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# PROCEEDINGS OF THE 24th INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE

*Participating  
Societies*



VOLUME 2    Advanced Rotating Machines  
                 Thermal Electrochemical Systems  
                 Thermoelectrics  
                 RTG's  
                 Photovoltaics  
                 Space Solar Dynamic Systems  
                 Magnetohydrodynamic Power  
                 Generation  
                 Burst and Pulse Power  
                 Space Dynamic Conversion  
                 Thermionics  
                 Space Nuclear Reactors

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## PREFACE

The scope of the Intersociety Energy Conversion Engineering Conference (IECEC) series has grown from a straightforward treatment of energy conversion engineering to a broad involvement in all aspects of energy systems, including primary resource processing, utilization and environmental issues in addition to conversion and storage. The other notable trend has been toward increased international participation and, as the papers in this volume attest, IECEC-89 can truly claim to be an international forum on energy engineering with a significant proportion of the papers being presented being from beyond the confines of the United States. It is a particular pleasure to include, for the first time, a sizeable contribution from the USSR.

These developments are indeed appropriate for energy conversion engineering has to be undertaken within the broader context of energy systems and energy issues which are not constrained by national boundaries. The increasing and proper concern for the impact of energy systems not only locally but also globally is particularly reflected in the nearly 500 papers appearing in a Proceedings which has now grown to six volumes. In these, the reader will find a comprehensive coverage of recent work on energy systems and technologies relevant to the expected conditions of the 1990's and beyond. The international character of IECEC-89 shows not just through participation from many countries but the large measure of common ground evident in the contributions made by the many national and international organizations involved in the energy engineering field.

The organization of this large amount of interrelated material poses considerable challenges which have been met in the first instance by dividing the Conference and, by extension, the Proceedings, into a number of major topical areas. From a narrow applications viewpoint, it is tempting to view aerospace and terrestrial energy system issues separately since they generally involve meeting different criteria. This has not been done in the present Conference in large measure because an IECEC objective is to find and emphasize points of commonality. Accordingly, a blend of interests will be found throughout, as for example, in Volume 2 devoted to energy conversion technologies where space and terrestrial photovoltaics are grouped together.

To facilitate use of the volumes, the Table of Contents is repeated in each Volume and an author Index appears in Volume 6. In addition, the now well-established feature of IECEC, the SAE cumulative index for the past four years is also included in Volume 6. This may be used to locate recent related work reported at the IECEC and, in due course, it will be updated to include the current Conference.

The task of preparing these Proceedings has only been possible through the unstinting efforts of the Program Committee, Session Organizers and the IECEC-89 staff whose many contributions are gratefully acknowledged by the Editors. In fairness to other technologies in which the Institute of Electrical and Electronics Engineers is prominently involved, the critical role of computers, FAX machines and other aspects of modern communications technology in permitting the assembly of this body of material also deserves recognition.

William D. Jackson, *Editor*  
Dorothy A. Hull, *Associate Editor*

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# VOLUME II

## Conversion Technologies and Space Nuclear Reactor Systems

### CONVERSION TECHNOLOGIES I ADVANCED ROTATING MACHINES

- |        |                                                                                                                                                                                                                                                             |     |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 899301 | <b>Modes of Operation of the Slip Ring Induction Machine in Wind Energy Conversion Systems</b><br>M.T. El Hagry, A.A. Mohamed and M.N. Iskander, <i>Electric Research Institute of Cairo, Egypt</i>                                                         | 665 |
| 899302 | <b>Methodology of Asymmetrical Fault Analysis of a 6-Phase Synchronous Machine</b><br>S.E. Abo-Shady, Y.A. Al-Turki and K.A. Bin-Ali, <i>Jeddah Oil Refinery, Saudi Arabia</i>                                                                              | 671 |
| 899426 | <b>Energy Conservation Aspect of Induction Motors Using Improved Design and Power Controllers</b><br>S.S. Murthy, C.S. Jha, S.R. Lakshmi and A.K. Rai, <i>Indian Institute of Technology, New Delhi, India</i> ; and D.A. Desai, <i>Kirkeskar Elec. Co.</i> | 677 |

### SPACE ENERGY CONVERSION TECHNOLOGIES V STATIC CONVERSION I: THERMOELECTROCHEMICAL SYSTEMS

- |        |                                                                                                                                                                                                                                                                      |     |
|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 899500 | <b>Advances in Design and Performance of SHE System Components</b><br>J.R. McBride, R. Novak, D.J. Schmatz, W.P. Copple, J.T. Brockway, N. Arnon and G.A. Grab, <i>Ford Motor Co., Dearborn, MI</i> ; T.K. Hunt, <i>Environmental Research Institute of Michigan</i> | 683 |
| 899615 | <b>Novel Fabrication Technique for Improving the Figure-of-Merit of Thermoelectric Materials</b><br>J.S. Beaty and R. Masters, <i>Thermoelectron Technology Corporation</i> ; J.W. Vandersande and C. Wood, <i>Jet Propulsion Lab, Pasadena, CA</i>                  | 689 |

### SPACE ENERGY CONVERSION TECHNOLOGIES VIII STATIC CONVERSION II: THERMOELECTRICS

- |        |                                                                                                                                                                                      |     |
|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 899292 | <b>The Preparation of SiGe Thermoelectric Materials by Mechanical Alloying</b><br>B.A. Cook, B.J. Beaudry, J.L. Harringa and W.J. Barnett, <i>Ames Laboratory, Ames, IA</i>          | 693 |
| 899503 | <b>Multiple Doping of Silicon-Germanium Alloys for Thermoelectric Applications</b><br>J.P. Fleurial, C.B. Vining and A. Borshchevsky, <i>Jet Propulsion Laboratory, Pasadena, CA</i> | 701 |

899405      **Recent Investigations of SiFe/GaP Thermoelectric Materials at TTC and GE**      706  
R. Masters, *Thermo-Electron, Waltham, MA*; and J. Nakahara, *General Electric Company, Philadelphia, PA*

899134      **Effect of Ga and P Dopants on the Thermoelectric Properties of N-Type SiGe**      711  
S.L. Draper, *NASA*; J.W. Vandersande and C. Wood, *Jet Propulsion Laboratory, Pasadena, CA*; and R. Masters and V. Raag, *Thermo Electron Technologies*

#### **SPACE ENERGY CONVERSION TECHNOLOGIES X RTGs I**

899237      **RTG's for Space Exploration at the End of the Twentieth Century**      715  
A. Chmielewski, *Jet Propulsion Laboratory, Pasadena, CA*

#### **SPACE ENERGY CONVERSION TECHNOLOGIES XII RTGs II**

899408      **DIPS Power Conversion Cycle Selection**      721  
A.G. Stadnik, *Rockwell International, Rocketdyne Division, Canoga Park, CA*

899435      **Dynamic Isotope Power Subsystem (DIPS) Ground Support**      727  
V. Keshishian, *Rockwell International, Rocketdyne Division, Canoga Park, CA*

#### **RENEWABLE RESOURCE SYSTEMS I PHOTOVOLTAICS I**

899041      **Central Station Photovoltaic Plant with Energy Storage for Utility Peak Load Leveling**      731  
B. Chowdhury, *Electrical Engineering Department, University of Wyoming, Laramie, WY*

899105      **Microprocessor Control of a Hybrid Energy System**      737  
W.B. Lawrance, C.V. Nayar, T.L. Pryor and S.J. Phillips, *Curtin University, Perth, Australia*

899104      **Effect of Meteorological Conditions on the Performance of Crystalline Photovoltaic Modules**      743  
S. Rahman, *Virginia Polytechnic Institute, Blacksburg, VA*

899463      **Magnification of Starting Torques of DC Motors by Maximum Power Point Trackers in Photovoltaic Systems**      749  
J. Appelbaum and S. Singer, *NASA Lewis, Cleveland, OH*

899559      **Wave Energy Research and Technology Assessment for Coastal North Carolina**      755  
G. Hagerman, *SEASUN Power Systems*; T. Heller, *Virginia Power*; and B. Zickefoose, *North Carolina Alternative Energy Corporation*

