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The NASA CSTI High Capacity Power Program

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THE NASA CSTI HIGH CAPACITY POWER PROGRAM

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Abstract

The SP-100 program was established in 1983 by DOD, DOE, and NASA as a joint program to develop the technology necessary for space nuclear power systems for military and civil applications.

During 1986 and 1987, the NASA Advanced Technology Program was responsible for maintaining the momentum of promising technology advancement efforts started during Phase I of SP-100 and to strengthen, in key areas, the chances for successful development and growth capability of space nuclear reactor power systems for future space applications.

In 1988, the NASA Advanced Technology Program was incorporated into NASA's new Civil Space Technology Initiative (CSTI). The CSTI program was established to provide the foundation for technology development in automation and robotics, information, propulsion, and power. The CSTI High Capacity Power Program builds on the technology efforts of the SP-100 program, incorporates the previous NASA advanced technology project, and provides a bridge to the NASA exploration technology programs.

The elements of CSTI high capacity power development include conversion systems—Stirling and thermoelectric, thermal management, power management, system diagnostics, and environmental interactions. Technology advancement in all areas, including materials, is required to provide the growth capability, high reliability and 7 to 10 years lifetime demanded for future space nuclear power systems. The overall program will develop and demonstrate the technology base required to provide a wide range of modular power systems while minimizing the impact of day/night operation as well as attitudes and distance from the Sun.

Significant accomplishments in all of the program elements will be discussed, along with revised goals and project timelines recently developed.

Introduction

The CSTI program, conceived by NASA's Office of Aeronautics and Space Technology as a first step in the revitalization of the U. S. civil space technology base, emphasizes technology developments considered essential for reliable and efficient access to and operations in low Earth orbit, as well as for support of advanced scientific space mission operations. The goal of the CSTI program is to produce a validated space technology base in selected areas. Exploiting progress already made in NASA's Space Research and Technology program, CSTI is directed at specific technology advances in (1) transportation, (2) operations, and (3) science. The High Capacity Power Program Element is one of several space technologies considered essential to successful accomplishment of potential future civil space mission objectives.

A wide range of potential future civil space missions have been identified which could be enabled or substantially enhanced by the use of nuclear reactor power and propulsion. The identified power requirements can range from tens of kilowatts of electrical power required for support of robotic deep-space science missions, to the many hundreds of kilowatts or megawatts of electrical power required to support sustained human lunar and planetary surface operations as well as the very high powered nuclear propulsion systems that would be needed for round-trip crew transfer and large-scale planetary cargo options.

The CSTI High Capacity Power (HCP) Program element complements the ongoing Tri-Agency (DOD/DOE/NASA) SP-100 program, which is directed toward the development and validation of technology for a versatile space nuclear reactor power system with the capability to generate tens to hundreds of kilowatts of electrical power for at least 7 years at full power. The HCP program is aimed at identifying and providing options for achieving significantly higher performance and system growth potential, sizably reduced mass, and longer lifetimes

at acceptable systems reliability for civil space applications. The objective of the HCP program is to develop the advanced technology for improved static and dynamic conversion systems, which when coupled with the nuclear reactor technology being developed in the SP-100 program, will meet civil space program goals. The systems benefits accruing from the HCP program are illustrated in Fig. 1. The SP-100 reactor system using thermoelectrics to produce 100 kW of power, is itself a significant advance in size and power density at 22 W/kg. NASA's current nuclear power systems, radioisotope thermoelectric generators, are long lived and reliable, but are restricted to power on the order of 1 kWe by cost and mass considerations (5 W/kg). Advanced thermoelectrics can enhance both RTG's and SP-100 performance—to 27 W/kg in the CSTI HCP program, and beyond in the base R&T effort underway at JPL. Stirling power conversion, coupled to the SP-100 heat source, can advance power and power density in two technology steps, 1050 and 1300 K, as illustrated in Fig. 1. The baseline CSTI program will develop the 1050 K superalloy Stirling space technology, while the Exploration Technology Program, scheduled for initiation in 1993, will carry on the development required, to reach the 1300 K refractory Stirling goal in 1999, based upon the technology developed earlier at 1050 K. Stirling/nuclear power capability will enable applications such as the lunar base shown in Fig. 2, presently envisioned as requiring 550 kWe. Reference 1 presents the details of the design illustrated in Fig. 2. Other possible applications for Stirling space power in the multihundred kilowatt range include electric propulsion power for science and unmanned cargo missions to the outer planets, power for air and ocean radar traffic control systems, high power communication platforms, Earth observing platforms, and in-space materials processing facilities. Reference 2 provides a description of potential future civil space missions that could be enabled or substantially enhanced by the use of nuclear reactor power.

Project Management

The elements of CSTI HCP development include Stirling and thermoelectric conversion systems, thermal management, power management, system diagnostics and environmental interactions. Technology advancements in all areas, including materials, is required to meet the performance goals of Fig. 1 and to attain the high reliability over the

7 to 10 years lifetime demanded for future space nuclear power systems.

The funding planned for the baseline HCP project is listed by element in Table 1. Including prior years, total funding is about \$61 million. The major milestones and activities covered by this funding are shown on Fig. 3. The project culminates in a 1050 K Stirling system test in 1996, demonstrating all the relevant power conversion elements needed to produce electrical power from the SP-100 reactor heat source.

The project personnel level during FY91 is about 50 civil servants and 16 support service contractors at NASA Lewis plus 2-1/2 full time staff members at JPL.

The High Capacity Power Project has undergone significant changes since the IECEC paper given in 1989 (Ref. 3). Funding has been extended for 2 years (1995 and 1996), a 1050 K Stirling system test has been added, and the thermoelectric development is scheduled to be halted in FY94, after a $Z = 1.0 \times 10^{-3} \text{ K}^{-1}$ has been developed and the $Z = 0.85 \times 10^{-3} \text{ K}^{-1}$ has been carried through the multicouple demonstration phase. Advancing thermoelectric figure of merit (Z) beyond 1.0 will be funded from other sources. The 1300 K Stirling system demonstration, scheduled for 1999, will be funded under the Exploration Technology Program, now scheduled to start in FY93.

Stirling Power Conversion

The 1050 K superalloy Stirling power converter development is proceeding as outlined on Fig. 4. Results of the most recent 650 K space power research engine (SPRE) development at NASA Lewis and MTI are given in Ref. 4. The component test power converter (CTPC) is intended to develop the 525 K cold end technology and the 1050 K hot end technology at the 12.5 kWe size. The 25 kWe 1050 K, single cylinder superalloy space Stirling power converter will be tested in FY93, improved during FY94 and 95, then proven in a system test during FY96. Elements of the system to be included are given in the highlighted section of the nuclear Stirling diagram of Fig. 5.

The most recent results are the successful motoring of the CTPC at temperatures up to 400 K with internally pumped gas bearings over the full

operating range. Figure 6 shows the CTPC cold end hardware. The Stirling contract effort at MTI is supported by a wide range of NASA Lewis in-house testing as well as University grants and materials development.

Thermoelectronics

The Advanced Thermoelectric Project being carried out at JPL has been significantly changed by results obtained recently. The n-type SiGe/GaP can now be fabricated with $Z = 0.8$ to $0.9 \times 10^{-3} \text{ K}^{-1}$ in an overdoped condition. Heat treatments are being developed to achieve $Z = 1.0 \times 10^{-3} \text{ K}^{-1}$ for these samples. Figure 7 gives the results showing nine samples with Z between 0.85 and $1.0 \times 10^{-3} \text{ K}^{-1}$. The p-leg Z will be increased to 0.70 to $0.75 \times 10^{-3} \text{ K}^{-1}$ by adding inert scattering centers (50 to 100 Å in size) to reduce the thermal conductivity. The status of this work is given on Fig. 8. Once the inert scattering centers are proven for the p-leg, the method will be applied to the n-leg and the resulting increase should result in a combined $Z = 1.0 \times 10^{-3} \text{ K}^{-1}$ over the temperature range of interest. In the meantime, modules and multicouples will be on test to demonstrate the $Z = 0.85 \times 10^{-3} \text{ K}^{-1}$ SiGe/GaP as required to meet the SP-100 performance specification. The thermoelectric development project plan is depicted in Fig. 9.

