS 5060-A1D-D5	3000	290	3300	3000
6.0	2800	3750	ACS 5060-A2A-D5	3300	315	3700	4000
6.0	3150	4220	ACS 5060-A2B-D5	3700	355	3700	4000
6.0	3550	4760	ACS 5060-A2C-D5	4200	400	3700	4000
6.0	4000	5360	ACS 5060-A2D-D5	4600	440	3700	4000
6.0	4500	6030	ACS 5060-A2E-D5	5300	510	3700	4000
6.0	5000	6700	ACS 5060-A2F-D5	6100	585	3700	4000
6,600 V							
6.6	1600	2140	ACS 5066-A1A-D5	1900	170	3300	3000
6.6	2000	2680	ACS 5066-A1B-D5	2400	210	3300	3000
6.6	2250	3020	ACS 5066-A1C-D5	2800	240	3300	3000
6.6	2500	3350	ACS 5066-A1D-D5	3300	290	3300	3000
6.6	3000	4020	ACS 5066-A2A-D5	3600	315	3700	4000
6.6	3150	4220	ACS 5066-A2B-D5	4100	355	3700	4000
6.6	3550	4760	ACS 5066-A2C-D5	4600	400	3700	4000
6.6	4000	5360	ACS 5066-A2D-D5	5000	440	3700	4000
6.6	4500	6030	ACS 5066-A2E-D5	5800	510	3700	4000
6.6	5600	7500	ACS 5066-A2F-D5	6700	585	3700	4000
6,900 V							
6.9	1600	2140	ACS 5069-A1A-D5	2000	170	3300	3000
6.9	2000	2680	ACS 5069-A1B-D5	2500	210	3300	3000
6.9	2250	3020	ACS 5069-A1C-D5	2900	240	3300	3000
6.9	2800	3750	ACS 5069-A1D-D5	3500	290	3300	3000
6.9	3150	4220	ACS 5069-A2A-D5	3700	315	3700	4000
6.9	3550	4760	ACS 5069-A2B-D5	4200	355	3700	4000
6.9	4000	5360	ACS 5069-A2C-D5	4800	400	3700	4000
6.9	4500	6030	ACS 5069-A2D-D5	5200	440	3700	4000
6.9	5000	6700	ACS 5069-A2E-D5	6100	510	3700	4000
6.9	6000	8040	ACS 5069-A2F-D5	7000	585	3700	4000

Notes:

* Indicative information referring to a typical 4-pole induction motor under nominal supply voltage conditions.

** Weight indications are approximate; listed without excitation unit (for synchronous motors)

General dimensions ACS 5000 air cooled for operation with external transformer

Cabinet height: 2360 mm excl. cooling fans
2863 mm incl. cooling fans
2963 mm with redundant cooling fans

Cabinet depth: 1100 mm

Excitation unit for synchronous motor drives (stand-alone cabinet)

Dimensions: 800 x 1000 x 2360 mm (L x D x H)

Weight: approx. 700 kg

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Data sheet ACS 5000 water cooled for operation with external transformer

Motor data			Converter	Converter data			
Voltage	Shaft power *		Type code	Power	Current	Length**	Weight ***
kV	kW	hp		kVA	A	mm	kg
6,000 V							
6.0	6830	9150	ACS 5060-W1A-D5	7000	670	7130	8000
6.0	8480	11360	ACS 5060-W1B-D5	8700	840	7130	8000
6.0	10140	13590	ACS 5060-W1C-D5	10400	1000	7130	8000
6.0	12680	16990	ACS 5060-W2A-D5	13000	1250	9130	10000
6.0	15210	20380	ACS 5060-W2B-D5	15600	1500	9130	10000
6.0	17750	23790	ACS 5060-W3A-D5	18200	1750	13030	12000
6.0	20280	27180	ACS 5060-W3B-D5	20800	2000	13030	12000
6.0	23300	31220	ACS 5060-W4A-D5	23900	2300	15815	20000
6.0	25350	33970	ACS 5060-W4B-D5	26000	2500	15815	20000
6.0	30420	40760	ACS 5060-W4C-D5	31200	3000	15815	20000
6,600 V							
6.6	7510	10060	ACS 5066-W1A-D5	7700	670	7130	8000
6.6	9360	12540	ACS 5066-W1B-D5	9600	840	7130	8000
6.6	11120	14900	ACS 5066-W1C-D5	11400	1000	7130	8000
6.6	13940	18680	ACS 5066-W2A-D5	14300	1250	9130	10000
6.6	16670	22340	ACS 5066-W2B-D5	17100	1500	9130	10000
6.6	19500	26130	ACS 5066-W3A-D5	20000	1750	13030	12000
6.6	22330	29920	ACS 5066-W3B-D5	22900	2000	13030	12000
6.6	25640	34360	ACS 5066-W4A-D5	26300	2300	15815	20000
6.6	27890	37370	ACS 5066-W4B-D5	28600	2500	15815	20000
6.6	33440	44810	ACS 5066-W4C-D5	34300	3000	15815	20000
6,900 V							
6.9	7800	10450	ACS 5069-W1A-D5	8000	670	7130	8000
6.9	9750	13070	ACS 5069-W1B-D5	10000	840	7130	8000
6.9	11700	15680	ACS 5069-W1C-D5	12000	1000	7130	8000
6.9	14530	19470	ACS 5069-W2A-D5	14900	1250	9130	10000
6.9	17450	23380	ACS 5069-W2B-D5	17900	1500	9130	10000
6.9	20380	27310	ACS 5069-W3A-D5	20900	1750	13030	12000
6.9	23300	31220	ACS 5069-W3B-D5	23900	2000	13030	12000
6.9	26810	35930	ACS 5069-W4A-D5	27500	2300	15815	20000
6.9	29150	39060	ACS 5069-W4B-D5	29900	2500	15815	20000
6.9	35000	46900	ACS 5069-W4C-D5	35900	3000	15815	20000

Notes:

* Indicative information referring to a typical 4-pole induction motor under nominal supply voltage conditions.

** Length values are listed without excitation unit (for synchronous motors)

*** Weight indications are approximate; listed without excitation unit (for synchronous motors)

General dimensions ACS 5000 water cooled

Cabinet height: 2360 mm excl. cooling fans
2710 mm incl. auxiliary cooling fans

Cabinet depth: 1600 mm

Excitation unit for synchronous motor drives (stand-alone cabinet)

Dimensions: 800 x 1000 x 2360 mm (L x D x H)

Weight: approx. 700 kg

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Data sheet ACS 5000

Inverter type
Voltage Source Inverter Multilevel-Fuseless (VSI-MF),
9 levels line-to-line, with fast-switching power semiconductors – Integrated Gate Commutated Thyristors (IGCTs), without parallel or series connected devices

Motors
Induction, synchronous and permanent magnet motors

Standards
All common standards including EN, IEC, CE

Input
Medium voltage input transformer for 36-pulse diode rectifier
Variation: ±20% of nominal voltage (optionally up to +40%), down to –30% safe operation with derated output

Auxiliary voltage
Common 380 – 480 VAC, 3-phase, 50 Hz/60 Hz,
(up to 690 VAC for water cooled drives)

UPS (Uninterruptible Power Supply)
If available, a UPS can be connected for control power supply, 110 – 240 VAC, single phase or 110/220 VDC. Alternatively the drive can be equipped with back-up capacitors (for short term control power-loss ride-through)

Output frequency
0 to ±75 Hz, up to ±250 Hz optional (higher on request)

Output voltage
Standard: 6.0 – 6.9 kV
Optional: 4.16 kV

Efficiency of converter
Typically > 98.5% (incl. auxiliaries)

Input power factor
Fundamental: > 0.96 (Total: > 0.95)

Ambient temperature
+1 °C to 40 °C (higher with derating)
34 °F to 104 °F (higher with derating)

Enclosure classes

Standard:	IP 21	air cooled
	IP 32	water cooled
Optional:	up to IP 42	air cooled
	up to IP 54	water cooled

Control interface (optional)
- All common field buses including Profibus, Modbus, Allen-Bradley DeviceNet, Ethernet, ABB Advant Fieldbus AF100 (others on request)
- Extensive range of additional I/O features available

Standard protection functions
Converter:
Overcurrent, short circuit, earth fault, phase loss, overvoltage, undervoltage, overtemperature, output frequency, network disturbance, cooling supervision
Motor:
Overload, stall protection

Example options
- Motor supervision I/Os
  - Fault/alarm: overtemperature, vibration of bearings
  - PT 100: winding and bearing temperatures
- Transformer supervision I/Os:
  - Fault/alarm: overtemperature, Buchholz
  - PT 100: winding temperatures
- Hardwired signals for remote drive control
  - References: start/stop, speed/torque, etc.
  - Status feedback signals: ready/running
  - Analog signals: current/voltage/power, etc.
- Redundant cooling fan (air-cooled ACS 5000) and pump (water-cooled ACS 5000) for enhanced reliability
- Synchronous bypass functionality (for starting of up to six different motors)
- Integrated transformer, input voltage range
  - 6.0 – 6.9 kV, 50 Hz/60 Hz
  - 10.0 – 11.0 kV, 50 Hz/60 Hz
  - 11.0 – 13.8 kV, 50 Hz/60 Hz on demand

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EXHIBIT 3

Introduction to Electrical Engineering - Basic Vocational Knowledge
4. Electrical Energy
4.1. Energy and Power
4.2. Efficiency
4.3. Conversion of Electrical Energy into Heat
4.4. Conversion of Electrical Energy into Mechanical Energy
4.5. Conversion of Electrical Energy into Light
4.6. Conversion of Electrical Energy into Chemical Energy and Chemical Energy into Electrical Energy

4.4. Conversion of Electrical Energy into Mechanical Energy

The conversion of electrical energy into mechanical energy is a frequent utilisation of electrical energy. Thus, electric motors are used for moving air in air-conditioning plants, in water pumps, for the drive of machines and vehicles, and many other electrical equipment. The fact that electrical energy is easily convertible into mechanical energy and the possibility of adapting the motor to be used to the given technical task have led to the preferred use of electric motors in practice. In most cases, electric motors are considerably cheaper and require less maintenance than engines. For the various applications, types of electromotors are available which are optimally adapted to the purpose.

Let us consider at first a few important physical quantities of rotary motion. The shaft of a motor rotates at a certain rotational speed n which is usually measured in revolutions per minute (rpm). Fig. 4.6. shows a belt drive. The smaller belt pulley is mounted on the shaft of the motor and the larger pulley on the machine to be driven. The V-belt transmits the force from the motor to the machine. The force transmitted by the V-belt is an essential quantity for computation. The force multiplied by the radius r is called torque M.

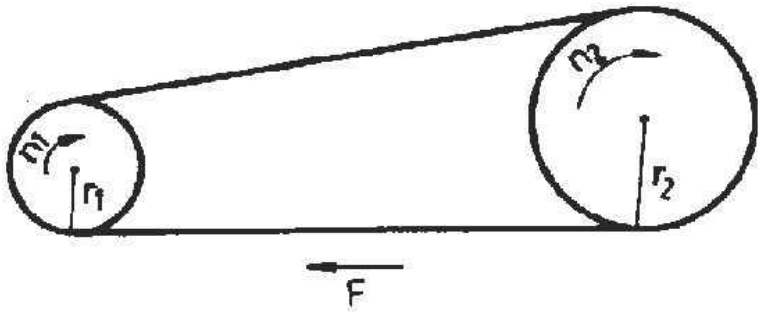


Fig. 4.6. Belt drive

$$M = F \bullet r$$
$$[M] = N \bullet m$$

(4.7.)

where:

M torque

F force

r radius

The sketch shows that the torque acting at the belt pulley with the radius r_1 is smaller than the torque at the belt pulley with the larger radius r_2. For the rotational speeds of the belt pulleys the relation

$n_1 : n_2 = r_2 : r_1$ holds.

(4.8.)

where:

n speed of rotation

r radius

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The mechanical power delivered by the motor is expressed by the following formula:

$P = 2 \bullet \pi$ [1] $M \bullet n$
$[P] = Nm/s = W$

(4.9)

[1] π Greek letter pi

where

P power

M torque

n speed of rotation

Example 4.7.

On the belt pulley of a motor having a radius of 50 mm, a force of 20 N is acting. The rotational speed is 1000 rpm. What is the power delivered by the motor?

Given:

$r = 50$ mm
$F = 20$ N
$n = 1000$ rpm

To be found:

P in W

Solution:

$P = 2 \bullet M \bullet n$
$P = 2 \bullet F \bullet r \bullet n$
$P = 2 \bullet 3.14 \bullet 20\ N \bullet 50\ mm \bullet 1000\ rpm$
$P = 2 \bullet 3.14 \bullet 20\ N \bullet 0.05\ m \bullet 1000/60 \bullet 1/s$
$P = 105$ W

The power delivered by the motor is 105 W.

An important item for judging the performance of a motor is the dependence of the rotational speed on the torque (and thus on the load) and the current path at the instant of switching on. The dependence of the efficiency on the torque should also be taken into consideration for an appropriate use. In Fig. 4.7. these dependences are represented for a three-phase squirrel-cage induction motor. This motor, which is the most widely used type, is shown in Fig. 4.8. The characteristics show that the rotational speed is reduced only slightly under load. This property is desired in many drives. When, however, the stalling torque - also known as pull-out torque - M_k is reached, which is above the rated torque M_n, the motor will stall suddenly.

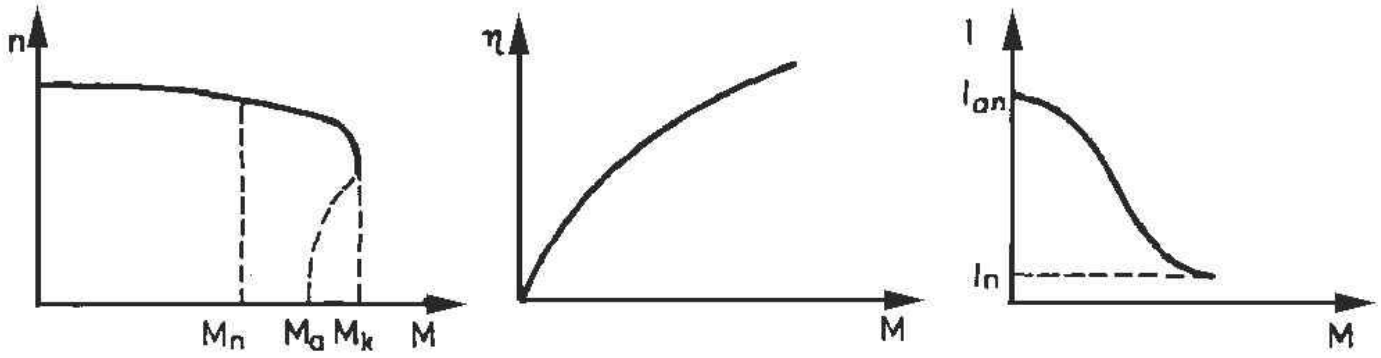


Fig. 4.7. Characteristics of the three-phase asynchronous motor

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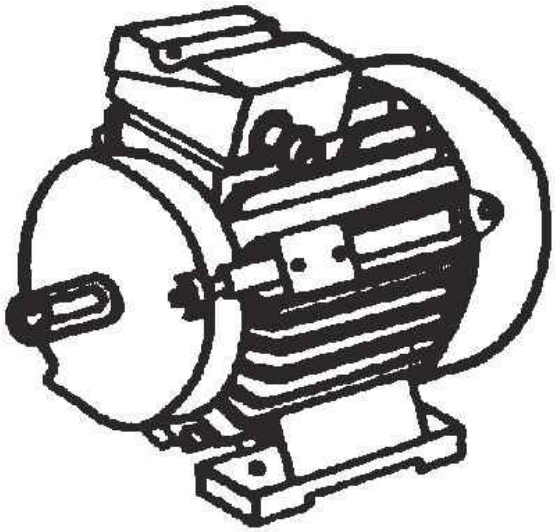


Fig. 4.8. Three-phase squirrel cage induction motor

At the instant of switching on, only the starting torque M_q is available which is frequently insufficient for heavy drives to cause the motor to start up. Additional measures are then required in order to allow the motor to start up without load at first. This motor is not suited as a drive motor for vehicles because it cannot produced the required starting moment. The efficiency η increases with increasing load. In order to operate the motor with as high an efficiency as possible, a load with the rated moment should be effected. Therefore, the motor power for drives should be chosen according to the required power. It should be noted that at the instant of switching on the input of current I_{an} is several times higher than for rated operation I_n. The fuses in series with the motor must comply with these conditions. Frequently switching on and off is unfavorable except for special motors.

As a drive motor for vehicles, the series-wound motor is particularly suitable. The dependence of the rotational speed on the torque is shown in Fig. 4.9. It is evident that the motor produces a very high torque at a low rotational speed; this is conducive to the starting of electric vehicles.

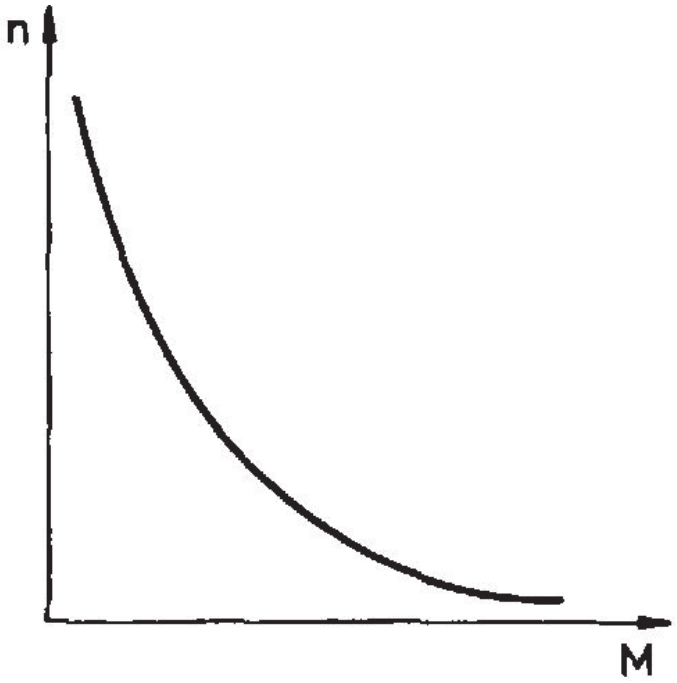


Fig. 4.9. Characteristic of the series motor

If, for example, a squirrel-cage induction motor is to be used for driving a centrifugal pump which is frequently used as a water pump, a motor having a suitable power must be selected. For this purpose, first we have to know the dependence of the required torque on the rotational speed of a centrifugal pump (Fig. 4.10.). The point of intersection of the pump characteristics and the motor characteristics should coincide with the rated torque of the motor.

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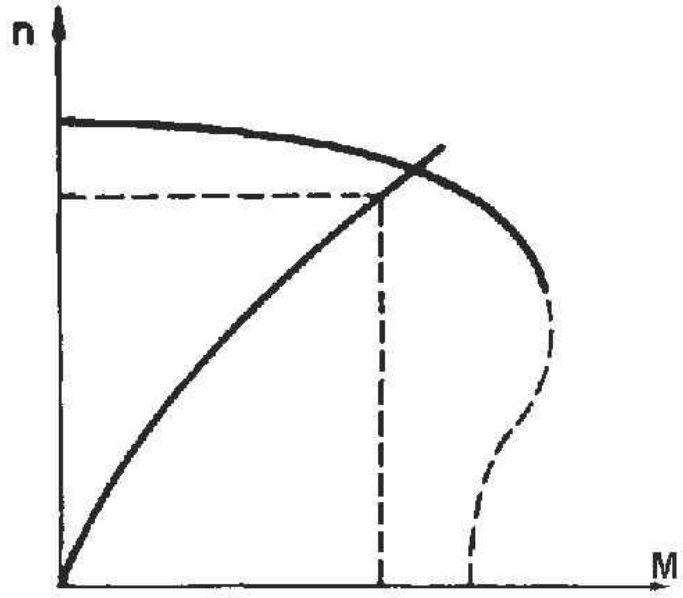


Fig. 4.10. Interaction of a centrifugal pump and a three-phase squirrel cage induction motor

For many drives, the electromotor is an ideal solution. Its construction is sturdy and it calls for limited maintenance only. Various designs enable an optimum adaptation to the different drive requirements in the various fields of application. The mechanical power delivered by the motor is determined by the rotational speed and the torque. Every motor has its typical characteristics from which conclusions can be drawn as to the practical use.

Questions and problems:

1. Quote some examples of devices which are operated by means of electric motors!

2. Calculate the power delivered by a motor when its belt pulley having a diameter of 100 mm rotates at a speed of 1350 rpm and a force of 50 N acts on the pulley!

3. Why is a three-phase squirrel-cage induction motor not suitable for driving electric vehicles!

4. Why is a series-wound motor not suitable for driving a drilling machine?

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EXHIBIT 4

Irrigating Smart
Conserves Water
Saves Money
Reduces Energy
Irrigation Pumping Plant Efficiency Testing

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NM STATE UNIVERSITY

Variable Frequency Drives (VFD)

Christopher G. Henry, Biological and Agricultural Engineering, University of Arkansas
Blair Stringam, Extension Plant Sciences, New Mexico State University

A brief explanation of variable frequency drives and how to apply them for irrigation pumping plants.

What Is a Variable Frequency Drive?

A variable frequency drive, known as a VFD, is an electronic drive system used to control electric motors. Its purpose is varying motor speed by controlling input frequency and voltage.

Variable frequency drives convert AC voltage to DC current and can be thought of as "pulsing" this DC current to the motor to vary the motor speed. Variable frequency drives are energy saving and load management devices that belong to a group of devices sometimes known also as adjustable speed drives. VFDs save energy by varying the input energy required for a corresponding load.

Variable frequency drives are an alternative to soft starts and are useful when slower motor speeds can provide energy savings. They allow for automation, as well as for large motor applications on single phase service applications, and serve as a load management tool. When a VFD is used to start a motor, the motor starts slowly before coming up to full speed. A VFD can be thought of as putting a "throttle" on an electric motor.

Why Use a VFD for Irrigation?

Variable frequency drives have several advantages that are useful for irrigation systems:

- Variable frequency drives provide for a gradual increase in speed to full motor load. Full motor torque is available with a VFD even at slow speeds. This is important for mixed flow and axial pump applications where there is significant startup load on the motor at zero speed. From a power utility perspective, this long time for startup reduces startup load, or initial line loading, that is often several times the full motor load. For across the line motors, the utility must be able to accommodate the voltage drop and the inrush current necessary for motor startup. A VFD reduces this inrush current by spreading the voltage drop across a longer period of time.



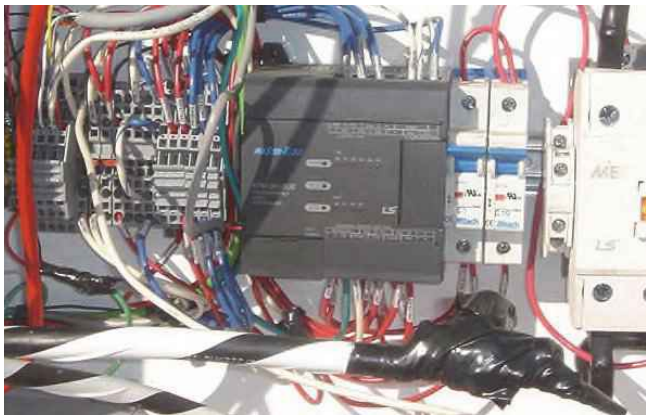
VFD pump panel controls. Auto (sensor driven) or manual mode (upper left), start/stop (top center), variable speed dial (upper right), power to panel indication (lower left), VFD operational indication (bottom middle) and fault indication (lower right).

- Variable frequency drives may overcome the 10-15 horsepower motor limitation for single-phase service. Because the VFD converts AC to DC for the motor, the phase of the input source does not matter. This allows for larger motors to be used where only single-phase service is available. Transformers must be sized

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to provide the required current, but where there is a high-three-phase service installation cost, VFDs can be more cost-effective.

- Variable frequency drives allow for constant pressure and automation. VFDs include microcomputers or microcontrollers and can accept instructions from programmable logic controllers. Some VFDs have industrial controller capability. Programmable logic controllers are industrial controllers that provide the ability to accept inputs from sensors and outputs to control motors. For example, in irrigation systems, a pressure sensor can be used to report pressures to the drive to maintain constant system pressure. This is especially useful for center pivots and microirrigation systems, where flow rates may vary but constant pressure is desired. On a center pivot, end guns, corner systems and variable rate irrigation alter the flow demand. A VFD can maintain constant pressure by varying motor speed (flow) when these components are cycled.



Programmable logic controllers can be used to control variable frequency drives and other processes, such as maintaining constant pressure in an irrigation system.

- Variable frequency drives reduce the thermal and mechanical stress on motors and pumps and reduce water hammer in irrigation systems. The slow start, compared to the rapid start of an across the line motor, reduces wear on motors, pumps and irrigation systems. Especially with older irrigation systems, the reduction of water hammer can extend the life and reduce the potential for leaks and failures.

How Variable Frequency Drives Work

The rotation speed of an induction motor is fixed and determined by the frequency of the supply voltage. Alternating the current supplied to the stator windings of the motor produces a magnetic field that rotates. Within the winding of the motor are pairs of magnetic poles. Dividing 60 hertz by the number of magnetic pole pairs in the motor will give the revolutions per second and thus the revolutions per minute of the motor.

An eight-pole motor, for example, has four pole pairs and the magnetic field therefore will rotate at 15 revolutions per second. This is equivalent to 900 revolutions per minute (assuming an electrical signal of 60 hertz where 60 hertz divided by 4 equals 15 revolutions per second). When the rotating magnetic field is induced, the rotor of the motor will attempt to follow. The load on the motor, however, causes the rotor speed to slip slightly behind the rotating field speed.

Induction motors rotate close to synchronous speed. The most effective and energy efficient way to alter the speed of the motor is to change the frequency of the applied voltage. Variable frequency drives change the fixed frequency supply voltage to a continuously variable frequency. This allows for adjustable motor speeds.

The conversion is accomplished using rectifier and inverter stages. In the rectifying stage, the rectifier converts three-phase (or single-phase) 60 hertz power from the given utility supply to direct current voltage (standard industrial motors are 208, 230, 380, 415, 460 and 575 volts). Voltage, and thus motor speed, is varied by altering the firing pattern of electronic switches or insulated gate power transistors. In the inverter stage, the insulated gate power transistors, sometimes referred to as power transistors, or thyristors, switch the rectified DC voltage on and off to produce an alternating current at the desired new frequency. A control system with an electronic circuit receives continuous feedback from the driven motor and adjusts the output voltage to frequency conversion.

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As electronics continue to advance, the AC-DC-AC conversion process of a variable frequency drive is likely to become more efficient while costs decline. Current efficiencies exceed 97.5 percent.

Applications of VFDs

Applying variable frequency drives to centrifugal pumps results in significant energy reduction – if slowing the motor down for the purpose of flow or pressure regulation will have a benefit. Motor-driven equipment often is operated at reduced loads or restricted flows, and the opportunity to decrease energy consumption becomes much greater compared to equipment operating at maximum throttle or flow. Centrifugal pumps consume energy proportionate to the cube of the flow rate, and a small reduction in speed or flow can lead to a great reduction in energy consumption. When lower flow rates are required, decreasing the speed can lead to large energy savings.

The variable frequency drive and the motor must be compatible. Generally, existing motors in good condition can be used with a VFD. Motor windings are the primary concern, since the VFD will cause more electrical distortion than an across-the-line application.

An insulation test called a "Meggar test" can be used to determine the resistance between motor windings and ground. A resistance of 300,000 ohms or greater is acceptable. The test should be performed just after the motor has been operated, since dust and moisture can affect the test results. Do not perform an insulation test with a VFD connected to the test unit, because the high voltage used in an insulation test can damage a VFD.

In some cases, a motor should be rebuilt before being put into service with a variable frequency drive. In addition, the manufacturers of the motor and the VFD must be contacted to determine the compatibility of the equipment. High- or premium-efficiency induction style cast iron motors are preferable to lower-efficiency motors because of the windings and components.

Slowing a motor can create additional heat the fan motor may not be able to dissipate as well as it would at full speed. If upgrading a pumping plant or considering rewinding a motor, consult the VFD provider about compatibility. Most submersible motors are compatible with VFDs. Because these motors are liquid-cooled, slower operation does not hamper heat removal. (Special VFD parameters are required for submersible pump motors, so consult with your VFD provider).

Considerations for Variable Frequency Drives

Consult your utility provider for any discounts or credits that can be given for installing a variable frequency drive as a load management device, and ask if there are any known issues with VFDs in the service area. In some rare situations, power supply quality (interruptions, voltage dips, voltage swells and harmonic generation) can be a concern that would limit the effectiveness of, or require filters for, a VFD installation. In most cases, a VFD will be a welcomed solution by the utility to reduce the effects of startup motor loads on the utility grid.

Find a reputable dealer and service provider who are knowledgeable about VFDs for your irrigation application. Service providers are not always associated with irrigation companies, although some irrigation manufacturers now offer VFDs as original equipment (center pivots, for example).

A VFD for irrigation should have manual, automatic and off modes. The manual mode is used to test the motor and drive for operation, without any automation or sensor input. There should be an emergency kill switch or lockout somewhere on the panel that stops all movement or shuts down all power.



Safety shutoff/ lockout for VFD panel.

Motor speed can be altered manually, such as with a rheostat or dial control, as shown on page 1. It can be determined from motor load, such as a pressure sensor or flow meter. It is advisable to control the

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VFD using a programmable logic controller or PLC. PLCs are inexpensive (a few hundred dollars) and greatly expand the ability and control possibilities of the VFD.

If a centrifugal pump surges, or has lost prime, or a part has broken, the system should be able to shut down without causing further damage. Centrifugal pumps that run dry can boil the water in the volute, so incorporating this safety feature into a VFD is an added safety option. A high-pressure and low-pressure shut-off should be incorporated into the logic of the PLC or VFD control system. If a pump cavitates, some VFDs can sense changes or irregularities in motor loading (or rapid pressure changes through the PLC) and may be able to shut a pump down before pump damage occurs. Depending upon the application, these safety features could offset the cost of a VFD by avoiding potential pump repairs.

VFDs involve electronic equipment that generates significant amounts of heat during operation. VFDs should be mounted in white NEMA-3R (outdoor, falling or driven rain) enclosures with ventilation for most irrigation applications. These cabinets have been used in agricultural settings and operate well as long as the filters are properly maintained and cleaned. Inadequate airflow will cause excessive heat, leading to early failure of a VFD. The filters are easy to clean by simply removing them, washing them with water and reinstalling them.



White panels and ventilation are used to reduce heat loads for VFDs. Air is drawn from the bottom of the cabinet (right) and exhausted through the top. Fans are thermostatically controlled, but the filters need to be periodically cleaned for everything to work properly.

As with any electrical installation in the agricultural environment, install proper safety shut-off and lightning protection. Lightning arresters or surge protection devices are designed to protect against stray voltage and current from direct or nearby lightning strikes. These devices (often disposable) are designed to absorb or limit the voltage spike before it passes through the motor and other electronics in a panel.

Cost Savings Using VFDs

Savings of a variable frequency drive system can be illustrated by the following example. If a 40-horsepower motor is operated below its maximum capacity for about 40 percent of the pumping season, a VFD could save as much as $6,000 during six months of operation per year. If the estimated cost for the VFD for this example is about $5,000 and another $3,000-$4,000 is required for installation costs, the payback time would be less than two years.

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EXHIBIT 5

Chapter 1

B. Jayant Baliga

Power Semiconductor Devices for Variable Frequency Drives

1.1. INTRODUCTION

Improvements in the performance of variable frequency drives have been directly related to the availability of power semiconductor devices with better electrical characteristics [1, 2]. It has been found that the device performance determines the size, weight, and cost of the entire power electronic system. For power-switching applications, an ideal power device must be able to support a very large voltage in the off-state with negligible leakage current, carry high current in a small area with a low on-state voltage drop, and be able to switch rapidly between the on- and off-states. In addition, it is preferable for the device to be able to regulate the rate of rise of current when it is turned on and to limit the current in the circuit under faulty operating conditions without the aid of external circuit elements. Although much progress has been made in achieving these goals, the ideal device continues to elude the power semiconductor designer, thus providing strong motivation for further research and development in this area.

The introduction of the power thyristor in the marketplace in the 1950s marked the beginning of the revolution in solid-state-device–based power electronics. Since then, a steady growth in the ratings of the thyristors and their operating frequency has enabled extension of their application to motor control. The growth in thyristor ratings can be traced with the aid of Figure 1-1. Starting with the introduction of 500 volt devices, the blocking voltage capability has been scaled to exceed 6500 volts. This very high voltage blocking capability has been achieved by the ability to pro-

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duce very uniformly doped high-resistivity N-type silicon by neutron transmutation doping (NTD). The NTD process allows the conversion of a silicon isotope into phosphorus by the absorption of a thermal neutron. A very uniform doping concentration can be produced throughout the wafer if a uniform neutron flux distribution can be achieved. The sudden increase in blocking voltage capability for thyristors in the 1980s indicated in Figure 1-1a can be traced to the availability of NTD silicon wafers. There has been a concomitant increase in the current-handling capability for the power thyristors as indicated in Figure 1-1b. Since the on-state current density for the device has not changed over the years due to the relatively unchanged thermal impedance of the device package, this increase in current ratings has been possible by the availability of larger-diameter silicon wafers. Single devices are now manufactured with wafers of 4 inches in diameter.

Following the introduction of power thyristors in the 1950s, many bipolar power devices were introduced with improved electrical characteristics during the next 20 years. Among these, the power bipolar transistor was the key to extending the operating frequency of power systems above 1 kHz. Bipolar power transistor ratings were continuously increased over the years until devices with 600 volt block-

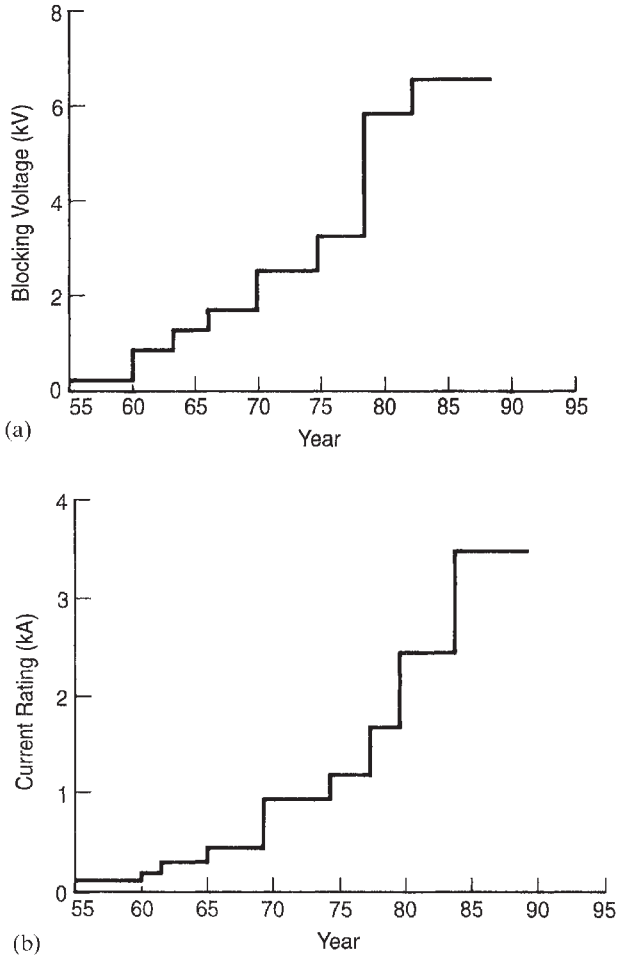


Figure 1-1. Growth in power thyristor ratings (a) blocking voltage, (b) on-state current.

ing capability became available with current-handling capability of several hundred amperes. These devices have been extensively used for motor control applications. In addition, bipolar power transistors with 1500 volt blocking capability have been developed for TV deflection circuits. A basic limitation of the power bipolar transistor is that it is a current-controlled device. Although much effort has been performed on device optimization to maximize the current gain, the current gain at typical on-state current densities is only about 10. This creates a significant problem in driving the power bipolar transistor. The control circuits must be assembled from discrete components leading to a bulky and expensive system that is often difficult to manufacture. For this reason, the power bipolar transistor has been replaced by the insulated gate bipolar transistor (IGBT) in the 1990s.

The development of the gate turn-off (GTO) thyristor was the key to extending the power rating of many systems to the megawatt range. It has found widespread application to traction drives (electric streetcars and locomotives). Devices have been developed with the capability for blocking 8000 volts and switching 1000 amperes. As in the case of the power bipolar transistor, the GTO is a current-controlled device. A very large gate current is required to enable turn-off of the anode current. When optimized for blocking high voltages, the current gain of the GTO is found to be less than 5. In addition, large snubbers are required to ensure turn-off without destructive failure. Consequently, the cost of the system is increased by the need for large snubbers and control circuits.

In the 1970s, devices called the static induction transistor (SIT) and the static induction thyristor (SITH) were introduced in Japan. Research on these devices was also performed in the United States on these devices under the name of vertical junction field effect transistors (VFET) and the field-controlled diode or thyristor (FCD, FCT) [5]. Although these devices were found to have some attractive characteristics, such as superior radiation tolerance and a very high cutoff frequency, they have not found much commercial acceptance for variable frequency drives. The two principal reasons for this are, first, these devices have normally on characteristics with poor high-temperature blocking, and second, a large gate drive current (nearly equal to the anode current) is need to achieve rapid turn-off.

Modern power semiconductor technology evolved by the assimilation of the metal-oxide-semiconductor (MOS) technology originally developed for CMOS integrated circuits. This first led to the advent of the power MOS-gated field effect transistors (MOSFETs) in the 1970s. Although these devices were initially touted by the industry to exhibit the characteristics of the ideal device, their performance was found to be unsatisfactory for medium-power applications where the operating voltages exceed 300 volts, thus relegating them to the low-voltage, high-frequency applications arena.

The introduction of the insulated gate bipolar transistor in the 1980s was aimed at providing a superior device for the medium-power applications by attempting to combine the best features of the bipolar power transistor and the power MOSFET. Although the IGBT has been widely accepted for motor control applications, its characteristics do not approach those of the ideal device. This has motivated research on MOS-gated thyristor structures, which have recently been commercially introduced for high-power applications. Further, theoretical analysis has shown that

power devices made from silicon carbide could have electrical characteristics approaching those of the ideal device. Over the long term, these devices could completely displace silicon devices used for power electronics.

The objective of this chapter is to provide an overview of power semiconductor devices from the point of view of their application to adjustable speed motor drives. The intention is to concentrate on the impact of the modern MOS-gated power devices upon system efficiency. The commercially available switches that have been considered in this analysis are the power MOSFET, the insulated gate bipolar transistor, and the MOS-controlled thyristor (MCT). To assess the impact of ongoing research on silicon device technology, the analysis includes the base resistance controlled thyristor (BRT) and the emitter switched thyristor (EST). It is also illustrated in this chapter that the development of power rectifiers with improved high-frequency switching characteristics is critical to the development of systems operating above the acoustic frequency limit, which is important for reduction of ambient noise, particularly in commercial applications. In the future, it is anticipated that silicon carbide-based switches and rectifiers will significantly enhance the performance of variable speed drives. For this reason, the power loss reduction that can be achieved by replacement of silicon devices with silicon carbide-based devices is also analyzed.

1.2. BASIC VARIABLE SPEED DRIVE

The most commonly used adjustable speed drive technology is based upon the pulse width modulated (PWM) inverter [1, 2] in which the input AC line power is first rectified to form a DC bus. The variable frequency AC power to the motor is then provided by using six switches and flyback rectifiers. The switches are connected in a totem pole configuration as illustrated in Figure 1-2. The power delivered to the motor is regulated by adjusting the time duration for the on- and off-states for the power switch. By using a sinusoidal reference waveform, a variable frequency output current can be synthesized by using a switching frequency well above the motor operating frequency. To reduce the acoustic noise from the motor, it is desirable to increase the switching frequency for the transistors to above the acoustic range (preferably above 15 kHz).

A typical set of current and voltage waveforms in the transistor and rectifier during one switching cycle are shown in Figure 1-3. These waveforms have been linearized to simplify the power loss analysis. It is assumed that the motor current is initially flowing through the flyback rectifier at the bottom of the totem pole circuit. At time t_1, the upper transistor is switched on with a controlled rate of rise of current. During the time interval from t_1 to t_2, the motor current transfers from the rectifier to the transistor. Unfortunately, the PiN rectifiers that are used in these circuits are unable to recover instantaneously from their forward conduction state to their reverse blocking state. Instead, a large reverse current flow occurs with a peak value I_{PR} prior to the rectifier becoming capable of supporting reverse voltage. This reverse recovery current flows through the transistor. It is worth pointing out that

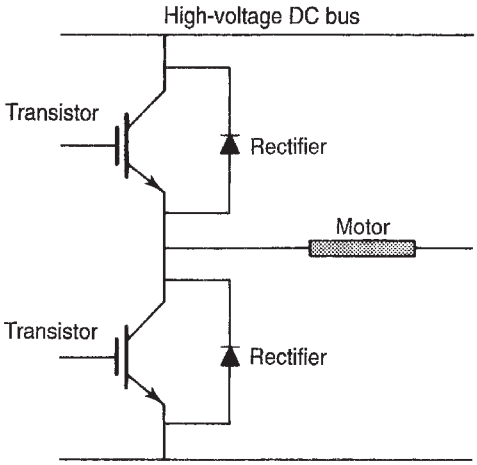


Figure 1-2. Typical totem pole configuration used in a pulse width modulated motor drive.

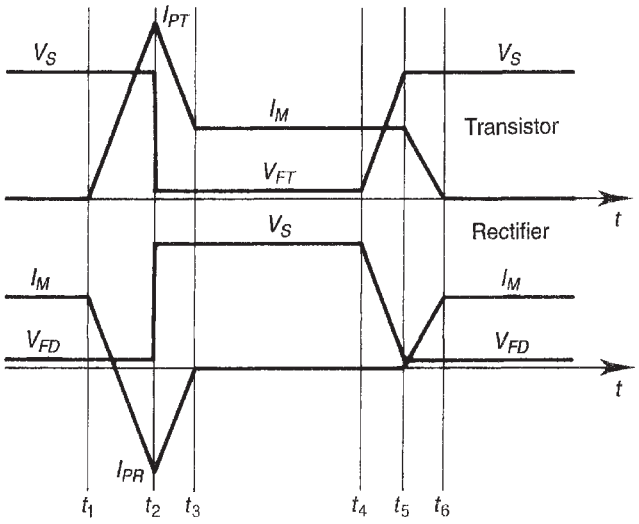


Figure 1-3. Linearized current and voltage waveforms for the switch and rectifier.
V_s-DC supply voltage
V_{FT}-on-state voltage drop for the transistor
V_{FD}-on-state voltage drop for the rectifier
I_M-motor current (on-state current in the transistor and rectifier)
I_{PR}-peak reverse recovery current for the rectifier
I_{PT}-peak transistor current during its turn-on.

the net transistor current during this time interval is the sum of the motor current I_M and the diode reverse recovery current. Further, during this time, the transistor must support the entire DC bus voltage because the rectifier is not yet able to support voltage. This produces a significant power dissipation in the power switch when it is being turned on. This will be referred to as the turn-on power loss for the transistor. Further, the transistor is subjected to a high stress due to the presence of a high current (I_{PT}) and a high voltage (V_S) simultaneously. This can place the transistor in a destructive failure mode if the stress exceeds its safe operating area limit. At time t_2, the rectifier begins to support reverse voltage, and its reverse current decreases to zero during the time interval from t_3 to t_2. During this time, the transistor current falls to the motor current, and a large power dissipation occurs in the diode because it is supporting a high voltage while conducting a large reverse current.

The other important switching interval is from t_4 to t_6 during which the transistor is turned off and the motor current is transferred to the rectifier. During the first part of this time interval from t_4 to t_5, the voltage across the transistor rises to the bus voltage while its current remains essentially equal to the motor current because of the large inductance in the motor winding. In the second portion of this time interval from t_5 to t_6, the current in the transistor decreases to zero while it is supporting the bus voltage. Since there is a large current and voltage impressed on the transistor during both these time intervals, there is significant power dissipation in the transistor during its turn-off.

Due to relatively long turn-off time for bipolar power transistors and the first IGBTs introduced into the marketplace, the emphasis has been on reducing the power loss in the switches during their turn-off. It has been found that methods employed to reduce the turn-off time for the switches is usually accompanied by an increase in their on-state voltage drop, which increases their on-state power dissipation during the time interval t_2 to t_4. It has been customary to compare power switches by calculating the sum of the on-state and turn-off power losses as a function of frequency [3] as given by

$$P_L = \delta\, I_F V_F + t_F I_F V_S f \tag{1.1}$$

where δ is the duty cycle, I_F is the on-state current, V_S is the DC bus voltage, t_F is the turn-off time for the switch, and f is the switching frequency. The results of such calculations for the devices discussed in this chapter are given in Figure 1-4. The calculations were performed for the case of a motor current of 15 amperes, a DC bus voltage of 400 volts, and a duty cycle of 50%. The device characteristics used for the calculations are provided in Table 1-1. Unfortunately, this method for comparison grossly underestimates the power losses in the motor drive circuit because it does not take into account the turn-on losses and the power dissipation incurred in the

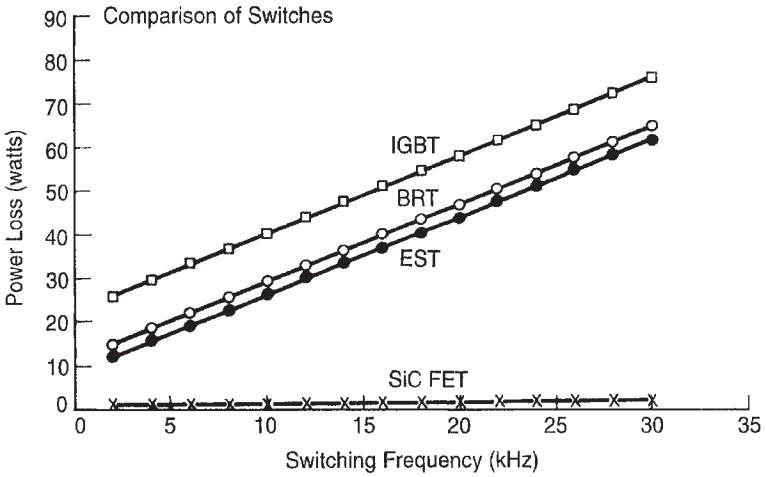


Figure 1-4. Comparison of power switches based upon a simple analysis, including on-state and turn-off losses only. The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes.

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TABLE 1-1 CHARACTERISTICS OF POWER SWITCHES USED FOR POWER LOSS CALCULATIONS*

Device	Forward drop	Current density	Turn-off time
IGBT	3.0 V	100 A/cm^2	0.3 μsec
BRT/MCT	1.1 V	100 A/cm^2	0.3 μsec
EST	1.5 V	100 A/cm^2	0.3 μsec
SiC FET			
Case 1	0.1 V	100 A/cm^2	0.01 μsec
Case 2	0.1 V	100 A/cm^2	0.05 μsec

*All the devices are assumed to have a breakdown voltage of 600 volts.

rectifier. It is, therefore, important to perform the power loss analysis by considering the entire waveform for the transistor and rectifier as shown in Figure 1-3 for the complete switching period. The power losses obtained with this method will be provided in this chapter to illustrate the significance of the power rectifier reverse recovery behavior upon the power dissipation. Before such calculations are presented in this chapter, the basic structures and electrical characteristics of various switches and rectifiers will be discussed. Since the most commercially successful power devices with a high input impedance have been based upon MOS-gated structures, this review will not include the bipolar power devices but will focus upon the characteristics of power semiconductor devices with MOS-gated structures.

1.3. POWER MOSFET

The development of the power MOSFET was based upon the technology created for the fabrication of CMOS logic circuits [4]. The metal-oxide-semiconductor structure has an inherent insulator between the gate electrode and the semiconductor resulting in a high input impedance under steady state conditions. The structure of the power MOSFET is shown in Figure 1-5a,b. As in the case of bipolar discrete power devices, a vertical device architecture was adapted to obtain a high current-handling capability by placing the high-current electrodes (source and drain) on opposite surfaces of the wafer. This avoids the problems associated with interdigitation of the source and drain metal. In addition, a refractory gate (usually polysilicon) is used to enable fabrication of the device by using the double-diffused process to form the DMOS structure shown in the figure. This process allows fabrication of devices with submicron channel length by adjustment of the relative diffusion depth of the P-base and N+ source regions without the need for expensive high-resolution photolithographic tools.

The vertical DMOS device structure can support a large voltage across the P-base/drift region junction. The maximum blocking voltage is determined by the onset of avalanche breakdown of this junction or at the edge termination. A larger blocking voltage can be obtained by using a thicker, higher resistivity drift region.

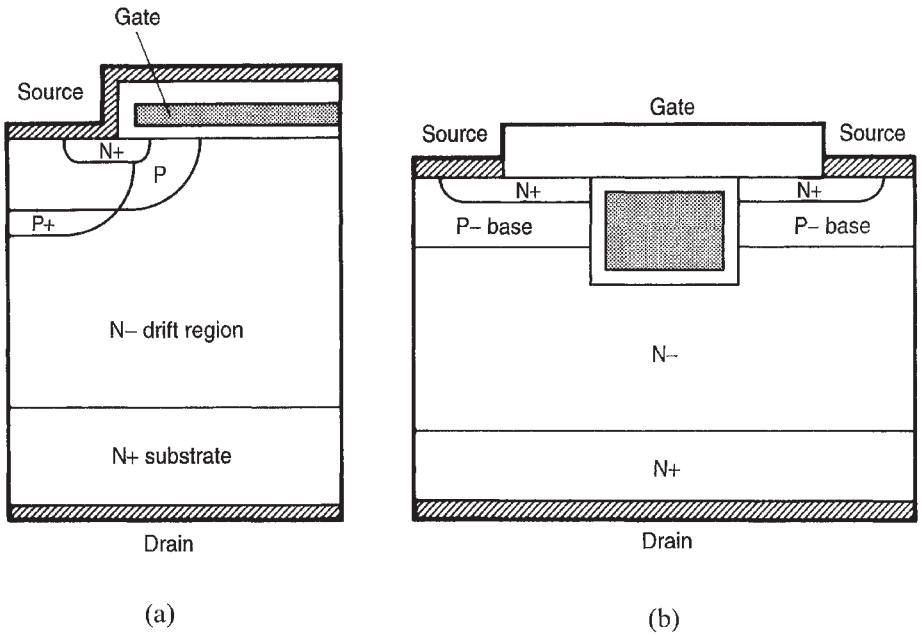


Figure 1-5. (a) Power MOSFET structure fabricated using the DMOS process; (b) Power MOSFET structure fabricated using the UMOS process.

When a positive gate bias is applied, an inversion layer is formed at the surface of the P-base region. This forms a channel between the source region and the drift region through which current can flow. The on-state current is conducted using only majority carriers (electrons for the n-channel structure). This feature of the power MOSFET provides very fast switching performance as compared with previous bipolar transistors.

The current rating of the power MOSFET is determined by the joule heating produced in the internal resistances within the device structure. There are many resistance components in the power MOSFET structure [5]. Among these, the most significant are the channel resistance (R_{ch}); the resistance between the P-base diffusions, which is called the JFET resistance (R_J); and the resistance of the drift region (R_D). During the last five years, power MOSFETs with trench-gate structures (see Figure 1-5b) have been investigated with the goal of reducing the on-state resistance. In this structure, the JFET resistance is eliminated. Further, the trench-gate process allows increasing the MOS-channel density by a factor of 5 times leading to reduction in the on-resistance. This is particularly significant for power MOSFETs with low (< 100 volt) blocking voltage capability. In the case of high-voltage-power MOSFETs, the resistance of the drift region becomes dominant for both the DMOS and the UMOS structures, and its value increases very rapidly with increasing breakdown voltage. This results in the on-state voltage drop of silicon power MOSFETs, as determined by the product of the on-state current and the on-resistance, becoming unacceptable for the types of variable speed motor drives being discussed in this chapter. Thus, in spite of its many other attractive features, the

power MOSFET is not considered a viable device for high-voltage variable speed drive applications. This will be evident from the power loss calculations presented later in the chapter.

1.4. INSULATED GATE BIPOLAR TRANSISTOR

To provide a high-input impedance device for high-voltage applications, the insulated gate bipolar transistor was proposed in the 1980s [6]. In the IGBT, an MOS-gated region is used to control current transport in a wide-base high-voltage bipolar transistor. This results in a device with the attractive characteristics of the high-input impedance of a power MOSFET combined with the superior on-state characteristics of bipolar devices. In fact, it has been shown that the on-state characteristics of the IGBT are superior to those for a high voltage transistor and approach those of a thyristor [5].

A cross-sectional view of the IGBT structure is provided in Figure 1-6 together with its equivalent circuit. Its structure is similar to the power MOSFET with the exception that a P+ substrate is used instead of the N+ substrate. This structural similarity has allowed rapid commercialization of the device because the process for the fabrication of the IGBT is nearly identical to that for the power MOSFET. However, its operating physics is quite different as indicated by the equivalent circuit. This circuit indicates the presence of a parasitic thyristor between the collector and emitter terminals. The latch-up of this thyristor results in loss of gate control and destructive failure of the IGBT. In commercial devices, the latch-up has been suppressed by using a variety of techniques such as the P+ region under the N+ emitter to reduce the resistance R_P. These methods are aimed at preventing the

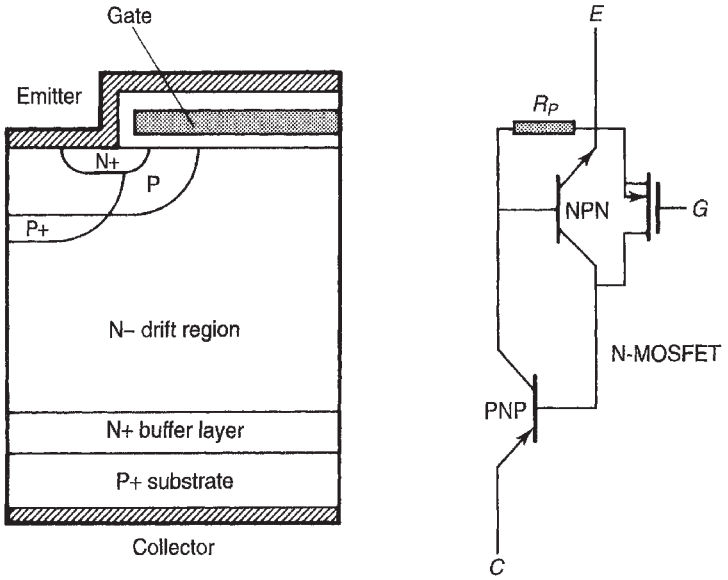


Figure 1-6. Cross section of the asymmetric insulated gate bipolar transistor structure and its equivalent circuit.

activation of the NPN transistor so that the IGBT can operate as a wide-base PNP transistor driven by an integrated MOSFET.

Both forward and reverse blocking capability are inherent in the IGBT structure because the voltage can be supported by the reverse biasing of the P-base/N-drift region junction in the forward quadrant and the P+ substrate/N-drift region junction in the reverse quadrant [5]. However, commercial devices are available with only forward blocking capability because they are made with a N+ buffer layer interposed between the N-drift region and the P+ substrate, as shown in Figure 1-6. This structure is referred to as the punch-through (PT) structure because the depletion layer extends throughout the N-drift region during forward blocking and punches-through to the N+ buffer layer. The buffer layer structure provides superior on-state and safe operating area characteristics for DC circuit applications. Some manufacturers have been developing devices using the nonpunch-through (NPT) design shown in Figure 1-7 but have optimized the device only for DC applications. This structure can support a large reverse voltage if the lower junction is properly terminated [6]. In the future, the symmetrical blocking structure may become available due to its demand for AC circuit applications.

The IGBT can be turned on by the application of a positive gate bias to form an n-channel at the surface of the P-base region. With a positive collector potential, current flow can now occur across the forward-biased P+ substrate/N-drift region junction. As shown in Figure 1-6, the equivalent circuit for the IGBT consists of a wide-base PNP transistor being driven by a MOSFET in the Darlington configuration. This produces a low on-state voltage drop in the IGBT during current conduction, while retaining the gate-controlled current saturation properties of the power MOSFET. Since the current transport in the IGBT occurs by the injection of a high concentration of minority carriers into the N-drift region, its switching behavior is determined by the rate at which these carriers are removed during turn-off. For applications at low frequencies, such as off-line appliance controls, as-fabricated

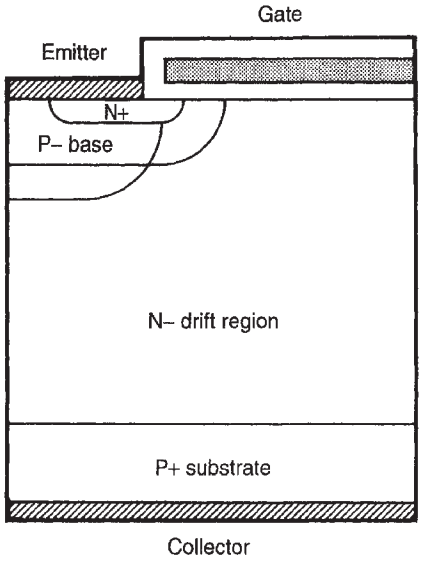


Figure 1-7. Cross section of the symmetric insulated gate bipolar transistor structure.

devices with relatively long minority carrier lifetime (10 microseconds) are acceptable. However, for adjustable speed motor control, where turn-off times of less than 0.5 microseconds are desirable, it is necessary to reduce the minority carrier lifetime by using electron irradiation [7]. Unfortunately, in all bipolar power devices, devices with shorter turn-off times have a larger on-state voltage drop. A trade-off curve between the on-state voltage drop and the turn-off time can be generated for any device structure by using lifetime control to alter the switching speed. A comparison of the trade-off curve for the asymmetric and symmetric IGBT structures can be performed with the aid of Figure 1-8. It can be seen that the trade-off curve for the asymmetric structure is superior for the blocking voltage of 600 volts. Careful optimization of the IGBT structure by adjusting the lifetime in the drift region and the buffer layer doping for the asymmetric structure has led to commercial devices with on-state voltage drops of 3 volts and turn-off times of 0.3 microseconds. Devices are now commercially available with ratings of several hundred amperes with blocking voltages as high as 1500 volts, and it can be anticipated that the ratings of IGBTs will continue to grow by an increase in both the die size and the blocking voltage rating.

The availability of high-performance IGBTs has made them the device of choice for variable speed drives. A calculation of the power losses incurred during device operation with a 50% duty cycle is shown in Figure 1-9 when the IGBT is used with a PiN rectifier. The electrical characteristics of the devices are given in Tables 1-1 and 1-2. It can be seen that the power loss increases rapidly with increase in operating frequency, indicating that the switching losses are more important than the conduction losses. It is interesting to analyze the power losses in the IGBT during various phases of operation. The power losses in the IGBT during the on-state, turn-off, and turn-on are shown in Figure 1-10 together with the total power loss in the IGBT. Note that although the on-state power loss in the IGBT is dominant at switching frequencies below 5 kHz, the switching power losses become dominant at higher frequencies. More important, the turn-on power loss is seen to be larger than the turn-off power loss. This occurs because of the large reverse recovery current for the PiN rectifier which the IGBT switch must conduct during its turn-on (see Figure

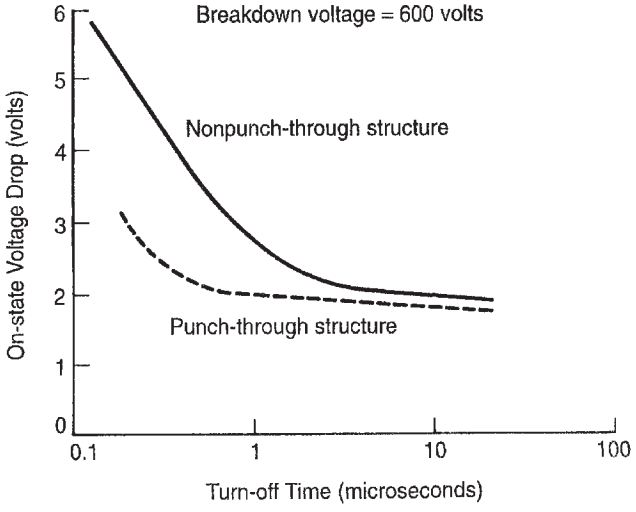


Figure 1-8. Comparison of the trade-off curve between on-state voltage drop and turn-off time for the symmetric and asymmetric IGBT structures.

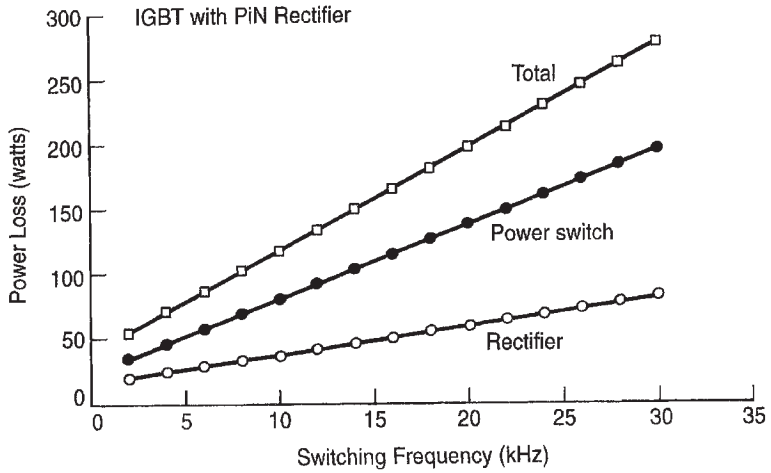


Figure 1-9. Power loss for drive with IGBT and PiN rectifier. The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes.

1-3). From these charts, it can be concluded that a reduction in the power losses can be achieved by improving the reverse recovery performance of the power rectifier. Thus, progress in power rectifier technology has been essential to obtaining high performance variable frequency drives.

1.5. POWER RECTIFIERS

With the advent of high performance power switches, such as IGBTs, it has become very important to develop power rectifiers with good high-frequency switching characteristics. In addition to high reverse blocking capability, the important characteristics for power rectifiers are (1) low on-state voltage drop, (2) short reverse recovery switching time, (3) small peak reverse recovery current, and (4) soft reverse recovery behavior. The last requirement stems from the high-voltage spikes that can occur if the reverse recovery di/dt is large.

TABLE 1-2 CHARACTERISTICS OF POWER RECTIFIERS USED FOR POWER LOSS CALCULATIONS*

Device	Forward drop	Current density	Reverse recovery time	Peak recovery current
PiN	2.0 V	100 A/cm^2	0.5 μsec	45 amps
MPS/SSD	1.0 V	100 A/cm^2	0.25 μsec	10 amps
SiC				
Case 1	1.0 V	100 A/cm^2	0.01 μsec	0 amps
Case 2	1.0 V	100 A/cm^2	0.05 μsec	0 amps

*All the devices are assumed to have a breakdown voltage of 600 volts.

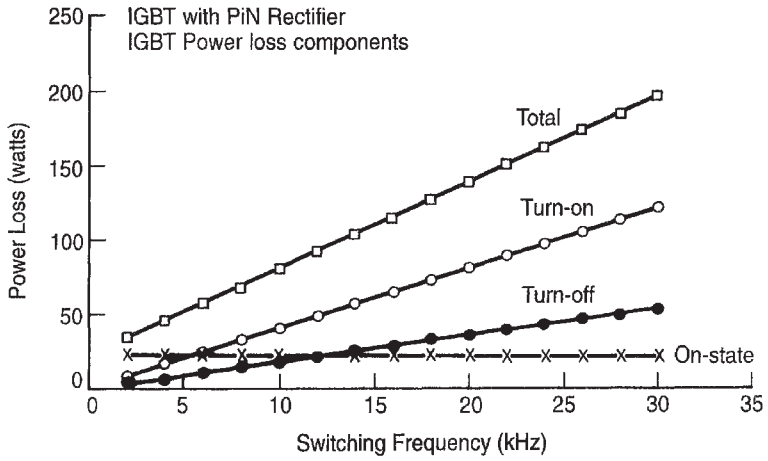


Figure 1-10. IGBT power loss components for drive with IGBT and PiN rectifier. The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes.