#### **RENEWABLE RESOURCE SYSTEMS III PHOTOVOLTAICS II**

899550      **Outdoor Stability Performance of Thin-Film Photovoltaic Modules at SERI**      761  
L. Mrig, *Solar Energy Research Institute, Golden, CO*

899558      **Thin Film Photovoltaics**      765  
K. Zweibel and H.S. Ullal, *Solar Energy Research Institute, Golden, CO*

## SPACE ENERGY CONVERSION TECHNOLOGIES I

### ADVANCED SPACE SOLAR CELLS

|        |                                                                                                                                                                                                                                                                            |     |
|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 899225 | <b>Large Area Solar Cells for Future Space Power Systems</b><br>D.R. Lillington, B.T. Cavicchi, M.S. Gillanders, G.T. Crotty and<br>D.D. Krut, <i>Spectrolab Inc., Sylmar, CA</i>                                                                                          | 773 |
| 899562 | <b>High Specific Power (AlGaAs) GaAs/CuInSe<sub>2</sub> Tandem Junction Solar Cells for Space Applications</b><br>N.P. Kim, B.J. Stanbery, R.M. Burgess and R.A. Mickelsen, <i>Boeing Electronics</i> ; R.W. McClelland, B.D. King and R.P. Gale, <i>Kopin Corporation</i> | 779 |
| 899416 | <b>Concepts for Thin-Film GaAs Concentrator Cells</b><br>M.B. Spitzer, R.P. Gale, R. McClelland, B. King, J. Dingle and R. Morrison, <i>Kopin Corporation, Taunton, MA</i>                                                                                                 | 785 |
| 899223 | <b>Gallium Arsenide-on-Germanium Solar Cells</b><br>P.A. Iles, F. Ho and M. Yeh, <i>Applied Solar Energy, City of Industry, CA</i> ; G. Datum and S. Billetts, <i>Lockheed</i>                                                                                             | 791 |
| 899239 | <b>High Efficiency Heteroepitaxial Solar Cells for Space Power Applications</b><br>S.M. Vernon, S.P. Tobin, C.J. Keavney and S.J. Wojtczuk, <i>Spire Corporation, Bedford, MA</i>                                                                                          | 799 |

## SPACE ENERGY CONVERSION TECHNOLOGIES II

### SPACE PHOTOVOLTAIC TECHNOLOGY: CELL AND ARRAY COMPONENT PERFORMANCE

|        |                                                                                                                                                                                                                         |     |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 899418 | <b>Thermal Annealing of GaAs Concentrator Solar Cells</b><br>H. Curtis and D. Brinker, <i>NASA Lewis, Cleveland, OH</i>                                                                                                 | 805 |
| 899534 | <b>Pilot Line Production of High-Efficiency GaAs Solar Cells</b><br>K.A. Bertness, M.L. Ristow, M.S. Kuryla, H.C. Hamaker and J.G. Werthen, <i>Varian Research Center, Palo Alto, CA</i>                                | 811 |
| 899619 | <b>High Efficiency GaAs/GaSb Tandem Solar Cells and Tandem Circuit Cards</b><br>L.M. Fraas, J. Avery, J. Martin, V.S. Sundaram, G.R. Girard, V. Dinh, N. Mansori, J.W. Yerkes and B.A. Arau, <i>Boeing, Seattle, WA</i> | 815 |
| 899620 | <b>Analysis of Interdigitated Back Contact Silicon Solar Cells for Space Use</b><br>D.C. Marvin and S.L. Froedge, <i>The Aerospace Corporation, El Segundo, CA</i>                                                      | 821 |

## SPACE ENERGY CONVERSION TECHNOLOGIES III

### ADVANCED SPACE SOLAR ARRAYS: PERFORMANCE AND REQUIREMENTS

|        |                                                                                                                                                                                                                                                                                    |     |
|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 899621 | <b>Advanced Photovoltaic Solar Array Program Status</b><br>R.M. Kurland, <i>TRW S&amp;TG, Redondo Beach, CA</i> ; and P.M. Stella, <i>Jet Propulsion Laboratory, Pasadena, CA</i>                                                                                                  | 829 |
| 899533 | <b>The Mini-Dome Lens Space Concentrator Array: Recent Component Test Results and Current Array Development Status</b><br>M.J. O'Neill, A.J. McDanal and J.L. Perry, <i>Entech, Inc., Dallas, TX</i> ; D.J. Flood, M.F. Piszczor and C.K. Swartz, <i>NASA Lewis, Cleveland, OH</i> | 835 |
| 899436 | <b>Photovoltaic Power System Operation in the Mars Environment</b><br>J. Appelbaum and D. Flood, <i>NASA Lewis, Cleveland, OH</i>                                                                                                                                                  | 841 |

**SPACE ENERGY CONVERSION TECHNOLOGIES VI  
ADVANCED SOLAR DYNAMIC SPACE POWER-MISSIONS,  
TECHNOLOGY AND APPLICATIONS**

|        |                                                                                                                                               |     |
|--------|-----------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 899603 | <b>Free Piston Space Stirling Technology Program</b><br>G.R. Dochat and M. Dhar, <i>Mechanical Technology Inc., Latham, NY</i>                | 849 |
| 899365 | <b>Two-Tiered Design Analysis of a Radiator for a Solar Dynamic Powered Stirling Engine</b><br>D.C. Hainley, <i>NASA Lewis, Cleveland, OH</i> | 855 |

**SPACE ENERGY CONVERSION TECHNOLOGIES IX**

|        |                                                                                                                                                                                                           |     |
|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 899366 | <b>A Program for Advancing the Technology of Space Concentrators</b><br>G.D. Naujokas and J. Savino, <i>NASA Lewis, Cleveland, OH</i>                                                                     | 861 |
| 899367 | <b>Design of an Auto-Deployable Technology Demonstration Solar Concentrator</b><br>A. Pintz, C. Castle, R. Reimer and G.D. Naujokas, <i>Cleveland State University, Cleveland, OH</i>                     | 867 |
| 899364 | <b>An Advanced Concentrator for Solar Dynamic Power Systems in Space</b><br>K. Beninga and R. Davenport, <i>SAIC, San Diego, CA</i>                                                                       | 875 |
| 899363 | <b>Conceptual Design of a Self-Deployable, High Performance Parabolic Concentrator for Advanced Solar-Dynamic Power Systems</b><br>H.J. Dehne and D.R. Duffy, <i>Acrux Corporation, Mountain View, CA</i> | 881 |

**SPACE ENERGY CONVERSION TECHNOLOGIES XI  
SPACE STATION SOLAR DYNAMIC POWER SYSTEMS—COMPONENT TECHNOLOGY**

|        |                                                                                                                                                                                                                                                   |     |
|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 899234 | <b>Concentration of Off-Axis Radiation by Solar Concentrators for Space Power</b><br>K.S. Jeffries, <i>NASA Lewis, Cleveland, OH</i>                                                                                                              | 887 |
| 899076 | <b>Material Compatibility and Simulation Testing for the Brayton Engine Solar Receiver for the NASA Space Station Freedom Solar Dynamic Option</b><br>H.J. Strumpf, R. P. Rubly and M.G. Coombs, <i>Allied Signal Space Company, Torrance, CA</i> | 895 |
| 899228 | <b>A Brayton Cycle Solar Dynamic Heat Receiver for Space</b><br>L.M. Sedgwick, S.D. Johnson, H.L. Nordwall and E.J. Kaufmann, <i>Boeing Aerospace, Seattle, WA</i>                                                                                | 905 |
| 899492 | <b>Advanced Solar Brayton Space Power Systems</b><br>A. Pietsch and D.J. Brandes, <i>Allied Signal Aerospace, Tempe, AZ</i>                                                                                                                       | 911 |
| 899235 | <b>Compatibility of Selected Superalloys with Molten LiF-CaF<sub>2</sub> Salt</b><br>J.D. Cotton and L.M. Sedgwick, <i>Boeing Aerospace, Seattle, WA</i>                                                                                          | 917 |
| 899226 | <b>Numerical Model of Solar Dynamic Radiator for Parametric Analysis</b><br>J.L. Rhatigan, <i>NASA Lewis, Cleveland, OH</i>                                                                                                                       | 923 |

