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SP-100 Advanced Technology Program

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SP-100 ADVANCED TECHNOLOGY PROGRAM

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E-3576

Abstract

The goal of the triagency SP-100 Program is to develop long-lived, compact, lightweight, survivable nuclear reactor space power systems for application to the power range 50 kWe to 1 MWe. The successful development of these systems should enable or significantly enhance many of the future NASA civil and commercial missions. The NASA SP-100 Advanced Technology Program strongly augments the parallel SP-100 Ground Engineering System Development program and enhances the chances for success of the overall SP-100 program. The purpose of this paper is to discuss the key technical elements of the Advanced Technology Program and the progress made in the initial year and a half of the Project.

Introduction

The NASA, DOD, and DOE triagency SP-100 Program has recently embarked on a major effort to demonstrate the technology readiness of nuclear reactor space power systems for space applications by 1992. This program is termed the SP-100 ground engineering system (GES) in which system safety and typical reactor and aerospace (conversion, heat rejection, etc.) performance and lifetime potential will be demonstrated. The NASA-managed advanced technology program (ATP) portion of the tri-agency Program is focussed on developing advanced aerospace technology that will greatly augment the initial SP-100 design capabilities.

As indicated in Fig. 1, the objectives of the ATP are to augment the GES development and testing of major components and to provide significant component and subsystem options for increased efficiency, survivability and growth at reduced weights and higher reliabilities. As is shown in Fig. 1, it is felt that the ATP can provide growth to the megawatt power levels with a factor of 2 to 3 increase in specific power, using the reactor developed in the GES Program. The above results were generated for a GES program focussed on a 300 kWe space power system. The Program was recently redirected to demonstrate the technology readiness of a 100 kWe system. Using this latter reactor($\sim$2.5 MW_t) the Advanced Technology Program offers the potential for a factor of 2 $\rightarrow$ 8 increase in efficiency, growth to 800 kWe and double the specific power, when operating at the design reactor outlet temperature of 1350 K. Or, the ATP can provide the design performance at reduced reactor outlet temperatures thus providing a back-up position should there be difficulties in attaining the 1350 K reactor outlet temperature. Even with the GES focus on the 100 kWe power system it is felt that the reactor and ATP efforts will provide the technology data base for growth to the megawatt power level. The key elements of the ATP and the progress to date will now be described.

The NASA Advanced Technology Program

The major elements of the NASA ATP are shown in Fig. 2. The Program is guided by an overall Missions and Systems Analysis Task to better define the specific power system requirements and quantify the benefits to be derived from the technology development. Technology development efforts are being carried out in the areas of Energy Conversion, Thermal Management, Power Conditioning and Control, Materials and Structures and Spacecraft Environmental Effects.

Advanced Energy Conversion

In the area of energy conversion development, efforts are on free piston Stirling engine and advanced thermoelectric technology development. These technologies will increase the GES baseline efficiency by factors of 2(thermoelectric) to 8(Stirling) with concomitant reductions in overall system mass. The objectives and approach for the free piston Stirling engine project are shown in Fig. 3. The performance numbers (100 W/kg) are for the 300 kWe GES design.

In this project to date we have successfully completed testing of the 25 kWe Space Power Demonstration Engine. The Engine developed 25 kW of internally generated (PV) power which was 91 percent of the predicted value. However, due to problems with eddy current flows in the linear alternator, the electrical power output was 17 kWe or only 70 percent of the predicted power. Independent tests are now being run to bring the alternator efficiency to its 93 percent efficient design point. Upon completion of the SPDE testing, the opposed piston engine was cut in half and two 12.5 kWe Space Power Research Engines (SPRE) are being tested. By reducing the SPRE expansion space volume and making tighter dispacer clearance, the performance shown in Fig. 4 was attained. The figure shows that there is good agreement between the engine performance and code predictions. The SPRE has also produced 12.4 kW of PV power at partial piston stroke and should produce over 16 kW of PV power at full piston stroke operation. This performance exceeds the original predicted value of PV power. Other Stirling accomplishments are given in Fig. 5.

The original objectives and approach for the advanced thermoelectric tasks are shown in Fig. 6. The effort was originally focussed on the development of rare earth chalcogenide "p" leg thermoelectric materials to provide a high figure-of-merit when used with previously developed rare earth "n" legs.