Many high-voltage power rectifier structures have been proposed and investigated to achieve the above goals [8–13]. Three of these structures, called the merged pin/Schottky (MPS) rectifier, self-adjusting P emitter efficiency diode (SPEED), and static shielded diode (SSD), are illustrated in Figure 1-11 for comparison with the PiN rectifier. In all these structures, the goal is to reduce the amount of stored charge within the N-drift region during the on-state by reducing the injection efficiency of the upper P+/N-junction in the rectifier. A reduction in the stored charge is desirable because this results in a shorter reverse recovery time with a smaller peak reverse recovery current. It has been found that although this can be accomplished by simply reducing the doping concentration of the P+ region, it results in a very high on-state voltage drop. This does not occur in the MPS and SSD structures because of the highly doped P+ region within the structures in spite of a reduction in the stored charge by a factor of up to eight times. A careful comparison between the electrical characteristics of all the proposed rectifier structures has been performed with the same parameters for the drift region [14]. The trade-off curve between on-state voltage drop and the stored charge (which is a measure of the reverse recovery behavior) is shown in Figure 1-12. It can be seen that the MPS and SSD structures provide the best method for reducing the stored charge without a severe increase in the on-state voltage drop. With these structures, it is possible to obtain rectifiers with on-state voltage drop of about 1 volt with one-half the reverse recovery time and one-third the peak reverse recovery current of the PiN rectifier.

The impact of replacing the PiN rectifier with the MPS rectifier is illustrated in Figure 1-13, which provides the total power losses in the drive and the power losses in the IGBT and power rectifier. By comparison with Figure 1-9, it can be seen that the total power loss has been reduced by nearly a factor of 2 by replacement of the PiN rectifier with the MPS rectifier. This is due to not only a smaller power loss in the rectifier but also in the IGBT. This is evident from Figure 1-14 where the power loss

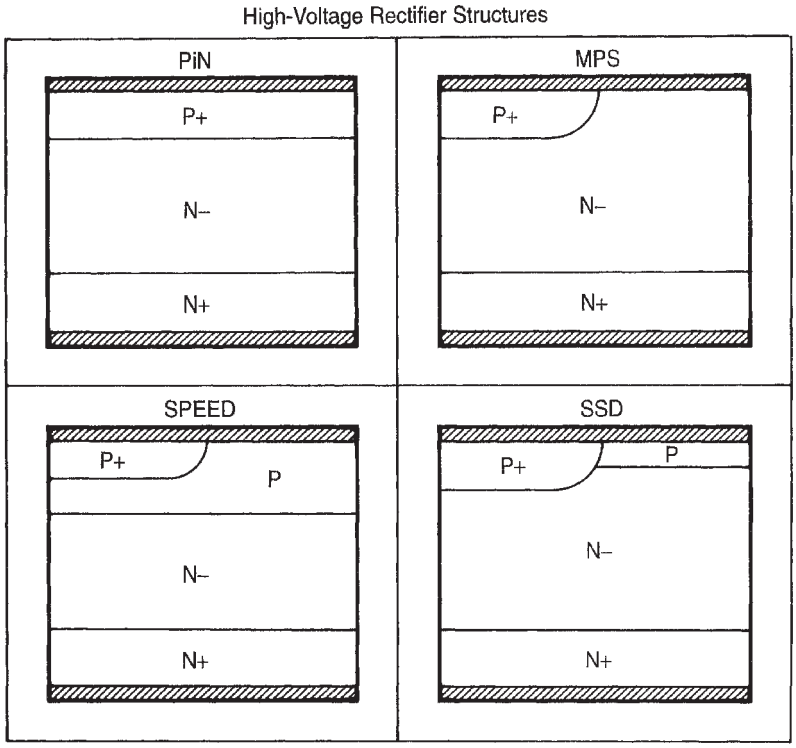


Figure 1-11. Power rectifier structures.

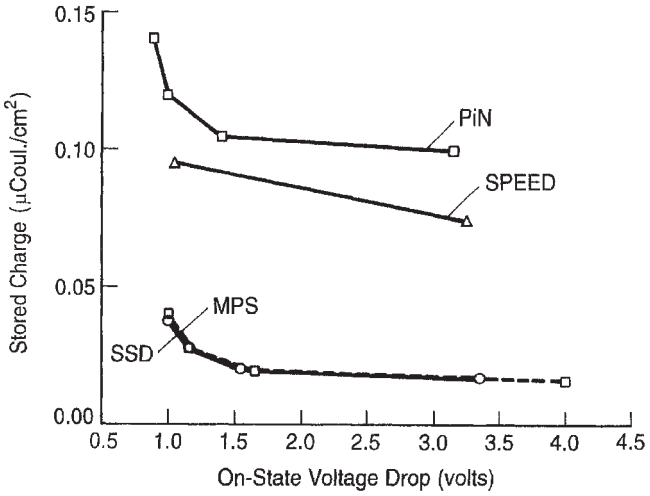


Figure 1-12. Comparison of the trade-off curve between on-state voltage drop and stored charge for various power rectifier structures.

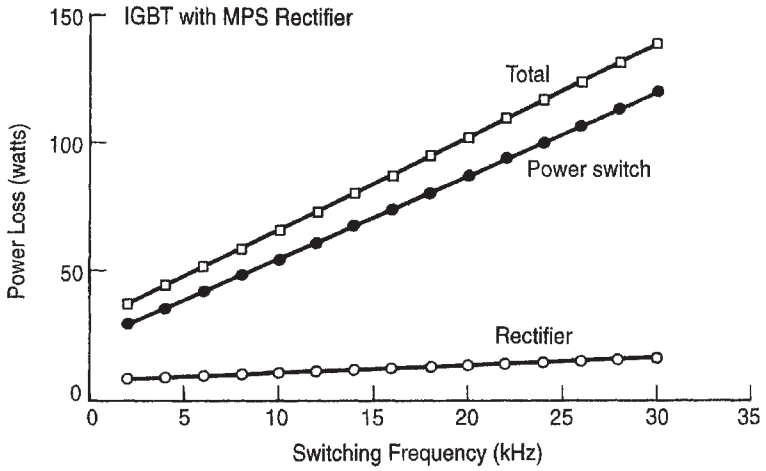


Figure 1-13. Power loss for drive with IGBT and MPS rectifier. The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes.

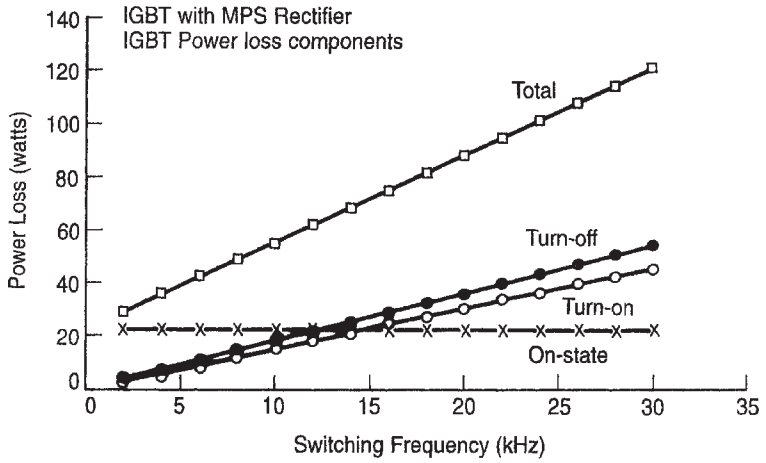


Figure 1-14. IGBT power loss components for drive with IGBT and MPS rectifier. The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes.

components in the IGBT are provided. By comparison of the power loss components in this case to those obtained for operation of the IGBT with the PiN rectifier (see Figure 1-10), it is evident that a significant reduction in the turn-on losses for the IGBT is responsible for the improved performance. These charts demonstrate the importance of the rectifier characteristics on the system performance.

1.6. MOS-GATED THYRISTORS

Although the on-state voltage drop of the IGBT is much superior to that for the power MOSFET at high blocking voltages, its on-state voltage drop increases with increasing switching speed [7]. It is well known that power thyristors have superior on-state characteristics when compared with bipolar transistors. Consequently, there has been considerable interest in the development of thyristor structures that can be switched on and off under MOS-gate control. The MOS-gated turn-on of a vertical thyristor structure was first demonstrated in 1979 [15], and this method is now incorporated in all MOS-gated thyristor structures. The ability to turn off the thyristor current using an MOS-gated structure is much more difficult due to the regenerative action occurring within the thyristor. Several promising methods to achieve this capability have been proposed and demonstrated experimentally. Among these approaches, the most promising are the MCT, the BRT, and the EST structures.

The MOS-controlled thyristor (MCT) structure [16–18] is shown in Figure 1-15 with its equivalent circuit. The thyristor that carries the on-state current is formed by the coupled N+PN- and PN-N+P+ transistors. The MCT can be turned on by using the n-channel MOSFET formed across the NPN transistor [15] and has excellent on-state voltage drop (approximately 1.1 volt). No current saturation is observed in the on-state; that is, this device does not exhibit any forward-biased safe operating area (FBSOA). This can be a problem for drives that rely upon the device for providing short-circuit protection (as done quite commonly by using IGBTs). However, the regenerative action of the thyristor can be broken by short circuiting the N+ emitter/P-base junction by gating on the p-channel MOSFET

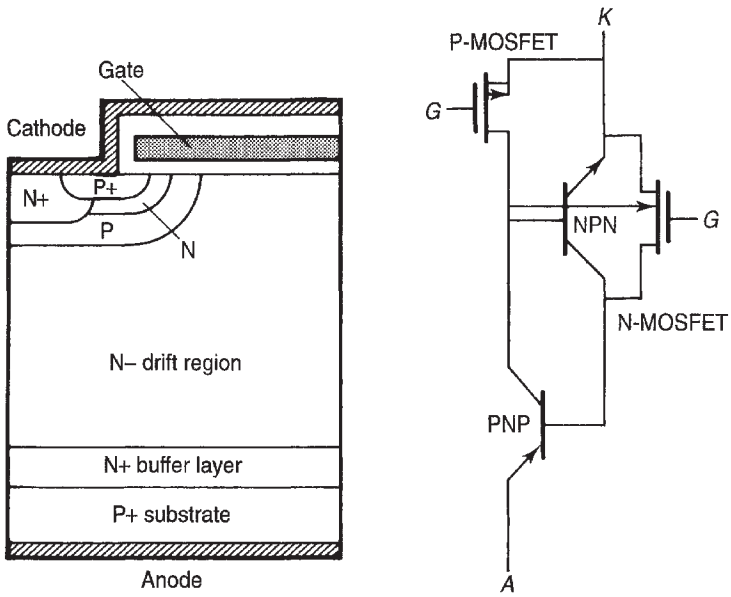


Figure 1-15. Cross section of the MOS-controlled thyristor (MCT) and its equivalent circuit.

integrated into the P-base region. It has been shown that devices with blocking voltages of 3000 volts can be made with good on-state voltage drop. Although the maximum controllable current density for small test devices has been shown to be extremely large, for large multicellular power devices it is in the range of 200 amperes per square centimeter [19]. It has also been found that the device must be operated with snubbers because of a limited reverse biased safe operating area [17]. One of the drawbacks of this MCT structure is that its triple-diffused junction structure is more complex than the double-diffused junction structure for the IGBT making its manufacturing more difficult. In spite of these issues, an MCT with current rating of 75 amperes and 600 volt forward blocking capability has recently become commercially available.

To address this fabrication problem, two MOS-gated thyristor structures were proposed which rely upon the DMOS process for their fabrication [20–21]. In the base resistance controlled thyristor (BRT) structure shown in Figure 1-16, the MOSFET used to turn off the device is formed adjacent to the P-base region using the same process steps as used for IGBTs. In the on-state, the current flows via the vertical thyristor formed between the N+PN- and PN-N+P+ transistors. The device has been shown to exhibit excellent on-state characteristics with a forward voltage drop of 1.1 volt. The thyristor regenerative action can be stopped by diverting the holes flowing into the P-base region, via the lateral p-channel MOSFET, into the cathode electrode. Although it has been shown that a high current density can be turned off in small devices, this device suffers from the same drawbacks as the MCT in terms of lacking any significant FBSOA.

In comparison with the IGBT, the MCT and BRT have a lower on-state voltage drop for the same turn-off switching time (see Table 1-1). The impact of this upon

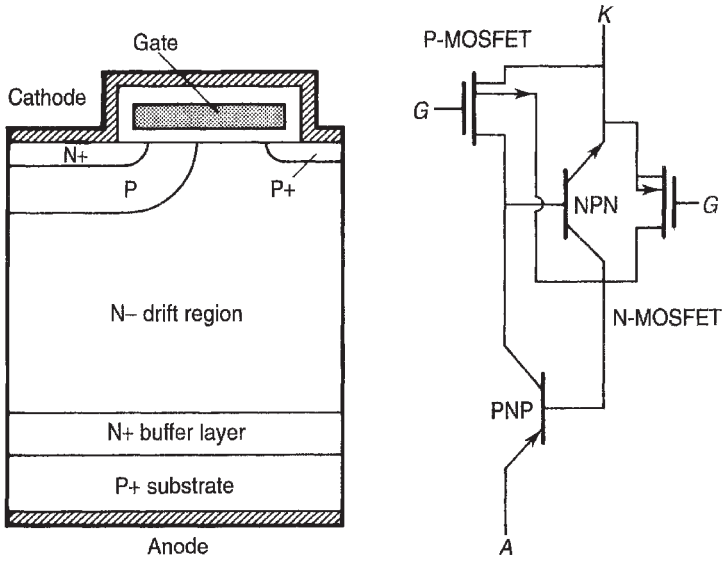


Figure 1-16. Cross section of the base resistance–controlled thyristor (BRT) structure and its equivalent circuit.

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the power losses for the motor drive circuit is shown in Figures 1-17 and 1-18 when the device is used with either a PiN rectifier or an MPS rectifier. In comparison with the IGBT, although a reduction in the total power loss is observed at low operating frequencies due to the reduced on-state voltage drop, the impact is small at the higher operating frequencies. This indicates that the choice of the power switch is less critical than the choice of the power rectifier from the point of view of reducing the power losses in the drive.

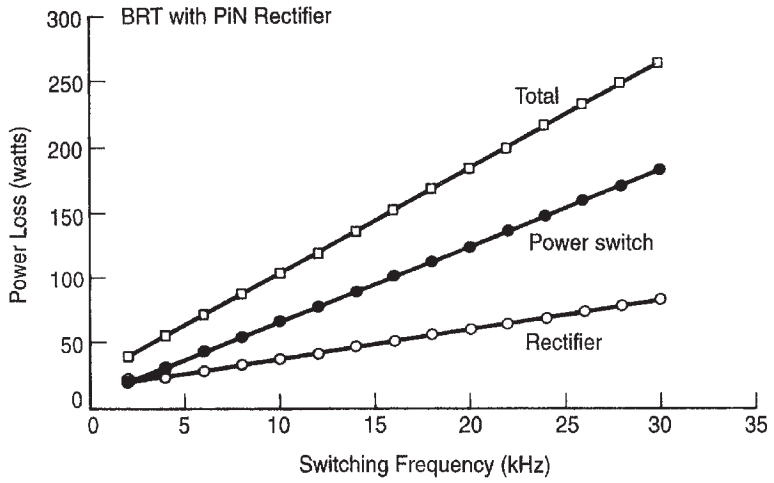


Figure 1-17. Power loss for drive with BRT (or MCT) and PiN rectifier. The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes.

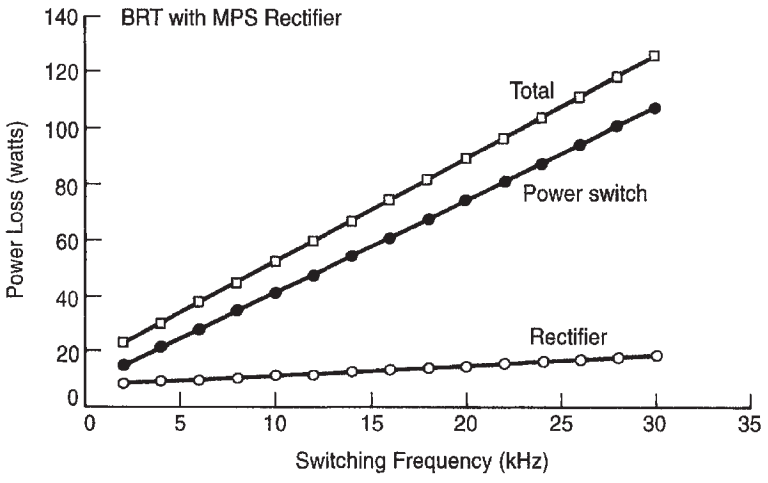


Figure 1-18. Power loss for drive with BRT (or MCT) and MPS rectifier. The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes.

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The emitter switched thyristor structure is shown in Figure 1-19 with its equivalent circuit. As implied by its name, in the EST, MOS-gated control is achieved by forcing the thyristor current to flow through a MOSFET channel. In the EST structure, this MOSFET is integrated into the P-base region of the thyristor. This not only provides MOS-gated–controlled turn-off capability but it also allows current saturation within a thyristor-based structure for the first time [22]. The FBSOA of the EST has been shown to be comparable to that for the IGBT [23]. However, this device has a slightly higher forward voltage drop than the MCT and BRT because the voltage drop across the MOSFET adds to the voltage drop across the thyristor because they are in series as indicated in the equivalent circuit. The typical on-state voltage drop of the EST is about 1.5 volts for a turn-off switching time of 0.3 microseconds as given in Table 1-1.

The power losses in the motor drive circuit for the case of an EST were calculated for the case of operation with a PiN rectifier and an MPS rectifier for the same load and bus voltage as the IGBT. These results are plotted in Figures 1-20 and 1-21 for comparison with the IGBT and BRT (MCT) cases. In each case, although the power loss is slightly greater than that for the BRT (MCT) case, the difference becomes small at higher operating frequencies. It can therefore be concluded that the EST may be a better choice than the BRT or MCT because of its excellent FBSOA.

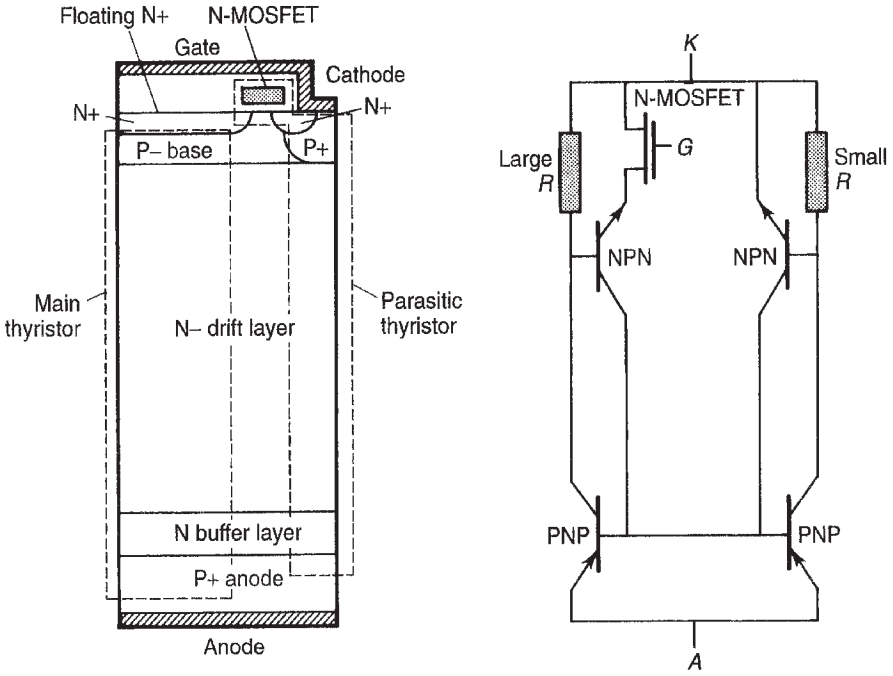


Figure 1-19. Cross section of the emitter switched thyristor (EST) structure and its equivalent circuit.

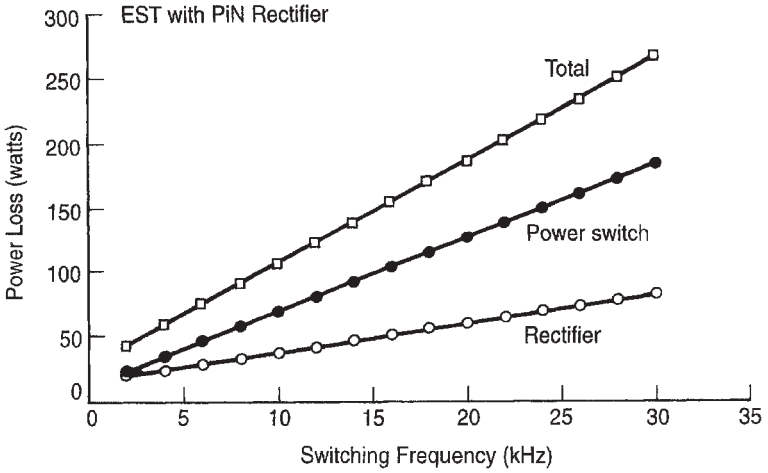


Figure 1-20. Power loss for drive with EST and PiN rectifier. The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes.

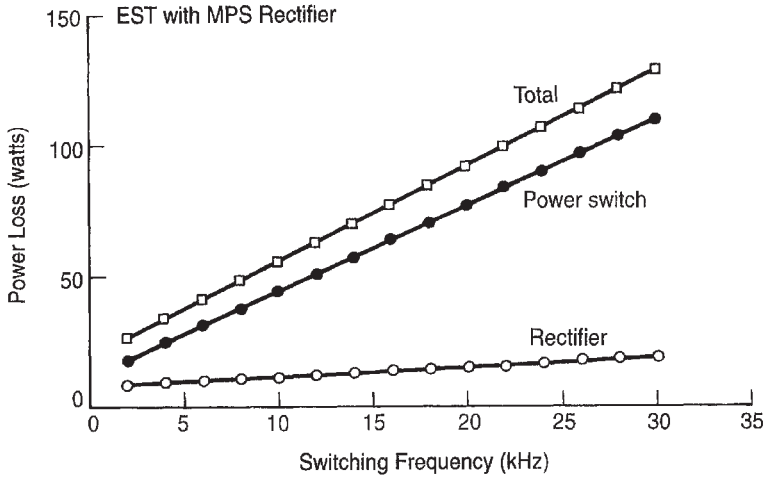


Figure 1-21. Power loss for drive with EST and MPS rectifier. The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes.

1.7. NEW SEMICONDUCTOR MATERIALS

From the foregoing discussion, it can be surmised that further improvement in the power losses in the drive can be accomplished only by a reduction in the switching time for the power switch and the rectifier, as well as a reduction in the peak reverse recovery current for the rectifier. Recent theoretical analyses [24–25] have shown that very-high-performance FETs and Schottky rectifiers can be obtained by replacing silicon with gallium arsenide, silicon carbide, or semiconducting diamond. Among these, silicon carbide is the most promising because its technology is more mature

than for diamond and the performance of silicon carbide devices is expected to be an order of magnitude better than the gallium arsenide devices. In these devices, the high breakdown electric field strength of silicon carbide leads to a 200-fold reduction in the resistance of the drift region. As a consequence of this low-drift region resistance, the on-state voltage drop for even the high-voltage FET is much smaller than for any unipolar or bipolar silicon device as shown in Table 1-1. These switches can be expected to switch off in less than 10 nanoseconds and have superb FBSOA. The analysis also indicates that high-voltage Schottky barrier rectifiers with on-state voltage drops close to 1 volt may be feasible with no reverse recovery transient. A plot of the on-state characteristics of SiC Schottky barrier rectifiers with different reverse blocking capability is shown in Figure 1-22. From these plots, it can be concluded that SiC Schottky barrier rectifiers with on-state voltage drop close to 1 volt will be possible with reverse blocking capability of up to 2000 volts. Recently, these theoretical predictions have been experimentally confirmed by the fabrication of Schottky barrier rectifier with breakdown voltages of 400 volts [26].

The low-drift region specific on-resistance for silicon carbide is also expected to allow the fabrication of power FETs with very low on-state voltage drop. A comparison of the specific on-resistance (on-resistance for 1 cm^2 device area) of silicon carbide drift regions for the three principle polytypes (3-C, 6-H, and 4-H) with silicon is provided in Figure 1-23. As pointed out earlier, an improvement in specific on-resistance by about two orders of magnitude is projected for all three polytypes. It is important to point out that in spite of the differences between the critical breakdown field strengths for the three polytypes, the specific on-resistance for the three cases is nearly identical because the difference in electron mobility provides a compensating factor. Using the projected drift region specific on-resistance, the on-state voltage drop of a SiC FET operating at an on-state current density of 100 amperes per square centimeter is calculated to be only 10 millivolts. If the additional resistances in the vertical FET structure are taken into account, the on-state voltage

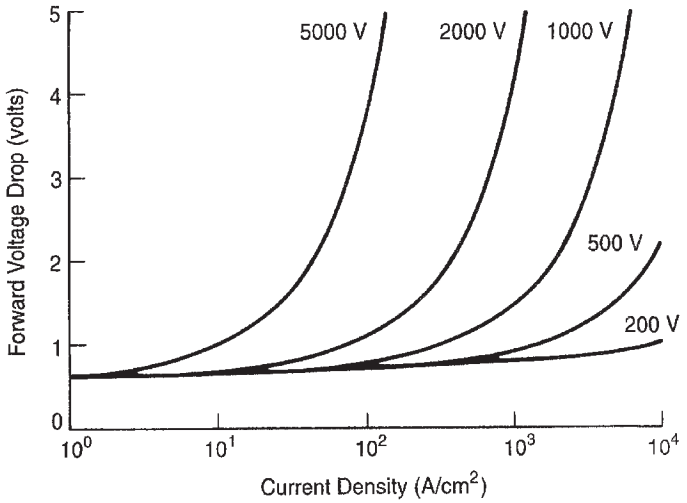


Figure 1-22. Calculated on-state characteristics of silicon carbide Schottky barrier rectifiers.

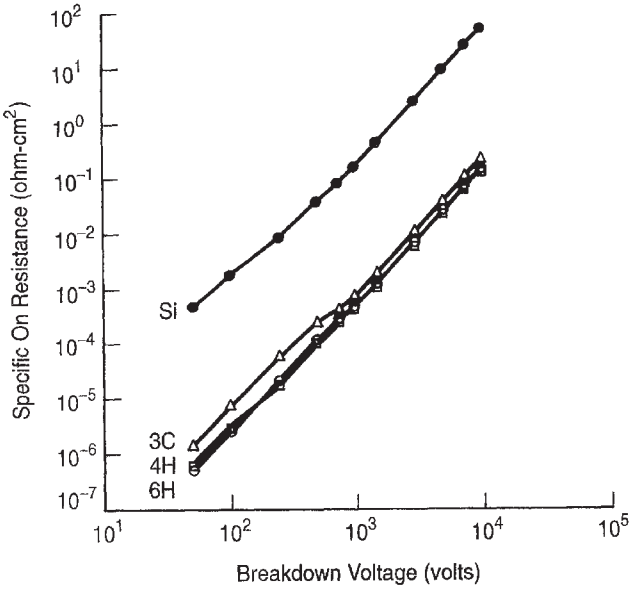


Figure 1-23. Comparison of the calculated specific on-resistance for three polytypes of silicon carbide drift regions with silicon.

drop can be anticipated to be less than 0.1 volts. For this reason, the power loss calculations for the SiC FET has been performed using an on-state voltage drop of 0.1 volts in this analysis. The most attractive SiC FET structure is the trench-gate device illustrated in Figure 1-5b. However, high-quality interfaces have not been obtained on thermally grown oxides on P-type SiC. Considerable research is now underway to explore methods for forming a gate insulator with good interface properties for fabrication of power MOSFETs.

If the silicon power switch and rectifier are replaced with the silicon carbide devices, it becomes possible to reduce the turn-off time to 10 nanoseconds because both the switch and the rectifier behave as nearly ideal devices. The power losses calculated for this case are shown in Figure 1-24 for comparison with the silicon devices. It is obvious that the power losses have been drastically reduced at all switching frequencies. Note that the power loss in the SiC rectifier is higher than that in the SiC FET because of its larger on-state voltage drop. This calculation assumes that the short switching time of the SiC devices can be utilized without encountering severe di/dt and dv/dt problems in the system. If this becomes a problem, it may be necessary to increase the switching time by adjusting the input gate waveform driving the SiC FETs. Calculations of the power losses in the drive when the turn-off time is increased from 10 nanoseconds to 50 nanoseconds have been performed and are given in Figure 1-25. In comparison with Figure 1-24, it can be seen that this results in an increase in the power loss in the switch, which doubles the total power loss. However, this power loss is still much smaller than that for the silicon devices.

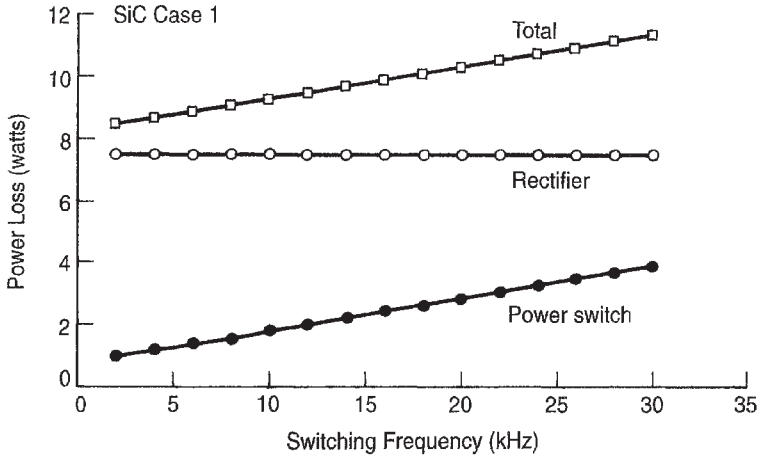


Figure 1.24. Power loss for drive with silicon carbide devices (Case 1 with 10 nanosecond turn-off time for switch). The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes.

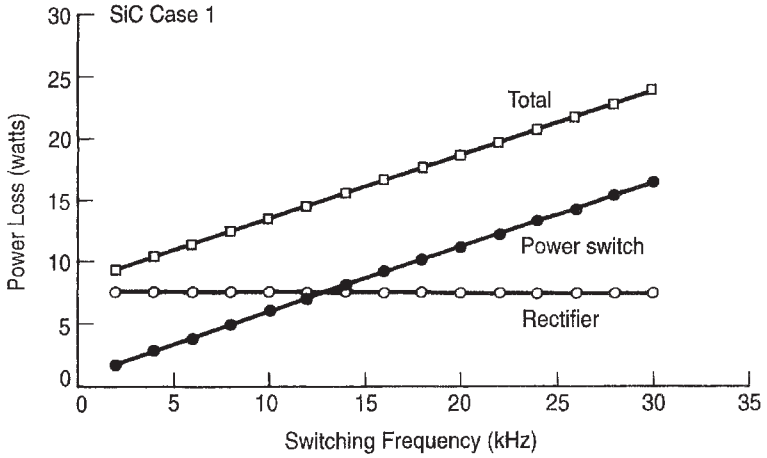


Figure 1.25. Power loss for drive with silicon carbide devices (Case 2 with 50 nanosecond turn-off time for switch). The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes.

1.8. DEVICE COMPARISON

A comparison of the power losses for all the devices considered in the previous sections of this chapter can be performed with the aid of Figure 1-26 where the total loss for each case has been plotted. From this figure, it is clear that the impact of replacing the PiN rectifier with an MPS rectifier (or any other rectifier with faster reverse recovery time, reduced reverse recovery current, and comparable on-state

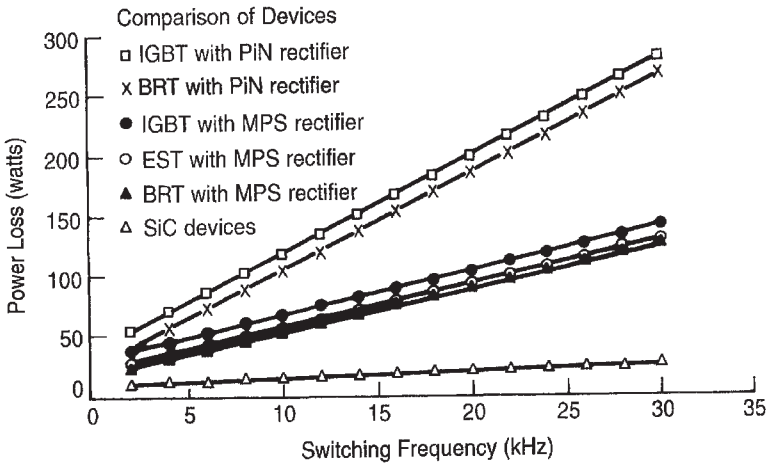


Figure 1-26. Comparison of total power losses for all the devices. The DC bus voltage is assumed to be 400 volts, and the motor current is 15 amperes. The results for the BRT are also applicable to the MCT.

voltage drop) is much greater than replacement of the IGBT with the BRT (or any other MOS-gated thyristor-based device with on-state voltage drop of about 1 volt) unless the operating frequency is relatively low. It is also obvious that the silicon carbide devices are an extremely attractive choice for reducing power losses in variable speed motor drives.

1.9. SMART POWER CONTROL CHIPS

The development of the IGBT resulted in greatly simplifying the gate drive circuits for motor drive applications. Since the IGBT gate drive circuit has much fewer components than the base drive circuit for bipolar transistors and only relatively small currents are needed to control the IGBT, it became possible to integrate the gate drive circuit into a monolithic chip for the first time. This, in turn, created the opportunity to add other functions (such as protection against adverse operating conditions) and logic circuits to interface with microprocessors.

In a three-phase leg motor drive circuit, it is possible to partition the drive in two basic ways. In one case, all the drive circuits for the lower switches in the totem pole configuration are integrated together on one chip, while all the drive circuits for the upper switches in the totem pole configuration are integrated on a second chip. This avoids the need to integrate level shifting capability within the chip but requires a separate high-voltage chip for providing this feature. Alternately, the drive can be partitioned with the drive circuits for both the upper and lower switch in each phase leg integrated on a monolithic chip. To achieve this capability, technology has been developed to integrate the level shift circuits for the upper switch. This also requires the ability for the drive circuit to rise in potential to above the DC bus voltage in

order to turn on the upper switch [27–28]. Three such control chips would be required in a three phase system.

In the smart power control chip, the sensing and protection circuits are usually implemented using analog circuits with high-speed bipolar transistors. These circuits must sense the following adverse operating conditions: overtemperature, overcurrent, overvoltage, and undervoltage. It is obvious that an overtemperature and overcurrent condition can cause thermal runaway leading to destructive failure, while an overvoltage condition can lead to avalanche injection-induced failure. The undervoltage lockout feature is also necessary because sufficient gate drive voltages are not generated at low bus voltages leading to very-high-power dissipation in the output transistors. An example of this condition is during system start-up. The bipolar transistors used in the analog portion must have a high-frequency response because of the high di/dt during short-circuit conditions. When the current exceeds a threshold value, the feedback loop must react in a short duration to prevent the current from rising to destructive levels.

The smart power chips used today are manufactured using a junction isolation technology. In these chips, the high-voltage-level shift transistors are usually lateral structures made using the RESURF principle to obtain a high breakdown voltage with thin epitaxial layers. It is anticipated that dielectric isolation (DI) technology will replace the junction isolation (JI) technology that is now being used for most smart power integrated circuits (ICs). Dielectric isolation offers reduced parasitics, a more compact isolation area, and the prospects for integrating MOS-gated bipolar devices that occupy less space that the lateral MOSFETs.

2.0. CONCLUSION

This chapter has been written with the point of view of reviewing power switch and rectifier technology of relevance to variable speed motor drive applications. By performing power loss calculations during a typical switching cycle, it has been shown that improvement in the reverse recovery behavior of power rectifiers is critical for reducing the total power loss. Although MOS-gated power switches with lower on-state voltage drop are useful for reducing the power loss in systems operating at low switching frequencies, they become of less importance for systems operating at higher frequencies of interest for motor control operation above the acoustic range. It has been shown that, in the future, power switches and rectifiers fabricated from silicon carbide offer tremendous promise for reduction of power losses in the drive. Thus, it can be concluded that advances in power semiconductor technology continue to look very promising for improving the performance of motor drives.

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EXHIBIT 6

Heat Sink

Manufacturing Technologies

The most important issue in thermal management of electronics devices is to design cooling systems to maintain the device junction temperature below a set limit called maximum junction temperature. It has been proven that every 10°C reduction in junction temperature will double the life expectancy of the device. In addition the performance of the device will increase with the reduction of the junction temperature. The most common and economical way to date for cooling devices has been air cooling using heat sinks.
The concept of using a heat sink is to transfer heat from the component level to a space where more air flow is available to dissipate the heat. Some of the parameters that are used to determine the selection of heat sink are amount of heat to be dissipated, maximum allowable junction temperature, thermal resistance of the device and natural or forced convention cooling and if forced the air flow in the system.

There are numerous ways to manufacturing heat sink. The most common ways of manufacturing of air-cooling heat sinks are as follows [1]

1. Extrusion
2. Stamping
3. Die Casting
4. Bonding
5. Folding
6. Forging
7. Skiving
8. Machining

Extrusion

Extrusion as a process by which a solid block is converted into a continuous length of uniform cross-section, by forcing it to flow under high pressure, thought a die orifice, which is so shaped, as to impart the required form to the product. Typically, billets of material are placed within a strong walled enclosure, and are caused to extrude through the die, under a powerful pressure exerted by a ram, actuated hydraulically or mechanically.[2]



Figure 1.- Typical Image of Extruded Heat Sink [3]

Extrusion is the most widely used method for heat sink manufacturing. Usually extrusions are 2 dimensional features and followed by machining process like adding features attach the component. A typical fin thickness is 0.60mm -

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2mm, but there have been cases where it can go as low as 0.4mm. Capital investment and product cost are moderate, and secondary operations contribute approximately 15-20% of the part cost, and control product parameters such as tolerance, flatness, and surface finish. The flatness is an important factor for the performance of heat sink. The industry standard for flatness is 0.007in/in for heat sinks. In cases where this is not achieved directly from the extrusion, additional process like passing the heat sinks through time saves is carried out.

Stamping

Stamping is a process carried out using a power press, fitted with a metal stamping die, which transforms sheet metal into light weight, inexpensive, parts, capable of producing several thousand small parts per process stroke.

Actual obtainable volume depends on the size, geometry, and weight of the heat sinks, and the type of hardness of the material used. Heat sinks of any size could be manufactured by stamping, and can be commercially found up to 10cm in length. Thickness of the coil stock is a limiting factory, and maximum thickness is approximately 4mm. [4]



Figure 2.- Typical Image of Stamped Heat Sink [5]

Typical shapes for larger stamped heat sinks are U-Shapes with lances to form fins. Cost estimates for progressive and secondary dies are $8000 - $16000 and $1500 respectively. In certain application the heat sinks are fabricated with solder tips so that they can be attached directly to the board. Some disadvantages related to stamped heat sinks are sheared edges, die marks, and surface roughness.

Die-Casting

In the die-casting method molten metal is forced under pressure into metal dies or molds to produce accurately dimensioned parts. It is considered the fastest of all casting processes and is often employed where rapidity and economy in production are essential. The large initial investment required is offset by low part cost and minimal secondary operations, allowing economic manufacture for large production volumes. The thermal conductivity of cast heat sinks may be worsened by porosity caused by gases evolving during solidification. High tooling cost associated with die-casting results in large capital investment [6].



Figure 3.- Typical Image of Die-Casted Heat Sink [7]

To address the demand of high heat dissipation they one combine the stamping and die casting process to achieve extremely dense array of fins in a heat sink. A modified die-casting process involves the extension of basic die-casting principles, whereby the base of the heat sink is die-cast around a fixtured array of extremely thin stamped fins. The fins are separated by spacers, which prevent the die-cast material from flowing into the fin-to-fin spacing. While it may be possible to manufacture heat sinks of different materials, aluminum is the most commonly used material for this technique.

The absence of a so-called interface between the fins and the base eliminates the impact of an interface resistance. This process allows much higher aspect ratios while fulfilling requirements of small inter-fin spacing.

Some of the other manufacturing process that is used to achieve dense fins for high heat dissipation is as follows [8]:

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Bonding

Bonded heat sinks are often built-up extrusions, typically manufactured by assembling extruded plates into slots on an extruded or machined heat sink base, and held in place by an interface, usually a two part thermosetting thermally conductive epoxy or a solder. The bonding agent does however represent a thermal barrier. These heat sinks are often costlier to manufacture, and the base typically requires special machining. Process limitations are usually related to the strength of the bonding agent and dimensional constraints for the slot in the heat sink base.



Figure 4.- Typical Image of a Bonded fin Heat Sink [9]

Hybrid heat sinks utilizing different materials for the fins and the base can be accommodated by this process. Bonded fin arrays are most commonly rectangular plate fin arrays.

Folding

Folded heat sinks are built-up sheet metal, manufactured by folding sheet metal into a serpentine fin array. The folded sheets of metal are attached to the base of the heat sink by soldering or brazing, which results in an additional thermal resistance at that interface. However, this contact resistance between the folded fins and the heat sink base is smaller than expected, due to the fact that the "bends" of folded fins are typically flattened while bonding or brazing, thus increasing the contact surface area.



Figure 5.- Typical Image of Folded Heat Sink [10]

Difficulty in achieving smaller fin pitches required to construct dense arrays is a common issue. Similar to the bonding process, this manufacturing method allows flexibility in designing hybrid heat sinks made up of a combination of different materials.

Forging

In forged heat sink, the fin arrays are formed by forcing raw material into a molding die by a punch, which usually weighs about 500 tons (453,592.4 Kg). Common problems in forging are the choking of material in the molding die cavity, which could lead to fins of uneven height. Secondary processes may include cutting the fins, machining the base, polishing, or etching. While hot forging is inherently easier, cold forging results in denser and stronger fins.

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Figure 6.- Typical Image of Forged Heat Sink [11]

Some of the attractive benefits of forging include high strength, superior surface finish, structural rigidity, close tolerance capabilities, continuity of shape, and high uniformity of material. Aluminum and magnesium alloys are easily forged, and an important economic advantage is a typically low rejection rate for the process.

Skiving

In the skiving process, fins are machined using special tooling, whereby precisely sliced layers from an extruded metal block are bent at the base of the slice to form slender curved fins. Since the fins and base is an integral unit, the interface resistance seen in folded and bonded heat sinks is not present. This process was originally developed to manufacture sparse natural convection arrays, but recent efforts have been focused towards achieving tighter fin spacing, necessary for forced convection cooling.

Aluminum 6063 is the preferred material on account of its superior machinability and strength, but copper arrays can also be made. The depth of cut determines the fin thickness and can be very low between 0.25 – 0.8mm, resulting in extremely thin fin structures, yielding light and competitive heat sink designs. The distance between fins can be shortened as much as 0.5mm and their height can reach 60mm thus the ratio of height thickness is around 150 times.

Some of the drawback of this process is if secondary machining is required, it creates a lot of variation and burrs during the process. Since the base is curved, usually there is a tolerance for the number of fins to be +/- 2 fins.



Figure 7.- Typical Image of Skived Heat Sink [12], [13]

Machining

Heat sinks are machined out of a metal block by material removal to create the inter-fin spaces. Most commonly they are manufactured by gang saw cutting on a computer numerical control (CNC) machine. The gang saw consists of multiple saw cutters on an arbor with precise spacing, which depends on the heat sink geometry to be machined. In some cases machining is done using end mills. The advantage of this process is that there is minimum lead time. Solid bar stock is readily available and parts can be made very quickly as compared to other process which requires a lot of tooling lead time. Often, during machining, the fins are damaged and distorted, and require extensive secondary operations. Material is also consumed in an unproductive manner by the generation of scrap metal.

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Figure 8.- Typical Image of Machined Heat Sink

Based on the type of application, the lead time, budged and thermal performance required different methods of manufacturing are used to produce heat sinks.

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EXHIBIT 7

DIRECTORY

Agriculture
Construction & Industrial
Marine
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Military & Government
Mining
Oil & Gas »
Cementing & Pumping
Coiled Tubing & Well Intervention
Compressed Air Systems
Data Acquisition & Control Centers
Engines
Fracturing & Well Stimulation »
Acidizing Units
Chemical Additive Units
Data Acquisition & Control Centers
Fracturing Blenders
Fracturing Pumps
Hydration Systems
Offshore Units
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Data Acquisition & Control Centers				
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Control Cabin Size L × W × H	33'0" × 8'6" × 13'6"	44'0" × 8'6" × 13'6"	26'0" × 8'0" × 7'8"	22'0" × 8'0" × 7'8"
Carrier Type	Stewart & Stevenson trailer	Stewart & Stevenson trailer	Kenworth, Mercedes Benz or other truck chassis	Kenworth, Mercedes Benz or other truck chassis
Carrier Drive Configuration	Tandem Air Ride	Tandem Air Ride	4×2, 4×4, 6×4, or 6×6	4×2, 4×4, 6×4, or 6×6
Maximum Number of Fracturing Unit Controls	24	24	24	24
Maximum Number of Blender Controls	2	2	2	2
Maximum Number of Chemical Additive/Hydration Controls	2	2	2	2
Number of Discrete Physical Data Channels	16-24	16-24	16-24	16-24
Number of Virtual Data Channels	500	500	500	500
Fracturing Pump Control System	IPC - PC	IPC - PC	IPC - PC	IPC - PC
Blender, Chemical Additive and Hydration Control System	AccuFrac - PC	AccuFrac - PC	AccuFrac - PC	AccuFrac - PC
Touchscreen IPC - PC Interfaces	3	3	3	3
Industrial Computers	3	3	3	3
ACCUFRAC® - PC and Modeling Software Screens	6	7	7	6
Printers	2	2	2	2
Generator System	20 kW stand alone diesel engine driven	20 kW stand alone diesel engine	20 kW chassis engine driven	10 kW stand alone diesel engine
Communication System	3-station internal intercom, 18 external radios	5-station internal intercom, 18 external radios	5-station internal intercom, 18 external radios	4-station internal intercom, 12 external radios

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EXHIBIT 8

US006330525B1

(12) **United States Patent**
Hays et al.

(10) **Patent No.: US 6,330,525 B1**
(45) **Date of Patent: Dec. 11, 2001**

(54) **METHOD AND APPARATUS FOR DIAGNOSING A PUMP SYSTEM**

(75) Inventors: **Coy L. Hays**, Tulsa, OK (US); **Gary A. Lenz**, Eden Prairie, MN (US)

(73) Assignee: **Innovation Management Group, Inc.**, Tulsa, OK (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/631,094**

(22) Filed: **Aug. 2, 2000**

Related U.S. Application Data

(62) Division of application No. 09/002,053, filed on Dec. 31, 1997.

(51) **Int. Cl.**[7] **G21C 17/00**

(52) **U.S. Cl.** **702/183**; 702/182; 376/245; 73/54.1

(58) **Field of Search** 702/183, 182; 376/245, 246, 247, 249; 73/54.01

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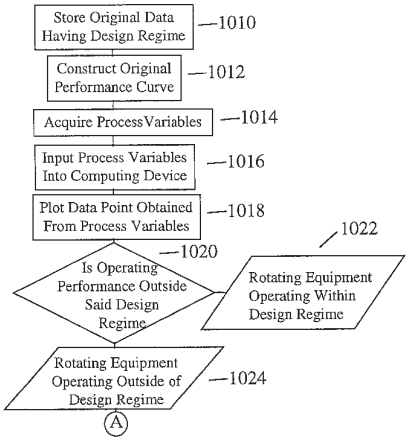
(List continued on next page.)

Primary Examiner—Kamini Shah
(74) *Attorney, Agent, or Firm*—Head, Johnson & Kachigian

(57) **ABSTRACT**

An apparatus and method for diagnosing rotating equipment commonly used in the factory and process control industry are provided. The apparatus and method are intended for use in assisting a maintenance engineer in the diagnosis of turbines, compressors, fans, blowers and pumps. The preferred embodiments are an apparatus and method for diagnosing pumps, with a focus on centrifugal pumps. The apparatus and method are based on the comparison of the current pump signature curves resulting from the acquisition of process variables from sensors monitoring the current condition of the pump and the original or previous pump performance curve from prior monitoring or knowledge of the pump geometry, installation effects and properties of the pumped process liquid. The diagnostic apparatus and method can be applied to any rotating machine, but the apparatus and method for pumps are described herein.

34 Claims, 51 Drawing Sheets



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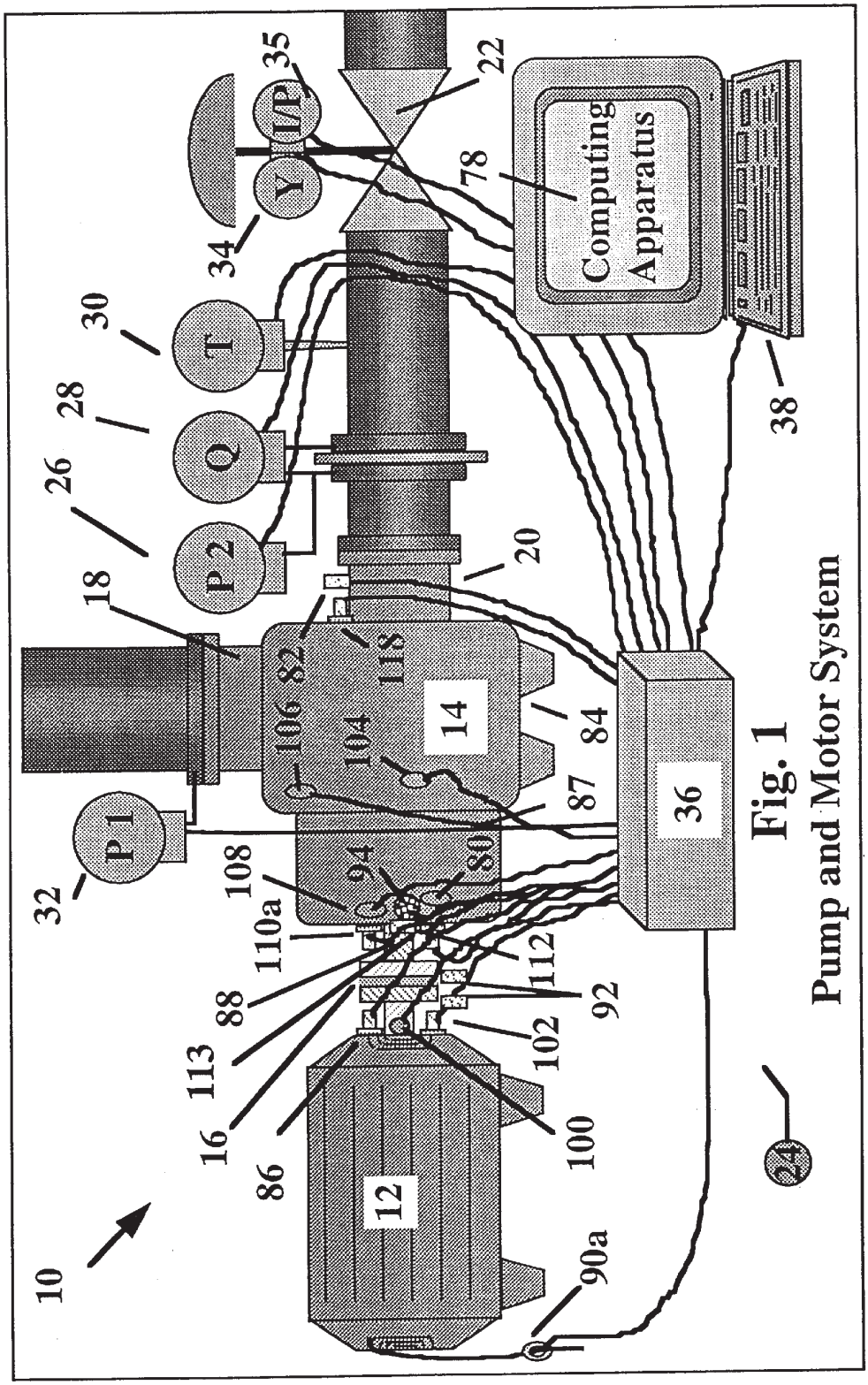


