INEEL/EXT-01-00938
Rev. 01

Multi-Megawatt Power System Analysis Report

G. R. Longhurst
E. A. Harvego
B. G. Schnitzler
G. D. Seifert
J. P. Sharpe
D. A. Verrill
K. D. Watts
B. T. Parks

November 2001

Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC

INEEL/EXT-01-00938
Rev. 01

Multi-Megawatt Power System Analysis Report

Glen R. Longhurst
Edwin A. Harvego
Bruce G. Schnitzler
Gary D. Seifert
J. Phillip Sharpe
Donald A. Verrill
Kenneth D. Watts
Benjamin T. Parks

November 2001

Idaho National Engineering and Environmental Laboratory
Idaho Falls, Idaho 83415

Prepared for the
U.S. Department of Energy
Assistant Secretary for Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-99ID13727

ABSTRACT

Missions to the outer planets or to near-by planets requiring short times and/or increased payload carrying capability will benefit from nuclear power. A concept study was undertaken to evaluate options for a multi-megawatt power source for nuclear electric propulsion. The nominal electric power requirement was set at 15 MW_e with an assumed mission profile of 120 days at full power, 60 days in hot standby, and another 120 days of full power, repeated several times for 7 years of service. Of the numerous options considered, two that appeared to have the greatest promise were a gas-cooled reactor based on the NERVA Derivative design, operating a closed cycle Brayton power conversion system; and a molten lithium-cooled reactor based on SP-100 technology, driving a boiling potassium Rankine power conversion system. This study examined the relative merits of these two systems, seeking to optimize the specific mass. Conclusions were that either concept appeared capable of approaching the specific mass goal of 3-5 kg/kW_e estimated to be needed for this class of mission, though neither could be realized without substantial development in reactor fuels technology, thermal radiator mass efficiency, and power conversion and distribution electronics and systems capable of operating at high temperatures. Though the gas-Brayton systems showed an apparent advantage in specific mass, differences in the degree of conservatism inherent in the models used suggests expectations for the two approaches may be similar. Brayton systems eliminate the need to deal with two-phase flows in the microgravity environment of space.

CONTENTS

FIGURES

TABLES

MULTI-MEGAWATT POWER SYSTEM CONCEPT EVALUATON

1.0 INTRODUCTION

As part of the Special Purpose Fission Technology (SPFT) program conducted by the U. S. Department of Energy's Office of Nuclear Energy, Science and Technology (DOE-NE), the INEEL was chartered to[1]:

- Review past multi-megawatt (MMW) concepts and studies,
- Compare current requirements for a MMW system, working in coordination with the National Aeronautics and Space Administration (NASA),
- Update one or two previous concepts and/or define a new concept for a MMW system that is compatible with the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) engine concept[2],
- Assess long-lead technologies that would need to be worked on to support development of such a system,
- State performance levels (efficiencies, operating temperatures, etc.) that would be required of these technologies, and
- Identify technical issues associated with development that would need to be addressed as part of a technology development program.

This document reports the initial investigation, and the comparative trade study, in response to the above charter. Here we summarize findings of our review of previous developments, as provided in the literature, indicate our preliminary assessment of the readiness of various technologies considered, and make recommendations for reactor technology development programs needed to reach a desired power/propulsion system specific mass of 3-5 kg/kWe.

The discussion that follows addresses reactor technologies and, to the extent that they are needed to define a reactor concept, power conversion to electricity, heat rejection, and power conditioning.

The reactor concepts selected for further consideration are a gas-cooled reactor operating on a closed Brayton cycle, and a liquid-cooled reactor operating on a Rankine cycle. We provide a specific mass comparison of the two power systems.

2.0 CONCEPTS REVIEW

2.1 Reactor Technology

Past reactor concepts have been varied, and many more designs and configurations have been proposed than built and tested. While a number of such concepts were reviewed, those with sufficient promise of near-term availability to be considered in this context are principally divided into two categories. One uses molten metal as the primary coolant. The second uses pressurized gas. Neither of these can be considered off-the-shelf hardware.

2.1.1 Liquid-Cooled Reactors

Liquid-metal-cooled reactors have the advantage of a very high thermal conductivity and high specific heat coolant. Provided the operating pressures are maintained well above the saturation pressure for the operating temperature, complications arising from two-phase flow in the reactor in a microgravity environment can be avoided. Single phase in the reactor requires a heat exchanger to transmit the heat to a secondary fluid that can be boiled to operate a Rankine system or to a gas that is simply heated for Brayton cycle operation. Liquid metal coolants offer the advantage of high temperature operation at low to moderate pressures.

SNAP

One of the early reactor development programs was the SNAP series. Of these, a significant one was the SNAP-50/ASPR (Advanced Space Power Reactor). The SNAP-50 program operated until 1965, when it became the SPR program. The SPR-6 in that series utilized UN fuel with W-25Re structure[3]. The reactor was Li cooled and had a potassium Rankine cycle for power conversion. It was designed to produce 10 MWe and designers were hopeful of a system specific mass of 7 kg/kWe. The general configuration of the SPR-6 is shown in Figure 1.

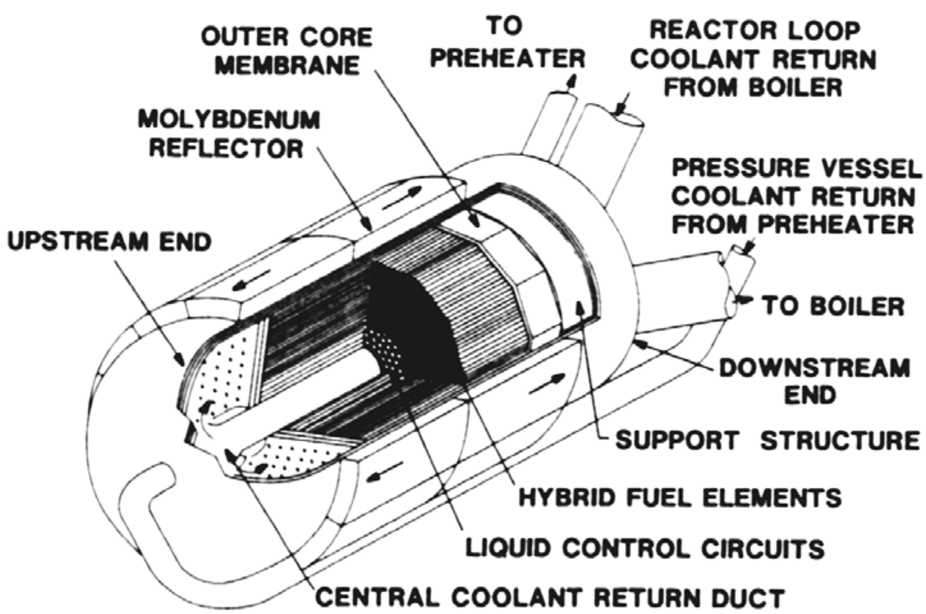

Figure 1. SPR-6 reactor configuration

MPRE

In an effort to simplify the liquid-metal cooled design, the Medium Power Reactor Experiment (MPRE) was conducted to see if potassium could be boiled directly in the reactor. The program was not completed, but difficulties were encountered with film boiling. Without taking care to generate finely dispersed nucleation sites, film boiling was found to dominate heat transfer and destabilize local temperatures. Concerns over mixed phases in a microgravity environment were also present[4].

SP-100

The SP-100 reactor was designed as a nominally 100-kWe power source for space applications. Major features of the reference design included the following.

- The reactor core was lithium cooled and operated with a fast-fission spectrum.
- The design goal was for a cumulative full-power operating duration of 7 years.
- The reactor fuel was uranium nitride with Nb-1Zr cladding.
- The design value for the reactor outlet temperature was 1,350 K.
- Power conversion was out-of-core thermoelectric conversion.
- Direct-coupled heat pipe radiators were to be used for heat rejection.

Figure 2 shows the general arrangement of the SP-100 with its associated systems[5]. The SP-100 was never built, although several components were developed and tested for it.

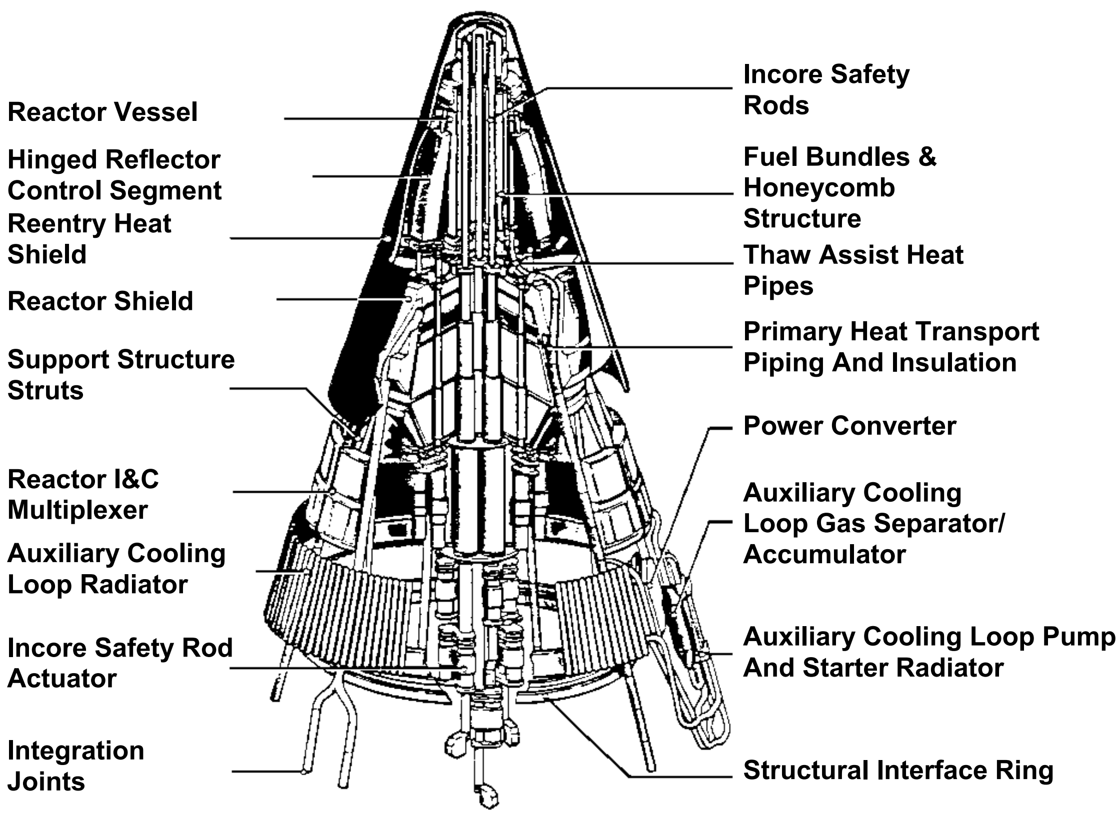

Figure 2. SP-100 system configuration.

For application to the present mission requirement, the SP-100 design would be modified[6,7]. One upgraded design would use SP-100 fuel, but it would require increasing the power output by a factor of 150 to 15 MWe by increasing the reactor size. Reactor outlet temperature would still be limited to 1,350 K, as determined by the operating temperature allowed for the cladding. The thermoelectric conversion planned for the SP-100 would be replaced by a more thermodynamically efficient dynamic system in the multi-megawatt application.

