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NUCLEAR ALKALI METAL RANKINE POWER SYSTEMS FOR SPACE APPLICATIONS*

J. C. Moyers and R. S. Holcomb

Oak Ridge National Laboratory
P. O. Box Y
Oak Ridge, Tennessee 37831

To be presented at
Twenty-First Intersociety
Energy Conversion Engineering Conference
San Diego, California

August 25-29, 1986

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*Work done at Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc. for U.S. Department of Energy under Contract No. DE-AC05-84OR21400.

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Oak Ridge National Laboratory
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ABSTRACT

Nuclear power systems utilizing alkali metal Rankine power conversion cycles offer the potential for high efficiency, lightweight space power plants. Conceptual design studies are being carried out for both direct and indirect cycle systems for steady state space power applications. A computational model has been developed for calculating the performance, size, and weight of these systems over a wide range of design parameters. The model is described briefly and results from parametric design studies, with descriptions of typical point designs, are presented in this paper.

SPACE POWER SYSTEMS for applications requiring large amounts of electric power for long mission lifetimes probably will use nuclear reactors as the prime energy source. The alkali metal Rankine cycle is a promising power conversion subsystem which, when coupled to a high temperature reactor and heat rejection radiator, provides an efficient and lightweight space power system. A program to design and develop such a system to produce 100-300 kW(e) was conducted at ORNL during 1959-1966 [1].** That program provided much of the underlying basis for renewed interest and current activity in the evaluation and development of designs for larger systems of this type, aimed at meeting the space power needs of the future.

Current activity at ORNL is directed toward the development of conceptual designs of nuclear-powered alkali metal Rankine power systems that will provide high reliability, minimum weight, and launch geometry that will fit within launch vehicle payload envelopes. The computer program ALKACYCL [2] was developed to provide a rapid means for determining performance of the Rankine power conversion subsystem over a range of specified conditions. ALKACYCL has been incorporated into a comprehensive design program that includes design and mass determination procedures for the reactor, power conversion, and heat rejection subsystems. Although still under development, the comprehensive program is providing guidance in the selection of design parameters and system characteristics.

An abbreviated schematic flow diagram [3] of a system utilizing a boiling-potassium-cooled reactor is shown in Fig. 1. This diagram is also applicable to a liquid-lithium-cooled reactor system when the reactor and recirculating jet pump are replaced by a reactor, an intermediate lithium-heated once-through potassium boiler, and an electromagnetic lithium pump. Potassium vapor, after expanding through the power turbine, is condensed in a heat-pipe-cooled condenser. Liquid potassium is then returned via a turbine-driven feed pump and a train of regenerative feed heaters to the reactor or boiler. A jet pump draws the condensate from the condenser, providing flow control by varying the degree of cavitation in the suction of the feed pump.

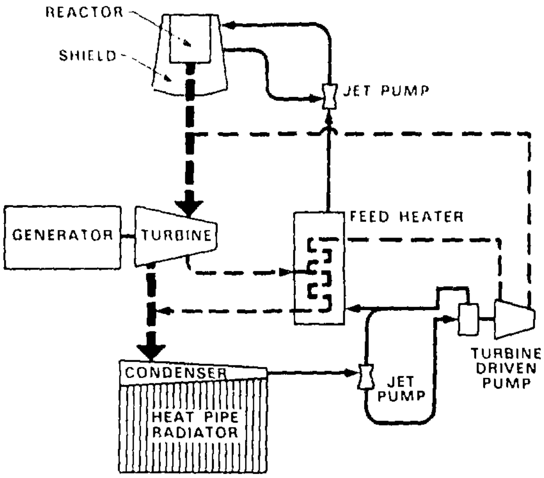

Fig. 1. Schematic flow diagram of the direct cycle system.

COMPREHENSIVE COMPUTATIONAL MODEL

The computational model utilizes input values for parameters describing the system arrangement and conditions to provide performance and design characteristics and mass estimates for the major subsystems comprising the total power system. Design and performance characteristics are determined by detailed engineering procedures rather than by empirical algorithms. Mass estimates are developed by basic design principles augmented in some cases by empirical coefficients determined from the literature.