Fig. 1
Pump and Motor System

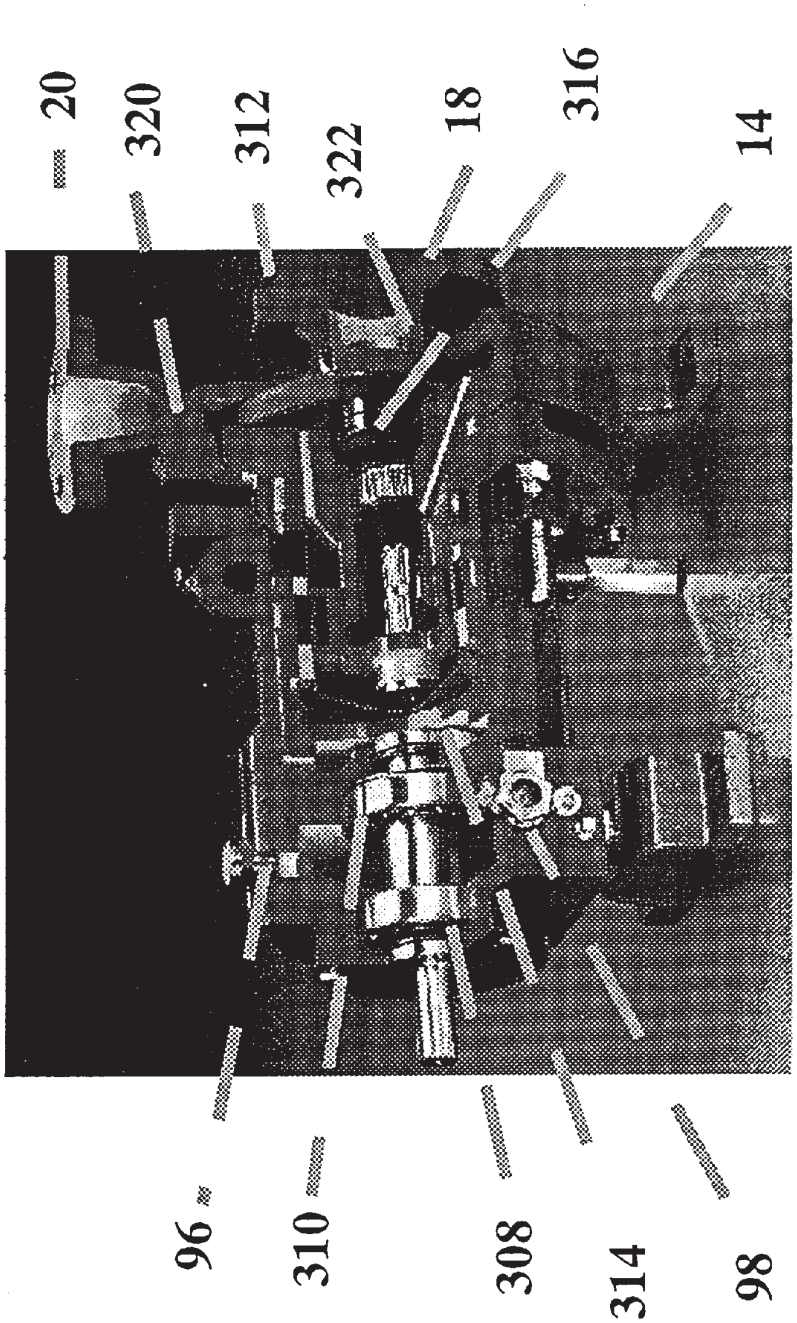


Figure 1b. Pump Cross Section

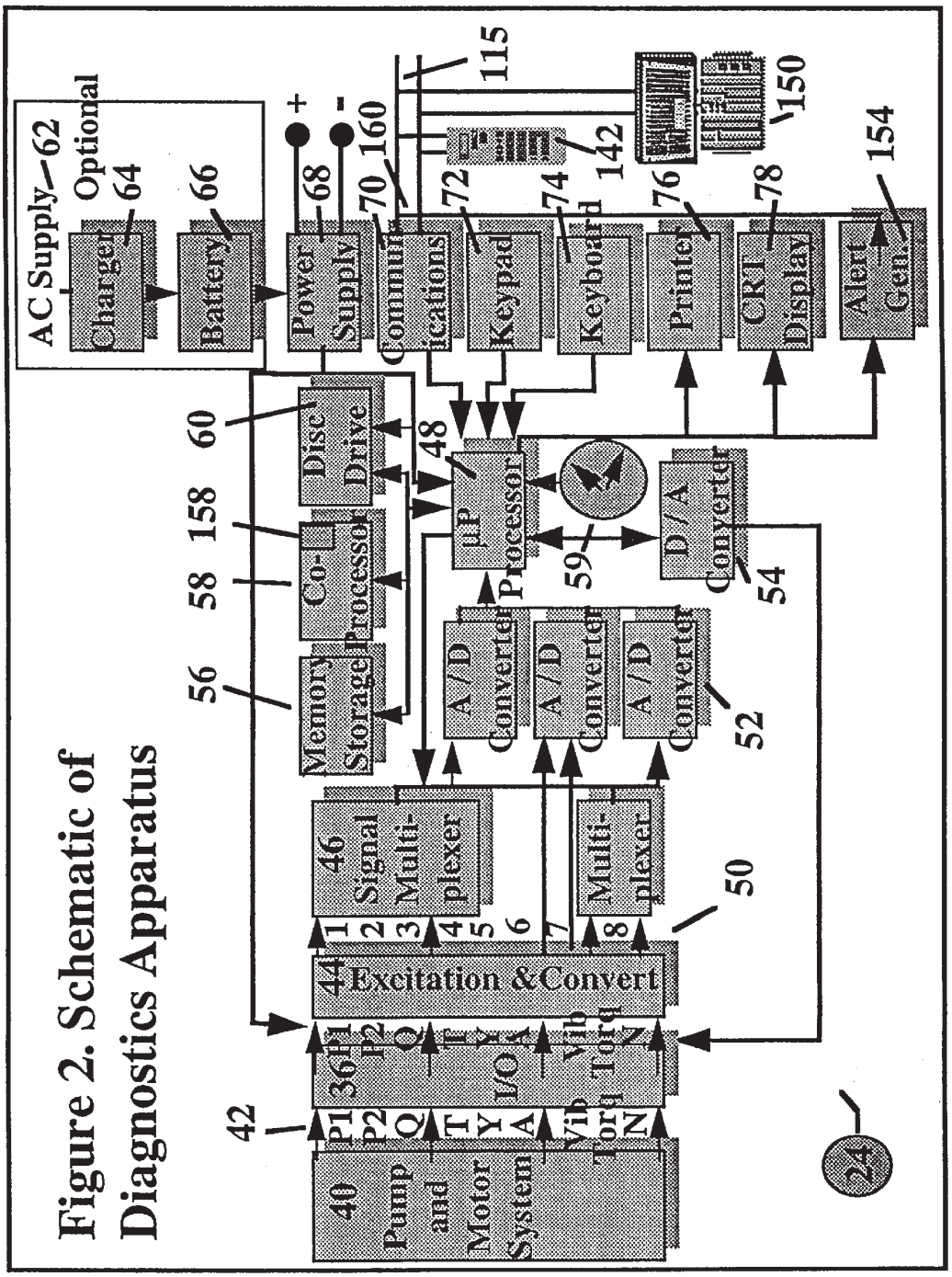


Figure 2. Schematic of Diagnostics Apparatus

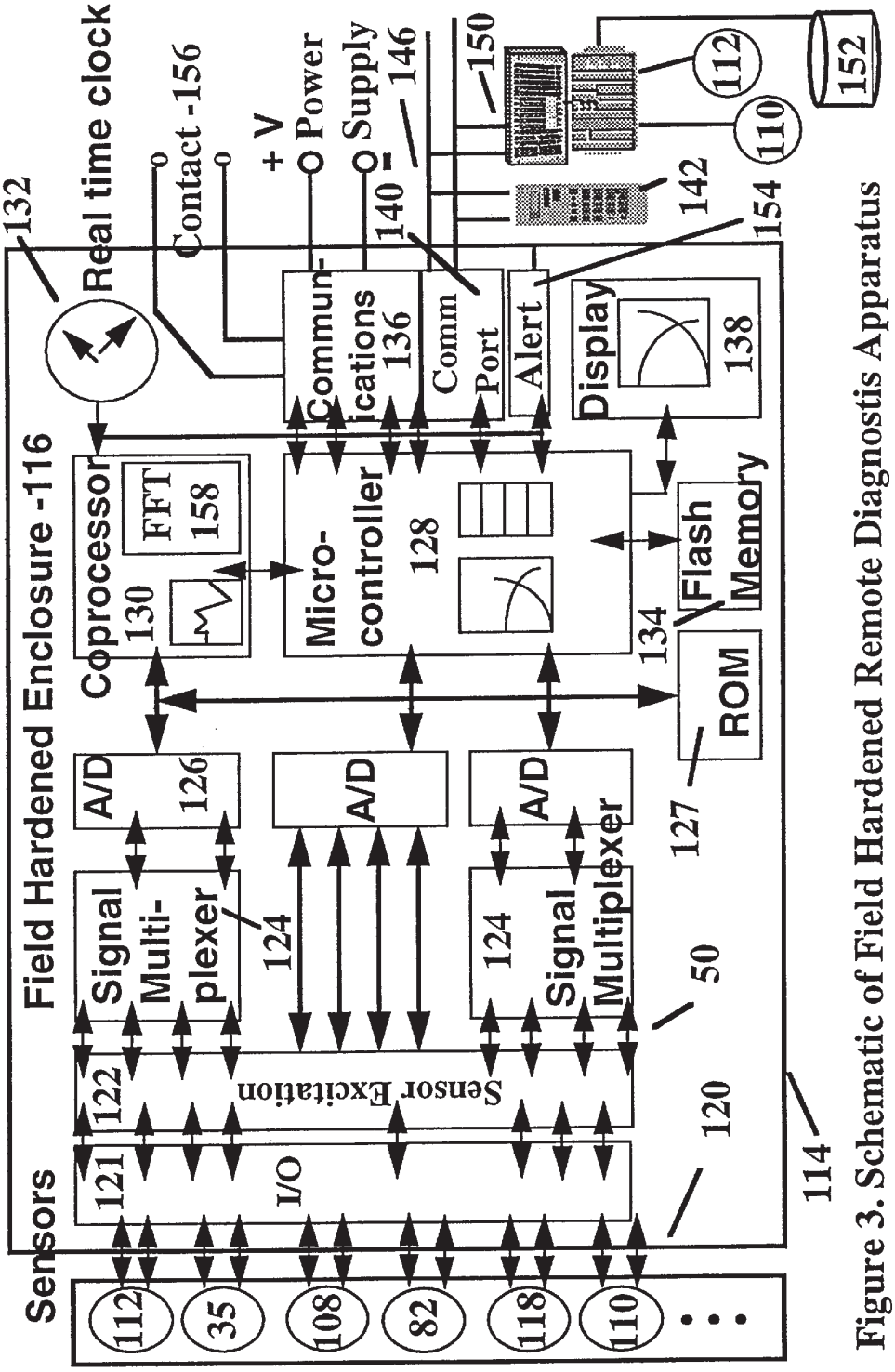


Figure 3. Schematic of Field Hardened Remote Diagnostis Apparatus

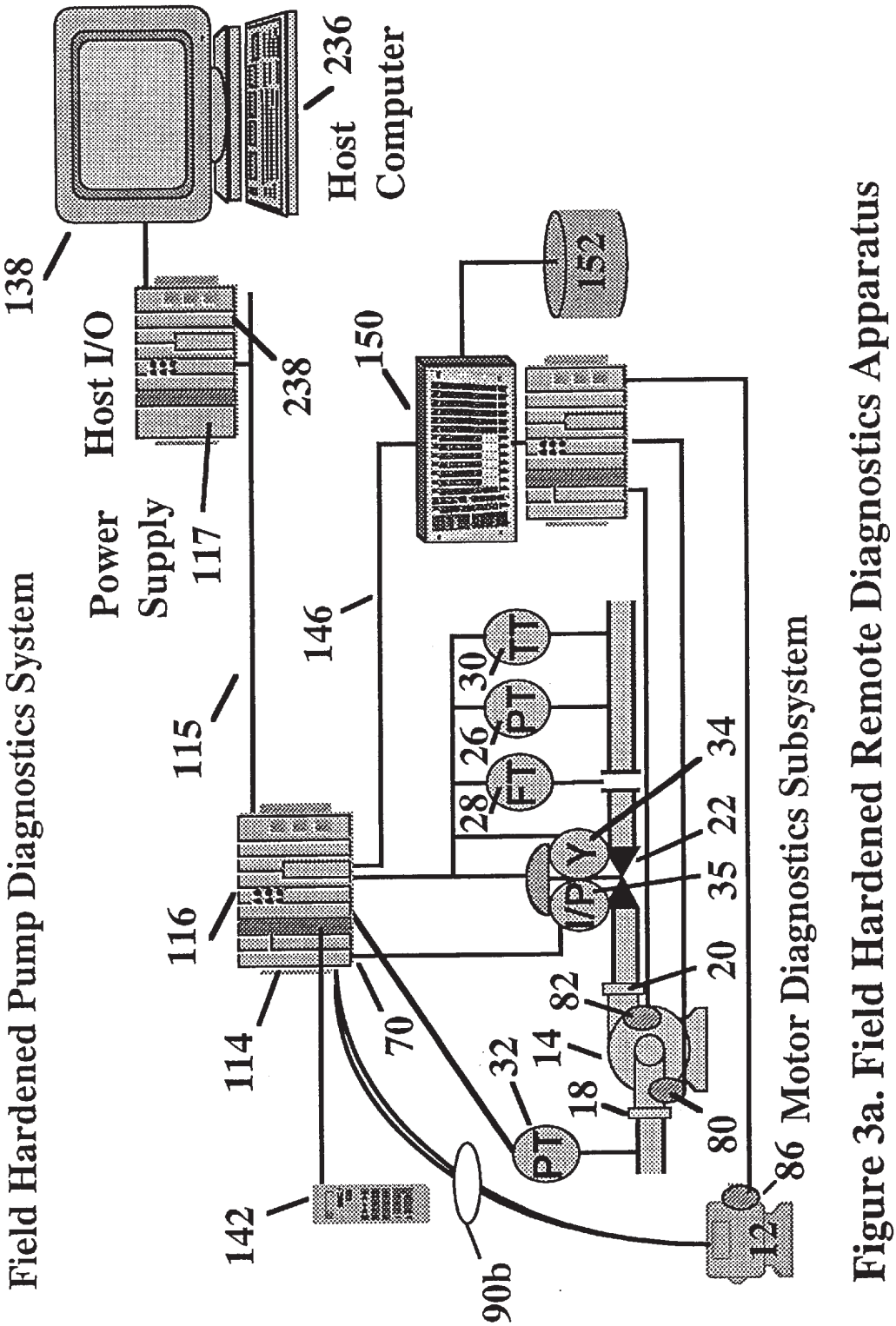


Figure 3a. Field Hardened Remote Diagnostics Apparatus

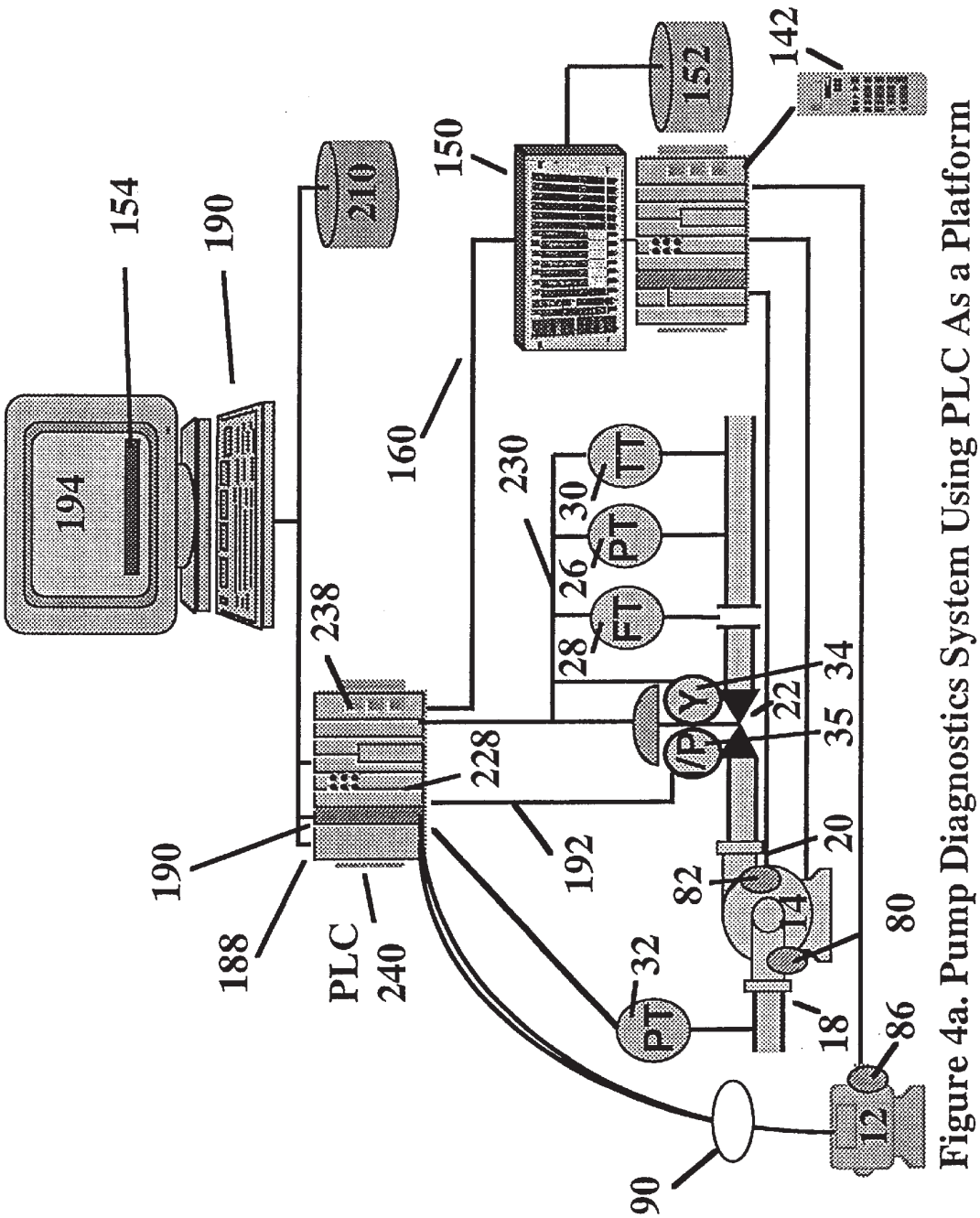


Figure 4a. Pump Diagnostics System Using PLC As a Platform

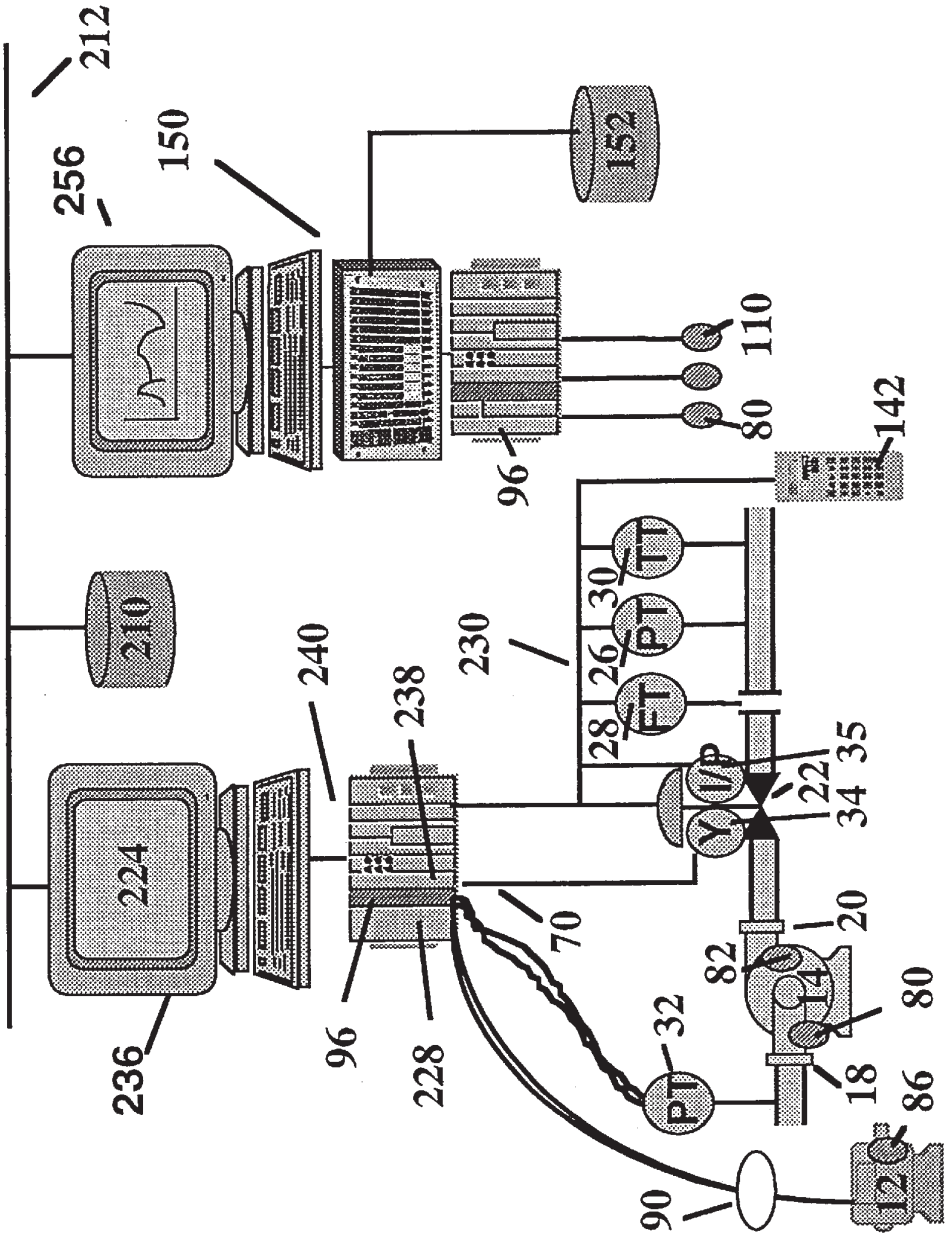
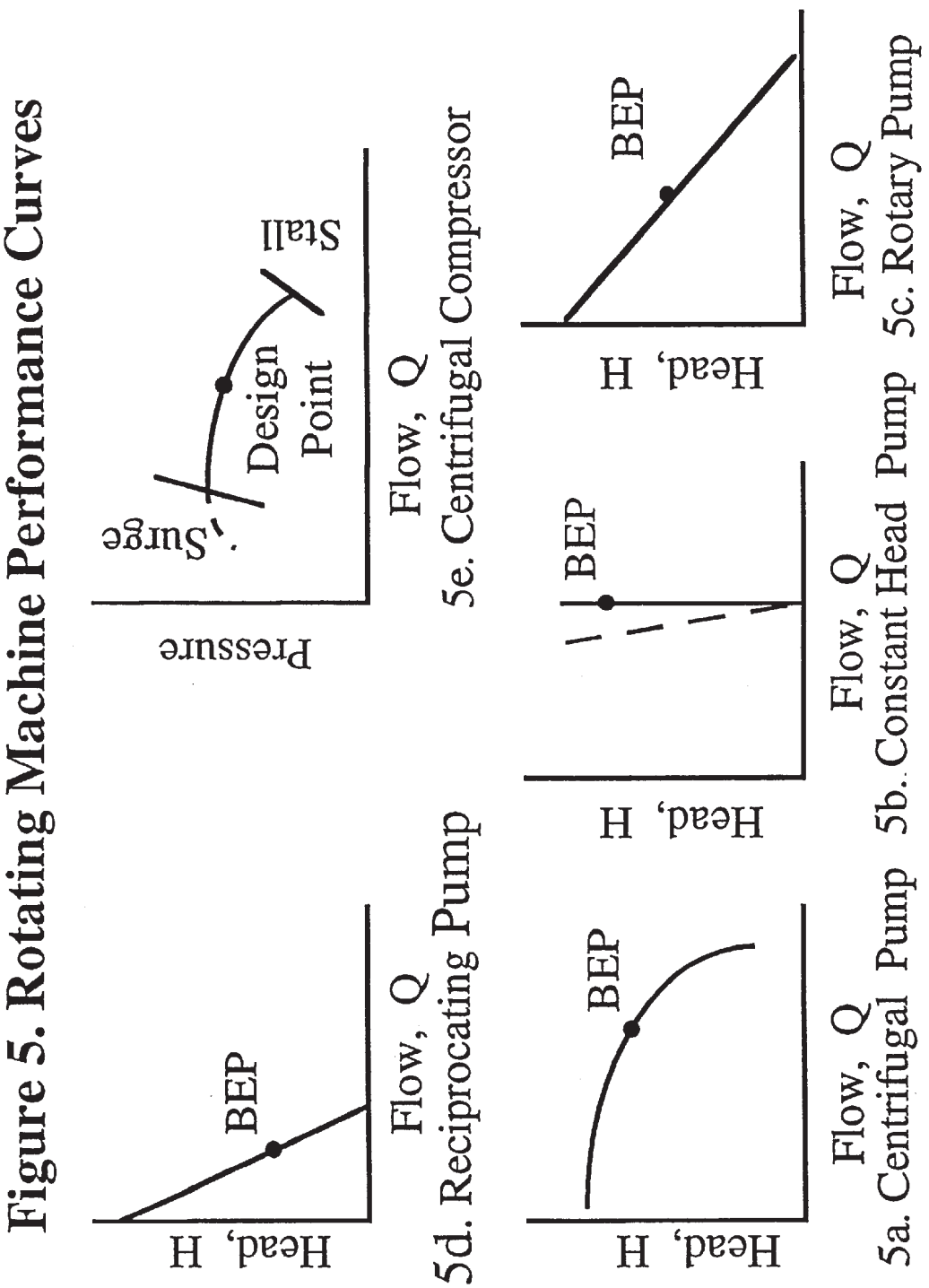


Figure 4b. Pump Diagnostics System Using Host Computer Platform


Figure 5. Rotating Machine Performance Curves
Head, H
BEP
Flow, Q
5a. Centrifugal Pump
Head, H
BEP
Flow, Q
5b. Constant Head Pump
Head, H
BEP
Flow, Q
5c. Rotary Pump
Head, H
BEP
Flow, Q
5d. Reciprocating Pump
Pressure
Surge
Design Point
Stall
Flow, Q
5e. Centrifugal Compressor

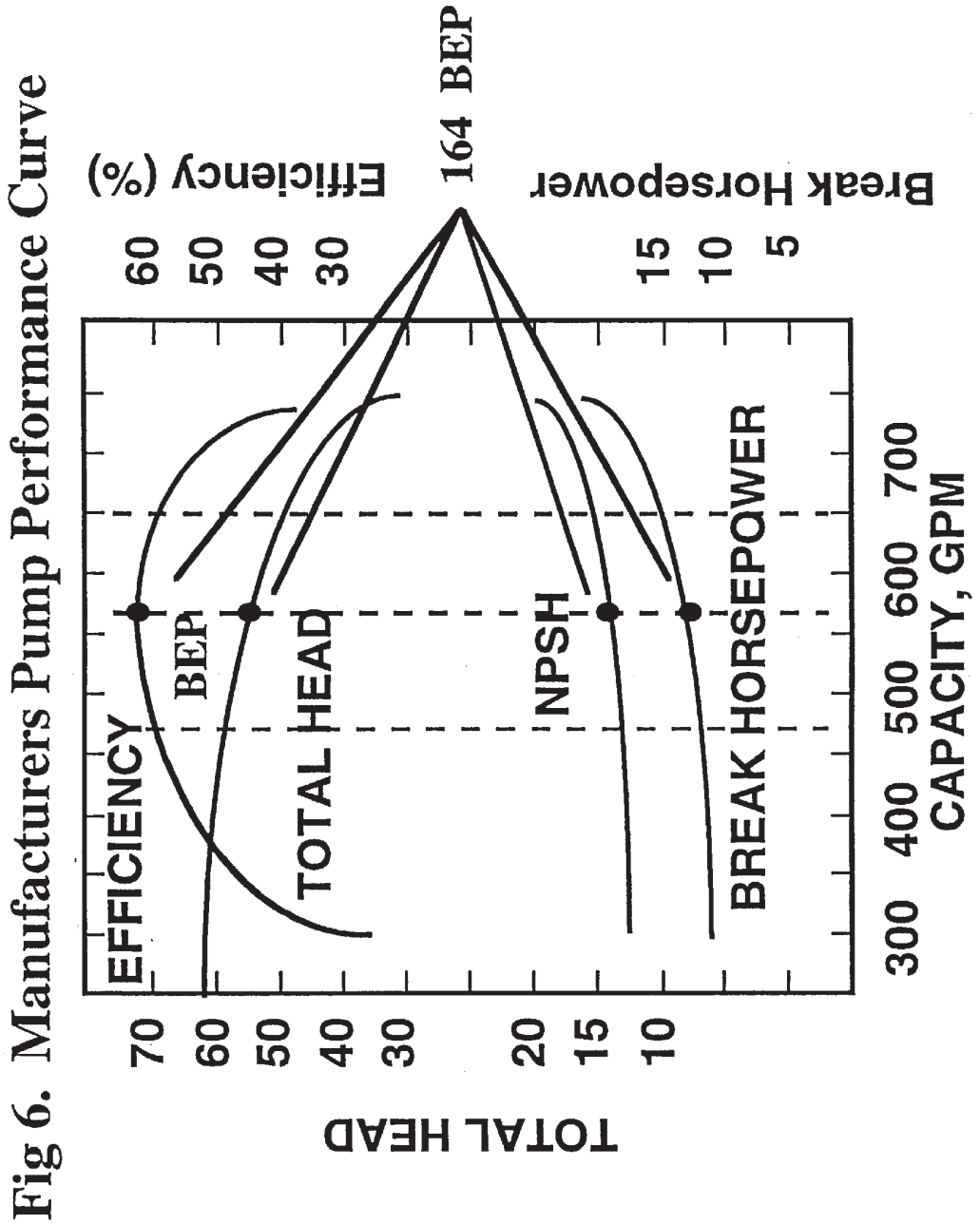
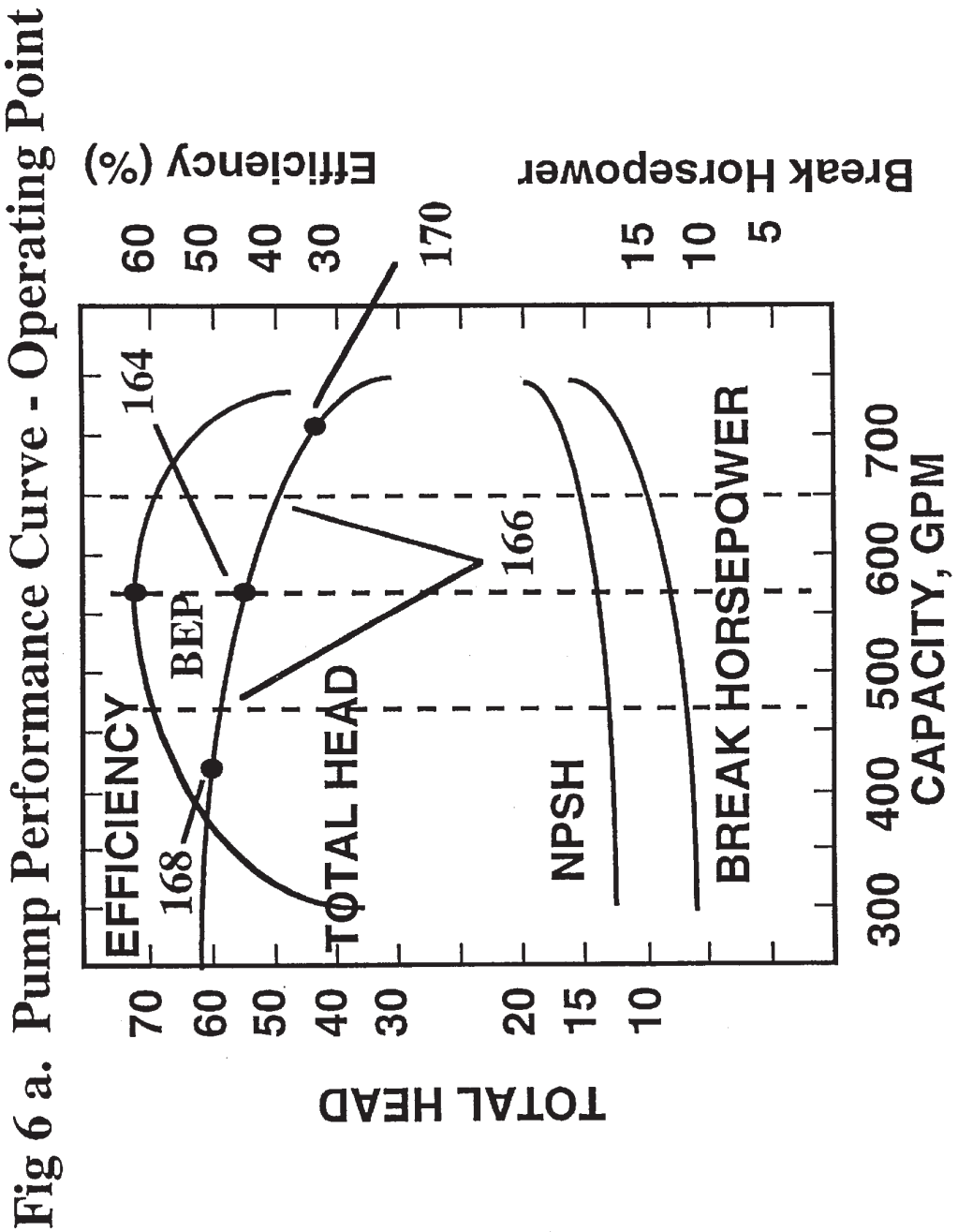
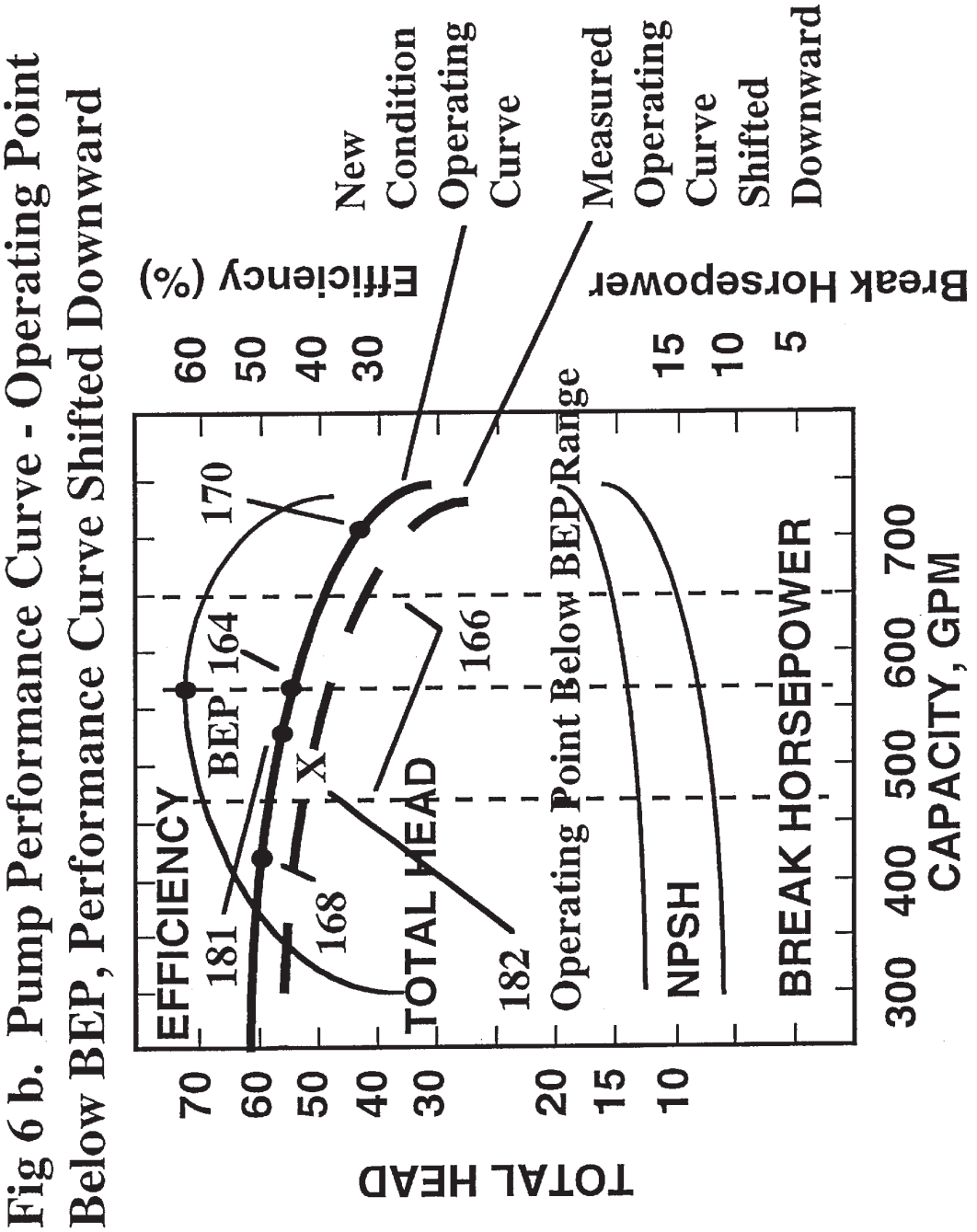


Fig 6. Manufacturers Pump Performance Curve


Fig 6 a. Pump Performance Curve - Operating Point
Efficiency (%)
Break Horsepower
60
50
40
30
170
15
10
5
164
166
168
EFFICIENCY
BEP
TOTAL HEAD
NPSH
BREAK HORSEPOWER
70
60
50
40
30
20
15
10
300
400
500
600
700
CAPACITY, GPM
TOTAL HEAD


Fig 6 b. Pump Performance Curve - Operating Point Below BEP, Performance Curve Shifted Downward
New Condition Operating Curve
Measured Operating Curve Shifted Downward
Efficiency (%)
Break Horsepower
TOTAL HEAD
EFFICIENCY
BEP
X
TOTAL HEAD
NPSH
BREAK HORSEPOWER
Operating Point Below BEP Range
CAPACITY, GPM
181
170
164
168
166
182

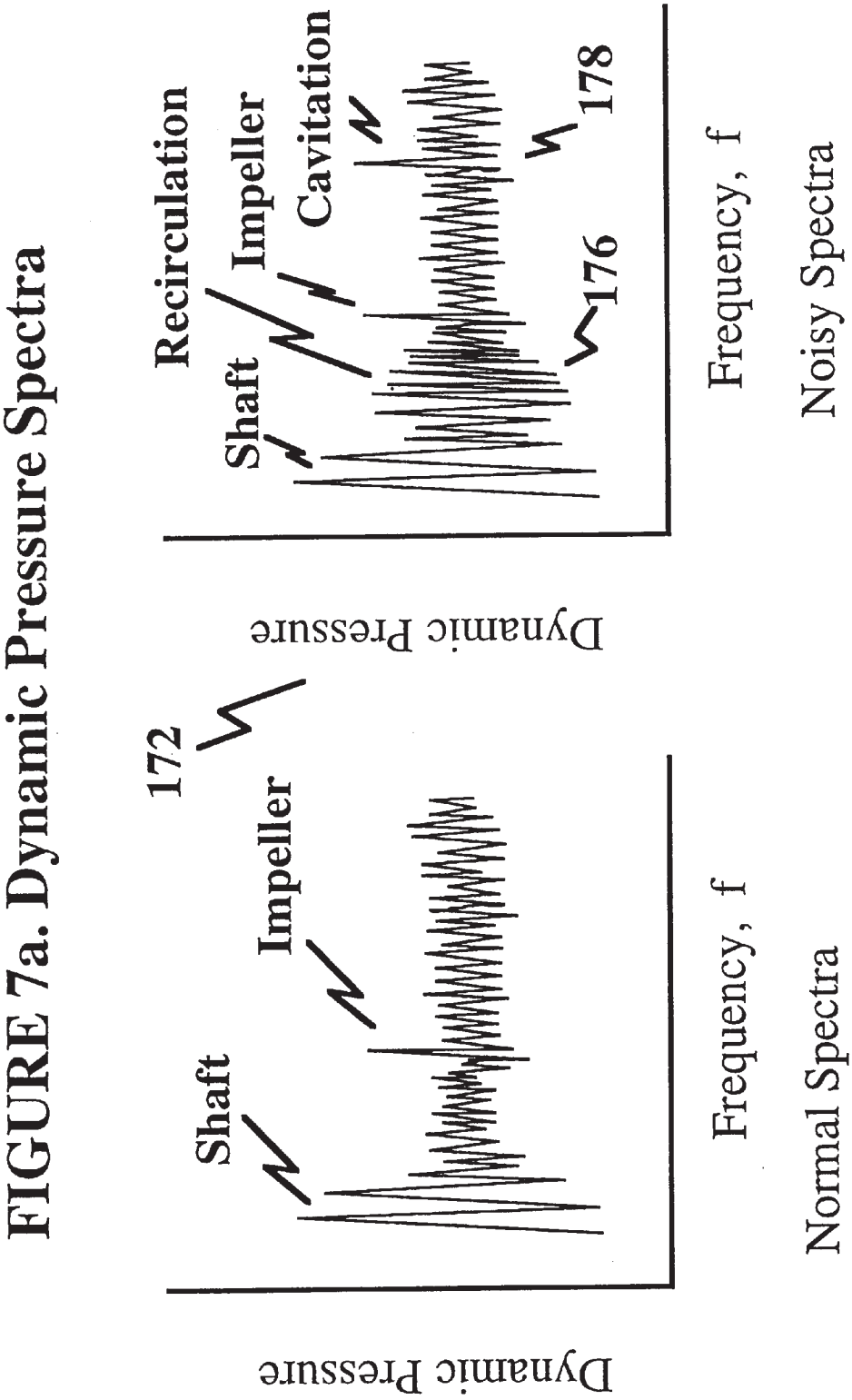


FIGURE 7a. Dynamic Pressure Spectra

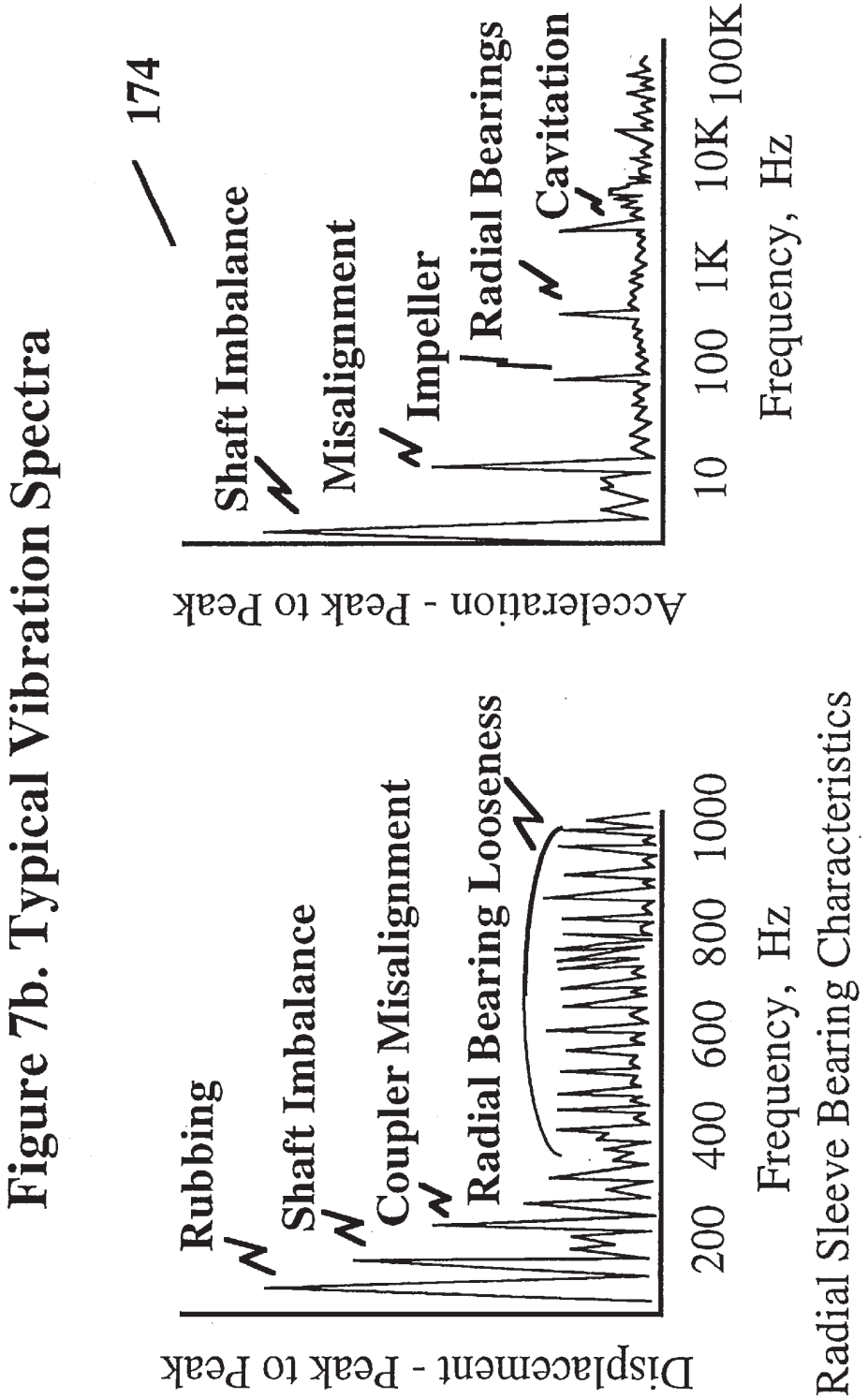
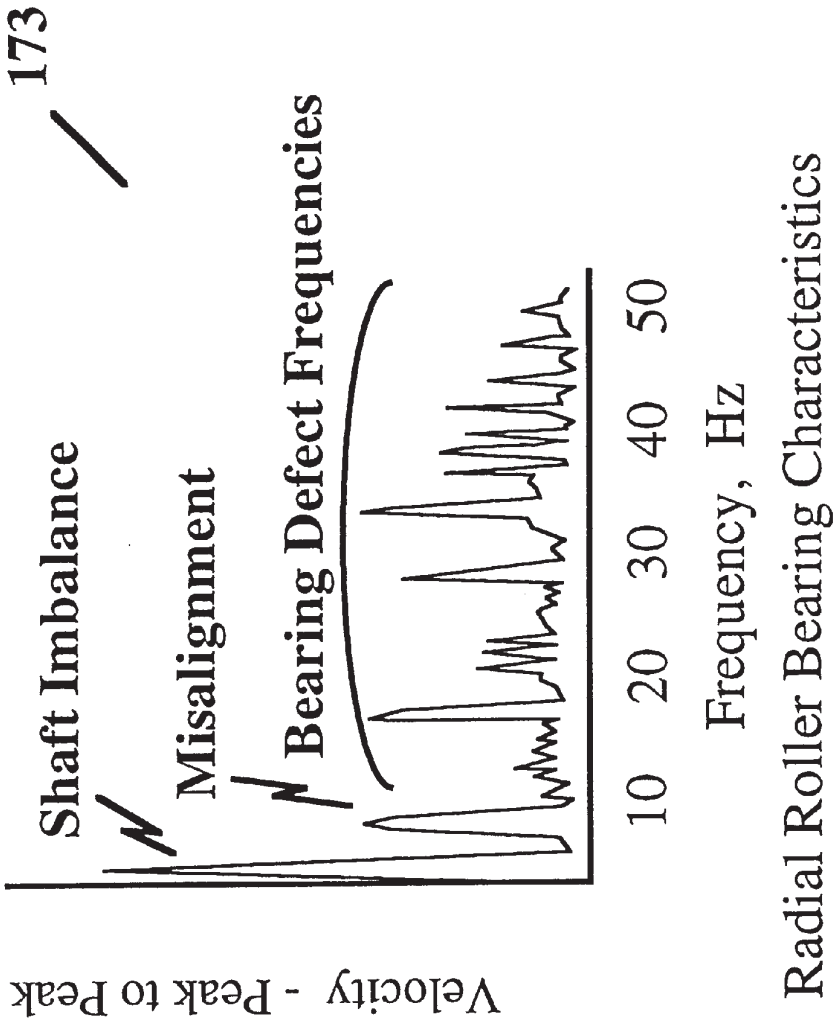

Figure 7b. Typical Vibration Spectra
174
Shaft Imbalance
Misalignment
Impeller
Radial Bearings
Cavitation
Acceleration - Peak to Peak
10 100 1K 10K 100K
Frequency, Hz
Rubbing
Shaft Imbalance
Coupler Misalignment
Radial Bearing Looseness
Displacement - Peak to Peak
200 400 600 800 1000
Frequency, Hz
Radial Sleeve Bearing Characteristics

Figure 7b. contd. Typical Vibration Spectra



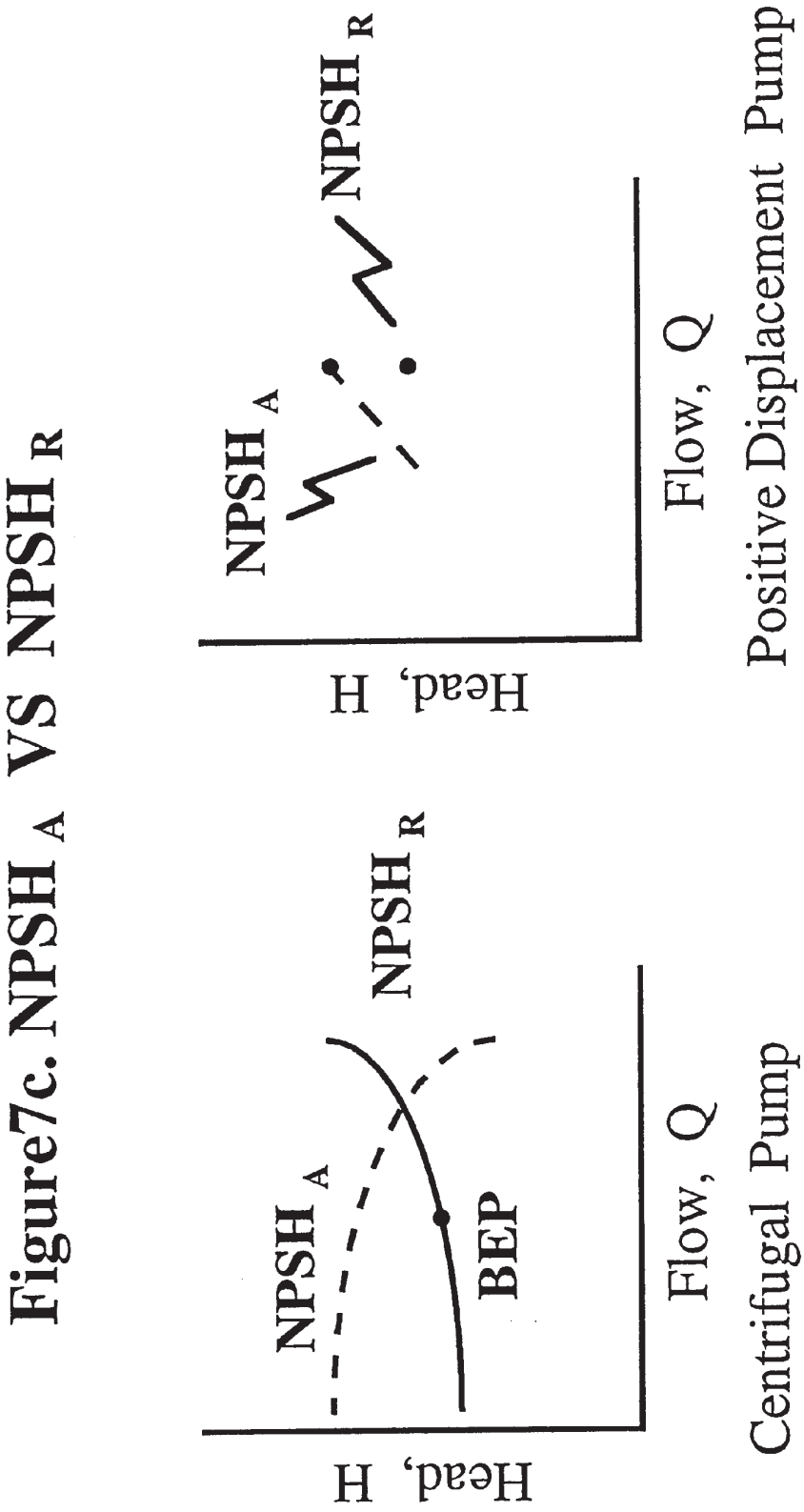
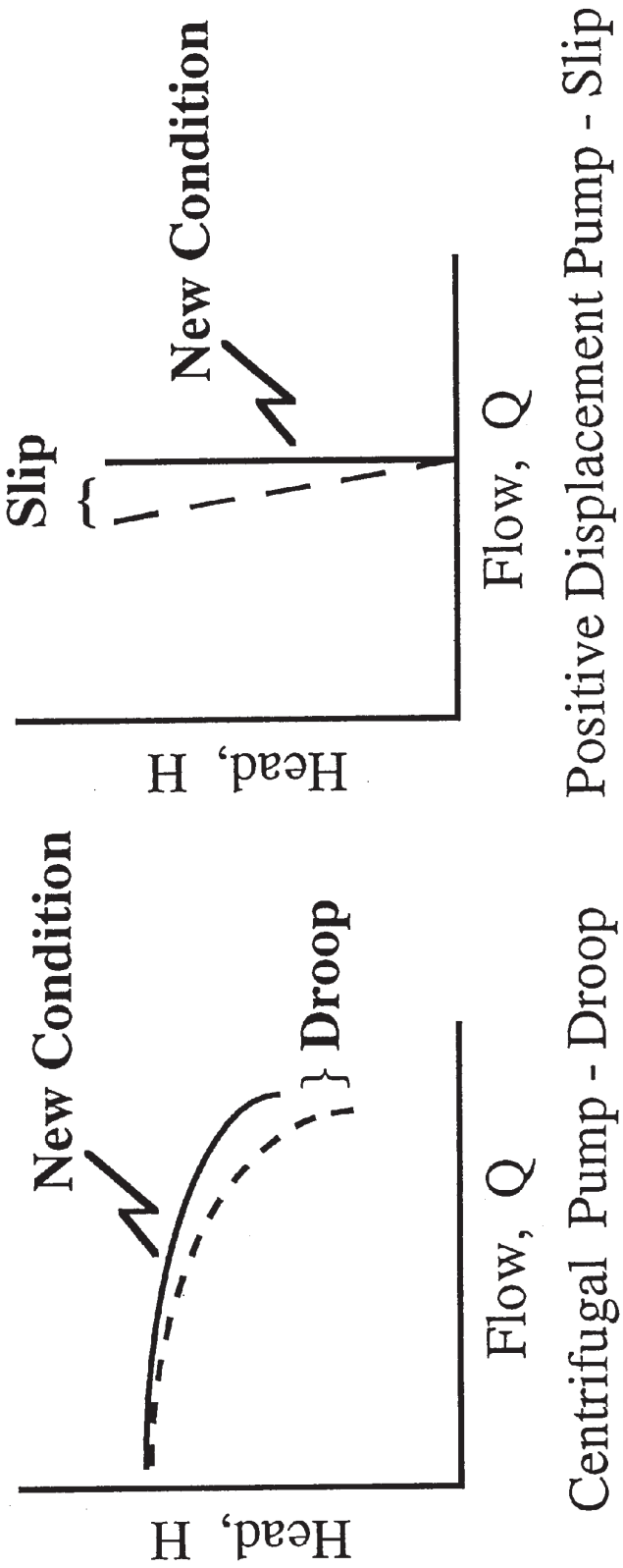

Figure7c. NPSH A VS NPSH R
Positive Displacement Pump
Centrifugal Pump
Head, H
Flow, Q
NPSH A
NPSH R
BEP

Figure7d. Performance Curves - Droop & Slip



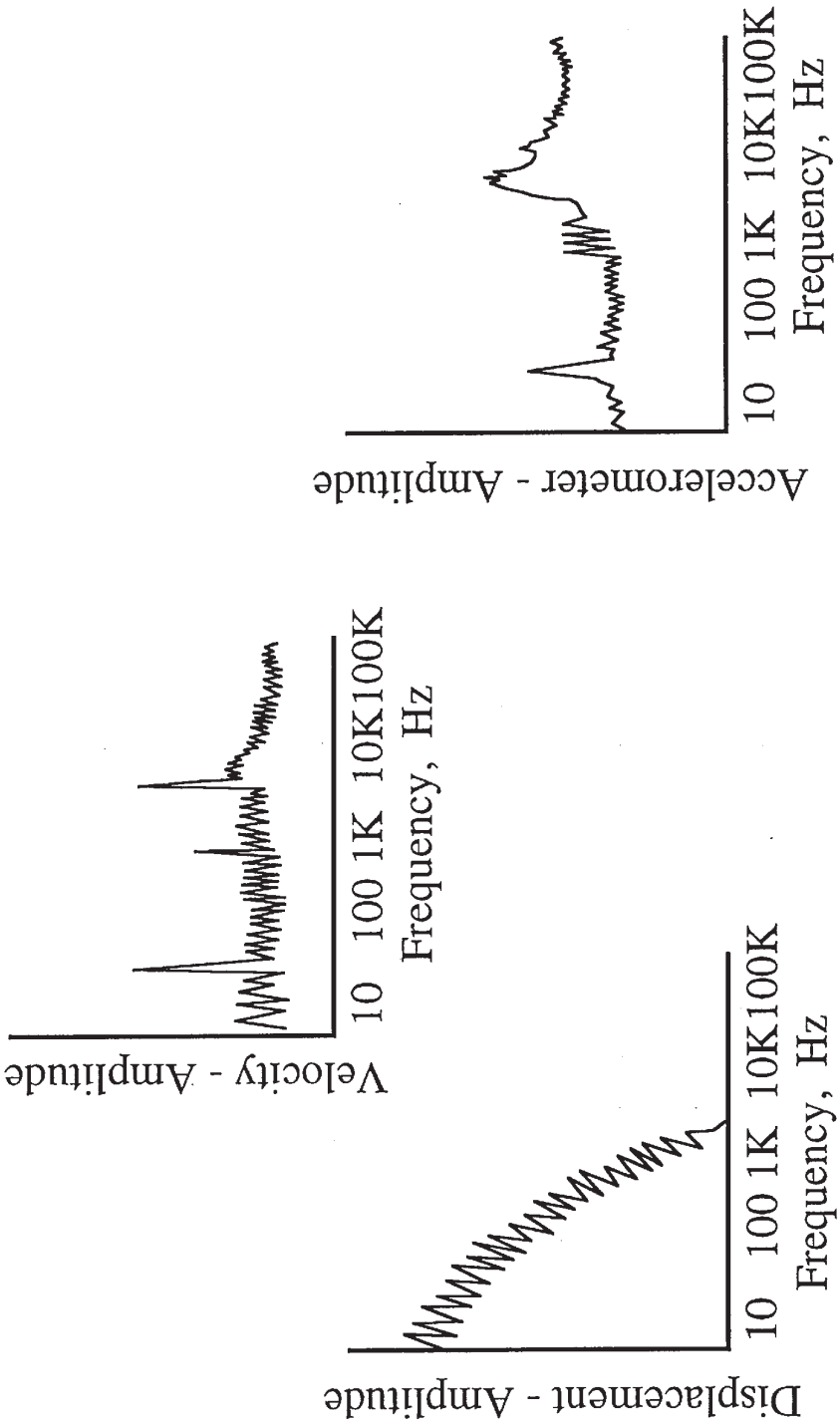
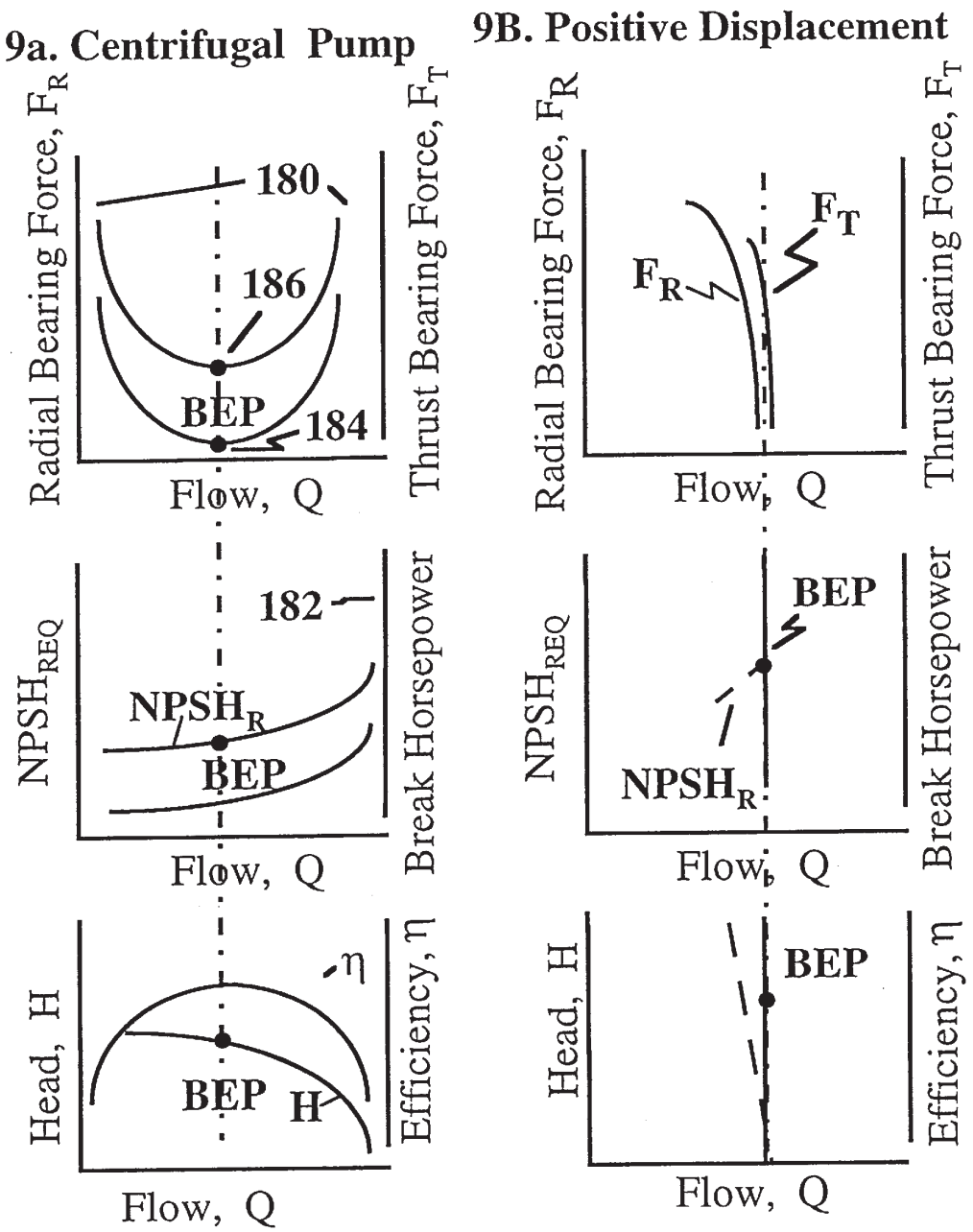


Fig 8. Spectra of Same Vibration Source Obtained with Diffierent Types of Transducers

Figure 9. Pump Secondary Performance Curves



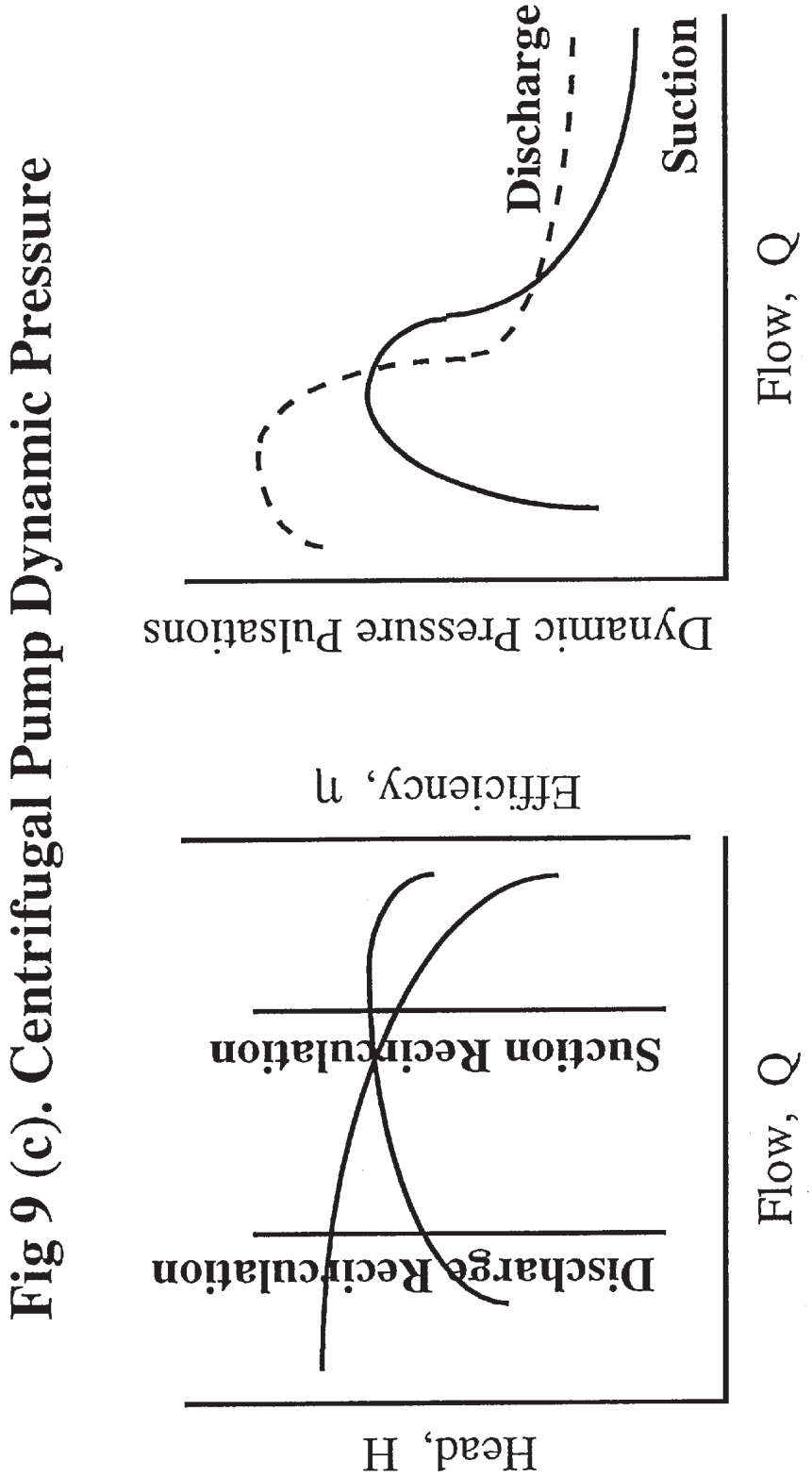


Fig 9 (c). Centrifugal Pump Dynamic Pressure

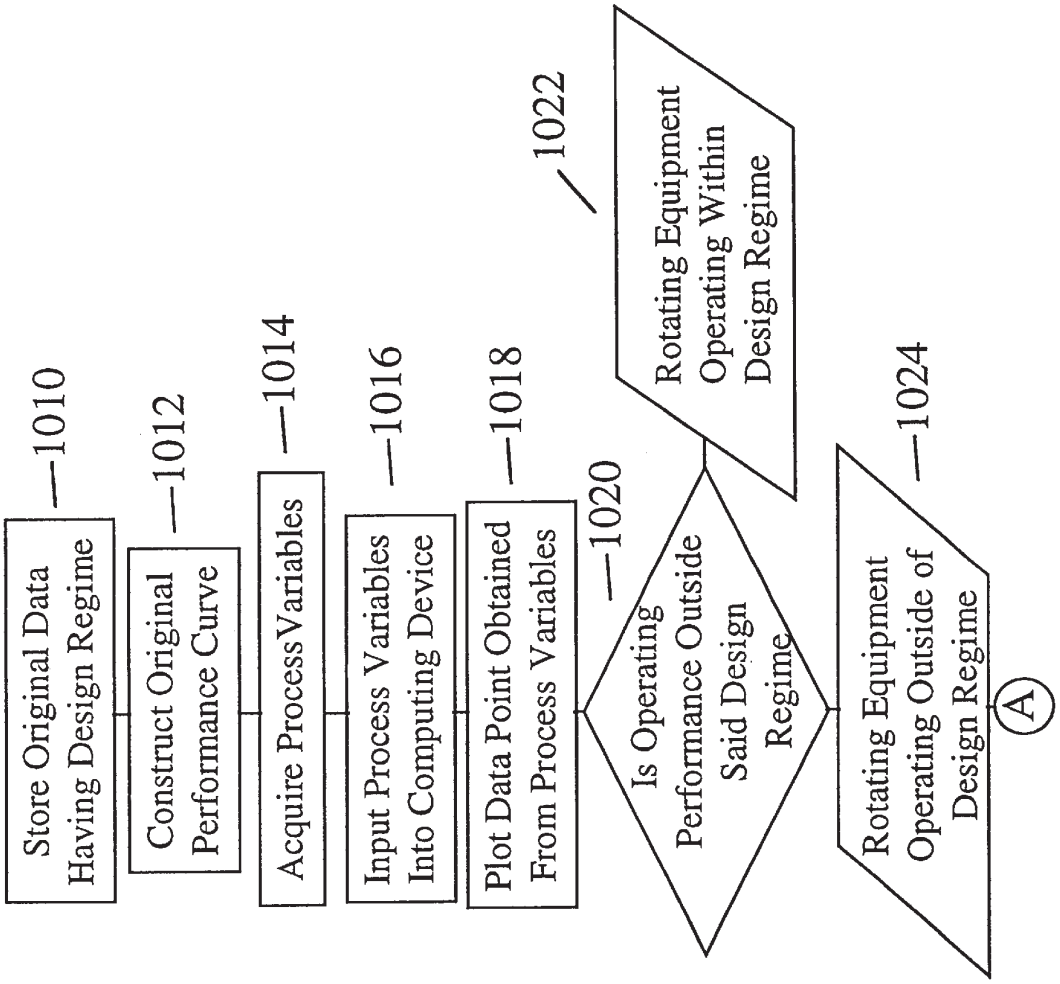

Store Original Data Having Design Regime
1010
Construct Original Performance Curve
1012
Acquire Process Variables
1014
Input Process Variables Into Computing Device
1016
Plot Data Point Obtained From Process Variables
1018
Is Operating Performance Outside Said Design Regime
1020
Rotating Equipment Operating Within Design Regime
1022
Rotating Equipment Operating Outside of Design Regime
1024
A

FIGURE 10

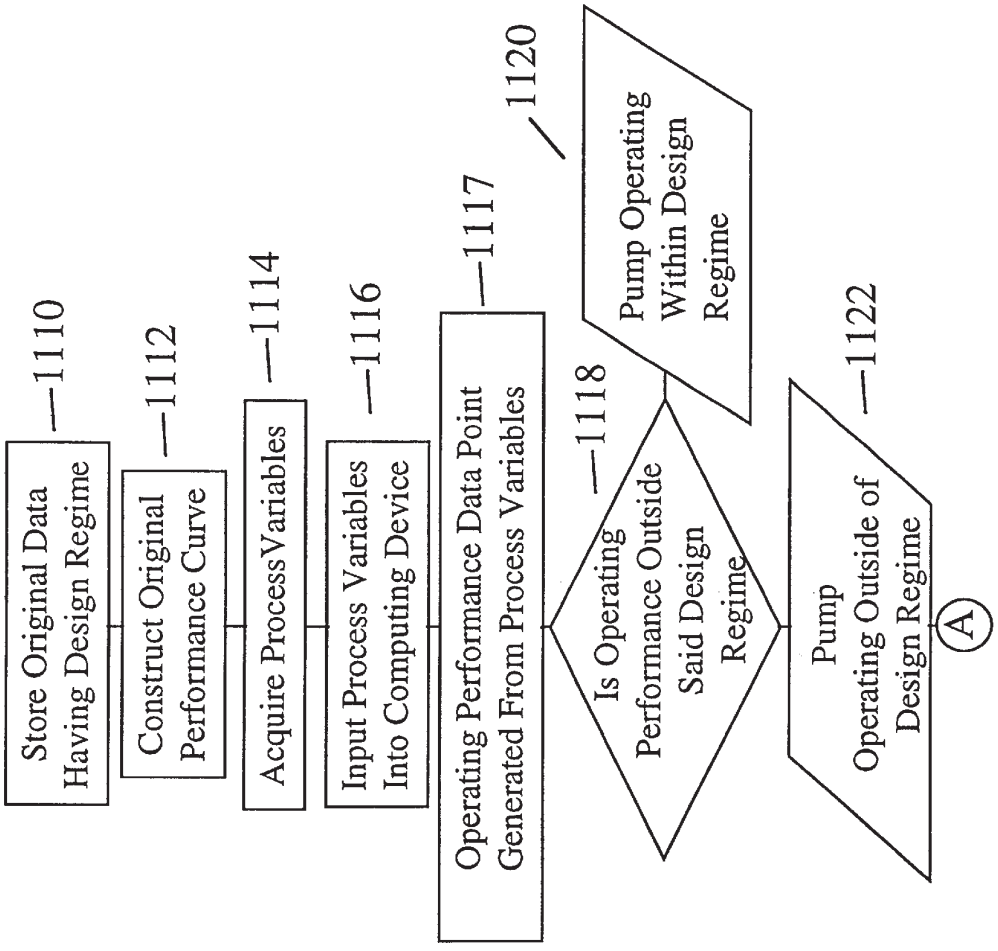

Store Original Data Having Design Regime
1110
Construct Original Performance Curve
1112
Acquire Process Variables
1114
Input Process Variables Into Computing Device
1116
Operating Performance Data Point Generated From Process Variables
1117
Is Operating Performance Outside Said Design Regime
1118
Pump Operating Within Design Regime
1120
Pump Operating Outside of Design Regime
1122
A

FIGURE 11

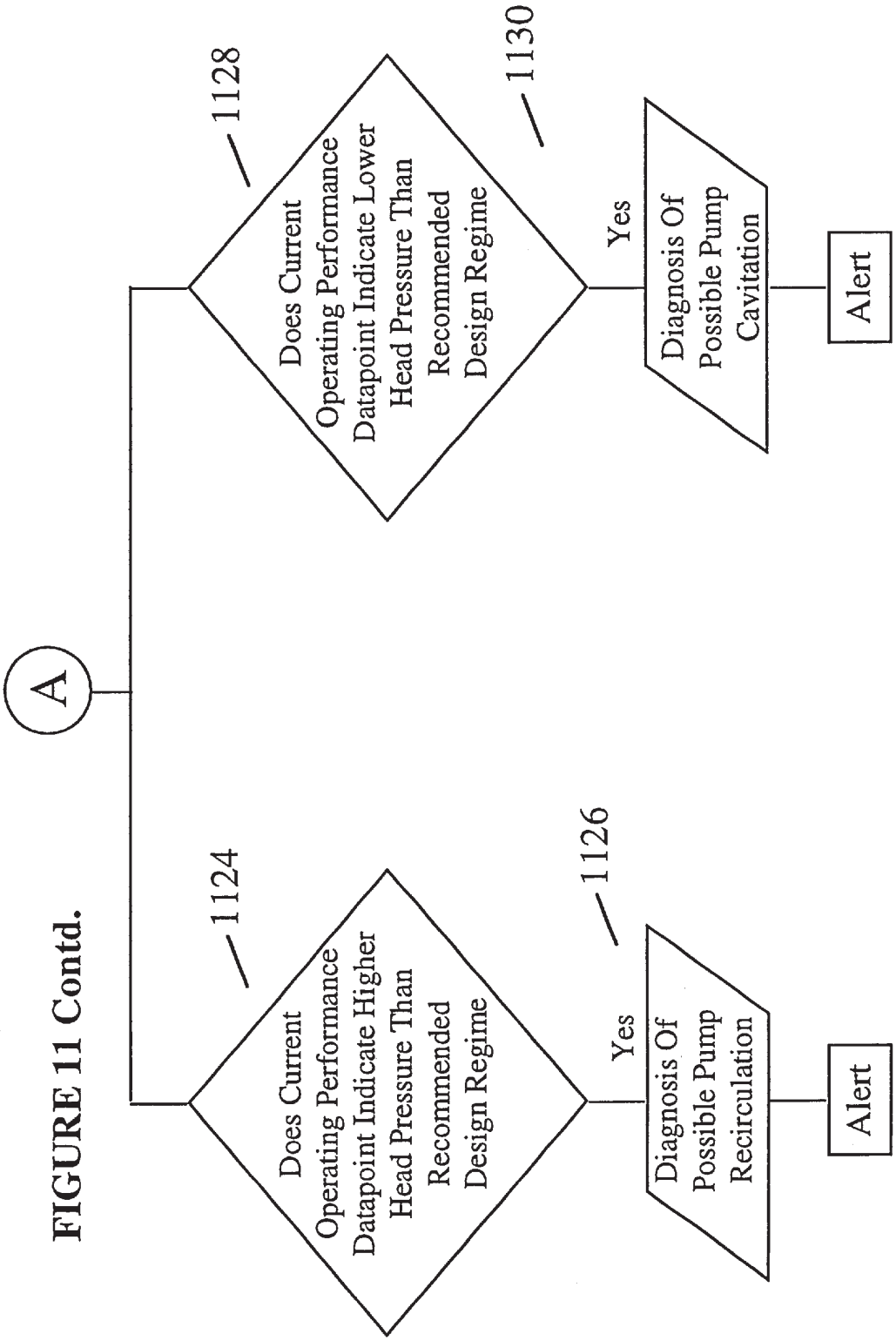


FIGURE 11 Contd.