**SPACE ENERGY CONVERSION TECHNOLOGIES XIII  
ADVANCED SOLAR DYNAMIC SPACE POWER SYSTEMS—  
RECEIVERS/THERMAL STORAGE**

|        |                                                                                                                                                                                                                                                |     |
|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 899187 | <b>The Cavity Heat Pipe Stirling Receiver for Space Solar Dynamics</b><br>J.B. Kessell, <i>Sanders Assoc., Nashua, NH</i> ; and D. Lacey,<br><i>NASA Lewis, Cleveland, OH</i>                                                                  | 931 |
| 899007 | <b>Brayton Advanced Heat Receiver Development Program</b><br>G. Heidenreich and R.S. Downing, <i>Sundstrand Aviation, Rockford, IL</i> ;<br>D.E. Lacey, <i>NASA Lewis, Cleveland, OH</i>                                                       | 937 |
| 899410 | <b>Thermal Performance of Specific Heat Receiver Concepts for<br/>Advanced Solar Dynamic Applications</b><br>R. Crane and G. Bharadhwaj, <i>University of Florida, Gainesville, FL</i>                                                         | 943 |
| 899491 | <b>Flight Experiment of Thermal Energy Storage</b><br>D. Namkoong, <i>NASA Lewis, Cleveland, OH</i>                                                                                                                                            | 953 |
| 899324 | <b>High Temperature Fluoride Composites for Latent Thermal<br/>Storage in Advanced Space Solar Dynamic Power System</b><br>Y. Takahashi, Y. Abe, R. Sakamoto, K. Tanaka and M. Kamimoto,<br><i>Electrotechnical Laboratory, Ibaraki, Japan</i> | 959 |

**CONVERSION TECHNOLOGIES II  
MHD I—RETROFIT AND POWER TRAIN STUDIES**

|        |                                                                                                                                                                                                                                                                                                                                                                                                  |     |
|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 899497 | <b>Development of a Prototypical MHD Coal Combustor</b><br>G. Listvinsky, J. Alpay, L. Hill, K. King, D. Paul, D. Vanevenhoven,<br>K. Natesan and D.Y. Wang, <i>TRW S&amp;TG, Redondo Beach, CA</i>                                                                                                                                                                                              | 965 |
| 899498 | <b>Experimental Investigation on the Effects of the TRW Two-Stage<br/>Coal Combustor on the Performance of the AVCO Mk VI MAD<br/>Generator</b><br>J. Pinsley, B. Pote and A. McClaine, <i>Avco Research Lab., Burtell, MA</i>                                                                                                                                                                   | 971 |
| 899464 | <b>Conceptual Design of the Scholtz MHD Retrofit Plant</b><br>L. Van Bibber, F.E. Bernard, R.R. Holman, R. Putkovitch and<br>D.A. Wiseman, <i>Westinghouse AESD, Pittsburg, PA</i> ; W.D. Jackson,<br><i>H.M.J. Corp.</i> ; G.R. Seikel, <i>SeiTec</i> ; J. Cuchens, <i>Southern Electric<br/>Integration</i> ; C.M. Maxwell, <i>STD Corp.</i> ; N. Johanson, <i>University of<br/>Tennessee</i> | 979 |
| 899019 | <b>The Feasibility of MHD Retrofit in India</b><br>S. Sridharan, K.V.S. Sundaram and S.K. Somasundaram, <i>Bharat Heavy<br/>Electricals, Tiruchy, India</i>                                                                                                                                                                                                                                      | 985 |
| 899333 | <b>Coal-Fired MHD Topping Cycle Hardware Development and Test<br/>Progress at the Component Development and Integration<br/>Facility</b><br>A. Hart, R. Glovan, I. Stepan and J.M. Richards, <i>MSE, Inc., Butte, MT</i>                                                                                                                                                                         | 991 |

**CONVERSION TECHNOLOGIES III  
MHD II—GENERATORS, HEAT RECOVERY AND SEED REPROCESSING**

|        |                                                                                                                                                                                                                                    |      |
|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899086 | <b>Axial Current Conduction in Polarized Slag Layers on Coal-Fired<br/>MHD Generator Walls</b><br>J. Lohrasbi and D. Lofftus, <i>MSE, Inc., Butte, MT</i>                                                                          | 999  |
| 899017 | <b>Theoretical Examination of the Growth and Attenuation of<br/>Acoustic and Entropy Waves In Ideal Faraday Generators</b><br>M. Kulkarni, <i>Johnson Controls, Milwaukee, WI</i> ; J.P. Barton, <i>University<br/>of Nebraska</i> | 1005 |
| 899607 | <b>Evaluation of Materials for the MHD Steam Bottoming Plant</b><br>K. Natesan and W. Swift, <i>Argonne National Laboratory, Argonne, IL</i>                                                                                       | 1011 |

- |        |                                                                                                                                                                                                                                                                |      |
|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899328 | <b>High Power Density Generator Concepts for Aerospace Electric Power</b><br>R.A. Hawsey, J.M. Bailey, W.J. Allington, S.V. McGrath, W.K. Sartory,<br>C.M. Simmons, R.J. Thomas and R.W. Young, Sr., <i>Oak Ridge National Laboratory, Oak Ridge, TN</i>       | 1109 |
| 899475 | <b>Multi-Foil Thermal Insulation for the Dynamic Isotope Power System</b><br>W.R. Determan, J. Emmons, <i>Rockwell International, Canoga Park, CA</i> ; and F.N. Huffman, J. Dunlay, D. Wortham and G. Field, <i>Thermo Electron Technologies, Waltham, MA</i> | 1115 |

#### BURST SPACE POWER

- |        |                                                                                                                                                           |      |
|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899551 | <b>Conceptual Design of a Category III Multimegawatt Space Nuclear Power System</b><br>R.E. Feddersen and J.R. Coiner, <i>Grumman Space, Bethpage, NY</i> | 1121 |
| 899193 | <b>Application of Cermet Fueled Reactors to Multimegawatt Space Power Systems</b><br>G.B. Kruger and J. Lobach, <i>General Electric Company</i>           | 1125 |
| 899133 | <b>Accelerating Hypersonic Airplanes with Ground Power</b><br>H. Oman, <i>Boeing Aerospace, Seattle, WA</i>                                               | 1131 |

#### CONVERSION TECHNOLOGIES V

##### THERMIONICS I: PHYSICS AND ADVANCED TECHNOLOGIES

- |        |                                                                                                                                                                                                                                                                        |      |
|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899299 | <b>Experimental and Theoretical Study of the TEC Pulse Mode with Cs and N<sub>2</sub> Filling</b><br>V.A. Zherebtsov, M.A. Lebedev, A.A. Sobolev, E.E. Antonov,<br>Y.P. Korchevoy and I.Y. Podoluk, <i>Institute of Physics &amp; Power Engineering, Obninsk, USSR</i> | 1137 |
| 899087 | <b>Theory of the Initial Stage of Low Pressure Arc Discharge with Thermionic Cathode</b><br>V.I. Babanin and A.Y. Ender, <i>USSR Academy of Sciences, Leningrad, USSR</i>                                                                                              | 1143 |
| 899305 | <b>A Phenomenological Model of the Arc Mode of a Thermionic Energy Converter</b><br>V.Z. Kaibyshev, <i>USSR Institute of Atomic Energy, Moscow, USSR</i>                                                                                                               | 1149 |