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*Research sponsored by the U. S. Department of Energy under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

**Numbers in brackets designate references at end of paper

REACTOR SUBSYSTEM - The reactor core design is based on a fast spectrum, metallic-clad rod fuel element containing UN pellets. Peak pellet burnup is limited to 10 atom % and peak heat flux for the potassium- and lithium-cooled reactors are 50 and 30 W/cm^2, respectively. Rod diameter is determined by heat flux and burnup but is limited to a *minimum* of 0.64 cm for mechanical stability. Control is provided by in-core assemblies and by rotatable drums located around the core periphery.

The potassium-cooled reactor is designed for recirculation boiling with an exit quality of about 25% to avoid the potential problem of rod burnout. The reactor includes provision for liquid-vapor separation and the recirculating jet pumps within the pressure vessel head. The lithium-cooled system boiler utilizes a twisted ribbon inside the tubes to force the liquid outward against the tube wall to enhance boiling heat transfer and to assist in achieving nearly 100% dry vapor at the boiler outlet.

The tantalum-based alloy ASTAR-811C is the current choice for fuel rod cladding and structural components operating at temperatures above 1100 K, and Nb-1 Zr is used at lower temperatures. The design stress is two-thirds that which produces 1% creep during system lifetime.

The shield configuration and dimensions are selected to provide a fast neutron fluence of 10^{13} neutrons/cm^2 and a total gamma dose of 10^5 rad at a plane that is 15 meters from and perpendicular to the axis of the cylindrical reactor vessel. The shield is thickest along the axis that faces the payload but also covers the sides of the reactor in order to reduce scattered radiation. The shield utilizes layers of lithium hydride *in a honeycomb matrix* and tungsten.

Externally provided information required for the reactor submodel is limited to system lifetime. Other required information, provided by the power conversion system submodel, includes net electrical power output, turbine inlet and condensing temperature, and power conversion efficiency. The submodel produces descriptions of the reactor, the boiler (if lithium-cooled) and the shield, including dimensions and mass estimates.

POWER CONVERSION SUBSYSTEM - The power conversion subsystem is described in detail in Ref. 2. The principal flow of dry saturated alkali metal vapor leaving the boiler (or potassium-cooled reactor) is to the main power turbine, with a relatively small stream diverted to the feed pump drive turbine. As the vapor expands through the main turbine, interstage and/or external separators are used to maintain the liquid content of the stream at less than 10% to avoid the potential for erosion of turbine blading. Upon exhausting from the turbine, the vapor is condensed in tapered annular spaces surrounding the evaporator sections of the radiator heat pipes. Condensate is drawn from the small ends of the condensing annuli by a jet pump that is driven by a side stream of liquid taken from the discharge of the turbine-driven feed pump. Liquid discharging from the jet pump flows to the intake of the feed pump and is then pumped through the shell sides of a succession of from zero to three (as specified) feed heaters back to the boiler. One of the heaters is heated by feed pump turbine exhaust; other heaters, if more than one are specified, are heated by vapor extracted from appropriate stages in the main turbine or taken from the boiler outlet line if necessary to provide the specified boiler feed temperature. Drains from the various heaters are cascaded to successively lower-temperature heaters and ultimately flow to the condenser.

Turbine blade tip velocity is a parameter that is dependent upon the strength of the turbine rotor material and is treated as an input variable in the model to allow evaluation of the effects of advanced rotor materials. This parameter has a strong effect on turbine size and rotational speed and, therefore, on the mass of the turbine and generator.

Most of the required externally provided input information for model operation pertains to the power conversion submodel. Input includes turbine inlet and outlet temperatures, dry stage efficiency for the turbine, and the number of stages of feed heating.

The submodel produces a complete mass and energy balance for the power conversion subsystem, as well as mass estimates for the major components.

HEAT REJECTION SUBSYSTEM - The major heat rejection load from the power system is from the power turbine condenser and is rejected by a heat pipe radiator operating at a temperature somewhat lower than that of the condenser. A smaller rejection load, from cooling of the shield and the generator, is rejected by a low-temperature heat pipe radiator.