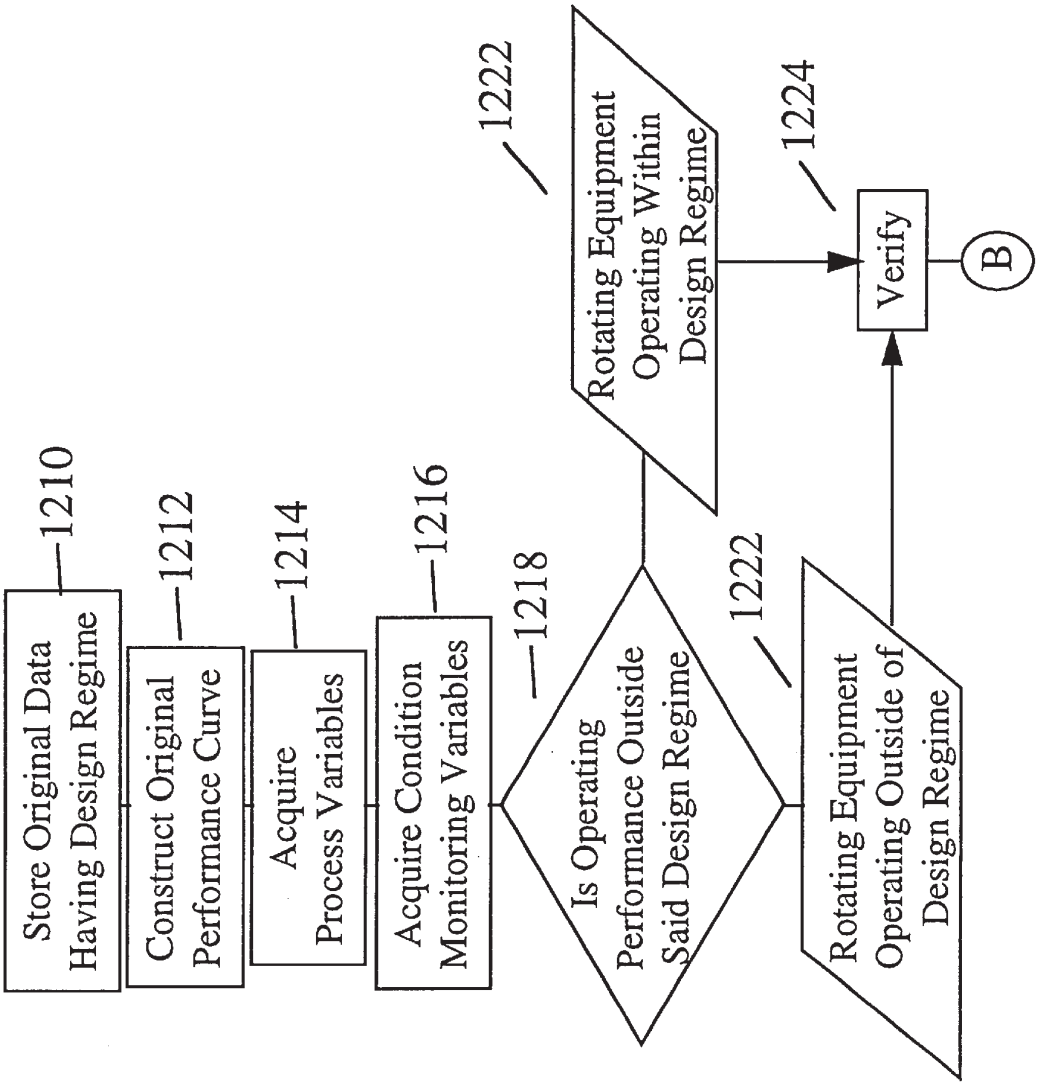

Store Original Data Having Design Regime
1210
Construct Original Performance Curve
1212
Acquire Process Variables
1214
Acquire Condition Monitoring Variables
1216
Is Operating Performance Outside Said Design Regime
1218
1222
Rotating Equipment Operating Within Design Regime
1222
Rotating Equipment Operating Outside of Design Regime
1224
Verify
B

FIGURE 12

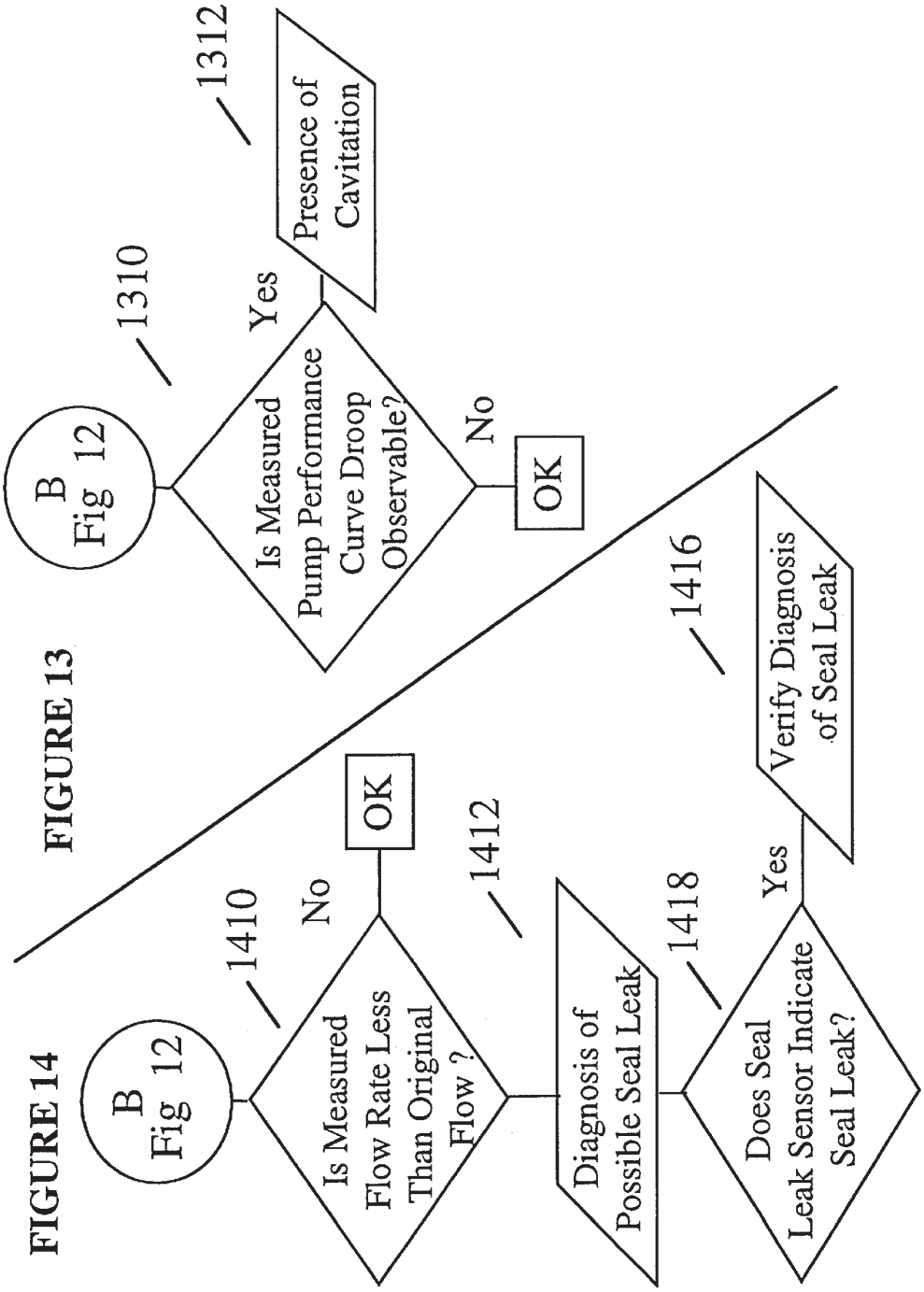


FIGURE 13

FIGURE 14

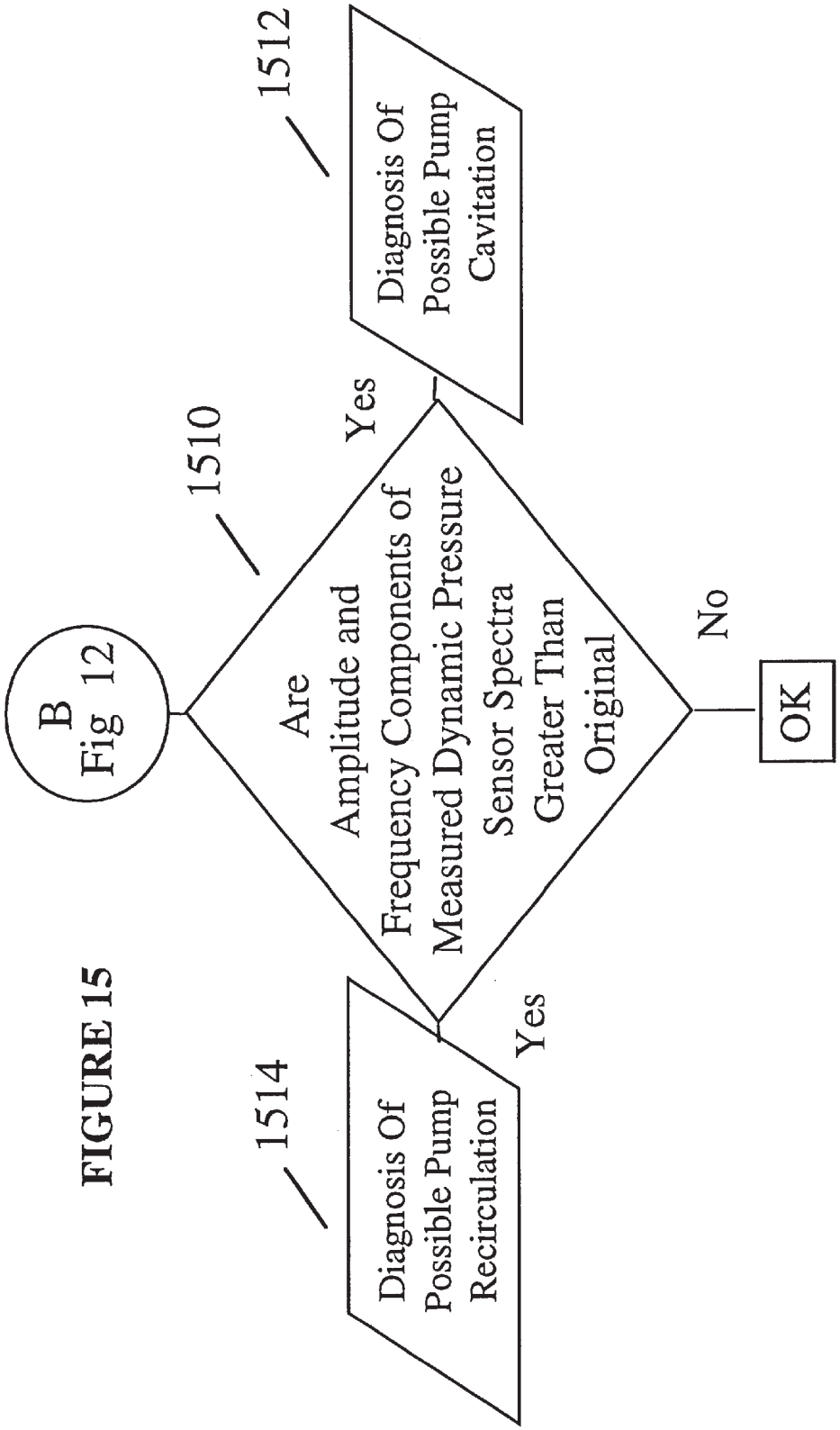
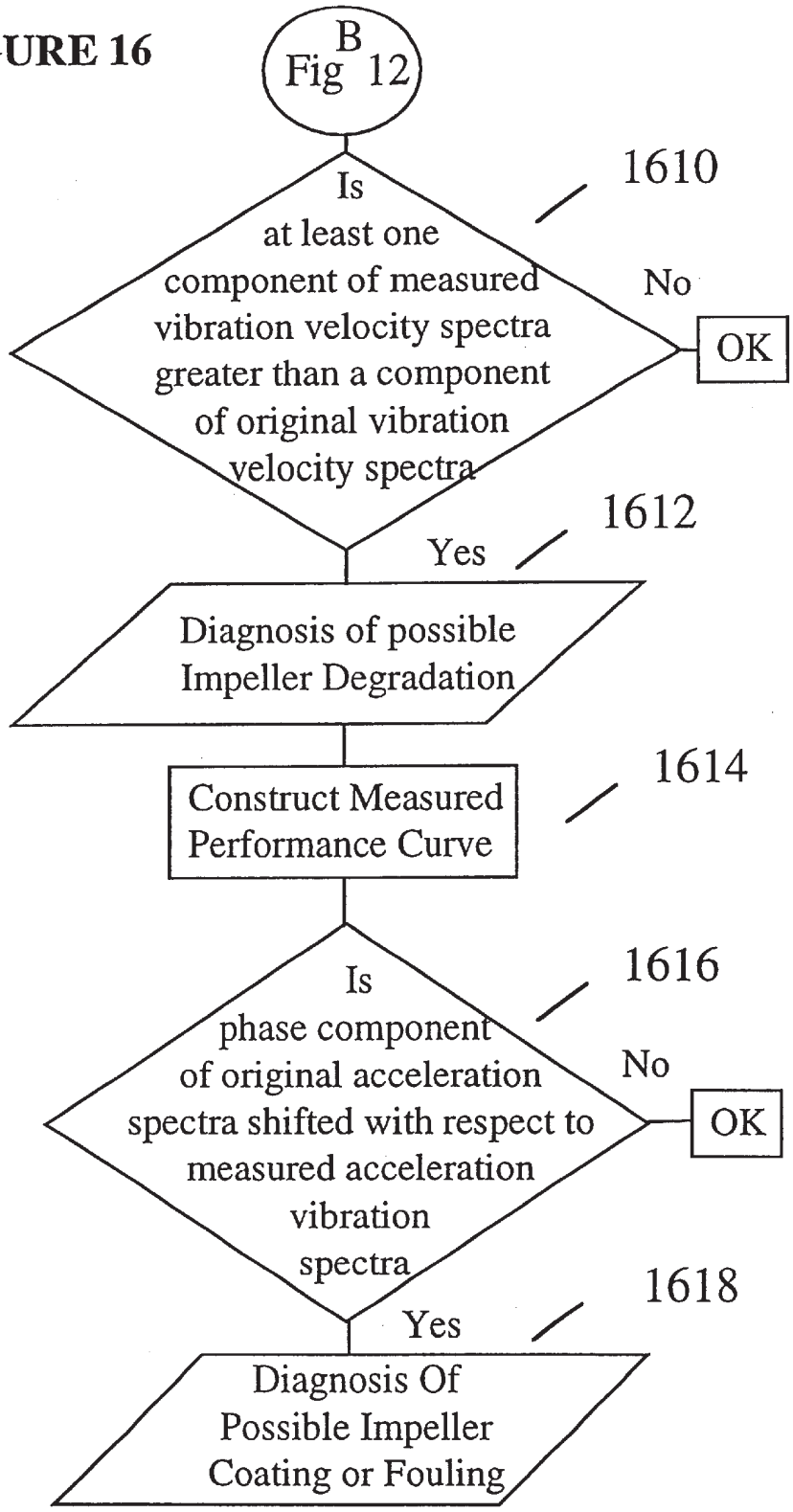

B
Fig 12
1510
Are Amplitude and Frequency Components of Measured Dynamic Pressure Sensor Spectra Greater Than Original
Yes
No
OK
1512
Diagnosis Of Possible Pump Cavitation
Yes
1514
Diagnosis Of Possible Pump Recirculation

FIGURE 15

FIGURE 16


B
Fig 12
1610
Is at least one component of measured vibration velocity spectra greater than a component of original vibration velocity spectra
No
OK
Yes
1612
Diagnosis of possible Impeller Degradation
Construct Measured Performance Curve
1614
1616
Is phase component of original acceleration spectra shifted with respect to measured acceleration vibration spectra
No
OK
Yes
1618
Diagnosis Of Possible Impeller Coating or Fouling

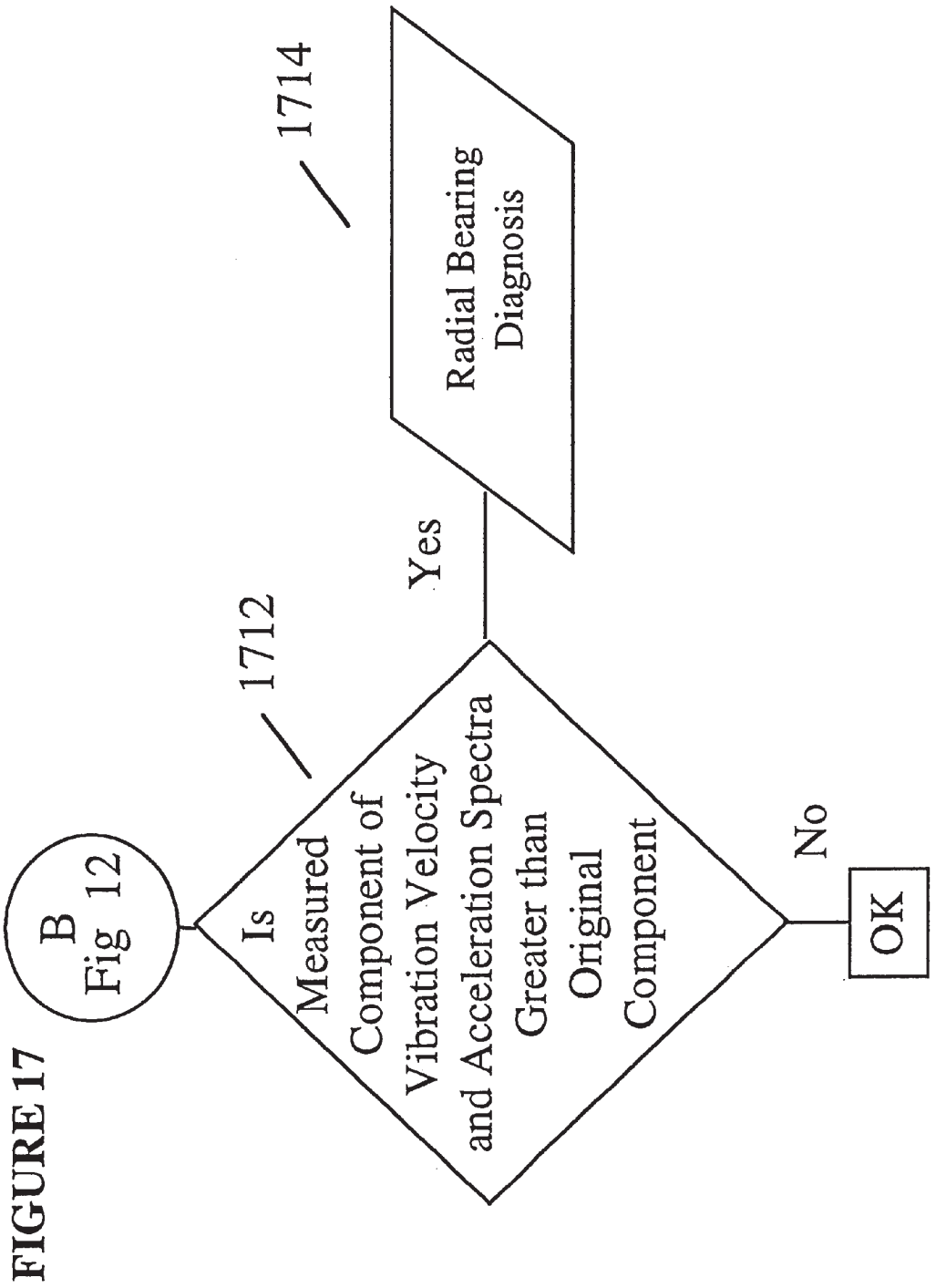
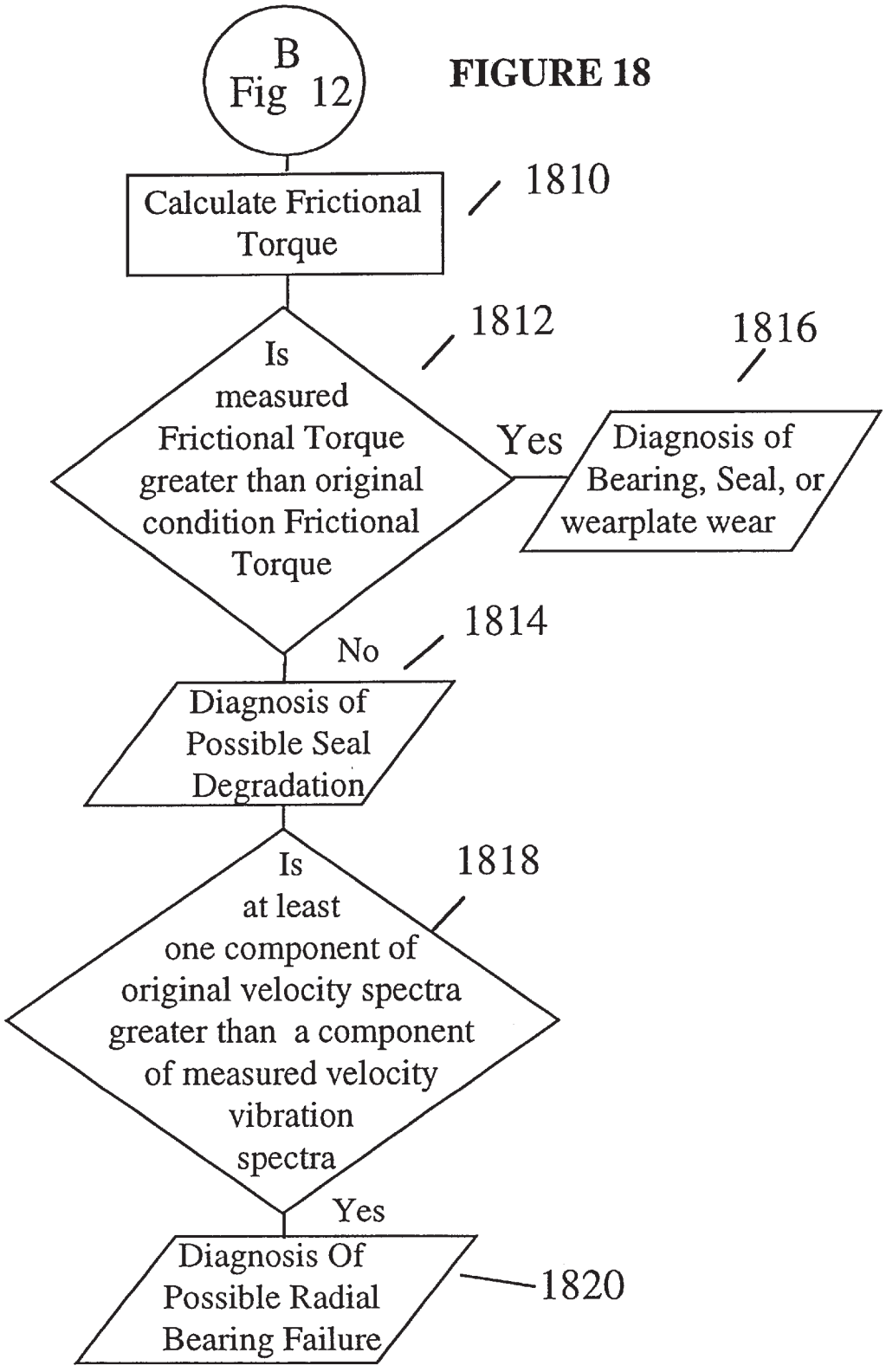

B
Fig 12
Is Measured Component of Vibration Velocity and Acceleration Spectra Greater than Original Component
1712
Yes
No
Radial Bearing Diagnosis
1714
OK

FIGURE 17

FIGURE 18


B
Fig 12
Calculate Frictional Torque
1810
Is measured Frictional Torque greater than original condition Frictional Torque
1812
Yes
Diagnosis of Bearing, Seal, or wearplate wear
1816
No
1814
Diagnosis of Possible Seal Degradation
Is at least one component of original velocity spectra greater than a component of measured velocity vibration spectra
1818
Yes
Diagnosis Of Possible Radial Bearing Failure
1820

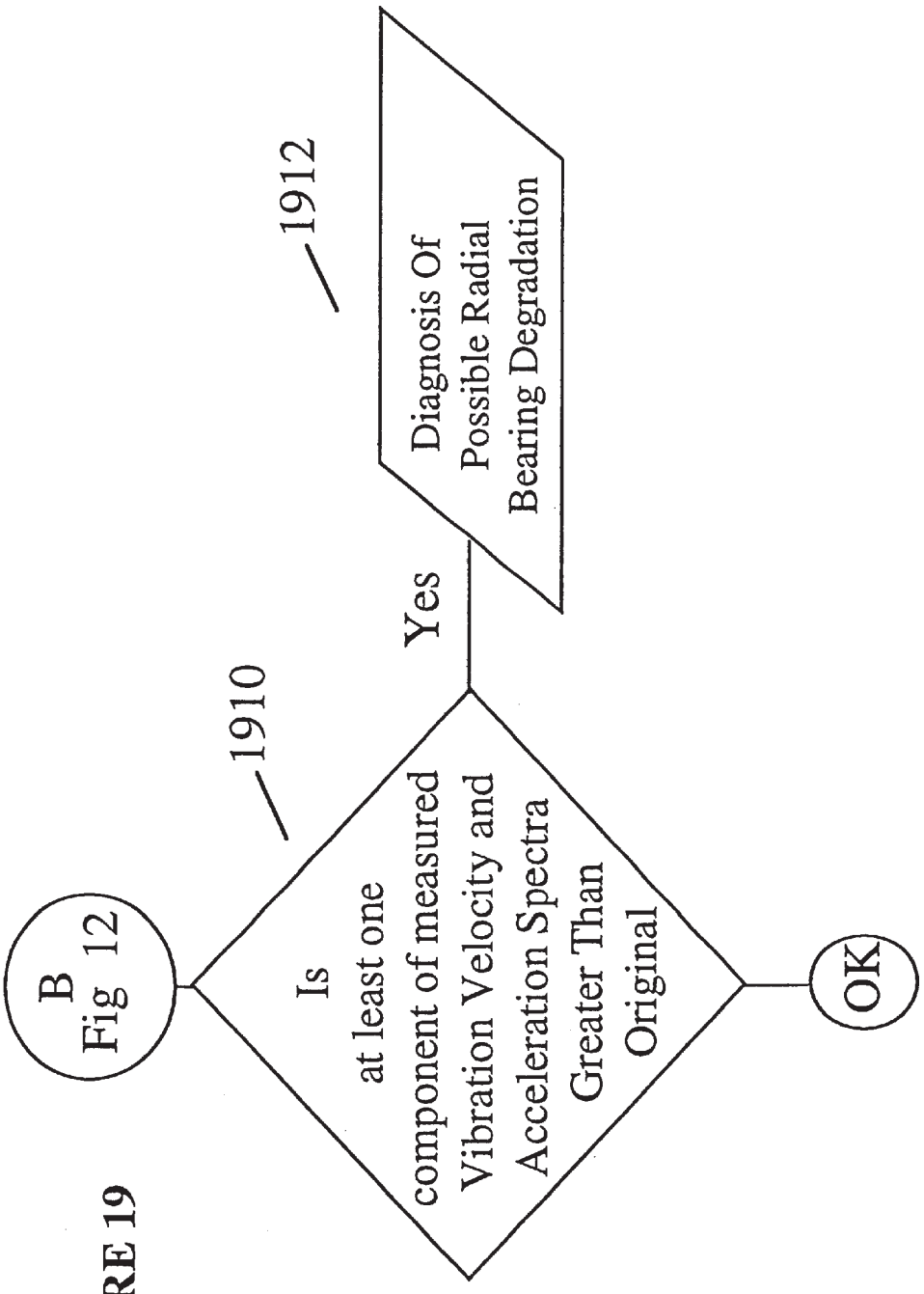

B
Fig 12
1910
Is
at least one
component of measured
Vibration Velocity and
Acceleration Spectra
Greater Than
Original
Yes
1912
Diagnosis Of
Possible Radial
Bearing Degradation
OK

FIGURE 19

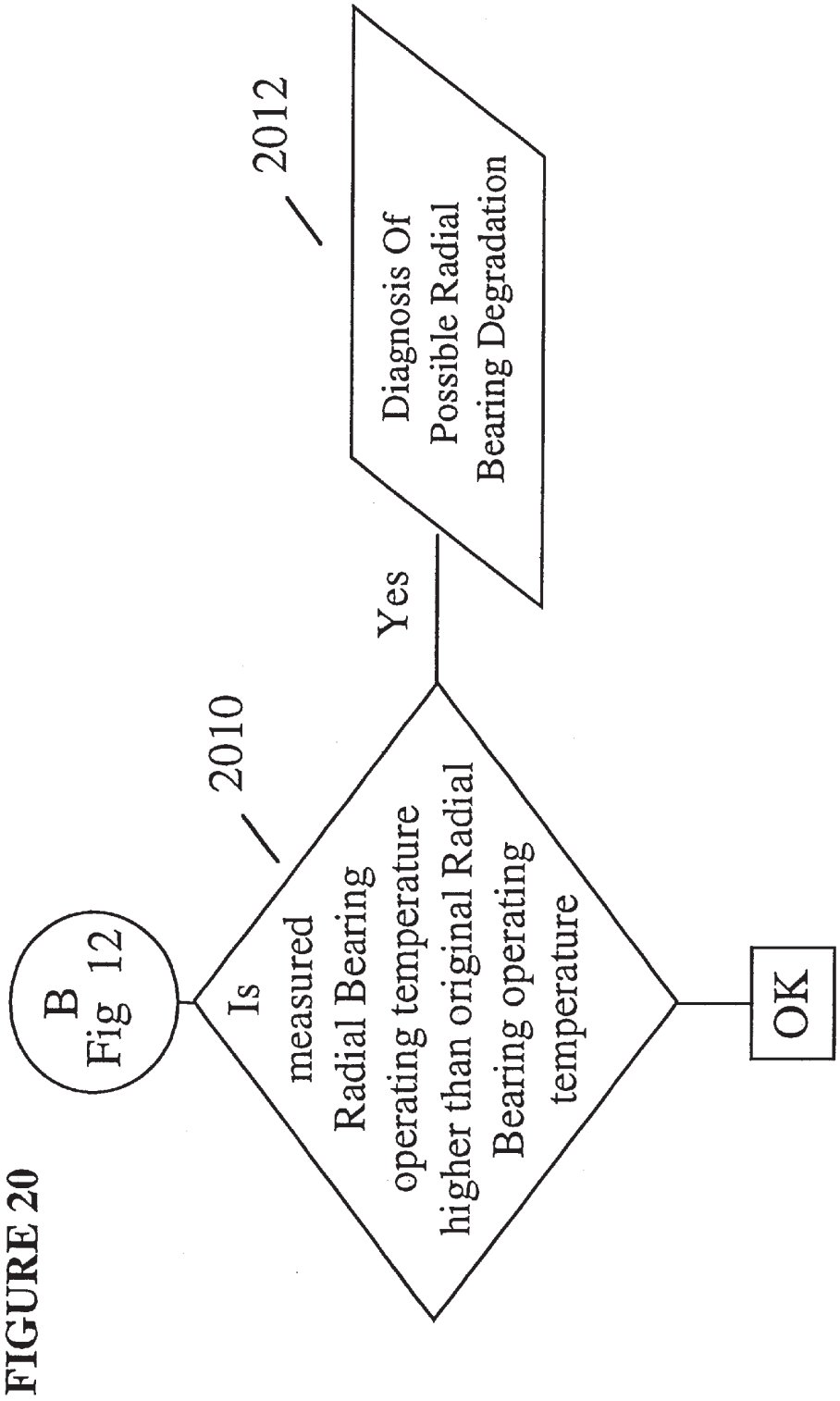

B
Fig 12
2010
Is measured Radial Bearing operating temperature higher than original Radial Bearing operating temperature
Yes
2012
Diagnosis Of Possible Radial Bearing Degradation
OK

FIGURE 20

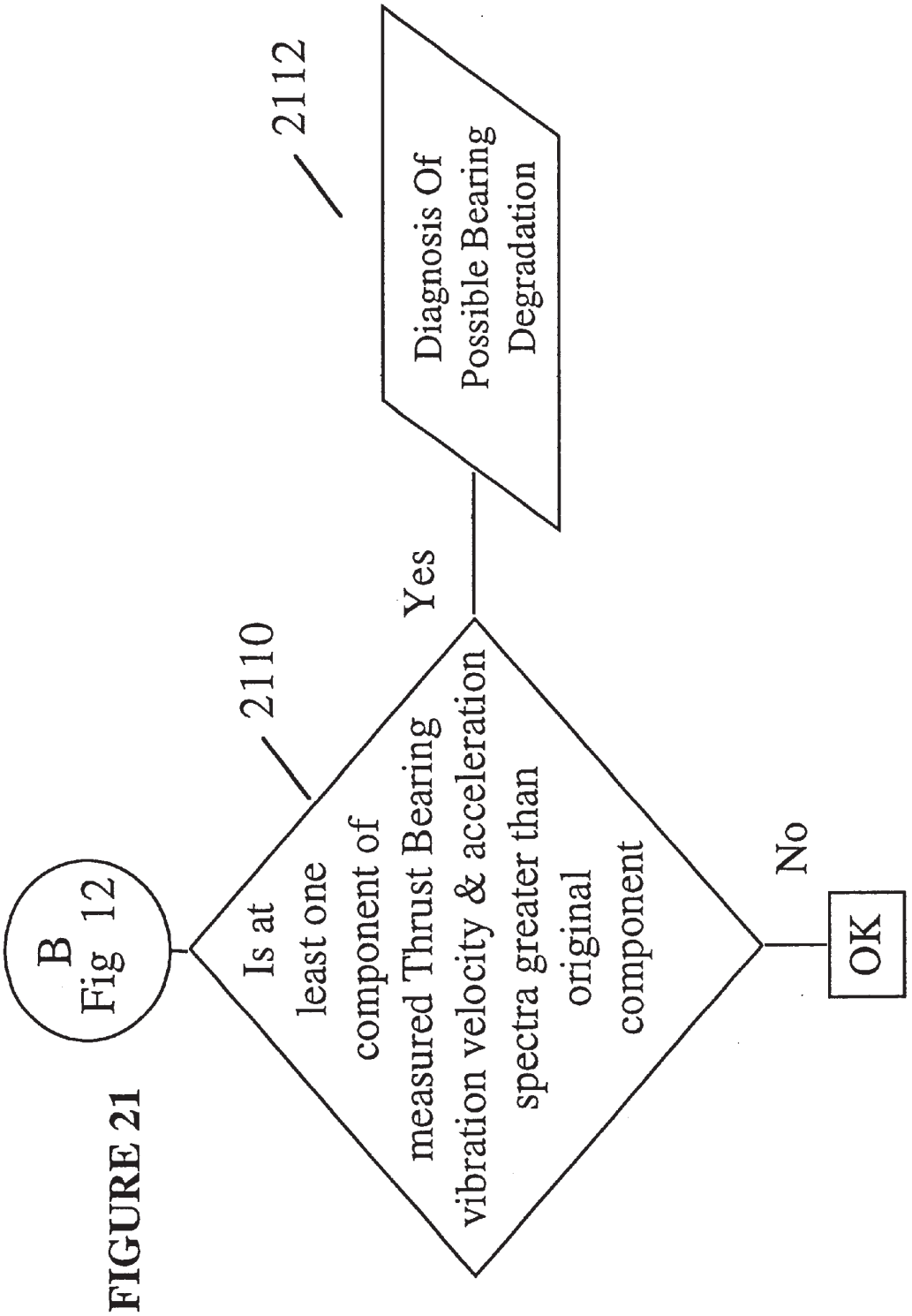

B
Fig 12
Is at least one component of measured Thrust Bearing vibration velocity & acceleration spectra greater than original component
2110
Yes
No
Diagnosis Of Possible Bearing Degradation
2112
OK

FIGURE 21

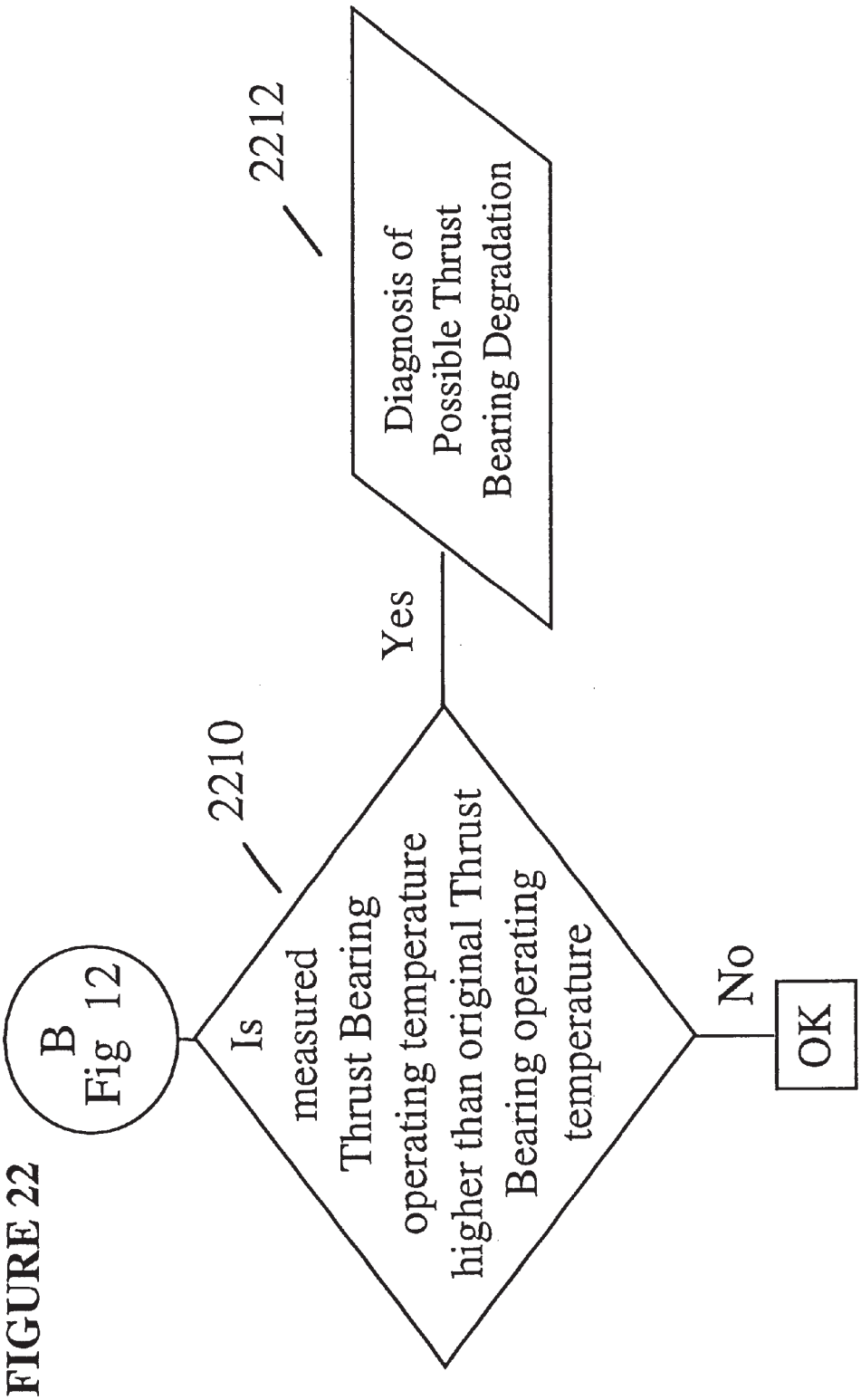

B
Fig 12
2210
Is measured Thrust Bearing operating temperature higher than original Thrust Bearing operating temperature
Yes
2212
Diagnosis of Possible Thrust Bearing Degradation
No
OK

FIGURE 22

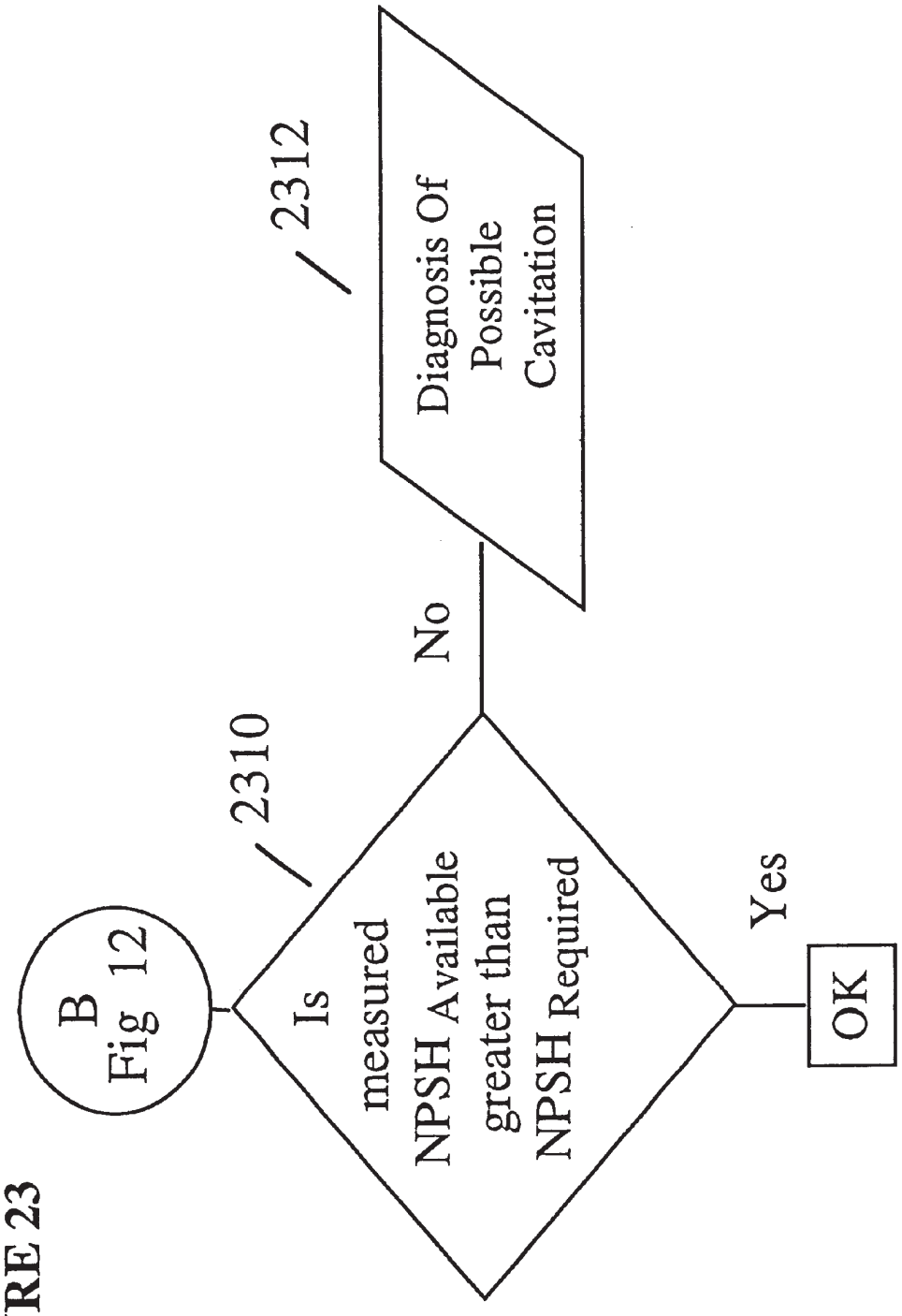

B
Fig 12
2310
Is measured NPSH Available greater than NPSH Required
No
2312
Diagnosis Of Possible Cavitation
Yes
OK

FIGURE 23

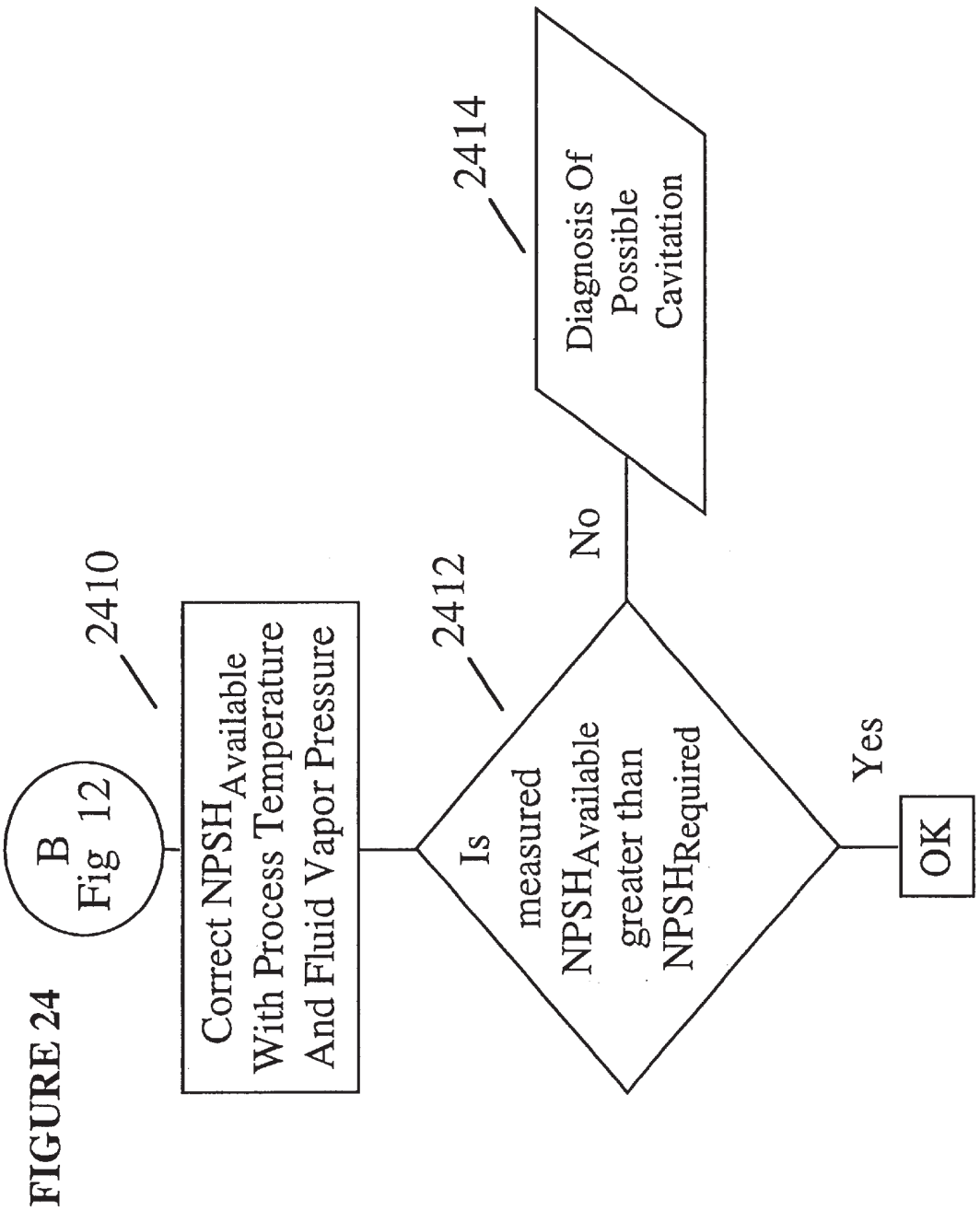

B
Fig 12
2410
Correct NPSHAvailable With Process Temperature And Fluid Vapor Pressure
2412
Is measured NPSHAvailable greater than NPSHRequired
No
2414
Diagnosis Of Possible Cavitation
Yes
OK

FIGURE 24

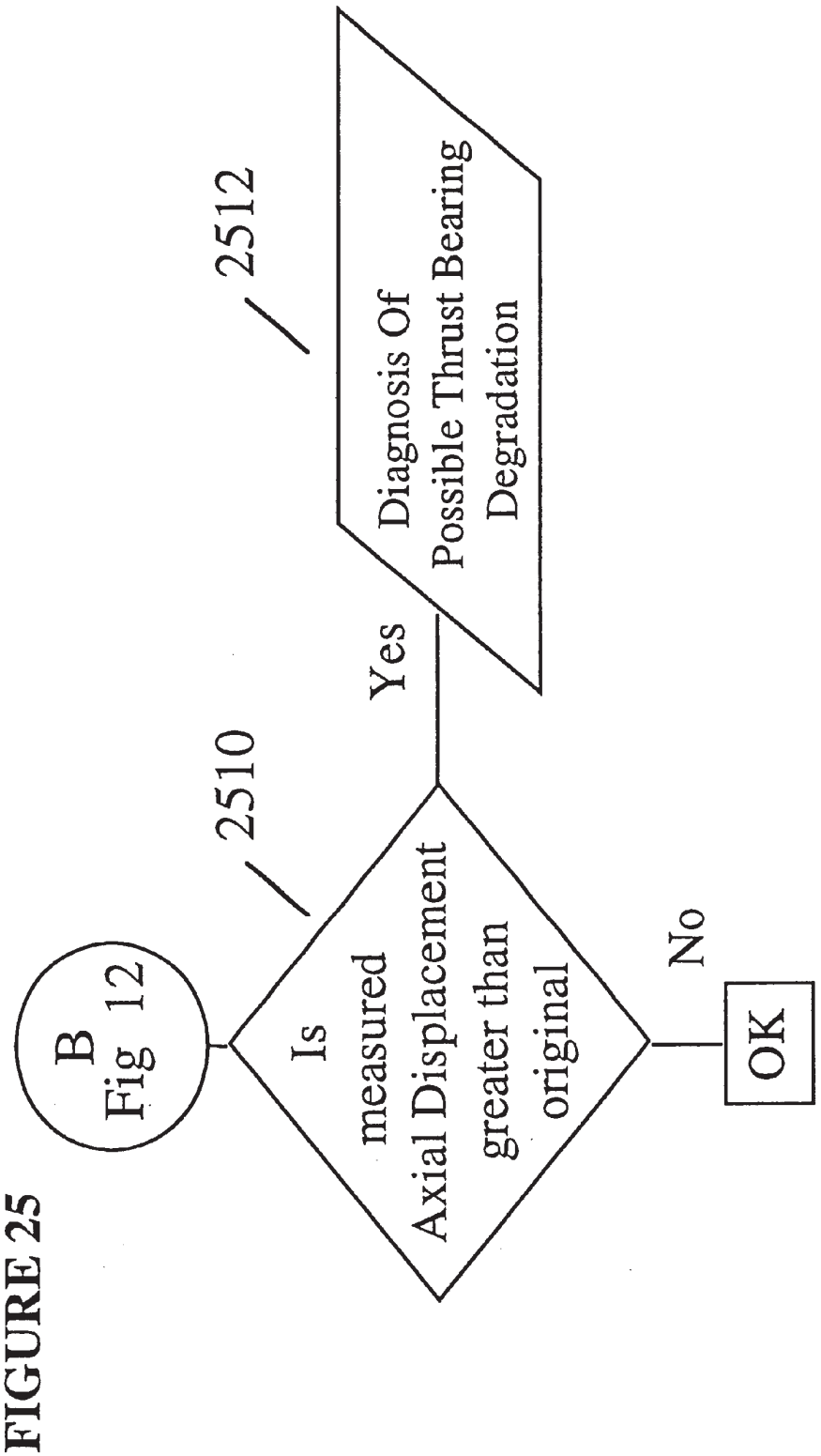

B
Fig 12
2510
Is
measured
Axial Displacement
greater than
original
Yes
2512
Diagnosis Of
Possible Thrust Bearing
Degradation
No
OK

FIGURE 25

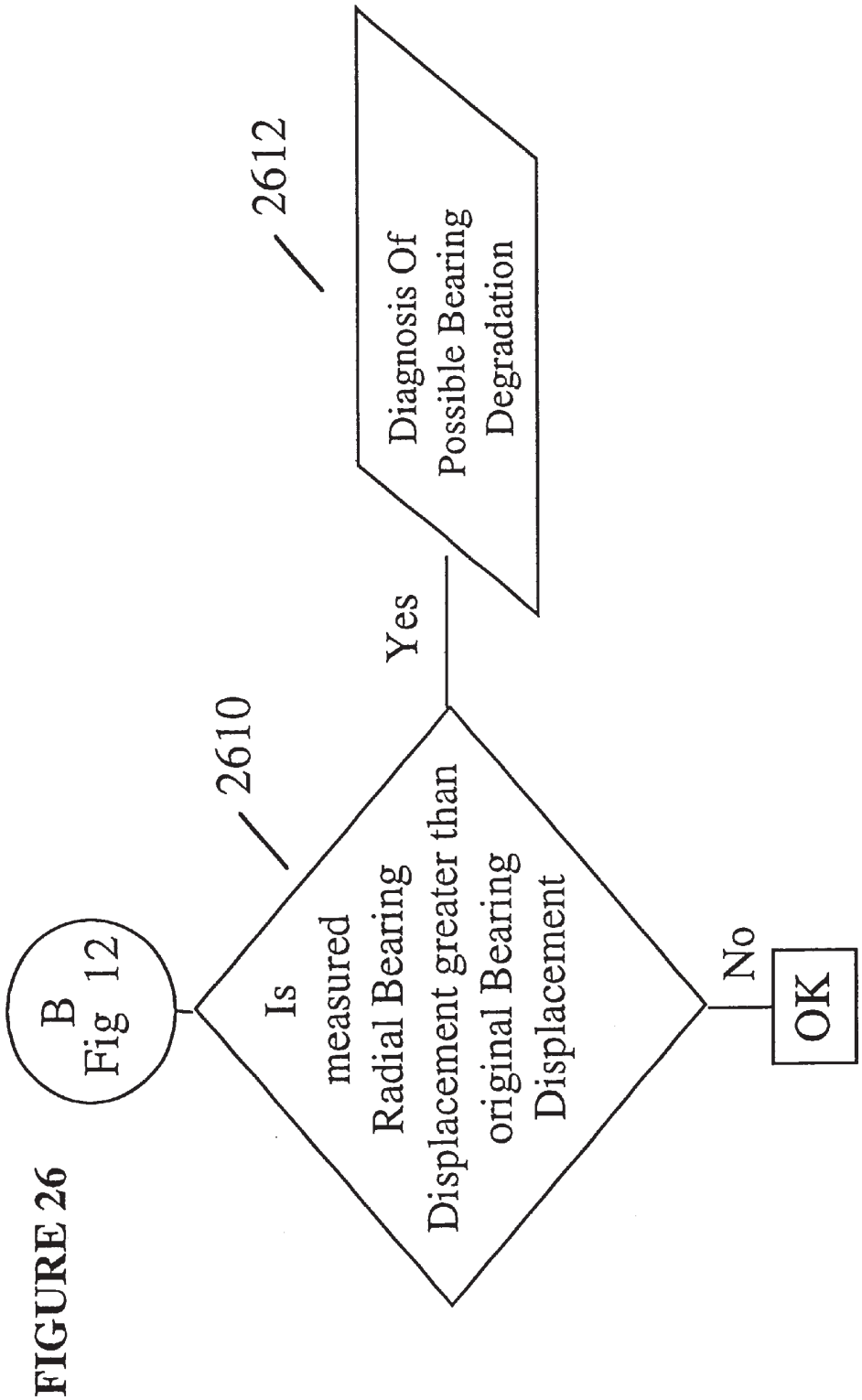

B
Fig 12
2610
Is
measured
Radial Bearing
Displacement greater than
original Bearing
Displacement
Yes
2612
Diagnosis Of
Possible Bearing
Degradation
No
OK

FIGURE 26

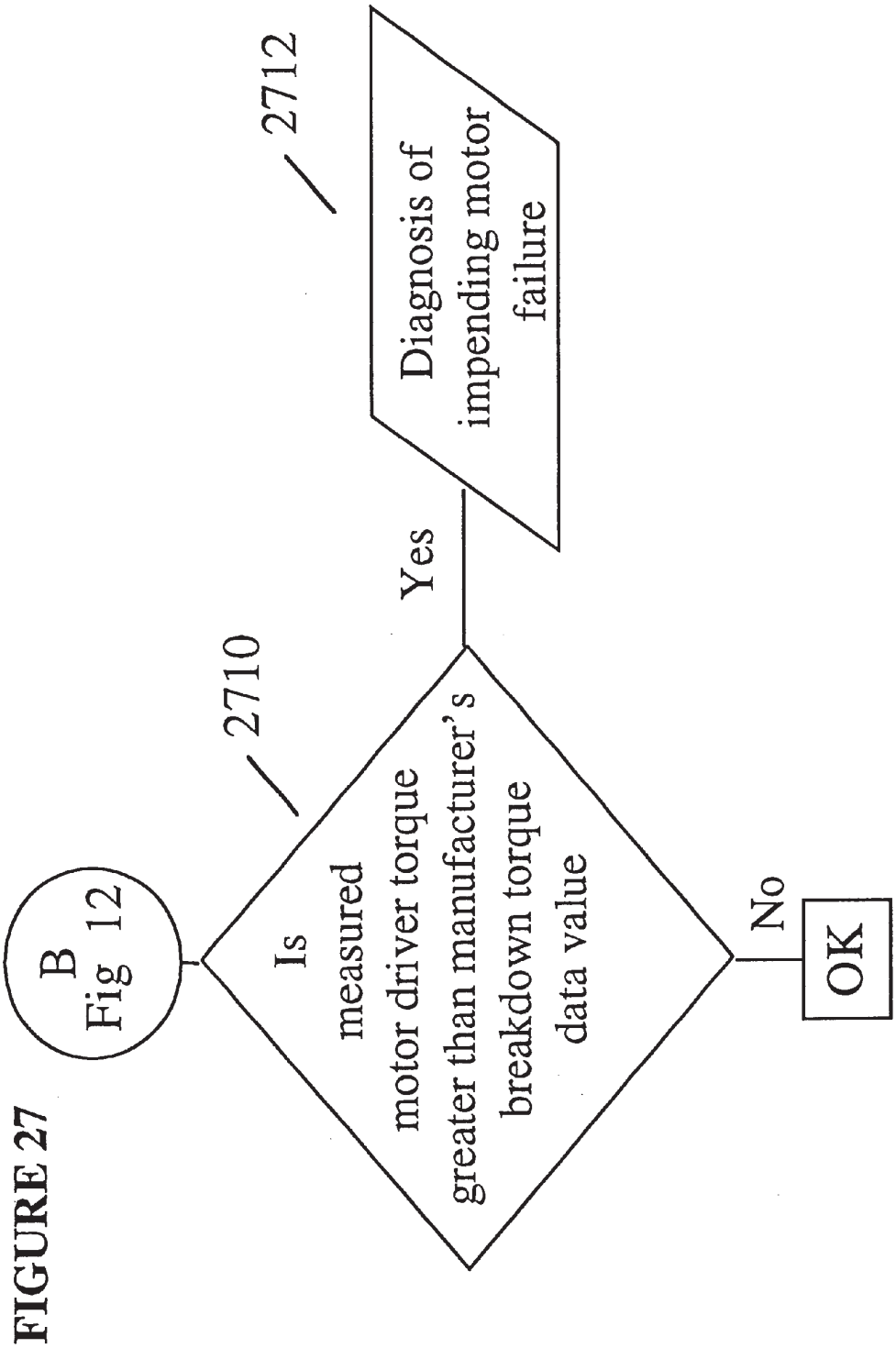

B
Fig 12
2710
Is measured motor driver torque greater than manufacturer's breakdown torque data value
Yes
2712
Diagnosis of impending motor failure
No
OK

FIGURE 27

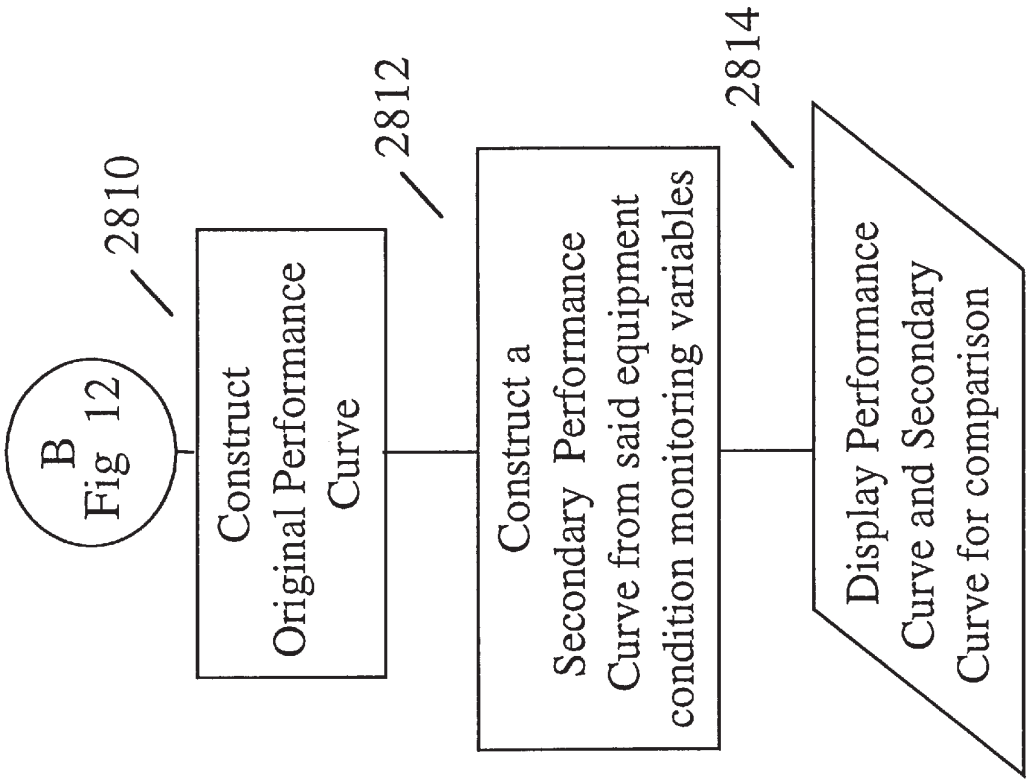

B
Fig 12
2810
Construct
Original Performance
Curve
2812
Construct a
Secondary Performance
Curve from said equipment
condition monitoring variables
2814
Display Performance
Curve and Secondary
Curve for comparison