We have completed screening of the "p" type rare earth compounds and have concluded that the success potential for developing these materials is quite limited. However, in recent experiments at the Jet Propulsion Laboratory, samples of a silicon-germanium thermoelectric material doped with gallium phosphide have been produced that demonstrate a considerable improvement in figure-of-merit over standard silicon-germanium. These results appear to be a function of annealing time and temperature. A typical set of results for an annealing temperature of 1475 K, "n" leg material is shown in Fig. 7. The research effort is being redirected to exploit this promising development, focusing on a systematic analytical and experimental program, aimed at developing a basic understanding of these processes and developing higher performance thermoelectric devices that are stable and repeatable.

Thermal Management

The objectives and approach to the thermal management task is shown in Fig. 8. The accomplishments to date are summarized in Fig. 9. We have initiated a contracted study of advanced radiator concepts for the GES reference thermoelectric system and an advanced Stirling system. A detailed heat pipe code has been developed and will be used to guide a new high temperature heat pipe development effort. Tungsten fiber reinforced niobium composites (ST300-W/Nb) have been produced with significant increases in strength/weight ratio over the GES reference niobium-1-zirconium refractory. In addition surface modification techniques have been developed that provide emissivities that exceed the 0.85 GES reference design value without the use of coatings.[1] The results for similiar treatments of the niobium-1-zirconium reference design material are shown in Fig. 10.

Power Conditioning and Control

The objectives and approach for the advanced power conditioning and control tasks are shown in Fig. 11. The main thrust of the task is develop high temperature (500 to 600 K), radiation tolerant systems for the GES reference and advanced Stirling systems. The development of these systems will allow multiorbit operation and reduce the shield and power conditioning waste heat radiator masses. The accomplishments are summarized on Fig. 12. Briefly, we have exposed commercial solid state switches to gamma and neutron fluxes and seen a definite degradation in direct current gain under either source of radiation. We have demonstrated the potential for high temperature, gigarad tolerant solid state switches using deep impurity double injection devices and have identified a development program for low voltage high power inverters.

Materials and Structures

The objectives and approach for the materials and structures task are shown in Fig. 13. In general the focus is on developing advanced refractory and/or composite materials for the reactor, radiator, and structures with increased strength and/or lighter weight. The successful development of these materials will reduce the mass of the overall power system, or provide increased reliability and survivability through increased design margin in the materials properties. These materials could also be enabling for the power system should there be shortcomings in the GES development goals. There have been many accomplishments made in the materials area. The niobium-1-zirconium creep strength data base is being established, the tungsten reinforced niobium material composite mentioned earlier is being developed, material needs for high temperature Stirling Engines have been identified and microstructure analyses have been made in support of the thermoelectric task. Two other areas will be highlighted in this paper. NASA Lewis has continued to develop the data base on the niobium-1-zirconium -0.1 percent carbon refactory alloy PWC-11. This alloy could provide some design margin over the GES reference material. The results for the stress level at 1350 K for 1 percent strain in 7 yr are shown for a variety of conditions on Fig. 14. The figure shows the change in creep strength for the various conditions. One should note, however, that for all conditions the PWC-11 is far superior to the niobium-1-zirconium. Results for a graphite fiber reinforced copper matrix composite being developed for space radiators are shown in Fig. 15. The material is seen to demonstrate a significant improvement in the thermal conductivity/density ratio over the reference niobium-1-zirconium material and could lead to significant reductions in radiator mass.

Spacecraft Environmental Effects

The objectives and approach for the spacecraft environmental effects task are shown in Fig. 16. In general the effort is focussed on identifying potential interactions and failure modes, and developing mitigation techniques and design guidelines to ensure 10 to 15 yr life under the mission-specific environmental conditions. The accomplishments to date are shown in Fig. 17. Typical materials have been exposed to atomic oxygen and mitigation techniques identified. All SP-100 reference materials are to be flown on a space flight experiment and a study of the SP-100 specific interactions has been initiated.