#### CONVERSION TECHNOLOGIES V

##### THERMIONICS—COMPONENTS AND METHODS (USSR)

- |        |                                                                                                                                                                                                                                                                               |      |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899294 | <b>Behavior of Carbon on Tungsten Monocrystal (110) and (112) Faces When Simulating Interaction with Thermionic Converter Interelectrode Medium</b><br>V.I. Yarygin, R.V. Savvov, V.R. Agafonov, D.V. Dodnov and Z.B. Skrebova,<br><i>Institute of Physics, Obninsk, USSR</i> | 1155 |
| 899304 | <b>Variation of Emission-Adsorption Properties in an Operating TEC Collector</b><br>V.A. Koryukin, V.P. Obrezumov, V.I. Vybyvanets and I.V. Kurchatov,<br><i>USSR Institute of Atomic Energy, Moscow, USSR</i>                                                                | 1161 |
| 899303 | <b>A New Method for Measuring Heat of Electron Evaporation from Thermionic Energy Converter Emitter</b><br>Y. Dzhashiashvil, V.Z. Kaibyshev and I.R. Kurchatov, <i>USSR Institute of Atomic Energy, Moscow, USSR</i>                                                          | 1165 |

|        |                                                                                                                                                                         |      |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899554 | <b>Evaluation of the Solid Liquid Separation Steps in the Formate Process-Based MHD Seed Reprocessing Option</b><br>D. Rasnake and A. Sheth, <i>UTSI, Tullahoma, TN</i> | 1019 |
| 899555 | <b>MHD Seed Recovery and Regeneration</b><br>R. McIlroy, P. Probert, D. Jackson and E. Lahoda, <i>Babcock &amp; Wilcox, Alliance, OH</i>                                | 1025 |

#### CONVERSION TECHNOLOGIES IV MHD III ALTERNATIVE CONCEPTS

|        |                                                                                                                                                                                                                                            |      |
|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899579 | <b>Closed-Cycle Magnetoplasmadynamic (MPD) Generator Ducts with Various Cesium-Seeded Working Fluids</b><br>M.E. Talaat, <i>University of Maryland, College Park, MD</i>                                                                   | 1033 |
| 899332 | <b>On the Feasibility of a Closed Loop MHD Generator Working with Helium Gas</b><br>P.J. Karditsas, <i>University of Maryland, College Park, MD</i>                                                                                        | 1039 |
| 899552 | <b>OMACON Liquid-Metal MHD Natural-Gas-Fired Systems</b><br>E. Pierson, <i>Argonne National Laboratory, Argonne, IL</i> ; and G. Berry, <i>Purdue University, Calumet, IN</i>                                                              | 1045 |
| 899400 | <b>Promising Applications of the Liquid Metal MHD Energy Conversion Technology</b><br>H. Branover and A. El-Boher, <i>Ben-Gurion University, Beer Sheva, Israel</i> ;<br>E. Greenspan and A. Barak, <i>Israel Atomic Energy Commission</i> | 1051 |

#### BURST AND PULSE POWER

|        |                                                                                                                                                                                          |      |
|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899326 | <b>High Energy Density Capacitors for Space Power Conditioning</b><br>M.F. Rose, <i>Auburn University, Auburn, AL</i>                                                                    | 1059 |
| 899327 | <b>Extracting Pulse Power from Batteries</b><br>H. Oman, <i>Boeing Aerospace, Seattle, WA</i>                                                                                            | 1067 |
| 899561 | <b>Design of a Ten Megawatt Rocket Driven Disk MHD Generator</b><br>A. Solbes, J. Weede, R. Hession and P. Mitchell, <i>TRW S&amp;TG, Redondo Beach, CA</i>                              | 1073 |
| 899126 | <b>A Novel Optoelectronic Closing and Opening Switch for Pulsed Power</b><br>K.H. Schoenbach, V. Lakdawala, M.S. Mazzola and S.T. Ko, <i>Old Dominion University, Norfolk, VA</i>        | 1079 |
| 899574 | <b>Experimental Program for Investigation of High Power Density MHD</b><br>J.T. Lineberry, H.J. Schmidt and J.N. Chapman, <i>University of Tennessee, Space Institute, Tullahoma, TN</i> | 1085 |

#### SPACE ENERGY CONVERSION TECHNOLOGIES IV DYNAMIC CONVERSION

|        |                                                                                                                                                                            |      |
|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899473 | <b>A Simplified Sizing and Mass Model for Axial Flow Turbines</b><br>S.L. Hudson, <i>Sandia National Laboratories, Albuquerque, NM</i>                                     | 1091 |
| 899129 | <b>A Thermodynamic Data-Base for the Design of NaK Rankine-Cycle Turbines</b><br>P.C. Lu, <i>University of Nebraska, Lincoln, NB</i>                                       | 1097 |
| 899596 | <b>Space Power Demonstration Engine Linear Alternator Dynamometer Test Results</b><br>M. Dhar, J. Rauch, S. Huang and R. Bolton, <i>Mechanical Tech., Inc., Latham, NY</i> | 1103 |

## CONVERSION TECHNOLOGIES VII THERMIONICS PERFORMANCE TESTING

|        |                                                                                                                                                                                                                                          |      |
|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899196 | <b>Design and Testing of a Heat Pipe Cooled Thermionic Energy Converter</b><br>W.B. Veltkamp, L.R. Wolff, J.M.W.M. Schoonen, R. Bakker,<br>M.P.A. Houtermans, A.M. dePijper, <i>Eindhoven University, Eindhoven,<br/>The Netherlands</i> | 1171 |
| 899567 | <b>Thermionic Fuel Element Verification Program: Summary of Results</b><br>S. Samuelson, <i>Department of Energy, Washington, DC</i> ; R.C. Dahlberg,<br><i>General Atomics, San Diego, CA</i>                                           | 1177 |
| 899625 | <b>Advanced Research Directions In Thermionic Energy Conversion</b><br>E.B. Kennel, <i>Wright Research and Development Center, WPAFB, OH</i> ;<br>L.H. Caveny, <i>Strategic Defense Initiative Organization, Washington,<br/>DC</i>      | 1183 |

## SPACE NUCLEAR REACTOR SYSTEMS I SPACE REACTOR APPLICATIONS

|        |                                                                                                                                                                                                       |      |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899009 | <b>A Look at the Soviet Space Nuclear Power Program</b><br>G.L. Bennett, <i>NASA Headquarters, Washington, DC</i>                                                                                     | 1187 |
| 899494 | <b>CSTI High Capacity Power</b><br>J.M. Winter, <i>NASA Lewis, Cleveland, OH</i>                                                                                                                      | 1195 |
| 899423 | <b>A Conceptual Study of the Use of a Particle Bed Reactor Nuclear Propulsion Module for the Orbital Maneuvering Vehicle</b><br>J. Malloy and D. Potekhen, <i>Babcock &amp; Wilcox, Lynchburg, VA</i> | 1209 |

## SPACE NUCLEAR REACTOR SYSTEMS II SP100 TECHNOLOGY

|        |                                                                                                                                                                                               |      |
|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899287 | <b>SP-100, A Flexible Technology for Space Power from 10s to 100s of KWe</b><br>P.R. Pluta, M.A. Smith, D.N. Matteo, <i>General Electric, Valley Forge, PA<br/>and San Jose, CA</i>           | 1215 |
| 899289 | <b>SP-100 Reactor Design and Performance</b><br>N.A. Deane, R.E. Murata and G.B. Kruger, <i>General Electric, San Jose, CA</i>                                                                | 1225 |
| 899288 | <b>Thermoelectric Electro-agnetic Pump Design for the SP-100 Reference Flight System</b><br>M. Zarghami, J.C. Atwell, S.A. Salamah and U.N. Sinha, <i>GE Astro Division,<br/>San Jose, CA</i> | 1227 |
| 899243 | <b>An Assessment of Helium Gas Behavior in SP-100 Primary Class Reactors</b><br>J. McGhee, M.S. El-Genk, R. Rothrock, <i>University of New Mexico,<br/>Albuquerque, NM</i>                    | 1231 |
| 899310 | <b>Reliability and Vulnerability Studies of the SP-100 System</b><br>W.J. Rider and M.S. El-Genk, <i>University of New Mexico, Albuquerque,<br/>NM</i>                                        | 1237 |
| 899618 | <b>SP-100 Advanced Radiator Designs for Thermoelectric and Stirling Applications</b><br>M.P. Moriarty and W.R. Determan, <i>Rockwell International, Canoga<br/>Park, CA</i>                   | 1245 |

### SPACE NUCLEAR REACTOR SYSTEMS III TECHNOLOGY I

|        |                                                                                                                                                                                     |      |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899167 | <b>Criteria for Establishing Nuclear Power System Radiation Levels for a Spacecraft</b><br>C.F. Guenther and W.R. Brukwinski, <i>Lockheed Missiles and Space Co., Sunnyvale, CA</i> | 1251 |
| 899422 | <b>SP-100/Brayton Power System Concepts</b><br>D.F. Owen, <i>Rockwell International, Rocketdyne Division, Canoga Park, CA</i>                                                       | 1257 |