FIGURE 28

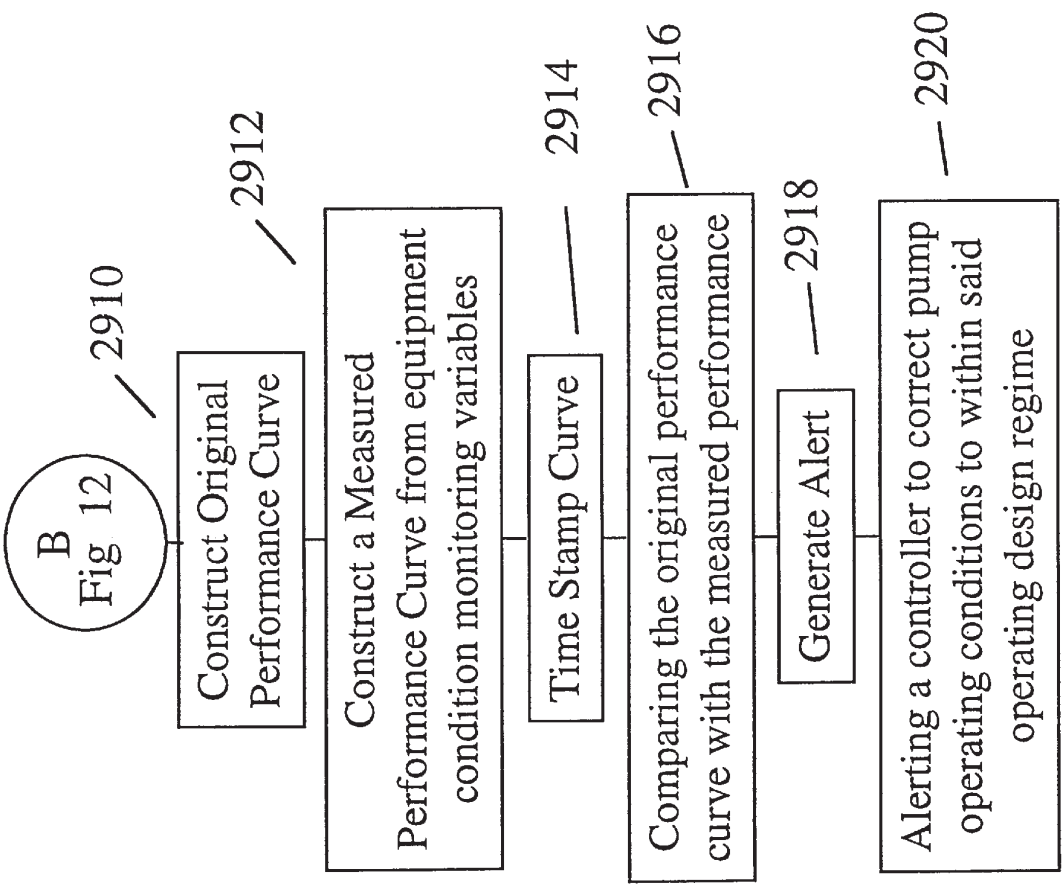
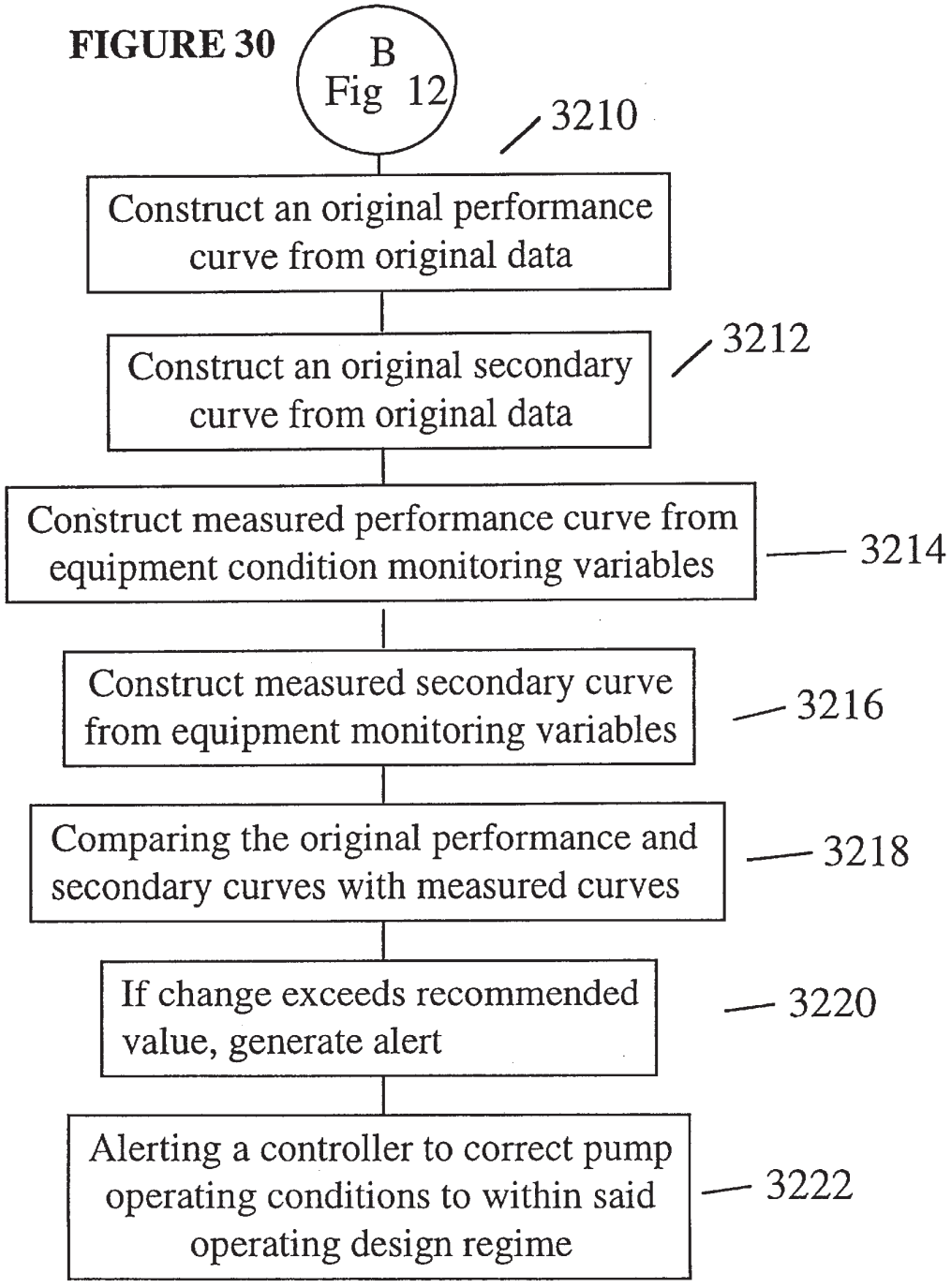

B
Fig 12
2910
Construct Original Performance Curve
2912
Construct a Measured Performance Curve from equipment condition monitoring variables
2914
Time Stamp Curve
2916
Comparing the original performance curve with the measured performance
2918
Generate Alert
2920
Alerting a controller to correct pump operating conditions to within said operating design regime

FIGURE 29

FIGURE 30


B
Fig 12
3210
Construct an original performance curve from original data
Construct an original secondary curve from original data
3212
Construct measured performance curve from equipment condition monitoring variables
3214
Construct measured secondary curve from equipment monitoring variables
3216
Comparing the original performance and secondary curves with measured curves
3218
If change exceeds recommended value, generate alert
3220
Alerting a controller to correct pump operating conditions to within said operating design regime
3222

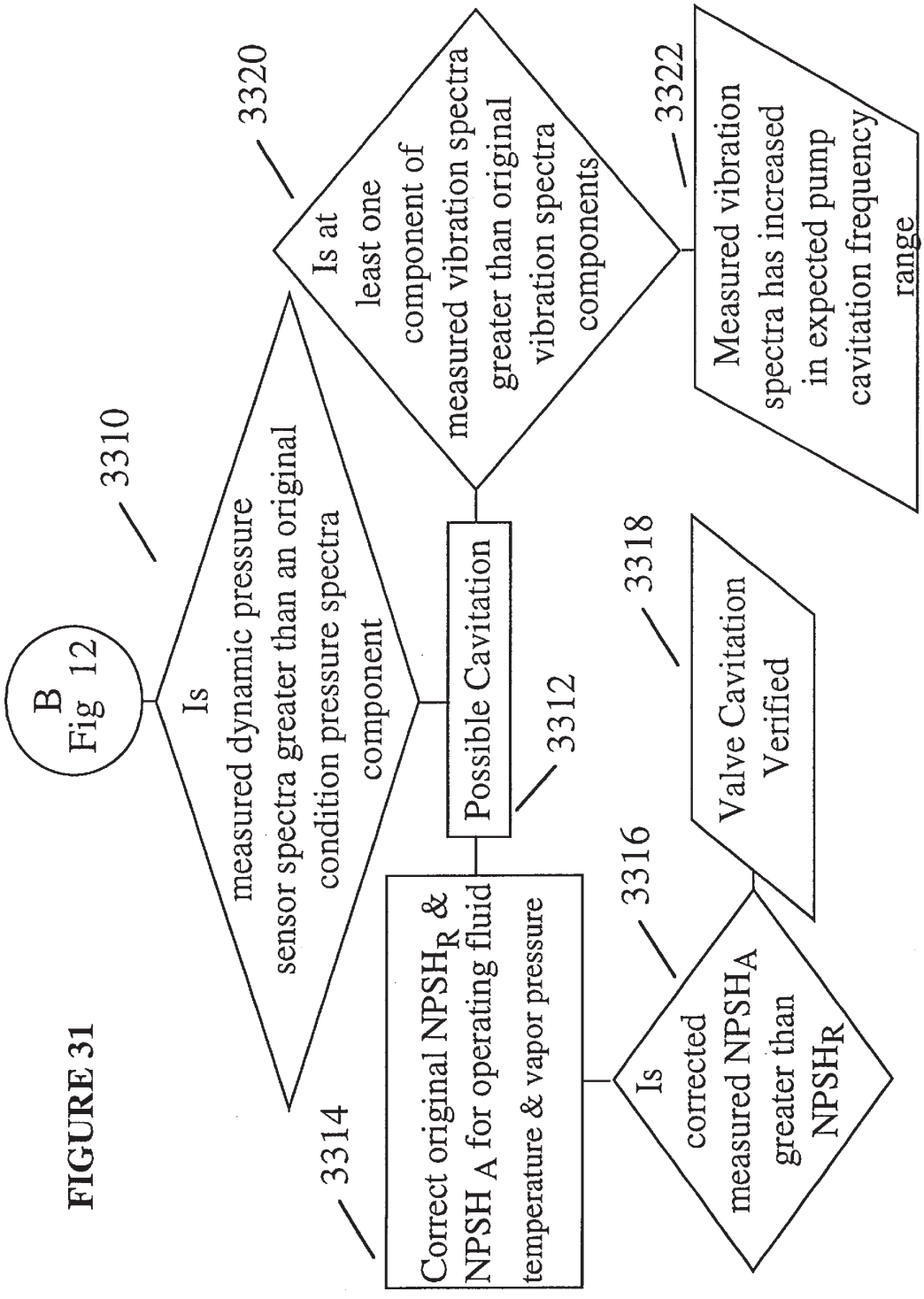

B
Fig 12
3310
Is measured dynamic pressure sensor spectra greater than an original condition pressure spectra component
3314
Correct original NPSH$_R$ & NPSH$_A$ for operating fluid temperature & vapor pressure
3316
Is corrected measured NPSH$_A$ greater than NPSH$_R$
3318
Valve Cavitation Verified
3312
Possible Cavitation
3320
Is at least one component of measured vibration spectra greater than original vibration spectra components
3322
Measured vibration spectra has increased in expected pump cavitation frequency range

FIGURE 31

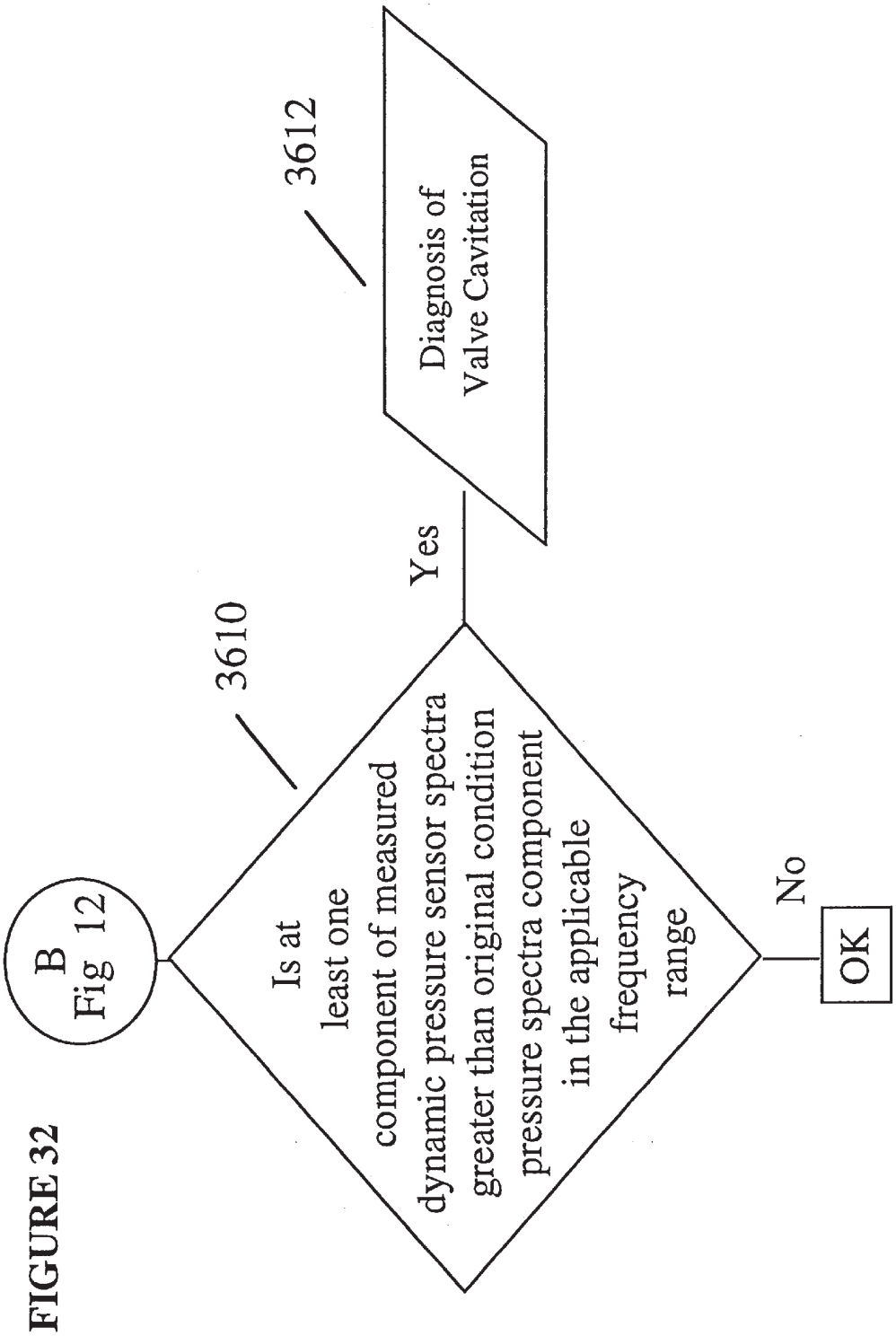

B
Fig 12
3610
Is at least one component of measured dynamic pressure sensor spectra greater than original condition pressure spectra component in the applicable frequency range
Yes
3612
Diagnosis of Valve Cavitation
No
OK

FIGURE 32

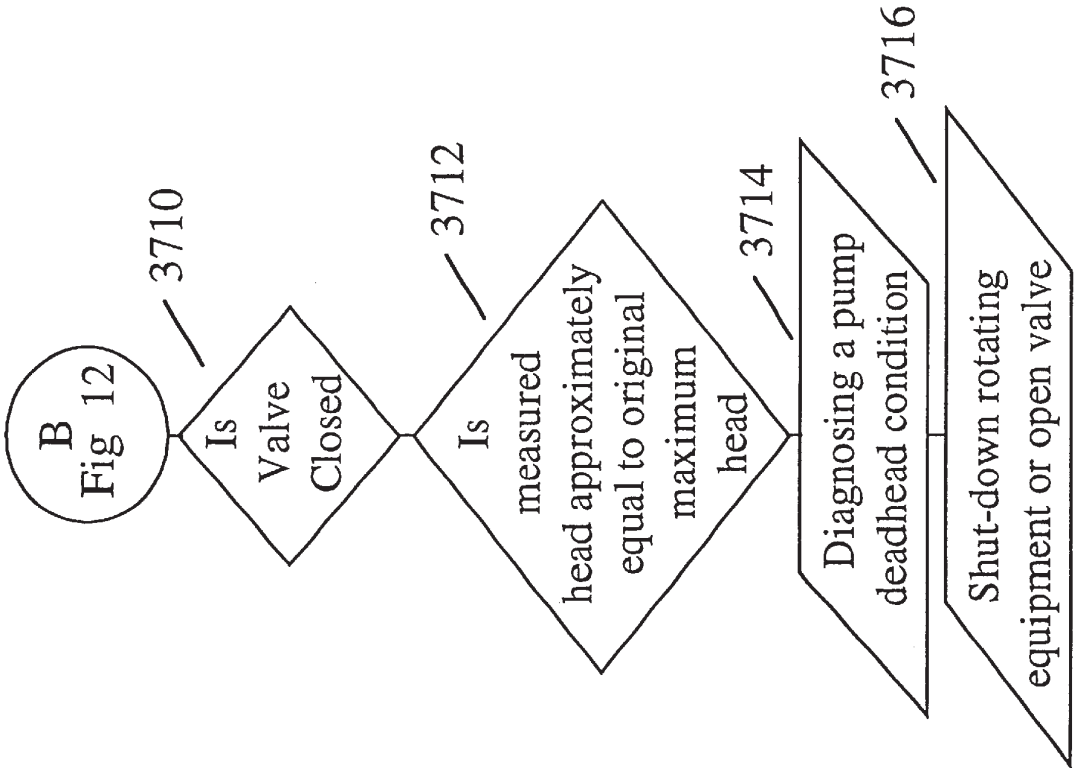

B
Fig 12
3710
Is
Valve
Closed
3712
Is
measured
head approximately
equal to original
maximum
head
3714
Diagnosing a pump
deadhead condition
3716
Shut-down rotating
equipment or open valve

FIGURE 33

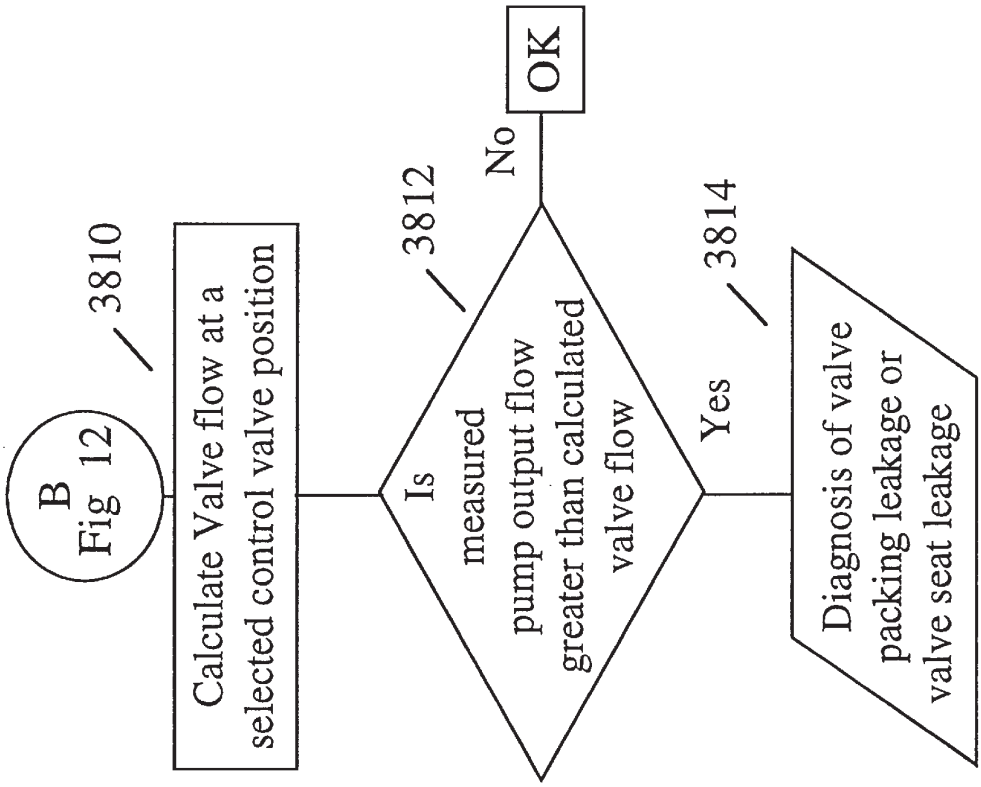

B
Fig 12
3810
Calculate Valve flow at a selected control valve position
3812
Is measured pump output flow greater than calculated valve flow
No
OK
Yes
3814
Diagnosis of valve packing leakage or valve seat leakage

FIGURE 34

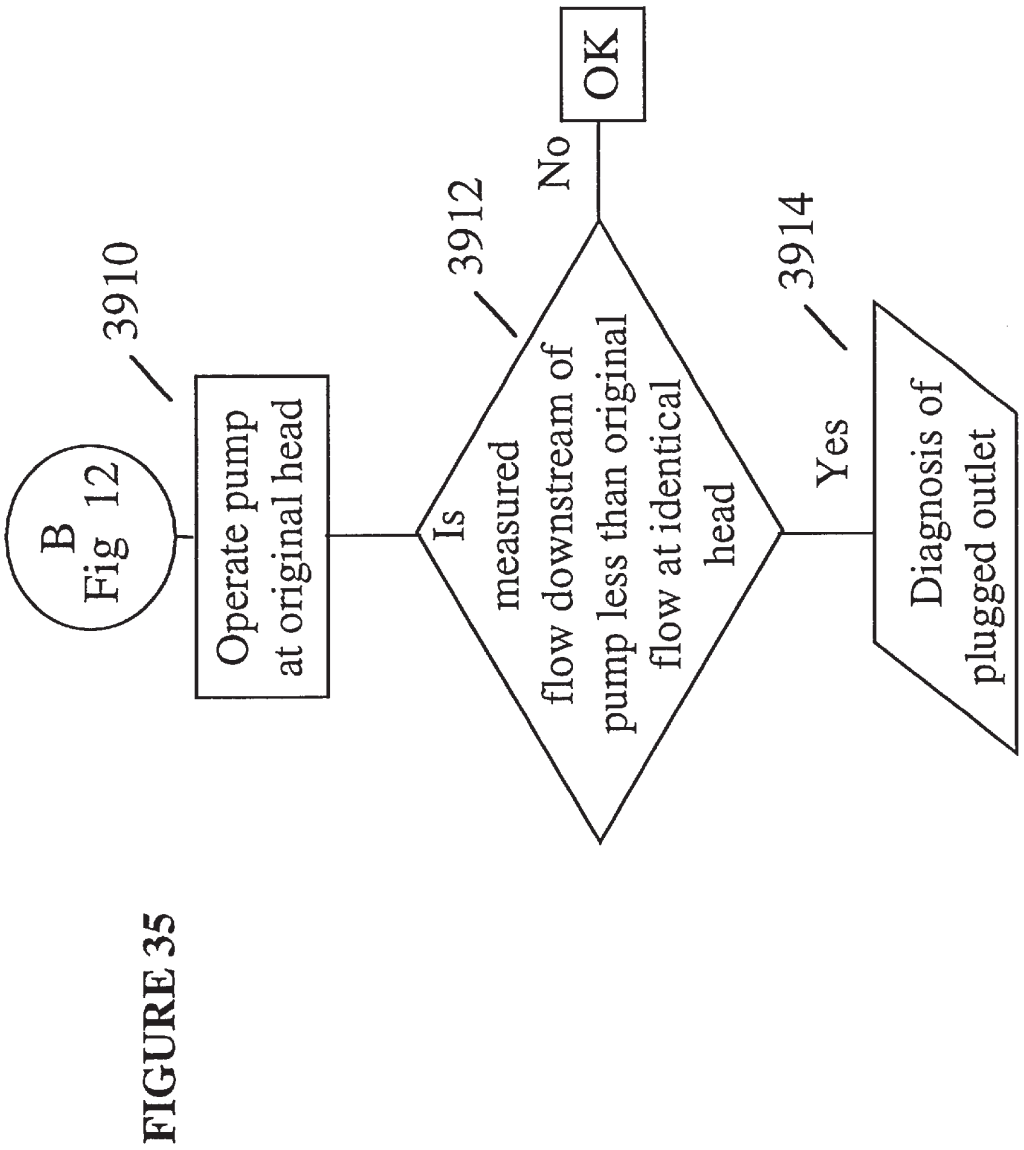

B
Fig 12
3910
Operate pump at original head
3912
Is measured flow downstream of pump less than original flow at identical head
No
OK
Yes
3914
Diagnosis of plugged outlet

FIGURE 35

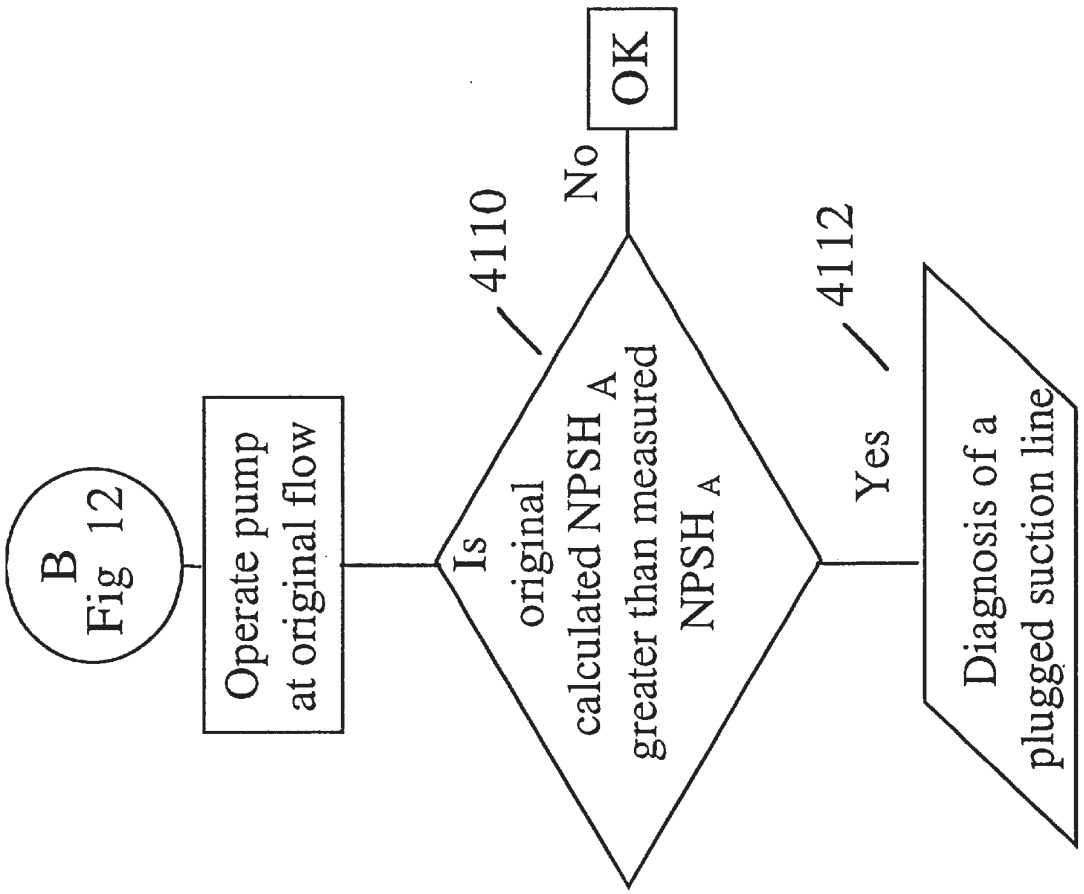

B
Fig 12
Operate pump at original flow
Is original calculated NPSH A greater than measured NPSH A
4110
No
OK
Yes
4112
Diagnosis of a plugged suction line

FIGURE 36

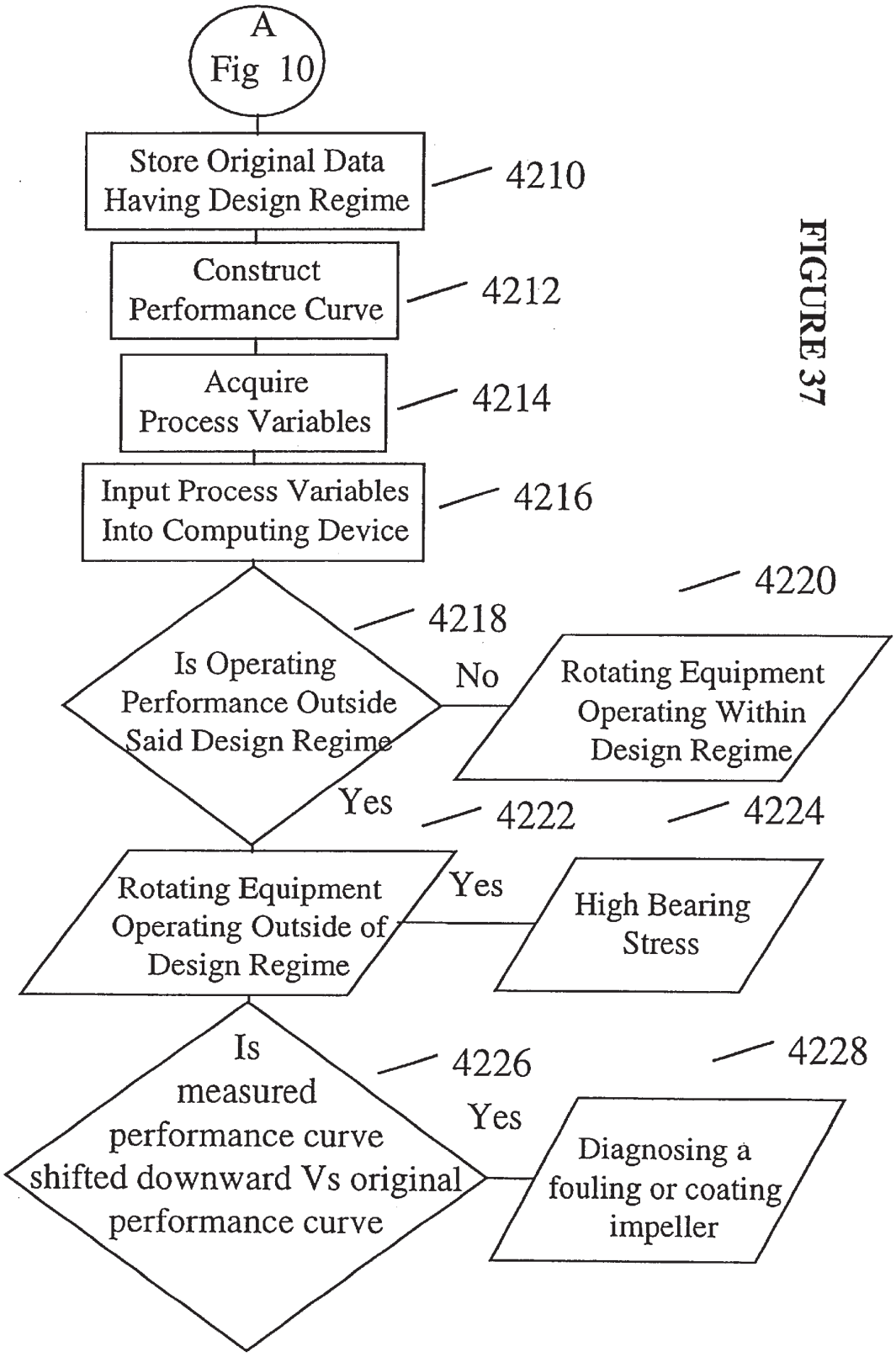

A
Fig 10
Store Original Data Having Design Regime
4210
Construct Performance Curve
4212
Acquire Process Variables
4214
Input Process Variables Into Computing Device
4216
4218
Is Operating Performance Outside Said Design Regime
No
4220
Rotating Equipment Operating Within Design Regime
Yes
4222
Rotating Equipment Operating Outside of Design Regime
Yes
4224
High Bearing Stress
Is measured performance curve shifted downward Vs original performance curve
4226
Yes
4228
Diagnosing a fouling or coating impeller

FIGURE 37

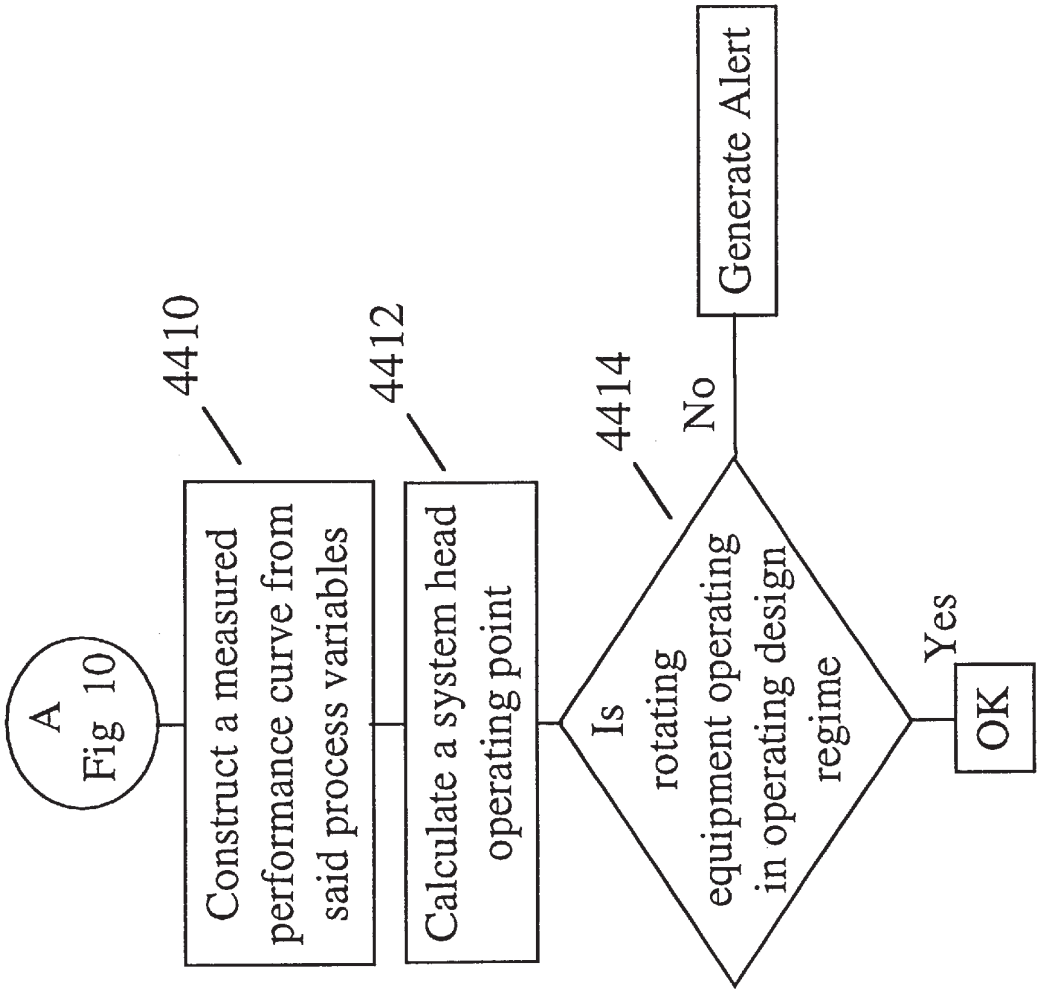

A
Fig 10
4410
Construct a measured performance curve from said process variables
4412
Calculate a system head operating point
4414
Is rotating equipment operating in operating design regime
No
Generate Alert
Yes
OK

FIGURE 38

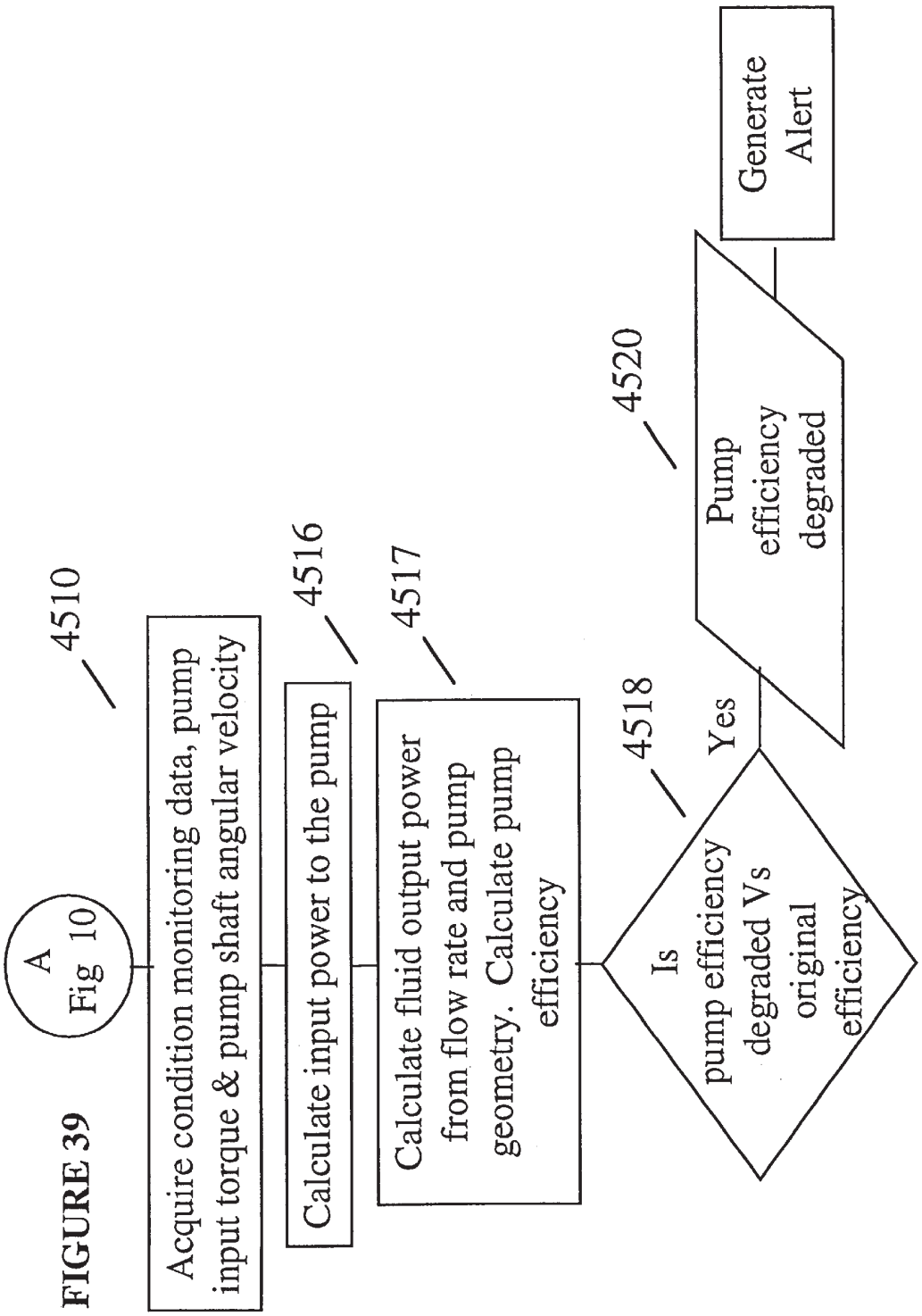

A
Fig 10
4510
Acquire condition monitoring data, pump input torque & pump shaft angular velocity
4516
Calculate input power to the pump
4517
Calculate fluid output power from flow rate and pump geometry. Calculate pump efficiency
4518
Is pump efficiency degraded Vs original efficiency
Yes
4520
Pump efficiency degraded
Generate Alert

FIGURE 39

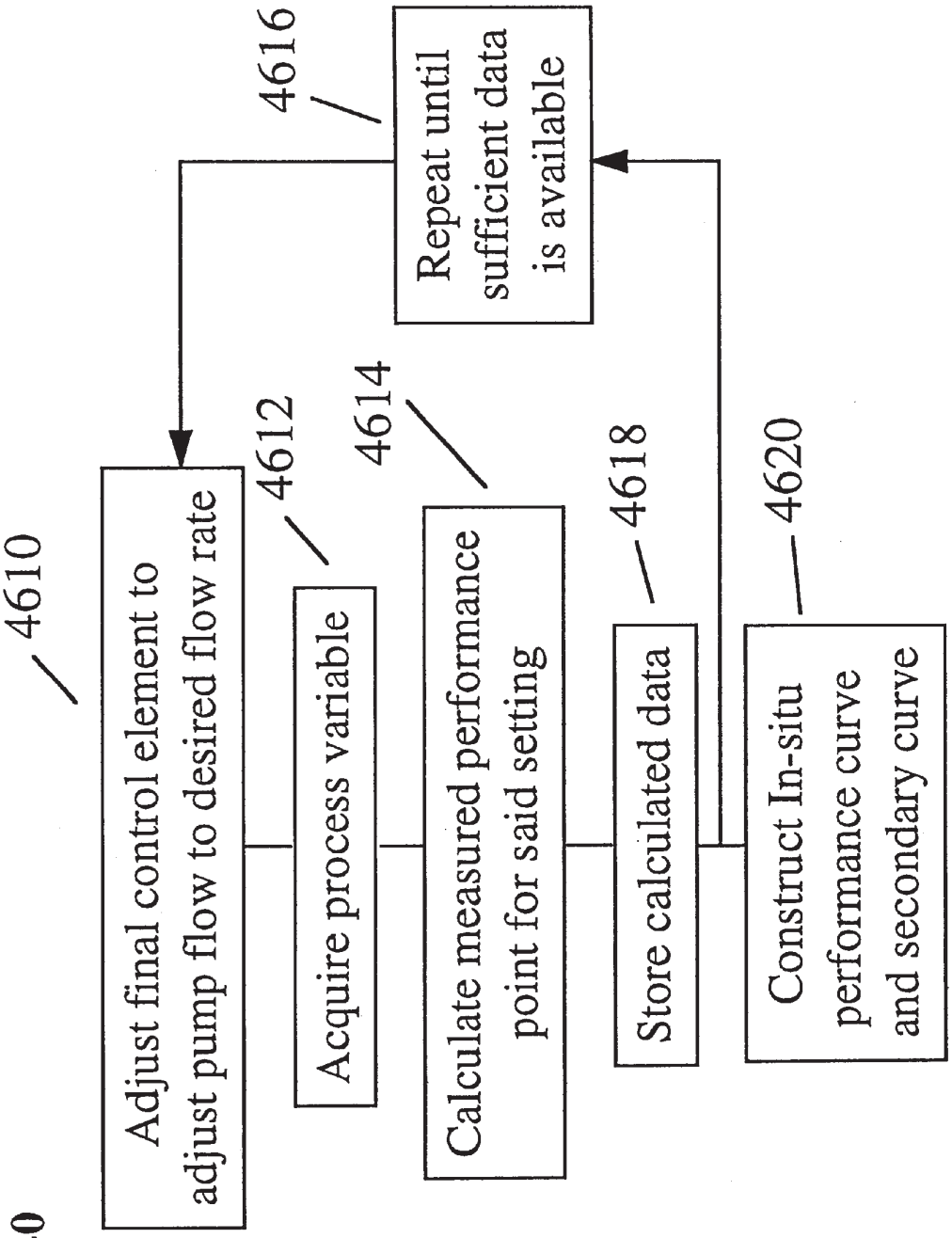

4610
Adjust final control element to adjust pump flow to desired flow rate
4612
Acquire process variable
4614
Calculate measured performance point for said setting
4618
Store calculated data
4620
Construct In-situ performance curve and secondary curve
4616
Repeat until sufficient data is available

FIGURE 40

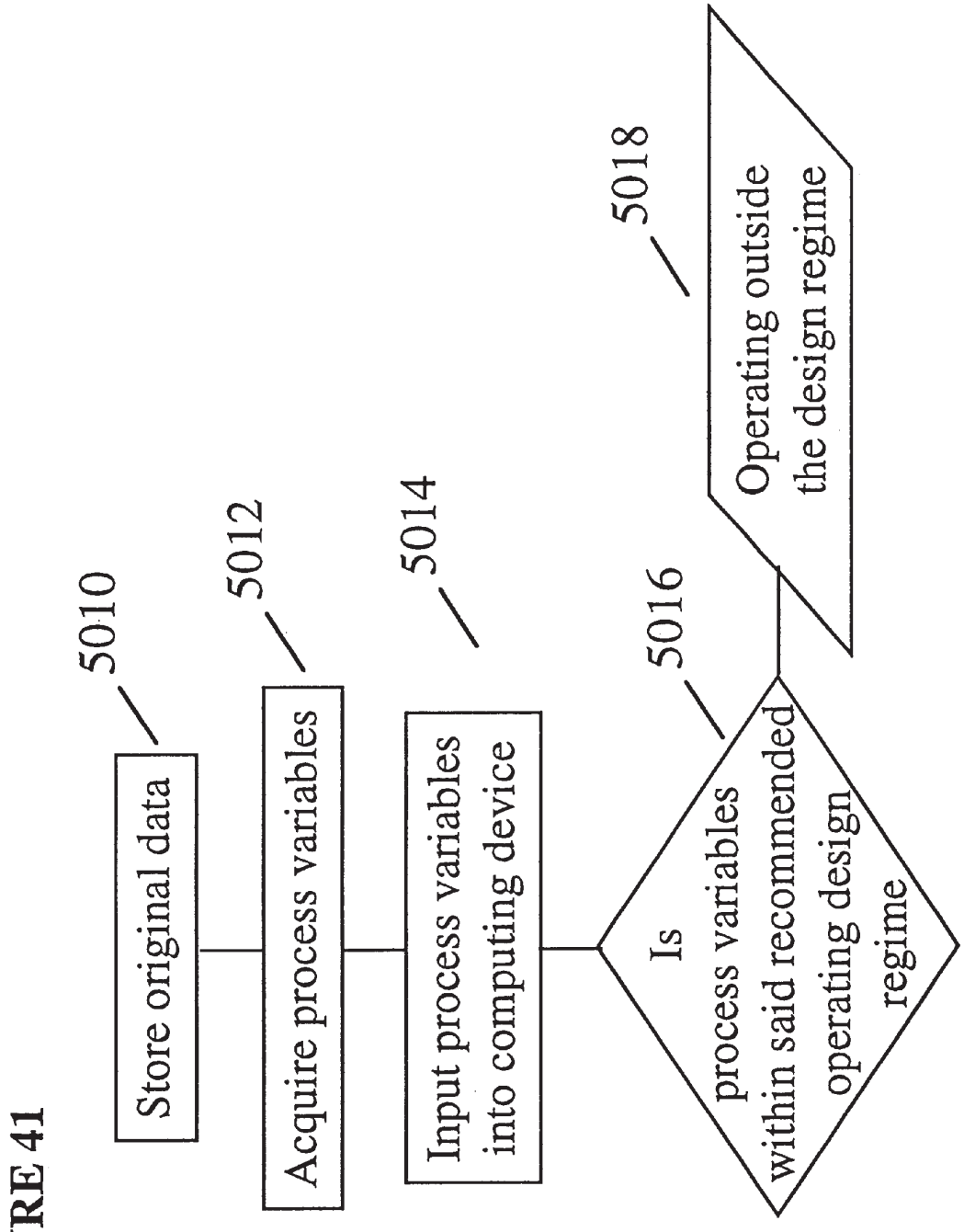

5010
Store original data
5012
Acquire process variables
5014
Input process variables into computing device
5016
Is process variables within said recommended operating design regime
5018
Operating outside the design regime

FIGURE 41

METHOD AND APPARATUS FOR DIAGNOSING A PUMP SYSTEM

This is a divisional application of copending Ser. No. 09/002,053 filed Dec. 31, 1997.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a method and apparatus for diagnosing a pump system.

2. Background

Pumps are among the least reliable components in a process plant with the average Mean Time To Repair (MTTR) averaging two years. Recent advances in vibration sensor based condition monitoring are now routinely used to measure the vibration profile of a pump system to determine if large velocity or acceleration vibration levels are present. Such vibration levels are indicative of a failed or failing pump.

Pump maintenance is most often required due to operating a pump under conditions where bearing loads are high and where there is fluid induced damage to the impeller, i.e., cavitation and recirculation. The desirability of operating at the pump's Best Efficiency Point (BEP) is well known in the pump industry. At the BEP, bearing forces are designed to be at a minimum, vibration levels are lowest, and cavitation and recirculation are avoided. Examples of the impact on pump life due to off-BEP operation can be found in *Pump Characteristics and Applications* by M. S. Volk.

No commercial product, method or system has the ability to provide an operator or maintenance engineer with the actual operating pump performance curve and process operating point. An understanding of the operating point or range versus the intended operating range on a pump performance curve is key to operating a pump near its BEP and to diagnosing pump component damage when operating in off-BEP regions.

Vibration monitoring equipment such as that provided by Bently Nevada is well-known for condition monitoring of rotating equipment. The Bently Nevada system consists of sensors (typically accelerometers, displacement sensors, proximity velocity transducers and temperature sensors) that are appropriately mounted to rotary equipment such as turbines, compressors, fans, pumps and drive units such as motors.

Monitoring machine performance through vibration signature analysis is a practice spanning more than two decades. Many standards used for overall vibration measurements are based on specific rotational frequencies and integer multiples of these specific rotational frequencies. Vibration data is routinely collected either manually or with on-line systems from bearings on rotating machines. Bearing vibration measurements should include measurements in both the horizontal and vertical planes of each bearing. At least one axial vibration is made for each shaft.

Vibration readings on the bearing housing, using an accelerometer (acceleration) or a velocity transducer (velocity), provide sufficient data to detect the onset of bearing failure. Displacement or proximity probes measuring the motion the shaft relative to the bearing also provide useful data for diagnosing bearing failure. The motion of the shaft within the bearing as measured by the proximity sensor is commonly called an "orbit".

Rotating machines and pumps, by their very nature are dynamic machines. Vibration and proximity sensor data is also dynamic and is typically collected as trend data, FFT and waveforms. Most faults are identified by distinct frequency peaks or patterns and therefore frequency bands may be defined which bracket specific faults. These bands may be specifically scanned for amplitude changes which signal the need for further analysis. These scans will include comparing recorded vibration levels against alarm levels as well as a statistical analysis of variation and comparison to baseline values. The defined frequency bands will include the calculated or measured resonant frequencies of the major rotating machine mechanical components such as the shaft, impeller, radial bearings and thrust bearings. Analysis of vibrational data to identify known faults are further described in the CSI Application paper:

"Vibration Monitoring of Common Centrifugal Fans in Fossil Fired Power Generation".

Further analysis will include a review of the amplitude and phase versus frequency spectra, sometimes a referred to as the Bode plot, for the proximity and vibration sensors. Multiples of the machine component resonant frequencies, commonly termed harmonics, are also examined.

These known vibration monitoring techniques are applied in combination with the rotating machine performance curves to provide for root cause analysis the rotating machine in a method previously not performed.

The sensors are mounted for the purpose of detecting impending motor bearing or pump bearing failures through sensor signal analysis using conventional spectral analysis such as the Fast Fourier Transform (FFT).

The use of a vibration spectra is well known, but such use often requires a human expert to examine the spectra and deduce damage. Expert analysis is required since the frequency components for all of the mechanical components (bearings, impeller, piping, etc.) are all present at the same time. Therefore, discrimination of the vibration by component requires substantial skill. As vibration sensors provide a spectral output (frequency domain), the vibration peaks correspond to a multiplicity of failure modes that may be present at the same time. A single vibration spectra is likely to show the shaft frequency, impeller frequency, radial bearing fundamental frequency, thrust bearing fundamental frequency, motor harmonic frequency, pump/piping resonant frequency, mounting plate frequency, etc. In addition to these fundamental frequencies, the harmonics or multiples, and submultiples of these frequencies will also be present.

Traditional condition monitoring systems are used to detect damage that has already occurred to a rotating machine. The pump diagnostics method is able to detect rotating machine operating conditions that may lead to pump damage. The pump diagnostics method also provides an ability to focus the maintenance engineer or technician to examine a specific area of vibration spectra for evidence of a pending failure detected through knowledge gained from the pump performance signature.

Additional analysis is provided through the measurement of the pump to motor shaft alignment using position or proximity sensors and through the measurement of the shaft "orbit" within the bearing. Temperature measurements are strategically positioned to provide data on bearing "hot spots". Bently's system provides for off-line or "pseudo real time" acquisition of the above data and field processing of the sensor dynamic data which can be communicated to a centrally located display for viewing either via a proprietary communication or the Modbus protocol. Real time analysis has not been possible in the past due to bandwidth limitations in communications protocols.

Vibration sensors (piezoelectric accelerometers, velocity transducers and proximity sensors) are available from many suppliers such as Bently Nevada, Vibrametrics, Dytram and CSI and are often used with FFT algorithms for determination of vibration spectra for rotary equipment.

Vibration monitoring systems are available in portable "walk around" versions versus in situ systems where the vibration spectra is measured periodically. These portable vibration systems can provide for diagnosis of bearing failure, but are not as effective in determining the "root cause" for the bearing failure.

A diagnostics method is needed that provides for guidance in the repair of a failing pump, but most importantly, provides the operator with a root cause analysis that enables elimination of the cause of failure, which is often operation of the pump outside the BEP range. Available condition monitoring-only solutions provide limited guidance on elimination of the cause of failure as they observe the failure of the mechanical components, but do not identify the operating condition that caused the failure.

a. Electric Motor Diagnostics

Several manufacturers provide partial solutions for the off-line diagnosis of electric motors. Framatome and Liberty Technologies both provide for PC based electric motor diagnostics systems consisting of vibration sensors to detect motor bearing failure, a measurement of motor voltage wherein current and phase are coupled to an FFT for the calculation of a motor signature, and temperature sensors to sense elevated motor winding temperatures and, in some cases, flux analysis, and insulation characteristics of the motor windings and shaft alignment sensors to measure motor-to-coupler alignment.

CSI has recently announced a motor diagnostic system that provides data logging of key motor diagnostic attributes that are manually collected and uploaded to a PDM device at regular intervals.

Siemens has a smart motor system that provides pseudo real-time diagnostics information such as that summarized above via a sensor system connected to a field mounted motor analysis computer.

Current motor diagnostics systems capture only motor and motor power related diagnostic information such as power (P), voltage (V), current (I), phase (Ø), and flux (f). Current systems do not have the ability to look at the influence of the rotating machine (load) and its influence on the motor.

b. Alignment Systems

The need to provide for precise alignment of the pump and driver source through a coupling means or intermediate gear box is well known. A number of suppliers exist for the systems to facilitate optimum alignment of the pump to power source. Such systems may include traditional dial indicators, electronic position sensors and most recently laser alignment systems such as the ones manufactured by Vibra Align Inc. and Ludeca, Inc. These systems provide assistance to the pump technician for the installation or validation of proper motor and driver alignment with the pump. Many alignment systems provide an electronic output that can be displayed at the pump in the field.

c. Pump Diagnostic Systems

Pumps are one of the least reliable devices in a process plant. The proper pump selection and application, installation, use and maintenance must be assured for long life.

Pump manufacturers such as Gould Pumps commonly provide a pump performance curve with each pump. A pump curve is intended to assist a user in properly selecting the correct pump and pump impeller as well as to assist a user in operating a pump in the most efficient manner while producing the desired flow and pressure (head). Pumps are often used with constant speed power sources such as a 1800 RPM electric motor, or with a variable speed drive (VSD) where the pump speed can be changed to vary the pump flow and head output. When pumps are used with variable speed drives, distinct pump performance curves can be provided by the manufacturer at each desired speed. However, such curves are often calculated using the pump affinity law from the originally provided pump curve. The pump affinity laws are well known and are described in Yedidiah, *Centrifugal Pump User's Guidebook.*

Several manufacturers use commercial personal computer systems for the measurement and calculation of the pump performance curve at the factory for new or repaired pumps. These systems are sometimes used by pump manufacturers to calculate and provide the pump performance curves for the end user. These systems may include sensors for determining pump shaft speed (RPM), inlet and outlet pressures, outlet flow, shaft horsepower (brake horsepower) and fluid temperature. Standard algorithms, such as those described by Yedidiah, author of *Centrifugal Pumps User's Guidebook*, are applied to provide the pump performance curve.

MARINTEK has undertaken work for the development of a knowledge-based diagnostics system called ROMEX, which is designed for rotating machines. The ROMEX system is a PC-based system which integrates data from commonly used condition monitoring systems and covers mechanical and performance related faults with coverage of the rotating machine rotor, stator, coupler, bearing, blades, aerodynamics and combustion chamber for gas turbines. The ROMEX system does not use a pump performance curve as a method for diagnosing possible off-BEP operating conditions or changes in the pump performance curve as a primary source of diagnostics for pump maintenance.

d. Pump Sensor Fusion

Recent published research from the Colorado School of Mines and their SHARP system (System Health Assessment and Real-Time Prediction) suggest that a diagnosis of pump health can be made via the fusion of physical variables such as pump inlet pressure, outlet pressure and flow in conjunction with a large artificial intelligence system made by Gensym. Artificial intelligence expert systems are used with some maintenance systems and often involve hundreds and even thousands of rules necessitating a large and expensive computing workstation. The SHARP system does not use the pump performance curve as a primary source of diagnosis for pump maintenance.

e. Pump Field Diagnostics Systems

Ingersoll-Dresser Pump has a remote pump monitoring system tradenamed PumpTrac® which provides for the collection of vibration data, physical process variables including pressure, flow, temperature and motor amperage. The monitoring systems provide for the trending and data logging of input variables, an alarm mode for each variable and a phone modem connection for alerting a plant operator of an alarm. The system is able to provide pump variable monitoring for up to eight pumps.

Ingersoll-Dresser's PumpTrac Remote Pump Monitoring System has a hardened pump diagnostics system with I/O that displays local trending data of the input sensors, typically pump inlet and outlet pressures, process and gearbox oil temperatures, flow and vibration condition monitoring sensors. The display provides trend displays for each variable with the ability to display multiple windows so visual correlation of process variable trends with vibration can be made.

Further, the Ingersoll-Dresser system has the ability to set soft alarm points that can be actuated when an alarm point is exceeded. In one option, a soft alarm can actuate a traditional modem built into the system to call a predetermined number to indicate what variable has been exceeded with data messages or a pre-recorded message.

The Ingersoll-Dresser device requires AC power and a dedicated telephone line. The system is not networked with process industry standard protocols and the use of AC power prevents certification to industry electrical intrinsic safety standards.

The Ingersoll-Dresser PumpTrac system provides the variables needed to establish a pump performance curve described in the present application, but does not provide the pump curve. However, the PumpTrac system does not provide for use of the secondary performance curves which provides a basis for root cause analysis of pump component failures, which is described in the method herein.

f. Field Diagnostics Systems

Field diagnostics systems are known for air operated valves and motor operated valves such as commercial systems available from Framatome, ABB, Liberty Technologies and Fisher Controls. There is no known field diagnostic for rotating equipment.

g. Point Diagnostics Devices

Several manufacturers provide sensors that can be applied to a pump system for the partial determination of pump health. These sensors may measure the corrosion of the pump casing based on a thickness measurement through ultrasonic thickness detection systems such as those manufactured by Stresstel, or by corrosion sensors such as those manufactured by Diagnetics. Similar portable monitoring devices, such as manufactured by Vibrametrics, provide point measurements of pump casing corrosion and thickness.

Pump and gearbox oil contamination and breakdown are commonly known problems with pump systems. In situ measurements of oil conditions can be provided by devices such as the Digital Contamination Alert particle counter provided by Diagnetics or through taking oil samples for off-line laboratory analysis.

High bearing stress resulting from operation outside said design regime will lead to bearing degradation. Bearing degradation can be detected via vibration monitoring. If degradation is severe enough, bearings will exhibit wear, which can be detected by oil sample analysis for wear particles.

None of these techniques identify improper operation which results in equipment stress leading to progressive damage, and ultimately, failure.

h. Need For Root Cause Analysis Method and Apparatus

Consequently, there is needed a rotating equipment diagnostic method and apparatus that identifies the operating conditions which create damaging stress to said equipment.

Further, there is needed a diagnostic method and apparatus that is effective in determining the root cause for bearing failure of rotating equipment. Additionally, there is a need for a diagnostic method that provides guidance in the repair of a failing pump by supplying the root cause analysis to an operator. By supplying root cause analysis to an operator, the diagnostic method enables elimination of the cause of failure.

Further, a system that has the ability to look at the influence of a load from a rotating machine.

A system is further needed that uses a pump performance curve as a method for diagnosing possible operating conditions outside of the recognized, recommended operating design regime or BEP.

Still further, there is a need for a system that does not require large and expensive artificial intelligence computing workstations yet still accomplishes the forgoing function.

There is further a need for a second level of pump component diagnosis that provides an ability to conduct root cause analysis of a pump or rotating equipment failure or an operating condition responsible for the failure.

SUMMARY OF THE INVENTION

The present invention provides an apparatus for a diagnostics system for rotating equipment commonly used in the process control industry. Also provided is a method for diagnosing rotating equipment commonly used in the factory and process control industry.

a. Apparatus

The system apparatus is intended to provide diagnostics of impending failure of turbines, compressors, fans, blowers, generators and pumps. The system can be effectively used for validating correct installation of a rotating machine and ancillary equipment attached to the machine. The system may also be used to diagnose change in the operating condition of a system for purposes of diagnosing maintenance and/or diagnosing change in the operation and control of the system. Additionally, the system may be used to verify that maintenance was properly conducted through a validation of the performance signature curves on the newly installed equipment, and acquisition of equipment base line performance data for use with maintenance information systems to provide a maintenance records audit trail. Further, the system may be used for continuous monitoring of rotating machine health and for advising a control system operator of operation outside of a recommended design regime or BEP operation to provide the opportunity to correct the machines operation conditions to BEP regime for reducing pump wear.

The apparatus can be applied to diagnose any rotating machine. However, the preferred embodiment of this apparatus is for the diagnosis of a pump system.

Thus, the present invention is a rotating equipment or pump diagnostics system intended to provide field diagnosis of a rotating equipment or pump system, which includes rotating equipment, such as a pump and, optionally, rotating equipment or pump system ancillary components, such as a coupler for connecting the rotating equipment to a driver source, or pump to a driver source or gear box and a driver source and a driver source controller. The driver source is typically an electric motor, diesel engine or turbine, and the driver source controller is typically a motor control system or variable speed drive and measurement devices for key process and equipment monitoring variables.

The pump diagnostics method will be most frequently embedded in firmware resident in a microcontroller in the pump diagnostics apparatus.

Four embodiments of the pump diagnosis apparatus are envisioned. The embodiments will have a common set of core elements, with additional elements provided to optimize the apparatus for its intended end use.

Apparatus Common Elements.

Elements common to all of the apparatus embodiments described include:

(a) sensors for process control variables and condition monitoring and Input/Output (I/O);

(b) A/D converters and signal conditioning appropriate to the type of sensor;

(c) a microcontroller (μC) for providing signal reduction and execution of the method described in the Pump Diagnosis Method;

(d) an output device;

(e) memory for storage of tables, logging data, and storing the data and pump signatures resulting from the method;

(f) tables of pumped fluid properties, tables of rotating machine geometry and installation dimensions; and

(g) a data input device.

The four embodiments of the apparatus include: (a) a portable, battery powered field diagnostics apparatus; (b) a field-hardened, remote powered, networked diagnostics apparatus; (c) a diagnostics apparatus with controller; and (d) a diagnostic apparatus with host computer.

Portable Battery-Powered Field Diagnostics Apparatus.

The portable, battery powered field diagnostics apparatus preferably may be a laptop computer, field hardened smart terminal, pen operating system based terminal, or Apple Newton®, etc. The field diagnostics apparatus preferably has sensors, I/O, A/D converters, a microcontroller for executing the required signal conditioning and method described herein, memory, fluid property tables, rotating machine dimensional and performance signatures, installation geometry tables, an input device (keypad) and a display and optionally a network connector. The primary end use of this apparatus will be to guide field repair of a rotating machine and for validation of a successful repair and installation.

Field Hardened, Remote Powered Network Monitoring Apparatus.