Further upgrades of SP-100 technology may come by replacing the SP-100 fuel with an advanced fuel form. Cladding the UN fuel with ASTAR 811C could raise the reactor outlet temperature to 1500 K. A more significant change to cermet fuel with W-Re-Mo cladding, may raise the fuel operating temperature to 1,850 K and the reactor outlet temperature to 1,500 K.

2.1.2 Gas-Cooled Reactors

Gas-cooled reactor concepts have been investigated for many years. In the commercial power industry, the Ft. St. Vrain reactor is probably the best known in the US, but very successful systems have been built and operated in Europe, particularly in Germany. Gas cooling offers the convenience of only a single coolant phase in both the reactor and in the power conversion system. Single phase cooling avoids the complexities of boiling heat transfer with its attendant thermal and reactivity inhomogeneities and turbine damage from condensing fluid droplets. Those may be particularly troublesome in a microgravity environment. In addition, cooling gases are usually He or a mixture of He and Xe, which are chemically inert and avoid the potential corrosive effects that liquid metals or other materials may have on structures. Of the many gas-cooled reactor concepts examined, only two will be reviewed here.

2.1.2.1 NERVA/Rover

The Rover program was the US effort to develop nuclear thermal rockets. Many different configurations were designed and tested as part of Rover from the early 1960s through the early 1970s, accumulating over 1,000 minutes of operation above 1 MW_t. One of the last and most successful gas-cooled reactors in that series was the NERVA (Nuclear Engine for Rocket Vehicle Application). It operated at 1,100 MW_t for about 5 minutes[4]. Figure 3 shows a representative fuel configuration for this class of reactors.

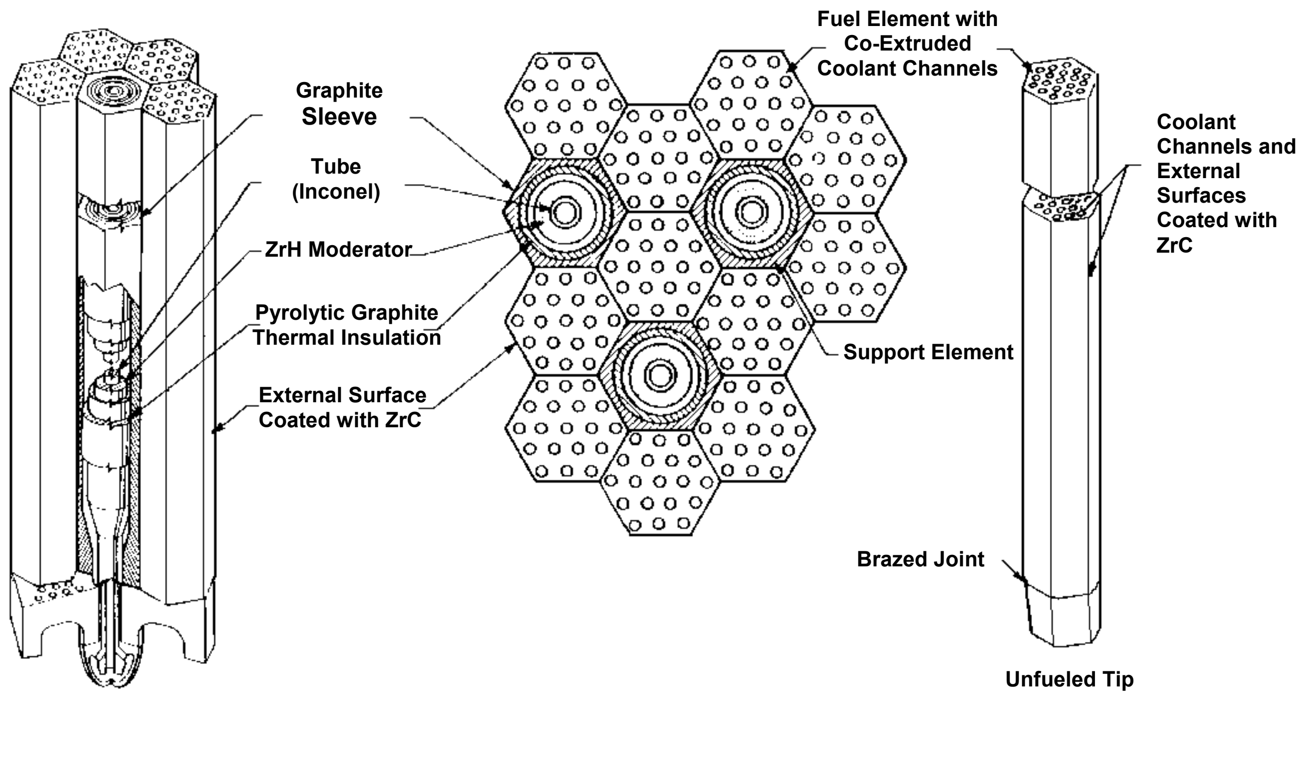

Figure 3. NERVA fuel configuration.

The basic fuel element was hexagonal with 19 coolant holes extruded with the form. Fuel compositions evolved with program progress. Fuel compositions tested included UO_2 extruded in a carbide matrix, UC_2 particles with pyrolytic graphite coatings extruded in a graphite matrix, and finally a composite of U, Zr, and C particles. All exterior and tube interior surfaces of these fuel elements were coated with zirconium carbide to inhibit reaction of the carbon with the hydrogen fuel.

Distributed among these fuel elements were “tie rods,” each of which had an Inconel tube down the center for cooling. Helium or helium-xenon working gas was circulated through the tie tubes. The cooling channel in the tie tube was surrounded by an annulus of zirconium hydride moderator. Outside of another gas gap channel was a pyrolytic graphite thermal insulator and finally a graphite sleeve to complete the hexagonal form. By controlling the placement and distribution of these tie rods, designers could control engine size and radial power density profile.

Under the Rover program, this fuel form was subjected to high temperature tests for short periods, the regime in which these reactors were designed to operate. The Russians have reported tests up to 3,000 K for one hour in a nuclear thermal propulsion configuration have been made, but US tests were mostly at 2,550 K and below, and then only for a few minutes. The 44-MW_t Nuclear Furnace (NF-1) was operated at 2,500 K for 109 minutes. There are no long-duration test data available for temperatures that high. Estimated masses of these reactor designs may be correlated by the relationship[8]

$$M = 1.8 + 0.00154 \ P \qquad (1)$$

where M is the mass in metric tons, and P is the power in MWth. These would be lighter than reactors designed to operate for years, but by that formula, a 60 MWth reactor (15 MWe) would have a mass of 1.89 metric tons.

For commercial gas-cooled reactors, fuels demonstrated have included UCO and UO_2 fuel kernels with SiC coating (Germany). An advanced fuel form for NERVA-type reactors would be comprised of UO_2 fuel kernels with ZrC coating. These kernels are under development in Japan and Germany.

2.1.2.2 NERVA Derivative

For application to the multi-megawatt propulsion mission, a NERVA Derivative design has been proposed[9]. Called the “Enabler”, this design is shown conceptually in Figure 4. Operating with C coated UC_2 fuel, the proponents of this design believed it was capable of 1,640 K reactor outlet temperature and to have a system specific mass of 3.1 kg/kW_e for a 10 MW_e system operating for 7 years. By changing to ZrC particle coating, it was thought to be operable with a reactor outlet temperature of 1,920 K and, because of the higher operating temperature, to have a system specific mass of only 2.8 kg/kWe. These claims may have been optimistic since heat rejection technology was perhaps overestimated and turbine materials to withstand such high temperatures have yet to be proven. Currently available commercial gas turbine technology allows turbine inlet (firing) temperatures of 1,700 K.[10]

On the other hand, commercial SiC coated UCO and UO_2 particle fuel has been amply demonstrated to have typical operating temperatures of 1,473 – 1,523 K.[11] No significant fission product release was seen in elevated temperature tests for periods up to 500 hours at 1,873 K for either fuel. ZrC coated UC_2 particle fuel was designed for operation at 3,200 K for 7 hours and should be able to achieve a sustained operating temperature up to 2,100 K, though that has not been conclusively proven. Advanced carbide fuels offer the potential for even higher temperature operation.

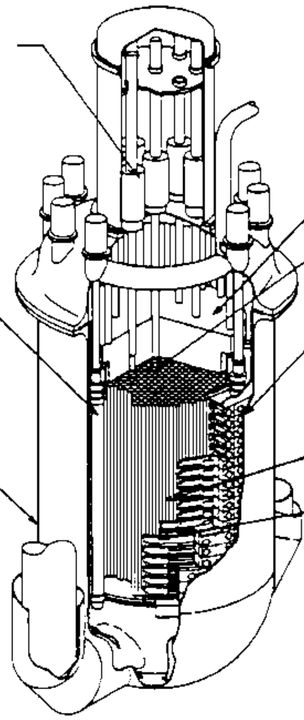

Figure 4. Configuration of the NERVA Derivative "Enabler" reactor design.

2.1.3 Other Cooling Options

Another option for heat removal from the reactor core is the use of liquid metal heat pipes. A lower power concept presently under development at the Marshall Space Flight Center uses heat pipes to drive a Stirling cycle engine for the production of electrical power.[12] Neither the heat pipe system nor Stirling engine technology scale well to the MW_e level.

Yet another option proposed for low power uses thermionic power conversion, so the heat from the reactor is carried away, at least partially, by electrons boiling from an emitter and crossing a gap to a cooled collector and by concomitant radiation between the emitter and the collector. Thermal efficiencies for thermionic power converters up to 17% have been reported.[13] Again, scaling to MW_e levels for thermionic systems is not practical.

2.2 Power Conversion Technology

Technologies for converting the reactor thermal power into electricity should be considered in connection with the reactor. These are divided into two classes, static and dynamic. Static methods involve only the flow of heat with no moving mechanical parts. Dynamic systems have moving parts.

2.2.1 Dynamic Systems

Dynamic systems are the most desirable for multi-megawatt applications because of several features: they operate at reasonably good thermodynamic efficiencies, their masses are reasonably small, and there is a wealth of industrial experience with the technologies. Dynamic systems discussed here include the closed Brayton cycle, the Rankine cycle, the Stirling cycle, and MHD systems.

2.2.1.1 Brayton Cycle

Brayton cycle power systems are in wide use throughout the world[14]. Open cycle Brayton systems power jet aircraft and auxiliary power units on tanks and in automobiles. For the multi-megawatt propulsion mission, however, the cycle must be closed such that the gases leaving the turbine will be returned to the compressor. Figure 5 shows the layout of a typical Brayton cycle proposed for power conversion in the MMW propulsion mission.[15]

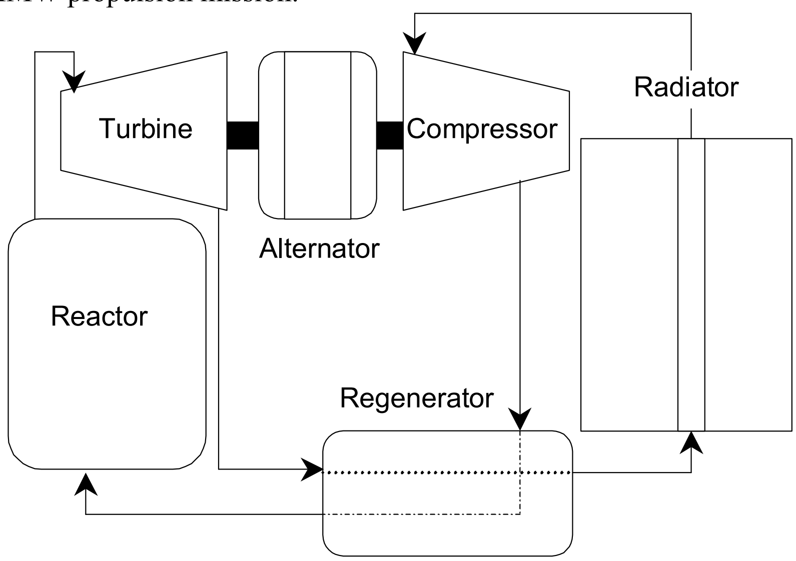

Figure 5. Typical Brayton cycle configuration.

