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A Power Conversion Concept for the Jupiter Icy Moons Orbiter

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An analytical study was performed to compare design options for a reactor power system that could be utilized on a Jupiter Icy Moons Orbiter mission employing nuclear electric propulsion. The resulting concept uses a liquid-metal cooled reactor and closed-Brayton-cycle power conversion. The power conversion system consists of two, independent Brayton converters each capable of providing the full design output power. The converter design is based on state-of-the-art superalloy hot-end construction permitting turbine inlet temperatures of 1150 K and cycle efficiencies in excess of 20%. The waste heat-rejection system includes a mechanically pumped liquid-metal heat-transport loop and water heat-pipe radiator panels. The power management and distribution system provides the power electronics, electrical controls, switchgear, and cabling to deliver 400 Vac (volts alternating current) to the electric propulsion system and 120 Vdc (volts direct current) to the spacecraft bus. This paper discusses some of the key tradeoffs considered in arriving at the proposed concept and provides a summary of the power system performance and mass.

Introduction

THE Jupiter Icy Moons Orbiter (JIMO) is a bold new mission under study by NASA's Office of Exploration Systems. The JIMO project is investigating the potential of nuclear-electric-propulsion (NEP) technology to efficiently deliver scientific payloads to three Jovian moons: Callisto, Ganymede, and Europa in a single mission. A critical element of the NEP vehicle is the reactor power system, consisting of the fission reactor, power conversion, heat rejection, and power management and distribution (PMAD). Power system trades studies were performed, and a candidate NEP vehicle concept was developed that could be considered for the JIMO mission. The NEP system consisted of a 100-kWe reactor power system and a 6800-s specific impulse, ion propulsion system. A simplified block diagram for the NEP vehicle concept is shown in Fig. 1.

The emphasis of this paper is on the nonnuclear elements of the reactor power system including the power conversion, heat rejection, and PMAD. A liquid-metal (lithium) cooled reactor concept was assumed for the study, although both heat-pipe and gas-cooled reactors are viable alternatives. A truncated conical radiation shield with a 10-deg half-angle attenuates reactor-induced radiation to 25 krads-silicon gamma dose and 1×10^{11} neutrons/cm^2 fluence (based on 1-MeV equivalent silicon damage) at the payload located 30 m from the reactor over the approximate 12-year mission duration. The reactor also included a liquid-metal to gas heat exchanger that accommodates the integration of a closed-Brayton-cycle (CBC) power conversion system. The CBC conversion system was selected for the study based on its high efficiency and suitability for the power level of interest. Free-piston Stirling and thermoelectric power conversion technologies are also potential candidates. The heat-rejection and PMAD concepts are oriented to CBC power conversion, although aspects of the designs would be applicable to the other conversion options.

Trade Studies

There were many conceptual design trade studies that were conducted related to the power subsystems. System-level studies examined design and off-design operating modes, determined startup requirements, evaluated subsystem redundancy options, and quantified the mass and radiator area of reactor power systems from 20 to 200 kWe. The majority of this activity centered on Brayton-cycle analysis and optimization, aimed at defining cycle performance and subsystem interface requirements. In the Brayton converter subsystem, studies were performed to investigate converter packaging options and assess the induced torque effects on spacecraft dynamics caused by rotating machinery. In the heat-rejection subsystem (HRS), design trades were conducted on heat-transport approaches, material and fluid options, and deployed radiator geometries. In the PMAD subsystem, the overall electrical architecture was defined, and trade studies examined distribution approaches, voltage levels, and cabling options.

Reactor Power System

The power system conceptual design process is iterative and involves technology assessments, system analysis, subsystem design, and vehicle integration studies. Technology assessments provide a basis for selecting design parameters that are consistent with launch date. Some examples of important design parameters are reactor outlet temperature, radiator panel areal mass (defined as mass per unit area or kg/m^2), and alternator output voltage. These must be selected based on current technology readiness levels and realistic projections for technology advancement prior to launch. Systems analysis is conducted using the technology design parameters as inputs to analytical models to arrive at an initial concept. Subsystem design provides further definition and serves to either substantiate or revise the design parameter assumptions. Finally, vehicle integration studies examine the feasibility of the design working within the spacecraft and mission framework. At each stage in the process, new information usually causes the designers to reassess previous assumptions and adjust the overall concept. The following sections describe some of the system-level trades conducted during the study.