### SPACE NUCLEAR REACTOR SYSTEMS IV TECHNOLOGY II

|        |                                                                                                                                                                                                                 |      |
|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 899012 | <b>Concept, Design Approaches Suited to Space Nuclear Power Systems in the Range of 20kWe</b><br>Z.P. Tilliette, F. Carre, E. Proust, <i>CEA, Saclay, France</i>                                                | 1263 |
| 899072 | <b>Space Nuclear Power Integration Studies for a Surveillance-Satellite Mission</b><br>P.G. Bailey and V.L. Teofilo, <i>Lockheed Missiles and Space Co., Sunnyvale, CA</i>                                      | 1269 |
| 899216 | <b>A Passive Fast Driver Reactor Concept Utilizing SP-100, TFE and VHTT Technologies for Low Power Space and Terrestrial Applications</b><br>P.T. Choong, <i>Rasor Associates, Inc., Humboldt, CA</i>           | 1275 |
| 899311 | <b>A Feasibility Study Using Thermoelectric Converters for the LMFBF Derivative Erato-20 kWe Space Power System</b><br>M. El-Genk, F. Carre and J.M. Tournier, <i>University of New Mexico, Albuquerque, NM</i> | 1281 |
| 899369 | <b>SP-100 GES/NAT IHX Design and Development</b><br>R. Hundal, R.A. Markley, B.A. Kessinger and G.B. Brown, <i>Westinghouse Corporation, Madison, PA</i>                                                        | 1289 |

## ANALYSIS OF INTERDIGITATED BACK CONTACT SILICON SOLAR CELLS FOR SPACE USE

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## ABSTRACT

The Silicon Interdigitated Back Contact (IBC) solar cell is a relatively new design which has been demonstrated to have greater than 25% efficiency at 100 suns Air Mass 1.5. This is far superior to conventional silicon concentrator cells which are approximately 18% efficient. The purpose of this report is to assess the utility of these cells for space applications. The end of life (EOL) performance of this cell design in the radiation environment of space is a critical question since the high efficiency of the design requires the use of very high quality, long diffusion length silicon. The radiation induced degradation of this material is expected to lead to severe efficiency losses.

Background

Silicon solar cells have served as the photovoltaic converters on virtually all satellites. The state of the art efficiency of these cells has risen from approximately 10% in the 1960's to nearly 15% Air Mass Zero (AM0) in the mid 1980's. The improvements in performance have been incremental during this period, resulting from the addition of such features as front and back surface field structures, back surface reflectors, and textured front surfaces. Each of these represents a modification of the solar cell, however the basic structure of the solar cell has remained unchanged. It consists of a large area (4-50 square centimeters) p-n junction, with a metal grid for the front face contact and partial or complete metal coverage for the back contact. The features listed above are essentially modifications to the interfacial regions of the cell where much of the device physics occurs. These modifications improve the cell efficiency by reducing either the carrier recombination rate or light loss at the interfaces. In 1977 a group at Purdue University demonstrated 15% (AM1.3, 63 suns) efficiency and projected 20% (AM1.3, 300 suns) efficiency in radically redesigned solar cells [1], named the Interdigitated Back Contact (IBC) solar cell. Further work at the University of Louvain, Belgium has confirmed these findings. In 1987 researchers there fabricated IBC cells with demonstrated [2] conversion efficiencies of 25.6% at 100 suns.

The major difference between the IBC cell and a conventional cell is apparent in Figure 1. In the IBC cell the p-n junction is at the rear of the device (opposite the face where light enters) and consists of narrow stripes under the contact metalization. This change in the junction area and location carries with it a number of implications for device performance. The placement of the contact grids only on the rear surface of the cell eliminates grid shadowing losses, which typically amount to 7-10%. Reduction of the junction area decreases the dark current which in turn increases open circuit voltage ( $V_{oc}$ ). In an IBC solar cell most light absorption occurs in a region doped much lower than a conventional cell emitter resulting in much less recombination. Finally, the series resistance of this design is expected to be lower since the  $n^+$  and  $p^+$  contacts are close together, resulting in higher fill factors.

The Point Contact cell is similar in philosophy, but uses junction "islands" connected to contact grids rather than junction "lines" that are coincident with the metal grid. This further reduces the junction area but at the expense of added fabrication complexity. The predicted and observed performance of the two designs are similar.

Apart from any efficiency advantages, IBC solar cells offer additional flexibility in panel construction methods. The absence of front contacts permits the use of simpler one side interconnect schemes without the need for wrap-through or wrap-around solar cells. The assembly of this type of panel is simple and more easily automated than the conventional strain relief interconnect procedure.

A primary concern about IBC cells in space applications is the expected sensitivity to radiation damage. The origin of the sensitivity is easily seen as follows. Light incident on the front surface of the cell is strongly absorbed in the first few micrometers of silicon, creating electron-hole pairs. These must then diffuse through the entire thickness of the device without recombining in order to reach the doped contact regions at the rear of the cell which separate them. Thus, silicon with minority carrier diffusion lengths of at least 100  $\mu m$  is

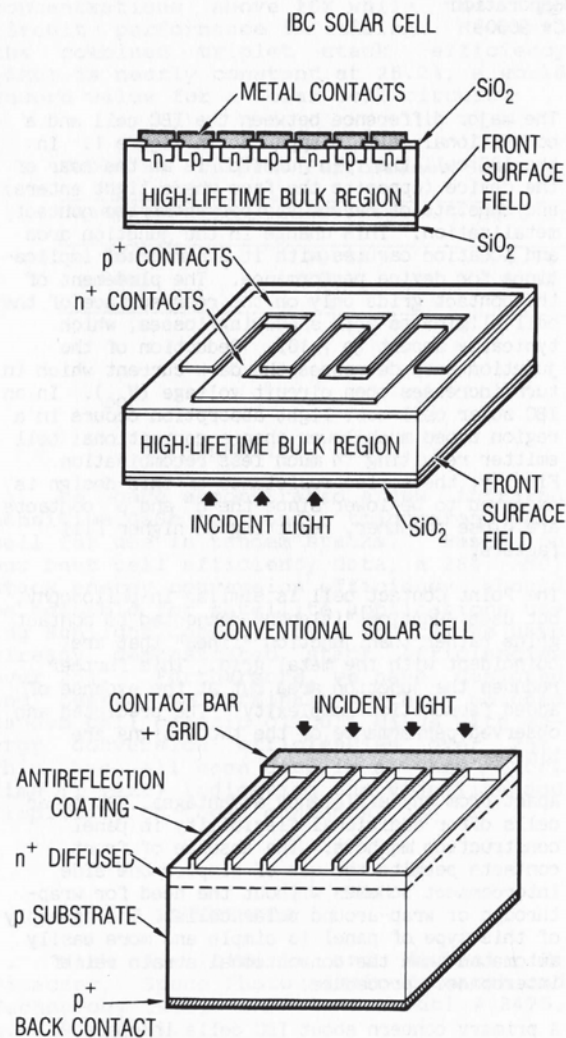


Fig. 1 Physical structure differences between IBC and conventional solar cells

typically required. This is no problem for present technology, except when the effects of particle irradiation are included. The damage caused by 1 MeV electron passage through the cell reduces the diffusion length substantially. For example empirical results [3] on 10 ohm-cm silicon show an initial diffusion length of 700  $\mu\text{m}$  falls to 34  $\mu\text{m}$  after  $1.0 \times 10^{15}$  1 MeV electron/cm<sup>2</sup> irradiation. A priori one would therefore conclude that cells of this design are unsuitable for radiation environments.

The purpose of this study is to evaluate the IBC cell design for use in space missions that encounter such an environment. As described above the primary incentive for use of such cells is increased efficiency. This is especially true when the cells are operated under concentrated light. However, since concentrating photovoltaic arrays have only been flown as demonstrations or experiments, the one sun operation of IBC cells is emphasized.

