SPR-8
Multi-Megawatt Space Power System (MMW-SPS)
Concept Description and Concept Refinement Plan

C. E. Walter

April 15, 1985

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MULTI-MEGAWATT SPACE POWER SYSTEM (MMW-SPS)

CONCEPT DESCRIPTION and
CONCEPT REFINEMENT PLAN

APRIL 15, 1985

PRINCIPAL INVESTIGATOR:
C. E. WALTER
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THE SPR-8 MULTI-MEGAWATT SPACE POWER SYSTEM

1. Mission

The SPR-8 MMW-SPS concept can satisfy both continuous and burst mode power requirements. At 10 MWe continuous mode power for 5 yr and 75 MWe burst mode power for 200 sec, the SPR-8 concept can power radar systems for detecting ballistic missile launchings and for discriminating between warheads and decoys. When enemy action is detected the SPR-8 MMW-SPS can power a rail gun, free electron laser, or particle beam and destroy the missile in the boost phase or warheads in space flight.

2. General System Description

The SPR-8 concept is based on the SPR-6 system (Ref. 1) for providing continuous mode power. The system uses a fast UN-fueled, lithium-cooled reactor. Heat is transferred from the lithium coolant to potassium in a shell and tube heat exchanger-boiler. Potassium vapor is expanded through a turbine in a saturated Rankine cycle. After passing through the turbine the potassium is condensed in a compact heat exchanger by transferring heat to the radiator working fluid. An advanced radiator design is envisioned. Much work will be required in radiator technology to achieve low mass and plan form. For completeness of the SPR-8 system concept, a charged liquid droplet radiator is assumed but other types should be considered. Mechanical pumps are used for simplicity, but other types should also be evaluated. A block diagram of the SPR-8 system is given in Figure 1.

This concept can be presented in a fairly specific manner, since considerable effort was expended at LLNL on analyzing similar systems in the late 1960's. The necessary technology program for SPR-6 received much attention at that time. Because of its design parameters, the SPR-6 system concept provides a good basis for meeting the MMW-SPS continuous mode power requirement. Considerable advancements in technology must be made, however, to reduce the power system specific mass. An estimate of the SPR-8 system mass is given in Table 1.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass, Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>4</td>
</tr>
<tr>
<td>Shield</td>
<td>8 - 12</td>
</tr>
<tr>
<td>Heat transport</td>
<td>6</td>
</tr>
<tr>
<td>Power conversion and conditioning</td>
<td>9</td>
</tr>
<tr>
<td>Heat rejection</td>
<td>7</td>
</tr>
<tr>
<td>Instrumentation, controls, structure</td>
<td>2</td>
</tr>
<tr>
<td>Burst mode power</td>
<td>42</td>
</tr>
<tr>
<td><strong>Total System Mass:</strong></td>
<td><strong>78 - 82 Mg</strong></td>
</tr>
</tbody>
</table>
The SPR-8 concept uses lithium as reactor coolant and potassium for turbine working fluid. A flywheel is used to supply burst mode power.
To bring the SPR-8 system concept into sharper focus, it is presented here in the context of providing a continuous mode power level of 10 MWe for 5 years and a burst mode power level of 75 MWe for 200 sec. Higher and lower power levels and operating times could be accommodated. A concept for providing rechargeable burst power utilizing flywheel energy storage has been proposed by ORNL (Ref. 2). The mass of the burst power system is stated there to be 10 Kg/KWh, a value which is properly optimistic. Improvements in composite material strength-to-weight ratio and in alternator design will be required to significantly reduce this value of specific mass. The SPR-8 system utilizes the ORNL burst mode power concept which in itself would weigh 42 Mg for the 75 MWe-200 sec capability. Thus at best, it appears that only a portion of the burst mode subsystem could be carried within one shuttle payload. A link-up in space of SPR-8 subsystems would be required.

3. Subsystem Description

The SPR-8 system consists of reactor, shield, power conversion, heat transport, heat rejection, structure and instrumentation and controls subsystems to provide continuous mode power and a flywheel energy storage system to provide burst mode power. Brief descriptions of these subsystems and their functions are given below. Additional information may be obtained from Ref. 1.

a. Reactor Subsystem: A fast reactor utilizing UN fuel, W or Mo refractory alloy cladding, and lithium-7 coolant provides 30 MW of thermal power. The reactor core is composed of a tightly-packed bundle of 8000 cylindrical fuel elements and 4000 cylindrical coolant channels. The fuel elements and coolant channels, all of equal outside diameter (0.5 cm) are supported at the downstream (payload) end by a tungsten alloy support structure which also attenuates gamma radiation. All interstices and clearance gaps between the fuel and the cladding contain lithium-7. Basic chemical compatibility of the reactor materials permits this arrangement. Fission products would have to penetrate two walls of refractory alloy to reach the flowing coolant.