The geometry of the radiators, as modeled, depends upon the power system rating. For small systems, the radiator is a conical surface with an apex half-angle of about 20 degrees, with the reactor and shield enclosed in the cone. Finned longitudinal heat pipes form the cone surface. When the system rating increases beyond that which requires the base dimension of the cone to equal the diameter of the launch vehicle bay, the heat pipes are extended to form a cylindrical section following the conical section. In these geometries, the low temperature radiator occupies a full-length section of the assembly. At even larger system ratings, beyond which the total length of the reactor-radiator assembly would exceed the launch bay length, a triform geometry for the main radiator is used. The low-temperature radiator consists of flat panels, located at one end of the triform, facing away from the main radiator and shielded from the main radiator on the back side. The conical-cylindrical geometry for smaller systems is fully assembled prior to launch; the triform geometry requires in-orbit assembly of the outer wing and low-temperature panels.

Input requirements for the heat rejection submodel include the operating temperature of the low-temperature radiator and the launch vehicle bay dimensions. Thermal loads for both parts of the radiator are provided by the power conversion submodel. The submodel also provides dimensional information and the estimated mass of the heat rejection system.

MISCELLANEOUS - A mass of 0.25 kg/kW for power conditioning equipment is included in the model. Additional mass for armoring or shielding of components and for redundant heat pipes in the radiators has not been included but will be incorporated in the future.

PARAMETRIC DESIGN ANALYSIS RESULTS

The computational model has been used to perform a limited evaluation of the influence of various parameters on system design, performance, and mass. The results that follow are for a 2500-kW(e) system that utilizes a boiling potassium-cooled reactor. Design lifetime is 7 years and the low-temperature radiator temperature is 600 K. Similar trends prevail for systems of other ratings or that utilize a lithium-cooled reactor.

THERMAL EFFICIENCY - Net power system thermal efficiency, relating net electrical output to reactor thermal power, is shown in Fig. 2 for a range of turbine inlet and condensing temperatures. Three stages of feed heating were employed at condensing temperatures at or below 1150 K but the limited temperature span between condenser and reactor inlet required reducing the heating stages at higher condensing temperatures. The effect on efficiency of reducing the degree of regenerative heating is clearly seen in the figure. Carnot ratio ranges from 0.67 to 0.70 when 3 heating stages are used and from 0.64 to 0.67 when 0 to 2 stages are used.

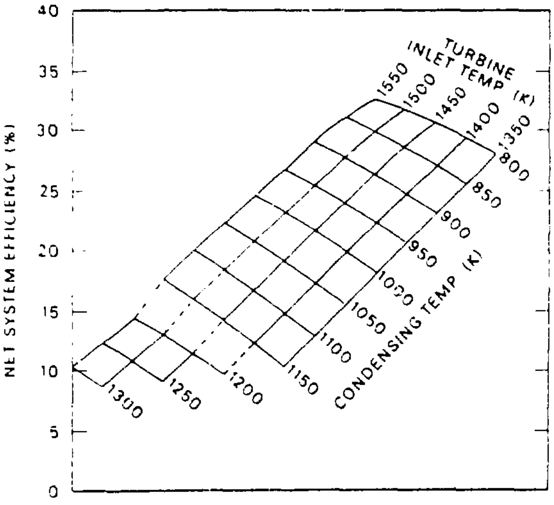

Fig. 2. Net system efficiency versus turbine inlet and condensing temperatures.

RADIATOR AREA - The combined radiative area of the main and low-temperature radiators is shown as a function of turbine inlet and condensing temperatures in Fig. 3. For a given turbine inlet temperature, the combined effects of lower system efficiency (and therefore higher rejection heat load) and higher heat dissipation ability per unit area as condensing temperature increases produce a clearly defined minimum area at some condensing temperature. Minimum area results from a ratio of condenser-to-turbine inlet temperatures of about 0.75, a value also resulting from a simple theoretical determination using the Carnot efficiency and the Stefan-Boltzmann relation. Radiator mass generally follows the same trends as area except for discontinuities where geometry or material of construction changes.