The field hardened, continuously monitoring apparatus is comprised of sensors, I/O, A/D converters, a microcontroller for executing the method, a communication port for connecting the apparatus to a host computer, memory, data logging, and communication capability for real time acquisition and diagnosis of the rotating machine, and optionally for a remote display or host displaying the pump signatures.

The field hardened, remote powered, network monitoring apparatus may be either a 2-wire powered apparatus, common to the process control business, a multi-wire communicating DC powered apparatus or an AC powered communicating apparatus. A special embodiment of the field mounted apparatus will include the ability to power the apparatus and communicate with the apparatus over a standard 2-wire system with a variety of communication protocols. Examples of communication protocols include HART, Foundation Fieldbus, PROFIBUS Pa., Ethernet TCP/IP and proprietary protocols such as Honeywell's Del., Yokogawa's Brain, Foxboro's Foxnet, etc.

The 2-wire embodiment includes a field hardened enclosure and is powered with a DC power supply used with 2-wire communication systems and is capable of complying with industry standard (FM, CSA, CENELEC, etc.) safety requirements for intrinsic safety and explosion proof certifications. The 2-wire apparatus has a subset of the total functionality described due to a power limit (typically 10 volts and 4 ma for HART and up to 50 ma and 9 volts for fieldbus) required by safety standards.

A second embodiment of the field mounted and hardened apparatus is a multi-wire communicating apparatus. The multi-wire communicating apparatus provides DC power at a higher power level than is used for intrinsic safety standards, but is in compliance with wire industry standard protocols such as Modbus (RS232, RS485), Foundation Fieldbus H2, Profibus FMS, Ethernet TCP/IP, ControlNet etc. In the multi-wire communicating apparatus embodiment, power is provided over one set of wires from a remote power supply. Communication is provided over the remaining wires using industry standard protocols. This version of the apparatus typically will be safety certifiable only for "Explosion Proof" based on the design of the mechanical enclosure provided to house the electronics.

An AC powered (120V or 220V) embodiment is also possible as is utilized in Ingersoll-Dresser Pump's Remote Pump Monitoring System, trademarked PumpTrac (1995).

Diagnostics Apparatus with Process Controller.

A third embodiment of the apparatus is a controller typically found in process plants. Typical controllers that could be used with modification for a rotating machine apparatus diagnosis include: motor controllers found in motor control centers used to control motor/pump systems, variable speed drive controllers, DCS system controllers, programmable logic controllers (PLC's), compressor or turbine control systems, single or multiloop controllers, etc.

Diagnostic Apparatus—Host Computer.

A fourth embodiment of the apparatus is a host computer typically used for maintenance information systems. The apparatus includes sensors or data from sensors gathered from a database (data historian from a digital control system), I/O and AID converters as appropriate, a microprocessor with the pump diagnostics method, a database for storing pump diagnostic results, alarm and alert management system, communications for networking with other host computers, such as DCS, a maintenance engineer's PC via an Ethernet TCP/IP network, the Internet, or the plant information management (IS) system network.

b. Method.

The method of the present invention may be used to assist a maintenance engineer in the diagnosis of rotating equipment including turbines, compressors, fans, blowers and pumps. The preferred embodiment is a method for diagnosing pumps of all types; constant head pumps such as positive displacement or reciprocating pumps and in particular, variable head centrifugal pumps.

The method is based on the use of the pump performance curve as the basis for determining the degradation of the pump due to off design operation; fluid damage from erosion, cavitation and recirculation; and through normal wear and tear.

The primary "pump performance curve" and pump "head curve" is well known in the industry and for purposes of this patent will include the relationships between the dependent head or pressure and the independent variable, flow. This relationships are traditionally plotted on a graph, with the dependent pump performance variables plotted on the ordinate and flow, the independent variable plotted on the abscissa.

Additional variables may also be plotted versus flow, and for purposes of this method will be described as "secondary performance curves". For purposes of this patent, "secondary performance curves" will include, but are not limited to the relationships between the dependent pump performance variables, net positive suction head, brake horsepower, pump efficiency, thrust bearing force, radial bearing force, motor torque, pump specific speed, dynamic pressure, net positive suction head available, etc. all plotted vs flow, the independent variable. These secondary curves provide a basis for root cause analysis of pump component failures.

The method is based on a comparison of the current pump signature curves and operating point resulting from the acquisition of process variables from sensors that measure a current condition of the rotating equipment or pump, and the original data in the form of an original or previous pump performance signature curves from prior monitoring, and knowledge of the rotating equipment or pump geometry, installation and piping geometry, ancillary equipment

knowledge and geometry, and properties of the pumped fluid. This diagnostics method can be applied to any rotating machine, but the method for pumps is described herein. The diagnostics method can be used in conjunction with an apparatus that provides for the acquisition of the required variables, the computation of the required pump signatures, operating points and curves, the display of computed variables, a logic element for deducing and diagnosing the pump by component, and optionally, a communication to a host computer.

The computing apparatus may be a portable, battery-powered field hardened PC with I/O for use in field diagnosis of the rotating machine, or a field mounted continuously monitoring apparatus with data I/O, logging, and communication capability for real time acquisition and diagnosis of the rotating machine, and optionally displaying the pump signatures on a remote display or host. The computing apparatus may also take the form of a host with I/O and a means of executing the claimed method. Hosts capable of using this method include a compressor or turbine control system, a maintenance information system, a personal computer, supervisory control and data acquisition system (SCADA) or a traditional process control system. The method may also be implemented in a motor controller or a PLC often used in a motor control center for the motor used to drive the pump.

The apparatus may also be used with more than one rotating machine or pumps through the multiplexing or networking of the sensors from multiple pumps.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a representation of a rotating machine and motor system.

FIG. **1***b* is a cross sectional view of the pump.

FIG. **2** is a schematic of diagnostic apparatus of the present invention.

FIG. **3** is a schematic of a field hardened remote embodiment of the invention.

FIG. **3***a* is a field hardened remote embodiment of the invention.

FIG. **4***a* is a pump diagnostic apparatus using a programmable logic controller (PLC) as a platform.

FIG. **4***b* is a pump diagnostic apparatus using a host computer as a platform.

FIG. **5** is a typical pump performance curve.

FIG. **6** is an original performance curve.

FIG. **6***a* is a pump performance curve at operating point.

FIG. **6***b* is a pump performance curve with operating point below BEP performance shifted downward.

FIG. **7***a* is a typical dynamic pressure sensor spectra.

FIG. **7***b* is a typical velocity and acceleration vibration spectra.

FIG. **7***c* is a $NPSH_{Avail}$ v. $NPSH_{Req'd}$ graph.

FIG. **7***d* is an H v Q curve illustrating a "droop" condition.

FIG. **8** is a graphical representation of spectra of same vibration source obtained from different types of transducers.

FIG. **9** is a graphical representation of data pump secondary performance curves.

FIG. **9***a* is a graphical representation of centrifugal pump secondary performance curves.

FIG. **9***b* is a graphical representation of positive displacement pump secondary performance curves.

FIG. **9***c* is a graphical representation of centrifugal dynamic pressure curves.

FIG. **10** is a flow chart representing one embodiment of the method of the invention.

FIGS. **11** through **41** are additional flow charts representing embodiments of the method of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

a. Apparatus

Referring to FIG. **1**, shown is a rotating machine and motor system designated generally **10**. It should be understood that the apparatus for diagnosing a rotating machine and motor system may be used to diagnose rotating equipment including pumps, turbines, fans, blowers, compressors or other types of equipment. A pump and motor system is shown in FIG. **1** for purposes of example only. Pump and motor system **10** includes motor **12** and a rotating machine or rotating equipment, such as pump **14**. Motor **12** may be an electric motor, diesel engine or turbine, or other power source. Motor **12** is operatively connected to rotating equipment **14** via coupler **16**. Rotating equipment **14** has inlet **18** and outlet **20**. Downstream from outlet **20** of rotating equipment **14** is typically provided a final control element, such as control valve **22**.

The diagnostic apparatus for one embodiment of the invention is designated generally **24** (FIG. **2**). The system can be used effectively used for:

a) validation of correct installation of pump **14** and ancillary equipment attached to pump **14**;

b) diagnosis of change in an operating condition of pump and motor system **10** for purposes of maintenance and for changing the operation and control of pump and motor system **10**;

c) verification that maintenance was properly conducted through a validation of the correct dynamic performance of the repaired equipment; and

d) collection of equipment base line or original performance data for use with maintenance information systems to provide an audit trail of maintenance records.

Diagnostics apparatus **24** can be applied to any rotating equipment. However, the preferred embodiment of this apparatus is the diagnosis of the centrifugal pump. Diagnostic apparatus **24** includes process sensors for measuring process conditions and for generating process variables, which are key to determining a change or degradation of performance of pump and motor system **10**. Sensors, including process sensors, may communicate variables and diagnostics parameters via a network connection to a host computer including digital control systems (DCS's) such as the Foxboro I/A®, supervisory control and data acquisition (SCADA) systems such as that provided by the Intellution Fix®, or a maintenance information system such as that provided by the SAP for the purpose of providing predictive and preventative maintenance information. Process sensors may include outlet pressure sensor **26**, shown in FIG. **1**, which is positioned proximate outlet **20** of pump **14**, for determining pump outlet pressure. Process sensors may also include flowmeter **28** for determining a flow rate of product downstream of rotating machine **14**, or other sensors for monitoring process conditions.

Further examples of process sensors include temperature sensing device **30**, which is approximately positioned upstream or downstream of rotating machine **14** for determining temperature of a process fluid; inlet pressure sensor **32**, which is positioned proximate rotating equipment inlet

18 of rotating machine 14 for determining rotating machine inlet pressure; and valve position sensor 34. Valve position sensor 34 is preferably mounted on control valve 22 and communicates with input/output device 36 for converting electrical signals to digital signals. Valve position sensor 34 is provided to determine the position of a control valve or shaft. Additionally, valve position sensor 34 provides input for a method to calculating flow through pump or rotating equipment 14. The flow through valve 22 can be calculated from the valve position, the pressure drop across the valve and known fluid properties and geometry from the valve supplier. The flow through valve 22 may then be and stored as original data. This information enables a baseline head vs. flow (H v Q) performance reference curve to be developed in the absence of a flowmeter. Additionally, knowledge of valve position provided by valve position sensor 34 is used to alert possible deadheading of pump or rotating equipment 14.

Input/output device 36 of diagnostic apparatus 24 communicates with process sensors for receiving process variables therefrom. Input/output device 36 transmits process variables received from process sensors to computing device 38.

The computing apparatus may be:

a) a portable, battery powered field hardened PC with I/O for use in field diagnosis of the rotating machine, shown in FIG. 2, or

b) a field mounted continuously monitoring apparatus, shown schematically in FIG. 3, with data I/O, logging, and communication capability for real time acquisition and diagnosis of the rotating machine, and optionally displaying the pump signatures on a remote display or host, shown in system with a remote host in FIG. 3*a*, or

c) a host with I/O shown in FIG. 4*b* and a means of executing the method described herein. Hosts capable of using this method include a compressor or turbine control system, a programmable logic controller (PLC), a maintenance information system, a personal computer, supervisory control and data acquisition system (SCADA) or a traditional process control system, or

d) the method may be implemented in a motor controller or a PLC, shown in FIG. 4*a*, often used in a motor control center for the motor used to drive the pump.

FIG. 2 is a schematic of diagnostic apparatus 24. Box 40 represents pump and motor system 10. Data is shown being transmitted from pump and motor system box 40, as represented by a plurality of arrows generally designated 42. Examples of data being transmitted include process variables generated by process sensors and condition monitoring variables generated by machine sensors, to be discussed below. Data is transmitted to a sensor excitation and conversion device, represented by box 44. Converted data signals are then transmitted from sensor excitation and conversion device 44 to signal multiplexers, represented by box 46. Alternately, the sensor inputs may be inputted directly to the A/D converter shown in box 52.

Sensor data may be multiplexed to microprocessor 48 to provide for asynchronous measurement of selected inputs which are not time critical or do not need to be sampled continuously. Converted data transmitted by sensor excitation and conversion device 44 to signal multiplexers 46 is represented by arrows, designated generally 50. From signal multiplexers 46, data is then preferably transmitted to an A/D converter, such as those manufactured by Analog Devices and Crystal Semiconductor, represented by box 52. Examples of microprocessor 48 include Motorola's 16-bit 68 HC16 or 32-bit LC302. D/A converter, represented by box 54, is provided in the preferred embodiment so that microprocessor 48 may communicate with the pump and motor system, represented by box 40. Diagnostic apparatus 24 may also include a real time clock 59 with optional battery backup that can be used to time stamp data acquired synchronously or asynchronously. Real time data may be alternatively acquired via the network 115 from a host computer as is provided with Foundation Fieldbus or Ethernet networking technology.

In the preferred embodiment, microprocessor 48 is in communication with memory storage 56, co-processor 58, and a disk drive or other data storage or retrieval means 60. Co-processor 58 is optional. Examples of a suitable co-processor include Texas Instrument's DSP microcontroller, with embedded frequency analysis algorithms such as fast fourier transform (FFT) or wavelets. Co-processor 58 may be provided to process spectral data from sensors such as accelerometers. The co-processor is used to off load microprocessor 48. Additionally, diagnostic apparatus 24 may be provided with the following: an A/C power supply receiving device 62, as is commonly known in the art; charger 64; battery 66; power supply 68, commonly known in the art; communication receiving device 70; keypad 72; keyboard 74; and an output device, such as printer 76 and CRT display 78.

In the preferred operation of diagnostic apparatus 24, microcomputing device 48 receives data 42 from input/output device 36 and stores data in memory storage 56. To establish an original condition, original data must be entered into memory storage 56. For purposes of this application, original data includes tables of machine geometry, machine installation parameters, ancillary equipment parameters original performance curves and fluid properties of the pumped product, as well as previous condition data. Previous condition data refers to data gathered in a previous set of measurements that is stored for retrieval and comparison purposes. Therefore, measured data, including process variables and condition monitoring variables, may be compared to original data to determine performance deterioration of rotating machine and motor system 10. Microprocessor device 48 of diagnostic apparatus 24 compares measured data with original data for generating an output via printer 76, CRT display 78 or other output devices based on the comparison.

Referring again to FIG. 1, in the preferred embodiment diagnostic apparatus further comprises machine sensors for generating condition monitoring variables. Machine sensors allow data to be gathered from individual components for determining specific problems with pump and motor system 10. Computing device 38 is used to compare condition monitoring variables with stored original data for diagnosing rotating equipment degradation and for generating an output based upon that comparison. A discussion of various types of machine sensors follows.

Machine sensors may include rotating equipment vibration sensor 80, which is preferably mounted on rotating equipment 14 for determining vibration of rotating equipment 14. Vibration sensor 80 is in communication with input/output device 36 for providing condition monitoring variables to computing device 38. A further machine sensor is dynamic pressure sensor 82, which is positioned in the product fluid stream downstream from rotating equipment outlet 20 or positioned within rotating equipment casing 84 of rotating equipment 14 and is in contact with the process fluid.

Diagnostic apparatus 24 (FIG. 2) may include additional machine sensors, including motor vibration sensor 86, which

is preferably mounted proximate a bearing for determining bearing vibration. Motor vibration sensor **86** is preferably in communication with input/output device **36** for providing condition monitoring variables thereto.

By receiving data from gearbox vibration sensor **88**, which is mounted proximate gearbox **87** of rotating equipment **14**, and from motor supply sensor **90**, which senses motor current and motor voltage, and from alignment sensor **92**, diagnostic apparatus **24** may diagnose whether rotating equipment **14** requires impending maintenance.

Diagnostic apparatus **24** may also include rotating machine seal leakage detector or sensor **94**. Seal leakage sensor **94** is mounted proximate a shaft seal on rotating machine **14** for detecting seal leakage. Seal leakage sensor **94** provides condition monitoring variables to input/output device **36** for providing computing device **38** with condition monitoring variables.

Diagnostic apparatus **24** may include additional machine sensors, such as oil contamination sensor **96**. Oil contamination sensor **96** is preferably mounted in gearbox **87** or on an oil sump for detecting oil contamination. Oil contamination sensor **96** provides condition monitoring variables to input/output device **36** for providing computing device **38** with condition monitoring variables.

Additional machine sensors, such as viscosity degradation sensor **98**, may also be provided. Viscosity degradation sensor **98** is preferably mounted proximate a gearbox for detecting oil viscosity degradation. Oil viscosity degradation sensor **98** is for providing computing device **38** with an oil condition monitoring variable.

Additional machine sensors include torque sensor **100**, which is preferably mounted proximate to the shaft of rotating machine **14**. Torque sensor **100** is in communication with input/output device **36** for providing computing device **38** with torque data. Machine sensors may also include angular velocity sensor **102**, preferably mounted proximate to shaft of rotating machine **14**. Angular velocity sensor **102** is in communication with input/output device **36** for providing computing device **38** with angular velocity data for computing input power to rotating machine **14** and computing the output fluid power of rotating machine **14** and the efficiency of rotating machine **14**.

Additional machine sensors include corrosion sensor **104**. Preferably, corrosion sensor **104** is mounted on rotating machine casing **84** for measuring degradation of rotating machine casing **84** resulting from undesirable conditions, such as corrosion, pump cavitation or erosion. Corrosion sensor **104** is preferably in communication with input/output device **36** for providing condition monitoring variables thereto. A typical corrosion sensor uses electrical potential generated by corrosion to provide a voltage measurement. Corrosion sensor **104** can be located anywhere in rotating equipment **14** of pump and motor system **10** where high corrosion is expected, e.g., a thin section or areas of high flow.

Further machine sensors include ultrasonic thickness sensor **106**. Ultra-sonic thickness sensor **106** is preferably mounted on rotating machine casing **84** for measuring degradation of rotating machine casing **84** from undesirable conditions such as corrosion, pump cavitation or erosion. Ultrasonic thickness sensor **106** is preferably in communication with input/output device **36** for providing condition monitoring variables thereto.

Additional machine sensors include accelerometer **108**, bearing temperature sensor **110**, bearing vibration sensor **112**, and axial displacement sensor **113**.

Diagnostic apparatus **24** may be configured in one of two classes. In a first class, embedded systems, such as microcontrollers, contain software that is burned into the chip's logic, i.e., firmware. The embedded system provides a software instruction set which is permanent. Embedded systems are used in a field hardened embodiment of diagnostic apparatus **24**, discussed below.

Another form of the embedded system embodiment uses downloadable executable code in electrically alterable memory such as EEPROM or FLASH for equipment identification numbers, specific flow data—fluid parameters, pump performance curves, etc.

A second class of diagnostic apparatus comprises a real time computing platform. Configurable logic will normally be remotely located in a computing host. Examples include personal computers, workstations, PLC, DCS, and minicomputers. A secondary form of this real time computing platform is a portable real time computing platform. A portable computing device allows testing to be performed near pump and motor system **10**, thereby allowing for observation of the equipment. In one embodiment of the invention, diagnostics apparatus **114**, FIG. **3**, operates via a bus wherein there exists no central controller. Such a system is provided with the enhanced digital HART protocol, proprietary protocols, such as Honeywell's Del., Yokogawa's Brain, proprietary protocols as provided by Bailey and Foxboro for their field instruments, and emerging field buses such as Foundation Fieldbus, Profibus, or World FIP, Ethernet, etc.

In a more fully featured embodiment shown in FIG. **3***a*, the diagnostic apparatus **24** is powered by and communicates over a multi-wire network, such as a three-wire network in which DC power **117** is remotely provided over a separate set of wires or a four-wire network in which DC power is remotely provided over a separate set of wires. Protocols typically used include Modbus (RS232 and RS485), Foundation Fieldbus H2, Profibus H2, and Ethernet, I/P, TCP/IP, UDP/IP, etc.

In one embodiment of the invention, shown in FIG. **1**, machine sensors are integrated with input/output device **36** and computing device **38** for comparing measured performance signatures of rotating machine **14** at a second time with an original condition signature at a first time for diagnosing degradation of rotating machine performance. In the preferred embodiment, process sensors and machine sensors are electrically isolated from the apparatus. Comment: Electrical isolation is well known. It is accomplished with transformers or optically with OPTO/couplers.

In another embodiment of the invention, shown in FIG. **4***a*, a PLC is used as the diagnostic apparatus platform, and the PLC's microcontroller **188**, which is positioned proximate rotating machine **14** for controlling rotating machine **14**. For example, microcontroller **188** may control rotating machine **14** by issuing a control set point to control valve **22**, I/P **35**. Preferably, microcontroller **188** possesses firmware for providing instructions to rotating machine **14**.

A further embodiment of the invention, shown in FIG. **3***a*, provides that field hardened computing device **114** of diagnostic apparatus **24** is positioned proximate rotating machine **14** and that computing device **114** provides a control signed to the control valve **22** or variable speed drive. By providing that diagnostic apparatus **114** controls the process as a hardware platform, one benefit is the ability to utilize a combination of known condition monitoring variables, e.g., vibration variables from machine sensors, with process variables from process sensors. Process sensors provide information about the performance of pump and motor system **10**. Machine sensors provide knowledge of the health of rotating equipment and motor system **10**. Examples of machine sensors that provide vibration vari-

ables include motor vibration sensor **86** or bearing vibration sensor **112**. When known condition monitoring variables and process variables are combined, decisions can be made through logical deduction about the condition of pump and motor system **10**, the process and the ability of pump and motor **10** to provide its intended function.

Referring now to FIG. **3**, a field hardened remote embodiment of the invention is shown. Field hardened computing device, designated generally **114**, of diagnostic apparatus **24** is designed to be positioned proximate rotating machine **14**.

Field hardened, networked diagnostic apparatus **114** may be used with pumps using standard communication protocols used in the process control and factory automation industries.

Preferably, field hardened apparatus **114** is configured to download executable code specific to a particular rotating machine **14** for operating rotating machine **14**. Field hardened remote embodiment **114** is preferably encased in field hardened enclosure **116**, is remote-powered, and is a networked. In a preferred embodiment, field hardened computing device **114** has digital communications with a network **146** and serves both as a publisher and a subscriber of data over the network. Preferably, field hardened computing device **114** is powered by a remote power supply **115**, shown in FIG. **3***a*. The field hardened embodiment is preferably designed for operation in inclement environments without additional protection. The device may be mounted on or proximate to the pump or other rotating machine **14** and should be designed to withstand high humidity, extreme temperatures, high EMF (electrical noise), rain and snow and other harsh environmental conditions. Additionally, field hardened apparatus **114** should be provided with explosion-proof protection, i.e., be designed not to cause a spark or explosion in hazardous gases. Such an apparatus may be powered by and communicate over a two-wire loop.

The process control industry routinely uses field-hardened sensors, actuators, and instruments that are remotely powered with a DC power supply **115** (typically 12–24 V) over a twisted shielded pair of wires. Communication is also provided in a full duplex fashion with process industry protocols to and from the field device from host computers such as a PLC or DCS.

Field hardened apparatus **114** is preferably capable of satisfying international safety standards for electronic apparatus such as FM, SAA, JIS, CENELEC, and CSA two-wire intrinsic safety and explosion proof devices. Field hardened enclosure **116** is also preferably moisture proof (NEMA **4**) and capable of achieving IEC CE mark requirements for heavy industry electrical field mounted instruments. Intrinsic safety standards limit the available power to the field device to avoid ignition of hazardous or flammable gases that may be in the area near the device. Use of low power consumption electronics and microcontrollers is essential to meet these safety requirements.

Field hardened apparatus **114**, shown in FIG. **3**, is encased in field hardened enclosure **116**, and receives data from process and machine sensors, designated generally **118**. Data received from process and machine sensors **118** is represented by arrows designated generally **120**, and is transmitted to I/O, **121** and then to an excitation and conversion device, represented by box **122**. Converted data signals are then preferably transmitted from sensor excitation and conversion device **122** to signal multiplexers, represented by box **124**. Converted data is then preferably transmitted to an A/D converter, represented by box **126**, which communicates with microcontroller **128**. Conditioned sensor data signals may be optionally transmitted directly to an A/D converter **126** without use of the multiplexer **124**. Microcontroller **128** is preferably in communication with co-processor **130**, which has the ability to time-stamp data received. ROM **127** communicates with A/D converter **126**, microcontroller **128** and co-processor **130** for providing instructions. Time-stamping of data is facilitated by an optional real time clock **132**. Additionally, microcontroller **128** is in communication with electrically alternatable memory **134** for acquisition of pump system, fluid property, pump signature data. Communications device **136** is in communication with microcontroller **128** for transmitting information to a network. Finally, in the preferred embodiment, field hardened apparatus **114** is provided with display **138** so that an operator can get information from the device in the field. An optional communication port **146** permits data transfer from handheld vibration monitors **142** or pump diagnostic subsystems **150**.

Referring now to FIG. **4***a*, an additional embodiment of diagnostic apparatus **24** uses a programmable logic controller (PLC) **240** as a platform. Programmable logic controllers are commonly used for control in factory and process control applications and are frequently used for motor control in motor control centers. PLCs by construction provide I/O, the ability to power sensors and actuators through the I/O, A/D converters and a microcontroller with configurable logic algorithms. PLCs also have communication interfaces **190** with standard process control protocols as well as support for remote PC hosts and printers. PLC logic is often configured using a HMI 194 such as those provided by S-S Technologies as well as PLC manufacturers such as Allen Bradley or Siemens. The PLC has all of the necessary elements for implementing the disclosed diagnostic method.

The shortcomings of a PLC implementation include the inability to obtain intrinsic safety (two-wire) approvals due to the high power consumption of a PLC and the need to house a PLC in a Division II, sheltered environment. The PLC does, however, provide an ideal platform for the diagnostics method as it is a cost effective package for the necessary elements and has the ability to provide the logic configuration needed for the pump diagnostics method. Further, the diagnostics method running on the PLC can provide the diagnostics alerts **154** for off-BEP operation of a pump so that operator could provide immediate corrective control action to operate the pump in a BEP regime through a change in the control set point.

In this embodiment, shown in FIG. **4***a*, diagnostic apparatus **240** uses a PLC platform for providing sensor I/O, A/D conversion and signal conditioning. The PLC platform additionally provides microcontroller **188** and method logical elements that are embedded in firmware resident in the PLC's microcontroller **188**. This embodiment further includes a PLC output **192** and communication network port **190**.

Additionally, this embodiment of diagnostic apparatus **240** may further include logic configurator **194** for establishing pump method logic in PLC language and for downloading pump logic into PLC microcontroller **188**. Examples of logic include ladder logic, sequence charts, function blocks, etc. The apparatus may further include a function block with sensor inputs, outputs, alerts and the pump method.

A further embodiment of diagnostic apparatus **240**, shown in FIG. **4***b*, wherein a host computer **236** is used as the platform. A host computer is most often used for maintenance information or maintenance systems, but may also be the DCS control system. The apparatus will include sensors

or data from sensors gathered through from a database (data historian from a digital control system) **210**, I/O **228** and A/D converters as appropriate **238**, a microprocessor with the pump diagnostics method, a database for storing pump diagnostic results **210**, alarm and alert management system, communications **212** for networking with other host computers **256**, such as DCS, maintenance engineer's PC via an Ethernet TCP/IP network, the Internet, or the plant information management (IS) system network.

The host computer embodiment of diagnostic apparatus **240** acquires sensor input via point-to-point or multidrop wired sensors or transmitters such as **32**, **28**, **26**, and **30**, wired to I/O **228**, which provide conversion and networks digital sensor data via a bus to the microprocessor based host. Sensor data may be alternatively gathered via a bussed sensor network **230** commonly called fieldbus.

Commercial workstations, PCs, and servers like the IBM 400 are the preferred computing platforms for maintenance information systems. I/O interfaces with appropriate A/D converters and signal conditioning which convert the required sensors (physical and condition monitoring) to digital data are readily available from companies like GE Fanuc and National Instruments. The maintenance information system can process sensor inputs using diagnostics methods within the workstation or PC microprocessor. Plug-in communication output boards are readily available from National Instruments for the many process communication protocols, and can be readily networked with the DCS or maintenance engineer's PC with Ethernet TCP/IP based network protocols.

Host computers are able to share data over a network connection through the use and support of standard data sharing network services such as those provided by Microsoft's Windows environment through OLE, OPC, JAVA, netDDE, DDE and to databases through standard database services like ODBC, OLEDB, SQLSERVER, etc.

In the host computer platform embodiment, shown in FIG. **4***b*, the diagnostic apparatus **236** may further include sensors wired to a central input/output **228**, A/D card **238** with sensor signal conditioning, a card connection to an input/output network, sensor input/output network **240**, such as a DCS data highway, computer **236**, such as a PC DCS workstation, etc., that includes data input bus **240**, computing element, memory, input device, such as a keyboard, network communications, a display **224**, data storage **210**, real time clock, and a software-based implementation of the pump method.

Diagnostic apparatus **236** preferably includes an alert device that responds to a condition of rotating equipment **14**. An alert is transmitted to a host computer **256** via the network **212**.

Apparatus may further include network services, such as OLE, OPC, Net DDE, or ODBC, for publishing pump data and alerts with software applications resident on the computer.

In the preferred embodiment, shown in FIG. **3***a*, diagnostic apparatus **114** possesses communication port **70** for importing condition monitoring variables from portable hand-held data logging device **142**. Examples of data logging devices include hand-held vibration monitoring systems, oil analysis devices, corrosion and ultra-sonic thickness gauges, etc. Preferably, portable hand-held data logging device **142** possess a database for storing the input devices. Additionally, portable hand-held data logging devices **142** may use an intelligent network device.

Diagnostic apparatus **114** may additionally possess process communication port **70** for communicating with intelligent network devices. Examples include Hart, Foundation Fieldbus, Profibus, Modbus, Ethernet TCP/IP, etc. An example of an intelligent network device for communicating with process variable digital bus **70** includes a control valve position sensor **34**, shown in FIG. **3***a*.

Diagnostic apparatus **114** may further include monitoring system digital bus **146** for communicating with intelligent network devices having computing engines for collecting condition monitoring variables.

In one embodiment of the invention, diagnostic apparatus **114** includes condition monitoring subsystems **150** for rotating machine **14**. The apparatus can serve to collect data from other smart diagnostics subsystems such as a smart motor and provide a database for the entire rotating equipment system over a network for analysis by others with a maintenance information system, expert system, control system or SCADA system. Condition monitoring subsystems **150** are interfaced with computing device **114** via standard communication network interfaces for transmitting subsystem data over a standard communication network. Examples of condition monitoring subsystems include a Bentley Nevada Trendmaster 2000, a smart motor, and gearbox condition monitoring system and Fisher Controls Fieldvue® valve diagnostics system. A Bentley Nevada system is primarily used with compressors and steam turbines for determining vibration and uses a proximity sensor positioned near a shaft for determining eccentricity or orbit of the shaft in the bearing.

In a further embodiment of the invention, diagnostic apparatus **114** comprises external processed data storage device **152** for storing subsystem data. The storage of subsystem data is necessary when diagnostic apparatus **114** is a network client having a memory database for storing data from a network rotating machine subsystem. In this embodiment, subsystem data is stored as a substitute for direct sensor or pump subsystem component condition monitoring inputs. If any other subsystem is analyzed, then data must be stored. Otherwise, diagnostic apparatus **114** must include its own sensors. One reason that subsystem data must be stored is that a subsystem may already have a fast fourier transform (FFT). Therefore, this embodiment of diagnostic apparatus **114** must treat data differently since information has already been preprocessed.

In the embodiment of the invention, schematic FIG. **3** shows co-processor **158** of diagnostic apparatus **114** is in communication with microcontroller **128** for providing spectral signal reduction of condition monitoring variables from the frequency domain sensors **118**. These include pump vibration sensor **80**, motor vibration sensor **110**, dynamic pressure sensor **82**, and bearing vibration sensor **112**, shown in FIG. **1**.

Further examining the diagnostic apparatus schematic, FIG. **3**, diagnostic apparatus **114** is preferably provided with alert device **154** for indicating when undesirable equipment conditions occur. Undesirable equipment conditions are determined by comparing process or equipment conditions with user configured levels for sensor-computed variables or high limits. Examples of undesirable equipment conditions include vibration levels that exceed the manufacturer's recommended amplitude levels.

In one embodiment, when an alert indicates an undesirable equipment condition, an optional contact closure **156** is provided to shut down pump and motor system. Contact closure **156** is located in diagnostic apparatus **114** to switch voltage or current to provide an alert or safe equipment operation. For example, in one embodiment, contact closure **156** is always "ON" and disconnects when an alert is

generated. Conversely, contact closure **156** may default to the "OFF" position and connect when an alert is generated. Other uses for contact closures include lighting a warning light, disconnecting a motor, reducing power to a motor, etc. If a variable speed drive motor is utilized, contact closure **156** can be located proximate the motor or may be positioned in a control room. The combination of contact closure **156** with diagnostics results in improved control of the pump and motor system **10**.

FIG. **3***a* shows field hardened apparatus **114**, in a process control system connected to an host computer, **236**, typically a DCS system.

Diagnostic apparatus **114** may additionally include a final control element, such as control valve **22** whereby the final control element is responsive to the output communication **70** generated by computing device **38** for operating pump **14** and motor system **12** in a recommended operating design regime. A final control element is typically used to control flow through pump **14** to meet piping and process system requirements, and may be used to conduct tests required to generate a performance curve. Closing control valve **22** by providing an output signal to the valve I/P **35** increases resistance and causes rotating equipment or pump **14** to operate at a higher pressure and a lower flow rate. Similarly, opening control valve **22** results in reduced system resistance, increased flow and lowering pressure.

Another example of a final control element is a variable speed drive connected to the pump which may be used as a controller. A variable speed drive works to provide a required flow and pressure demand by adjusting the speed of the rotating equipment **14**.

FIG. **3** shows diagnostic apparatus **114** includes, in the preferred embodiment, optional real time clock **132** in communication with computing device **128**, for time stamping process variables and original data for time-based comparisons.

Diagnostic apparatus **114** may further comprise a display for displaying a performance signature at a first time and at a second time.

In an additional embodiment shown in FIG. **2**, diagnostic apparatus **24** is a portable battery-powered field apparatus. In this embodiment, diagnostic apparatus **24** further includes co-processor **58** which contains a software resident spectral analysis engine **158**. Spectral analysis engine **158** is for processing signals from frequency domain sensors. Frequency domain sensors include rotating equipment vibration sensor **80** and dynamic pressure sensor **82**, as well as motor vibration sensor **110** and bearing vibration sensor **112**. Co-processor **58** receives data from microprocessor **48** or directly from frequency domain sensors.

Diagnostic apparatus **24** may also include a network communication port **160**. Network communication port **160** is for communication with portable vibration monitor **142** for communicating output from computing device **48** to a network **115**, and communication device **70** for communicating data from computing device **48** to a networked host.

b. Method

The method of practicing the invention enables diagnosis of rotating equipment commonly used in the factory and process control industry. The method is intended to be used to assist a maintenance engineer in the diagnosis of turbines, compressors, fans, blowers and pumps. The preferred embodiment is a method for diagnosing pumps, particularly centrifugal pumps.

The method of the invention is based on a comparison of measured pump signature curves resulting from the acquisition of process variables from sensors monitoring a current condition of the pump and the original or previous pump performance curve from prior monitoring or knowledge of pump geometry, installation data, ancillary equipment data and properties of pumped process liquid.

The diagnostics method can be used in conjunction with diagnostic apparatus **24**, shown in FIG. **2**, apparatus **114** shown in FIGS. **3** and **3**a, PLC apparatus shown in FIG. **4***a* or PC host **236** shown in FIG. **4***b*, which provides for the acquisition of process and condition monitoring variables, the computation of the required pump signatures and curves, the display of the computed curves, a logic element for deducing and diagnosing the pump by component, and optionally a communication to a host computer.

The method of the invention identifies and interprets changes in the performance curve, or pump performance curve, by monitoring and analyzing key pump conditions. Typical pump performance curves are shown in FIG. **5**. Changes in the pump performance curve may be used to diagnose a root cause of pump component failures. The diagnosis is beneficial in failure prognosis, maintenance planning, changing the operating condition of the pump to avoid damage and is often used with a companion host system.

The centrifugal pump performance curve in FIG. **6** is provided by a pump manufacturer based on a standard test described by the Hydraulics Institute, the recognized standards authority for the pump industry. The pump performance curve is routinely used by the end user to properly select the appropriate pump and impeller to provide the desired fluid flow or head condition.

Changes to the pump performance result from the use, wear, misapplication and operation of the pump outside the design conditions. These changes alter the pump performance curve. These changes can be used as the first step in diagnosing: 1) root cause analysis of failing pump components; 2) incorrect pump application or installation; 3) pump operation at flow/pressure conditions different than original design (BEP).

The method of the invention uses the pump performance curve to identify possible problems, which are often due to pump misapplication or failing components. Misapplication problems are diagnosed by comparing the measured operating conditions with the BEP region or recommended operating design regime of the pump performance curve. Misapplication results in operation outside the recommended operating regime, leading to pump stress, wear and failure.

Pumps are designed by the manufacturer to operate at the best efficiency point (BEP) or recommended operating design regime. The highest reliability occurs at the best efficiency point of the pump. Pump designs preferably minimize radial and thrust bearing loads, vibration levels, preclude recirculation or cavitation, and provide for the best conversion of mechanical energy to fluid energy at the BEP. Operation at conditions different from the BEP (off-BEP) can result in rapid deterioration of the pump. The diagnosis of off-BEP operation can facilitate pump component failure analysis. If diagnostic information is communicated to a control system, adjustments to pump operation for operating closer to the BEP increases pump life.

The method of the invention utilizes the full range, at all operating conditions, of pump performance curves. The pump operating variables of head, pump efficiency, brake horsepower, net positive suction head required, and specific speed are plotted vs. flow rate, as shown in FIG. **9**. The current pump operating performance curve is plotted vs. the original or previous (at last maintenance/commissioning) pump performance curve and is adjusted for operating fluid properties.

In particular, the method of the invention for diagnosing rotating equipment includes forming a hypothesis of component failure from the a pump operating condition. Referring now to FIG. **10**, to generate a hypothesis, diagnostic apparatus **24** first stores original data, represented by box **1010**. Original data may further include geometric parameters of a pump system and the components of a pump system, a new or original condition pump performance curve, a previously measured pump performance curve, fluid properties data, maintenance record data and output display drivers. Original data may be used to construct an original performance curve for rotating equipment or pump **14**, as shown in FIG. **6**, and represented in box **1012** of FIG. **10**. The original data possesses a recommended operating design regime **166**, referred to as Best Efficiency Point (BEP) **164** when referring to a pump as shown in FIG. **6***a*. Recognized recommended operating design regime **166** is shown in FIG. **6***a* on an example pump curve. The acquisition of process variables from process sensors that gather process data from pump or rotating equipment **14** is represented by box **1014**.

The method of the invention includes inputting process variables from process sensors into computing device **38** (FIG. **1**), as represented by box **1016**. A process data point is then obtained from the process variables, as represented by box **1018**, which represents an operating condition of rotating equipment or pump **14**. Computing device **38** then compares the process data point with the original data, as represented in box **1020**, to determine whether the operating performance is outside of recognized recommended operating design regime **166** (FIG. **6***a*). If the data point is determined to be inside the recommended operating design regime **166**, the pump is operating efficiently. If the data point is determined to be outside the recommended operating design regime **166**, the pump is operating inefficiently, as represented by boxes **1022** and **1024**, in FIG. **10**.

In a preferred embodiment, computing device **38** also determines from a comparison of process data with original data whether the process data point, referred to in box **1018**, is below the recommended operating design regime **166**, as shown in FIG. **6***a*, wherein the process data point is designated **168**. Operating a pump below the recommended operating design regime **166** will cause a pump to experience possible recirculation. Therefore, diagnostic apparatus **24** (FIG. **2**) will then form a hypothesis that the pump is operating in an area of possible recirculation. Additionally, diagnostic apparatus **24** performs an analysis to determine whether the process data point is operating above the operating design regime **166**. If a pump is operating above the recommended operating design regime **166**, as represented by data point **170** in FIG. **6***a*, the pump will experience possible cavitation. Thus, diagnostic apparatus **24** will hypothesize that the pump may be operating in an area of cavitation. This process is set forth in FIG. **11**.

Referring now to FIG. **11**, initially, original data having a recommended operating design regime **166** must be stored as represented in box **1110**. A head vs. flow curve is then constructed from original data, as is represented in box **1112**. Process variables are then acquired from process sensors, as represented by box **1114**, and the process variables are input into computing device **38**, as represented by box **1116**. An operating performance data point is generated from the process variables as represented by box **1117**. Diagnostic apparatus **24** then determines whether the pump is operating outside the recommended design regime **166**, as represented by boxes **1118**, **1120** and **1122**.

If it is determined in box **1118** that the pump is operating outside of design regime **166**, as indicated in box **1122**, then computing device **38** determines whether a current operating performance data point indicates a higher head pressure than the recommended design regime **166**, as represented in box **1124**. If so, a diagnosis of possible pump recirculation is made by diagnostic apparatus **24**, as represented in box **1126**. Additionally, diagnostic apparatus **24** determines whether the operating performance data point indicates a lower head pressure than the recommended design regime **166**, as indicated in box **1128**. If the current operating performance data point is lower than the recommended design regime **166**, then a diagnosis of possible pump cavitation is made by diagnostic apparatus **24**, as indicated in box **1130**.

A similar analysis will be conducted regardless of whether the rotating equipment is a pump or other type of rotating equipment. However, if the rotating equipment is not a pump, but is a gas rotating machine such as a compressor, fan, turbine or blower, then the diagnosis in the case of a current operating performance data point operating at a higher head pressure than the recommended design regime **166** will be surge as is shown in FIG. **5***e* for a compressor. An operating performance data point indicating a lower head pressure than the recommended design regime **166** will result in a diagnosis of stall as shown in FIG. **5***e*.

After a hypothesis has been formulated by diagnostic apparatus **24**, in the preferred embodiment diagnostic apparatus **24** performs a step of verifying whether the process data point is outside the design regime **166**, shown in FIG. **6***a*, and determines the cause of degraded performance. The step of verifying the hypothesis may be performed by analyzing equipment monitoring variables generated by machine sensors. When pump **14** is operating outside recommended operating design regime **166**, or outside BEP **164**, pump component failure can be hypothesized and verified through the use of a second tier of condition monitoring variables and curves.

Four secondary curves which permit confirmation of expected degraded pump components are included in this diagnosis method. The four secondary curves (condition signatures) include: 1) dynamic pressure sensor spectra **172** shown in FIG. **7***a*; 2) velocity **173** and acceleration vibration spectra **174** obtained from an FFT analysis of accelerometer sensor data shown in FIG. **7***b*; 3) bearing forces **180** vs. pump flow rate curve, shown in FIG. **9**; and 4) a break horse power **182** vs. pump flow rate curve, shown in FIG. **9**.

The vibration spectra for both velocity and acceleration provide a basis for diagnosing radial and trust bearings, damage to the pump impeller from recirculation or cavitation causing impeller imbalance, pump shaft imbalance wear of pump seals and wear plates and degradation of ancillary pump system components.

Dynamic pressure spectra **172** provides for a means of measuring pump pressure noise which will indicate insufficient net positive suction head leading to flashing or cavitation and for evidence of recirculation. Dynamic pressure pulsations are also known to increase dramatically whenever the NPSH available drops below the NPSH required as shown in FIG. **7***c*. The NPSH required is computed from the manufacturer's recommended levels adjusted for fluid vapor pressure and operating temperature.

Examples of machine sensors, shown in FIG. **2**, used to monitor pump and motor system **10** include rotating machine vibration sensor **80**, dynamic pressure sensor **82**, motor vibration sensor **86**, gearbox vibration sensor **88**, motor supply sensor **90**, which may be a motor current or motor voltage sensor, alignment sensor **92**, seal leak detector or sensor **94**, oil contamination sensor **96**, viscosity degra-

dation sensor **98**, torque sensor **100**, angular velocity sensor **102**, corrosion sensor **104**, ultrasonic thickness sensor **106**, accelerometer **108**, bearing temperature sensor **110**, bearing vibration sensor **112**, displacement sensor **113**, and an motor insulation resistance sensor **90** or other sensors to monitor equipment conditions.

Referring now to FIG. **12**, it can be seen that in the preferred embodiment of the method, original data is stored as represented by box **1210**. Original data is used to construct an original performance curve, as designated by box **1212**. An example of an original performance curve is shown in FIG. **6**. Process variables are acquired from process sensors, as represented by box **1214**. Condition monitoring variables are acquired from machine sensors, as indicated by box **1216**. A hypothesis is formed by diagnostic apparatus **24** regarding whether rotating machine and motor system **10** is operating outside of recommended operating design regime **166**, shown in FIG. **6***a*, as represented by box **1218**, as shown in FIG. **10**. If diagnostic apparatus **24** determines that rotating equipment **12** is operating within recommended operating design regime **166**, as indicated in box **1220**, or if diagnostic apparatus **24** determines that rotating equipment **12** is operating outside recommended operating design regime **166**, as represented by box **1222**, diagnostic apparatus **24** then performs a verification step, as indicated by box **1224**.

The general method described herein is applicable to pumps as well as other types of rotating equipment.

Referring now to FIG. **13**, a method for verifying that a pump is cavitating includes constructing an original performance curve from original data, constructing a measured performance curve from process variables, and then comparing the measured performance curve with the original pump performance curve for determining if the pump is cavitating. By performing the comparison of the performance curves, it can be determined whether a "droop" condition exists. An example of a "droop" condition is shown in FIG. **7***d*. If diagnostic apparatus **24** determines that there is an observable droop, as indicated in box **1310**, then a diagnosis can be made that cavitation exists, as indicated in box **1312**. This determination can be made because a droop condition indicates that insufficient net positive suction head is available, which results in pump cavitation.

Referring now to FIG. **14**, an additional verification step that can be undertaken that includes acquiring a measured flow rate from process sensors, such as flowmeter **28**. Diagnostic apparatus **24** may determine if the measured flow rate is less than the original flow rate, as indicated in box **1410**. If measured flow rate is less than the original flow rate, then a diagnosis of possible seal leakage is made, as represented by box **1412**. [**45**] Apparatus **24** then gathers and examines leak sensor data from optional seal leak detector **94**, as represented by box **1418**. Diagnostic apparatus **24** then makes a diagnosis of verification as represented by box **1416**.

The step of verifying a hypothesis and diagnosing specific problem areas by diagnostic apparatus **24** may be accomplished in a variety of ways and by examining a variety of machine sensors. The various machine sensors each gives diagnostic apparatus **24** information about different components for verifying or disproving a hypothesis and providing information on various aspects of pump and motor system **10**. Each verification step is valuable for its information regarding a particular component and for its ability to verify or disprove a hypothesis generated by diagnostic apparatus **24** and provides a root cause analysis for the failure. Hereinbelow is a description of various verification methods that deal with different components of diagnostic apparatus **24**.

Referring now to FIG. **15**, a verification step includes acquiring original condition dynamic pressure spectra having amplitude, frequency and phase components as well as acquiring equipment condition monitoring variables comprised of measured dynamic pressure sensor spectra having amplitude, frequency and phase components. FIG. **7***a* shows an example of dynamic pressure spectra wherein an increase in amplitude in frequency region **176** indicates a condition of recirculation and an increase shown in the amplitude of higher frequency region **178** indicates cavitation.

Diagnostic apparatus **24** makes a determination whether amplitude and frequency components of measured dynamic pressure sensor spectra **172** is greater than original condition amplitude and frequency components, as represented by box **1510**. Diagnostic apparatus **24** then makes a diagnosis of possible pump cavitation, as represented by box **1512**, or a diagnosis of possible pump recirculation, as represented by box **1514**.

Referring to FIG. **16** and to pump cross sectional drawing FIG. **1***b*, an additional verification step may be conducted wherein original condition bearing velocity vibration spectra **174** and original condition acceleration vibration spectra are acquired, as well as measured velocity vibration spectra and measured acceleration vibration spectra. Each of the measured and original condition acceleration and vibration spectra has components of amplitude, frequency and phase. Diagnostic apparatus **24** compares at least one of these components selected from the group of amplitude, frequency and phase, as indicated in box **1610**, to determine whether possible impeller degradation exists, as indicated in box **1612**. It is noted that a continuous high level of vibration at impeller resonant frequency indicates impeller **316** degradation. Increased impeller vibration occurs prior to impeller degradation. Therefore, impeller degradation is preventable. If, during a comparison of the measured velocity vibration spectra, as represented in box **1610**, it is determined that the measured vibration velocity spectra is higher than original condition velocity spectra, then it is possible that impeller degradation exists. If a diagnosis of possible impeller degradation is made by diagnostic apparatus **24**, as represented by box **1612**; then in one embodiment of the method, a measured pump performance curve is constructed as represented by box **1614**.

A determination is then made whether a phase shift has occurred, as represented by box **1616**, and if so, a diagnosis of possible fouling or coating of an impeller in the rotating equipment is made, as represented by box **1618**.

Referring now to FIG. **17**, an additional verification step may be conducted wherein original data is comprised of original condition velocity vibration spectra **174** from rotating machine vibration sensor **80** and original condition acceleration vibration spectra from accelerometer **108**, (FIG. **1**) wherein the original and measured velocity and acceleration spectra have amplitude, frequency and phase components. A comparison is made of at least one of the components selected from the group of amplitude, frequency and phase of the original condition velocity vibration spectra with at least one of the components of the measured velocity vibration spectra, as well a comparison between one of the components of the original condition acceleration vibration spectra with at least one of the components of the measured acceleration vibration spectra, as represented in box **1712**. A determination is then made whether radial bearing **310** degradation exists, as represented in box **1714**.

Bearing frequency, resonant frequency and harmonics are distinct from impeller vibration, frequency and harmonics. Therefore, if the measured vibration velocity amplitude is

higher and the impeller frequency than original condition velocity vibration amplitude **173**, then possible impeller degradation exists.

Referring now to FIG. **18**, another verification step includes gathering equipment monitoring variables, including pump input torque data from torque sensor **100** and pump shaft angular velocity data from angular velocity sensor **102**. With this condition monitoring data, a frictional torque is calculated for the rotating equipment, as indicated in box **1810**. A comparison of the measured condition frictional torque with the original condition frictional torque is made, as represented by box **1812**, to determine whether bearings **310**, **312** and seal **314** or wear plate wear **320** is occurring. Diagnostic apparatus **24** will diagnose possible seal **314**, degradation if measured frictional torque is less than the original condition frictional torque, as represented by box **1814**. Alternatively, diagnostic apparatus **24** may diagnose bearings **310**, **312** seal wear **314** or wear plate **320** wear if the measured frictional torque is greater than original condition frictional torque, as indicated by box **1816**. Frictional torque may be calculated from the equation below:

$$Tp = \sum T's = I \times \frac{dN}{dt} = Tfl + Tb + Ts$$

where Tp=Torque to pump

I=Moment of Inertia of pump shaft/impeller assembly

N=Pump Speed, rpm

Tf=Fluid Torque

Tb=Frictional Torque of bearings

Ts=Frictional Torque of Seal/packing

The measured torque delivered by the motor can be compared to the motor manufacturer's recommended "torque to failure" to provide an early warning alert of imminent motor failure if the pump is not repaired and the high torque condition is not corrected.

In an additional verification step, original data is comprised of original vibration, acceleration and velocity spectra from rotating machine vibration sensor **80** or bearing vibration sensor **112**, and measured velocity spectra from accelerometer **108**, wherein both spectra have amplitude, frequency and phase components. After a diagnosis of possible bearing degradation is made, as indicated in box **1816**, a comparison is made of at least one of the components selected from the group of amplitude, frequency and phase of the original vibration velocity or acceleration at the radial bearing resonant frequency or harmonics or acceleration spectra, with at least one of the components of measured vibration velocity spectra **174** to determine whether the measured vibration amplitude is greater than the original vibration amplitude, as indicated in box **1818**. If so, a diagnosis of radial bearing **310**, FIG. **1***b*, failure is made, as indicated in box **1820**.

Referring now to FIG. **19**, measured radial vibration velocity spectra and measured radial bearing acceleration spectra are obtained from bearing vibration sensor **112**. Each of the original and measured radial bearing and acceleration spectra possesses components of amplitude, frequency and phase. A determination is made by comparing at least one of the components selected from the group of amplitude, frequency and phase of the original radial bearing vibration velocity spectra with a component of the measured radial vibration spectra as well as a comparison of the original radial bearing acceleration spectra with at least one component of the measured radial bearing acceleration spectra, as indicated in box **1910**. If at least one component of the measured vibration velocity and acceleration spectra is greater than the original component, then a determination is made by diagnostic apparatus **24** of possible bearing degradation, as indicated in box **1912**.

Referring to FIG. **20**, a further verification step requires a comparison of original radial bearing **310** operating temperature with measured radial bearing operating temperature as indicated in box **2010**. The original radial bearing operating temperature is obtained from original data and the measured radial bearing operating temperature is obtained from temperature sensor **118**. If the measured radial bearing operating temperature is determined by diagnostic apparatus **24** to be greater than original radial bearing temperature, then a diagnosis of possible radial bearing degradation is made, as represented by box **2012**.

Referring to FIG. **21**, a further verification step is that of comparing at least one of the components of amplitude, frequency and phase of original thrust bearing vibration velocity spectra with at least one of the components of measured velocity vibration spectra obtained from bearing vibration sensor **112**. Additionally, a comparison is made between at least one of the components of original thrust bearing acceleration spectra with at least one of the components of measured acceleration spectra obtained from accelerometer **108**, as represented by box **2110**. If it is determined that at least one of the components of the measured vibration velocity and acceleration spectra is greater than an original component of vibration velocity spectra, then a diagnosis of possible thrust bearing **312** degradation is made by diagnostic apparatus **24**, as represented by box **2112**.

Referring now to FIG. **22**, a further verification step may be conducted by comparing original thrust bearing **312** operating temperature obtained from original data, and measured thrust bearing operating temperature obtained from bearing temperature sensor **110** to determine whether thrust bearing degradation exists. If measured thrust bearing operating temperature is greater than original thrust bearing operating temperature, as indicated by box **2210**, then a diagnosis of possible thrust bearing degradation is made by diagnostic apparatus **24**, as represented by box **2212**. Original thrust bearing operating temperature is obtained from original data.

Referring to FIG. **23**, an additional verification step is conducted to determine if sufficient measured available net positive suction head exists to operate pump **14** without cavitation. Measured available net positive suction head is calculated by using a well known equation from data obtained from inlet pressure sensor **32** (FIG. **1**). This determination is made by determining if the measured net positive suction head is greater than the net positive suction head required, as represented by box **2310**. If so, a diagnosis of possible cavitation is made by diagnostic apparatus **24**, as indicated in box **2312**.

Referring now to FIG. **24**, an additional verification step is made to determine if sufficient measured net positive suction head available exists to operate without cavitation. However, in the preferred method, the additional step of correcting the measured net positive suction head for the measured operating temperature and fluid vapor pressure is made, as represented by box **2410**. A determination is then made whether the corrected measured net positive suction head available is greater than the required net positive suction head as represented by box **2412**. If not, then diagnostic apparatus **24** makes a diagnosis of possible cavitation, as indicated in box **2414**. The original required net positive suction head and the fluid vapor pressure, both

of which are available from original data, are compared with the measured net positive suction head and the measured net positive suction head and calculated utilizing the measured operating temperature of the process fluid is obtained by temperature sensing device **30** (FIG. **1**).

Referring to FIG. **25**, a further verification step is conducted to determine if thrust bearing degradation exists. Original axial thrust bearing displacement data is obtained from original data and measured axial thrust bearing displacement data is obtained from displacement sensor **113**. A comparison of the original axial thrust bearing displacement data with measured axial thrust bearing displacement data is conducted to determine whether measured axial displacement data is greater than original axial displacement data, as represented by box **2510**. If diagnostic apparatus **24** determines that measured axial displacement data is greater than original, and the bearing clearance is in excess of the manufacturer's recommended clearance, then a diagnosis of possible thrust bearing **312** degradation is made, as represented by box **2512**. It is noted that axial displacement sensor **113** measures the distance from thrust bearing **312** to a reference housing **322**. Typically, bearing **312** will move due to backpressure from rotating equipment **14** which forces thrust bearing **312** into its race, thereby compressing bearing **312**. A measurement may be made by an electronic proximity sensor such as those provided by Bently Nevada. Original axial thrust bearing displacement data is obtained from a manufacturer to provide an acceptable clearance specification for the thrust bearing. Displacement sensors may also be used to measure radial bearing clearance.

Referring now to FIG. **26**, an additional verification step may be conducted to determine whether radial bearing **310** degradation exists. A comparison is made between original radial bearing displacement data obtained from original data with measured radial bearing displacement data obtained from proximity sensor **113**. If measured radial bearing displacement data is determined to be greater than original radial bearing displacement data, as indicated in box **2610**, then diagnostic apparatus **24** determines that radial bearing degradation exists, as represented in box **2612**.

Referring to FIG. **27**, an additional verification step may be conducted to determine whether impending motor failure exists. This diagnosis is made by comparing the manufacturer's original motor breakdown torque, which is obtained from original data, with measured electric motor output torque **100**. Diagnostic apparatus **24** determines whether measured motor torque exceeds the manufacturer's recommended torque, as indicated by box **2710**. If so, a diagnosis of impending motor **12** failure is made, as presented by box **2712**.

Referring now to FIG. **28**, an additional verification step may be made wherein a display is generated of the performance curve and secondary curve for comparison. Examples of secondary curves in FIG. **9** include NPSH v. H&Q, BHP v. H&Q, efficiency v. H&Q, specific speed v. H&Q, bearing force v. H&Q, and Dynamic Pressure v. H&Q. To perform this verification step, a selected secondary curve is constructed from equipment condition monitoring variables, as represented by box **2812**. An original secondary curve is constructed, represented by box **2810**, and a display of the original performance curve and the secondary curve is made for comparison, as represented by box **2814**.

An additional step may be conducted to generate alerts if rotating equipment **14** is operating outside of its recommended design regime **166** or BEP regime **164** (FIG. **6***a*). One method of acquiring data sufficient to generate an alert includes constructing an original performance curve from original data, as represented by box **2910**, and then constructing a measured performance curve from equipment condition monitoring variables, as represented by box **2912**. Optionally, diagnostic apparatus **24** time-stamps the measured performance curve, as represented by box **2914**. Diagnostic apparatus **24** then compares the original performance curve and the measured performance curve to determine the change in the pump performance variables, as represented in box **2916**. If the change exceeds the manufacturer's recommended range, then diagnostic apparatus **24** generates an alert, as represented by box **2918**, so that action may be taken to prevent operation of rotating equipment **14** outside of its recommended design regime **166** (FIG. **6***a*).

Additionally, diagnostic apparatus **24** may alert a controller to correct pump operating conditions to within the operating design regime **166**, as indicated by box **2920**.

Additionally, a similar procedure may be undertaken, except that instead of constructing original performance curves and measured performance curves, a process data point may be plotted from process variables and a secondary data point may be plotted from equipment condition monitoring variables to determine if rotating equipment **14** is operating outside of its recommended design regime **166** (FIG. **6***a*).

Referring to FIG. **30**, the verification step may also include alerting a controller to correct pump operating conditions to within a design condition. The steps of alert and correction are accomplished by constructing an original performance curve from original data, as represented by box **3210**, constructing an original secondary curve from original data, as represented by box **3212**, constructing a measured secondary curve from condition monitoring variables as represented by box **3214**, constructing a measured secondary curve from equipment monitoring variables, as represented by box **3216**, and then comparing the original performance curve with the measured performance curve to determine the change in the pump performance variables, as represented in box **3218**. If the change exceeds the manufacturer's recommended range, an alert is generated, as represented by box **3220**. From the comparisons, diagnostic apparatus **24** may alert a controller to correct pump operating conditions to within an operating design regime **166** (FIG. **6***a*), as indicated by box **3222**.

Referring now to FIG. **31**, an additional verification step includes determining whether valve cavitation exists. This determination is made by comparing at least one of the components of amplitude, frequency and phase of measured dynamic pressure sensor spectra obtained from dynamic pressure sensor **82** (FIG. **1**) with at least one component of original condition dynamic pressure sensor spectra obtained from original data, as represented by box **3310**. If at least one component of measured dynamic pressure sensor spectra is greater than a component of original condition pressure spectra, as indicated by box **3310**, then diagnostic apparatus **24** hypothesis possible valve cavitation, as indicated by box **3312**.

An additional verification step may be made by determining if sufficient corrected measured net positive suction head available exists, such that the pump is not cavitating. This verification involves the step of correcting the original net positive suction head required for operating fluid temperature **30** (FIG. **1**) and fluid vapor pressure, as indicated in box **3314**. Diagnostic apparatus **24** then makes a determination of whether measured net positive suction head available is greater than net positive suction head required, as indicated in box **3316**. If so, diagnostic apparatus **24** makes a determination that the diagnosis of valve cavitation is verified, as

represented in box **3318**. That is, if $NPSH_R > NPSH_A$, it is likely that the pump is cavitating. However, if cavitation is detected and pump $NPSH_A > NPSH_R$, then the source of cavitation is a valve and not the pump **14**.

An additional verification step includes determining whether measured vibration spectra has increased in an expected pump cavitation frequency range. This determination is made by comparing at least one of the components of amplitude, frequency and phase of measured vibration spectra with at least one of the components of original condition vibration spectra to determine whether at least one component of measured vibration spectra is greater than a component of original condition vibration spectra, as represented by box **3320**. If so, then the measured vibration spectra has increased in the expected pump cavitation frequency range, as indicted by box **3322**, which verifies the determination of cavitation made above in box **3312**.

Referring to FIG. **32**, a further verification step may be made to verify pump cavitation. This diagnosis is made by comparing at least one of the components of amplitude, frequency and phase of measured vibration spectra with at least one of the components of original condition vibration spectra to determine whether at least one of the components of measured dynamic pressure spectra is greater than at least one of the components of original condition pressure spectra, as represented by box **3610**. It is noted, however, that the comparison must be made in the appropriate frequency range. If it is determined that at least one component of the measured dynamic pressure sensor spectra is greater than a component of the original condition pressure spectra, then diagnostic apparatus **24** diagnoses valve cavitation, as represented in box **3612**.

Referring now to FIG. **33**, an additional step of diagnosing a pump deadhead condition and sending a signal to shut down rotating equipment (FIG. **1**) **14** or open valve **22** is made by acquiring control valve shaft position data from control valve position sensor **34**. From control valve shaft position data, a determination is made whether valve **22** is closed, as represented in box **3710**. A determination is then made by comparing measured head with original condition head to determine whether head is at a maximum, as represented by box **3712**. If so, a diagnosis of pump deadhead condition is made, as represented in box **3714**, and diagnostic apparatus **24** sends a signal to the controller to shut down rotating equipment **14** or open valve **22** to alleviate pump deadhead condition, as represented by box **3716**.

Referring to FIG. **34**, additional steps may be undertaken to determine whether valve packing leakage or valve seal leakage is occurring. This determination is made by obtaining control valve flow data from original data and obtaining the control valve position from valve position sensor **34** (FIG. **1**). Diagnostic apparatus **24** then calculates valve flow from the valve data at the control valve position, as represented by box **3810**. A comparison is then made between measured pump output flow with calculated valve flow to determine if measured pump output flow is greater than calculated valve flow, as represented by box **3812**. If so, diagnostic apparatus **24** makes a diagnosis of valve packing leakage or valve seat leakage as represented by box **3814**. The equation used to calculate valve flow is as follows:

Qv=Cv*A*(ΔP/SG)**0.5

where: Qv=Valve Volumetric Flow

Cv=Valve Flow Coefficient at position, y (valve data)

ΔP=Pressure Drop Across the Valve

SG=Liquid Specific Gravity

A=Flow Area of the Valve

Referring now to FIG. **35**, additional steps may be undertaken to diagnose a plugged output pipe of rotating equipment **14**. The diagnosis requires that original head and original outlet pump flow be obtained from original data and that measured outlet pipe flow be obtained from flowmeter **28** (FIG. **1**) and measured pump head be calculated from process variables as described above. The method further includes operating the pump at a measured head equal to the original head, as indicated in box **3910**. Diagnostic apparatus **24** then makes a determination whether the measured pump outlet pipe flow is less than the original outlet pipe flow at the identical head, as represented by box **3912**. If the measured flow is less than the original flow, then diagnostic apparatus **24** makes a determination of a plugged outlet pipe **20**, as represented by box **3914**. This method of comparison is based on the presentation of data as shown in FIG. **6***b*, where the original flow at original head is represented by a point designated **180** and new measured flow point is designated **182**.

