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OVERVIEW OF SPACE POWER ELECTRONIC'S TECHNOLOGY UNDER THE CSTI HIGH CAPACITY POWER PROGRAM

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INTRODUCTION

The Civilian Space Technology Initiative (CSTI) is a NASA Program targeted at the development of specific technologies in the areas of transportation, operations and science. Each of these three areas consists of major elements and one of the operation's elements is the High Capacity Power element. The goal of this element is to develop the technology base needed to meet the long duration, high capacity power requirements for future NASA initiatives.

The High Capacity Power element is broken down into several subelements that includes energy conversion in the areas of the free piston Stirling power converter and thermoelectrics, thermal management, power management, system diagnostics, and environmental compatibility and system's lifetime. A recent overview of the CSTI High Capacity Power element and a description of each of the program's subelements is given by Winter (1989).

The goals of the Power Management subelement are twofold. The first is to develop, test, and demonstrate high temperature, radiation-resistant power and control components and circuits that will be needed in the Power Conditioning, Control and Transmission (PCCT) subsystem of a space nuclear power system. The results obtained under this goal will also be applicable to the instrumentation and control subsystem of a space nuclear reactor. These components and circuits must perform reliably for lifetimes of 7-10 years. The second goal is to develop analytical models for use in computer simulations of candidate PCCT subsystems. Circuits which will be required for a specific PCCT subsystem will be designed and built to demonstrate their performance and, also, to validate the analytical models and simulations. The tasks under the Power Management subelement will now be described in terms of objectives, approach and present status of work.

Solid State Power Switch Task

MASTER

The objective of the solid state power switch task is to test and evaluate both commercial and developmental-type devices under the conditions of high temperature and gamma and neutron irradiation. The rationale for high temperature and gamma and

neutron radiation-resistant electrical components is to realize a reduction in radiator mass by allowing high temperature operation and a reduction in reactor shielding mass by allowing high gamma dose and neutron fluence environments. The main focus of the experimental work under this task is to identify those switch characteristics that are most sensitive to temperature and gamma and neutron irradiation. From the experimental tests, the rate of degradation and failure mechanisms are determined as functions of temperature, gamma dose rate and total dose, and neutron flux and fluence. The results obtained under this task should enable the circuit designer to determine the useability of a particular switch for a specified circuit application.

A three step approach is used in the test program. In each step, whenever possible, all the electrical and switching measurements are made under in-situ conditions. Step 1 of the approach is to determine the separate effects due to temperature, gamma dose rate and total dose, and neutron flux and fluence. The results in this step form the baseline for comparison of results obtained in steps 2 and 3. Step 2 is to determine the combined effects of temperature and gamma irradiation and temperature and neutron irradiation. Step 3, which is perhaps the most difficult in terms of obtaining the desired gamma dose rate and neutron flux simultaneously, is to determine the combined effects of temperature, gamma, and neutron irradiation. It is possible that steps 1 and 2 will yield sufficient information to make step 3 unnecessary.

The type of solid state switches to be experimentally tested under this task include power diodes, transistors and thyristors. The transistors include the Bipolar Junction Transistor (BJT), the Metal Oxide Semiconductor Field Effect Transistor (MOSFET), the Insulated Gate Bipolar Transistor (IGBT) and the Static Induction Transistor (SIT). The thyristors include both the phase-control and inverter type Silicon Controlled Rectifier (SCR), and the MOS controlled thyristor (MCT).

The research facilities and equipment of the NASA-Lewis Research Center, Wittenberg University, the Ohio State University and the University of Cincinnati are used for the experimental tests and data analysis. The 10-kW research reactor facility at Ohio State University is used for in-situ neutron irradiation tests and the Cobalt-60 facility at the University of Cincinnati is used for in-situ gamma irradiation tests. At present, both the neutron and gamma irradiation tests are done under room temperature conditions, but a temperature-controlled fixture operable up to 525 K is presently being designed and fabricated. This high temperature test fixture will enable the in-situ investigation of thermal annealing under both neutron and gamma irradiation conditions.

The two basic mechanisms which cause radiation damage in solid state switches are ionization and displacement effects. Ionization effects generate electron-hole pairs and displacement

effects generate vacancy-interstitial pairs known as simple or point defects. Regions which contain large numbers of relatively closely spaced defects are called defect clusters. For most materials, displacement of an atom requires a minimum of about 25 eV of energy to be transferred from the incident particle to the target atom. Neutron irradiation primarily leads to displacement damage while gamma irradiation primarily leads to ionization damage.

The effects of neutron irradiation on the electrical and switching characteristics of NPN BJTs have been reported by Frasca and Schwarze (1988). The devices tested were the D60T 455010 (450 V/50 A) for neutron fluences up to  $1.6 \times 10^{13}$  n/cm<sup>2</sup>. The significant changes observed were: 1) a significant decrease in the current gain and the switching storage time due to the decrease in the minority carrier recombination lifetime caused by the radiation-induced recombination centers and 2) an increase in the leakage current due to the increase in electron-hole pairs caused by the radiation-induced generation centers.