In order to properly simulate the operation of these cells, a two-dimensional solution of the carrier transport equations is necessary. This is in contrast to the situation with conventional cells where a one dimensional treatment is often adequate. The distinction in treatments arises because of the localized nature of the p-n junction in IBC cells. The study methodology is to vary the critical design parameters and simulate the cell current-voltage behavior at both the beginning and end of life under an assumed radiation environment. Basic IBC cell design parameters include base thickness and doping, contact region doping and dimensions, and front surface field (FSF) parameters. These are similar to the parameters in conventional cells except for the additional degrees of freedom associated with the localized current collector regions, since in a conventional cell these cover the entire cell area on the front and rear faces.

#### The PISCES Simulator

The Poisson and Continuity Equation Solver (PISCES) computer code was developed at Stanford University. It is a true two-dimensional, two carrier device modeling program. As supplied in Version IIb, the range of processes included is quite extensive. Fermi-Dirac carrier statistics, Auger and Shockley-Read-Hall (SRH) recombination, doping induced band gap narrowing (BCN), and interface recombination are all treated. In addition, steady state and transient solutions are available. The program has been modified at Aerospace to include optical generation of carriers, thus allowing solar cell simulation. Optical generation functions for AMO and AM1 light incident on silicon and gallium arsenide have been devised and implemented.

There are several features of PISCES which make it particularly useful for simulating optoelectronic devices such as solar cells. Because the solution is obtained for both carrier types, there is no restriction to low injection regimes. In addition the surface or interface recombina-

tion velocities may be set arbitrarily, thus allowing independent treatment of various interface types: semiconductor/oxide, semiconductor/metal, and semiconductor/air.

When used for absolute efficiency studies, as opposed to comparative studies, the accuracy of the generation function is important. In order to assess the accuracy of the AMO/silicon generation function, several simulations of IBC cells reported in the literature [4] were reproduced. These reports also used a two-dimensional simulator to investigate the reported variation of IBC cell efficiency with cell thickness, illumination intensity, and interface recombination. In order to obtain agreement in absolute efficiencies, it was necessary to normalize the PISCES results to the known intensity of AMO light. This was done by computing the ratio of the known AMO carrier generation in a given thickness of silicon [5] to the simulated short circuit current value obtained from PISCES in the case of no recombination. All subsequent simulations of the same cell design were adjusted by this ratio, thus ensuring accurate absolute efficiencies. Having done this, the agreement in all cases tested was very good not only with respect to relative variations, but also in the absolute sense.

## RESULTS AND DISCUSSION

### Scope of the Study

The purpose of this study is to evaluate the usefulness of Interdigitated Back Contact (IBC) solar cells in space applications. The scope of the study includes optimization of the IBC cell design under several different constraints and assessment of the effects of certain design parameters on cell performance. Since optimization is achieved by selecting parameters which produce the results desired to meet specific performance requirements, it is necessary to first understand how each parameter affects cell performance. Cell performance is assessed on the basis of overall cell efficiency  $\eta$ , maximum power  $P_{max}$ , short circuit current  $I_{sc}$ , open circuit voltage  $V_{oc}$ , fill factor FF, and collection efficiency. These are the parameters commonly used to judge solar cell performance, with perhaps the exception of collection efficiency. This quantity measures the fraction of photogenerated carriers which are ultimately delivered as current at the contacts. This is distinct from the cell efficiency which is defined as the fraction of incident optical power which is ultimately delivered as electrical power at the contacts. The collection efficiency is related to the overall efficiency through the open circuit voltage and fill factor.

A subset of all the possible design parameters was selected for study in order to have a manageable task. These include cell thickness, contact width, spacing and thickness, front surface field doping and thickness, and light intensity. The remaining fixed parameters and constants are shown in Table 1. The baseline

cell design is specified by the parameters in Table 2. These particular values were selected as representative of established silicon technology as applied to IBC structures. The carrier lifetime values for radiation scenario 1 are computed using an optimistic radiation degradation coefficient [6] obtained from a recent analysis of conventional silicon solar cell degradation. We regard these values as optimistic because they are extracted from experimental data by making certain unverified but reasonable assumptions. The assumed dose is  $1E15$

Table 1. Constant cell design parameters

|                                     |                               |
|-------------------------------------|-------------------------------|
| electrode width                     | 25 $\mu m$                    |
| p <sup>+</sup> doping concentration | $5E18 \text{ cm}^{-3}$        |
| n <sup>+</sup> doping concentration | $5E18 \text{ cm}^{-3}$        |
| p doping concentration              | $1.40E15 \text{ cm}^{-3}$     |
| p Auger recombination               | $1.2E-31 \text{ cm}^6 s^{-1}$ |
| n Auger recombination               | $1.7E-31 \text{ cm}^6 s^{-1}$ |
| hole mobility                       | $475 \text{ cm}^2/Vs$         |
| electron mobility                   | $1380 \text{ cm}^2/Vs$        |
| front surface recombination         | 1E3 cm/s                      |
| p <sup>+</sup> /oxide recombination | 1E4 cm/s                      |
| n <sup>+</sup> /oxide recombination | 1E6 cm/s                      |
| metal contact resistance            | 0                             |
| front surface reflectivity          | 0                             |

Table 2. Baseline cell design

|                                          |                  |
|------------------------------------------|------------------|
| p <sup>+</sup> width                     | 35 $\mu m$       |
| n <sup>+</sup> width                     | 145 $\mu m$      |
| p <sup>+</sup> thickness                 | 1.0 $\mu m$      |
| n <sup>+</sup> thickness                 | 0.3 $\mu m$      |
| p thickness                              | 50 $\mu m$       |
| t <sub>n</sub> in base                   | 136 $\mu s$      |
|                                          | 1.10 $\mu s$ (a) |
|                                          | 0.32 $\mu s$ (b) |
| t <sub>n</sub> in p <sup>+</sup> contact | 0.128 $\mu s$    |
|                                          | 78 ns (a)        |
|                                          | 78 ns (b)        |
| t <sub>p</sub> in n <sup>+</sup> contact | 32.6 ns          |
|                                          | 12 ns (a)        |
|                                          | 12 ns (b)        |
| FSF doping                               | 5E18 p type      |
| FSF thickness                            | 0.5 $\mu m$      |
| Doped region spacing                     | 20 $\mu m$       |

(a) After radiation scenario 1:

$$K_L = 2.5E-11 \text{ for p base}$$

$$K_L = 1.10E-9 \text{ for p}^+ \text{ region}$$

$$K_L = 3.10E-8 \text{ for n}^+ \text{ region}$$

(b) After radiation scenario 2:

$$K_L = 8.40E-11 \text{ for p base}$$

$$\text{Other } K_L \text{ same as scenario 1}$$

1 MeV electron/cm<sup>2</sup>. Scenario 2 assumes the same dose, but with an experimentally obtained radiation degradation coefficient [3] for the base region. As pointed out in Reference 6, this degradation coefficient is probably pessimistic because of the overly simplistic method by which it was obtained from the data. The second line of Table 3 shows that this baseline cell has a 1 sun efficiency of 14.87% BOL.

Table 3. BOL effects of cell thickness

| cell<br>thickness<br>( $\mu\text{m}$ ) | % $\eta$ |       | $P_{\text{max}}$<br>$\text{mWcm}^{-2}$ |       | $I_{\text{sc}}$<br>$\text{mAcm}^{-2}$ |       | $V_{\text{oc}}$<br>mV |      | % FF  |       | % Collection<br>efficiency |       |
|----------------------------------------|----------|-------|----------------------------------------|-------|---------------------------------------|-------|-----------------------|------|-------|-------|----------------------------|-------|
|                                        | 1x       | 100x  | 1x                                     | 100x  | 1x                                    | 100x  | 1x                    | 100x | 1x    | 100x  | 1x                         | 100x  |
| 25                                     | 13.67    | 15.26 | 18.54                                  | 20.60 | 42.59                                 | 47.09 | 541                   | 662  | 80.10 | 66.08 | 99.76                      | 99.53 |
| 50                                     | 14.87    | 14.31 | 20.07                                  | 19.31 | 45.47                                 | 49.79 | 548                   | 680  | 80.54 | 57.04 | 99.49                      | 99.03 |
| 200                                    | 15.06    | 10.98 | 20.33                                  | 14.82 | 47.34                                 | 47.35 | 548                   | 676  | 78.36 | 46.30 | 95.08                      | 87.07 |

A COMSAT "Violet" cell was simulated to provide a basis for comparison with conventional silicon technology. A 250  $\mu\text{m}$  thick cell of this type at 1 sun gave approximately 14.67% BOL and 13.2% EOL (under scenario 1) efficiency. The EOL efficiency under scenario 2 was 12.3%. This predicted degradation is in good agreement with measurements reported in [3].