The central region of the core is occupied by the coolant (Li-7) return passage and a number of liquid (Li-6) control tubes. Pressure of the lithium surrounding the core, acting on a thin membrane of refractory metal, provides active radial constraint of the fuel/coolant tube bundle.

The fueled core, 87 cm long with a 62 cm diameter, is in a tantalum alloy vessel which contains the reactor operating pressure of 2.5 MPa. This high operating pressure is chosen to balance the saturated potassium vapor pressure in the boiler.
Surrounding the core is a 2-cm thick molybdenum side reflector which separates along its girth at the center of the core. The amount of separation is varied to control neutron leakage and thus reactivity.

The dual reactor control system (neutron absorption in the central core region and neutron leakage at the outer core boundary) provides redundant and independent reactivity effects. Each effect is sufficient to control the reactor*. The core volume is about 260 l and contains about 1400 Kg of UN (1325 Kg U with 70% average enrichment, 930 Kg U-235). The average core power density is a modest 114 KW/l, for a corresponding fuel power density of 263 KW/l.

Fuel burnup due to fission during 5 years operation at 30 MW is 64.4 Kg. This translates to 41,320 Mwd/Mg or 4.9% (FIMA). Achieving this fuel performance will greatly improve the mass characteristics of space power systems. Reactor mass is estimated to be 4 Mg.

b. **Shield Subsystem:** Part of the shield in circular geometry, is incorporated in the reactor as described above. Additional shielding of lithium hydride and tungsten would be provided to reduce radiation at the payload. The shadow cast by the shield at the dose plane would be oblong, with its long axis in the plane of the radiator. A rough estimate of the shield mass is 8 to 12 Mg depending on various unspecified requirements. Alternate materials for moderating and absorbing neutrons will be evaluated. Candidates are YH₂, BN, B₄C.

c. **Heat Transport Subsystem:** The heat exchanger-boiler is constructed from tantalum alloy in a counter-flow shell and tube arrangement. Subcooled potassium from the radiator first enters a preheater section and cools a small stream of lithium which is used to cool the reactor and boiler pressure vessels below 1400 K. The potassium then flows through a large number of boiler tubes and leaves as saturated vapor. Helical flow swirlers inside the boiler tubes prevent boiling instability.

Mechanical pumps are chosen for all fluid loops because of their higher efficiency and lower mass than electromagnetic pumps. Piping is included in this subsystem. Estimated mass is 6 Mg.

* Note: Reactivity effect due to the higher burnup in SPR-8 than in SPR-6 has not been taken into account. Some changes will be necessary for SPR-8.
d. **Power Conversion and Conditioning:** Four full-admission axial flow turbines drive four alternators to generate a combined output of 10 MWe. Turbine blades and casing are made from TZC or Mo - 1 at. % HfN. The alternator rotor uses H-11 steel with a nickel alloy core. The alternator is a radial gap homopolar machine.

High temperature electronics are used to allow a reduction in the size of the auxiliary cooling radiators which are required. Estimated mass for this subsystem is 9 Mg.

e. **Heat Rejection Subsystem:** An advanced type radiator is required to allow heat rejection at 750 - 800 K without an excessive weight penalty. A review of recently proposed designs indicates that electrostatically charged liquid droplets offer a compact way of directly radiating heat to space. A rough estimate of the radiator mass is 7 Mg.

f. **Balance-of-Plant Subsystem:** In addition to the subsystems identified above, the SPR-8 concept includes controls and instrumentation, and structural components. A description of these is not available, but their mass is estimated to be 2 Mg based on SPR-6 data.

g. **Burst Mode Subsystem:** Uncontained flywheel rotors and power input/output systems are used per ORNL design (Ref. 2) to provide 75 MWe for 200 sec. The estimated mass of the burst mode subsystem is 42 Mg.