The effects of neutron and gamma irradiation on the electrical and switching characteristics of n-channel enhancement mode power MOSFETs have been reported by Frasca and Schwarze (1989). The devices tested were the IRF250 (200 V/30 A) and MTM15N50 (500 V/15 A) for neutron fluences up to  $3.8 \times 10^{13}$  n/cm<sup>2</sup> and gamma doses up to  $1.5 \times 10^6$  rads. The most significant change under gamma irradiation was the rapid decrease in the gate-to-source threshold voltage beyond a gamma dose of 1-5 krad due to the positive charge build-up near the oxide-semiconductor interface. As the gamma dose approaches  $10^5$  rads, the gate-to-source voltage approaches zero for both of the devices tested. When this happens the positive charge build-up is such that an n-channel enhancement mode MOSFET begins to operate as a depletion mode device and a negative gate-to-source voltage is required to turn off the device. The noticeable changes under neutron irradiation for the fluence above  $10^{13}$  n/cm were: 1) a sharp increase in leakage current for both devices and 2) a small change in source-to-drain on-resistance with the 500 V device showing a more pronounced change than the 200 V device.

The effects of neutron and gamma irradiation on the electrical and switching characteristics of the SIT are being reported in this symposium by Frasca and Schwarze (1990).

#### Soft Magnetic Materials Task

The objectives of this task are 1) to develop a high temperature, high frequency test system to accurately measure and plot the core loss and dynamic hysteresis B-H loops of soft magnetic materials (i.e. non-permanent magnetic materials), and 2) to use the developed test system to make experimental core loss and hysteresis loop measurements of candidate soft magnetic materials for characterization and evaluation purposes.

The approach for this task is to initially characterize candidate soft magnetic materials for operating temperatures up to 50 kHz and temperatures up to 575 K under sinusoidal voltage excitation. The next step is to conduct these same frequency and temperature tests under non-sinusoidal voltage excitation with particular emphasis on square wave excitation. Temperature tests beyond 575 K will need to use a high temperature vacuum furnace since the silicone oil presently used in the temperature bath is limited to 575 K operation.

The candidate materials to be investigated include alloys of the following nominal composition: 1) 80% Ni - 20% Fe; 2) 50% Ni - 50% Fe; 3) 3% Si - Fe; 4) 50% Co - 50% Fe; 5) 27% Co - Fe; and 6) iron-based amorphous alloys. These materials are available in different core geometries, but for this test program the preferred geometry will be tape-wound toroids.

The initial development of the core loss and dynamic B-H loop test and measurement system was done at the NASA-Lewis Research Center (LeRC). For system check-out purposes, an 80% Ni - 20% Fe and two different iron-based amorphous alloys were tested up to 50 kHz and 475 K. An improved version of the test system is being developed through a grant with the University of Pittsburgh at Johnstown. Also, under this grant, several of the above candidate materials will be experimentally investigated and their magnetic and electrical properties for both sine and square wave excitation will be characterized and evaluated for frequencies up to 50 kHz and temperatures up to 575 K.

#### Rare-Earth Permanent Magnet Task

The objective of this task is to experimentally characterize the magnetic properties of rare-earth samarium-cobalt permanent magnets as a function of long term temperature stability. The design and development of a test and calibration system to accurately measure the magnetic properties in terms of temperature stability is also a key element of this task. A primary application of these magnets is the linear alternator for the free piston Stirling converter. Present space power system's designs require that the alternator's magnets operate at temperatures of at least 525 K for lifetimes of 7-10 years.

The approach will be to first concentrate on characterizing the  $\text{Sm}_2\text{Co}_{17}$  type of magnets and then to investigate the  $\text{SmCo}_5$  magnets. In all cases, the magnet test samples will be 1-cm cubes. The test program will consist of two phases. In the first phase the test samples will be tested in-situ up to 575 K. The temperature limit of the presently available temperature-controlled test fixture is 475 K and this is due to the insulation on the fixture's B- and H-sense coils. A temperature-controlled test fixture for operation up to 575 K is presently being designed and fabricated under contract. The purpose of these in-situ tests is to determine the changes in the magnet's remanence and coercivity properties as a function of temperature.

These changes are obtained by plotting the B-H demagnetization curves at temperatures up to 575 K. The phase one results will also serve as a screening test for samples to be tested in phase two. At the present time, Sm<sub>2</sub>Co<sub>17</sub> samples from five different vendors are being tested and evaluated up to 475 K.

Phase two of the test program will investigate the magnet's long term temperature stability properties. The present plans for conducting these tests are to use a high temperature vacuum furnace to expose the magnet samples to a specified temperature for different lengths of time. The temperature range for these tests will be between 475 and 575 K. After a specified time interval the heated samples will be removed from the furnace and allowed to cool to room temperature at which time the demagnetization curves will be plotted. The primary purpose of these tests is to determine if any permanent changes occur in the magnet's remanence and coercivity properties due to metallurgical changes. A metallurgical change is indicated if the test sample cannot be remagnetized to its initial room temperature characteristics. A unique test, measurement, and calibration facility has been developed at NASA-LeRC to conduct both phases of the test program.