Advanced Materials

Materials development is necessary to assure the success of all advanced power systems. A comprehensive program is underway at NASA Lewis to develop composite radiator fin materials (covered under Thermal Management), advanced refractory materials, and advanced refractory composites. In addition, a data base must be developed to qualify all critical materials of construction at their design operating conditions. Materials include PWC-11, IN-718, U-720, Gr/Cu, W/Nb, and MoHfC/Nb. Long term stability of PWC-11 has been proven (Fig. 10) as has the strength advantage of properly produced alloy compared to both Nb-1Zr and out-of-spec alloy (Fig. 11). A plan for the development of PWC-11 has been proposed by NASA Lewis to the SP-100 Interface Control Board and is shown in Fig. 12.

Refractory wire reinforced composites provide another significant increase in strength over PWC-11, as illustrated in Fig. 13. Tungsten lamp filament wires and MoHfC wires are under consider-

ation as reinforcement for a Nb matrix. The elements and the plan for refractory composite development are given in Fig. 14.

Materials under consideration for Stirling power converter construction include Inconel-718 and Udimet-720 at 1050 K and a list of refractory materials for the 1300 K Stirling (Table 2). While the refractory Stirling will not be completed under the baseline program, the technology groundwork and initial system designs need to be in place to allow timely completion of the program.

Thermal Management

The goal of the thermal management effort is to develop heat input and heat output concepts optimized for both static and dynamic power conversion systems using nuclear heat sources. Specific goals include no single point failures, and development of low mass high efficiency components such as pumps, heat exchangers and radiators. Specific goals for radiators include 5 kg/m^2 specific mass, survivability up to 10 years in the space environment, at 0.99 probability level.

The thermal management project plan is shown in Fig. 15. The advanced radiator concepts contracts are in Phase IV—developing subsystems for an 875 K concept for thermoelectric conversion and a 600 K concept for Stirling conversion. Space Power Incorporated is developing a LiNaK pumped loop system for 600 K applications. The loop, with cooling fins in place, will be demonstrated in a simulated space environment during Phase IV. Rockwell International is developing a carbon-carbon structure wherein the fin and heat pipe is an integrated structure and a metallic liner is inserted for heat pipe fluid containment. For the thermoelectric conversion rejecting heat at 875 K, the fluid is potassium and the liners are titanium or niobium. The fin structure methods are developed (Fig. 16) and liner structures with braze materials have been identified.

The high conductivity composite fin development at NASA Lewis is outlined on Fig. 17. The objective is to produce a composite Gr/Cu fin attached to a titanium heat pipe to operate in the 475 to 500 K temperature regime. Composite fins have been produced, tailoring of the coefficient of thermal expansion is underway, and braze materials and techniques have been selected for attachment of the two.

Another development for water heat pipes is the fiber-fabric concept at DOE/PNL. The fabric is used to contain the high working fluid (H_2O) pressure at 475 to 500 K, and also to provide protection against meteoroid and debris penetration. An 0.025 titanium liner/Nextel fabric heat pipe is under test at NASA Lewis. The next generation 0.0025 in. thick titanium liner with carbon fabric is in production at PNL.

A significant effort at NASA Lewis is the enhancement of radiator surface emissivity through surface morphology changes. Some results of atomic oxygen texturing on carbon-carbon composites are presented in Fig. 18. Arc texturing of copper at 12 to 15 A and 20 to 100 Hz produced an emittance of 0.83 at 550 K. Tests presently underway will determine the durability of the texturing and the stability of any surfaces particles in residence after texturing.

Power Management

Power Management is the link between the electrical power source and the user. The work under CSTI High Capacity Power in FY91 has concentrated on three tasks: (1) power conditioning for a free piston Stirling power converter, (2) radiation effects on semiconductor power switches, and (3) temperature and frequency effects on soft magnetic materials.

Reference 5 presents recent results on the dynamic analyses of free-piston Stirling Engines. A test laboratory at NASA Lewis is currently operating a SPIKE engine (1 kWe free-piston) to determine the influence of ac and dc loads on engine/alternator dynamic behavior and controllability. The first system test was recently completed and control system characterization is proceeding. Four SPIKE engines are available to include multiple engine synchronization and control in the test series.

Commercial semiconductor power switches have been evaluated for radiation effects at the SP-100 user-interface specified values of 0.5 Mrad gamma and $10^{13} n/cm^2$ fluence. Of the power devices tested to date, phase-controlled and inverter-type thyristors seem best suited for the SP-100 application. At $2 \times 10^{13} n/cm^2$ fluence, however, the thyristors deteriorate and temperatures to 360 K do not anneal the damage. SiC devices are under development at NASA Lewis with the goal of

500 K temperature capability as well as resistance to radiation effects.

Reference 6 gives temperature and frequency effects on soft magnetic materials. Both crystalline and amorphous materials have been investigated at frequencies to 50 kHz and temperatures to 575K. References 7 and 8 give results to date.

System Diagnostics

Space power systems require electrical current sensors which are immune to electromagnetic interference and static discharge effects. Fiber-optic sensors can meet both requirements and are also lightweight and can be placed at reasonable distances from central electronics.

A fiber-optic current sensor, initially developed in 1990, needed improved vibration tolerance and better accuracy over a wider temperature range. The improved sensor, developed at NIST, is ready for testing at NASA Lewis to verify the accuracy of ± 1 percent full scale over a -65 to 125 °C temperature range with vibration tolerance of 18 g random and 20 g sinusoidal from 5 to 2000 Hz.

The fiber-optic voltage sensor, also under development at NIST, is still sensitive to vibration. Single mode fibers are being applied to both input to the sensor head and output to solve the vibration problem.

Reference 9 gives an update on both current and voltage sensor development.

Environmental Interactions

Space systems of the future will be larger, longer-lived, and higher powered. They must operate predictably and reliably in their total environment and be compatible with user requirements. Systems involving nuclear power generation in the range of 10 to 1000 kWe are under consideration for lunar and planetary power supplies. Interactions with lunar and Martian dust as well as the Martian atmosphere need to be understood. Large power systems above 1 MWe for nuclear electric propulsion, will interact strongly with the plasma and field environments, both natural and system generated. The high voltages anticipated for high power systems may also induce electrical breakdown of neutral gases. Electric thrusters will generate neutral and

low energy plasmas as well as the primary beam, which will contribute significantly to the local environment.

S³ corporation performed the first computer simulation of the SP-100 configuration with NASCAP/LEO and NASCAP/POLAR to determine interactions with the space plasma. Mitigation strategies were developed in conjunction with GE (SP-100 Contractor) to alleviate possible problems at the joint between the user and the spacecraft. The computer code is being extended to cover interplanetary space. As time and funding allow, simulations of nuclear electric propulsion systems will be done, as well as simulation of lunar and Martian dust and the Martian atmosphere.

Samples of interest to SP-100 and the CSTI High Capacity Power Program will be flown on the Effects of Oxygen Interactions on Materials (EOIM-3) experiments scheduled for STS-46 in June 1992. The space flight results will be correlated with theory and with ground experiments based upon previous results and a Kapton "standard sample" flown on all experiments. Samples selected for flight test include refractory metals Nb-1Zr, Mo-13Re, PWC-11, radiator coating, superalloys for Stirling, spacecraft structural materials 6061-T6A, 304SS, and SP-100 multilayer insulator materials W thin film/A1, Mo thin film/A1.