Cycle Analysis

The power systems analysis was performed using a Glenn Research Center computer model called NUCOPT, which accounts for the reactor, power conversion, heat rejection, and PMAD subsystems.[1] The proposed power system concept includes two 105-kWe Brayton converters, based on an anticipated mission requirement to provide "fail-op" redundancy (defined as continued full power capability after component failure) in the power conversion subsystem. A Brayton converter consists of a turboalternator, recuperator, gas cooler, and bleed cooler with interconnecting gas ducts. The only moving part is a single-shaft, radial turbocompressor supported by gas foil bearings. The converters are fully redundant with completely independent gas circuits.

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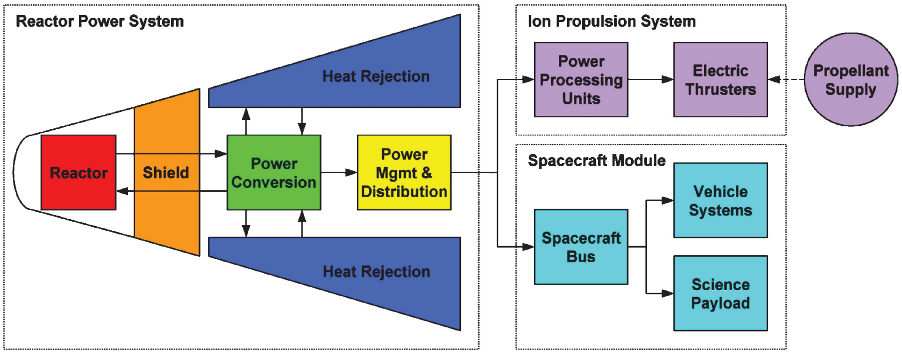

Fig. 1 NEP vehicle block diagram.

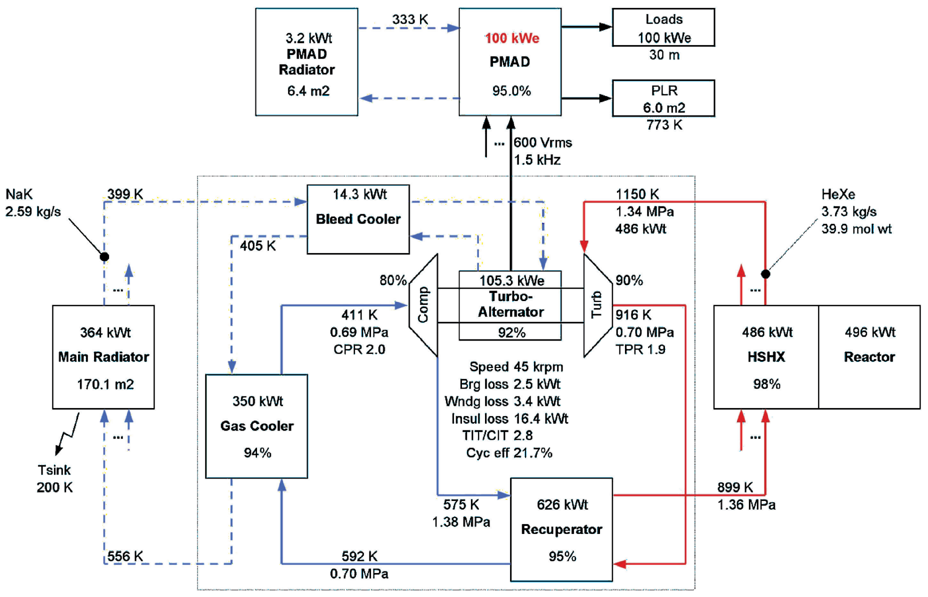

Fig. 2 Brayton cycle diagram.