#### Power Conditioning for a FPSE/LA Converter Task

The objective of this task is to investigate the Power Conditioning, Control and Transmission (PCCT) subsystem for a free piston Stirling engine/linear alternator (FPSE/LA) power converter in terms of power module networking, voltage regulation and load control, system stability, transient effects, fault tolerance and survivability. The primary goal is to identify, analyze, test, and evaluate PCCT architectures which will enable the application of FPSE/LA power converters to future space power systems. The identification of PCCT technology issues and concerns, and their impact on program progress, is also a very important part of this task's objective.

The approach is to conduct both analytical and experimental work on a power conversion system consisting of a single FPSE/LA module and its associated controls and load and then to extend these investigations to networking of power modules in either series or parallel combinations.

The analytical work will consist of either developing or utilizing presently available analytical models of the engine, alternator and controls to conduct simulation studies which characterize conversion system performance. One of the primary purposes of the simulation studies is to investigate the conversion system in terms of stability and transient effects. An initial linear model of the FPSE/LA and load has been developed to investigate stability issues. The model was used to investigate system stability in terms of sensitivity to variations in load resistance, alternator inductance, and tuning capacitance. This linear model has several shortcomings since it

does not include any losses and any of the nonlinear effects in the working gas dynamics. Present plans are to extend the work on this linear model to include these effects.

Since a strong coupling exists between load conditions and engine operation, it is a fundamental requirement that any instabilities, faults, or transient effects caused by engine/alternator/load interactions be identified and fully characterized. These interactions will be of particular concern when multiple power modules are networked. An experimental program plan is now being formulated which begins to address these interaction issues. The first effort will be to install and make operational a 1 kW FPSE/LA converter presently available at NASA-LeRC. Specific tests being considered for this converter include engine transient response, load reactance and non-linearity sensitivity effects, and fault protection. The experience gained from the 1 kW tests will be used to conduct similar tests on the 12.5 kW FPSE/LA power converter available at NASA-LeRC. The next step will be to install and make operational a second 1 kW FPSE/LA for the purpose of conducting multi-engine tests. The results and experience obtained from both the simulation studies and the experimental tests should develop the technology base required to establish the free piston Stirling power converter as a potential contender for high capacity power applications.

#### Power Circuits Task

The objective of this task is to investigate, develop and demonstrate high power inverter and converter circuit technology applicable to the Power Conditioning, Control, Transmission and Distribution (PCCTD) subsystem of a space nuclear power system. The specific mass and efficiency of the PCCTD are important technology drivers, but from a total systems's mass consideration, efficiency can be more of a driver than specific mass. Any inefficiency in the PCCTD requires higher input power for a specified bus power and this, of course, means increased source, power conversion and radiator mass, particularly, if any of these subsystems have a high specific mass. Even though efficiency and specific mass are very important converter and inverter design parameters, other design criteria are equally important in terms of useability, reliability, performance, and lifetime. These design criteria include circuit complexity and ease of control, component stresses, fault tolerance, transient and instability behavior, EMI, line and load regulation, power quality, and modularization capability.

The first step of the approach is to identify candidate inverter and converter circuit topologies that show promise of meeting the above mentioned criteria. The next step is to perform analysis and simulation studies that characterize the operating performance of these candidate topologies. This step also includes the experimental verification of these studies through the design, fabrication and testing of converters and

inverters with power levels of a few kilowatts. The final step is to utilize the results of step two to conduct comparative studies and experiments of DC and high frequency AC PCCTD subsystems.

Most of the work conducted under this task is being done under a University of Toledo grant. The major emphasis of this grant work has been on high power resonant type topologies that show promise of being highly efficient and reliable. Specific resonant circuits investigated and characterized include the cascade series-resonant and the resonant phase-controlled parallel-loaded and Mapham converters and inverters. A description of the analytical and experimental results for the cascade series-resonant converter is described in several papers (Shetler and Stuart 1989; and Ray and Stuart 1988) and in a patent granted to the University of Toledo (Stuart 1989). The use of the cascade series-resonant converter as the means to accomplish low to high voltage conversion is described by Stuart and Schwarze (1987) for a thermoelectric space power system. The design procedure for a phase-controlled parallel-loaded resonant converter is described by King (1989) along with verification by data taken on a laboratory 2.5 kVA, 20 kHz converter. The present grant work is focused on the analysis, design, and experimental verification of both voltage-fed and current-fed force-commutated DC/DC high power converters. After this research is completed, the grant effort will focus on a comparative study of both DC and high frequency AC PCCTD subsystems applicable to space power systems.

## CONCLUSION

The technology developed under the Power Management subelement of the CSTI High Capacity Power Program should help to advance the development of space power systems required for future NASA missions. Perhaps of equal importance to the development of the technology base is the development of a valuable experience base. The experience gained by all the participants who contribute to this technology base should be most useful in identifying any possible gaps in the technology base and in providing the technical resources needed to resolve future technical issues in the area of Power Management.

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