Summary

The NASA CSTI High Capacity Power Program is a broad-based effort to provide significant improvements in the technology associated with space nuclear power and its relationship with the mission environment. The inherent advantages of nuclear reactor power—compactness, high power at low mass, long life and reliability—must be coupled with aerospace technology which can capitalize on these advantages. The CSTI High Capacity Power Program supports and advances all the nonnuclear aspects of the national SP-100 Space Nuclear Reactor Program. The project described herein will provide a technology demonstration of a 1050 K Stirling space power system, and lay the groundwork for a 1300 K Stirling space power system to utilize the full capability of the SP-100 reactor. In addition, the thermoelectric technology to demonstrate the $Z = 0.85 \times 10^{-3} \text{ K}^{-1}$ design goal will be established and the capability to reach $Z = 1.0 \times 10^{-3} \text{ K}^{-1}$ with

SiGe/GaP will be demonstrated. The focused nature of the project will ensure that the technology advances are in place by the late 1990's so that NASA's long-term goals in civil space exploration and exploitation may be achieved.

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TABLE 1. - CSTI HIGH CAPACITY POWER

[Baseline funding estimate - \$k.]

Element number	Program element	FY90	FY91	FY92	FY93	FY94	FY95	FY96	
11	Conv. system for nuclear application								
	11-1 Stirling	5825	5726	5522	2257	2310	2494	2511	(a)
	11-2 Thermolectrics	800	400	600	300	300	----	----	
21	Thermal management	1800	1391	1265	600	600	700	800	(a)
31	Power management	250	100	200	100	100	100	100	(a)
41	Systems diagnostics	100	100	100	50	50	50	50	(a)
51	Environmental interactions	175	54	100	50	50	50	50	(a)
	Total net R&D	8950	7771	7787	3357	3410	3394	3511	
	Program support	1457	2280	2100	892	933	1042	1109	
	Total	10 407	10 051	9887	4249	4343	4436	4620	

^aContinuing.

TABLE 2. - HIGH CAPACITY POWER REFRACTORY MATERIAL CANDIDATES FOR 1300 K STIRLING

Base material	MP, K	ρ , g/cc	Alloy name	Composition, wt %	Joinability	Fabricability	Alloy availability	Data availability	Vacuum, torr
W	3680	19.3	W-25Re-HfC	24 to 26% Re 1% HfC	5	4	4	3	10^{-6}
Ta	3270	16.6	ASTAR-811C	8% W 1% Re 1% HfC	8	8	10	5	10^{-8}
Mo	2880	10.2	TZM	0.08% Zr 0.5% Ti	2	8	10	4	10^{-6}
			TZC	1.25% Ti 0.1% Zr 0.15% C	2	6	10	4	10^{-6}
Mo/Re	2780	15.5	Mo-47.5 Re	47.5% Re bal Mo	8	6	8	3	10^{-6}
Nb	2740	8.6	FS-85	11% W 28% Ta 1% Zr	8	8	5	4	10^{-8}
			B-88	27% W 2% HfC	7	7	4	2	10^{-8}
			C-103	10% Hf 1% Ti 0.7% Zr	10	10	10	7	10^{-8}
			PWC-11	1% Zr 0.1% C	10	10	10	7	10^{-8}
			Nb-1Zr	1% Zr	10	10	10	8	10^{-8}

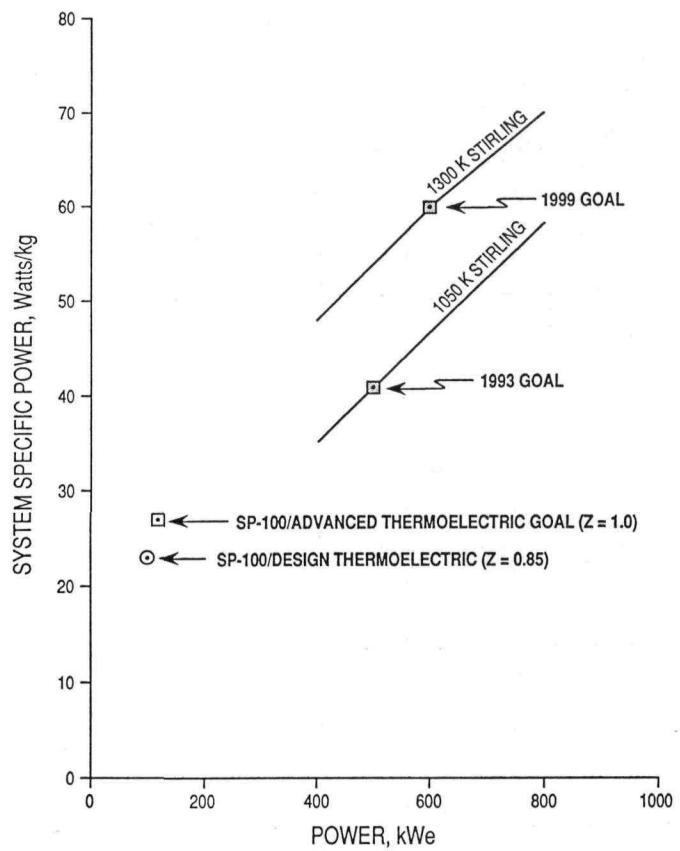


Figure 1.—Extended SP-100 reactor power system capability.

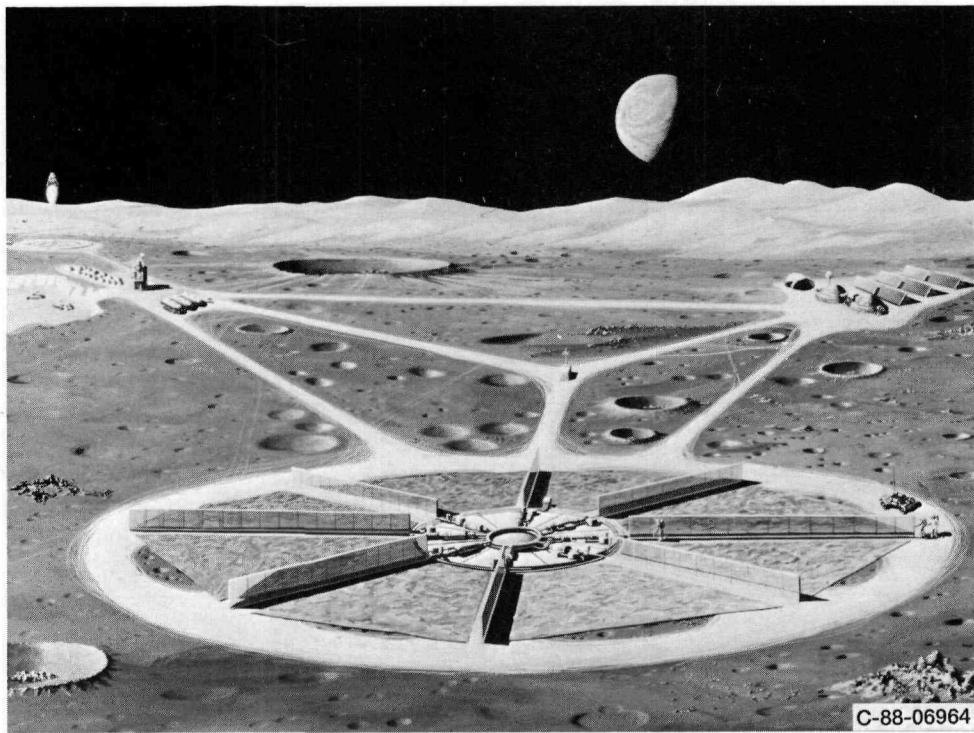


Figure 2.—Conceptual lunar base.