The Brayton state point diagram at the conclusion of the study process is shown in Fig. 2, with the cycle conditions indicated for the case where only one of the two Brayton units is operating (i.e., maximum unit power). The converter interfaces to the reactor through the heat source heat exchanger (HSHX), to the main radiator through the gas cooler, and to the PMAD through the alternator. An inert gas mixture (HeXe) with a 39.9 molecular weight was used as the Brayton working fluid. The HSHX gas outlet temperature was set at 1150 K, allowing the use of nickel-based superalloys for the hot-end converter components. The required HeXe mass flow rate was 3.73 kg/s. Waste heat rejection was performed with a pumped sodium-potassium (NaK) heat-transport loop (indicated by dashed lines in Fig. 2) coupled to the main radiator. The Brayton alternator delivers ac power to the PMAD module.

Figure 3 reveals an aspect of the cycle optimization process—showing reactor power, radiator area, and power conversion mass sensitivity to compressor inlet temperature (CIT). The minimum mass design point occurs at a CIT of 411 K. Lower CITs resulted in larger radiators despite the reduced waste heat load, because radiator area is more influenced by the cycle rejection temperature. Higher CITs resulted in greater reactor input power levels, requiring larger recuperators and gas coolers to process the thermal energy. The cycle analysis assumed component efficiencies of 90% for the turbine, 80% for the compressor, and 92% for the alternator, and the recuperator effectiveness was set at 95%. Total gas system pressure loss was assumed at 5%. Bearing and alternator windage losses were estimated at 2.5 and 3.4 kWt, respectively and total insulation losses were estimated at 16.4 kWt. The design point Brayton cycle efficiency was 21.7%, and the total end-to-end power system efficiency was 20.2%, resulting in a required reactor thermal power of 496 kWt.

The pumped NaK heat-transport loop interfaces with a two-sided main radiator having a total surface area of 170 m^2. The NaK is stored in a heated tank during launch, and the cooling loop is charged just before power system startup. The total waste heat load was 364 kWt, comprised of 350 kWt from the gas cooler and 14 kWt from an alternator bleed cooler. The alternator bleed cooler provides waste heat dissipation for bearing, windage, and alternator electromagnetic losses. Radiator inlet and outlet temperatures were 556 and 399 K, respectively. The total required NaK mass flow rate was 2.59 kg/s. The radiator area was determined based on an effective sink temperature of 200 K, fin effectiveness of 92%, and surface emissivity of 0.9.

The three-phase alternator produces 105 kWe at 45,000 rpm, 600 Vac (rms, line to line), and 1.5 kHz. The 95% efficient PMAD system delivers 100 kWe to the loads over a 30-m transmission distance. The PMAD includes power and control electronics, switchgear, and cabling. Also included is a full-power shunt parasitic load radiator (PLR) and a separate PMAD thermal control radiator. The PLR has an effective temperature of 773 K and a surface area of 6.0 m^2. The PMAD waste heat radiator has a total surface of 6.4 m^2, sized to maintain an electronics cold plate at 333 K with a 3.2 kWt heat load.

Operating Modes

Additional cycle analyses were performed to examine off-design operating modes for the Brayton converters. The sizing condition for the Brayton components was based on 100-kWe system output

Table 1 Mass vs subsystem redundancy

100 kWe Net	Single string	———		Study ref.	⟶	Full redundancy
Braytons	1 × 100%	1 × 100%	2 × 50%	2 × 100%	3 × 50%	2 × 10%
HRS	1 × 100%	2 × 50%	2 × 50%	2 × 50%	3 × 50%	2 × 100%
PMAD	1 × 100%	2 × 100%	2 × 50%	2 × 100%	3 × 50%	2 × 100%
Mass, kg	1836	2178	2362	2818	3543	3672
Rel. mass, kg	−982	−640	−456	0	725	854