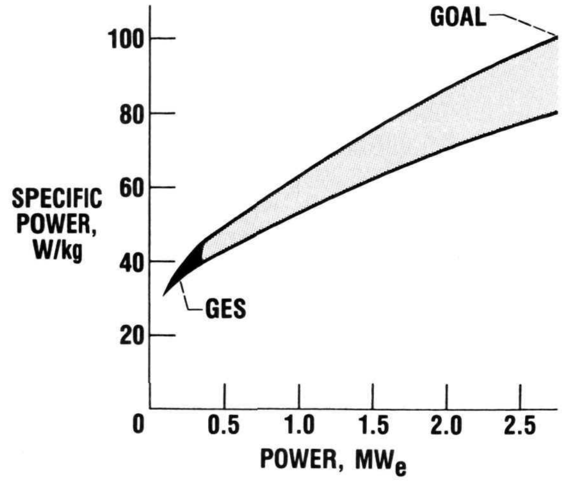
Conclusions

The SP-100 Advanced Technology Program is a broad-based Program with a high payoff potential. The Program supports all non-nuclear aspects of the SP-100 GES reference system and some of the materials research could provide some design margin to the reactor. It is felt that significant accomplishments have been made in the initial year and a half of the Program.

[1]The results on Fig. 9 are for stainless steel.

OBJECTIVE:

- TO AUGMENT GES ENGINEERING DEVELOPMENT AND GROUND TESTING OF MAJOR COMPONENTS
- TO PROVIDE SIGNIFICANT COMPONENT/SUBSYSTEM OPTIONS FOR INCREASED EFFICIENCY, SURVIVABILITY AND GROWTH AT REDUCED WEIGHTS AND HIGHER RELIABILITIES



GOAL

100 W/kg, 2.5 MW_e IN 1 SHUTTLE USING GES REACTOR

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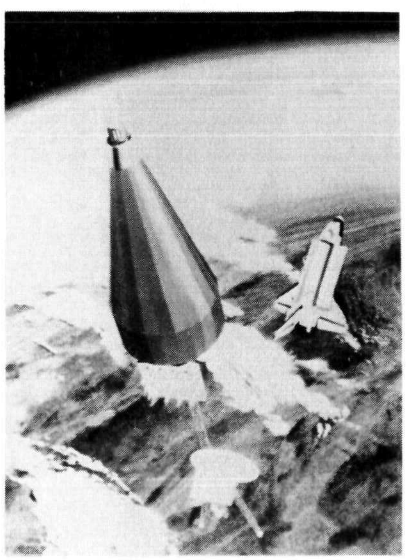
FIGURE 1. - NASA SP-100 ADVANCED TECHNOLOGY PROGRAM.



- MISSION ANALYSIS & REQUIREMENTS
- SYSTEMS ANALYSIS
- ADVANCED CONVERSIONS
  —STIRLING, THERMOELECTRIC
- THERMAL MANAGEMENT
  —RADIATORS, HEAT EXCHANGERS
- POWER CONDITIONING & CONTROL
  —HIGH TEMP/RAD HARD, 20 kHz
- MATERIALS & STRUCTURES
  —W FIBER REINFORCED Nb/1Zr
  —GRAPHITE FIBER REINFORCED Cu
- SPACECRAFT ENVIRONMENTAL EFFECT
  —ATOMIC OXYGEN, SPACE PLASMA

FIGURE 2. - NASA SP-100 ADVANCED TECHNOLOGY PROGRAM.

OBJECTIVE:

- **DEMONSTRATE THE TECHNOLOGY NECESSARY TO PROCEED INTO THE FINAL DEVELOPMENT OF SPACE-QUALIFIED FREE PISTON STIRLING ENGINES TO MEET FUTURE MISSION NEEDS**
- **POTENTIAL FOR 100 W/kg AND 2.5 MW_e**

APPROACH:

- **SEQUENTIAL TESTING OF THREE ENGINES — 650 K, 1075 K, 1350 K**
- **COMPONENT DEVELOPMENT**
- **BASIC RESEARCH-CODE DEVELOPMENT AND VALIDATION**

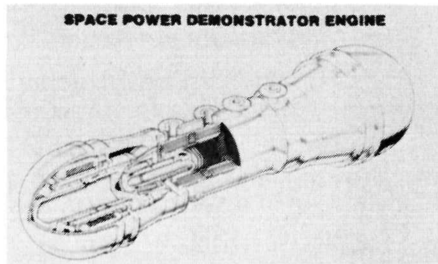


FIGURE 3. - ADVANCED CONVERSION - STIRLING ENGINES.