2.2.1.2 Rankine Cycle

The Rankine cycle has been used for many years in electric power plants. Heat sources range from coal, gas, and geothermal to nuclear reactors. Figure 6 shows the elements of a Rankine power system.[15] Typically, molten Li is used for the primary coolant and K is the working fluid for the power conversion system.

Not shown in either Figure 5 or 6 is the auxiliary cooling system for the reactor shield, the alternator, and certain other components. This secondary radiator would operate at lower temperature than the primary radiator. Also not shown in Figure 6 are the separators required to remove liquid at selected stages in the turbine nor the system needed to separate liquid from vapor in the condenser.

2.2.1.3 Stirling Cycle

Of the popular thermodynamic cycles, the Stirling cycle has the greatest intrinsic thermodynamic efficiency, but its inherent limitation to small units means high specific mass. The free-piston Stirling engine has undergone substantial development in the last few years. A Stirling engine demonstration was part of the SAFE (Safe and Affordable Fission Engine) project. The engine, a more or less standard model from the Stirling Technology Corporation, was joined to an electrically heated heat pipe array in a vacuum chamber to generate about 300 W in a non-nuclear demonstration.[12] This is far from levels

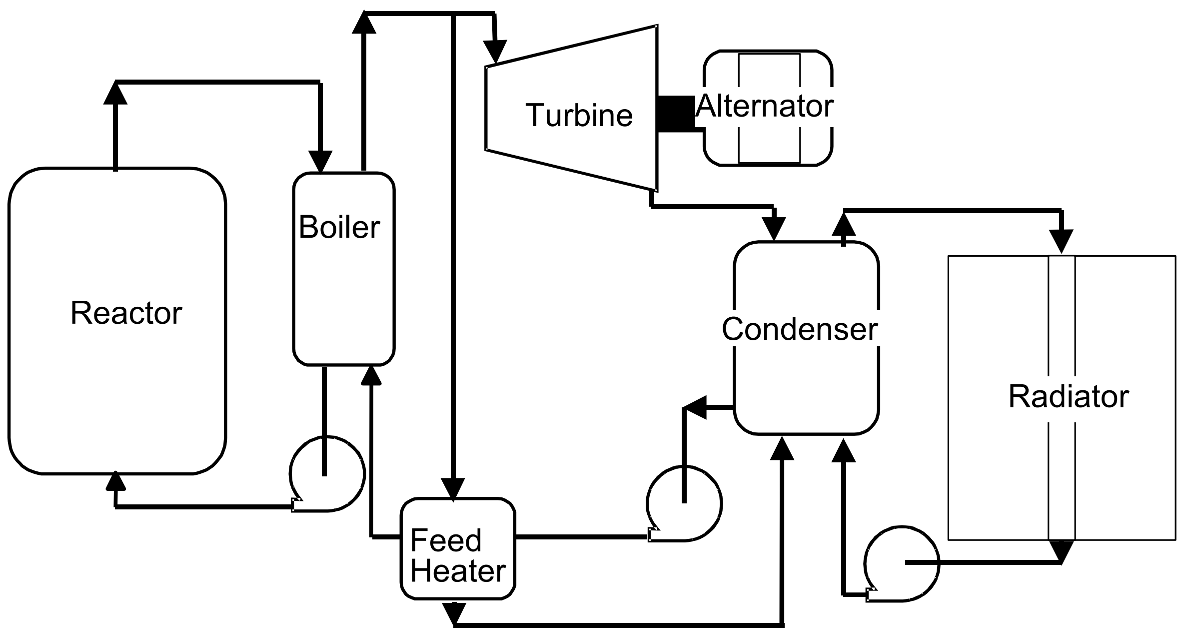

Figure 6. Liquid-metal cooled power system using the Rankine power cycle.

needed for the MMW mission. Scaling to larger power levels is difficult because the key to Stirling cycle efficiency is the capture and recycling of heat, which, by its nature, is limited in the speed and volumes over which it can proceed. Therefore, Stirling technology was not considered practical for further consideration here.

2.2.1.4 MHD

Several concepts for MHD power conversion have been proposed but are still considered highly advanced. One by Anghaie[16] makes use of the gaseous fuel in a vapor core reactor concept to provide direct power conversion using MHD, most likely with the Tulahoma disk MHD configuration.[17] This is similar to the concept proposed by Westinghouse.[18] Axial gas flow is directed radially over a disk located in a Helmholz coil pair. It is then returned to axial flow through a similar structure, generating MHD power in the process. The Marshall Space Flight Center is currently building a large blowdown facility that would allow operation of a prototype for about 10 seconds at 25 MW_{th}.[19]

Another MHD concept has been proposed by Berte.[20] His idea uses gaseous Cs as the working fluid and coolant in a solid core reactor. Residual radioactivity in the Cs stimulates ionization to improve electrical conductivity.

2.2.2 Static Systems

Static power conversion systems, as a group, operate at low thermal efficiencies because the currents involved are not conjugate with the driving potentials. It is generally acknowledged that they are not suitable for MMW power applications. Systems we considered include thermionic, thermoelectric, and alkali metal to electric conversion (AMTEC) systems.

The electric potential developed by thermionic systems is typically only a few volts, but it can be used to drive respectable currents when temperature differentials are large. Concepts making use of thermionic power generation have been built, tested, and used for a number of applications.

Thermoelectric and AMTEC[21-23] conversion systems were looked at but not considered for the high power applications of a MMW system.

2.2.3 Comparison

There has been considerable progress in both Brayton and Rankine cycle performance over the last few decades. Anex[24] compared overall thermal efficiency for Brayton systems alone with those from combined gas Brayton and steam Rankine cycles for commercial power plants. Growth in efficiency due to improvements in Brayton cycle technology, mostly due to higher turbine inlet temperatures rose from about 20% in the early 1950s to about 35% in the 1990s. Less progress was indicated for the Rankine systems

A comparison of specific masses estimated by various proponents[15,25,27] of both Brayton and Rankine systems is given in Figure 7. Rankine systems have considerable industrial experience on earth using water as the working fluid, but challenges of boiling, condensation, and separation in a microgravity environment are nontrivial. Further, long-term serviceability with potassium has yet to be demonstrated for Rankine system components. Operating Brayton systems at high temperatures offers the prospect of attractive specific masses, particularly if turbine inlet temperatures above 1,700 K can be achieved, but that has not been done. The best current technology seems to be the GE H-Class turbines, which operate at inlet temperatures of 1,700 K.

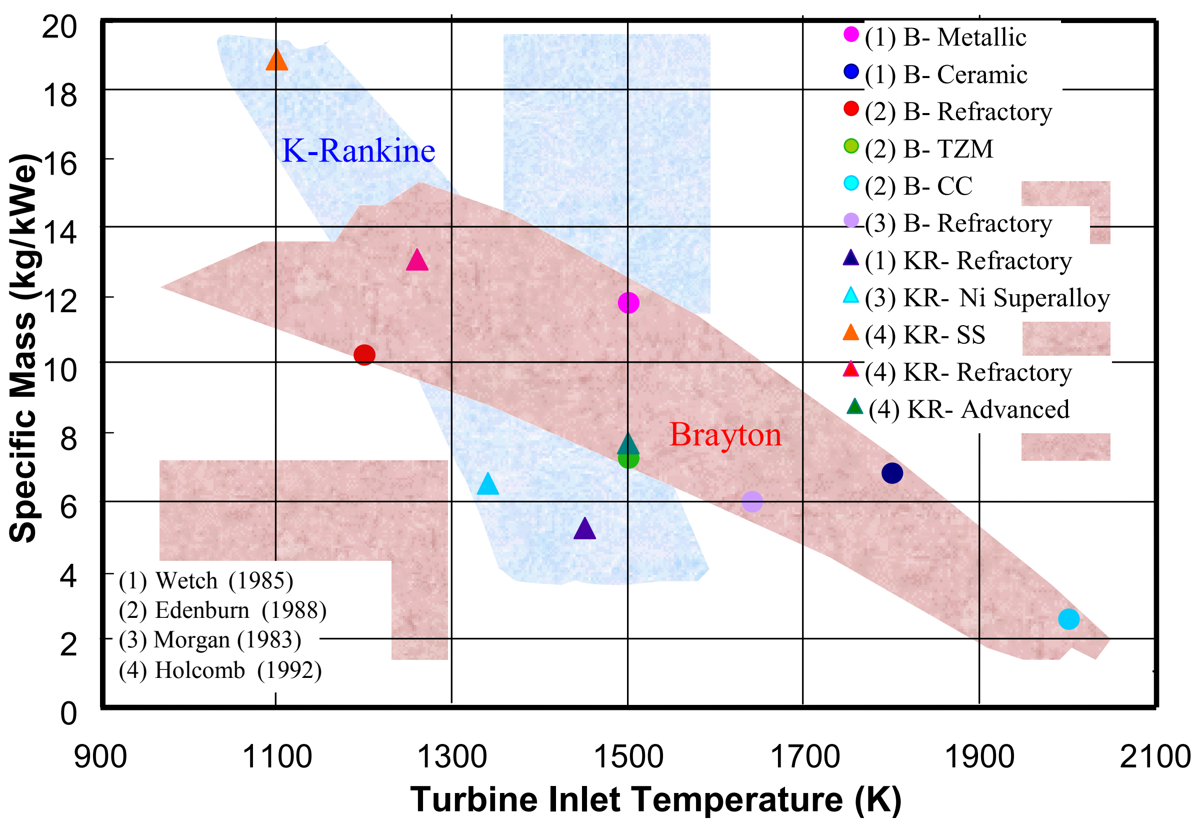

Figure 7. Specific mass trends for Rankine and Brayton systems as a function of turbine inlet temperatures.

We selected only Rankine and Brayton systems for further evaluation. Conventional wisdom is that while Stirling cycle systems have clear advantages when heat supply temperatures are moderate (<900 K) and power requirements are 50 kW or less, in comparison with Brayton cycles and probably Rankine systems, they have limited utility for the MMW application.[28] A number of unknowns need to be resolved before the MHD systems can move forward. Some of these issues include fundamental measurements on conductivities of the proposed working gases and operation at less than full power levels.

2.3 Heat Rejection

In space, waste heat may be radiated away into the coldness of the universal background temperature, or it can be conducted into matter, such as a gas stream, that is released into space. Almost all design concepts for MMW systems rely on radiator systems. Radiators of many different configurations have been proposed.[15, 29-37] Those considered include tube and fin, heat pipe, free droplet, and moving belt radiators.