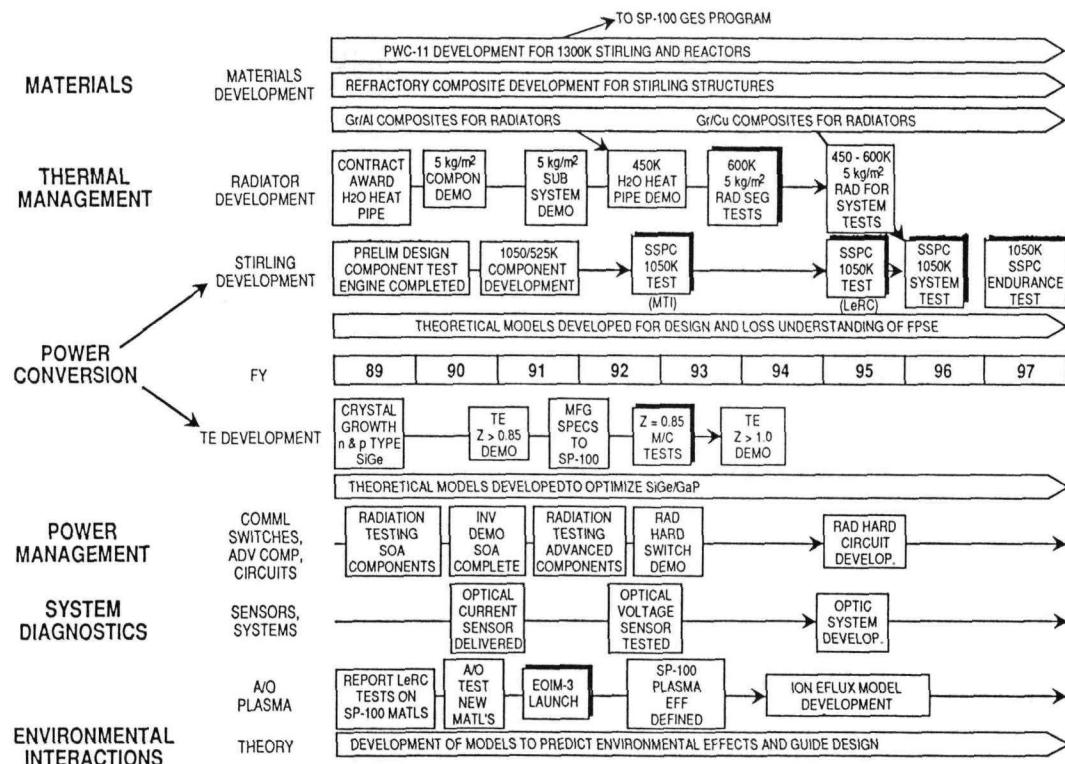


Figure 3.-High capacity power, baseline project schedule.

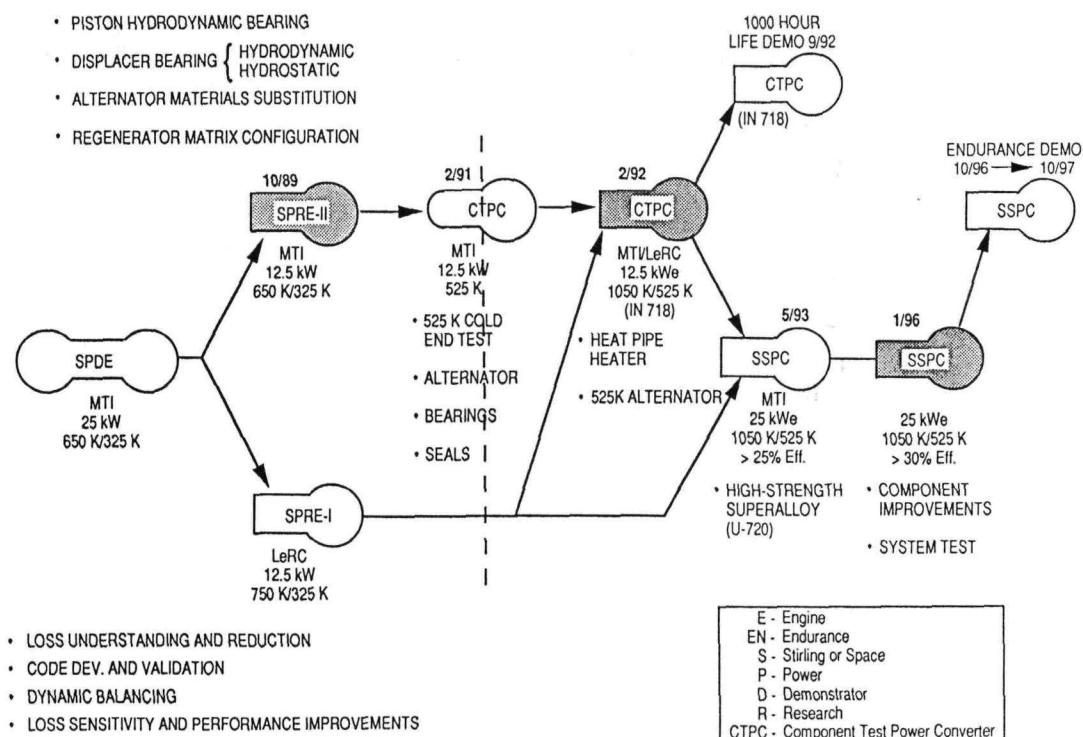


Figure 4.-Stirling development baseline project.

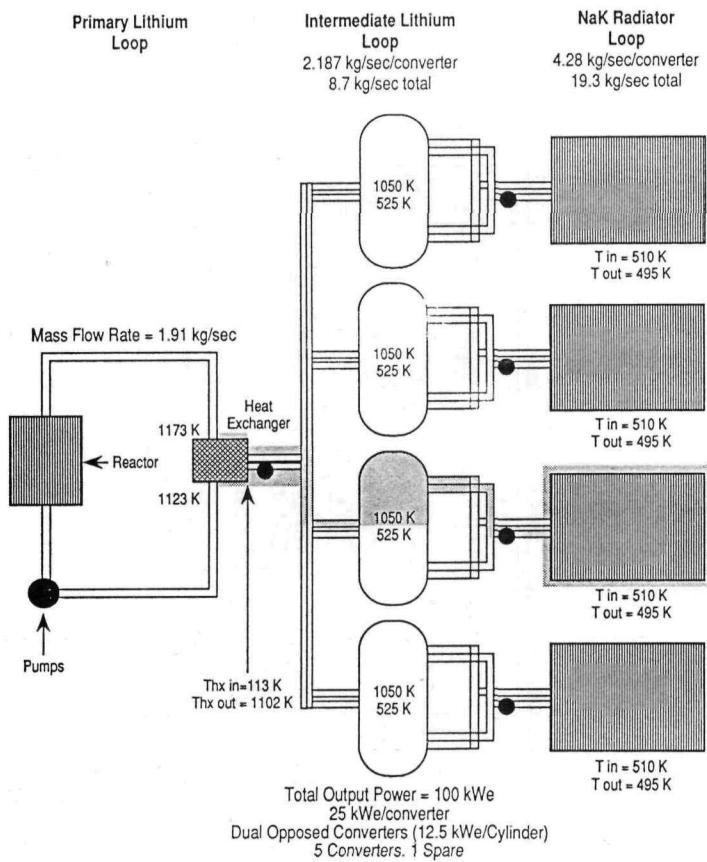


Figure 5.-SP-100/Stirling lunar base.