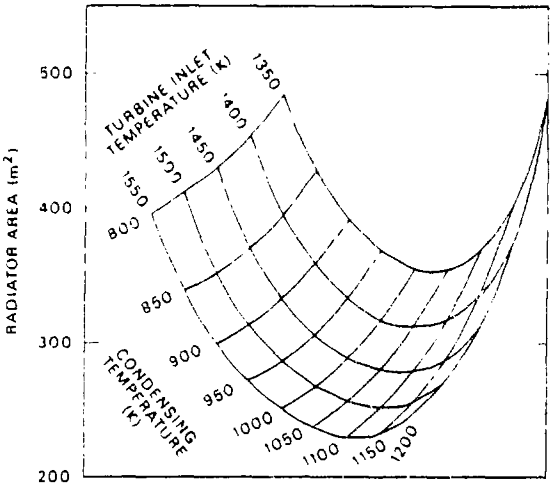

Fig. 3. Radiator area versus turbine inlet and condensing temperatures.

REACTOR MASS - Reactor mass as a function of turbine inlet and condensing temperatures is shown in Fig. 4. Mass decreases with both temperatures, reflecting the effects of both changes in system efficiency (therefore thermal rating) and temperature-related changes in design. Curves of constant thermal rating are superimposed on the figure to show the strong effect of turbine inlet (reactor outlet) temperature on mass.

SHIELD MASS - The two-pi shield mass is shown in Fig. 5. The trends of mass versus turbine inlet and condensing temperatures reflect the overall dimensions of the reactor and the effects of reactor thermal rating on shield thickness.

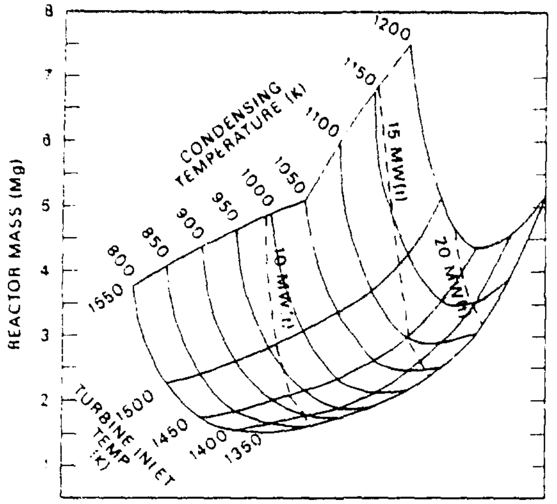

Fig. 4. Reactor mass versus turbine inlet and condensing temperatures.

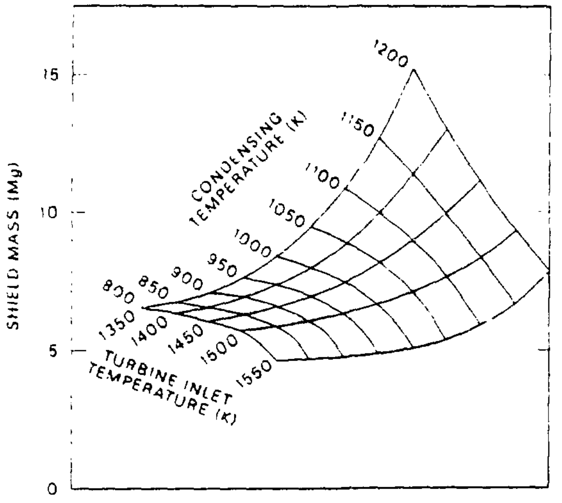

Fig. 5. Shield mass versus turbine inlet and condensing temperatures.

POWER CONVERSION SUBSYSTEM MASS - The mass of the power conversion subsystem is shown in Fig. 6. The strong trend of decreasing mass with increasing condensing temperature reflects the effect of lower volumetric flow rates at the higher temperature turbine exhaust.

TOTAL POWER SYSTEM MASS - Total system mass is shown in Fig. 7 as a function of turbine inlet and condensing temperature. For each inlet temperature, there is a condensing temperature that yields minimum mass. However, there is surprisingly little variation in minimum mass over the 200 K range of turbine inlet temperatures considered. Also, the curves are shallow over a rather broad range of condensing temperatures. The discontinuity occurring at a condensing temperature of 1100 K is due to a change in radiator material at that temperature.