4. **Major System Parameters**

**Reactor**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel</strong></td>
<td>UN</td>
</tr>
<tr>
<td><strong>Clad</strong></td>
<td>W-25Re, Mo-HfN, or other alloy of W or Mo</td>
</tr>
<tr>
<td><strong>Coolant</strong></td>
<td>Li-7</td>
</tr>
<tr>
<td><strong>Thermal Power</strong></td>
<td>30 MW</td>
</tr>
<tr>
<td><strong>Core Power</strong></td>
<td>114 kW/l</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Fuel burnup</strong></td>
<td>5%</td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td>5 years</td>
</tr>
<tr>
<td><strong>Reactor diameter</strong></td>
<td>72 cm</td>
</tr>
<tr>
<td><strong>Reactor outlet temp.</strong></td>
<td>1650 K</td>
</tr>
<tr>
<td><strong>Fuel inventory</strong></td>
<td>1275 kg U, 930 kg U-235</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>dual: reflector leakage, core absorber (liquid Li-6)</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>4 Mg</td>
</tr>
</tbody>
</table>

**Shield**

- Layered arrangement of LiH, W
- Mass: 8 - 12 Mg
Heat Transport
- Shell and tube heat exchanger boiler with nearly balanced pressures on primary loop (lithium liquid) and secondary loop (two-phase potassium)
- Fluid management system (expansion, freezing and start-up, clean-up)
- Mechanical pumps
- Mass: 6 Mg

Power Conversion & Conditioning
- 10 MWe
- Potassium vapor turbine
- Turbine inlet temp: 1550 K
- High temperature radiation resistant semiconductor switching devices
- Mass: 9 Mg

Heat Rejection
- 20 MW
- Direct radiation at 600 to 1000 K, low vulnerability to micrometeoroids
- Charged liquid-droplets, with pitcher/catcher closely located
- Erection in space manually or by robots
- Mass: 7 Mg

Instrumentation & Controls & Structure
- Reliable, long life, radiation resistant transducers to measure neutron flux, temperature, pressure, flow rate, displacement and strain
- Micro-processor control of system parameters, use of adaptive control techniques
- Power conditioning as required by the user
- Structural metal, graphite, and organic composites
- Mass: 2 Mg

Burst Power
- Composite material flywheel energy storage (by ORNL)
- Mass: 42 Mg

Total System Mass
- Continuous Mode: 36 - 40 Mg
- Burst Mode: 42 Mg
  78 - 82 Mg
5. Enabling Technologies

Materials research in UN, refractory alloys (e.g., W-25Re, Mo-14Re, Mo-HfN), and fuel/clad/coolant/structure compatibility is required. Previous efforts at LLNL indicate this combination of materials would be compatible but this needs to be demonstrated.

The satisfactory performance of the fuel to burnups of 5% or greater needs to be demonstrated. Nitrogen evolution from the fuel into the coolant needs further study.

As with all concepts, improvements in radiator and shield design are needed since these are the heaviest components. Also, high temperature, radiation resistant power conditioning components need to be developed to permit higher temperature auxiliary cooling radiators.

Development of a potassium vapor turbine, particularly strengthened turbine blades, will be a critical enabling technology for this concept. Fortunately, the nitriding of blade material seems to hold promise.

Development of materials (fiber composites) to reduce the mass of the flywheel rotor is a critical area. There is the potential for increasing the energy density of the rotor by a factor of two.

6. Areas of Major Technical Risk

There is no concern about safely producing some continuous mode electric power in space over a seven year period nor about providing some burst mode power for specified short times. All the physical and mechanical principles involved are well understood and have been demonstrated in various ways.

The major technical risk is that it may not be possible to produce the desired power levels from a system constrained to be launched within the current shuttle (STS). Initial, unoptimized, calculations indicate that the mass of an SPR-8 system designed for 10 MWe continuous power, could be reduced to 36 Mg (without the flywheel). Reducing it to below 30 Mg may also be possible.

This risk will be safely negotiated if material technology development is successful. Likelihood of success in the material technology development area can be greatly improved with innovative component designs and optimization to extract as much "performance" as possible from each unit volume and unit mass of material.
7. Potential for Meeting Expanded Requirements

The requirements which have been tentatively established for MMW-SPS are stringent. To attempt to satisfy these requirements, the highest operating temperatures are needed. The SPR-8 concept utilizes materials with the highest known temperature capability for mechanical integrity. If somehow a high temperature thermodynamic cycle can be contained in a low temperature mechanical system without an excessive mass penalty, such a system concept might exceed the currently described capability of the SPR-8 concept. Even in that circumstance our approach to push up the peak cycle operating temperature in the SPR-8 concept by using improved materials is in the right direction for future MMW-SPS improvements.