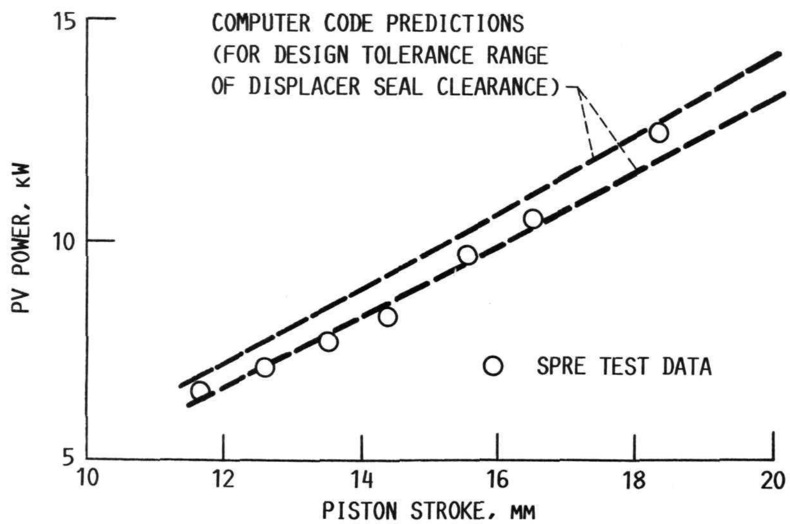


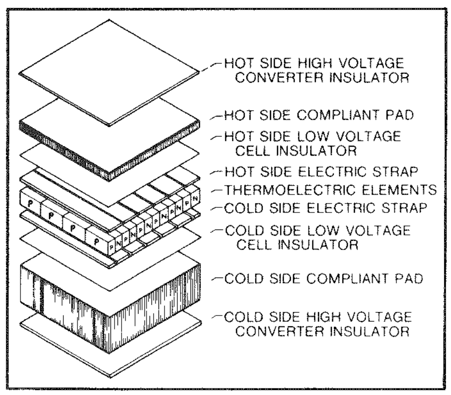
FIGURE 4. - SPRE PERFORMANCE VERSUS PISTON STROKE. ENGINE PRESSURE, 150 BAR; TEMPERATURE RATIO, 2.

- **SUCCESSFULLY TESTED FIRST SPIN LUBRICATED HYDRODYNAMIC BEARING**
  - **LONG LIFE**
- **PRELIMINARY DESIGN OF SIMPLER, PROTOTYPICAL SPACE STIRLING ENGINE (SSE) IN PROGRESS**
  - **1075 K**
  - **25 kW_e PER PISTON**
- **CODES UPDATED AND VALIDATED USING EXPERIMENTAL RESULTS**
  - **SCALING STUDIES**
- **BASIC RESEARCH INITIATED**
  - **LINEAR ALTERNATOR**
  - **OSCILLATING FLOW**
  - **BEARINGS**

FIGURE 5. - STIRLING ACCOMPLISHMENTS.

OBJECTIVE:

- **DEVELOP THE TECHNOLOGY FOR SIGNIFICANTLY IMPROVED ADVANCED THERMOELECTRIC POWER SYSTEMS (Z = 1.4, EFFICIENCY = 14%)**
- **POTENTIAL FOR 75 W/kg AND 1.9 MW_e**



APPROACH:

- **FOCUS ON 'p' LEG - SCREEN MATERIALS**
- **PROPERTY EVALUATION AND MATERIALS CHARACTERIZATION**
- **BASIC RESEARCH AND CODE DEVELOPMENT**
- **PROTOTYPICAL STACKS**
- **STABLE HIGH Z CONDUCTIVE COUPLE**

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FIGURE 6. - ADVANCED CONVERSION - THERMOELECTRICS.