Advantages of the pumped loop radiator include a well established fluid loop heat exchanger technology, a wide range of radiator fluids possible, and a wide range of operating temperatures. Disadvantages include limited heat rejection capability and the requirement for pumps, valves, and other moving parts. It also has potentially poor survivability from damage by meteoroids since a puncture of one of the fluid loops would result in loss of a considerable fraction of the cooling capability, depending on the segmentation built into the design.

Heat pipe radiators have received considerable attention in the last few years. Typical materials include Na as the working fluid, stainless steel mesh as a wick, and stainless steel tubing as the container. Carbon-carbon fiber material is also being considered for heat pipe structures.[38] Advantages of heat pipe technology include proven low specific mass heat transfer technology, high temperature operation and substantial heat rejection capability, high survivability (segmentation means puncture of an isolated heat pipe will not result in much loss of capability), and the ability for self starting with no moving parts. Limitations may include capillary force limits, viscous drag and sonic flow limits, entrainment of liquid in the flowing gas stream, and boiling rate limits. In comparison with pumped liquid radiators, heat pipe radiators have a more limited operating temperature range, since they are sealed systems, and optimal operation requires boiling and condensation at or near the pre-determined temperatures.

Membrane radiators collect fluid injected at the center of the membrane envelope, and reject heat through the rotating membrane as the fluid is driven by centrifugal forces along the inside surface of the membrane to a collection point. Advantages are that membrane systems may be relatively easy to deploy and have the potential low specific mass. Among the disadvantages are that significant technology development must be accomplished before these systems can be reduced to reality. Because of the large and integrated nature of the concept, there are potential survivability issues (single point failures can substantially degrade functionality). These systems are also complex in design with moving parts.

Exposed droplet radiators have extremely high surface area with minimal structural mass. This class includes charged particle, liquid droplet, and Curie point metallic particles radiating to space with each having generator and collector devices to close the cycle. Advantages of the droplet radiator concept include high survivability and low specific weight. Disadvantages are mainly the fact that these techniques are unproven technologies, particularly in the collection devices. Liquid droplets are very likely to have low emissivity, reducing efficiencies. Other concerns include inherent fluid/particle loss and the potential for spacecraft contamination. These systems have moderate complexity, and they will of necessity be designed with moving parts. Torque symmetry may be problematic in some implementations.

Another category of radiators includes liquid belts, heated drum belts, filaments, and some other concepts. Advantages of these kinds of radiators can be a very low specific mass and the potential for compact design for transportability. Disadvantages are a high vulnerability to debris damage and typically very complex design with moving parts. There is little experience in building such systems, and significant technology development would be required to generate a system for early implementation in the MMW system.

Performance of the various types of radiators has been estimated by their several proponents. Morgan et al. showed values of specific mass for a number of these concepts ranging from several thousandths of a kg/kW_{th} for exotic conceptual designs operating at 1,100 K to several tens of kg/kW_{th} for a shuttle fluid loop and Hermes system operating at 300 K.[29]. It should be remembered that the lowest of those values are probably optimistic, and only the higher specific mass data are actual results based on experiments or concept development.

Based on the relative state of development and attractiveness for the MMW application, heat pipe radiators were selected as the optimal technology for near term use. These are not yet fully qualified for use in space, and there are a number of outstanding technology issues, but solutions to these issues seem to be readily achievable given modest development effort. The materials combination to be used in these radiators will be determined based on specific system design parameters.

2.4 Power Conditioning

Systems for conditioning raw electrical power into forms usable by the various systems requiring electrical power will generally be fairly massive. Greatest among these for the MMW mission will be the RF drivers for the VASIMR engine, but there will also be numerous other loads that must also be supplied. Figure 8 shows relationships among the various components of the electrical system.

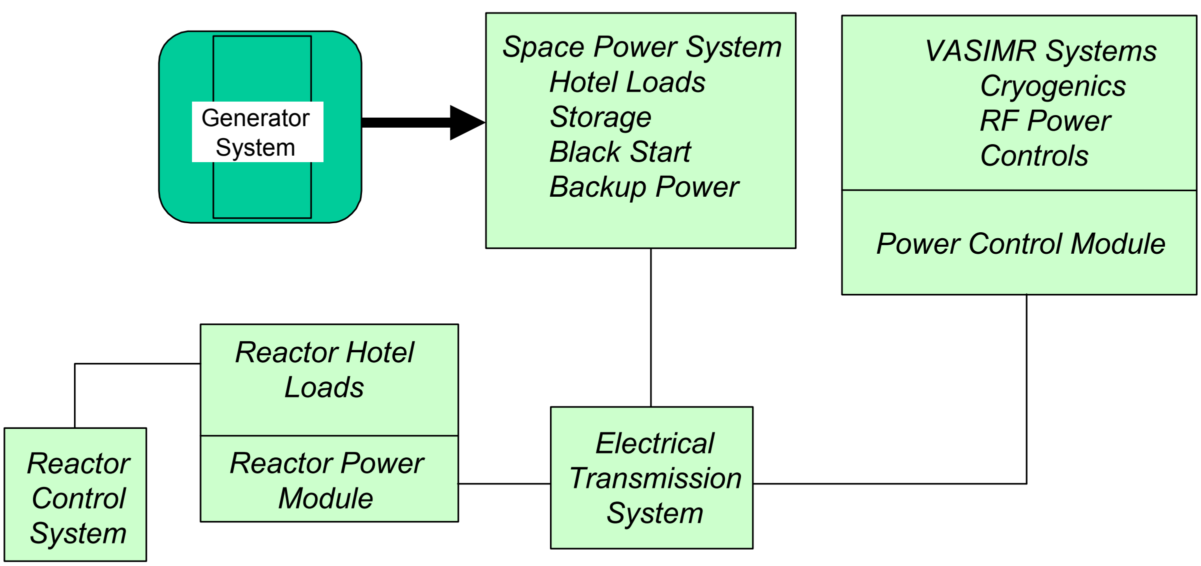

Figure 8. Functional relationships among various electrical system components.

The specific systems for generating RF power have not yet been identified. Present estimates are that frequencies of 4 MHz at 20-100 kV will be needed for ion cyclotron resonance heating of the VASIMR plasma. Present day components are not generally capable of operating at planned primary radiator heat rejection temperatures, so either there will need to be significant advances in component technology or there will need to be a refrigeration system or a low temperature heat rejection system. Trade studies will need to be performed to determine which of the latter two may be more advantageous. Some components in these kinds of systems are sensitive to radiation. Present-day semiconductor components do well to function dependably at 10^7 rads. Therefore, positioning these components to be in shielded areas or providing special shielding for them will be an important consideration.

Table 1 summarizes the performance expectations for these systems. Specific masses were not estimated, but these systems tend to be heavy because of the need to provide low-resistance pathways for electrical currents. We should point out that typical losses in most active components are on the order of 5% of power throughput. If the rated capacity is 15 MW and power must pass through the generator as well as one other system, nominally 1.5 MW will require rejection from the rated temperature of 450 K. That has significant consequences to radiator area and may justify a refrigeration system to get that power up to the main radiator temperature.

Table 1. Performance summary for the various components of the electrical systems.

System	Rating (MW)	Losses (%)	Temperature (K)
Generator	15[a]	6	TBD
Power Conditioning	TBD	6	450
Reactor Power Module[b]	15	6 (motors) 5 (power electronics) 2 (transformers)	450 (current technology motors and transformers) 450 and higher (advanced electronics[b])
Electrical Transmission	15	1	450
Power Control Module	10	5	450 and higher (advanced electronics[b])
Space Power System[c]	0.5 – 1.0	7	450 and higher (advanced electronics[b])

a. Based on 10 MW to VASIMR thrusters with balance for losses and other system functions. Power electronics assumed to be 10% of the load.
b. Current Technology Electronics – 450 K, Advanced Electronics – 850 K, Tube Tech/Diamonds/SiC 850 – 1300 K.
c. Space Power Hotel Loads TBD, assumed to be 5-7% of total.

2.5 System Integration

An interesting point can be demonstrated by a comparison given by Wetch[25] and shown here in Figure 9. This figure gives cumulative masses for various segments of a proposed Brayton cycle power system operating at 1,800 K turbine inlet temperature for a range of compressor inlet temperatures. Data are shown for an unrecuperated Brayton system and for a recuperated system operating at 80% effectiveness.

The interesting point in the figure is that the radiator mass is approximately twice the mass of the heat exchanger, the next most massive segment. The reactor was the least massive component. Electrical power conditioning mass was not included in this estimate.

It points out that in designing the MMW power system, it is critically important to consider all aspects of the system. For example, considerable premium is attached to operating the system at as high a temperature as possible and thus minimizing the mass of radiator structure needed.

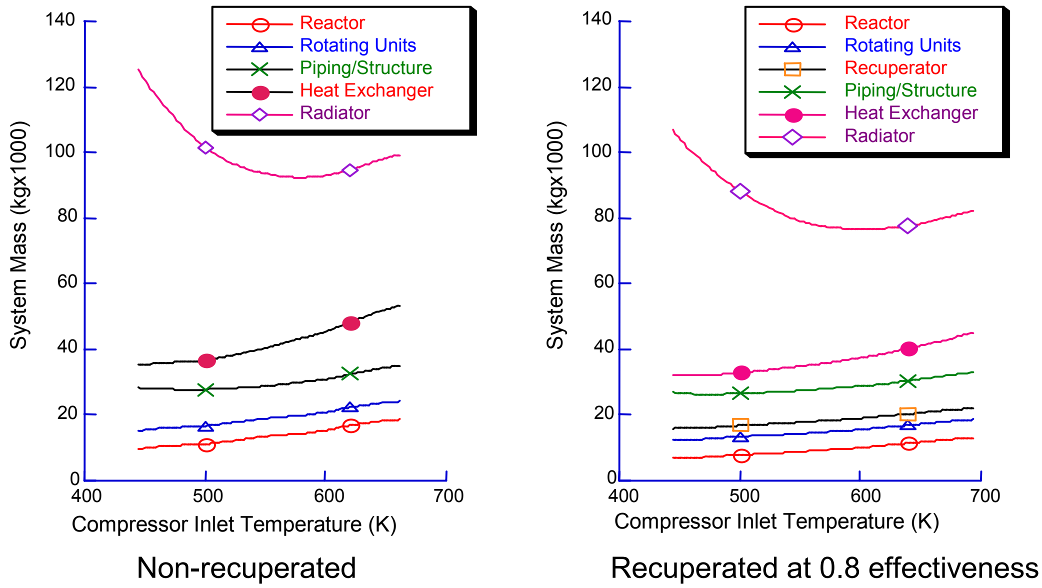

Figure 9. Cumulative system masses for various segments of a proposed Brayton cycle power system (from Wetch[25]).

2.6 Recommended Approach

2.6.1 Reactor/Power Conversion

After reviewing the technologies in the literature and touched on in the preceding discussion, there was no clear and compelling reason to choose either gas-cooled or liquid-metal-cooled reactor technologies as the best option for a near term MMW power system. Either a gas-cooled reactor of the NERVA Derivative type using a mixture of He and Xe as the working gas, operating in a Brayton cycle similar to the system shown in Figure 5, or a Li-cooled reactor based on the SP-100 design and driving a potassium Rankine power conversion system appear capable of providing the required power. Various configurations of these systems were subsequently analyzed and compared.