8. Concept Refinement Plan

The SPR-8 reactor concept is based on a material system which has received much theoretical consideration. Unfortunately, there is only little experimental data on how these materials operate as a system at the conditions intended, temperature and radiation being the principal conditions of concern. An important issue, then, is to review the theoretical basis which supports the choice of this material system in the context of the MMW-SPS mission. Resolution of the material system issue requires review of a second important issue: power system characteristics, as a function of conditions imposed on the material system.

Accordingly, our SPR-8 concept refinement plan for the near term is to:

a. Review theoretical basis (and experimental data) for the material system of the SPR-8 reactor and primary loop.

b. Perform parametric studies of the SPR-8 space power system to establish trends for system characteristics. For example; How do component masses vary as reactor temperature is changed? How does system mass vary as a function of continuous power or burst power level and operating times? These studies would be as detailed as time and funds permit, with the reactor and power conversion subsystems receiving the most emphasis.

c. Provide preliminary power system design descriptions for selected discrete operating points (power, time).

d. Perform a preliminary safety analysis to assure that nothing in the design would prevent safe operation.

REFERENCES


SPR-9
MULTI-MEGAWATT SPACE POWER SYSTEM (MMW-SPS)

CONCEPT DESCRIPTION
and
CONCEPT REFINEMENT PLAN

APRIL 15, 1985

PRINCIPAL INVESTIGATOR:
C. E. WALTER
LAWRENCE LIVERMORE NATIONAL LABORATORY

Enclosure 2
THE SPR-9 MULTI-MEGAWATT SPACE POWER SYSTEM

1. Mission

The SPR-9 system concept provides 10 MWe power in a continuous mode for a time period of five years. The system will be capable of producing 100 MWe on demand for a period of 2000 sec on a one-time basis at any time during the five year period. (Subsequent operation of the system has not been considered.) Thus the SPR-9 system provides power to perform missions of ballistic missile surveillance and decoy discrimination, with high resolution radar, orbital transfer by means of electric propulsion, and warhead destruction in space by means of rail guns, free electron lasers, or particle beams.

2. General System Description

The total mass of the system potentially could be reduced to 30 Mg, giving a specific mass of 3 kg/kWe. In addition, it appears that the system could be accommodated within the payload volume of the space shuttle.

The conceptual design presented here is a 10-MWe, Brayton cycle, nuclear space power system with an overall system efficiency of 28%. Designated SPR-9, this system utilizes Brayton cycle technology coupled with an advanced radiator design. With its one-time burst power capability, its primary application is as a power source designed to meet demands for both continuous and burst mode power.

The SPR-9 power plant consists of a 36-MW nuclear reactor based partly on Pluto/Tory technology (Ref. 1 and 2), a combination shield/burst-power working fluid, and a power conversion system. A block diagram of the system is shown in Fig. 1. Helium or helium/xenon coolant is heated in the reactor to 1800 K and passed through a Lysholm expander (Ref. 3 and 4) and subsequently through a conventional gas turbine operating at lower temperatures. Each of four Lysholm expander-turbine sets produces 2.5 MWe with an overpower capability to compensate for at least one set failing during mission lifetime and also to accommodate H₂ working fluid during the burst mode. Waste heat is rejected through an advanced radiator system with a minimum temperature of 600 K. The reactor is separated from the payload by a layered shield consisting of layers of tungsten, liquid hydrogen, and lithium-6 loaded steel. The large mass of liquid hydrogen is kept refrigerated by thermoelectric coolers which consume a small fraction of the total electric power output.

The burst power mode is achieved by raising reactor power and turbo-pumping the liquid hydrogen from the shield to the reactor where it is heated to 1800 K and 2 MPa and directed to the turbines. The compressors are valved out of the circuit since all of the liquid hydrogen is pumped directly to the reactor by the turbopump. The hydrogen in the turbine exhaust is ejected into space. This technique allows the mass of the stored burst power working fluid to be utilized as a neutron and gamma shield prior to execution of the burst.
Figure 1. The SPR-9 concept uses helium/xenon as reactor coolant and turbine working fluid for continuous mode power and hydrogen for burst mode power. Reactor and turbine are used in both modes.
The reactor core consists of a homogeneous distribution of uranium of varying enrichment in a boron carbide (B₄C) moderator which contains almost exclusively isotopically separated Boron-11. Graphite and BeO are alternative moderator materials.