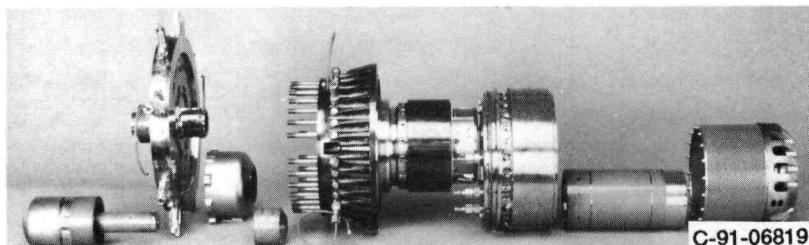
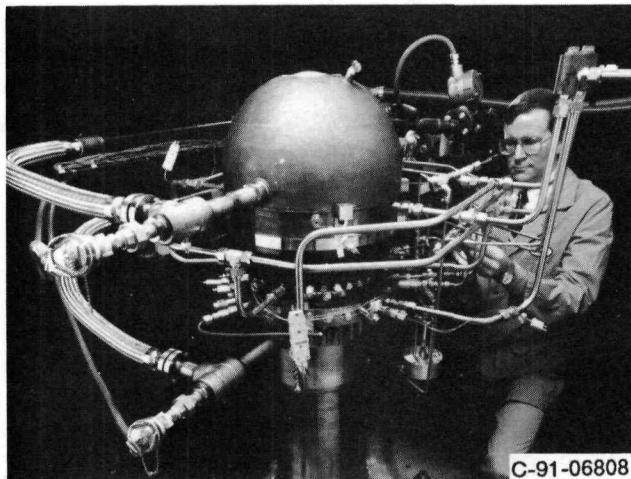


Figure 6.-Component test power converter (CTPC) cold end motoring test.

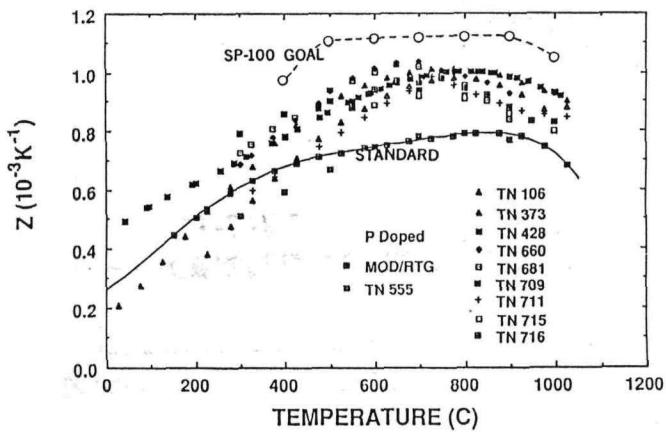


Figure 7.-Improved n-type SiGe/GaP.

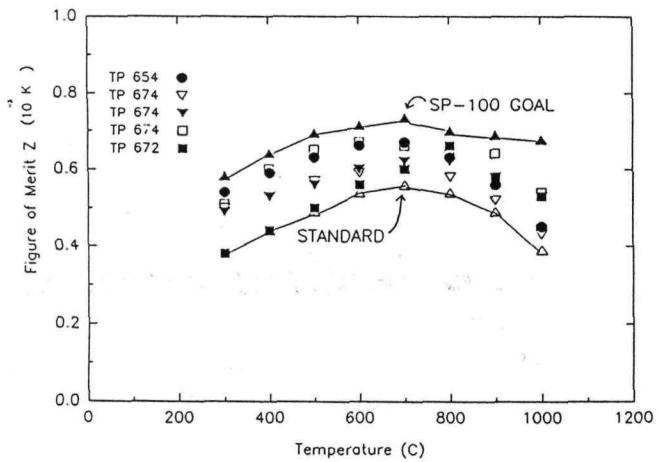
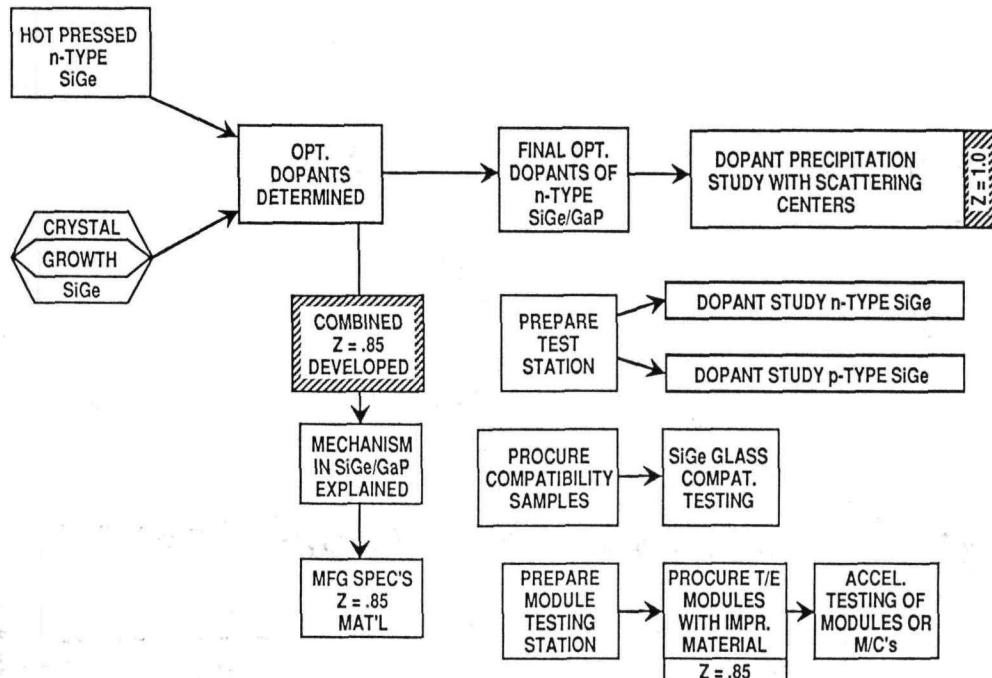


Figure 8.-Z for p-type SiGe.



89	90	91	92	93	94	95	96
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Figure 9.-Thermoelectric development .

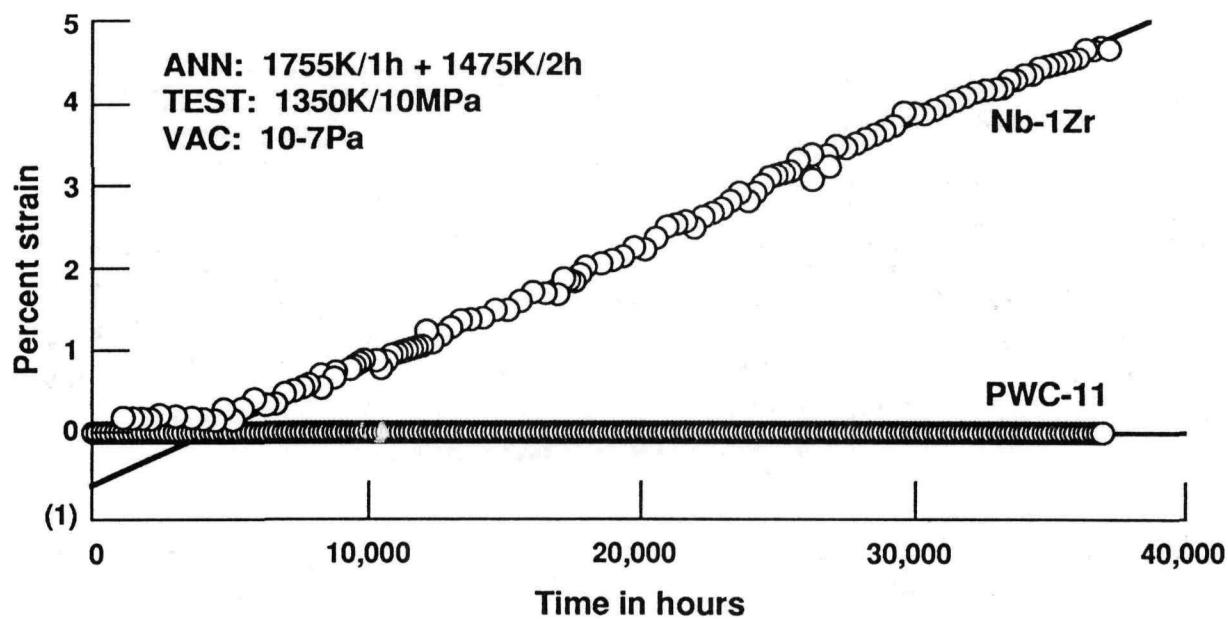


Figure 10.—Creep curves for Nb-1Zr & PWC-11 (0.06C).