2.6.2 Heat Rejection

The most promising candidate for heat rejection is heat-pipe radiator banks. While these will require some engineering development, the technology for building them is progressing, and in the time frame of interest it should be reasonably in hand. Compared with pumped fluid radiators, these systems are more resistant to impact failures associated with the space environment, and they don't require moving parts. Other concepts discussed require more development than can be considered reasonably available in the next decade.

There is an issue for heat pipe radiators on Brayton systems as compared with their use on Rankine systems. For Rankine systems, heat rejection is at the saturation temperature of the working fluid for the design pressure. Because heat pipes are typically designed to boil at a specific temperature, they should work very well in that application. For Brayton systems, however, heat is rejected over a range of temperatures from the turbine outlet temperature to the compressor inlet temperature, often several hundred degrees. For some, there is a concern that heat pipes will not be well suited to that situation. Heat pipe advocates point out that even using the same materials, heat pipes can be designed to operate at different temperatures by installing different working fluids, and they work reasonably well, even away from their designed optimum temperature.

2.6.3 Power Conditioning

As discussed above, considerable advances will be needed in most areas to design and build efficient and reliable systems for meeting power conditioning requirements. We have no specific recommendations for these systems at this point.

Aside from the general need for heat removal from electrical systems, an area for specific consideration will be the extent to which superconducting circuits in transformers, motors, transmission lines, etc. can be useful in improving performance and reducing required heat rejection system mass. Providing the operating environment for such superconductors could be problematic but worth the cost.

3.0 TRADE STUDY

To further investigate options for reactor configuration and power conversion system technology, we performed a design trade study in which we employed some existing analytical tools.

3.1 System Constraints

A target specific mass of 3-5 kg/kW$_e$ had been set for the power system, which included the propulsion unit but not the fuel. In addition, the system was subject to several constraints based on operational specifications and modes of transportation into space. Operational specifications for this design included a design lifetime of seven years, including a nominal electric power requirement of 15 MW$_e$ with an assumed mission profile of 120 days at full power, 60 days in hot standby, and another 120 days of full power, repeated several times. The assumed electrical load was 15 MW$_e$. Equipment for each power system was expected to fit into the launch bay of an advanced space transportation vehicle.

3.2 Concept Trade Study Set

Two main classes of power systems were considered. One used Brayton cycle power conversion (Figure 5), but included both gas-cooled and liquid-metal-cooled reactors. The other used a liquid-metal-cooled reactor and a liquid metal Rankine cycle power conversion system. That system is shown schematically in Figure 6. The configurations considered are listed in Table 2.

In each case, two levels of availability were assumed regarding reactor fuel technology. The first was relatively state-of-the art technology (which still may require considerable work to achieve), while the second was a "growth" or advanced technology.

For liquid metal cooled reactors, the near-term technology was UN fuel in Nb-1Zr cladding with a reactor coolant exit temperature of 1,350 K, as called for in the SP-100 design.[39] The "growth" option assumed a cladding change to ASTAR 811C, which is believed to allow a reactor coolant exit temperature of 1,500 K.

For gas-cooled reactors, we chose as a reference the NERVA Derivative technology.[9] As a baseline, we chose UC_2 (coated uranium carbide particles in a graphite matrix) fuel with NbC coating. This was assumed to have a gas exit temperature of 1,640 K. "Growth" options included UC_2 fuel with ZrC coating and UO_2 with SiC and ZrC coatings. Reactor outlet temperatures assumed ranged from 1,520 K for the UO_2/SiC option to 2,100 K for the UO_2/ZrC option, though it must be emphasized that the latter is well beyond turbine inlet temperature capabilities foreseeable in the near future.

Table 2. Concept trade study set developed for a 15 MW power system.

Concept	Fuel	Clad/ Coating	Neutron Spectrum	Reactor Coolant	Coolant Outlet Temp (K)	Power Conversion	Technology Base
Rankine							
UN/Nb-1Zr/Li-K	UN	Nb-1Zr	Fast	Li	1,350	K-Rankine	SP-100
UN/Nb-1Zr/Ga-K	UN	Nb-1Zr	Fast	Ga	1,350	K-Rankine	SP-100
UN/Nb-1Zr/Li-Na	UN	Nb-1Zr	Fast	Li	1,350	Na-Rankine	SP-100
UN/Nb-1Zr/Ga-Na	UN	Nb-1Zr	Fast	Ga	1,350	Na-Rankine	SP-100
UN/ASTAR 811C/Li-K	UN	ASTAR 811C	Fast	Li	1,500	K-Rankine	SP-100[a]
UN/ASTAR 811C/Ga-K	UN	ASTAR 811C	Fast	Ga	1,500	K-Rankine	SP-100[a]
UN/ASTAR 811C/Li-Na	UN	ASTAR 811C	Fast	Li	1,500	Na-Rankine	SP-100[a]
Brayton							
UC_2/NbC	UC_2	NbC	Thermal	He-Xe	1,640	He-Xe Brayton	NERVA Derivative
UC_2/NbC IHX	UC_2	NbC	Thermal	He-Xe	1,640	Brayton Indirect	Intermediate Heat Exchgr
UC_2/ZrC	UC_2	ZrC	Thermal	He-Xe	1,920	He-Xe Brayton	NERVA Derivative[a]
UO_2/SiC	UO_2	SiC	Thermal	He-Xe	1,520	He-Xe Brayton	Commercial HTGR
UO_2/ZrC	UO_2	ZrC	Thermal	He-Xe	2,100	He-Xe Brayton	Advanced HTGR
UN/Nb1Zr/Li	UN	Nb-1Zr	Fast	Li	1,350	He-Xe Brayton	SP-100

a. Growth Technology.

A final case considered was a liquid-cooled reactor operating a Brayton system through a heat exchanger. It used UN fuel with Nb-1Zr cladding. Reactor outlet temperature for this system was 1,350 K.

3.3 Approach

We evaluated these concepts in terms of their specific masses, counting all the elements of the power system, including the reactor, shield, power conversion, power conditioning (sometimes called power management and distribution (PMAD)), and heat rejection systems.

Liquid cooled reactor masses and masses of Rankine power conversion systems were estimated using ALKASYSM, a modified version of the ALKASYS-PC code.[Error! Bookmark not defined.] We modified ALKASYS-PC by adding flexibility to use other fluids than lithium and potassium as either primary coolant or working fluid, and to use an optional electric motor to operate the boiler feed pump in lieu of the vapor-driven turbine assumed in the code. The temperature at which structural material changed from Nb-1Zr to ASTAR 811C was also made arbitrary, and an option was added to allow blade tip velocity to be specified as a Mach number and limited rotational speeds to those that would not exceed 276 MPa blade root stress. Reactor structural materials assumed were Nb-1Zr for reactor temperatures less than 1,360 K, and the tantalum alloy ASTAR 811C above that. Fuel cladding is assumed in the code to be ASTAR 811C at all temperatures. The difference in overall reactor mass in accepting this assumption as compared with using Nb-1Zr density for the low-temperature cladding is inconsequential. For details regarding that code conversion see Ref. [40].

Gas-cooled reactor masses were based on the Enabler NERVA Derivative reactor design[9] using a polynomial fit to interpolate mass estimates at 5, 10, 40, and 70 MW_e to the 15 MW_e power used as a basis for comparison here. Scaling to different operating temperatures than 1,920 K given as the Enabler gas exit temperature was based on the assumptions that

1. Reactor overall mass density and configuration would remain essentially constant,
2. Reactor volume would increase as the 3/2 power of flow areas required to carry thermal power,
3. Thermal power from the reactor would change with thermodynamic efficiency of the Brayton systems connected to them,

Flow velocities and gas pressures would remain constant.

Dr. Lee Mason, from the NASA Glenn Research Center (GRC), provided masses for the components of the Brayton power conversion system using a model available at GRC.[41] His results included cycle thermodynamic efficiency for each of the Brayton systems identified in Table 2. They also included, among other things, compressor pressure ratio, turbine temperature ratio, radiator area, heat exchanger mass (when used), power conversion system mass, and power management and distribution system (PMAD) system mass. For consistency with the liquid-metal Rankine system analyses, we assumed that 1% of the reactor power was deposited in the shield. That heat combined with 5% of the alternator power were assumed radiated from a secondary radiator, assuming a radiator area of 1.39 m^2/kW_t (taken from GRC data), two sided radiators, and 6 kg/m^2 (planform) areal density. Primary radiator areas were reduced from GRC estimates to account for power in the secondary radiator that was included in the GRC primary radiator loads

Our basis for shield mass comparison was that used in the SP-100 study: an area located 22.5 m from the center of the reactor with required gamma doses not to exceed 5×10^5 rad and the fast neutron (1 MeV equivalent) fluence not to exceed 1×10^{13} n/cm^2 over a 7 year operating life. These are representative values for protection of near-term electronics and not for biological protection.

For liquid metal cooled reactors, shield masses were estimated using ALKASYS-PC logic, which is based on Refs.[42-44]. We chose the SP-100 circular shielded area 4.5 m in diameter. For gas-cooled reactors, shield masses were scaled from the Enabler NERVA Derivative design. In that study, shield masses were based on a gamma dose of only 5 rad/yr at a distance of 100 m from the reactor. Polynomial-interpolation of published data for powers around 15 MW_e was used to scale to 15 MW_e under those same constraints. The resulting shield mass was 11,100 kg. We used $1/r^2$ scaling on dose to relocate the protected area from 100 m to the 22.5-m position and the logic for shield thickness determination in ALKASYSM to scale from the shifted Enabler design dose to the reference doses. We then scaled for reactor size variations with reactor volume to the 2/3 power.

Primary thermal radiators in both system classes were assumed to have an areal mass density of 6 kg/m^2 (planform). That is an improvement over the nominally 20 kg/m^2 found in ALKASYSM results but consistent with values found in our own conceptual design (Appendix A), and it was the value used in GRC Brayton system analyses. Two-sided radiators were assumed.

PMAD and parasitic load heat rejection mass was included in the PMAD system mass for both system types.

Masses for the PMAD were assumed the same for both systems at 15,106 kg. We assumed as a baseline that both system types used four turbine/generator sets, though examination of a two-turbine set was performed for the Rankine system. For other components, masses found by the GRC Brayton analysis were assumed for Brayton systems, and those generated by ALKASYSM were accepted for the Rankine systems.

Assumptions beyond those mentioned above were required in the modeling analyses performed. These assumptions used are believed to be reasonably representative of current state-of-the-art, and they are listed in detail in Ref. [45].

3.4 Results

Results of calculations performed to evaluate the overall specific mass (kg/kW$_e$) for the two configurations chosen as baseline cases are shown in Table 3: Those cases were (1) direct heated gas using NERVA Derivative reactor technology for the Brayton system, and (2) lithium-cooled SP-100 reactor technology with potassium as the working gas in a Rankine system having a condenser temperature of 800 K.

Table 3. Parameter comparison for the two baseline comparison cases.