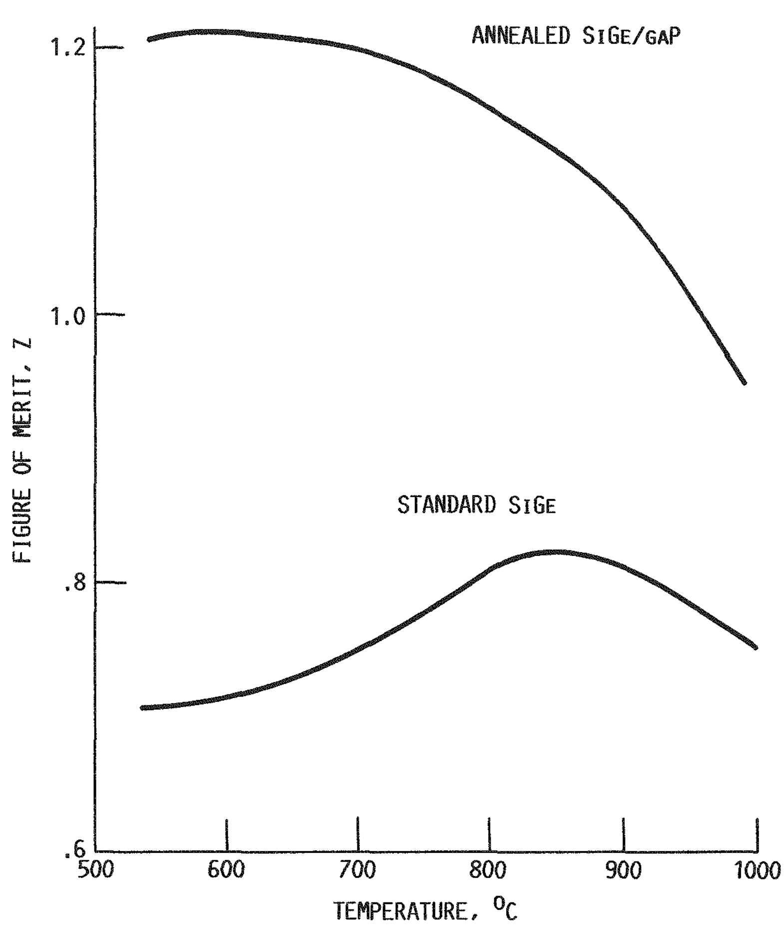
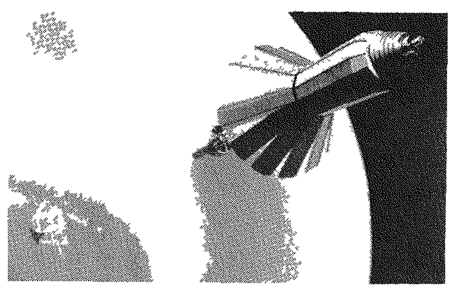


FIGURE 7. - PERFORMANCE IMPROVEMENT OF SiGe/GaP ALLOYS.

OBJECTIVE:

- **DEMONSTRATE THE TECHNICAL FEASIBILITY OF ADVANCED LIGHT-WEIGHT, SURVIVABLE, DEPLOYABLE RADIATOR CONCEPTS**
- **300 kW_e, <5 kg/m^2**
- **1/2 GES SPECIFIC MASS**



APPROACH:

- **IDENTIFY AND DEMONSTRATE VIABILITY OF ADVANCED RADIATOR CONCEPTS**
- **ADVANCED HEAT PIPES**
  - **— CODE DEVELOPMENT**
  - **— TESTING**
- **MATERIALS AND BASIC PHYSICS RESEARCH**

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FIGURE 8. - THERMAL MANAGEMENT.

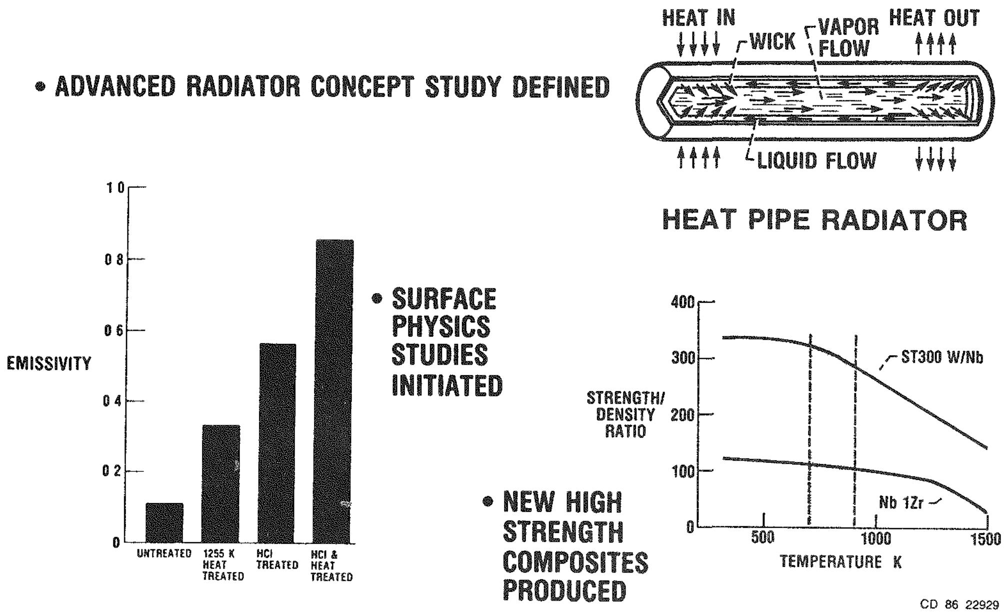


FIGURE 9. - THERMAL MANAGEMENT ACCOMPLISHMENTS.