A simple Monte Carlo calculation was performed to determine the critical masses of reactors having these moderators. The results for a base spherical reactor having a volume of 1 m³ and volume fractions of 33% void, 67% moderator/fuel are as follows:

<table>
<thead>
<tr>
<th>Moderator</th>
<th>Smeared Core Density</th>
<th>Critical Mass, U-235</th>
</tr>
</thead>
<tbody>
<tr>
<td>BeO</td>
<td>1.90 g/cm³</td>
<td>4 Kg</td>
</tr>
<tr>
<td>B₄C</td>
<td>1.73 g/cm³</td>
<td>8 Kg</td>
</tr>
<tr>
<td>C</td>
<td>1.63 g/cm³</td>
<td>600 Kg</td>
</tr>
</tbody>
</table>

Because of its good neutron and mechanical properties, chemical stability at high temperature, and non-toxicity, we believe that B₄C should receive further consideration.

The pressure vessel and piping are made of tantalum and molybdenum alloys. The power conversion system is located on the reactor side of the shield in order to utilize the incremental shielding capability of these components. The large size and suitability of the liquid hydrogen storage tank makes this arrangement attractive.

The radiator has an assumed operating temperature of 600 K based on the use of advanced radiators such as the "liquid droplet" concept.

A preliminary estimate of system mass is given in Table 1 (further weight reduction appears possible).

Table 1. Preliminary Mass Breakdown for SPR-9 Providing 10 MWe for 5 Years and 100 MWe for 2000s.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shield/Burst Fluid Unit</td>
<td>12 Mg</td>
</tr>
<tr>
<td>Reactor</td>
<td>5</td>
</tr>
<tr>
<td>Radiator</td>
<td>7</td>
</tr>
<tr>
<td>Alternator</td>
<td>7</td>
</tr>
<tr>
<td>Turbines</td>
<td>2</td>
</tr>
<tr>
<td>Structure</td>
<td>2</td>
</tr>
<tr>
<td>Reactor Piping</td>
<td>1</td>
</tr>
<tr>
<td>Compressors</td>
<td>1</td>
</tr>
<tr>
<td>Piping</td>
<td>1</td>
</tr>
</tbody>
</table>

Total System Mass: 38 Mg
3. Subsystem Description

a. Reactor Design: The SPR-9 reactor utilizes \( {^{235}}\text{U} \) fuel with variable uranium enrichment to flatten core power, a \( {^{10}}\text{B}_4\text{C} \) moderator which contains isotopically separated boron-11, and helium or helium/xenon as the coolant. Alternative moderator/fuel arrangements would be graphite and \( \text{UC}_2 \) or \( (\text{Zr}, \text{U}) \text{C} \text{orBeO}_2 \). The reactor pressure vessel and associated piping is made of tantalum or molybdenum alloy. All of these materials are quite compatible at the operating temperatures of 1800 K.

The reactor contains 40,000 coolant channels each with a diameter of 4.25 mm. The channels are fabricated from sintered \( {^{10}}\text{B}_4\text{C} \) with a hexagonal outer surface and a circular flow cross section. The \( {^{10}}\text{B}_4\text{C} \) provides moderating properties which are comparable to BeO but provides better temperature behavior and eliminates a toxicity hazard during fabrication and launch operations.

The residual boron-10 in the moderator material is used to compensate for the reactivity swing during reactor life. It also may be possible to use thorium "seeding" to accomplish this while reducing initial fissile loading. The reactor control system consists of a number of boron-10 carbide fibers grown on a central graphite fiber core. The fibers are wound into a control "rope" and wound in and out of the active core region with a spool mechanism. In addition variable reflector leakage will be used to provide a redundant and independent means of reactivity control.

The flow rate of helium (He-Xe) is about 25 m/sec and the flow regime is laminar. The pressure drop across the core is negligible. An 1800 K helium exit temperature produces a wall temperature of about 1850 K. At these temperatures the \( {^{10}}\text{B}_4\text{C} \) should be well behaved. The melting point of \( {^{10}}\text{B}_4\text{C} \) is 2700 K. Peak moderator temperatures are well below this value. Optimization of reactor porosity and coolant channel diameter can further reduce the wall and peak moderator temperatures.

