SP-100 Advanced Technology Program

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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.

Abstract

The NASA Advanced Technology Program is focused on developing advanced aerospace technology that will greatly augment the initial SP-100 design capabilities.

Introduction

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 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 kW Space Power Demonstration Engine. The Engine developed 25 kW of internally generated (PV) power at 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 kW 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 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 ($1300$-$WNb$) 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. The results for similar 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 advanced Stirling systems. The development of these systems will allow multi-orbit 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 and 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 refractory alloy $PNC-11$. 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 PNC-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.
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

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.

![Computer Code Predictions](image)

**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 kWₑ 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 MWₑ

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

FIGURE 6. - ADVANCED CONVERSION - THERMOELECTRICS.
OBJECTIVE:
• DEMONSTRATE THE TECHNICAL FEASIBILITY OF ADVANCED LIGHT-WEIGHT, SURVIVABLE, DEPLOYABLE RADIATOR CONCEPTS
• 300 kW, <5 kg/m²
• 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

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

FIGURE 8. - THERMAL MANAGEMENT.
ADVANCED RADIATOR CONCEPT STUDY DEFINED

- SURFACE PHYSICS STUDIES INITIATED
- NEW HIGH STRENGTH COMPOSITES PRODUCED

FIGURE 9. - THERMAL MANAGEMENT ACCOMPLISHMENTS.

Nb - 1% Zr

SPECTRAL EMISSIVITY AT 2.5 μm, 1159 K

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 kWₑ–1 MWₑ
  - 500 – 600 K
  - >1 MEGARAD

APPROACH:
- COMPONENT DEVELOPMENT AND TESTING
- SYSTEMS SIMULATION
- CIRCUIT-SYSTEM DEVELOPMENT
- SPECIAL APPLICATIONS

FIGURE 11. - ADVANCED POWER CONDITIONING AND CONTROL.

- \( \gamma \) - IRRADIATION OF HI-POWER TRANSISTOR SWITCHES TO 2 MEGARADS
- \( \gamma \) - 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

FIGURE 13. — MATERIALS AND STRUCTURES.

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

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.
**Title and Subtitle**

SP-100 Advanced Technology Program

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**Abstract**

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**Key Words (Suggested by Author(s))**

Stirling; Thermoelectrics; Refractory materials; Composites; Emissivity; Space environment; Thermal management; Power conditioning and control

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