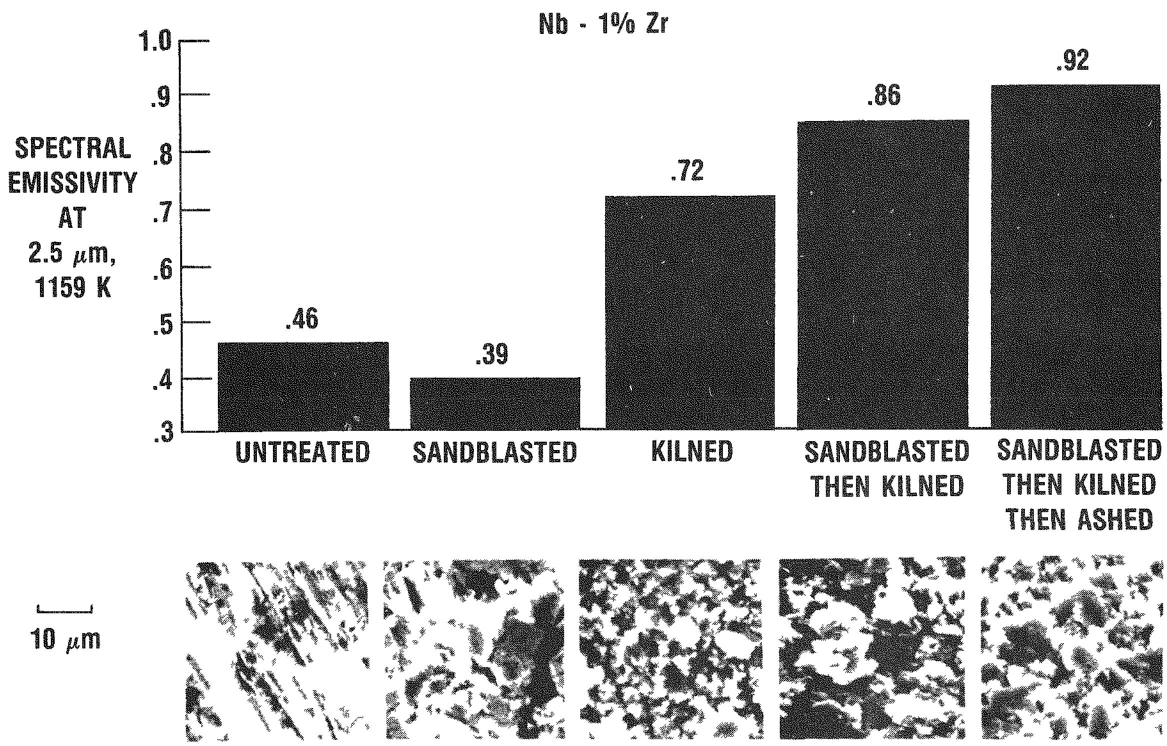
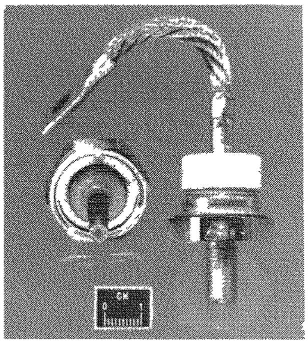


FIGURE 10. - RADIATOR SURFACE MODIFICATION FOR HIGH EMISSIVITY.

OBJECTIVE:

- **DEVELOP THE TECHNOLOGY FOR HIGH POWER, HIGH TEMPERATURE, RADIATION RESISTANT POWER CONDITIONING, CONTROL AND TRANSMISSION IN ADVANCED SP-100 SPACE POWER SYSTEMS**
  - **— 100 kW_e→1 MW_e**
  - **— 500 - 600 K**
  - **— >1 MEGARAD**



APPROACH:

- **COMPONENT DEVELOPMENT AND TESTING**
- **SYSTEMS SIMULATION**
- **CIRCUIT-SYSTEM DEVELOPMENT**
- **SPECIAL APPLICATIONS**

FIGURE 11. - ADVANCED POWER CONDITIONING AND CONTROL.