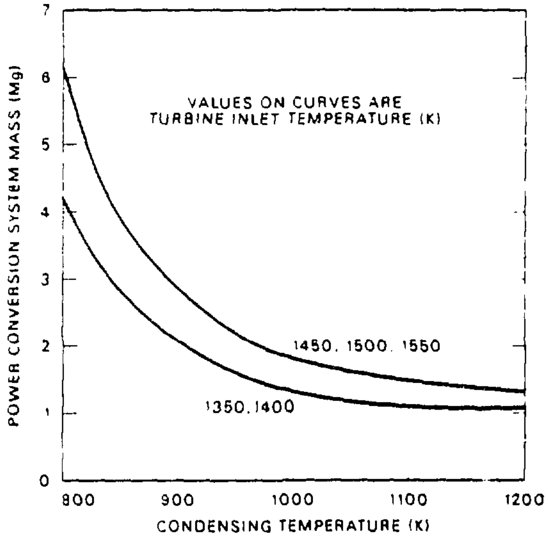

Fig. 6. Power conversion system mass versus turbine inlet and condensing temperatures.

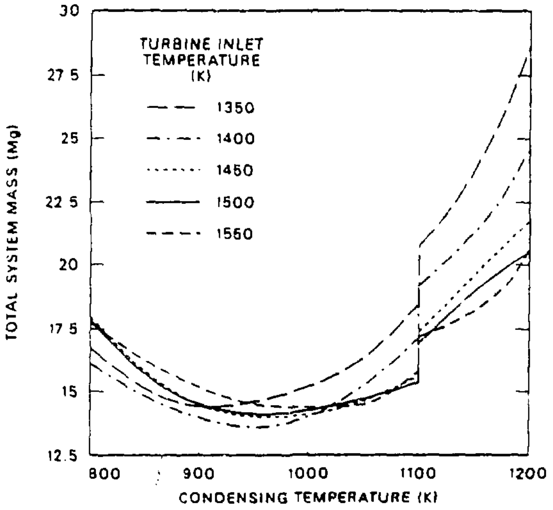

Fig. 7. Total system mass versus turbine inlet and condensing temperatures.

Total system mass was also evaluated for systems having turbine inlet and condensing temperatures of 1400 K and 950 K, respectively, with various electrical output ratings and system lifetimes. Both boiling potassium and lithium cooled reactors were included in this evaluation. Fig. 8 shows the relationship of total mass to system lifetime for systems rated at 2.5 MW output. Significant mass reduction for each type of reactor results at shorter lifetimes due to thinner shields, higher design stresses for the materials of construction, and lower inventory of fuel. Fig. 9 shows the relationship of total mass to electrical output rating for systems having 7-year lifetimes. Mass varies essentially linearly over the rating range of 1 to 10 MW, with a slight mass advantage for lithium-cooled reactor systems over the entire rating range.

TYPICAL POINT DESIGNS

Results from the computational model are illustrated by the calculated characteristics of 1000-kW(e) systems for both boiling potassium and lithium-cooled reactors as shown in Table 1. Turbine inlet and condensing temperatures of 1400 K and 950 K, respectively, were chosen for this example since the parametric study indicated that these conditions will yield near-minimum mass for the system.

The liquid lithium-cooled reactor is slightly smaller in size than the boiling potassium reactor. This is because of the higher surface heat flux which is permissible with lithium and the lower pressure drop with liquid lithium. The smaller reactor in turn permits a slightly smaller shield which yields a lower mass for both the reactor and shield in the lithium-cooled system.

The power conversion subsystem is the same for both systems. Two turbine-generators placed on the same axis but with opposed rotation are used to cancel the torque on the system. Several stages of expansion are required for the potassium turbine to limit the axial temperature gradient along the rotor and to match the vapor nozzle velocity to the blade tangential velocity to maintain reasonably good efficiency. Each generator would be directly coupled to or on the same shaft as its turbine, thus operating at high speed and frequency to minimize mass.

In comparing the system mass for the two systems, it may be observed that the dominant mass is in the reactor and shield, primarily in the shield. The smaller reactor and shield for the lithium-cooled system leads to a mass savings of about 300 kg compared to the boiling potassium system. The boiler and lithium pump required for the lithium-cooled system adds about 185 kg, with the net result that the lithium-cooled system has a total estimated mass of about 600 kg less than the boiling potassium system. This is a relatively small difference which may change somewhat in more detailed design studies. Thus, it appears that either system might be chosen without a serious penalty in system mass; either system will yield a low specific mass, on the order of 7 kg/kW. As indicated by the parametric results, specific mass decreases at larger system ratings.