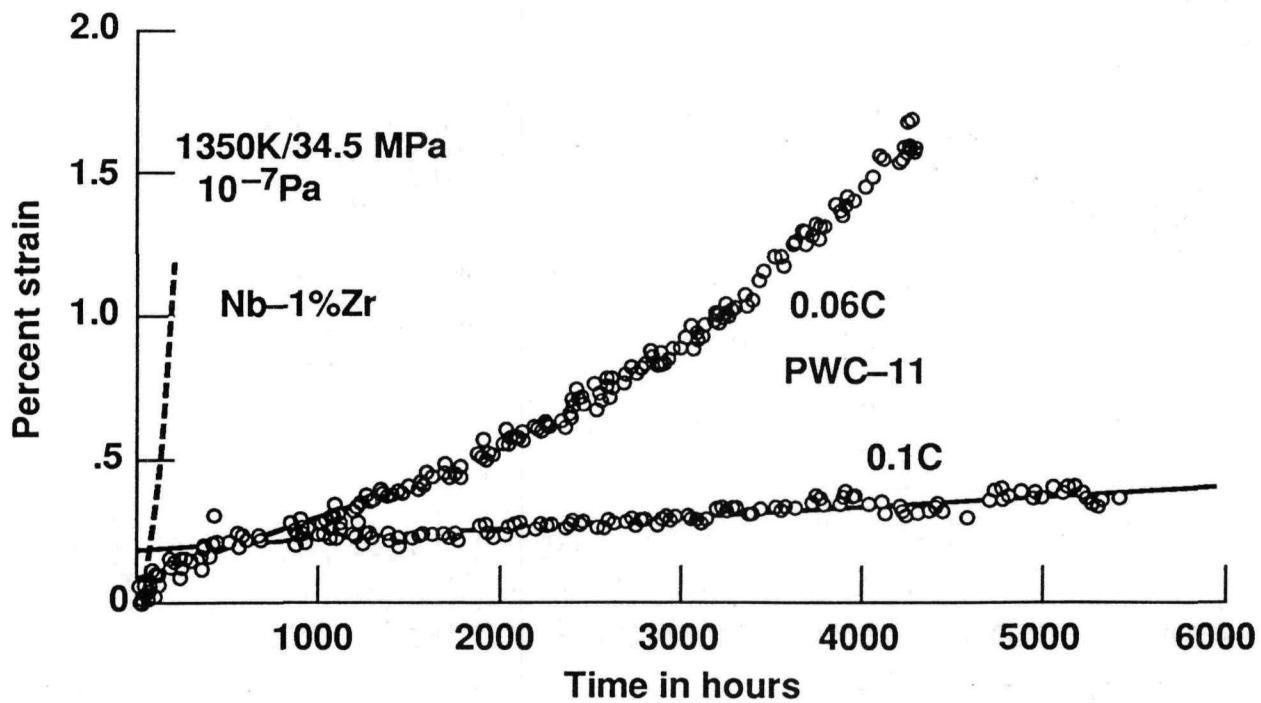


Figure 11.—Creep curves for Nb-1% Zr and PWC-11.

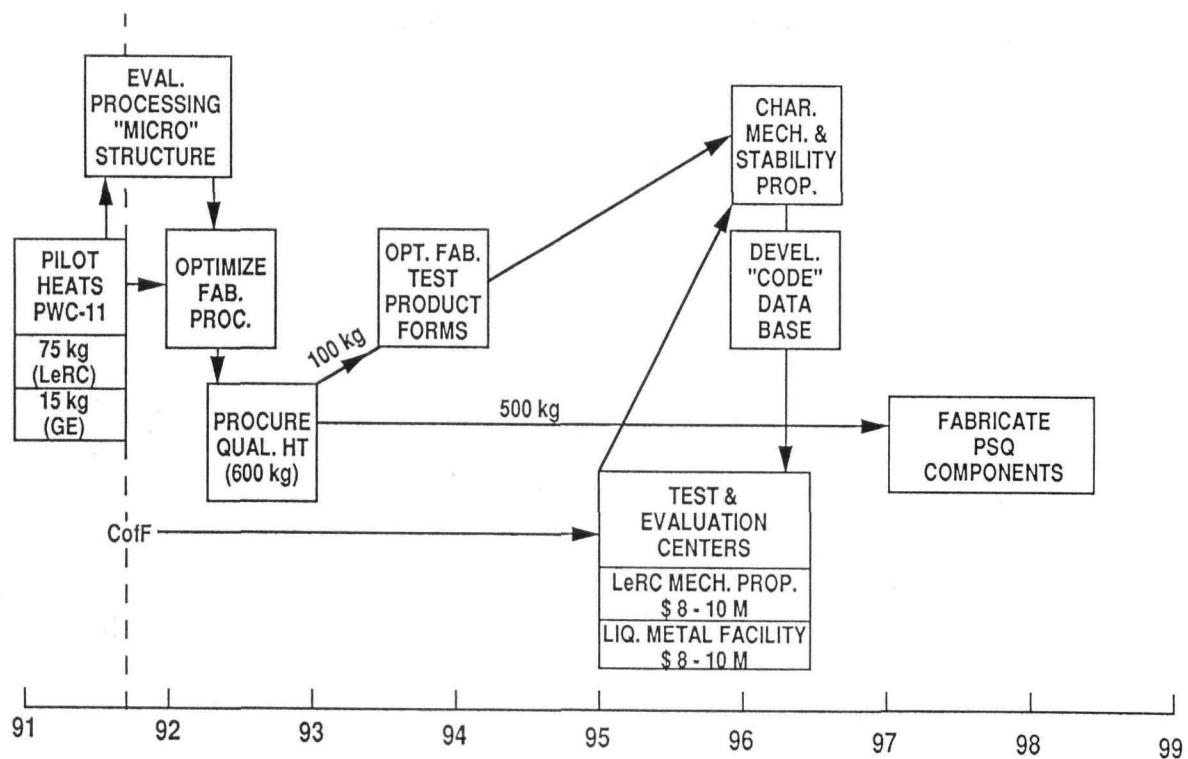


Figure 12.—PWC-11 material development plan.