- **γ - IRRADIATION OF HI-POWER TRANSISTOR SWITCHES TO 2 MEGARADS**
- **γ - IRRADIATION OF $(DI)^2$ CHIP TO 1 GIGARAD WITH MINOR IMPACT ON ELECTRICAL CHARACTERISTICS**
  - **- CODE DEVELOPMENT**
  - **- PROCESSING**
- **COMPUTER SIMULATION PROGRAMS IN PLACE**
- **STIRLING LINEAR ALTERNATOR**
- **NEUTRON IRRADIATION**

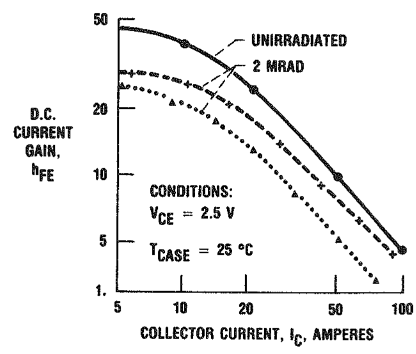
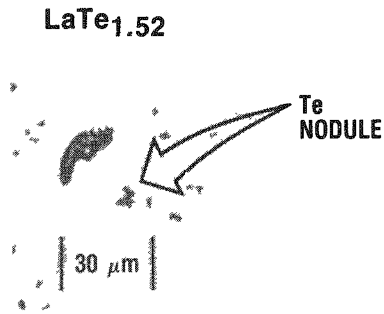


FIGURE 12. - POWER CONDITIONING AND CONTROL - ACCOMPLISHMENTS.

OBJECTIVE:

- EXTEND THE BASIC UNDERSTANDING AND MATERIALS TECHNOLOGY DATA BASE FOR ADVANCED NUCLEAR SPACE POWER SYSTEMS
- INCREASED STRENGTH, LIGHTWEIGHT SURVIVABLE, RELIABLE
- IMPROVED CONVERSION



APPROACH:

- BASIC RESEARCH
  - FABRICATION, JOINING, PROPERTIES
- APPLIED TECHNOLOGY
  - RADIATOR, STRUCTURES, CONVERSION SYSTEMS

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FIGURE 13. - MATERIALS AND STRUCTURES.

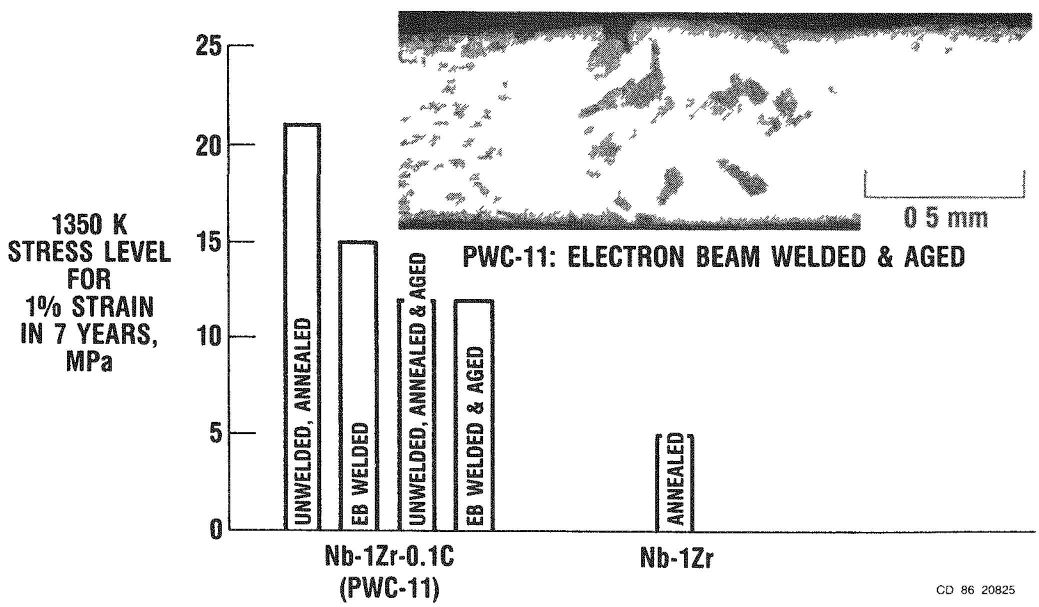
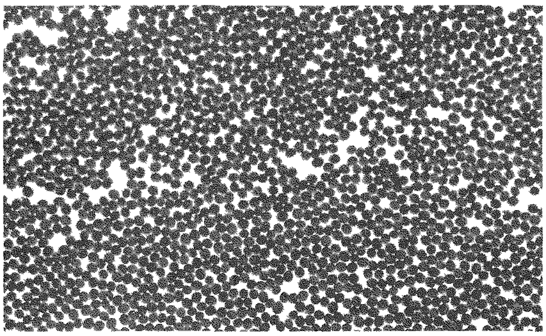