The reactor is contained in a 1 cm thick tantalum or molybdenum alloy pressure vessel designed for operation at 2 MPa. Helium enters the vessel and flows through the reflector and along the vessel wall directed by a graphite downcomer. This flow pattern serves to cool the vessel wall and the reflector. A tantalum or molybdenum alloy tungsten core support structure is provided. A lateral core support structure provides flexibility for growth of the moderator caused by differential thermal expansion.

b. Nuclear Shield: The nuclear shield used in SPR-9 utilizes the pressure vessel, the core support structure, the power conversion piping and equipment, the liquid hydrogen reservoir (9000 kg),
and layers of Li-6 loaded steel and tungsten. Because of the high cycle efficiency, a lower reactor thermal power is required for the same electric output further reducing the dose rates. The helium coolant is transparent to neutron interactions (except for the minor effect of He-3 trace content) and hence the coolant piping requires no shielding.

The liquid hydrogen reservoir is sufficiently large to thermalize the incoming neutron flux and Li-6 loaded steel is used to remove the thermal neutrons and some photons. Li-6 is used because of the low neutron cross-section for gamma ray production. On a unit mass basis, the liquid hydrogen effectively downscatters gamma rays to lower energies where tungsten is most efficient for removal. The metal components of the layered shield are cooled by the liquid hydrogen and the liquid hydrogen itself is cooled by either a thermoelectric refrigerator or by a Joule-Thompson cooler. The energy requirement for refrigeration is substantial, since on the order of 30 kW of heat must be removed. Adequate refrigeration will be provided by an increase in the electrical output.

c. Power Cycle: For continuous mode power, a high temperature closed Brayton cycle without regeneration is used. No attempt has been made to optimize the cycle for regeneration, intercooling, or reheat. The high reactor outlet temperature requires the use of cooled turbine metal blades or a ceramic rotor as in a Lysholm expander. Optimization of the expander inlet and outlet pressure ratios and the turbine inlet and outlet pressure ratios may be possible. A pressure ratio of 4 has been assumed. Efficiencies for expansion and compression are taken as 0.9. The turbine and compressor sets will be canned to prevent helium leakage.

For burst mode power, stored liquid hydrogen is valved into the system, vaporized, heated in the reactor to 1800 K, expanded over a pressure ratio of 8 through the turbine sets, and exhausted to space.

4. Major System Parameters

<table>
<thead>
<tr>
<th>Reactor</th>
<th>$^{\text{U}}<em>{92}B</em>{4}C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{\text{U}}<em>{92}B</em>{4}$</td>
<td>$^{\text{U}}<em>{92}B</em>{4}C$</td>
</tr>
<tr>
<td>Diameter</td>
<td>72 cm</td>
</tr>
<tr>
<td>Fuel Inventory</td>
<td>&lt;200 kg $U-235$</td>
</tr>
<tr>
<td>Control</td>
<td>Dual: reflector leakage, core absorber ($^{11}B_{4}C$ rope)</td>
</tr>
<tr>
<td>Mass</td>
<td>5 Mg</td>
</tr>
</tbody>
</table>
Operating Cond.:  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Continuous</th>
<th>Burst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Power</td>
<td>36 MW</td>
<td>200 MW/100 MW</td>
</tr>
<tr>
<td>Core Power Density</td>
<td>24 KW/l</td>
<td>135 KW/l</td>
</tr>
<tr>
<td>Fuel burnup (FIMA)</td>
<td>50%</td>
<td>290 MW/l</td>
</tr>
<tr>
<td>Lifetime</td>
<td>5 y</td>
<td>2000 s</td>
</tr>
<tr>
<td>Coolant</td>
<td>He-Xe</td>
<td>H₂</td>
</tr>
<tr>
<td>Outlet Temperature</td>
<td>1800 K</td>
<td>1800 K</td>
</tr>
</tbody>
</table>

Shield
- Liquid hydrogen with layered arrangement of Li-6, Fe, W
  - Mass: 12 Mg

Heat Transport
- Shell and tube heat exchanger/boiler with nearly balanced pressures on primary loop (lithium liquid) and secondary loop (two-phase potassium)
- Fluid management system (expansion, freezing and start-up, clean-up)
- Axial flow compressor (cont.), turbo pump (burst)
  - Mass: 2 Mg