Referring now to FIG. **36**, additional steps may be taken to diagnose a plugged suction line by determining if original net positive suction head available is greater than measured net positive suction head available. In order to make this determination, the original flow rate and original net positive suction head available may be obtained from original data. Measured net positive suction head may be calculated from the inlet pressure. A comparison is then made between the original net positive suction head available with the measured net positive suction head available. If the original net positive suction head available is greater than the measured net positive suction head available, as indicated in box **4110**, then a diagnosis of a plugged suction line **18** is made by diagnostic apparatus **24**, as indicated in box **4112**.

Original data for the pump performance curve, FIG. **6**, is typically provided at a design speed determined by the manufacturer. However, if a pump or rotating equipment is operated at a different speed than the design speed, then data must be corrected utilizing pump affinity equations. To calculate a speed change (N), the following affinity law relationships for flow (Q), head (H) and break horsepower (BHP) are utilized.

$Q1/Q2=N1/N2$ and $H1/H2=(N1/N2)^{0.5}$ and $BHP1/BHP2=(N1/N2)^3$

$$\text{Specific Speed } Ns = \frac{N \times Q^{0.5}}{H^{0.75}}$$

where: Ns is the specific Speed

N is the operating speed, rpm

H is the pump head, ft

Q is the flow rate, gpm.

Referring now to FIG. **37**, original data is gathered, as represented by box **4210**, and an original performance curve is constructed, as represented by box **4212**. Process variables are acquired, as represented by box **4214**. The process variables are input into computing device **38** (FIG. **1**), as represented in box **4216**. A comparison is then made between the original performance curve and the measured operating point to determine if rotating equipment **14** is operating outside of design regime **166**, as represented in box **4218**. If rotating equipment **14** is operating within design regime **166**, then diagnostic apparatus **24** so indicates, as represented in box **4220**. If the operating performance is outside of design regime **166**, diagnostic apparatus **24** so indicates, as represented by box **4222**. If it is determined that rotating equipment **14** is operating outside

of design regime **166**, as represented by box **4222** (FIG. **6***a*), then a diagnosis of high bearing stress is made by diagnostic apparatus **24**, as represented by box **4224**. It is noted that impending bearing failure will occur if a process operating point is either above or below a BEP regime **164** (FIG. **6***a*) on an original performance curve. If operation is outside of a design regime **166**, then bearing stress will be increasingly higher the further away from of design regime **166** that the process data point occurs. This is equally true for a high head-recirculation case or a high flow-cavitation case. This concept is illustrated graphically in FIG. **9***a*, where it can be seen that bearing forces are lowest at point **184**, which corresponds to BEP point **186**.

If a diagnosis is made that rotating equipment **14** is operating outside of recommended operating design regime **166**, as represented by box **4222**, an additional determination of whether a measured performance curve has shifted downward as compared with the original performance curve is made by diagnostic apparatus **24**, as represented by box **4226**. If so, a diagnosis of fouling or coating of an impeller **316** (FIG. **1***b*) is made, as represented in box **4228**.

Referring to FIG. **38**, in another embodiment of the invention, a determination of whether pump **14** is operating in a recognizable, recommended operating design regime **166** (FIG. **6***a*) is made by comparing a system head operating point with a measured performance curve. This determination is made by obtaining a calculated system demand curve at a specific flow rate from original data, wherein the calculated system design curve is determined by piping system geometry, fluid properties and pump operating conditions. Additionally, a calculated fluid frictional head loss at a specific flow rate is determined from original data, wherein the calculated fluid frictional head loss is determined by piping system geometry. Finally, a calculated velocity head at a specific flow rate is gathered from original data wherein the calculated velocity head is determined by piping system geometry.

The method includes the steps of constructing a measured performance curve from process variables as is known in the art, and which is represented by box **4410**. Next, a system head operating point is calculated from the calculated system demand curve at a flow rate, and the calculated fluid frictional head loss and the calculated velocity head, as represented in box **4412**. Diagnostic apparatus **24** then determines if rotating equipment **14** is operating in the recommended operating design regime **166**, shown in FIG. **6***a*, by comparing the intersection of system head operating point with the measured performance curve. If the operating point is outside the recommended range **166** then an alert can be generated. It is noted that pumps or rotating equipment produce flow and pressure, i.e., head, required by a fluid system. The fluid flow system is constructed of pipe sections, pipe fittings (elbow, tees, etc.), valves, and vessels. Each of these components exhibit fluid friction, and as the fluid flow passes through each element a pressure drop occurs due to friction with the element. The sum of the pressure drops throughout the system represents the system head and the pump provides exactly the required pressure head.

Some of the flow system components are variable frictional elements, such as a control valve. When a valve is closed, the pressure drop across the valve increases and the pump must put out higher pressure to correspond to this reduction in flow.

When the pump pressure or head increases, the operating or measured operating point will move to the left on a head (H) v flow (Q) curve. This represents higher head (H) pressure and lower flow (Q). If the system head operating point moves too far to the left, indicating increasing head, the pump may be operating outside of its design regime **166**, shown in FIG. **6**, and recirculation can occur. For the opposite case of decreasing pressure and increasing flow, cavitation would be a possibility.

A pump, valve and piping system must be correctly engineered to provide for operation of a pump within a design regime **166**, while delivering the pressure and flow required by the process.

Referring now to FIG. **39**, a diagnosis of degraded rotating machine efficiency can be obtained by comparing measured rotating machine efficiency with original performance curves. This can be accomplished by acquiring rotating machine input torque data from torque sensor **100** (FIG. **1**), as represented by box **4510**, and rotating machine shaft angular velocity data from angular velocity sensor **102**. The method calculates the measured rotating machine efficiency by calculating the input power to the pump, as represented in box **4516**, and by calculating the fluid outlet power calculated from the flow sensor **28** and pump geometry, represented by box **4518**. The rotating machine efficiency may then be calculated by the following equation:

Pump Efficiency, $\eta p = Pf/Pp$

where η p is the pump efficiency

Pp is the power delivered to machine by the motor (also known as brake horsepower)

Pf is the fluid power delivered by the machine.

Diagnostic apparatus **24** then determines whether measured pump efficiency is less than original condition efficiency, as represented by box **4518**. If so, then diagnostic apparatus **24** makes a determination that pump efficiency is degrading, as represented by box **4520**.

A further embodiment of the method of the invention is disclosed for conducting a field test to permit the actual measurement and construction of pump performance curves and secondary performance curves that can be compared with original performance data.

The method includes a mode for controlling the pump throughout its operating range consistent with the Hydraulics Institute test method, known in the art. This method provides for operating a pump through its range of operation by the driving of the valve I/P, **35** (FIG. **1**), or variable speed drive motor. This method can be used to construct pump performance curves in an automated fashion or for manually setting head or flow conditions to assist in the manual diagnosis of a rotating machine when a maintenance technician is looking to reproduce desired operating conditions.

The method operates the pump through its range of operation by controlling the rate of flow through the pump. The method is applicable to either a variable speed drive providing a full range of speed adjustment to the motor or via the control valve through a full range of valve flow control positions.

The method includes storing original data and adjusting a pump final control element to a desired setting, as presented in box **4610**. The pump final control element may be either a valve **22**, FIG. **1**, or a variable speed drive connected to a motor **12**. Process variables are acquired from operational rotating equipment **14** at the desired final control element setting, as represented in box **4612**. The process variables are then input into computing device **38**. Diagnostic apparatus **24**, FIG. **2**, constructs measured performance curves from the process variables, as represented by box **4614**, and repeats the steps of storing, acquiring, inputting and constructing a plurality of times wherein the pump final control element is adjusted to correspond to a defined set of test

conditions for constructing the measured performance curves, as represented by box **4616**. The measured performance points are stored, as represented in box **4618**. An in situ performance curve and secondary curve are finally constructed from process and condition monitoring variables, as represented in box **4620**.

In one embodiment of the field diagnostic test process, a means is provided for manually establishing flow or head conditions, including manually adjusting the valve **22**, manually adjusting the current or flow to motor **12**, or other methods of manually adjusting the pump final control element to a desired condition.

An additional embodiment of a method for diagnosing rotating equipment includes storing original data having a recognized, recommended operating design regime **166** (FIG. **6***a*), as represented by box **5010** and acquiring a process variable from operating rotating equipment **14**, FIG. **1**, wherein a process variable is selected from a group consisting of fluid outlet pressure obtained from outlet pressure sensor **26**, and fluid flow obtained from flowmeter **28**, as represented by box **5012**. The process variable is then input into computing device **38**, as represented in box **5014**, and a determination whether the process variable is within the recommended operating design regime **166** (FIG. **6***a*) is made, as represented by box **5016**. If not, then diagnostic apparatus **24**, FIG. **2**, diagnoses that pump and motor system **10** is operating outside the recommended design regime **166**, FIG. **6***a*, as represented by box **5018**.

Whereas, the present invention has been described in relation to the drawings attached hereto, it should be understood that other and further modifications, apart from those shown or suggested herein, may be made within the spirit and scope of this invention.

What is claimed is:

1. An apparatus for diagnosing a power system which includes a rotating machine, the apparatus comprising:

process sensors for generating process variables, said process sensors including:

an outlet pressure sensor positioned proximate an outlet of the rotating machine for determining rotating machine outlet pressure; and

a flow meter for determining a flow rate of product downstream of the rotating machine;

said apparatus further including:

an input/output device in communication with said process sensors for receiving process variables from said process sensors; and

a computing device in communication with said input/output device, said computing device having a memory, said memory for storing data from said input/output device, said computing device for receiving original data including tables of machine geometry, machine installation parameters, original performance curves and fluid properties of said pumped product, said computing device for comparing said process variables with said original data and for generating an output based upon said comparison.

2. An apparatus according to claim **1**, including machine sensors for generating condition monitoring variables, said machine sensors comprising:

a rotating machine vibration sensor mounted on the rotating equipment for determining vibration of the rotating machine, said vibration sensor in communication with said input/output device for providing condition monitoring variables thereto; and

said computing device for comparing said condition monitoring variables with said original data for diagnosis of rotating equipment degradation and for generating an output based upon said comparison.

3. The apparatus according to claim **2**, wherein said machine sensors further comprise:

a gear box vibration sensor mounted on a gear box for determining gear box vibration; and

a motor supply sensor mounted on electrical power supply service for determining electrical power to a motor;

an alignment sensor mounted on the motor for determining coupler alignment;

wherein said motor vibration sensor, said alignment sensor, said gear box sensor and said motor supply sensor are for providing condition monitoring variables to said input/output device for providing said computing device with condition monitoring variables to diagnose the rotating machine and alert an operator of impending rotating machine maintenance.

4. The apparatus according to claim **2**, wherein said machine sensors further comprise a rotating machine seal leakage sensor mounted proximate a shaft seal on the rotating machine for detecting seal leakage, said rotating machine seal leakage sensor for providing condition monitoring variables to said input/output device for providing said computing device with condition monitoring variables.

5. The apparatus according to claim **2**, wherein said machine sensors further comprise an oil contamination sensor mounted in a gearbox or on an oil sump for detecting oil contamination, said oil contamination sensor for providing conditioning monitoring variables to said input/output device for providing said computing device with condition monitoring variables.

6. The apparatus according to claim **2**, wherein said machine sensors further comprise a viscosity degradation sensor mounted proximate a gearbox for detecting oil viscosity degradation, said viscosity degradation sensor for providing condition monitoring variables to said input/output device for providing said computing device with an oil condition monitoring variable.

7. The apparatus according to claim **2**, wherein said machine sensors further comprise a dynamic sensor mounted on a pump casing for measuring pressure noise in said pump casing for providing condition monitoring variables to said input/output device for providing said condition monitoring variables to said computing device for diagnosing pump recirculation and cavitation.

8. The apparatus according to claim **2**, further comprising a valve position sensor mounted on said control valve and in communication with said input/output device, said valve position sensor for determining a position of a shaft of said control valve.

9. The apparatus according to claim **2**, wherein said machine sensors further comprise an corrosion sensor mounted on a rotating machine casing for measuring the degradation of the rotating machine casing from corrosion, pump cavitation or erosion, said corrosion sensor in communication with said input/output device for providing condition monitoring variables thereto.

10. The apparatus according to claim **2**, wherein said machine sensors further comprise an ultrasonic thickness sensor mounted on a rotating machine casing for measuring the degradation of the rotating equipment casing from corrosion, pump cavitation or erosion, said ultrasonic thickness sensor in communication with said input/output device for providing condition monitoring variables thereto.

11. The apparatus according to claim **2**, wherein said machine sensors are integrated with said input/output device and said computing device for comparing measured perfor-

mance signatures of the rotating machine at a second time with an original condition signature at a first time, for diagnosing degradation of the rotating machine.

12. The apparatus according to claim **2**, wherein said machine sensors further comprise:

a torque sensor mounted on a shaft of said rotating machine, said torque sensor in communication with said input/output device for providing said computing device with torque data;

an angular velocity sensor mounted on a shaft of said rotating machine, said angular velocity sensor in communication with said input/output device for providing said computing device with angular velocity data for computing input power to the rotating machine, speed of the rotating machine, and rotating machine efficiency.

13. The apparatus according to claim **2**, wherein said computing device serves as a host, said host in communication with a controller proximate the rotating machine for controlling the rotating machine, said microcontroller having firmware for providing control set point to said rotating machine.

14. The apparatus according to claim **2**, wherein said computing device is positioned proximate a rotating machine, said computing device for providing a control set point for said rotating machine.

15. The apparatus according to claim **2**, further comprising a communication port for importing condition monitoring variables from a portable handheld data logging device.

16. The apparatus according to claim **2**, further comprising a process variable digital bus in communication with networked intelligent devices.

17. The apparatus according to claim **2**, further comprising a monitoring system digital bus in communication with intelligent network devices with a computing device for collecting said condition monitoring variables.

18. The apparatus according to claim **2**, further comprising condition monitoring subsystems for the rotating machine, said condition monitoring subsystems interfaced with the computing device via standard communication network interfaces for transmitting subsystem data over a standard communication network.

19. Apparatus according to claim **18**, further comprising an external processed data storage device for storing the subsystem data wherein the apparatus is a network client having a memory database for storing data from a networked rotating machine subsystem.

20. The apparatus according to claim **2**, further comprising a co-processor in communication with said computing device for providing spectral signal reduction of said condition monitoring variables from said vibration sensor, said motor vibration sensor, said dynamic pressure sensor and said bearing vibration sensor.

21. An apparatus according to claim **1**, wherein said process sensors further comprise:

an inlet pressure sensor positioned proximate an intake of the rotating machine for determining rotating machine inlet pressure; and

a temperature sensor positioned upstream or downstream of the rotating machine for determining temperature of a process fluid.

22. The apparatus according to claim **1**, further comprising an alert device for indicating when undesirable equipment conditions occur.

23. The apparatus according to claim **22**, further comprising a contact closure for shutting down the apparatus when said alert device indicates an undesirable equipment condition.

24. An apparatus according to claim **1**, further comprising a final control element, said final control element responsive to said output for adjusting the rotating machine and motor system for operating the rotating machine in a recognized recommended operating design regime.

25. An apparatus according to claim **24** wherein said final control element is a control valve downstream of said rotating machine for regulating back pressure.

26. An apparatus according to claim **24**, wherein said final control element is a variable speed drive coupled to the motor, said variable speed drive for adjusting motor speed.

27. The apparatus according to claim **1**, further comprising a real time clock in communication with said computing device for time stamping process variables and said original data for time based comparison.

28. The apparatus according to claim **1**, further comprising a display for representing a performance signature at a first time and a second time.

29. The apparatus according to claim **1**, further comprising a co-processor with a spectral analysis engine for processing signals from frequency domain sensors.

30. The apparatus according to claim **1**, further comprising a network communication port in communication with said input/output device, said network communication port for communicating said output to a network.

31. An apparatus according to claim **1**, further comprising a communication device for communicating data from said computing device to a networked host.

32. The apparatus according to claim **1**, wherein said computing device is powered by and communicates over two wires.

33. The apparatus according to claim **1**, wherein said computing device is powered by and communicates with either 3-wire or 4-wire networks.

34. The apparatus according to claim **1** including multiplexer inputs in order to diagnose more than one said rotating machine.

* * * * *

EXHIBIT 9

US005917428A

United States Patent [19]

Discenzo et al.

[11] **Patent Number: 5,917,428**

[45] **Date of Patent: *Jun. 29, 1999**

[54] **INTEGRATED MOTOR AND DIAGNOSTIC APPARATUS AND METHOD OF OPERATING SAME**

[75] Inventors: **Frederick M. Discenzo**, Brecksville; **Perry A. DelVecchio**, Mentor; **Edward J. Tompkin**, Cuyahoga Falls, all of Ohio

[73] Assignee: **Reliance Electric Industrial Company**, Cleveland, Ohio

[*] Notice: This patent issued on a continued prosecution application filed under 37 CFR 1.53(d), and is subject to the twenty year patent term provisions of 35 U.S.C. 154(a)(2).

[21] Appl. No.: **08/745,167**

[22] Filed: **Nov. 7, 1996**

[51] **Int. Cl.**[6] **G08B 21/00**

[52] **U.S. Cl.** ..... **340/870.01**; 307/116; 340/648; 310/68 R; 310/68 B; 310/68 C

[58] **Field of Search** ..... 376/245; 340/870.01, 340/870.17, 870.07, 870.05, 648; 364/146, 552; 324/177, 772; 73/659; 318/490; 310/68 R, 68 B, 68 C; 307/116

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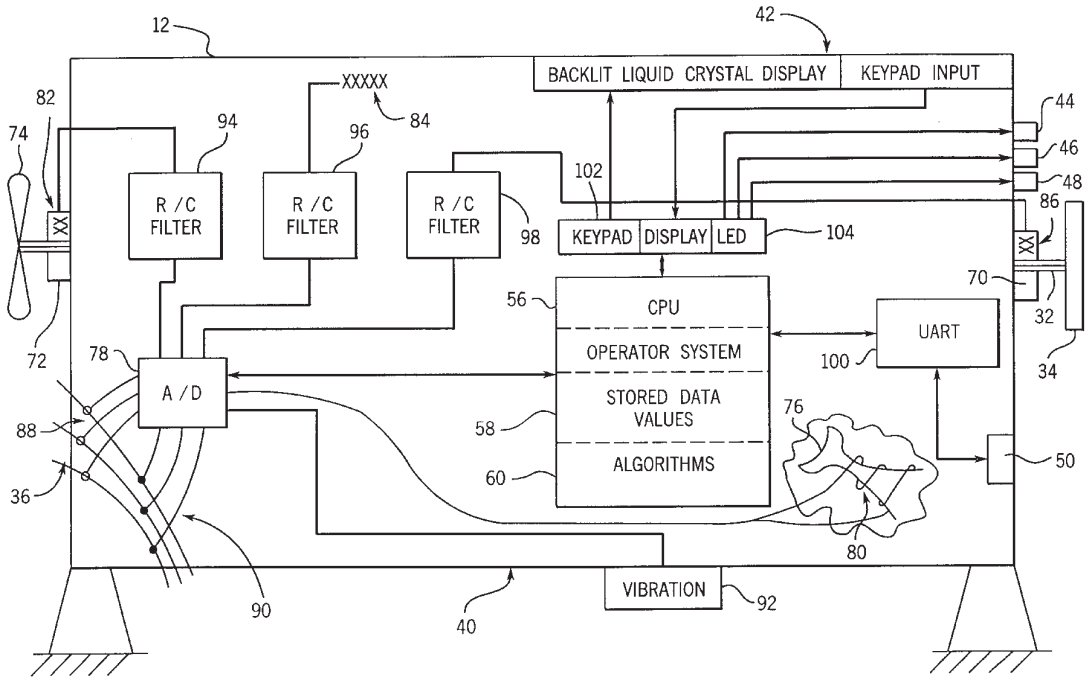
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Primary Examiner—Michael Horabik
Assistant Examiner—Albert K. Wong
Attorney, Agent, or Firm—John M. Miller; John J. Horn; William R. Walbrun

[57] **ABSTRACT**

A method and apparatus for real-time electric motor diagnostics and condition monitoring. While the motor is energized, dynamic operating parameters are determined and a notification signed is generated if predetermined criterion are satisfied. The diagnostic apparatus is integrated with the motor and includes a set of sensors, a processing unit, a memory and an output interface for communicating alarms, warnings and calculated operating parameter values or the like to a display device and to an external supervisor having wireless paging capability to alert a remote operator or maintenance personnel. In a normal operating mode, the processing unit calculates a general class of derived motor operating parameters such as over-temperature, over-voltage, over-current, excessive vibration, and phase imbalance. When an abnormal condition is observed, the processing unit modifies certain data acquisition parameters as necessary to effect an alternative data acquisition strategy which would more likely lead to data dispositive of the condition of the motor.

19 Claims, 9 Drawing Sheets



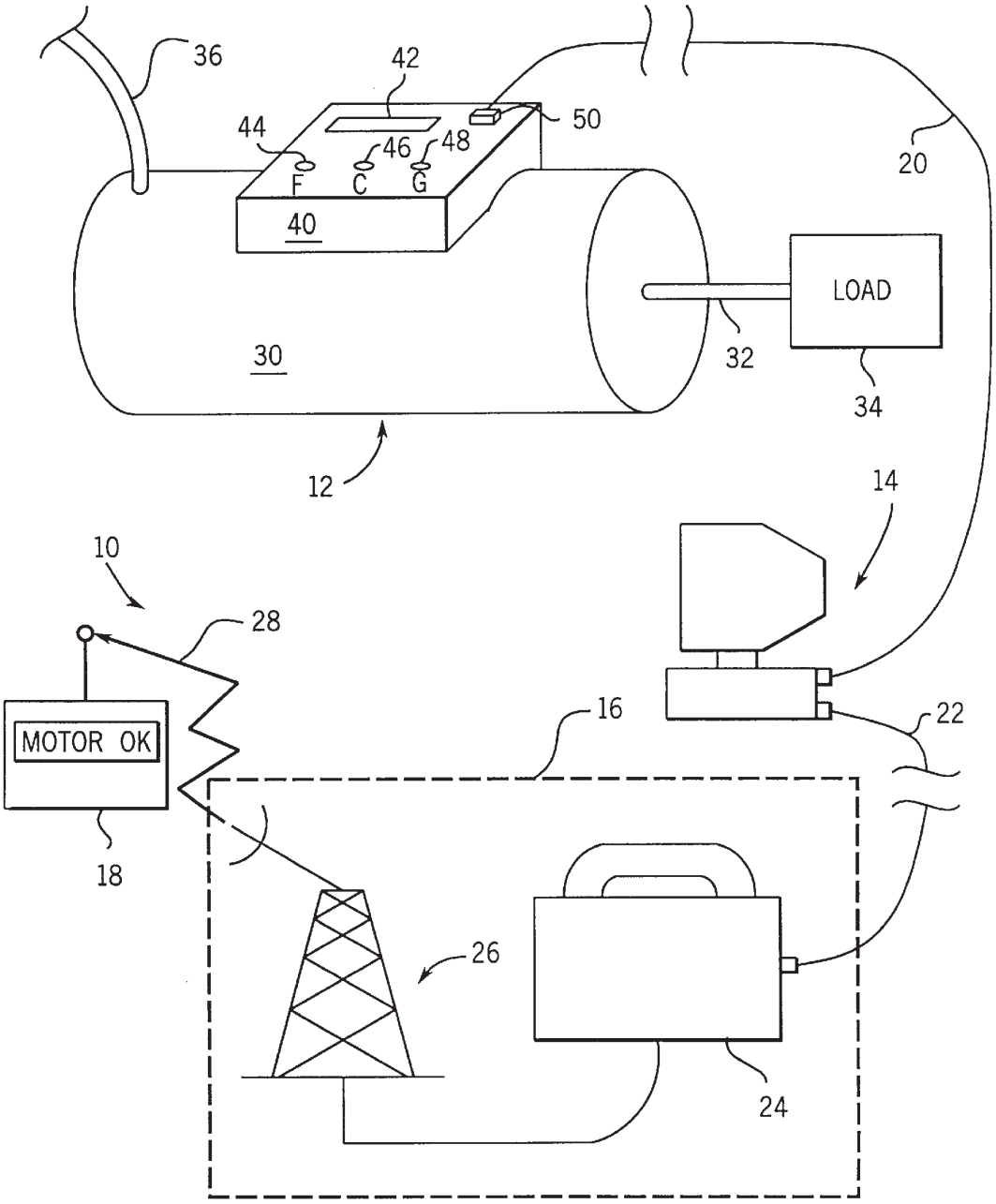

36
42
44
46
48
50
F
C
G
40
20
LOAD
30
32
34
12
14
10
28
MOTOR OK
16
22
18
26
24

FIG. 1

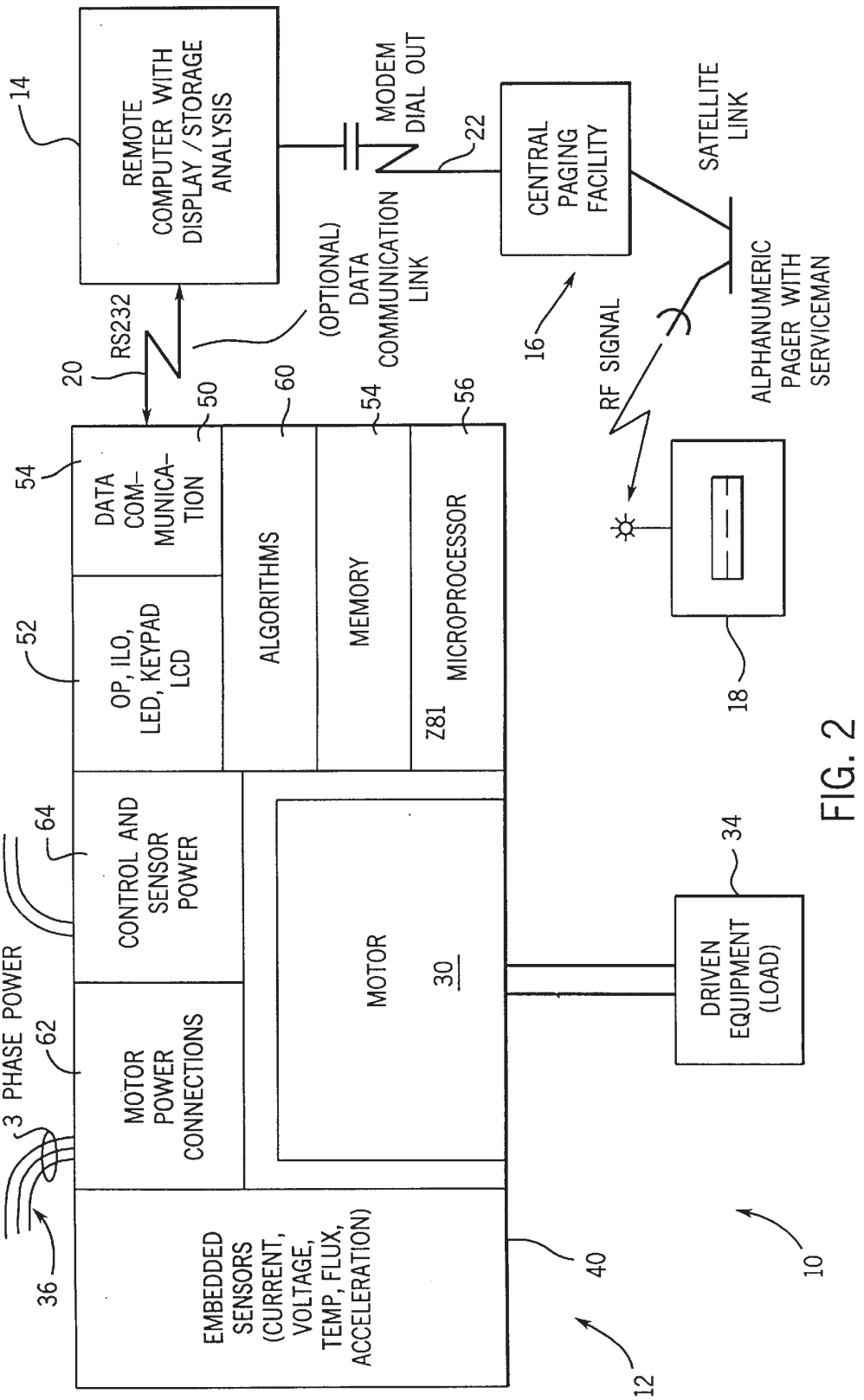

REMOTE COMPUTER WITH DISPLAY / STORAGE ANALYSIS
14
MODEM DIAL OUT
22
CENTRAL PAGING FACILITY
SATELLITE LINK
RS232
20
(OPTIONAL) DATA COMMUNICATION LINK
16
RF SIGNAL
ALPHANUMERIC PAGER WITH SERVICEMAN
50
60
54
56
54
DATA COM-MUNICA-TION
ALGORITHMS
MEMORY
MICROPROCESSOR
Z81
52
OP, ILO, LED, KEYPAD LCD
18
64
CONTROL AND SENSOR POWER
3 PHASE POWER
62
MOTOR POWER CONNECTIONS
MOTOR
30
34
DRIVEN EQUIPMENT (LOAD)
36
EMBEDDED SENSORS (CURRENT, VOLTAGE, TEMP, FLUX, ACCELERATION)
40
12
10

FIG. 2

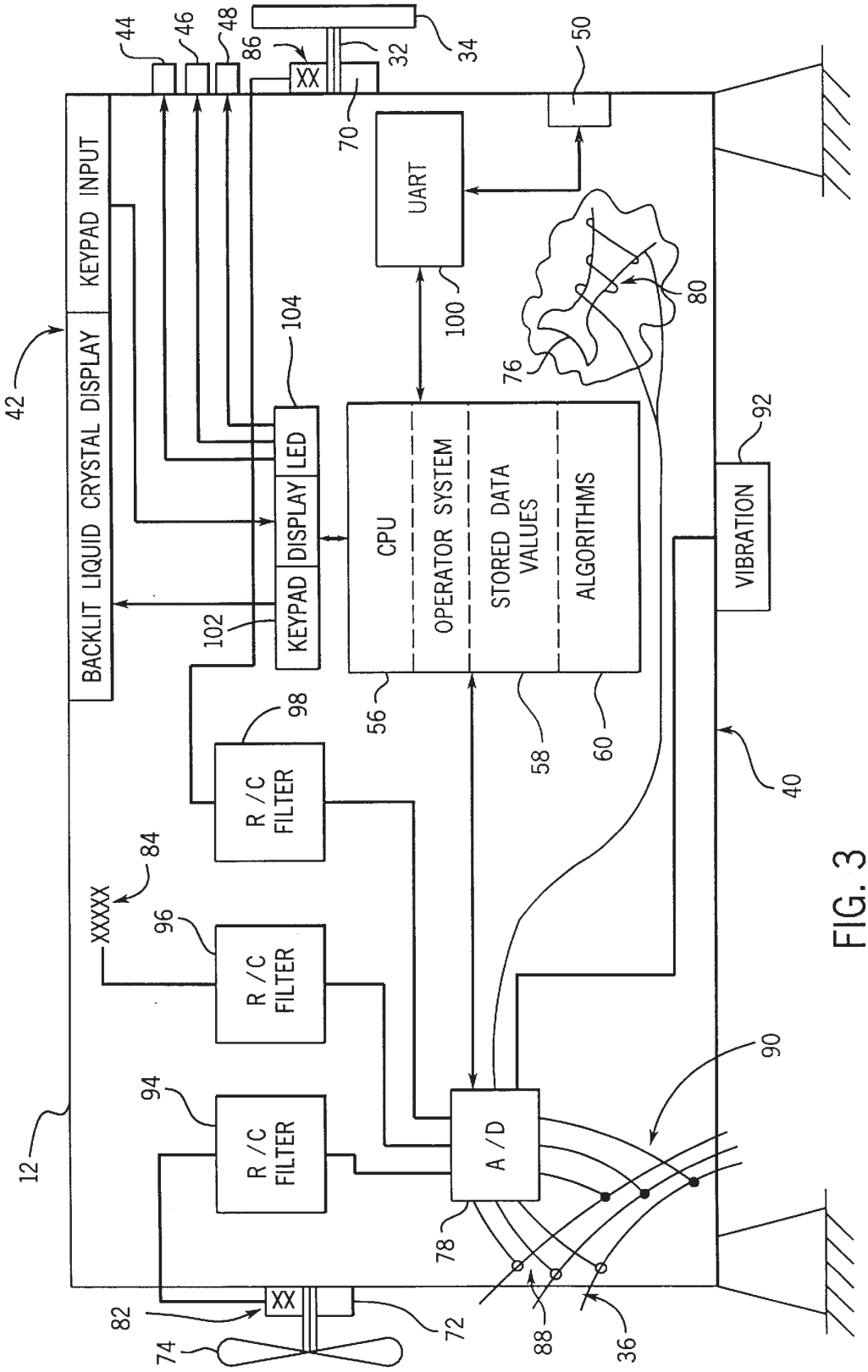

42
BACKLIT LIQUID CRYSTAL DISPLAY
KEYPAD INPUT
44
46
48
86
XX
32
34
50
70
UART
100
104
LED
DISPLAY
KEYPAD
102
CPU
OPERATOR SYSTEM
STORED DATA VALUES
ALGORITHMS
56
58
60
76
80
92
VIBRATION
40
98
R / C FILTER
84
XXXX
96
R / C FILTER
94
R / C FILTER
12
A / D
78
90
82
74
XX
72
88
36

FIG. 3

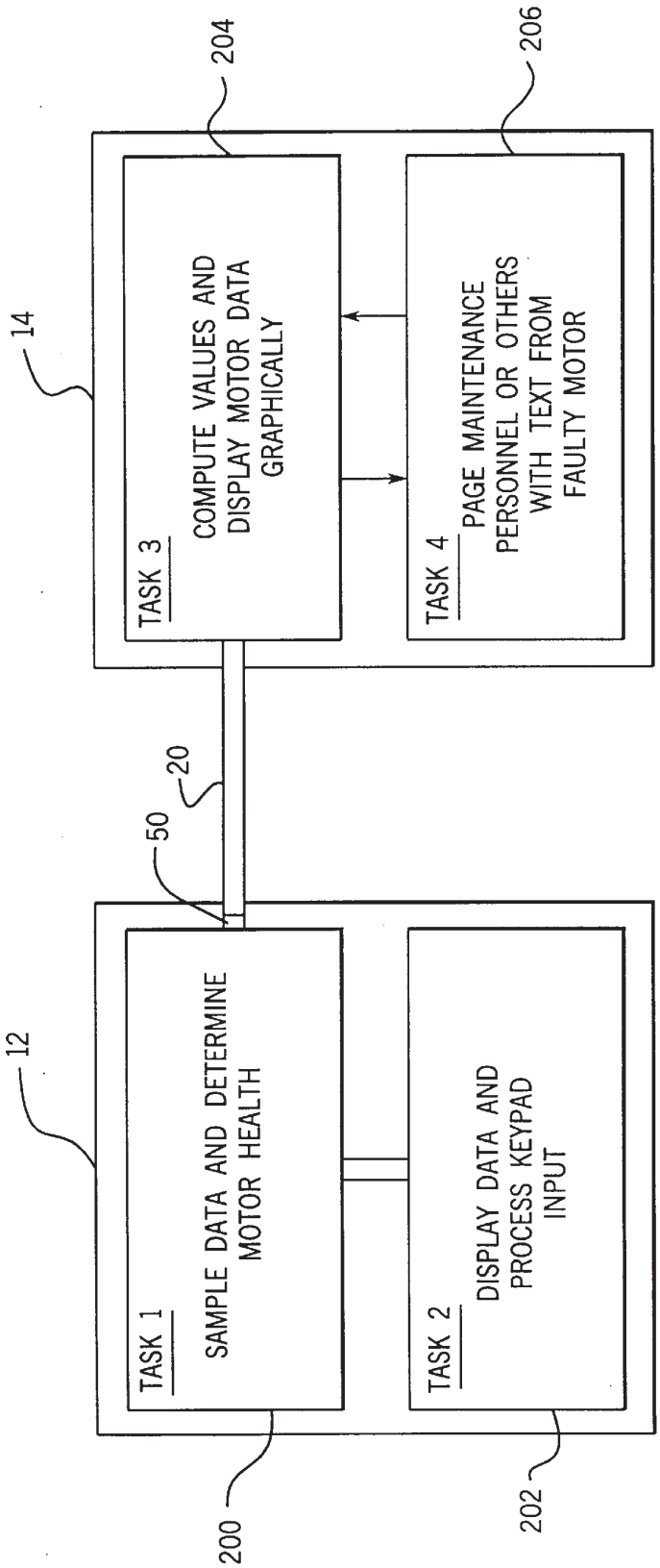
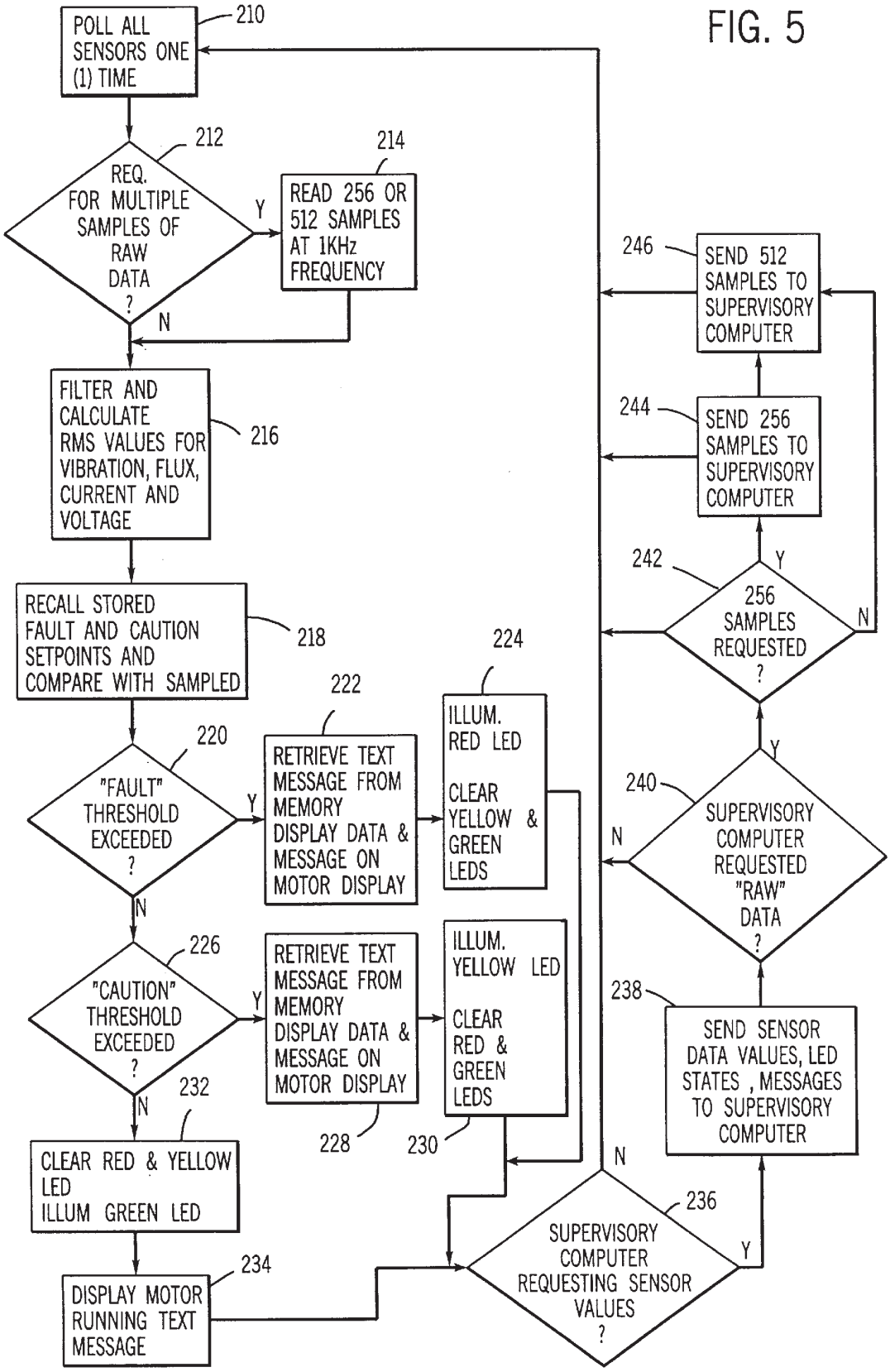

204
206
14
TASK 3
COMPUTE VALUES AND DISPLAY MOTOR DATA GRAPHICALLY
TASK 4
PAGE MAINTENANCE PERSONNEL OR OTHERS WITH TEXT FROM FAULTY MOTOR
20
50
12
TASK 1
SAMPLE DATA AND DETERMINE MOTOR HEALTH
TASK 2
DISPLAY DATA AND PROCESS KEYPAD INPUT
200
202

FIG. 4

FIG. 5


POLL ALL SENSORS ONE (1) TIME
210
REQ. FOR MULTIPLE SAMPLES OF RAW DATA ?
212
Y
N
READ 256 OR 512 SAMPLES AT 1KHz FREQUENCY
214
FILTER AND CALCULATE RMS VALUES FOR VIBRATION, FLUX, CURRENT AND VOLTAGE
216
RECALL STORED FAULT AND CAUTION SETPOINTS AND COMPARE WITH SAMPLED
218
"FAULT" THRESHOLD EXCEEDED ?
220
Y
N
RETRIEVE TEXT MESSAGE FROM MEMORY DISPLAY DATA & MESSAGE ON MOTOR DISPLAY
222
ILLUM. RED LED
CLEAR YELLOW & GREEN LEDS
224
"CAUTION" THRESHOLD EXCEEDED ?
226
Y
N
RETRIEVE TEXT MESSAGE FROM MEMORY DISPLAY DATA & MESSAGE ON MOTOR DISPLAY
228
ILLUM. YELLOW LED
CLEAR RED & GREEN LEDS
230
CLEAR RED & YELLOW LED
ILLUM GREEN LED
232
DISPLAY MOTOR RUNNING TEXT MESSAGE
234
SUPERVISORY COMPUTER REQUESTING SENSOR VALUES ?
236
N
Y
SEND SENSOR DATA VALUES, LED STATES , MESSAGES TO SUPERVISORY COMPUTER
238
SUPERVISORY COMPUTER REQUESTED "RAW" DATA ?
240
N
Y
256 SAMPLES REQUESTED ?
242
Y
N
SEND 256 SAMPLES TO SUPERVISORY COMPUTER
244
SEND 512 SAMPLES TO SUPERVISORY COMPUTER
246

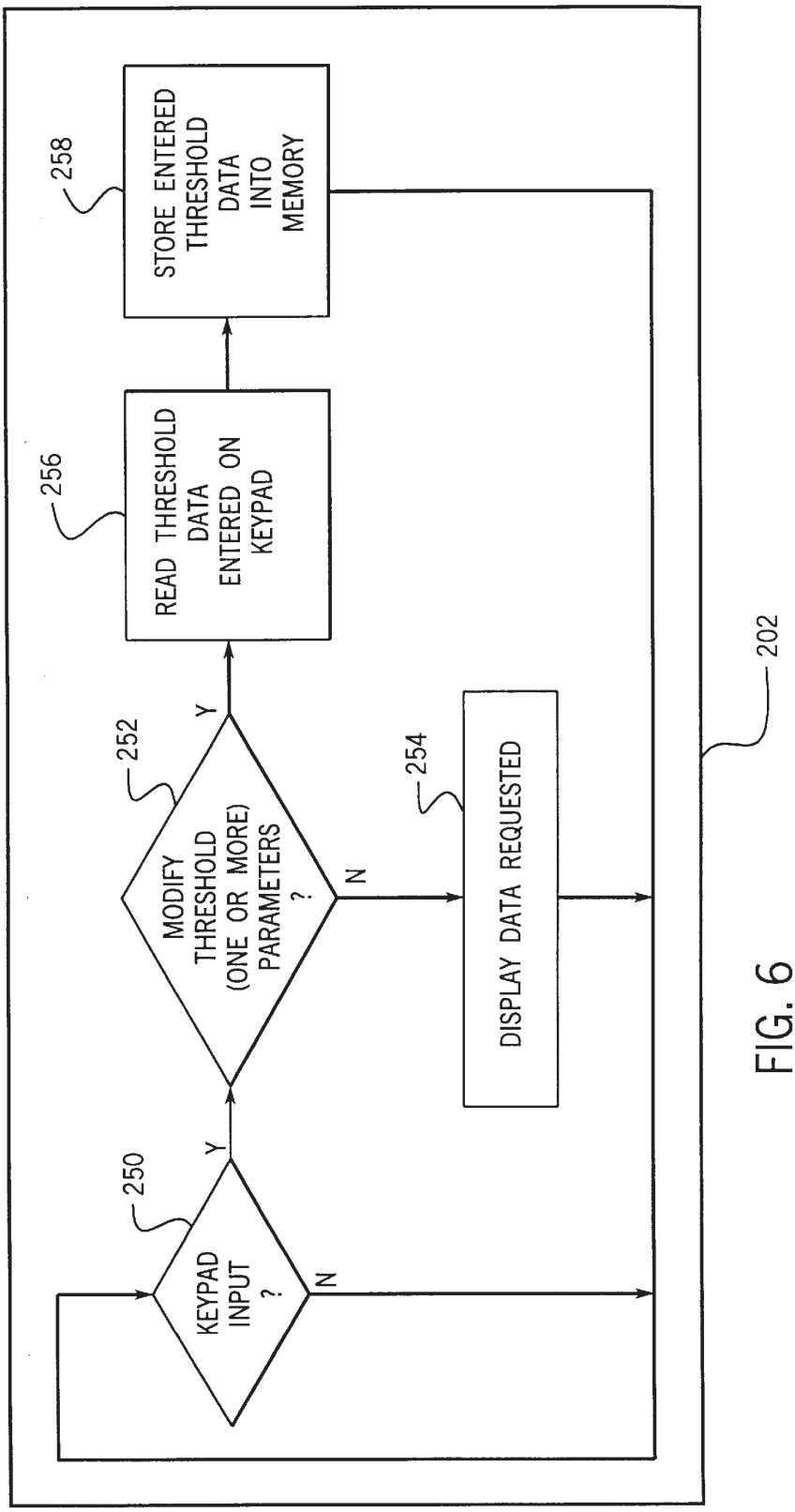

202
250
KEYPAD INPUT ?
Y
N
252
MODIFY THRESHOLD (ONE OR MORE) PARAMETERS ?
Y
N
254
DISPLAY DATA REQUESTED
256
READ THRESHOLD DATA ENTERED ON KEYPAD
258
STORE ENTERED THRESHOLD DATA INTO MEMORY

FIG. 6

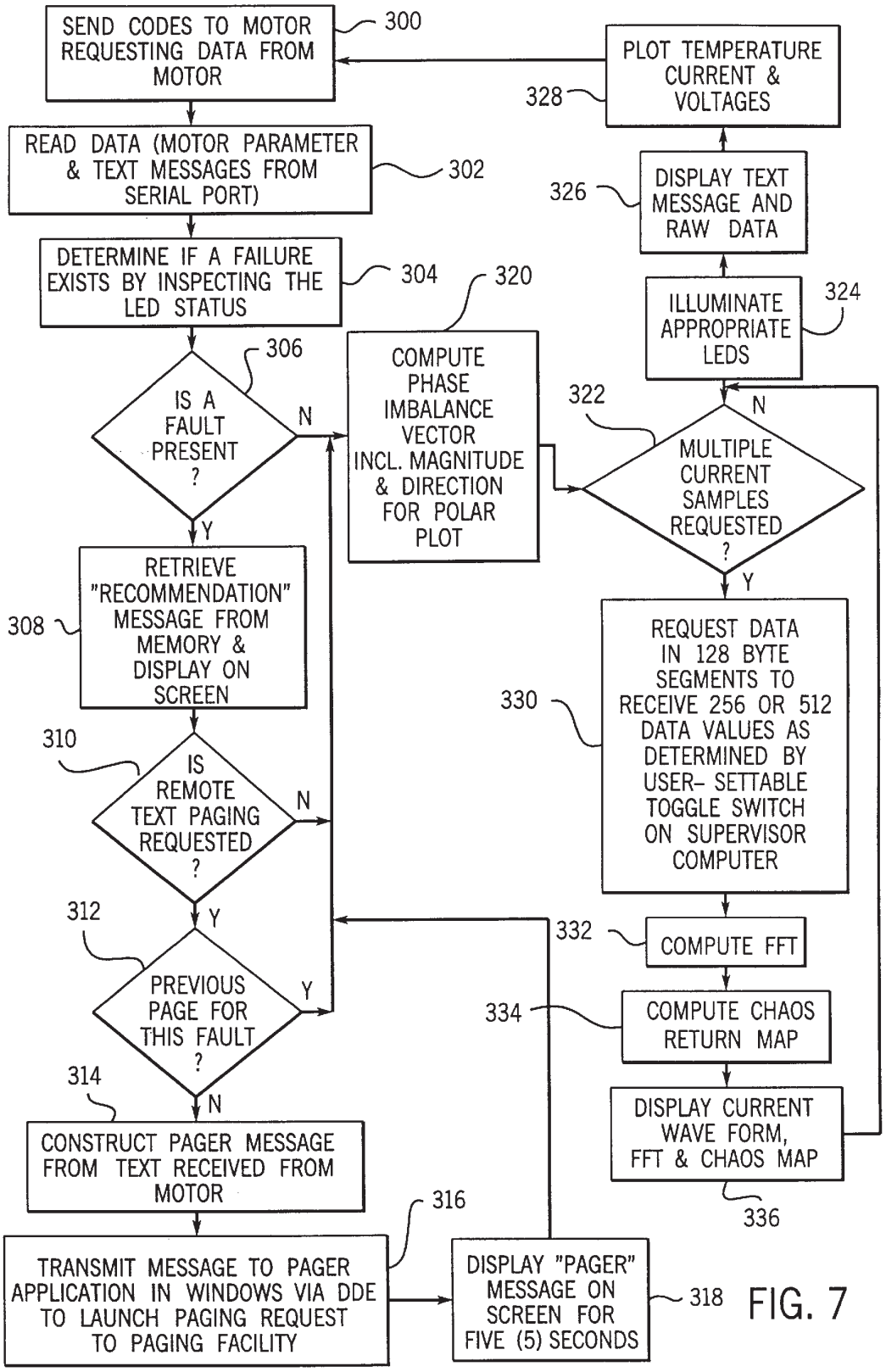

SEND CODES TO MOTOR REQUESTING DATA FROM MOTOR
300
READ DATA (MOTOR PARAMETER & TEXT MESSAGES FROM SERIAL PORT)
302
DETERMINE IF A FAILURE EXISTS BY INSPECTING THE LED STATUS
304
IS A FAULT PRESENT ?
306
N
Y
RETRIEVE "RECOMMENDATION" MESSAGE FROM MEMORY & DISPLAY ON SCREEN
308
IS REMOTE TEXT PAGING REQUESTED ?
310
N
Y
PREVIOUS PAGE FOR THIS FAULT ?
312
Y
N
CONSTRUCT PAGER MESSAGE FROM TEXT RECEIVED FROM MOTOR
314
TRANSMIT MESSAGE TO PAGER APPLICATION IN WINDOWS VIA DDE TO LAUNCH PAGING REQUEST TO PAGING FACILITY
316
DISPLAY "PAGER" MESSAGE ON SCREEN FOR FIVE (5) SECONDS
318
COMPUTE PHASE IMBALANCE VECTOR INCL. MAGNITUDE & DIRECTION FOR POLAR PLOT
320
MULTIPLE CURRENT SAMPLES REQUESTED ?
322
N
Y
REQUEST DATA IN 128 BYTE SEGMENTS TO RECEIVE 256 OR 512 DATA VALUES AS DETERMINED BY USER- SETTABLE TOGGLE SWITCH ON SUPERVISOR COMPUTER
330
COMPUTE FFT
332
COMPUTE CHAOS RETURN MAP
334
DISPLAY CURRENT WAVE FORM, FFT & CHAOS MAP
336
ILLUMINATE APPROPRIATE LEDS
324
DISPLAY TEXT MESSAGE AND RAW DATA
326
PLOT TEMPERATURE CURRENT & VOLTAGES
328

FIG. 7

MOTOR CONDITION MONITORING PRE-ALERT
DATA FORMAT
MOTOR-PC VIA RS232C

FIELD NO.	DATA FIELD NAME	SAMPLE VALUE	LENGTH (CHARS.)	TYPE
1	START OF MESSAGE-SOM NOTE: PC SENDS "R" TO MOTOR TO INITIATE TRANSMISSION OF FIELDS 1 THROUGH 17	SOM	3	CHARACTER
2	GREEN LED-LEDGRN	000.00-OFF 001.00-ON	6	FLOAT
3	YELLOW LED-LEDYEL	000.00-OFF 000.00-ON	6	FLOAT
4	RED LED-LEDRED	000.00-OFF 001.00-ON	6	FLOAT
5	INDEX OF FIELD CAUSING FAULT	000.00 (0 OR 7 THRU 17)	6	FLOAT
6	MESSAGE TEXT-MSGTXT	CAUTION-MOTOR NOW AT 180 C	40	CHARACTER
7	CURRENT 1-CUR1	123.45	6	FLOAT
8	CURRENT 2-CUR2	123.45	6	FLOAT
9	CURRENT 3-CUR3	123.45	6	FLOAT
10	VOLTAGE 1-VOLT1	123.45	6	FLOAT
11	VOLTAGE 2-VOLT2	123.45	6	FLOAT
12	VOLTAGE 3-VOLT3	123.45	6	FLOAT
13	TEMPERATURE BEARING LOAD-TEMPLOAD	123.45	6	FLOAT
14	TEMPERATURE BEARING FAN-TEMPFAN	123.45	6	FLOAT
15	TEMPERATURE STATOR-TEMPSTATR	123.45	6	FLOAT
16	ACCELERATION-ACCEL	123.45	6	FLOAT
17	MAGNETIC FIELD-FLUX	123.45	6	FLOAT
18-145	SAMPLED CURRENT ONE PHASE ONLY- CURSAMP. TRANSMIT INITIATED BY PC SENDING MOTOR "A"	123.45	6 X 128 (FIRST 128 SAMPLES)	FLOATS
146-273	SAMPLED CURRENT ONE PHASE ONLY- CURSAMP. TRANSMIT INITIATED BY PC SENDING MOTOR "B"	123.45	6 X 128 (SECOND 128 SAMPLES)	FLOATS
274-401	SAMPLED CURRENT ONE PHASE ONLY- CURSAMP. TRANSMIT INITIATED BY PC SENDING MOTOR "C"	123.45	6 X 128 (THIRD 128 SAMPLES)	FLOATS
402-529	SAMPLED CURRENT ONE PHASE ONLY- CURSAMP. TRANSMIT INITIATED BY PC SENDING MOTOR "D" NOTE-SENDING "D" TO MOTOR ALSO CAUSES ANOTHER 512 TO BE TAKEN.	123.45	6 X 128 (LAST 128 SAMPLES-COMPLETES THE 512 WAVEFORM)	FLOATS

NOTE THAT FIELD LENGTHS INCLUDES ANY SIGNS.

FIG. 8

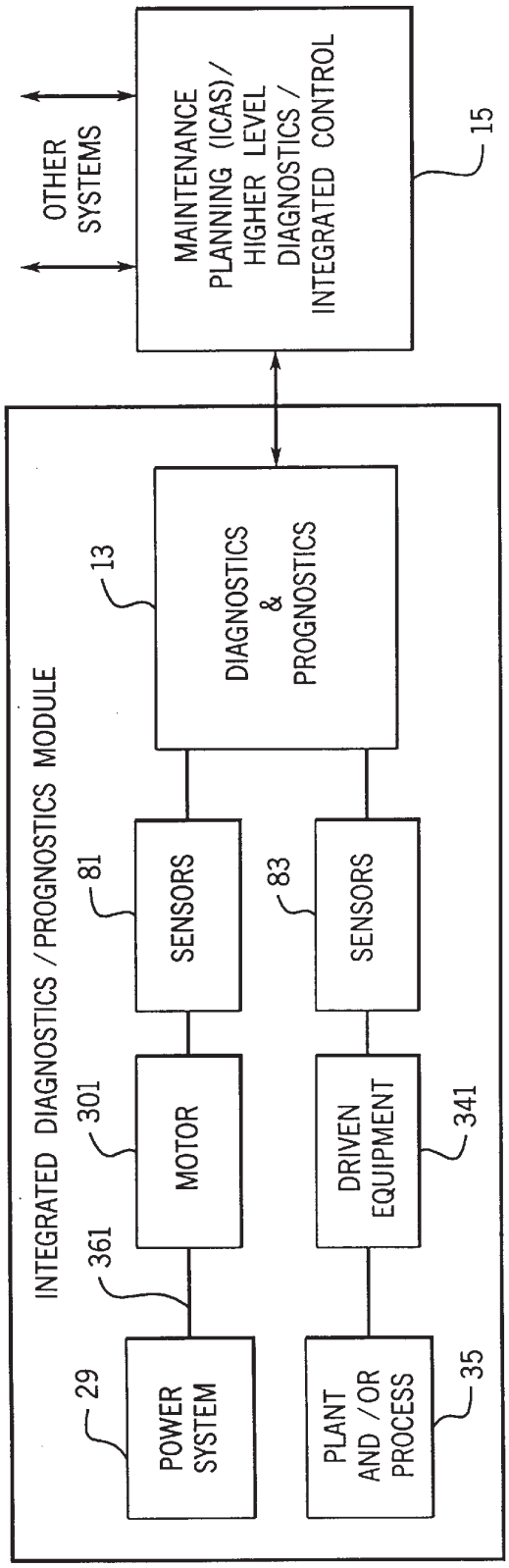

OTHER SYSTEMS
MAINTENANCE PLANNING (ICAS) / HIGHER LEVEL DIAGNOSTICS / INTEGRATED CONTROL
15
INTEGRATED DIAGNOSTICS / PROGNOSTICS MODULE
13
DIAGNOSTICS & PROGNOSTICS
81
SENSORS
83
SENSORS
301
MOTOR
341
DRIVEN EQUIPMENT
361
29
POWER SYSTEM
35
PLANT AND / OR PROCESS

FIG. 9

INTEGRATED MOTOR AND DIAGNOSTIC APPARATUS AND METHOD OF OPERATING SAME

BACKGROUND OF THE INVENTION

1. Field of Invention

The present invention relates to diagnostic apparatus and techniques for diagnosing and predicting failure in industrial machinery and, more particularly, to methods and apparatus for diagnosing the condition of rotating electrical and other machinery such as motors, generators, and gears wherein the diagnostics are integrated within the motor, generator, gear or other device.

2. Description of the Prior Art

A number of motor diagnostic methods and apparatus have been proposed in both the laboratory setting and elsewhere. U.S. Pat. No. 5,488,281 to Unsworth, et al. teaches a method and apparatus for predicting motor winding failure using zero crossing times. In that system, a motor controller is utilized which provides stator winding currents at a frequency of X cycles per second whereby the zero crossing times may be controlled and observed. In order to detect the zero crossing times and thus predict motor failure, the control system of the Unsworth, et al. apparatus alters the RMS supply line current by controlling the period of a notch introduced into the supply voltage each time the associated line current becomes zero. Thus, during the duration of the notch, a thyristor pair disposed in series with the motor lead wires operate as an open circuit. In that manner, instead of observing the sinusoidal supply voltage at the motor terminals, an internally generated motor back EMF voltage may be observed by the controller. Thus, in the Unsworth, et al. system, active motor control must be interrupted in order to detect and predict motor winding failures. Further, while the active motor control is interrupted, additional active inputs or signals must be introduced into the motor control circuit in order to induce the creation of observable motor parameters necessary to predict or conclude motor winding failures.

Another method and apparatus for determining the mechanical performance of polyphase electric motor systems is described in U.S. Pat. No. 5,521,482 to Lang et al. There, a fairly complicated apparatus is connected to the power lead wires connecting the motor to a power source. A plurality of signal conditioners are provided in order to generate signal levels suitable for use by a set of analog digital converters whereby the conditioned analog signals are converted to a digital representation thereof. A multiplexer is interposed between a central computer and the set of analog to digital converters thereby relieving the computer of the task of simultaneously reading each of the digital signals as they are generated in parallel. The computer is in turn connected to a communications port, a keyboard, a memory, a display unit and a printer. Although the above system may provide a method and apparatus for determining the electrical and mechanical performance parameters of a polyphase electric motor system in a laboratory or the like, it is not well suited for real time diagnosis of a motor operating in an industrial application.

The present invention overcomes many of the problems of the present conventional monitoring apparatus and techniques by providing a method and apparatus well suited for diagnosing motor conditions in the field while the motor is in use in production or the like. The present apparatus provides an integrated motor and motor diagnostic tool capable of passive observation of the operating parameters

in an unobtrusive manner and thus without interference to the process to which the motor is connected. Further, the present invention provides the capability of alerting an operator of various motor fault conditions as they occur and, in addition, to alerting the operator of less serious cautions regarding the operation of the motor as well.

SUMMARY OF THE INVENTION

Briefly stated, the present invention includes a diagnostic method and apparatus ideally suited for use with an electric motor of the type having a rotor, a stator, at least one bearing supporting the rotor, and a plurality of motor lead wires carrying electric current to the motor. Other applications are contemplated as well including electric generators, gear boxes, and in systems including "embedded motors" such as in consumer appliances or the like. The diagnostic apparatus according to the present invention includes at least one sensor in the motor for measuring a first physical condition of the motor and generating a first physical condition signal based on the measured first physical condition. A processing unit in the diagnostic apparatus is connected to the at least one sensor for determining the first operating condition of the motor based on the first physical condition signal. The processing unit generates an abnormal motor operation signal when the determined first operating condition is in a predetermined range. Further within the diagnostic apparatus, a signal communicating unit is responsive to the abnormal motor operation signal from the processing unit and communicates a motor diagnostic signal from the diagnostic apparatus to another device, a human, or any other supervisory control via a display unit or by wireless alphanumeric paging techniques.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention may take physical form in certain parts and arrangements of parts, preferred embodiments of which will be described in detail in this specification and illustrated in the accompanying drawings which form a part hereof and wherein:

FIG. **1** is a perspective view of the integrated motor and diagnostic apparatus according to the preferred embodiment of the invention;

FIG. **2** is a functional schematic diagram of the motor and integrated diagnostic apparatus illustrated in FIG. **1**;

FIG. **3** is a schematic diagram of the integrated motor and diagnostic apparatus illustrated in FIG. **2**;

FIG. **4** is a diagram showing the respective intelligent tasks performed by the components comprising the motor and diagnostic apparatus system illustrated in FIG. **1**;

FIG. **5** is a flow chart illustrating a first control and diagnostic function executed by the motor of the system illustrated in FIG. **4**;

FIG. **6** is a flow chart illustrating a second control and diagnostic function executed by the motor of the system illustrated in FIG. **4**;

FIG. **7** is a flow chart illustrating a first control and diagnostic task executed by the supervisory computer of the system illustrated in FIG. **4**;

FIG. **8** illustrates the motor condition and diagnosis parameter data exchanged between the motor and integrated diagnostic apparatus illustrated in FIGS. **2** and **3** and the supervisory computer and alphanumeric paging system shown in FIG. **1**; and,

FIG. **9** illustrates the present invention used in an application for monitoring the operating performance of driven equipment downstream of the motor.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention will be described in the context of the exemplary integrated motor and diagnostic system **10** shown in FIG. **1**. The integrated motor and diagnostic system **10** generally includes a motor and diagnostic unit **12**, a supervisory computer **14**, a central paging system **16**, and a remote operator pager **18**. The motor and diagnostic unit **12** is preferably connected to the supervisory computer **14** through a communication link **20**. Similarly, the supervisory computer **14** is connected to the central paging system **16** through a commercial communication link **22**. The central paging system **16** generally includes a local switchboard **24** and a remote broadcast tower **26** for generating an RF communication link signal **28** for delivery of alphanumeric messages or other signals or information from the supervisory computer **14** through the commercial communication link **22** and in turn to the remote operator pager **18**. In that manner, an operator may be alerted to the condition of the motor and diagnostic unit **12** from a remote location.