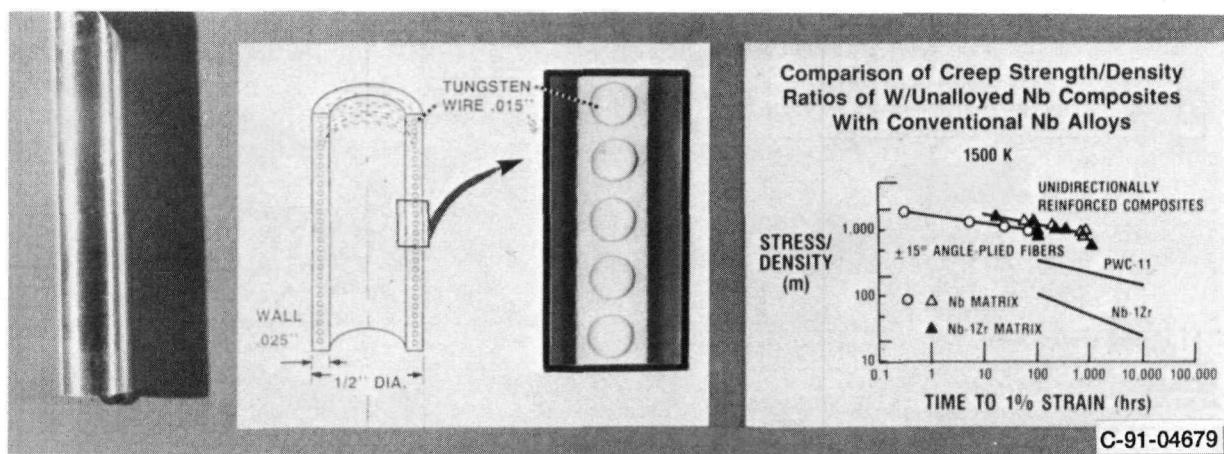


Figure 13.—Tungsten fiber reinforced Nb-1Zr matrix composites for space power applications. Fabricated using arc-spray process invented at NASA-Lewis Research Center.

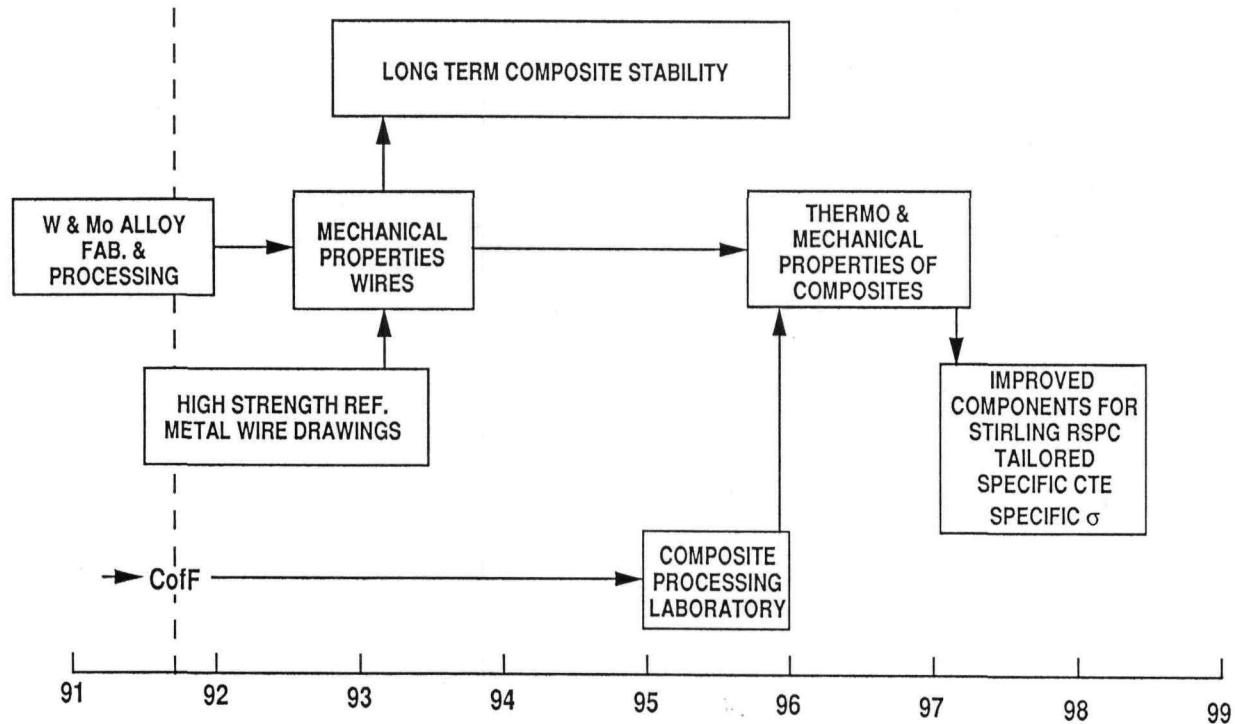


Figure 14.—Refractory composite development plan.

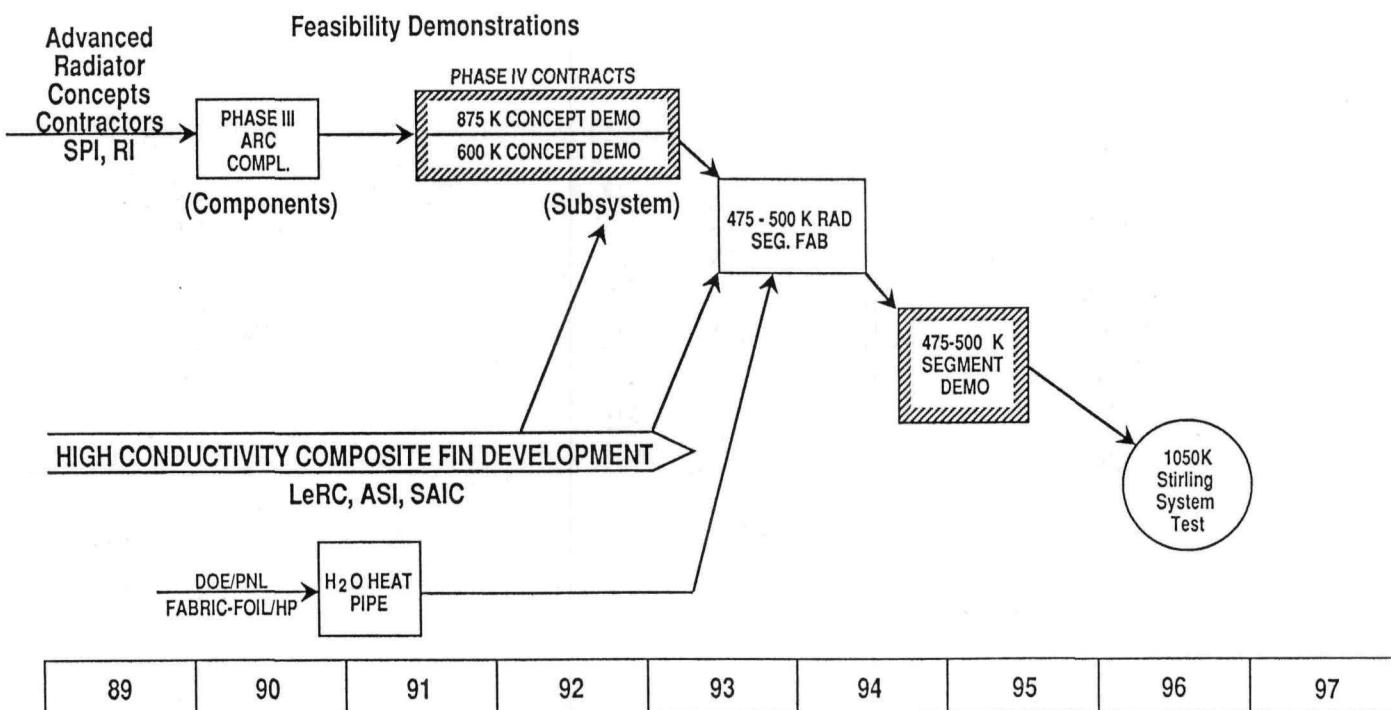
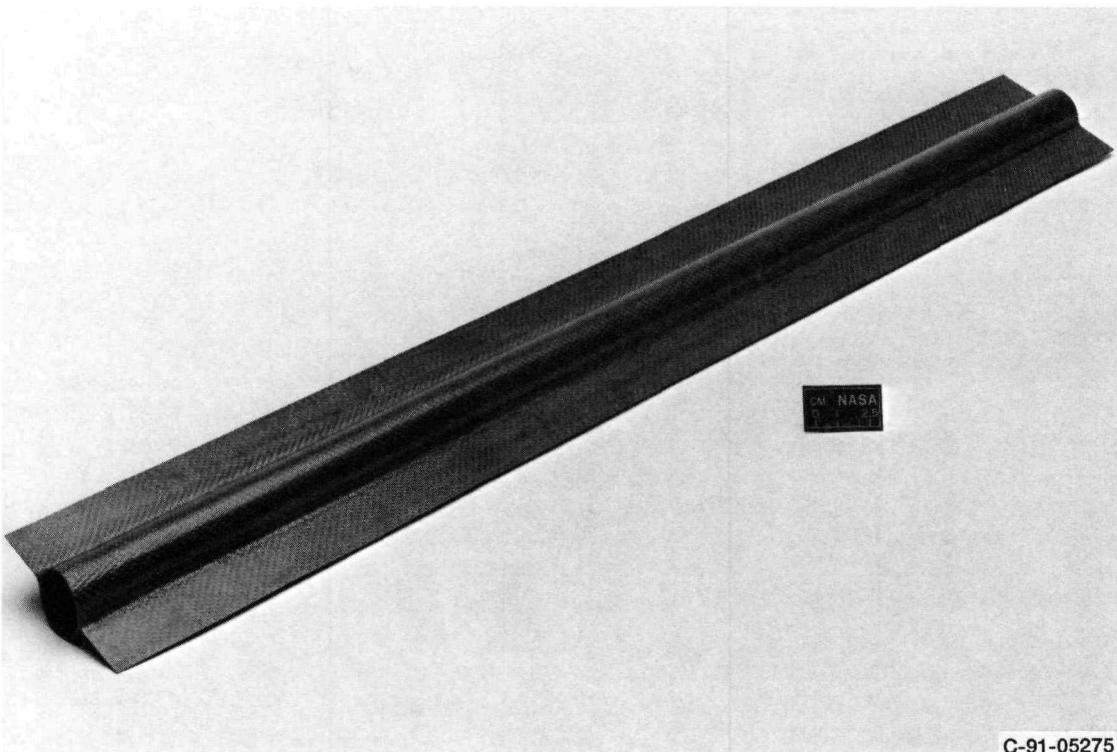