FIGURE 14. - PWC-11 AFTER WELDING AND AGING TREATMENT OFFERS 2.5X STRENGTH ADVANTAGE OVER Nb-1Zr.

- HIGH THERMAL CONDUCTIVITY
- HIGH MODULUS OF ELASTICITY
- HIGH ULTIMATE TENSILE STRENGTH
- HIGH TEMPERATURE OPERATION

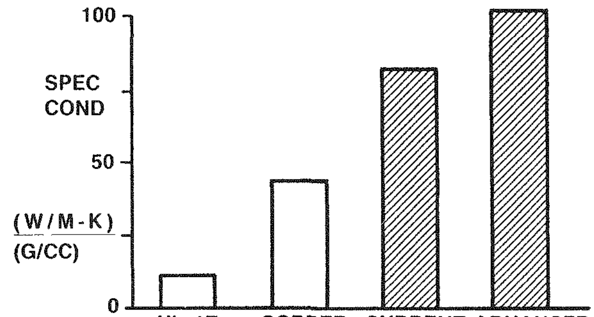
- LOW DENSITY

MICROSTRUCTURE
OF GRAPHITE/COPPER COMPOSITE



FABRICATED AT LEWIS RESEARCH CENTER

PROJECTED
THERMAL CONDUCTIVITY/DENSITY RATIOS

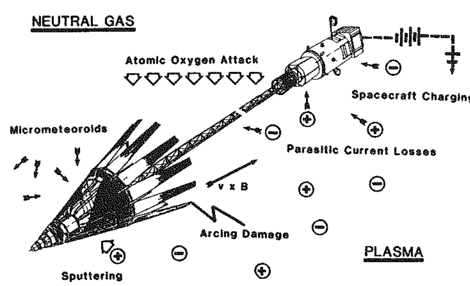


ADVANTAGES OF GRAPHITE/COPPER COMPOSITES OVER Nb-1Zr ALLOY:
- 15-FOLD INCREASE IN SPECIFIC THERMAL CONDUCTIVITY
- 7-FOLD INCREASE IN SPECIFIC MODULUS

RESULTING IN LIGHTER, STIFFER STRUCTURE WITH INCREASED SURVIVABILITY

FIGURE 15. - GRAPHITE FIBER REINFORCED COPPER MATRIX COMPOSITES FOR SPACE POWER RADIATOR PANELS.

OBJECTIVE:
- **DEMONSTRATE CAPABILITY OF SP-100 SYSTEMS TO OPERATE FOR 7-10 YEARS IN SPACE ENVIRONMENT**
- **TEMPERATURE, VOLTAGE**



APPROACH:
- **IDENTIFY INTERACTIONS AND FAILURE MODES**
  - **ATOMIC OXYGEN, PLASMA, METEOROIDS, CHARGING**
  - **GROUND AND FLIGHT TESTS**
  - **COMPUTER MODELING**
- **MITIGATION TECHNIQUES**
  - **GUIDELINES**
  - **COATINGS**

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FIGURE 16. - SPACECRAFT ENVIRONMENTAL EFFECTS.

- ATOMIC OXYGEN EXPOSURE
  - COATINGS
  - REFRACTORIES
- MATERIALS SAMPLES PREPARED FOR FLIGHT EXPERIMENT
  - EOIM
  - REFRACTORIES, COATINGS, TRANSMISSION CABLE
- DEFINED AND IMPLEMENTED CONTRACTOR EFFORT TO ASSESS IMPACT OF SPACE ENVIRONMENT INTERACTIONS ON REFERENCE SP-100 DESIGN

FIGURE 17. - SPACECRAFT ENVIRONMENTAL EFFECTS - ACCOMPLISHMENTS.

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