With continued reference to FIG. **1**, the motor and diagnostic unit includes an electric motor **30** having an output shaft **32** connected to a load **34**. The electric motor **30** receives power from a remote power source (not shown) through a set of power lead wires **36**. In addition, the motor and diagnostic unit **12** includes a diagnostic apparatus **40** integrated into the electric motor **30**. The diagnostic apparatus **40** provides an operator with a display device **42** for visually displaying various operating conditions of the motor **30**. Further, the diagnostic apparatus **40** includes a set of discrete motor condition display indicia including a fault indicia **44**, a caution indicia **46** and a normal operation indicia **48**. Lastly, in order to communicate with the supervisory computer, the motor and diagnostic unit **12** includes a communication port **50** for interfacing the diagnostic apparatus **40** with the supervisory computer **14** via the communication link **20**. The link **20** preferably adheres to the RS232C standard for communicating command and parameter information.

FIG. **2** shows a function block schematic representation of the system illustrated in FIG. **1** including the motor and diagnostic unit **12** connected to the load **34** through the output shaft **32** comprising the electric motor **30**. As illustrated, the diagnostic apparatus **40** is connected to the supervisory computer **14** via a communication link **20** through the communication port **50** provided in the diagnostic apparatus **40**. The supervisory computer **14** is connected to the central paging system **16** through a commercial communication link **22**. Preferably, the supervisory computer **14** includes an internal modem whereby communication with the central paging system **16** is via standard commercial telephone system using standard dial-up techniques. Lastly, the alphanumeric pager **18** is illustrated.

With continued reference to FIG. **2**, the diagnostic apparatus **40** includes a plurality of functional subsystems including a signal communicating unit **54** having a pair of subsystems namely, the communication port **50** described above and, in addition, a man machine interface **52**, commonly referred to in the art as an "MMI". The communication port **50** and the man machine interface **52** collectively form the signal communicating unit **54**. A processor unit **56** executes various diagnostic algorithms stored in an algorithm memory **60** and performs various diagnostic calculations utilizing a data memory **54**. An interface to the motor power lead wires **36** is provided by a motor power connection interface **62**. In addition, an interface is provided to a plurality of embedded sensors which will be described below through an embedded sensor interface **64**. Lastly, power is provided to the processor unit and to other components forming the diagnostic apparatus **40** from a control and sensor power unit **66**.

FIG. **3** is a schematic representation of the motor and diagnostic unit **12** shown in its preferred application wherein the diagnostic apparatus **40** is integrated within a three phase induction motor **30**. The induction motor illustrated includes a load bearing **70** on a front end thereof and a fan bearing **72** on the back end thereof. The output shaft **32** connects the load **34** to the motor **30**. Similarly, the other end of the output shaft connects a fan **74** to the motor **30**. The fan bearing **72** is on the same end of the motor as is the fan **74**. Correspondingly, the load bearing **70** is on the same end of the motor as is the load **34**. Also illustrated in FIG. **3** is a cut away sectional view of the motor exposing a stator tooth **76** of the induction motor having an air gap flux sensor **80** connected thereto for purposes described in greater detail immediately below.

The air gap flux sensor **80** is connected to the processor unit **56** via an analog to digital converter **78**. The analog to digital converter converts the analog signals generated by the plurality of sensors including the air gap flux sensor **80** into a digital value for ready use by the processor unit **56**. Other analog sensors connected to the processor unit **56** via the analog to digital converter **78** include a fan bearing temperature sensor **82**, a stator temperature sensor **84**, a load bearing temperature sensor **86**, a set of motor current sensors **88**, a set of motor voltage sensors **90**, and a vibration sensor **92**. The fan bearing temperature sensor **82**, the stator temperature sensor **84**, and the load bearing temperature sensor **86** are each preferably bi-metallic thermocouple-type sensors for generating an analog voltage proportional to the temperature at the thermocouple lead.

Each of the temperature sensors are preferably embedded into the target apparatus such as by drilling a hole into the stator core for providing a space to lodge the stator temperature sensor **84**. After the stator temperature sensor **84** is lodged into the hole provided therefore in the stator, a suitable epoxy material is disposed into the hole to fill the void providing a good mechanical and thermal connection between the stator temperature sensor **84** and the stator core into which the sensor is embedded. Similarly, each of the bearing temperature sensors **82, 86** are preferably embedded into their respective bearing components. Alternatively, the temperature sensors may be mounted into the motor end brackets near the bearing components. As illustrated in the figure, the thermocouple temperature sensors **82, 84, 86** are connected to the analog to digital converter **78** through the filter devices **94, 96, 98**. Each of the filters **94, 96, 98** provide a buffer to smooth any transience that might be experienced by the thermocouple temperature sensors. Preferably, the buffer proves an RC time constant large enough to mask high frequency noise on the thermocouple inputs.

With continued reference to FIG. **3**, the analog to digital converter **78** includes a set of motor current sensors **88** and a set of motor voltage sensors **90**. Each of these sets of sensors are connected directly to the power lead wires **36** connecting the electric motor **30** to a source of power. Preferably, the motor current sensors **88** are arranged as current transformers on each power line to generate a voltage proportional to the current flowing through the respective power lead wire. Further, each of the motor voltage sensors **90** preferably includes a voltage division circuit such as a resistor bridge circuit for providing an analog voltage signal to the analog to digital converter **72**

which is within the operating range of the converter. Preferably, the voltage conditioned by the divider circuit remains proportional to the incoming power voltage on the power lead wires **36**.

The air gap flux sensor **80** is illustrated as being wrapped around a stator tooth **76** of the stator of the electric motor **30**. The air gap flux sensor **80** provides a voltage proportional to the flux experienced at the stator tooth. One or more stator teeth may be selected to provide inputs along the axial length of the stator of the motor or circumferentially around the stator, or both. In some applications, it may be desirable to arrange multiple flux sensors or, alternatively, to monitor only the peak inputs from the multiple sensors.

Lastly, a vibration sensor **92** is mechanically connected to the casing of the motor **30** to provide a voltage signal proportional to the amount of vibration experienced by the motor. As illustrated, the vibration sensor **92** is connected to the motor casings at a central location. However, one or more vibration sensors may be disposed about the various internal and/or external surfaces of the motor to provide one or more vibration signals. The analog signals from the vibration sensors are converted to digital signals by the A/D mechanism **78** for use by the processor unit **56**.

With yet continued reference to FIG. **3**, the processor unit **56** executes various diagnostic algorithms from programs stored in an algorithm memory **60**. Further, the processor unit **56** utilizes a data memory **58** to perform various calculations and to store variables. A universal asynchronous receiver and transmitter **100**, commonly referred to in the art as "UART", is connected to the communication port **50** described above. In addition, the signal communicating unit **54** includes a keypad and display driver unit **102** and LED driver unit **104**. The keypad/display driver unit **102** provides suitable signal conditioning a logical interface between the processor unit **56** and the display unit **42**. Preferably, the display device **42** is a back lit liquid crystal display having a 2×24 character display. Similar to the above, the LED driver unit **104** provides a suitable logical interface and signal conditioning and the processor unit **56** and the set of display indicia on the diagnostic apparatus **40** including the fault indicia LED **44**, the caution indicia LED **46**, and the normal operation indicia LED **48**.

With reference now to FIG. **4**, the functional operation of the integrated motor and diagnostic system **12** will be described first with particular reference to the functional operation of the motor and diagnostic unit **12** and then with reference to the functional operation of the supervisory computer **14**.

Both the motor and diagnostic unit **12** and the supervisory computer **14** execute a respective set of instructions and logical operations in order to effect the motor diagnostic functions according to the present invention. Although the operation of the motor and diagnostic unit will be discussed in conjunction with the operation of the supervisory computer below, it is to be noted that according to the present invention, the motor and diagnostic unit **12** may be operated independent of the supervisory computer **14** such as when the communication link **20** is disconnected or during other conditions where the supervisory computer **14** is not necessary. Further, the supervisory computer is adapted to interface a plurality of motor and diagnostic units with one or more central paging systems. In addition, a plurality of diagnostic units may be connected to a plurality of supervisory computers which are in turn connected to a plurality of central paging systems. For convenience, the singular case/toplogy will be used to explain the invention.

The motor and diagnostic unit **12** executes a set of logical operations which may generally be grouped into a first task **200** and a second task **202**. The first task **200** comprises those operations which sample data and determine the health of the electric motor **30**. The second task **202** comprises those operations which display the collected and computed data and in addition, those tasks which process keypad input and output information. An operating system task (not shown) in the motor and diagnostic unit **12** operates generally to call the first task **200** and then, upon a return from task one, the operating system calls task two **202**. Thus, the operating system in the motor and diagnostic unit **12** calls the tasks **200**, **202** in an alternating fashion.

With continued reference to FIG. **4**, the supervisory computer **14** includes an operating system as well (not shown) which includes the basic functions necessary to operate the supervisory computer **14** including a display unit, a keyboard, disk drives and a modem. Preferably, the supervisory computer is PC based and therefore the operating system is preferably one of the commercially available systems such as DOS, Windows, or Windows 95. The operating system within the supervisory computer **14** periodically calls task three **204** which generally comprises those operations which compute various parameter values and display motor data on the supervisory computer in a graphical form. A fourth task **206** in the supervisory computer **14** is selectively launched by the third task **204** in the supervisory computer **14** when it becomes necessary to page a human operator such as a maintenance engineer with textual information or to send other data indicative of a faulty motor or for other reasons which may require the attention of the human operator. Thus, the fourth task **206** includes the programming necessary to interface the supervisory computer **14** with the central paging system **16** via a modem or the like in the supervisory computer **14**.

With reference now to FIG. **5**, the first task **200** executed in the motor and diagnostic unit **12** will be described in detail. Initially, as a first step **210** during the execution of the first task **200**, each of the plurality of sensors is polled for their values by the processor unit **56** and the A/D converter **78**. In step **210**, all of the thermocouple sensors are polled as well as the air gap flux sensor and the voltage and current sensors.

Next, in step **212**, a flag (not shown) in the data memory **58** is inspected to determine whether multiple samples of raw data are required to be polled. In the event that multiple samples of raw data are required as determined by the flag in the memory, a plurality of raw samples are polled by the processor unit and A/D converter in step **214**. A second flag in the data memory **58** is inspected to determine whether 256 or 512 samples are taken. In either case, the multiple raw sample data is polled at 1 KHZ into the data memory **58**.

In the event that multiple samples of raw data are not required, the first task **200** immediately transfers control to step **216** whereat the plurality of sensor value data obtained at step **212** is first filtered through the RC filters **94**, **96**, **98** or through software means and then manipulated in order to calculate root mean squared RMS values for motor vibration, motor voltage, motor current and flux parameter values. In step **216**, the RMS values are for the various motor parameters including vibration, voltage, current and flux values are determined according to well known techniques. The RMS values for each of the parameters are stored in the data memory **58** of the motor and diagnostic unit **12**.

Having obtained and stored the various RMS parameter values, respective sets of previously stored threshold values

for those parameters are inspected at step **218** in order to determine a comparison between the previously stored threshold values and the calculated values. The previously stored threshold values include ranges for motor fault conditions, a range for a motor caution condition, and a range for a normal operating condition. Each of the vibration, voltage, current and flux parameters are assigned a range of fault, caution, and normal operation threshold values in the data memory **58** such as through the keypad and display device **42** in a manner described below.

In step **220**, the calculated RMS values for vibration, voltage, current and flux parameters are compared against the previously stored fault threshold values for same. If any of the calculated RMS parameters exceed their respective fault threshold values, a message text is retrieved in step **222** from the data memory **58** and in turn displayed on the input and display device **42**. As an added precaution and in order to announce the fault condition in a more apparent manner, the fault indicia LED **44** is illuminated in step **224**. If only a single parameter indicates a motor fault, the task may selectively monitor only that particular faulty parameter ignoring the other raw data sensor inputs. A benefit is that a greater level of resolution is obtainable.

In step **226**, the calculated RMS values for vibration, voltage, current and flux parameters are compared against previously stored caution threshold values. If any of the calculated RMS values for vibration, voltage, current or flux exceed the previously determined caution threshold values, a textual message is retrieved from the data memory **58** and the retrieved message as well as the calculated RMS value exceeding the caution is displayed on the input and display device **42**. As with the fault condition, in order to more emphatically emphasize the caution condition, the caution indicia LED **46** is illuminated in step **230**.

In the event that each of the calculated RMS values for vibration, voltage, current and flux parameters do not exceed either the fault threshold range or the caution threshold range, each of the fault and caution indicia LEDs **44**, **46** are cleared in step **232**. In that event, the normal operation indicia LED **48** is illuminated. Further, in the event that no faults or caution conditions are found to exist, a motor running message is displayed on the input and display device **42** at step **234**.

The first task **200** determines at step **236** whether the supervisory computer **14** is connected to the motor and diagnostic unit **12** via the communication link **20** at step **236**. If it is determined that the supervisory computer is connected to the motor and diagnostic unit and further that the supervisory computer is requesting one or more sensor parameter values at step **236**, the motor and diagnostic unit **12** transmits the requested sensor value data to the supervisory computer at step **238**. In that event, the motor and diagnostic unit transmits the calculated RMS values for vibration, voltage, current and flux parameters as well as the status of the fault, caution, and normal operation indicia LEDs.

In step **240**, the first task **200** determines whether the supervisory computer **14** has lodged a request for the raw data collected at step **212**. If such a request has been lodged, it is determined in step **242** whether 256 samples are requested. If the smaller sample collection is requested, it is transmitted to the supervisory computer at step **244**. However, in the event that the larger data set is requested, the raw sample data is transmitted from the data memory **58** of the motor and diagnostic unit to the supervisory computer at step **246**.

As indicated above, the operating system within the motor and diagnostic unit alternately calls the first task **200** and the second task **202**. After completing execution of the first task **200** in the manner described above, the second task **202** shown in FIG. **6** is then executed by the motor and diagnostic unit. In the second task **202**, the motor and diagnostic unit determines in step **250** whether the status of the keypad input on the input and display device has changed since the previous execution of the second task. In the event that the status has changed, it is determined in step **252** whether any of the fault or caution threshold values stored in the data memory **58** are to be changed. If not, the requested data is displayed on the input and display device **42** at step **254**. However, if one or more threshold values are to be changed, the new value is read at step **256** and entered into the data memory **58** at step **258**. In the above manner, operator requested data is displayed on the input and display device **42** and, further, new threshold parameter data is entered into the data memory **58** of the motor and diagnostic unit **12** through the input and display device **42**.

With reference now to FIG. **7**, the third task **204** will be described in detail. Initially, in the event that the supervisory computer has a need for parameter value data, a request code is transmitted to the motor and diagnostic unit at step **300** requesting one or more data types or sets of parameter data from the data memory **58**. After transmitting the request code, the supervisory computer **14** reads the data from the motor and diagnostic unit transmitted via the communication link **20**. Typically, the data includes motor parameter data and text messages as well as the status of the fault, caution and normal operation indicia LEDs. FIG. **8** illustrates the preferred data types and further, illustrates the preferred data characteristics communicated between the motor and diagnostic unit **12** and the supervisory computer **14**.

With continued reference to FIG. **7**, step **304** of the third task **204** determines whether a failure or fault condition exists by inspecting the status of the transmitted fault indicia information (red LED item or yellow LED item in FIG. **8**). If a fault condition is determined to be present in step **306**, the supervisory computer **14** retrieves a recommendation message in step **308** from a memory location (not shown). The retrieved recommendation message is displayed on a screen connected to the supervisory computer. After displaying the recommendation message on the screen, it is next determined in step **310** whether a remote text paging is requested as determined by a flag (not shown) previously stored in the supervisory computer. If it is determined in step **312** that the page request has not already been acted on for the particular fault, a pager message is constructed in step **314** primarily from the text received from the motor and diagnostic unit. Next, in step **316**, the pager message is transmitted through the operating system of the supervisory computer and by launching the fourth task **206** to transmit the page request to the central paging system **16** via the commercial communication link **22**. Preferably, the paging request is executed by the fourth task **206** as a background process. In addition, the fourth task executing in the background preferably includes intelligence to selectively transmit the fault message to the appropriate personnel. In that regard, serious fault messages may be transmitted to a supervisory maintenance operator. On the other hand, mere cautionary messages may be transmitted to machine operators or other personnel for the exercise of the appropriate corrective action. Lastly, in step **318**, the supervisory computer displays the message intended to be transmitted to the remote operator pager **18** on a screen of the supervisory computer.

In step **306** if it is determined that a fault is not present based upon the data transmitted from the motor and diagnostic unit, the supervisory computer computes at step **320**, a phase imbalance vector including phase magnitude and direction, in order to display a polar plot of the phase voltage and current on a display screen of the supervisory computer. If it is determined in step **322** that multiple current samples were not requested from the motor and diagnostic unit, graphical representations of the fault, caution and normal operation indicia LEDs are illuminated on a display screen of the supervisory computer in step **324**. Further, in step **326**, a textual message as well as the raw parameter data values are displayed on a display screen of the supervisory computer. Lastly, a plot of the temperature, current, and/or voltage values are displayed on the display unit of the supervisory computer in step **328**.

If, in step **322**, it is determined that multiple current samples were requested, additional data is requested from the motor and diagnostic unit in 128 byte segments in step **330**. A fast fourier transform FFT is next calculated in step **332**. In addition, a complete chaos return map is computed in step **334** using the requested data in 128 byte segments. Lastly, in step **336**, one or more of the current wave form, fast fourier transform, and chaos map is displayed on a display unit of the supervisory computer **14**.

FIG. **9** illustrates the present invention in an application extending the diagnosis to include condition-based maintenance of machinery which is system-wide in scope and includes effective condition monitoring and analysis. An electric motor **30'** receives power from a power system **29** through a set of power lead wires **36'**. The motor **30'** is connected to a load **34'** which may be any piece of driven equipment. The article of driven equipment or load **34'** is in turn connected to other pieces of equipment in a plant and/or process **35**. A plurality of motor sensors **81** are connected to the motor **30'** in a manner described above with respect to the temperatue sensors, the vibration sensor and the current and voltage sensors. In addition, a plurality of load sensors **83** are connected to the article of driven equipment or load **34'**. The plurality of motor sensors **81** and the plurality of load sensors **83** are each in turn connected to a diagnostics and prognostics apparatus **13**. The diagnostics and prognostics apparatus **13** is in turn connected to a higher level maintenance planning or integrated control system **15**.

The diagnostics and prognostics apparatus **13** utilize various analytic techniques such as those which generally fall under the category of current signature analysis which has been shown to detect certain mechanical problems such as bearing failure, rotor problems and electrical insulation breakdown. Powerful filtering and other signal processing and classification algorithms are used by the diagnostic and prognostic apparatus **13** to relate sample sensor information to a plant model for root cause analysis and lifetime prediction. Both qualitative and quantitative motor, driven equipment, and system models are utilized.

The prognostication performed in the apparatus **13** of the future state of the system is in terms of both physical condition such as stator insulation and estimate of degradation rates and operation impact as a function of degradation. This prognostication not only protects equipment and insures operational readiness, it also allows integrated motor control centers to adjust system usage for optimum machinery system performance or to achieve targeted machinery life. The prognostication of system degradation executed in the unit **13** allows maintenance planning to proceed in a efficient manner to provide optimum plant system utilization. Several analytical methods are implemented in the unit **13** to accurately perform machinery diagnostics and prognostics. The system illustrated in FIG. **9** includes pattern recognition routines, signal classification algorithms, and models (both qualitative and quantitative) of the machine components and the machinery in its entirety. It is contemplated that all of these techniques and combinations be used in the system described in detail above and shown in FIGS. **1–8**.

While particular embodiments of the present invention have been shown and described, it should be clear that changes and modifications may be made to such embodiments without departing from the true scope and spirit of the invention. It is intended that the appended claims cover all such changes and modifications.

Having thus described the preferred embodiments of the invention, we now claim:

1. An integrated motor and diagnostic system comprising:

an electric motor including a rotor, a stator, at least one bearing supporting the rotor, and a plurality of motor lead wires carrying electrical current to the motor; and,

a diagnostic unit integrated into the electric motor, the diagnostic unit including:

at least one sensor on the motor for measuring a first physical condition of the motor and generating a first physical condition signal based on said measured fist physical condition;

a memory element including an FFT based diagnostic algorithm;

a processing unit coupled to said memory element and to said at least one sensor, said processing unit performing a diagnostic assessment of the motor based on said first physical condition signal and the diagnostic algorithm and generating a diagnostic signal; and,

a signal communicating unit coupled to the processing unit for communicating the diagnostic signal from the diagnostic apparatus.

2. The integrated motor and diagnostic system according to claim **1** wherein:

said diagnostic unit further comprises a plurality of sensors on the motor for measuring a plurality of first physical conditions of the motor and generating a plurality of first physical condition signals based on said plurality of first physical conditions; and,

said processing unit is connected to said plurality of sensors for determining said diagnostic assessment of the motor based on first preselected ones of said plurality of first physical condition signals and the diagnostic algorithm.

3. The integrated motor and diagnostic system according to claim **2** wherein said plurality of sensors include a set of sensors selected from the group consisting of a vibration sensor, a thermocouple sensor, an electric current sensor, an electric voltage sensor and a magnetic flux sensor.

4. The integrated motor and diagnostic system according to claim **1** further comprising a supervisory computer device operatively connected to the signal communicating unit for receiving said motor diagnostic signal from the signal communicating unit and selectively generating a diagnostic message based on said motor diagnostic signal.

5. The integrated motor and diagnostic system according to claim **4** wherein said supervisory computer device is adapted to communicate said diagnostic message to an operatively associated commercial pager system for transmission to a remote alphanumeric pager device.

6. The integrated motor and diagnostic system according to claim **1** wherein the processing unit includes means for

comparing said diagnostic signal with a first operating condition parameter stored in said memory.

7. The integrated motor and diagnostic system according to claim **6** wherein the signal communicating unit includes an operator interface having an input unit for receiving said first operating condition parameter into the system and an output unit for displaying said motor diagnostic signal.

8. The integrated motor and diagnostic system according to claim **7** wherein:

the input unit of the said operator interface includes means for receiving said first operating condition parameter from an operatively associated supervisory controller; and,

the output unit of said operator interface includes means for transmitting said motor diagnostic signal to said operatively associated supervisory controller.

9. The integrated motor and diagnostic system according to claim **1** wherein:

said system further comprises a plurality of sensors on the motor for measuring a plurality of first physical conditions of the motor and generating a plurality of first physical condition signals based on said plurality of measured first physical conditions; and,

said processing unit includes means for dynamically adjusting a sampling rate of selective ones of said plurality of sensors based on an operating condition of the motor.

10. The integrated motor and diagnostic system according to claim **1** wherein said electric motor includes a housing adapted to integrally couple with said diagnostic unit.

11. An integrated motor and diagnostic system comprising:

an electric motor including a rotor, a stator, at least one bearing supporting the rotor and, a plurality of motor lead wires carrying electric current to the motor; and,

a diagnostic unit integrated into the electric motor, the diagnostic unit including:

at least one sensor measuring a first physical condition of the motor and generating a first physical condition signal based on said measured first physical condition;

a memory element including a pattern recognition based diagnostic algorithm;

a processing unit coupled to said memory element and to said at least one sensor, said processing unit performing a diagnostic assessment of the motor based an said first physical condition signal and the diagnostic algorithm and generating a diagnostic signal; and,

a display device integrated into the electric motor and adapted to visually display said diagnostic signal of the motor.

12. The integrated motor and diagnostic system according to claim **11** further comprising a signal communicating unit responsive to the processing unit for communicating said diagnostic signal from the integrated motor and diagnostic system to an operatively associated external supervisory computer device.

13. The integrated motor and diagnostic system according to claim **12** further comprising a supervisory computer device operatively connected to the signal communicating unit for receiving said diagnostic signal from the signal communicating unit and selectively generating a diagnostic message at the supervisory computer device based on said first operating condition signal.

14. A integrated motor and diagnostic system comprising:

an electric motor including a rotor, a stator, at least one bearing supporting the rotor and, a plurality of motor lead wires carrying electric current to the motor; and,

a diagnostic unit integrated into the electric motor, the diagnostic unit including:

a plurality of sensors measuring a plurality of physical conditions of the motor and generating a plurality of physical condition signals based on said measured plurality of physical conditions;

a memory element including an FFT based diagnostic algorithm;

a processing unit coupled to said memory element and to said plurality of sensors, said processing unit performing a diagnostic assessment of the motor based on said plurality of physical condition signals and said diagnostic algorithm and generating a diagnostic signal; and,

a signal communicating unit responsive to the processing unit and adapted to communicate said physical condition signal and said diagnostic signal from the diagnostic apparatus to an operatively associated external device.

15. The integrated motor and diagnostic system according to claim **14** further comprising a supervisory computer device operatively connected to the signal communicating unit adapted to receive said diagnostic signal from the signal communicating unit and selectively generate a diagnostic message at the supervisory computer device based on said diagnostic signal.

16. The integrated motor and diagnostic system according to claim **15** wherein said diagnostic unit includes a display device integrated into the electric motor and adapted to visually represent said diagnostic signal.

17. The integrated motor and diagnostic system according to claim **16** wherein said plurality of sensors include a set of sensors selected from the group consisting of a vibration sensor, a thermocouple sensor, an electric current sensor, an electric voltage sensor and a magnetic flux sensor.

18. A motor diagnostic system comprising:

an electric motor;

a diagnostic unit integrated into said motor, said diagnostic unit comprising,

at least one sensor measuring a first physical condition of the motor and generating a first physical condition signal based an said first physical condition;

a memory element including a motor model based diagnostic algorithm;

a processing unit coupled to said memory element and to said at least one sensor, said processing unit performing a diagnostic assessment of the motor based on said first physical condition signal and the diagnostic algorithm and generating a diagnostic signal; and

a remote signal communications interface coupled to the processing unit for communicating said diagnostic signal and said first physical condition signal.

19. The motor diagnostic system according to claim **18** further comprising a supervisory computer device operatively connected to the remote communications interface for receiving said first physical condition signal from the interface and selectively generating a diagnostic message at the supervisory computer device based on said first physical condition signal.

* * * * *

EXHIBIT 10

Kansas Geological Survey, Public Information Circular (PIC) 32
A complete version of this PIC is available as a pdf document.

Hydraulic Fracturing of Oil and Gas Wells in Kansas

Daniel R. Suchy and K. David Newell
Kansas Geological Survey

Introduction

Hydraulic fracturing is a method of enhancing oil and gas recovery from wells by injecting water, sand, and chemicals into rock formations under very high pressure to fracture the rock and release trapped hydrocarbons. It has been used in the industry for decades, but questions have arisen concerning possible environmental problems associated with the practice, particularly suspected contamination of potable ground water and rivers and streams in certain areas. Currently the practice is regulated by the states, with rules varying from state to state. Some people, however, are asking for increased Federal regulation to govern its use (The Editors, 2011). This publication will discuss hydraulic fracturing, how it is used, how it is regulated, especially in Kansas, and possible environmental issues. Terms in **boldface** type are defined in the glossary at the end of the circular.

History of Hydraulic Fracturing

The first experimental hydraulic fracturing treatment in the United States took place in 1947 in the Hugoton gas field in Grant County, Kansas (fig. 1). It was done on a small scale to bypass pore space near the wellbore in the oil-bearing rock formation that was clogged by **drilling mud** during drilling operations (Montgomery and Smith, 2010). In 1949 a patent was issued to the Halliburton Oil Well Cementing Company, which then performed the first two commercial fracturing treatments in Oklahoma and Texas. At that time the engineering was simple and unsophisticated. Since then, significant advances have been made in materials and techniques, fracture modeling, fracturing fluids, and the types and amount of equipment needed (fig. 2). Today over 60% of all oil and gas wells drilled worldwide are fractured, with more than 50,000 **fracture stages** completed annually (Montgomery and Smith, 2010). In Kansas, over 57,000 wells have been hydraulically fractured since that first "frack job" in 1947 (KCC, 2011; fig. 3), and an estimated 90% of the wells drilled in Kansas over the next decade will be fractured (McCoy, 2011). Fracture stimulation has not only increased individual well production, sometimes manyfold, but also has increased estimated recoverable reserves of oil in the United States by 30% and gas reserves by 90% (Montgomery and Smith, 2010). Many oil and gas fields would not be economically viable without it.

Figure 1--First experimental fracturing job conducted in 1947 by Stanolind Oil in the Hugoton gas field of southwestern Kansas utilizing "1,000 gallons of naphthenic-acid and palm-oil- (napalm-) thickened gasoline" ... "and sand from the Arkansas River" (from Montgomery and Smith, 2010, p. 2).



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Figure 2--A very large, staged hydraulic fracturing job performed recently on a Marcellus Shale multi-well pad in Pennsylvania (modified from U.S. DOE and NETL, 2011, p. 6). Large numbers of trucks and equipment and voluminous quantities of fracturing fluids are needed to carry out an operation such as this. Fracking operations in Kansas normally are not done on such a large scale.

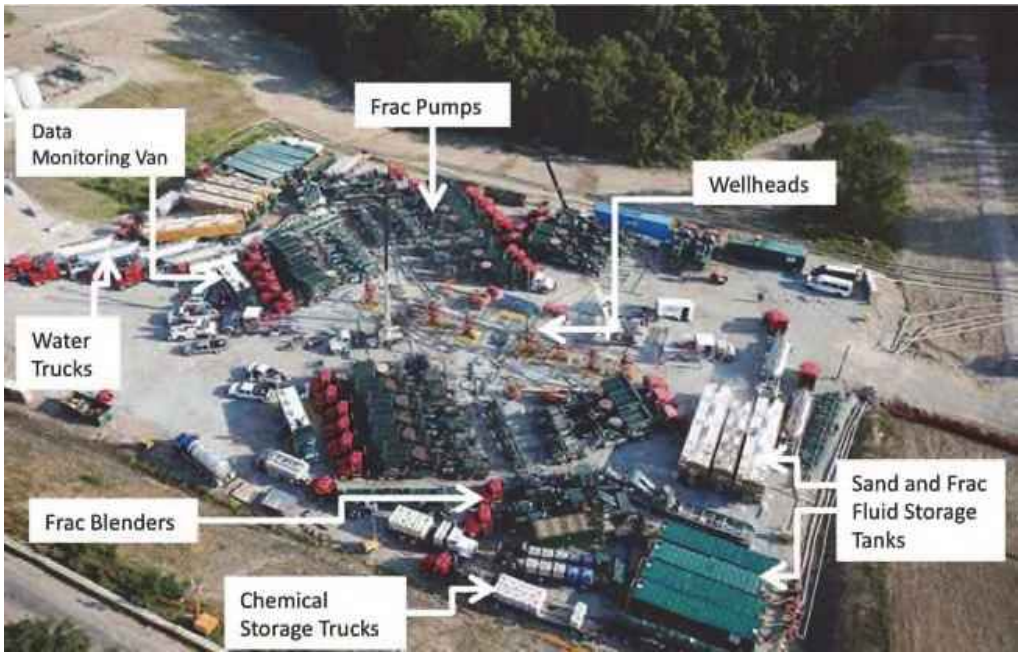
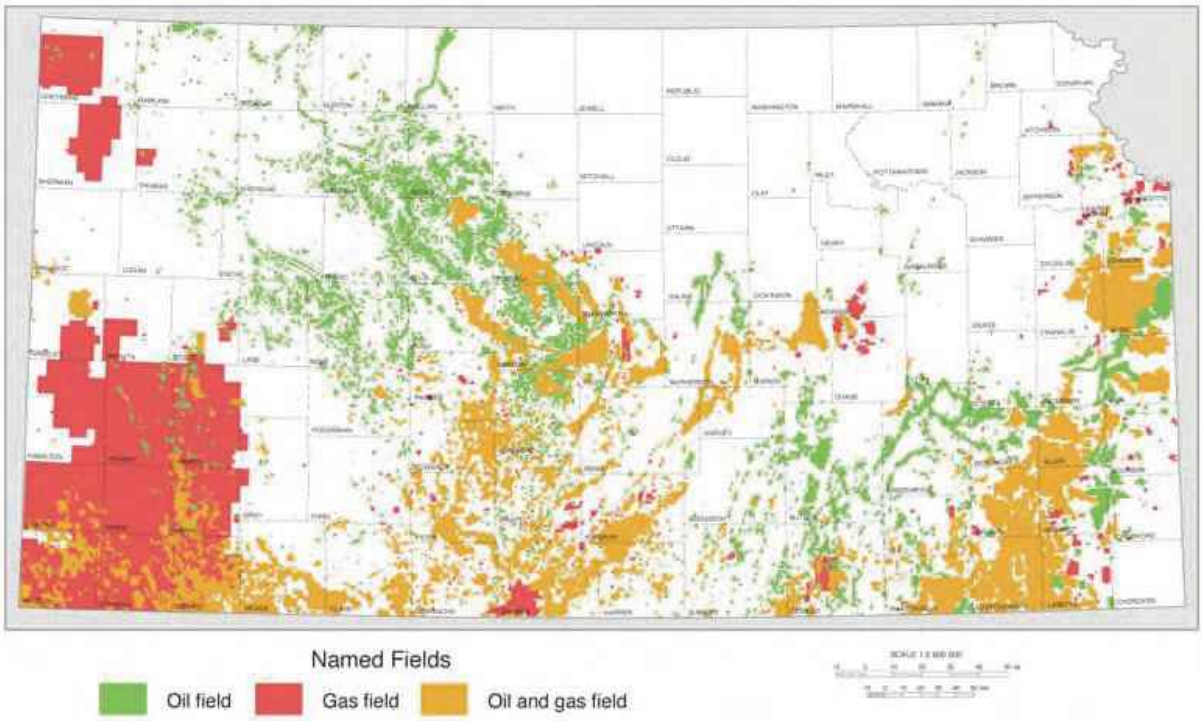


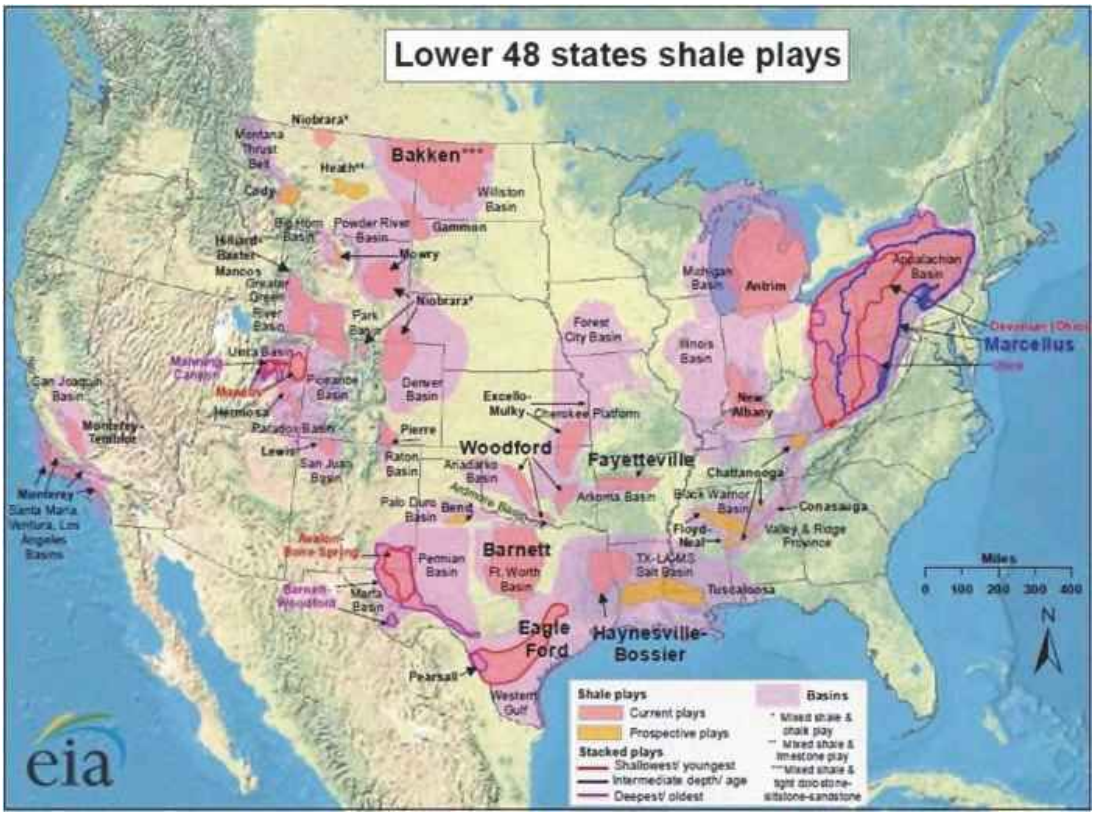
Figure 3--Over 430,000 oil and gas wells have been drilled in Kansas since the late 1800s. Of the roughly 244,000 wells drilled since 1947, over 57,000 of those wells have been hydraulically fractured.



Alongside advancements in hydraulic fracturing, horizontal drilling has become increasingly important in the past decade or so. In contrast to conventional vertical drilling, horizontal drilling begins vertically, then, at a given depth, turns gradually in a horizontal direction, in which the borehole proceeds for a long distance through a single formation. Coupling hydraulic fracturing with horizontal drilling has been instrumental in turning previously uneconomical and unconventional plays, such as **shale gas** (fig. 4), **tight gas sandstone**, and **coalbed methane**, into highly productive projects. A fundamental consequence of this recent coupling is that the scale of hydraulic fracturing operations has increased immensely in the last few years (fig. 2).

Figure 4--Major shale gas plays in the contiguous United States (from EPA, 2011, p. 10).

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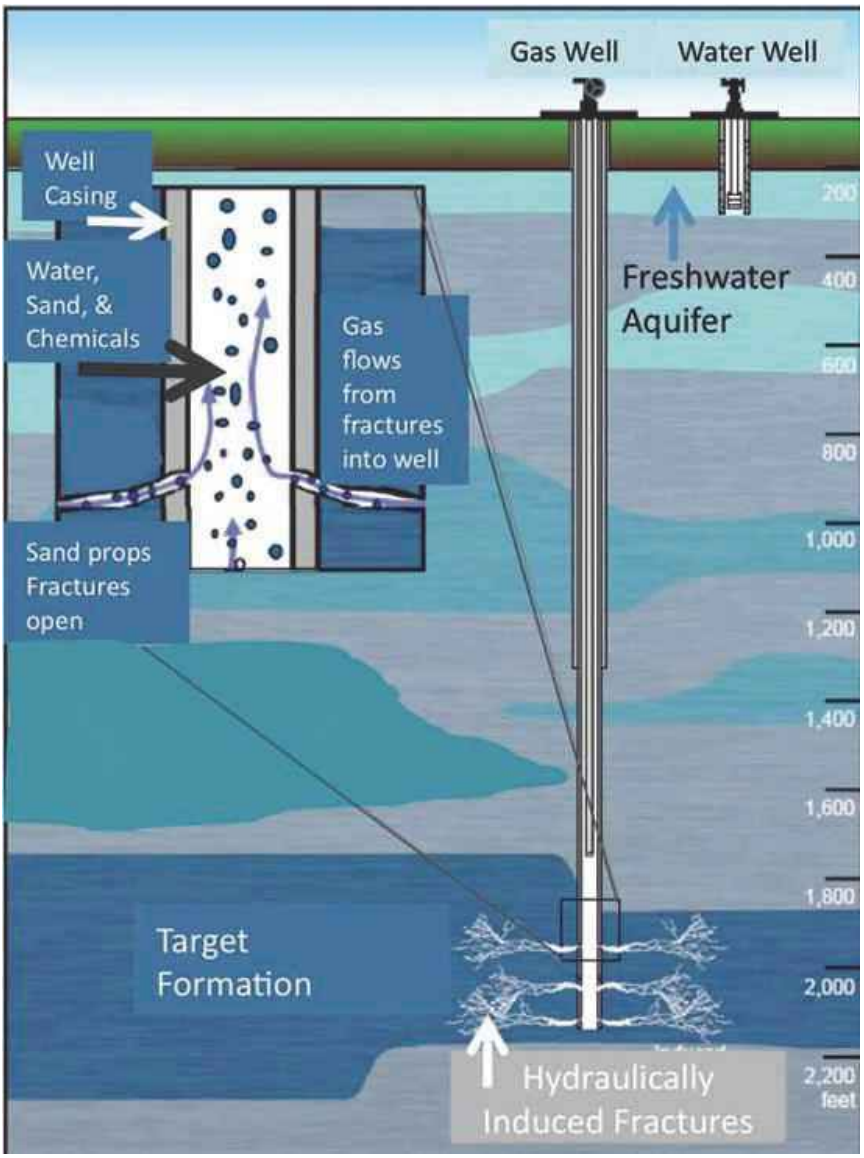
Hydraulic Fracturing Technology

Hydraulic fracturing, also known as hydrofracturing, hydro-fracking, fracking, or fracing, enhances the recovery of oil and gas from wells by fracturing formation rocks to release the hydrocarbons, allowing them to flow more easily through the rocks to the wellbore. Not all formations require such supplementary well completion techniques to permit extraction of hydrocarbons. Some rocks naturally contain abundant fractures and connected pore space that, although often only a millimeter or less across, allow fluids to move freely through them. Other rock formations, such as many shale gas reservoirs, are not permeable (i.e., the pores are not connected) and have few natural fractures and visible pore space. Gas or oil trapped within such impermeable rock can only be extracted by fracturing the rocks.

Hydraulic fracturing is performed soon after a well has been drilled and the metal **well casing** has been cemented into place by filling the annular space around the casing with cement. Selected segments of the wellbore are isolated, and specialized equipment is used to perforate holes through the production casing and cement of each segment. Water containing sand and chemical agents is then pumped at very high pressures, typically thousands of pounds per square inch, through the perforations into the surrounding rock. The intense pressure exerted by the water cracks the rock, creating minute fractures that propagate sometimes hundreds of feet away from the wellbore (fig. 5). Fracturing jobs are normally engineered to restrict the fractures to the target formation. The sand in the fracturing fluid, usually silica sand, is added as a "proppant"; that is, the fractures are propped open by the sand grains after the pressure is released. Although the fractures are held open only the width of a sand grain, it is enough to allow hydrocarbons trapped in the rocks to flow to the wellbore. Some wells are hydrofractured in more than one producing horizon, depending on where oil and gas occur in the subsurface.

Figure 5--Hydraulic fracturing in a vertical well (modified from EPA, 2011, p. 13).

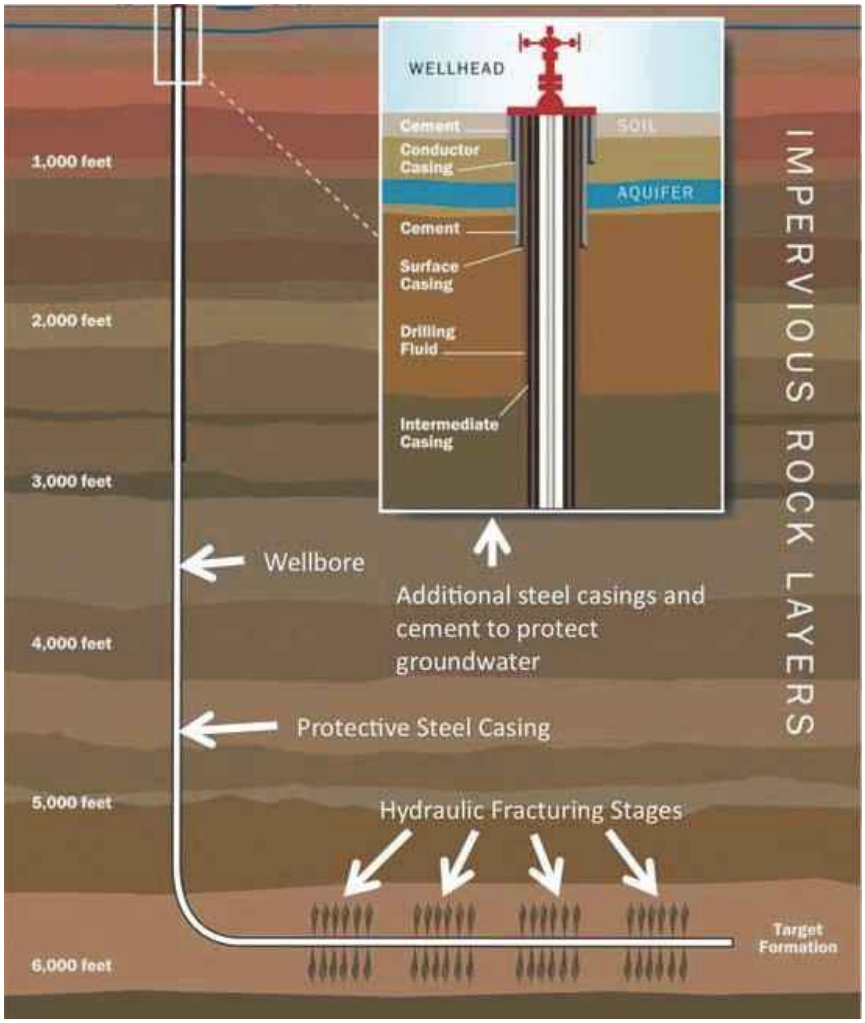
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Prior to the last decade, hydraulic fracturing was used primarily in vertical wellbores and in "conventional" rocks such as limestone and sandstone to stimulate oil and gas production (fig. 5). In recent years, operators have begun drilling more horizontal wells because they maximize the contact area within the targeted formation (fig. 6). Horizontal drilling has become especially useful in unconventional gas plays, such as tight gas sandstones, gas shales, and coalbed methane. In such operations, the horizontal part of a well can extend for 1,000 to 5,000 feet or more through a single rock formation. After the well casing and cement are installed in the well, perforations are made at several locations along that horizontal reach. Hydraulic fracture stimulation is then performed at those locations in stages, beginning at the far end and moving closer to the uphole end with each stage of the stimulation (fig. 6). This controlled procedure allows the operator to adjust for site-specific changes along the wellbore. For example, variations may occur in formation thickness, the integrity of the rock, the presence or absence of natural fractures, proximity to other wellbore fracture systems, and boreholes not centered in the formation at some points. Formation-specific data collected along the wellbore can be used to optimize the fracture patterns created.

Figure 6--Illustration of a horizontal well drilled into a shale layer that has been hydraulically fractured approximately 6,000 feet below the surface. Steel casings lining the well and cemented in place are designed to prevent fracturing fluids and produced hydrocarbons from entering surrounding formations. Freshwater aquifers used for irrigation or drinking water are usually separated from the fractured shale by hundreds or thousands of feet of rock. (Modified from a figure in KCC, 2011.)

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Strong economic incentives compel operators to avoid propagating fractures beyond the target formation and into adjacent strata (Ground Water Protection Council and ALL Consulting, 2009). Besides constituting a waste of time, materials, and money, fracturing outside the targeted formation could result in loss of the well or in excess water encroachment from surrounding strata, which increases production costs. Before a fracturing operation commences, sophisticated computer models are used to design the process based on known characteristics of the rocks and fractures in the formation, and to "evaluate the height, length, and orientation of potential fracture development" (Ground Water Protection Council and ALL Consulting, 2009, p. 57). Tests are run on the well casings, cement, and fracturing equipment before and during the entire operation to assure that the well and equipment are working properly and safely. Technologies such as microseismic fracture mapping and fracture tilt measurements are used to evaluate the success and orientation of the fractures created.

Fracturing Fluids

Fluids used for hydraulic fracturing consist primarily of water and a proppant (usually sand), with various additives that serve different purposes (table 1). Water and sand make up 98% or more of the fluid, while the additives constitute 2% or less (FracFocus.org, 2011). The additives used vary according to site-specific characteristics of the well, the target formation(s), the water source, and individual company practices. Some companies keep the compositions of their frack fluids confidential for proprietary reasons, or simply list all the ingredients and keep their relative percentages confidential, whereas other companies disclose the exact composition of their frack fluids. Companies can voluntarily disclose the chemical additives they use for hydraulic fracturing on the web-based registry, www.hydraulicfracturingdisclosure.org/fracfocusfind/. Although in most cases only a limited number of additives are used in any one well treatment, the 2011 Environmental Protection Agency (EPA) Hydraulic Fracturing Study Plan (EPA, 2011) lists nearly 1,000 chemicals that have been identified in various frack fluids and flowback/produced waters. A separate table in that document lists 30 naturally occurring substances that may be leached from the rocks by fracking activities, including radium, thorium, uranium, arsenic, hydrogen sulfide, and lead.

Table 1--Example of volumetric composition of typical hydraulic fracturing fluid (from EPA, 2011, p. 29).

Component/Additive Type	Example Compound(s)	Purpose	Percent Composition (by volume)	Volume of Chemical (gallons)
Water		Deliver proppant	90	2,700,000
Proppant	Silica, quartz sand	Keep fractures open to allow gas flow out	9.51	285,300

Acid	Hydrochloric acid	Dissolve minerals, initiate cracks in the rock	0.123	3,690
Friction reducer	Polyacrylamide, mineral oil	Minimize friction between fluid and the pipe	0.088	2,640
Surfactant	Isopropanol	Increase the viscosity of the fluid	0.085	2,550
Potassium chloride		Create a brine carrier fluid	0.06	1,800
Gelling agent	Guar gum, hydroxyethyl cellulose	Thicken the fluid to suspend the proppant	0.056	1,680
Scale inhibitor	Ethylene glycol	Prevent scale deposits in the pipe	0.043	1,290
pH adjusting agent	Sodium or potassium carbonate	Maintain the effectiveness of other components	0.011	330
Breaker	Ammonium persulfate	Allow delayed breakdown of the gel	0.01	300
Crosslinker	Borate salts	Maintain fluid viscosity as temperature increases	0.007	210
Iron control	Citric acid	Prevent precipitation of metal oxides	0.004	120
Corrosion inhibitor	N, n-dimethyl formamide	Prevent pipe corrosion	0.002	60
Biocide	Glutaraldehyde	Eliminate bacteria	0.001	30

In a typical fluid mixture, friction-reducing additives (called slickwater), often consisting of petroleum distillates or soap-like agents called surfactants, are used to facilitate pumping of the fluids and proppant at a higher rate and at lower pressures than if water alone were used (Ground Water Protection Council and ALL Consulting, 2009). Thickening agents, such as guar gum (also used as a thickener in food, toothpaste, and cosmetics), help suspend the proppant. Biocides eliminate bacteria that can cause biofouling of the fractures, corrosion of the pipes, or creation of unwanted byproducts such as poisonous H2S gas. Other stabilizing agents help prevent metal corrosion, and acids clear pore space clogged near the borehole by drilling mud.

Water Requirements and Management

According to the Ground Water Protection Council and ALL Consulting (2009, p. ES-4), "the drilling and hydraulic fracturing of a horizontal shale-gas well may typically require 2 to 4 million gallons of water." Some may require more. This is a one-time use, and the amounts are relatively small in comparison to, say, the amount of water used for irrigation. An average agricultural irrigation well in western Kansas, irrigating approximately 125 acres, pumps nearly 45 million gallons of water per year (calculated from 1998 water usage figures given in Rogers and Wilson, 2000). Hydraulic fracturing requirements vary from well to well, and as technologies and methods improve over time, the amount of water needed appears to be decreasing. The water used for hydraulic fracturing typically comes from local sources, such as rivers and lakes, ground water, municipal supplies, recycled flowback water from other frack jobs, and re-used water produced from the oil and gas formation. In areas where water supplies are limited, obtaining water can present a challenge. In Kansas, the Division of Water Resources, which governs how water is allocated and used in the state, issues permits to operators who pump water for industrial purposes such as fracking.

When a fracking treatment is completed and the pressure is relieved, the fracturing fluid, mixed with natural formation water, begins to flow back up the casing to the surface, where it is emptied into tanks or pits for later disposal. This water, which can vary from fresh to saline, contains compounds from the fracturing fluid, formation waters, and dissolved components from the rocks. A large portion of the fracturing fluid is recovered within a few hours to a couple of weeks, but much of the frack material stays in the ground until it is pumped to the surface with the produced hydrocarbons, and some may stay in the deep subsurface permanently. The Ground Water Protection Council and ALL Consulting (2009) state that "the volume of produced water may account for less than 30% to more than 70% of the original fracture fluid volume," and "in some cases, flowback of fracturing fluid in produced water can continue for several months after [oil and/or] gas production has begun." This water must be managed or disposed of properly. In Kansas, the Kansas Corporation Commission (KCC) regulates management of the storage pits and tanks, and the ultimate disposal of fracking fluids and produced water. Fracturing fluids can sometimes be re-used for the same purpose in another well, but oftentimes they are injected into deep disposal wells, which also are regulated by the KCC.

Protecting the Ground Water

In the majority of cases in Kansas, formations targeted for oil and gas production lie thousands of feet beneath the surface of the earth, whereas ground-water **aquifers** used for drinking water and irrigation lie within a few hundred feet of the surface (fig. 6). The drinking-water aquifer is therefore separated from the oil or gas reservoir by thousands of feet of impermeable rock and is thus protected from contamination by oil or gas. When hydraulic fracturing is applied to a formation, care is taken to confine fracturing to the targeted formation. With the additional safeguard of thousands of feet of overlying rock in most drilling situations, it is highly unlikely that fractures will propagate far enough through the rock to reach overlying aquifers.

The metal well casing installed in the borehole and the cement that seals the annular space around the casing (fig. 6) confine the fracking fluids and any produced hydrocarbons and other formation fluids within the casing and prevent them from entering surrounding formations. KCC regulations require that additional casings be installed through freshwater aquifers to add extra protection against ground-water contamination.

In some areas of Kansas, hydrocarbon reservoirs, especially gas reservoirs, lie closer to the surface and thus extra vigilance is required to reduce the risk of ground-water contamination. Additionally, with the advent of horizontal drilling, the risk of encountering natural faults or fractures that extend into overlying layers increases with the increasing horizontal lengths of the boreholes. Special precautions must be taken not only to assure good casing and cement installations, but also to employ good engineering and rock characterization to avoid natural faults that may be conductive to overlying aquifers, and to confine hydraulic fracturing to the target formation.

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In some areas where drilling occurred very early in the history of the oil and gas industry in Kansas, undocumented unplugged wells may still be present. These wells were drilled before serious oversight commenced, or before anyone truly understood many of the relevant stratigraphic and structural geologic principles. The KCC is plugging abandoned wells as it becomes aware of them and as the budget allows.

Is it Safe?

Many of the additives in fracking fluids are generally safe (water, sand, certain acids, etc.), but some additives and formation flowback chemical solutions (benzene, toluene, radium, saline waters, etc.) are less safe and need to be managed properly. Oil and gas statutes developed by the Kansas Legislature and regulations developed by the KCC serve to govern hydraulic fracturing in oil and gas wells and the subsequent management of fluids and chemicals. The KCC, as the regulatory agency, approves, oversees, and inspects such operations, and no ground-water contamination has been reported to them as a consequence of fracking operations in Kansas. Additionally, since the method was pioneered in Grant County in 1947, technologies and treatments have evolved and become more precise, controlled, and safe.

Other states have experienced concerns with fracking or with disposal of the resulting fluids. Questions have been raised about possible contamination of local water wells by natural gas or by fracking fluids in Pennsylvania, Colorado, Wyoming, and Texas, among others (Biello, 2010; Earthjustice, 2011; Lustgarten and ProPublica, 2011). A well blowout in Pennsylvania resulted in fracking fluids spilling onto the ground and flowing across fields and into streams (WNEP, 2011). Also in Pennsylvania, where few deep injection wells are available for disposal, fracking fluids have been taken to local wastewater-treatment plants, which are ill-prepared to deal with the huge volumes of additional wastewater and the types of contaminants found in them (The New York Times, 2011). As a result, high levels of undesirable contaminants, such as radium, benzene, toluene, trihalomethanes, and highly saline water have been released into major streams that supply drinking water for millions of people. In addition, methane, known to be a powerful greenhouse gas, is sometimes released into ground water or into the atmosphere due to improperly cased wells or leaking pipes (Food & Water Watch, 2011). Other airborne pollutants found at higher than allowable limits near fracking sites in Texas and Wyoming include methanol, formaldehyde, carbon disulfide, benzene, and other neurotoxins and carcinogens, as well as volatile organic compounds that can react with sunlight to create smog (Biello, 2010; Food & Water Watch, 2011). Concerns about induced seismicity, or earthquake activity related to injection of fluids into the subsurface, have been raised in some areas, but there is no evidence that hydraulic fracturing itself triggers earthquakes. Instead, small earthquakes may have been triggered by deep disposal of fluids from oil and gas operations (Zoback, 2012).

Some of these incidents may have resulted from fracking in unfamiliar formations or geologic situations, or perhaps due to unsuspected faults, unplugged abandoned wells, or other unexpected fluid migration routes. Inadequate means of dealing with the volumes of fluid generated can be a problem, as in Pennsylvania. In some cases, the problems may not be directly related to hydraulic fracturing itself, but rather to operating issues such as casing problems, or broken pit liners or mud tanks (Durham, 2011). Clearly, experience, good engineering, and good regulatory oversight are important for the successful management of hydraulic fracturing treatments.

For the most part, Kansas has not encountered the problems some other states have, and no documented cases of ground-water contamination by hydraulic fracturing have been reported in the state. Hydraulic fracturing has been employed for over 60 years in Kansas, in most cases hundreds or thousands of feet beneath any usable aquifers, thus posing little threat to them. Casing, cementing, and plugging regulations secure the safety and integrity of the wells when carried out properly. Deep disposal wells are available throughout much of the state, and they have been regulated and overseen by the KCC and Kansas Department of Health and Environment for many years; consequently, in Kansas, fracking fluids are not disposed of in wastewater-treatment plants. In short, Kansas' favorable geologic setting, its regulatory process, and its successful history of hydraulic fracturing and fluid management make it one of the safer regions of the country to employ the practice.

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Glossary

Aquifer: a geologic formation or body of rock that is porous and permeable enough to transmit ground water at a rate sufficient to yield significant quantities of water to wells or springs.

Coalbed methane: natural gas (primarily methane) produced from coal beds; the methane is adsorbed into the solid matrix of the coal, and the coal must be fractured and dewatered to release the gas.

Drilling mud: a mixture of mud-like substances used to lubricate the drill bit and drill stem when drilling an oil or gas well.

Fracture stages: each of the individual hydraulic fracturing operations carried out at different levels or locations within a single oil or gas well.

Shale gas: natural gas produced from shale, usually trapped in tiny unconnected pore spaces in impermeable shale that requires fracturing of the rock to release the gas.

Tight gas sandstone: sandstone that contains natural gas trapped in small unconnected pore spaces; needs fracturing to release the gas.

Well casing: "Heavy metal pipe, lowered into a bore hole during or after drilling and cemented into place. It prevents the sides of the hole from caving, prevents loss of drilling mud or other fluids into porous formations, and prevents unwanted fluids from entering the hole" (Bates and Jackson, 1980, p. 97). The types of casing permitted in Kansas are discussed in KCC regulations online (KCC, 2011).

KGS Publications PIC index

Kansas Geological Survey, Public Outreach
Comments to webadmin@kgs.ku.edu
Web version Dec. 11, 2011, revised May 15, 2012
http://www.kgs.ku.edu/Publications/PIC/pic32.html

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EXHIBIT 11

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Journal of Constructional Steel Research
Volume 98, July 2014, Pages 12-19

Mechanical properties of heat-treated high strength steel under fire/post-fire conditions

S.P. Chiew, M.S. Zhao, C.K. Lee

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https://doi.org/10.1016/j.jcsr.2014.02.003

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Highlights

- Mechanical properties of high strength steel at elevated temperatures are reported.
- Post-fire residual strength of heat-treatment hardened high strength steel is studied.
- Heat-treated hardened steel return to its parent material after fire exposure.
- A new reduction factor for post-fire residual strength assessment is proposed.

Abstract

Heat treated high strength steel (HSS) has attracted more and more applications in both on-shore and off-shore structures. According to the classical theories of metallurgy, the hardening effects in the microstructures that grant HSS its high strength may be weakened or eliminated by heat. Structures built using such materials may behave differently after they are heated and cooled down (e.g. during and after a fire situation). This experimental study investigated the mechanical properties of reheated, quenched and tempered (RQT) HSS plate manufactured to grade S690 at

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elevated temperatures as well

out that while RQT-S690 HS

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serious deterioration in streng

properties are different from those of traditional hot-rolled normal strength steels.

Previous Next

Keywords

Mechanical properties; Heat-treated high strength steel; Elevated temperatures; Post-fire; Characteristic strength reduction factors

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EXHIBIT 12

Metal Suppliers Online: Material Property Data

Alloy Steels 4340

- Availability - Real time from 5300 North American Suppliers
- Specifications
- Related Tradenames and Metal Names
- Chemistry Data
- Welding, Machining/ General Data
- Fabrication Videos **NEW**
- Physical Data
- Mechanical Data
- Links to Related Data
- Main Material Property List

Availability

Alloy Steels 4340 is stocked by 83 North American distributors and produced by 43 large mills. Distributors will offer small quantity buys while mills will generally only sell large quantities, with delivery times anywhere from 10 to 50 weeks depending on size and form required

This material is stocked primarily in Bar Products by 62 distributors but is also available to a lesser extent in Flat Rolled Products, Forging Products, Tubular Products, Wire Products, Fasteners, Piping Components, and Structurals.

For distributor (small quantity) availability click here

For mill (large volume) production click here

To view all click here

Specifications

The following specifications cover **Alloy Steels 4340**

- AISI 4340
- AMS 6409
- AMS 6415
- ASTM A29 (4340)
- ASTM A322 (4340)
- ASTM A506 (4340)
- ASTM A646 (4340-7)
- ASTM A752 (4340)
- MIL S-5000
- SAE J404 (4340)
- AMS 6359
- AMS 6414
- AMS 6454
- ASTM A320 (L43)
- ASTM A331 (4340)
- ASTM A519 (4340)
- ASTM A711
- ASTM A829
- SAE J1397 (4340)
- SAE J412 (4340)

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- UNS G43400

Property Results

Chemistry Data : [top]

Carbon	0.38 - 0.43
Chromium	0.7 - 0.9
Iron	Balance
Manganese	0.6 - 0.8
Molybdenum	0.2 - 0.3
Nickel	1.65 - 2
Phosphorus	0.035 max
Silicon	0.15 - 0.3
Sulphur	0.04 max

Principal Design Features	AISI 4340 is a heat treatable, low alloy steel containing nickel, chromium and molybdenum. It is known for its toughness and capability of developing high strength in the heat treated condition while retaining good fatigue strength.
Applications	Typical applications are for structural use, such as aircraft landing gear, power transmission gears and shafts and other structural parts.
Machinability	Machining is best done with this alloy in the annealed or normalized and tempered condition. It can be machined by all conventional methods. However in the high strength conditions of 200 ksi or greater the machinability is only from 25% to 10% that of the alloy in the annealed condition.
Forming	4340 has good ductility in the annealed condition and most forming operations are carried out in that condition. It can be bent or formed by spinning or pressing in the annealed state. Bend radii should be 3t or greater.
Welding	The alloy can be fusion or resistance welded. Preheat and post heat weld procedures should be followed when welding this alloy by established methods.
Heat Treatment	Heat treatment for strengthening is done at 1525 F followed by an oil quench. For high strength (over 200 ksi) the alloy should first be normalized at 1650 F prior to heat treatment. See "Tempering" for strength levels.
Forging	Forging may be done in the range of 2250 F max. down to 1800 F.
Hot Working	4340 has very good cold forming capability so that hot working should not be needed. Hot working in any but the annealed

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	condition can affect the strength level. Consult the alloy supplier in regard to hot working.
Cold Working	The 4340 alloy may be cold worked, in the annealed condition, by conventional methods and tooling. It has good ductility.
Annealing	A full anneal may be done at 1550 F followed by controlled (furnace) cooling at a rate not faster than 50 F per hour down to 600 F. From 600 F it may be air cooled.
Aging	Not applicable to this alloy.
Tempering	The temperature for tempering depends upon the strength level desired. Before tempering the alloy should be in the heat treated or normalized & heat treated condition - see "Heat Treatment". For strength levels in the 260 - 280 ksi range temper at 450 F. For strength in the 125 - 200 ksi range temper at 950 F. Do NOT temper the alloy if it is in the 220 - 260 ksi strength range as tempering can result in degradation of impact resistance for this level of strength.
Hardening	The alloy will harden by cold working or by heat treatment -- see "Heat Treatment" and "Tempering".
Other Comments	AISI 4340 is considered to be a "through hardening" steel such that large section sizes can still be heat treated to high strength.

Physical Data : [top]

Density (lb / cu. in.)	0.28
Specific Gravity	7.8
Specific Heat (Btu/lb/Deg F - [32-212 Deg F])	0.116
Melting Point (Deg F)	2600
Thermal Conductivity	21
Mean Coeff Thermal Expansion	6.6
Modulus of Elasticity Tension	33

Mechanical Data : [top]

MSO currently has no data available for this grade.

Videos :

MSO currently has no videos available for this grade.

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