Figure 15.–Thermal management baseline budget plan.



C-91-05275

Figure 16.—Carbon-carbon fin heat pipe structure.

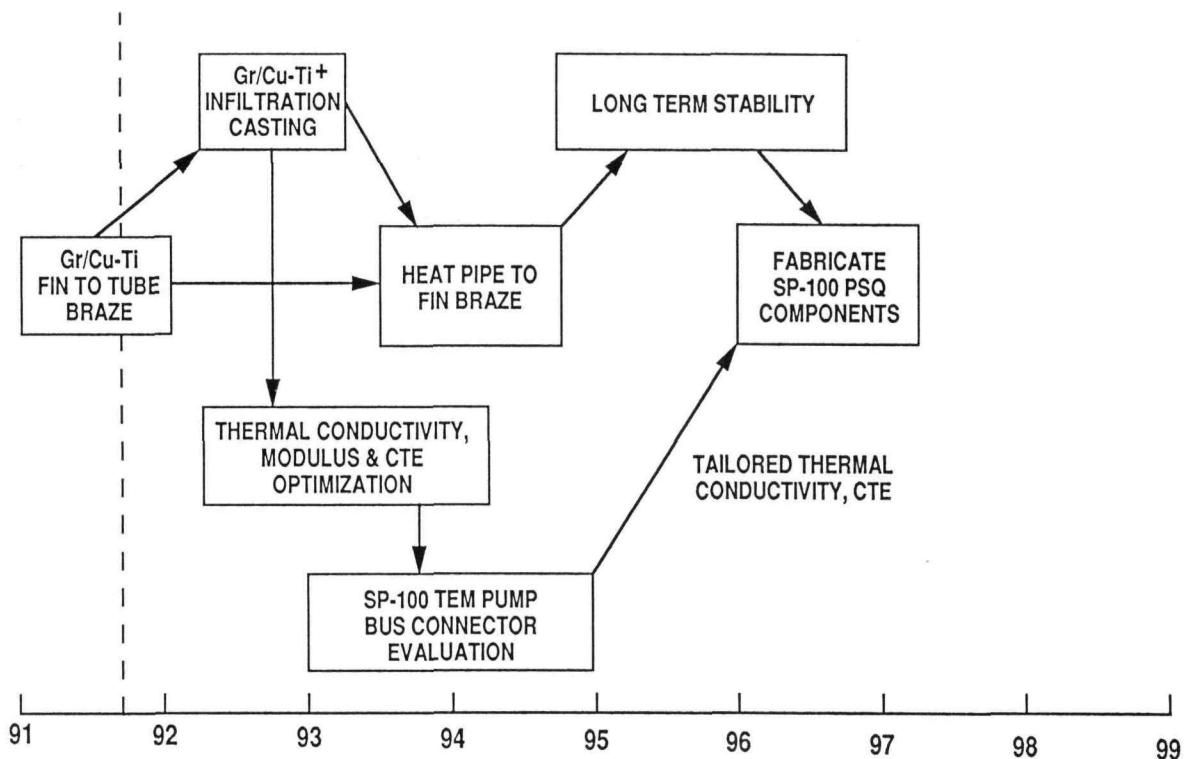
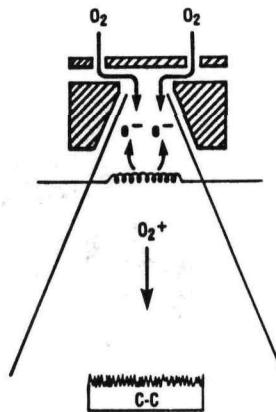
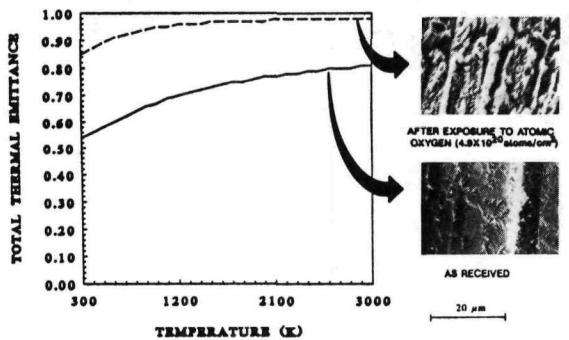


Figure 17.—Gr/Cu composite development plan.

C-90-01230

EXPOSURE TO DIRECTED ATOMIC OXYGEN CAN IMPROVE
THE THERMAL EMMITTANCE OF CARBON-CARBON COMPOSITE RADIATORS



- SIX DIFFERENT TYPES OF C-C COMPOSITES EVALUATED
 - UNTREATED THERMAL EMMITTANCE .45-.82 AT 800 K
 - AFTER A/O BEAM TEXTURING THERMAL EMMITTANCE .85-.9 AT 800 K
 - PEAK EMMITTANCE REACHED AT A/O EFFECTIVE FLUENCE OF 4×10^{20} AT/cm²
- CVD SiO₂ COATINGS ON C-C ARE BENEFICIAL
 - COATINGS ON UNTEXTURED C-C INCREASE EMMITTANCE FROM .67 TO .82 AT 800 K
 - COATING PREVENTS MASS LOSS AND PRESERVES EMMITTANCE IN A/O ENVIRONMENT
- APPLICABLE TO SP-100 AND SOLAR DYNAMIC SYSTEM C-C HEAT PIPE RADIATORS (500-860 K)

Figure 18.—Atomic oxygen beam textured carbon-carbon composites.

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