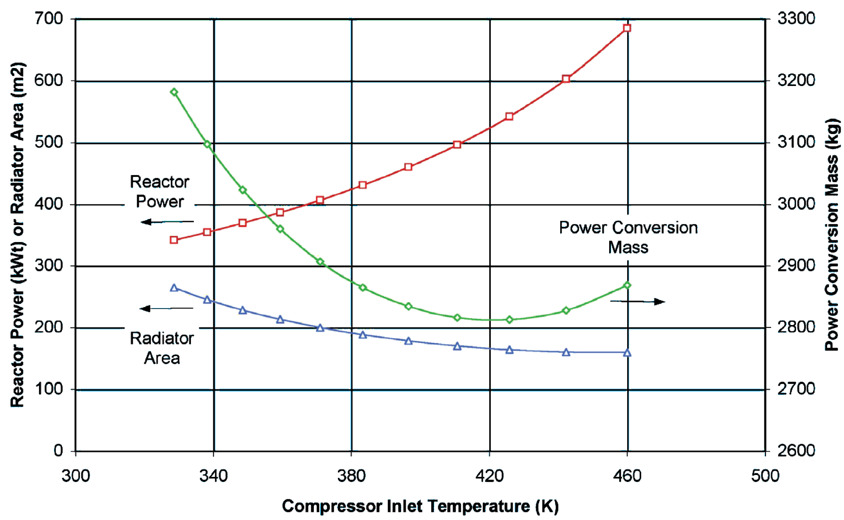

Fig. 3 Brayton-cycle optimization.

power, under a "converter-out" condition. Nominally, the two Brayton units would operate at 50% power. This is achieved by operating the units at a lower rotor speed and charge pressure. The lower rotor speed results in an alternator voltage decrease to 400 Vac. The major benefit of operating the units at part power is a reduction in the thermal stresses and bearing loads. An alternative approach is to operate a single unit and maintain a cold-standby unit.

Another operating mode that was considered was the minimum power coast mode. This mode would be utilized during interplanetary coasting (electric thrusters off) and upon arrival at the Jupiter moon science orbits. The goal was to reduce reactor thermal power and operating temperature to minimize reactor fuel burn-up, fission product generation, thermal stress, and material creep. The HSHX gas outlet temperature was set at 950 K. The Brayton unit output power and reactor thermal power was determined based on the need to maintain the NaK radiator coolant above its freezing temperature of 262 K without restowing radiator panels. The resulting cycle analysis, assuming off-design component efficiencies, indicated that the system output power could be reduced to 20 kWe with a corresponding reactor thermal power of 118 kWt. Alternatively, the reactor power system could be operated at full power throughout the mission, and the PLR could be utilized to shunt any excess power not required by the loads.

Startup Power

A representative startup approach was defined for the reactor power system, based on electrical power provided from the spacecraft bus solar arrays and/or batteries. Startup is initiated by energizing the PMAD controller and reactor instrumentation and control subsystem. After the reactor is started to 10% thermal power, the first radiator wing is partially deployed and oriented to the sun for heating. The radiator wing is charged with the NaK coolant, and the pump is started. Then the first Brayton unit is electrically motored (or rotated) to circulate the HeXe working fluid for approximately 15 min before a self-sustaining condition is achieved and positive power is being produced. As the reactor power is increased to 50% and full deployment of the first radiator wing is completed, the Brayton unit ramps to nominal operating power. At that point, all of the spacecraft loads would be transferred from the spacecraft bus to the alternator bus. The total time to achieve bus switch-over was estimated at 4 h, and startup energy for the Brayton unit was approximately 1 kW-hr. Deployment of the second radiator wing and startup of the second Brayton unit would be accomplished from the alternator bus.

A hot restart following a Brayton converter shutdown was estimated to require less than 0.2 kW-hr. The large thermal capacitance of the reactor and converter units should permit hot restarts for several hours following an unexpected shutdown, the limiting factor being the freezing of the radiator coolant.

Redundancy Trades

The mass of the Brayton converters, heat rejection, and PMAD for the baseline configuration was estimated at 2818 kg. This mass was based on two 100-kWe Brayton units, two 100-kWe PMAD modules, and a heat-rejection subsystem capable of dissipating the waste heat from a single Brayton unit at 100 kWe or two units at 50 kWe each. Alternatives to this configuration were evaluated relative to the full power capacity of the individual subsystems. Table 1 shows the mass differences for several alternative configurations. A single-string architecture would provide a 982-kg mass savings, whereas a configuration with full 100% redundancy in the Brayton converters, HRS, and PMAD would incur an 854-kg mass penalty.

Power Level Scaling

Figure 4 shows the mass and radiator area of the reactor power system for power levels from 20 to 200 kWe, based on the reference configuration. The total reactor power system mass for the 100-kWe design concept was 4115 kg, or 41 kg/kWe. A 20-kWe system has a specific mass of about 100 kg/kWe, whereas a 200-kWe system has a specific mass of 32 kg/kWe as a result of the favorable scaling characteristics of reactor-Brayton technology. Radiator area is relatively linear over this power range because the basic cycle temperatures were not varied.