Subsequent sections present the effect on cell performance of variations about this baseline design. Cell performance at illuminations of 1 and 100 suns were calculated to evaluate systems with and without light concentration. All simulations were performed at an operating temperature of 25°C.

#### Cell Thickness

Cell thickness effects are relatively simple to interpret. Thicker cells absorb a larger fraction of the incident light, especially the near bandgap infrared, making the cell more efficient. However, the increased distance to the contacts means that a longer diffusion length is required and therefore higher quality silicon. The increased distance also means that thicker cells will be more susceptible to radiation induced degradation.

Cells of 25, 50 and 200 micrometer thicknesses were simulated. The beginning of life (BOL) results in Table 3 show trends of increasing performance at 1 sun and decreasing performance at 100 suns as cell thickness is increased.

At 1 sun, efficiency increases by 1.4% (absolute) as cell thickness is increased from 25 to 200  $\mu\text{m}$ . This increase is due to the additional absorption efficiency, which overcomes the decrease in collection efficiency arising from the extra diffusion distance that a thicker cell requires. The increased terminal current gives rise to a slight increase in  $V_{\text{oc}}$ .

At 100 suns, the BOL efficiency drops by 4.28% (absolute) as the cell thickness increases. In this case the higher carrier density throughout the cell causes the collection efficiency to decrease much more rapidly than in the 1 sun

case. At first, this result seems contrary to the expectation that IBC cells are highly efficient under concentrated light. As is shown below, this baseline cell does not exhibit this behavior strongly because the contact regions are far from optimum.

The end of life (EOL) behavior following the more optimistic radiation scenario is shown in the upper part of Table 4. Clearly the thinnest cell has the best EOL performance, as expected. Also, each cell thickness shows little variation in EOL efficiency between 1 sun and 100 suns. The 25  $\mu\text{m}$  cell has a 2% advantage over the 50  $\mu\text{m}$  cell EOL for the baseline design at one sun. Table 4 shows the behavior of the 50  $\mu\text{m}$  cell under the more realistic scenario 2 radiation. The loss of almost a factor of 2 in efficiency between the two radiation scenarios demonstrates the need for accurate radiation modeling input data, which may be obtained from experiments on bulk material rather than completed cells.

#### Carrier Collection Region Thickness

The 50  $\mu\text{m}$  thick cell was selected to study the effects of carrier collection region thickness. Trends observed in this cell were verified in simulations of the 25  $\mu\text{m}$  thick cell, which are not presented here.

At light intensities of 1 sun and 100 suns, BOL cell performance improvements in efficiency,  $P_{\text{max}}$ ,  $V_{\text{oc}}$  and FF were observed when respective  $p^+$  and  $n^+$  regions were changed from 1.0/0.3  $\mu\text{m}$  to 3.0/0.9  $\mu\text{m}$  thick, as shown in Table 5. Collection efficiency and  $I_{\text{sc}}$  remained constant as expected. There was no change in performance when the  $n^+$  collection region thickness was further increased to 3.0  $\mu\text{m}$ . The results thus indicate that an approximate 0.8% increase in BOL efficiency can be obtained by increasing the thickness of the doped contact regions.

The EOL figures included in Table 5 show that most of this 0.8% BOL improvement is retained at EOL. Therefore, the conclusion of this portion of the study is that thicker doped contact regions will improve both BOL and EOL performance.

Table 4. EOL effects of cell thickness

| cell<br>thickness<br>( $\mu\text{m}$ ) | % $\eta$ |       | $P_{\text{max}}$<br>$\text{mWcm}^{-2}$ |       | $I_{\text{sc}}$<br>$\text{mAcm}^{-2}$ |       | $V_{\text{oc}}$<br>mV |      | % FF  |       | $P^+/N^+$<br>thickness<br>( $\mu\text{m}$ ) |     |
|----------------------------------------|----------|-------|----------------------------------------|-------|---------------------------------------|-------|-----------------------|------|-------|-------|---------------------------------------------|-----|
|                                        | 1x       | 100x  | 1x                                     | 100x  | 1x                                    | 100x  | 1x                    | 100x | 1x    | 100x  |                                             |     |
| 25 <sup>1</sup>                        | 11.49    | 11.83 | 15.51                                  | 15.97 | 38.15                                 | 38.80 | 510                   | 560  | 79.72 | 63.31 | 1.0                                         | 0.3 |
| 50 <sup>1</sup>                        | 9.49     | 9.88  | 12.81                                  | 13.33 | 32.37                                 | 37.86 | 502                   | 646  | 78.84 | 54.51 |                                             |     |
| 50 <sup>2</sup>                        | 5.05     | 5.32  | 6.82                                   | 7.18  | 18.77                                 | 19.70 | 482                   | 600  | 77.78 | 60.80 |                                             |     |
| 200 <sup>1</sup>                       | 1.00     | 1.05  | 1.33                                   | 1.41  | 3.93                                  | 3.46  | 443                   | 560  | 76.48 | 72.89 |                                             |     |
| 25 <sup>1</sup>                        | 11.98    |       | 16.18                                  |       | 38.53                                 |       | 526                   |      | 79.82 |       | 3.0                                         | 0.9 |
| 50 <sup>1</sup>                        | 10.09    |       | 13.63                                  |       | 33.84                                 |       | 506                   |      | 79.58 |       |                                             |     |

<sup>1</sup> Radiation scenario 1.<sup>2</sup> Radiation scenario 2.Table 5. Effects of  $P^+$  and  $N^+$  collection region thicknesses, BOL and EOL

| cell<br>thickness<br>( $\mu\text{m}$ ) | % $\eta$ |       | $P_{\text{max}}$<br>$\text{mWcm}^{-2}$ |       | $I_{\text{sc}}$<br>$\text{mAcm}^{-2}$ |       | $V_{\text{oc}}$<br>mV |      | % FF  |       | $P^+/N^+$<br>thickness<br>( $\mu\text{m}$ ) |     |
|----------------------------------------|----------|-------|----------------------------------------|-------|---------------------------------------|-------|-----------------------|------|-------|-------|---------------------------------------------|-----|
|                                        | 1x       | 100x  | 1x                                     | 100x  | 1x                                    | 100x  | 1x                    | 100x | 1x    | 100x  |                                             |     |
| 50                                     | 14.87    | 14.31 | 20.07                                  | 19.31 | 45.47                                 | 49.79 | 548                   | 680  | 80.54 | 57.04 | 1.0                                         | 0.3 |
| 50 <sup>1</sup>                        | 9.49     | 9.88  | 12.81                                  | 13.33 | 32.37                                 | 37.86 | 502                   | 646  | 78.84 | 54.51 |                                             |     |
| 50                                     | 15.62    | 16.22 | 21.08                                  | 21.90 | 45.47                                 | 49.85 | 572                   | 696  | 81.09 | 63.13 | 3.0                                         | 0.9 |
| 50 <sup>1</sup>                        | 10.09    |       | 13.63                                  |       | 33.84                                 |       | 506                   |      | 79.58 |       |                                             |     |
| 50                                     | 15.64    |       | 21.12                                  |       | 45.47                                 |       | 572                   |      | 81.19 |       | 3.0                                         | 3.0 |

<sup>1</sup>EOL, radiation scenario 1.