Parameter	Gas Brayton Baseline	Liquid Rankine Baseline
Turbine inlet temperature (K)	1,640	1,260
Reactor thermal power (kW$_t$)	61,579	59,108
Thermal efficiency (%)	24.4	25.4
Reactor mass (kg)	6,648	14,654
Shield mass (kg)	4,290	9,709
Heat exchanger mass (kg)	0	2,254
Turbine/generator mass (kg)	4,480	43,614
Main radiator temperature (K)	746-541	756
Main radiator area (m^2)	5,563	3,379
Secondary radiator area (m^2)	1,899	283
Total radiator mass (kg)	22,386	11,039
Power conditioning mass (kg)	15,106	15,106
Total mass (kg)	52,909	96,376
Specific mass (kg/kW$_e$)	**3.53**	**6.43**

The main contributors to the disparity in masses for these two cases are the great differences in turbine/generator mass, reactor and shield mass, and radiator mass. One important reason for the differences in these estimates is the relative conservatism built into the ALKASYSM design algorithms compared with the more aggressive designs in the GRC analysis. There are additional reasons turbine/generator masses should be different between these cases. One is the need for vapor-liquid separation equipment at one or more places in the turbine to keep the vapor quality in the turbine high. Also, one would expect greater robustness in the Rankine turbine because of liquid droplets when quality is less than unity. For the Brayton turbine, temperature and pressure ratios are optimized for efficiency. For the Rankine system, the turbine outlet temperature and pressure are set by the condensing temperature for the working fluid. The turbine mass, and therefore system overall specific mass, is highly sensitive to radiator temperature, as will be discussed later.

To examine the realism of the turbine mass estimates, we compared the turbine/generator masses predicted by the GRC Brayton model and by the ALKASYSM code for Rankine systems with data from General Electric Power Systems' large commercial turbine/generator sets[46]. The resulting plot is shown in Figure 10. The masses given in the GE data are for complete open cycle Brayton systems including turbines, generators, housings and structural supports, sitting on a pad. The log-linear fit shown gives a mass at 15 MW_e of 108,961 kg, while the turbine/generator mass predicted by ALKASYSM for condensing temperature of 800 K is 43,614 kg. The mass predicted by the Brayton model (see Table 3) is 4,480 kg, substantially below either of those values.

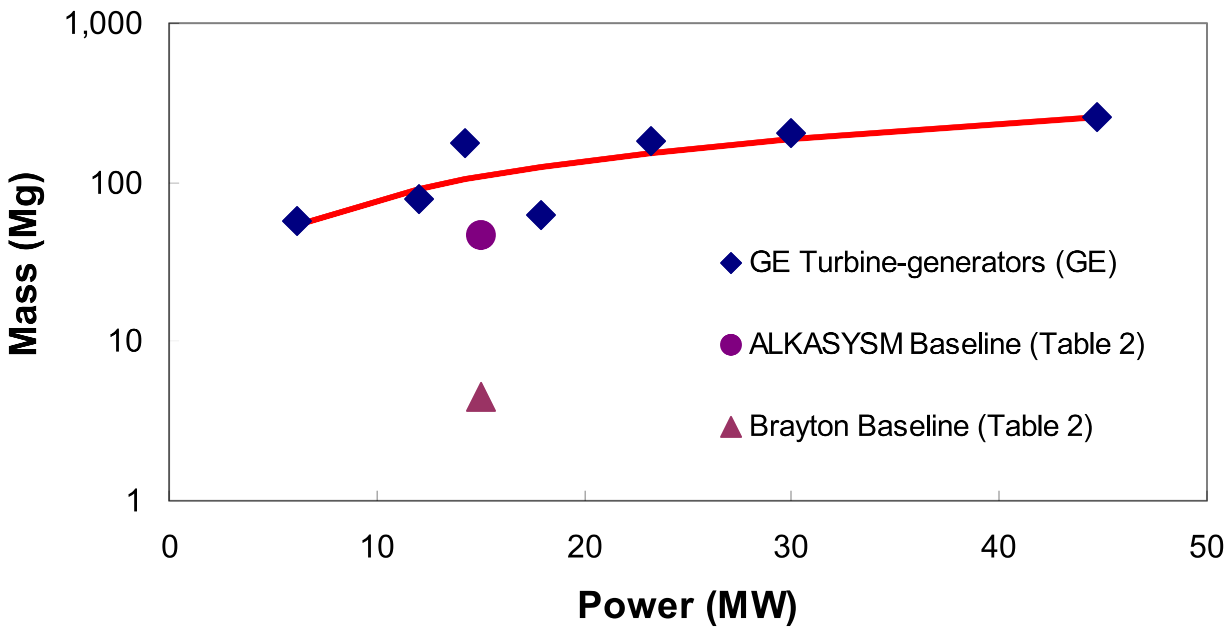

Figure 10. Comparison of commercial turbine masses with those predicted by the Glenn Research Center model and by ALKASYSM for baseline cases.

A further datum for comparison is an estimate made by Morgan et al.[15] that a 10-MW Brayton power conversion system for space applications would have a mass of about 25,800 kg. The fit in Figure 10 gives 79,505 kg for 10 MW_e terrestrial systems, more than three times the value of Morgan et al. The estimate of Morgan et al. for a liquid-metal power conversion system in space is 33% larger than for a Brayton system.

The turbine/generator mass values of Morgan et al. scaled to 15 MW_e using the log-linear slope of Figure 10, are 35,359 kg for the Brayton system and 47,008 kg for the Rankine system. The latter number is surprisingly close to the ALKASYSM prediction of 43,614 kg. If we used the 35,359-kg value for the baseline Brayton system, the overall specific mass for the Brayton reference case would increase from 3.53 to 5.59 kg/kW_e, not much different from the 6.43 kg/kW_e predicted by the more pessimistic ALKASYSM model for the liquid-metal Rankine reference case.

We now consider individual results for the two systems separately to show the effect of various parameter changes on the system specific mass.

3.4.1 Brayton Systems

Table 4 shows results for the Brayton power systems. Data in the upper part of the table are from the Glenn Research Center while data for radiators, reactor, and shield come from INEEL scaling.

Table 4. Results from Glenn Research Center and INEEL analysis of Brayton power systems.

Configuration (Table 2)	UC2/NbC	UC2/NbC IHX	UC2/ZrC	UO2/SiC	UO2/ZrC	UN/Nb1Zr/ Li
Turbine inlet temp (K)	1,640	1,640	1,920	1,520	2,100	1,350
Thermal power (kW_{th})	61,579	61,579	54,283	61,579	50,614	75,281
Compressor pressure ratio	2	2	2.2	2	2.3	1.9
Turbine temperature ratio	3	3	3.3	3	3.5	2.7
Thermal efficiency (%)	24.4	24.4	27.6	24.4	29.6	19.9
Heat exchanger mass (kg)	0	789	0	0	0	844
Turbine/generator mass (kg)	4,480	4,480	4,210	4,477	4,091	4,769
PMAD mass (kg)	15,106	15,106	15,106	15,106	15,106	15,106
Main radiator area (m^2)	5,563	5,563	3,294	7,639	2,502	11,232
Secondary radiator area (m^2)	1,899	1,899	1,798	1,899	1,747	2,090
Radiator Mass (kg)	22386	22386	15276	28614	12747	39966
Reactor Mass (kg)	6,648	6,648	7,000	5,932	7,209	6,741
Shield Mass (kg)	4,290	4,290	4,440	3,976	4,528	4,330
Total Mass (kg)	52,909	53,699	46,032	58,105	43,682	71,756
Specific Mass (kg/kW_e)	**3.53**	**3.58**	**3.07**	**3.87**	**2.91**	**4.78**

In analyzing these data, it is no surprise that the configuration with the highest turbine inlet temperature (UO_2/ZrC, 2100 K) has the lowest specific mass and vice versa. The highest specific mass shown is the one for which the reactor is cooled with lithium followed by a liquid-to-gas heat exchanger. It generates the most thermal power and has by far the largest radiator area because of the low temperature as well as the high power. Figure 11 shows graphically the relationship of the various mass components to turbine inlet temperature. Clearly, the greatest contributor to reduced system mass is reduction in radiator mass.

3.4.2 Rankine Systems

A number of analyses were performed for Rankine systems. We begin with Table 5, which is similar to Table 4, showing corresponding data for the assumption of 800 K condensing temperature. Note that turbine inlet temperatures have been reduced to make the reactor outlet temperatures 1,350 and 1,500 K, respectively. Note that changing from lithium to gallium in the primary circuit and from potassium to sodium in the secondary each result in an increase of system specific mass.

Several observations may be made from these data.

- The higher turbine inlet temperature results in increased system mass, though reactor mass is reduced by about one fourth.

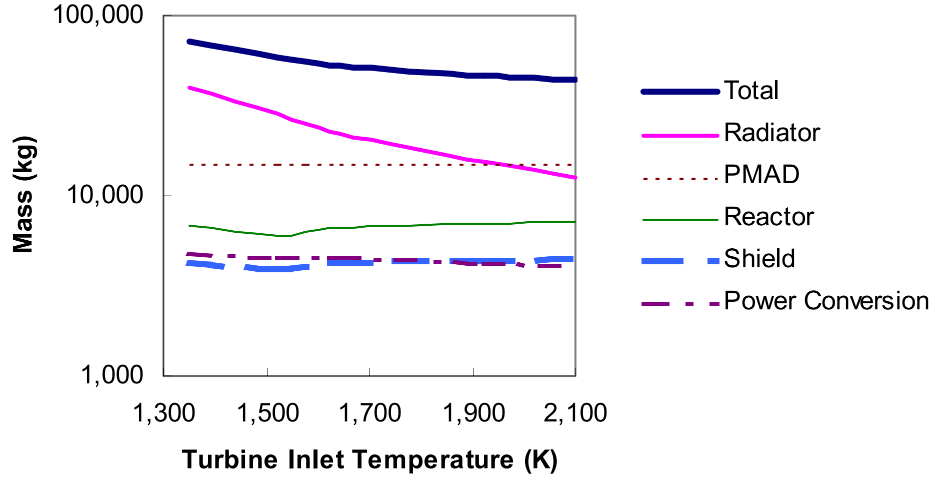

Figure 11. Brayton system mass decreases with increasing turbine inlet temperature.

Table 5. Results for various Rankine cycle configurations assuming 800-K condenser temperature.

Configuration (Table 2)	**UN/Nb-1Zr/Li-K**	**UN/Nb-1Zr/Ga-K**	**UN/Nb-1Zr/Li-Na**	**UN/ASTAR 811C/Li-K**	**UN/ASTAR 811C/Ga-K**	**UN/ASTAR 811C/Li-Na**
Turbine inlet temp (K)	1,260	1,260	1,260	1,410	1,410	1,410
Thermal power (kWt)	59,108	59,108	62,026	49,819	49,819	49,436
Thermal efficiency (%)	25.4	25.4	24.2	30.1	30.1	30.3
Heat exchanger mass (kg)	2,254	3,296	1,205	868	960	493
PMAD mass (kg)	15,106	15,106	15,106	15,106	15,106	15,106
Main radiator area (m^2)	3,397	3,397	3,626	2,665	2,665	2,635
Secondary radiator area (m^2)	283	283	289	264	264	263
Radiator mass (kg)	11,039	11,039	11,746	8,789	8,789	8,696
Reactor mass (kg)	14,654	42,496	15,313	11,691	35,092	11,612
Shield mass (kg)	9,709	5,621	9,895	8,216	3,855	8,196
Turbine/generator mass (kg)	43,614	43,614	292,801	57,820	57,820	468,938
Total mass (kg)	96,376	121,172	346,065	102,490	121,622	513,041
Specific Mass (kg/kW$_e$)	**6.43**	**8.08**	**23.07**	**6.83**	**8.11**	**34.20**

- Sodium as the working fluid in the Rankine system increases the mass of the turbines by about seven times, but it has little effect on reactor mass. The increased turbine size is due in part to the much greater specific volume of saturated sodium vapor than saturated potassium vapor at the same temperature, nominally by a factor of four. Liquid sodium also exhibits nominally twice the viscosity of liquid potassium, though it has a higher specific heat and thermal conductivity.