Brayton Subsystem

The Brayton-cycle analysis discussed earlier provides the basis for the Brayton subsystem design. The input design parameters

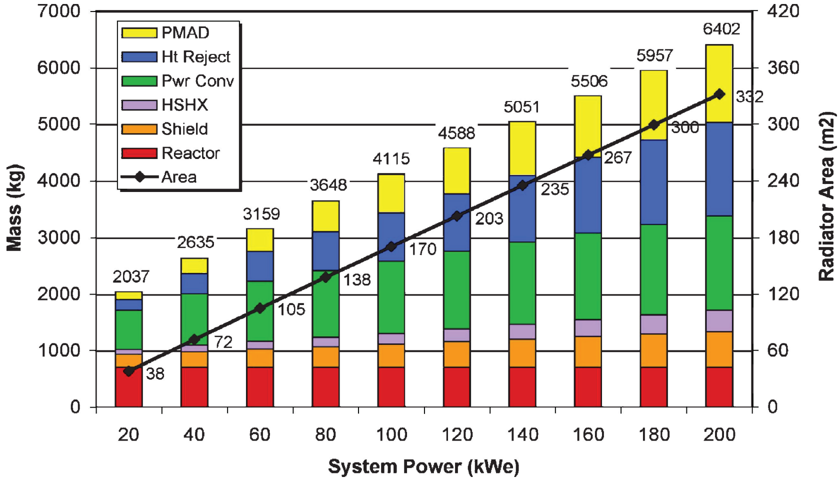

Fig. 4 System mass vs power.

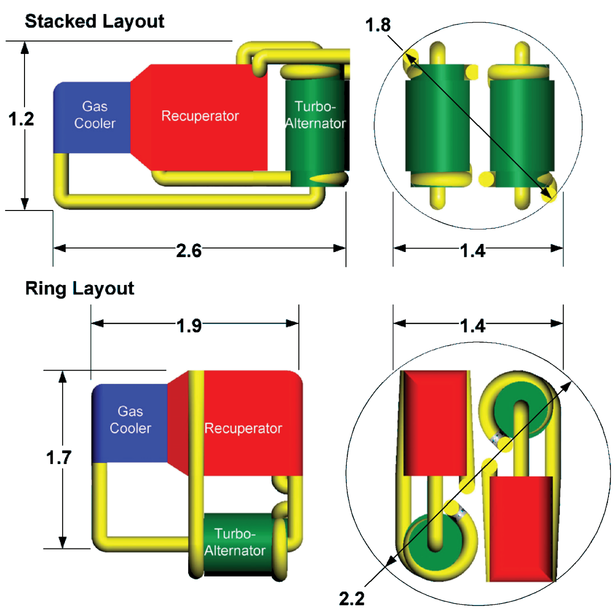

Fig. 5 Converter layout options.

are derived from previous converter development activities such as the 10-kWe Brayton rotating unit (BRU), 2-kWe mini-BRU, and 25-kWe Space Station *Freedom* Solar Dynamic Power Module.[2–4] Despite over 30 years of NASA technology development, Brayton power converters have never been operated in space. The BRU system, including the Brayton heat-exchanger unit recuperator/cooler, represents the longest duration ground test of a CBC conversion system at 38,000 hs. Both the BRU and mini-BRU units were fabricated using nickel-based superalloys for the hot-end components and tested at turbine inlet temperatures of about 1150 K. Scaling these designs to the 100-kWe-class seems achievable within the anticipated development timeline. However, life validation prior to launch will be a significant challenge. The proceeding sections discuss some of the Brayton-specific trades conducted during the study.

Converter Packaging

The Brayton converter subsystem consists of the turboalternator, recuperator, and gas cooler with interconnecting ducts. Several converter layout options were considered as shown in Fig. 5 (dimensions in meters). The "stacked" layout approach was preferred based on a smaller cross-sectional diameter. This allowed the Brayton units to be located closer to the reactor to minimize interface piping length without adversely effecting shield half-angle and shield mass. The overall assembly with the two 100-kWe units was 1.8 m in cross-section diameter and 2.6 m in length.