#### Carrier Collection Region Width

The 50  $\mu\text{m}$  baseline cell described in Table 2 was again selected for study of the effects of minority ( $n^+$ ) and majority ( $p^+$ ) carrier collection region widths. Since the baseline cell was near optimum for 1 sun, the overall cell efficiency was expected to decrease as the region widths were changed. However, an incremental decrease in the  $n^+$  region width from 145  $\mu\text{m}$  to 90  $\mu\text{m}$  resulted in higher cell efficiencies as shown in Table 6. This increase in cell efficiency at first seems contrary to intuition since the minority carrier diffusion length of 700  $\mu\text{m}$  (BOL) is sufficient for these carriers to reach the contact effectively irrespective of its size. One possibility is that the increased efficiency is due to the reduced  $n^+$ /oxide interface area,

which results in lower interface recombination losses. However the table shows that while the contact width is reduced, the collection efficiency is also decreasing. In fact the increase in efficiency is due to an increased  $V_{\text{oc}}$  and fill factor. This can be understood by remembering that the dark current of the cell  $I_0$ , which is caused by carrier injection from the contacts into the base region, is reduced when the area of the contact/base interface is reduced. Since  $V_{\text{oc}}$  varies as  $\ln(I_{\text{sc}}/I_0)$ , an increased  $V_{\text{oc}}$  is expected. Although the efficiency only increases by 0.25% at 1 sun BOL, it can be more significant at EOL. At 100 suns the improvement is 4.3% BOL. In this study we have not performed a detailed EOL optimization of a concentrator cell.

Table 6. Effects of P<sup>+</sup> and N<sup>+</sup> Collection Region Widths on 50  $\mu$ m Thick Cell, BOL

| % $\eta$ |       | P <sub>max</sub><br>mWcm <sup>-2</sup> |       | I <sub>sc</sub><br>mAcm <sup>-2</sup> |       | V <sub>oc</sub><br>mV |      | % FF |      | %<br>collection | P <sup>+</sup> /N <sup>+</sup><br>width<br>( $\mu$ m) |
|----------|-------|----------------------------------------|-------|---------------------------------------|-------|-----------------------|------|------|------|-----------------|-------------------------------------------------------|
| 1x       | 100x  | 1x                                     | 100x  | 1x                                    | 100x  | 1x                    | 100x | 1x   | 100x | 100x            |                                                       |
| 14.87    | 14.31 | 20.07                                  | 19.31 | 45.47                                 | 49.79 | 548                   | 680  | 80.5 | 57.0 | 98.98           | 35/145                                                |
| 14.79    |       | 19.96                                  |       | 45.41                                 |       | 548                   |      | 80.2 |      |                 | 35/135                                                |
| 14.84    | 15.25 | 20.04                                  | 20.59 | 45.43                                 | 49.75 | 548                   | 681  | 80.5 | 60.8 |                 | 35/125                                                |
| 14.93    | 16.47 | 20.16                                  | 22.24 | 45.18                                 | 49.59 | 552                   | 686  | 80.8 | 65.4 | 98.58           | 35/90                                                 |
|          | 17.54 |                                        | 23.68 |                                       | 49.45 |                       | 681  |      | 70.3 | 98.30           | 60/90                                                 |
| 14.90    | 18.40 | 20.10                                  | 24.84 | 45.10                                 | 49.42 | 551                   | 684  | 80.9 | 73.4 | 98.23           | 90/90                                                 |
| 15.12    | 18.76 | 20.41                                  | 25.32 | 45.09                                 | 49.23 | 560                   | 693  | 80.8 | 74.2 | 97.86           | 90/70                                                 |
| 15.00    | 18.73 | 20.24                                  | 25.29 | 44.90                                 | 49.21 | 560                   | 692  | 80.5 | 74.3 | 97.81           | 90/50                                                 |

#### Abrupt Front Surface Field

The front surface field (FSF) is a heavily doped region, p<sup>+</sup> in the present case, which covers the entire front face of the solar cell. Its purpose is to provide an electric field that repels one carrier type away from the front surface. This effectively reduces the surface recombination velocity by reducing the concentration of one type of carrier near the surface. The FSF is generally introduced by heavier doping in a thin layer near the interface. This doping may be a step function, in which case it is often referred to as a minority carrier mirror, or a graded region. The graded region, although more difficult to tailor experimentally, is somewhat more effective since the field is present over the entire region thickness.

The effects of FSF thickness and doping level were studied for the baseline cell geometry at BOL. For thicknesses of 0.25, 0.5 and 1.0  $\mu$ m at 1E18 doping no significant effect was observed at 1 sun. The FSF effectiveness is relatively constant over a rather broad range around 1E17-1E18, decreasing below this level due to the weakness of the electric field and decreasing above this level due to increased Auger recombination.

#### Design Refinements

Using the baseline cell as a starting point, the IBC cell design has been investigated to show how the parameters should be varied to produce an optimum design for various applications. In cases where radiation exposure is not present as the result of shielding or terrestrial use, the 1 sun cell should be at least 50  $\mu$ m thick, have contact doping widths approximately 90  $\mu$ m for both minority and majority carriers with 20  $\mu$ m spacing, and have doping thicknesses approximately 1  $\mu$ m and 3  $\mu$ m respectively. The efficiency of this cell will be near 16% AMO. A 100 sun

cell will be very similar but will have an efficiency near 20%.

For space use, where radiation is present, EOL performance must be considered. The baseline cell parameters are near optimum for EOL efficiency. The cell is further optimized for EOL performance by reducing cell thickness to 25  $\mu$ m and increasing the contact doping region thickness. The gain in EOL efficiency will be nearly 2% at both 1 sun and 100 suns as the cell is thinned from 50  $\mu$ m to 25  $\mu$ m. Thus, the improvement over the baseline cell at 1 sun and 100 suns under these conditions is a total of 2.5%, with 2% attributable to cell thinning and 0.5% to contact doping thickness.

Some additional consideration was given to optimization of the front surface field region and the doped contact spacing. The previous design used a 0.5  $\mu$ m thick front surface field (FSF) uniformly doped at 5E18 and 20  $\mu$ m region spacing. It was found that by replacing this with a Gaussian doping profile with a characteristic width of 15  $\mu$ m and a peak concentration of 1E17, the EOL efficiency was 12.3% with a 10  $\mu$ m collector region spacing.

However, the importance of the bulk/oxide passivation is greatly increased and this is under further study.

#### Conclusion

The design of IBC solar cells for space use has been investigated using 2 dimensional computer simulations. Near-optimal designs have been presented for missions using either planar or 100 sun concentration arrays, under high or negligible radiation fluences. In the low radiation environment the minority and majority carrier collection regions should be of comparable width, with thicknesses of 0.9  $\mu$ m and

3.0  $\mu\text{m}$  respectively. The FSF should be an approximately 0.5  $\mu\text{m}$  step with doping concentration of  $5 \times 10^{18} \text{ cm}^{-3}$ . These parameters are much more critical for 100 sun operation. The 1 sun efficiency of IBC cells exceeds 15% which makes them competitive with conventional design silicon cells. The 100 sun efficiency is nearly 19%, which also exceeds the conventional silicon cell capability. It is also in the expected efficiency range of GaAs concentrator cells, although the operating temperature of each is quite important in comparing efficiencies.

In a high radiation environment, a different design is used to maximize the EOL performance. At 1 sun after  $1 \times 10^{15}$  1MeV electron fluence, the design presented here shows greater than 12% efficiency which is superior to conventional silicon solar cells and only slightly lower than a COMSAT "violet" cell simulated with the same silicon properties. The carrier collection region widths in this design are in an approximately 4 to 1 ratio, unlike the low radiation case. The FSF is graded over 15  $\mu\text{m}$  with a peak doping concentration of  $1 \times 10^{18} \text{ cm}^{-3}$ . At 100 suns the EOL efficiency approaches 16%, which is comparable to that expected for GaAs concentrator systems. The effect of proton irradiation has not been addressed here, but the very deep junction should lead to high resistance to low energy front side proton irradiation.

The overall conclusion of this study is that properly designed IBC cells can yield performance which is comparable with (or superior to) competing silicon and gallium arsenide technologies. Therefore their use in space systems should be considered. It is especially important with IBC cells to optimize the design to the particular mission profile. The light intensity to be used and the radiation environment affect the design to a greater extent than in conventional cells. In addition these cells offer added simplicity and flexibility in panel fabrication.

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