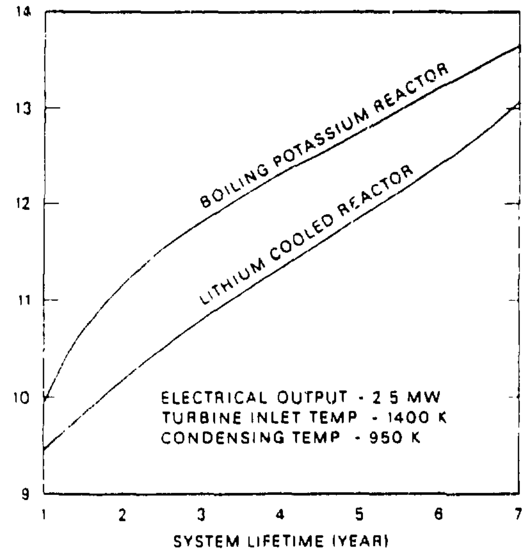

Fig. 8. Total system mass versus system lifetime.

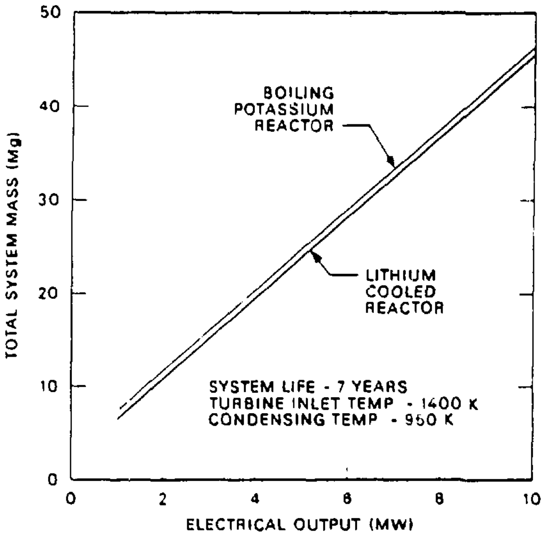

Fig. 9. Total system mass versus electrical output.

Table 1. Example Point Designs

	Boiling Potassium Reactor	Lithium Cooled Reactor
Thermal power, kW	4,370	4,470
Net electric power output, kW	1,000	1,000
Reactor		
Core diameter, cm	37	33
Core length, cm	43	38
Fuel pin diameter, cm	0.75	1.00
Fuel pin spacing, cm	0.90	1.125
Outlet temperature, K	1400	1490
Boiler		
No. tubes		67
Tube OD, mm		17.5
Tube wall thickness, mm		0.5
Shell OD, cm		19.4
Shell length, m		2.04
Potassium outlet temperature, K		1,400
Turbines (2 each)		
Inlet temperature, K	1,400	1,400
Inlet pressure, MPa	1.2	1.2
Exhaust temperature, K	950	950
Exhaust pressure, kPa	45	45
No. stages	7	7
Speed, RPM	24,000	24,000
Casing OD, cm	36	36
Casing length, cm	75	75
Generators (2 each)		
Output voltage, V	500	500
Output frequency, Hz	2,000	2,000
Temperature, K	600	600
Casing OD, cm	28	28
Casing length, cm	25	25
Radiator		
Heat pipe temperature, K	905	905
Heat pipe mean spacing, cm	10	10
Heat pipe OD, cm	3.3	3.8
Heat pipe length, m	11	11.2
Maximum diameter, m	4.5	4.5
Heat transfer area, m^2	134	137
Mass, kg		
Reactor and shield	5,280	4,470
Boiler and Li pump		185
Turbine-generators	510	510
Radiator	1220	1255
Piping and miscellaneous	125	90
Power conditioning	250	250
Total	7,385	6,760

CONCLUSIONS

Nuclear space power systems utilizing alkali metal Rankine power conversion cycles appear to offer low mass and high efficiency. Feasible designs are possible over a wide range of conditions, permitting the use of developed materials of construction and the exploitation of new materials as they become available and proven. The mass penalty for backing away from extending the capability of materials to their limit is not severe, allowing conservative designs without substantial loss in performance. The comprehensive computational model which is being developed for analyzing design options for this type of system has already proven to be an extremely useful tool.

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