Power Conversion & Conditioning
- 10 MWe/100 MWe
- Staged Lysholm expander and axial flow turbine
  - Turbine inlet temp.: 1800 K
- High temperature radiation resistant semiconductor switching devices
  - Mass: 10 Mg

Heat Rejection
- 26 MW (cont.)
- Direct radiation at 600 to 1090 K, low vulnerability to micrometeoroids
- Charged liquid-droplets, with pitcher/catcher closely located
- Erection in space manually or by robots
  - Mass: 7 Mg

Instrumentation & Controls & Structure
- Reliable, long life, radiation resistant transducers to measure neutron flux, temperature, pressure, flow rate, displacement and strain
- Micro-processor control of system parameters, use of adaptive control techniques
- Power conditioning as required by the user
- Structural metal, graphite, and organic composites
  - Mass: 2 Mg
Burst Power

- 100 MWe for 2000 seconds
- 50% overall efficiency

5. Enabling Technologies

Materials research in $\text{B}_4\text{C}$, $\text{UB}_4$, other moderator/fuel combinations and refractory alloys is required as well as work on the Lysholm expander, the gas turbine, and the radiator. The layered shield will have to be optimized. $\text{B}_4\text{C}$ absorber rope control system must be evaluated and reliable rope and actuators need to be developed. Radiation resistant, high temperature power conditioning components will also have to be developed.

Reducing both the mass and volume to meet shuttle requirements will also be a challenge.

6. Areas of Major Technical Risk

There is no concern about safely producing some continuous mode electric power in space over a five year period nor about providing some burst mode power for specified short times. All the physical and mechanical principles involved are well understood and have been demonstrated in various ways.

The major technical risk is that it may not be possible to produce the desired power levels from a system constrained to be launched within the current shuttle (STS). We have estimated 37 Mg for this concept and should be able to reduce that to below 30 Mg.

This risk will be safely negotiated if material technology development is successful. Likelihood of success in the material technology development area can be greatly improved with innovative component designs and optimization to extract as much "performance" as possible from each unit volume and unit mass of material.

7. Potential for Meeting Expanded Requirements

The requirements which have been tentatively established for MMW-SPS are stringent. To attempt to satisfy these requirements, the highest operating temperatures are needed. The SPR-9 concept utilizes materials with the highest known temperature capability for mechanical integrity. If somehow a high temperature thermodynamic cycle can be contained in a low temperature mechanical system without an excessive mass penalty, such a system concept might exceed the currently described capability of the SPR-9 concept. Even in that circumstance our approach to push up the peak cycle operating temperature in the SPR-9 concept by using improved materials is in the right direction for future MMW-SPS improvements.
8. Concept Refinement Plan

The SPR-9 space power system concept makes use of a low-critical-mass moderated reactor. These features reduce the safeguard exposure and facilitate, thus improve reliability of reactor control. In addition, the use of inert gas, dilute ceramic fuel, and Brayton power conversion avoids problems such as Rankine turbine blade erosion by liquid metal droplets, liquid metal compatibility, and fuel damage due to burnup.

The moderator material, boron-11, has not been considered in reactor designs previously because of the boron-10 impurity. Initial calculations indicate that since the boron-10 impurity burns out during operation, reactivity changes due to fuel and boron-10 burnup are slightly positive. These calculations should be reviewed and their validity for various size/operating power/time reactors should be confirmed. This review, together with a study of power system characteristics as a function of temperature, pressure, operating power/time, would allow a better assessment of this concept in meeting MMW-SPS requirements.

Accordingly, our SPR-9 concept refinement plan for the near term is to:

a. Perform neutronic parametric calculations to compare Be0 and $^{11}$B$_4$C moderated reactors.

b. Review reactivity calculations for boron moderated reactors designed to operate for 5 to 7 years. Establish critical mass and reactivity changes over the reactor life as a function of initial boron-11 purity.

c. Perform parametric studies of the SPR-9 space power system to establish trends for system characteristics. For example; How do component masses vary as reactor temperature is changed? How does system mass vary as a function of continuous power or burst power level and operating times? These studies would be as detailed as time and funds permit, with the reactor and power conversion subsystems receiving the most emphasis.

d. Provide preliminary power system designs for selected discrete operating points (power, time).

e. Perform a preliminary safety analysis to assure that nothing in the design would prevent safe operation. A study of the use of the control "rope" concept in light of accident considerations will be made. Alternative methods of adjusting power level will also be considered.
REFERENCES