- Turbine/generator mass is dominant in all cases shown. We examined a case similar to the Rankine baseline case, but where only two turbine/generator units were assumed rather than four. Specific mass increased by about 10% with fewer units.

- Gallium in the primary circuit nominally triples the mass of the reactor over the lithium primary circuit coolant case. Gallium has a lower thermal conductivity than lithium, implying larger areas for heat transfer, and it is an order of magnitude denser, which in itself will increase the reactor mass. It has a lower vapor pressure for a given temperature but a much lower specific heat, meaning higher mass flow rates to carry the required power. There are also issues of corrosion and intersolubility with structural materials for gallium.

- All of the Rankine concepts considered here are above the 5 kg/kW_e goal on the range of desired specific masses. However, recall that the estimates produced by the ALKASYSM code are conservative, and more aggressive designs could reduce masses by several tens of percent.

The temperature of the radiator and condenser has a strong influence on the system mass. Figure 12 shows how the various component masses vary as the temperature of the condenser is varied for Rankine-cycle cases where the reactor coolant exit temperature is 1,350 K. Similar behavior is seen in all of the other Rankine-cycle cases examined. Note that the ordinate is logarithmic. Increasing the condensing temperature above 800 K has little effect on overall mass, but reducing it increases mass markedly.

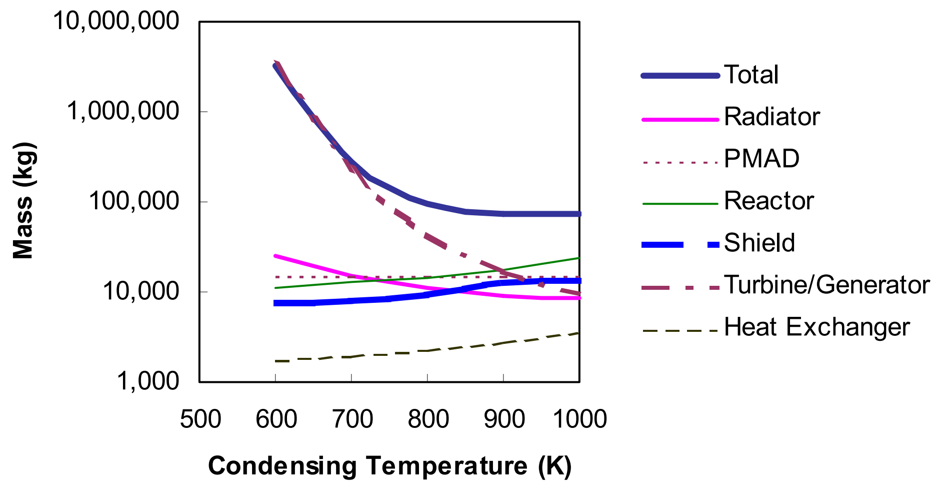

Figure 12. Variation in mass of Rankine system components with variations in condenser temperature for Li-cooled reactor having a 1,350-K turbine inlet temperature.

We present a comparison of the effects of changing to an electric motor on the baseline and "growth" configurations for the lithium-cooled potassium option in Table 6. Assumed condenser temperature was 800 K. It will be seen there that the addition of the motor results in a slight increase in reactor mass. The difference in specific mass is less than 1%.

A further comparison in Table 7 shows the effects of using direct boiling potassium in the reactors rather than a separate primary coolant, again for an assumed condensing temperature of 800 K.

Specific masses are a little lower for the direct boiling, high-temperature case due to lower reactor power allowing smaller components generally. Lower power is due to increased efficiency with higher turbine inlet temperature. Reactor mass is substantially increased for the 1,350-K coolant exit temperature while it is reduced for the 1,500-K case upon changing to direct boiling. That is due to the difference in

Table 6. Effects of changing from a vapor-driven turbine to an electric motor for feed pump power are minimal.

Configuration (Table 2)	UN/Nb-1Zr/Li-K Turbine	UN/Nb-1Zr/Li-Na Electric Motor	UN/ASTAR 811C/Li-K Turbine	UN/ASTAR 811C/Li-K Electric Motor
Turbine inlet temp (K)	1,260	1,260	1,410	1,410
Thermal power (kWt)	59,108	59,122	49,819	49,813
Thermal efficiency (%)	25.4	25.4	30.1	30.1
Heat exchanger mass (kg)	2,254	2,606	868	1,082
PMAD mass (kg)	15,106	15,106	15,106	15,106
Main radiator area (m^2)	3,397	3,402	2,665	2,745
Secondary radiator area (m^2)	283	283	264	264
Radiator mass (kg)	11,039	11,056	8,789	9,027
Reactor mass (kg)	14,654	14,657	11,691	11,690
Shield mass (kg)	9,709	9,710	8,216	8,216
Turbine/Generator mass (kg)	43,614	44,484	57,820	58,305
Total mass (kg)	96,376	97,619	102,490	103,426
Specific Mass (kg/kW$_e$)	**6.43**	**6.51**	**6.83**	**6.90**

Table 7. Direct boiling of the working fluid gives marginally improved performance.

Configuration (Table 2)	UN/Nb1Zr/Li-K	UN/Nb1Zr/Li-Na Direct Boiling	UN/ASTAR 811C/Li-K	UN/ASTAR 811C/Li-K Direct Boiling
Turbine inlet temp (K)	1,260	1,350	1,410	1,500
Thermal power (kWt)	59,108	52,577	49,819	45,945
Thermal efficiency (%)	25.4	28.53	30.1	32.65
Heat exchanger mass (kg)	2,254	0	868	0
PMAD mass (kg)	15,106	15,106	15,106	15,106
Main radiator area (m^2)	3,397	2,883	2,665	2,361
Secondary radiator area (m^2)	283	268	264	254
Radiator mass (kg)	11,039	9,453	8,789	7,846
Reactor mass (kg)	14,654	30,483	11,691	10,368
Shield mass (kg)	9,709	5,054	8,216	4,360
Turbine/Generator mass (kg)	43,614	39,229	57,820	53,239
Total mass (kg)	96,376	99,325	102,490	90,919
Specific Mass (kg/kW$_e$)	**6.43**	**6.62**	**6.83**	**6.06**

reactor configuration produced by the design algorithm, and in particular, in the mass of the pressure vessel, which is much larger for the 1,350-K case. If the radiator condensing temperature is increased from 800 to 900 K for the 1,500-K direct boiling case, the specific mass drops to 3.92 kg/kW$_e$, mostly because of a decrease in turbine/generator mass.

Another point to be made here is that none of the Rankine system radiators as sized by the ALKASYSM code would fit into the launch bay of present-day lift vehicles without some ingenious packaging and deployment mechanisms. The same problem would exist for the Brayton systems.

3.5 Trade Study Findings

This trade study compared specific masses for various configurations of gas-cooled reactors with Brayton cycle power conversion systems and liquid-cooled reactors having both Rankine and Brayton cycle power systems. The main conclusion was that either power system option has the potential to approach the specific mass objective of 3–5 kg/kW_e, but realization of that goal for either concept will require considerable effort. Gas-cooled Brayton cycle concepts examined appeared to fall within that band, while the liquid-cooled Rankine cycle systems were higher. Those results could be strongly influenced by more optimistic assessment of liquid-metal Rankine component masses and less optimistic estimates of Brayton system turbine/alternator masses.

Substituting electric motor driven feed pumps for turbine driven pumps slightly increased (less than 1%) system specific masses. Using direct boiling potassium instead of liquid lithium offered small (12%) reduction in specific mass for the advanced, high temperature system, but increased the specific mass for the nearer-term, lower-temperature case. Substituting gallium for lithium or sodium for potassium each resulted in much higher specific masses.

Increasing condensing temperature from 800 K to 900 K reduced system specific mass by approximately one fourth for Rankine systems, but further increases raised the specific mass. Going to lower condensing temperature drastically increased system specific mass. System specific mass for gas-cooled Brayton systems showed moderate improvement with increasing turbine inlet temperature, but it is not clear that temperatures above 1,700 K can be achieved in the near future.

4.0 KEY TECHNICAL ISSUES

A key topic for discussion here is the identification of key technical issues to be resolved if specific mass goals are to be met. Further, some technologies appear to be in need of advance if the required functions are to be achieved at all.

Although the principal focus of this work is the reactor, it is important to consider the entire power plant in assessing which technologies are in the best position for additional work.

4.1 Reactor

Perhaps the greatest single impact on the performance of a MMW power system is the development of high temperature, high burnup fuels and fuel cladding. Tricarbide fuels are high on the list of interesting ones to examine. Present day research and commercial power applications have not had the need to go to the high temperatures needed for success in this MMW endeavor. As a result, there are few experimental data on the ability of various fuel forms to resist swelling and retain fission products at elevated temperatures of 1300 K and higher. A related concern is the basic mechanical integrity of the fuel elements in the dynamic environment of a space vehicle. While cladding should mechanically constrain fuel and thus prevent unwanted shifts in local reactivity, it is also necessary in gas systems to prevent spallation of particles that could be erosive to turbine and compressor blades.

Safe assembly and startup is always a concern. While this doesn't appear to pose any insurmountable obstacles, design and process development must be advanced to ensure that the reactor systems can be safely and reliably assembled and reactor operation initiated in the space environment. Sharply decreasing reactor operating power or shutdown with subsequent restarting must also be demonstrated. Further, there must be the development of procedures for a safe and dependable end-state of the reactor systems once their mission is complete, particularly for a vehicle returning to earth.

4.2 Power Conversion

There is the need for development of rotating components and their supporting structures that will operate at higher temperatures than are presently available. Advances are being made in qualifying refractory alloys, single crystal materials, and even ceramics for such high temperature service, but, at least for Brayton systems, the MMW program would benefit by more extensive work in that area, reaching ever higher operating temperatures. Long life needs to be demonstrated in high-temperature Rankine systems using potassium as the working fluid.

Superconducting generators and motors can do a lot to minimize the overall system mass by eliminating the need to reject so much low-grade heat from the power conversion system. However, superconductivity comes at the price of operating at cryogenic temperatures, implying added mass for refrigeration systems. Methods for providing superconducting windings in generator stators, motors, and other electronic systems need to be explored. It will also be important to determine the extent and mechanisms by which neutron irradiation will degrade the superconductors.

Advanced power cycles should also be explored. While Stirling engines will do well for low-power applications and Brayton systems will do well at high power, attention may also be given to alternative approaches such as MHD power generation.

4.3 Power Conditioning

A need in the area of power conditioning technologies is the development of radiation resistant/high-temperature power electronics. Components based on ceramics or high-temperature semiconductors will be needed to allow the electronics systems to operate at temperatures attractive for heat rejection. Also, because the power conversion and conditioning is likely to occupy much of the mass budget, serious effort should also be directed to finding ways to build transformers, motors, etc. that are much lighter than standard terrestrial technologies employ.

Hgh power RF energy will be needed to drive the VASIMR. While klystrons have been built for high power levels and very high frequencies (GHz), effort should be made toward addressing specifically what the RF power needs will be and developing or adapting the technology to meet those needs. Mass reduction will be important in these components as well.

Besides the major components, more basic devices such as temperature and pressure sensors, computer logic and switches need to be qualified for the high temperature and relatively high radiation environment that will be seen by the power conditioning system.

Again, developments of superconducting motors, transformers, transmission lines, etc. could do a lot to reduce system mass and improve reliability.

4.4 Heat Management

The most immediate need is the maturation of low-mass heat pipe radiator technology. This includes advances in manufacturing methods and materials, demonstration of their survivability and functioning in the space environment, particularly radiation fields, and evaluation of their performance for Brayton systems where a wide range of radiating temperatures is likely to be encountered.

Cooling for superconducting components, while a reasonably mature technology for terrestrial applications, calls for qualification in the spacecraft environment. Less exotic but also advantageous would be the development of refrigeration for power electronics systems cooling, allowing them to operate at reasonable temperatures while shedding heat at the radiator temperature.

One of the greatest aids to achieving goals in system specific mass is the reduction in radiator specific mass. To that end, investing in the development of advanced (e.g., droplet or Curie point) radiators will have long-term benefits, though these would not be considered for a near-terms mission. In addition, key technology issues include allowed radiator temperature and the ability to fit the large radiators required for this power level into launch vehicles.

4.5 Energy Storage and Dumping

Another topic not dealt with much in the literature nor in current discussion is that of energy storage for restarts or energy dumping for standby periods when power demands are present but minimal.

5.0 CONCLUSIONS

Critical aspects for development of multi-megawatt power include reactor advances, power conversion system development, thermal radiator improvements, development of electronics and power conditioning systems compatible with high temperatures and high radiation fields.

Of many reactor concepts explored, the ones appearing most ready to proceed are a gas-cooled, NERVA Derivative based reactor operating with He-Xe gas in a closed-cycle Brayton power conversion system, and a Li-cooled SP-100 type reactor working through a heat exchanger to a potassium metal vapor Rankine power system. Both systems appear capable of approaching the specific mass goal of 3-5 kg/kW_e, though both will require substantial developments to reach it. The primary cooling system with the greatest likelihood for success will be heat-pipe radiators.

Significant research and development in reactor fuels that can operate at the high temperatures indicated above will required before either concept will be ready for use. Beyond that, the greatest improvements in system specific mass will come as radiators and turbine/generator systems are made more mass efficient. Because the required radiating area for the radiators is so large for these MMW systems, fitting them into launch vehicle cargo bays will also be very challenging.

REFERENCES

1. Wahlquist, E. J., December 2000, DOE-NE-50, Memorandum to Warren Bergholz, DOE-ID.
2. Chang-Díaz, F. R., et al., July 17-19 2000, "The Physics and Engineering of the VASIMR Engine," in *AIAA 2000-3756, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Huntsville, AL.
3. Angelo, Jr., J. A., and Buden, D., 1985, *Space Nuclear Power*, Orbit Book Company, Malabar, Florida, p. 181.
4. *Ibid.,* p. 202-203
5. Doherty, M. P., and Holcombe, R.S., April 1993, *Summary and Recommendations on Nuclear Electric Propulsion Technology for the Space Exploration Initiative,* NASA Technical Memorandum 105707.

6. Newkirk, D. W., et al., January 1991, "SP-100 Scaleup to 40 MWe," Eighth Symposium on Space Nuclear Power Systems, Albuquerque, NM, *AIP Conference Proceedings,* No. 217, pt.3, 1991, p. 1072-81.

7. Newkirk, D.W. et al., August 1991 "SP-100 Multimegawatt Scaleup to Meet Electric Propulsion Mission Requirements," Proceedings of the 26th Intersociety Energy Conversion Engineering Conference, Boston, MA.

8. Angelo, J.A., and Buden, D., *Op. Cit.* p. 183.

9. Pierce, B. L., January 1991, "Application of the Enabler to Nuclear Electric Propulsion," *Proceedings, Eighth Symposium on Space Nuclear Power Systems, Part One*, Albuquerque, NM, pp. 379-384.

10. General Electric, October 2, 2001,Internet site http://www.gepower.com/corporate/en_us/aboutgeps/releases/20010919.pdf.

11. Frewer, H. and Keller, W., 1985, "The Modular High-Temperature Reactor," *Nuclear Science and Engineering, 90*, pp. 411-426.

12. Pedersen K. et al., February 2001, "Results of 30 kWt Safe Affordable Fission Engine (SAFE 30) Primary Heat Transport Testing," *Space Technology and Applications International Forum 2001, Albuquerque, NM,* M. S. El-Genk, Ed., American Institute of Physics.

13. Fitzpatrick, G. O. et al., 1992, *"Cascaded Thermionic Converters,"* Proceedings of the Ninth Symposium on Space Nuclear Power Systems, El-Genk, M. S. and McVey, J. B., Eds., CONF 920104, American Institute of Physics, New York.

14. Harry, R. B. et al., January 1994, "Applications of Brayton Cycle Technology to Space Power,' *IEEE Aerospace and Electronics Systems Magazine, 9,* pp. 28-32.

15. Morgan, R. E. et al., August 1983, "Comparison of High Power Nuclear Systems for Space Applications," in *Proceedings of the 18th Intersociety Energy Conversion Engineering Conference,* Orlando, Florida, pp. 977-982.

16. Anghaie, S., January 2001, University of Florida Department of Nuclear Engineering, presentation at Marshall Space Flight Center.

17. Bitteker, L., January 2001, Marshall Space Flight Center, presentation at Marshall Space Flight Center.

18. Westinghouse Advanced Energy Systems Division, February 1988, *Supplemental Information on a Conceptual Design of a Space-Based Multimegawatt MHD Power System*, WAEST-TR-88-994.

19, Jones, J., January 2001, Marshall Space Flight Center, presentation at Marshall Space Flight Center.

20. Berte, M., January 2001, Horizon Defense & Aerospace Solutions, presentation at Marshall Space Flight Center.

21. Van Hagan, T. H., et al., July 1997, "Thermionic/ AMTEC Cascade Converter Concept for High-Efficiency Space Power," *IEEE Aerospace and Electronics Systems Magazine 12*, No. 7, p. 10-15.

22. Schock, A., et al., August 1997, "Design and Performance of Radioisotope Space Power Systems Based on OSC Multitube AMTEC Converter Designs," *Proceedings of the Thirty-Second Intersociety Energy Conversion Engineering Conference,* Honolulu, HI, 97CH6203.

23. Lodhi, M. A. K., and Daloglu, A., 2001, "Effect of Geometrical Variations on AMTEC Cell Heat Losses," *Journal of Power Sources 91,* p. 99-106.

24. Anex, R., et al., January 1999, "Innovation and the Transformation to Clean Technologies: Life Cycle Management of Gas Turbine Systems," *Proceedings of the 1999 NSF Design and Manufacturing Grantees Conference*, Long Beach, CA.

25. Wetch, J. R., et al., September 1988, "Megawatt Class Nuclear Space Power Systems Conceptual Design and Evaluation Report," NASA-1.126:179614-Vol. 3.

26. Edenburn, M. W., January 1988, "The Effect of Operating Temperature and Turbine Blade Cooling on Brayton Cycle Space Power Systems," *Transactions, 5th Symposium on Space Nuclear Power Systems,* San Diego, CA, pp. 565-570.

27. Holcombe, R. S., January 1988, "Potassium Rankine Cycle Power Conversion Systems for Lunar Mars Surface Power," *Proceedings, 27th Intersociety Energy Conversion Engineering Conference,* Albuquerque, NM.

28. Mason, L. S., February 2001, "A Comparison of Brayton and Stirling Space Nuclear Power Systems for Power Levels from 1 Kilowatt to 10 Megawatts," Space Technology and Applications International Forum (STAIF 2001), Albuquerque, NM.

29. Merrigan, M.A., and Reid, R.S., April 1998, *Multimegawatt Space Power Systems: Thermal Management, Annual Report 1987,* LA-11254-MS, Los Alamos National Laboratory.

30. Lipinski, R. J. et al., 1998, *A Fission-Powered Interstellar Precursor Mission,* SAND98-2441C.

31. Lipinski, R. J., et al., 1999, *Fission-Based Electric Propulsion for Interstellar Precursor Missions,* SAND99-2871C.

32. Walter, C.E., April 1985, *SPR-8 Multi-Megawatt Space Power System (MMW-SPS) Concept Description and Refinement Plan,* UCRL-ID-129627.

33. Howe, S. D., et al., September 1997, *Reducing the Risk to Mars: The Gas Core Nuclear Project,* LA-UR-97-3361, Los Alamos.

34. Houts, M. G., et al., January 1996, *Heatpipe Space Power and Propulsion Systems,* LA-UR-95-3965, Los Alamos.

35. Klein, A. C., et al., March 1993, *Fabric Composite Radiators for Space Nuclear Power Applications,* OSU-NE-9304, Oregon State University.

36. Difillippo, F. C., January 1998, *Nuclear Modules for Space Electric Propulsion,* 15th Symposium on Space Nuclear Power and Propulsion, Albuquerque, NM.

37. Houts, M. G. and Poston, D. I., 1998, *Heatpipe Power System Development,* LA-UR-98-3276, Los Alamos.

38. Moriarty, M. P. and Determan, W. R., August 1989, "SP-100 Advanced Radiator Designs for Thermoelectric and Stirling Applications," *Proceedings, 24th Intersociety Energy Conversion Engineering Conference,* Washington D. C., pp. 1245-1250.

39. Rutger, L. L. and Truscello,V. C., 1992, The SP-100 Power System," *AIP Conference Proceedings No. 246*, American Institute of Physics.

40. Longhurst, G. R., April 2001, "ALKASYS Code Adaptation," INEL/EXT-01-00539, Idaho Falls, ID, Idaho National Engineering and Environmental Laboratory.

41. Mason, L. S., March 2001, NASA Glenn Research Center, private communication with G. R. Longhurst.

42. Carlson, D. E., 1985, *A Parameter Study for the SP-100 Radiation Shield*, SP TN 101, Los Alamos, NM, Los Alamos National Laboratory.

43. Engle, Jr., W. W. et al., June 1971, *Optimization of a Shield for a Heat-Pipe-Cooled Fast Reactor Designed as a Nuclear Electric Space Power Plant,* ORNL/TM-3499, Oak Ridge, TN, Oak Ridge National Laboratory.

44. Robinson, R. A. et al., December 1996, *Brayton-Cycle Radioisotope Heat Source Design Study: Phase 1 (Conceptual Design) Report*, ORNL/TM-1691 (NASA CR-72090), Oak Ridge, TN, Oak Ridge National Laboratory, pp. 90-100.

45. Longhurst, G. R., et al., November 2001, *Multi-Megawatt Power System Trade Study*, INEEL EXT-091-00913 Rev. 1, Idaho Falls, ID, Idaho National Engineering and Environmental Laboratory.

46. General Electric Power Systems Internet site, February 2001, Internet site http://gepower.com/ products/prod_specs.htr.