Table 2 Torque study summary[a]

Two corotating Brayton units Rotor axis parallel with vehicle truss 357 kg/cm bearing stiffness	S/C axis	Maximum torque, N · m	Maximum accel, g
Steady-state net bias torque	R/P/Y	0	0
Steady-state cyclical torque	Roll	0.04	6×10^{-7}
(because of assumed rotor imbalance)	P/Y	26	3×10^{-5}
Single-unit startup	Roll	20	3×10^{-4}
Transient torque	P/Y	17	2×10^{-5}
(nominal case, 0 to 50 krpm in 10 s)			
Single-unit shutdown	Roll	196	3×10^{-3}
Transient torque	P/Y	17	2×10^{-5}
(worst case, 50 krpm to 0 in 1 s)			

[a]Spacecraft(s/c) moment of inertias very preliminary and conservative. Roll = 5000 kg-m^2. Pitch/yaw = 574,000 kg-m^2.

Torque Effects

A first-order analysis was performed using SIMULINK to understand the effects of induced torque from rotating machinery on NEP vehicle dynamics. The analysis considered a representative 100-kWe NEP vehicle with dual Brayton units. Each Brayton unit includes a 53-cm-long, 23-kg rotating assembly with two radial journal bearings and one axial thrust bearing. Primary variables included bearing stiffness (soft and hard), rotor orientation (parallel and transverse to vehicle truss), and operating scenarios (counter and corotating). Startup and shutdown events were also analyzed.

A sampling of the results is provided in Table 2. The net bias torque during steady-state operation is zero. Some low-level cyclical torque is possible as a result of an assumed (very slight) rotor imbalance. A nominal 10-s rotor spin-up resulted in a 20 N-m transient torque. A worst-case, 1-s rotor shutdown resulted in a 196 N-m transient torque. These temporary torques would have to be countered by the vehicle's reaction control system. Parallel vs transverse mounting had no significant effect on vehicle dynamics. Counter vs corotating also had no significant effect. However, counter-rotating pairs would minimize gyroscopic precession effects on vehicle maneuvers.

Turbine Inlet Temperature

The Brayton turbine inlet temperature (or HSHX gas outlet temperature) is a key parameter that influences system performance. Higher temperatures allow increases in cycle efficiency or decreases in radiator area, or a combination of both. However, the higher operating temperatures tend to increase mission risk because more advanced materials are required to handle the higher thermal stress. The baseline turbine inlet temperature was 1150 K. Temperatures above about 1200 K would require refractory alloys for the hot-end components. Figure 6 shows power conversion system mass and radiator area as a function of turbine inlet temperature. A turbine inlet

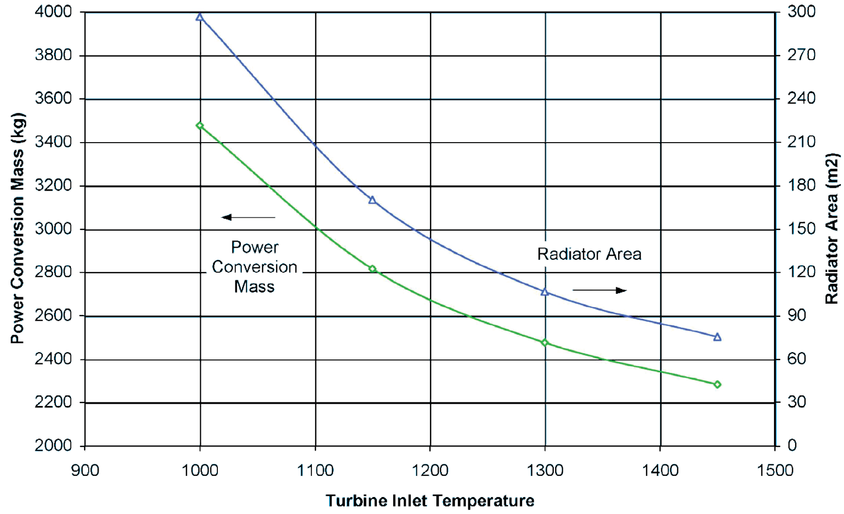

Fig. 6 Mass and area vs turbine inlet temperature.

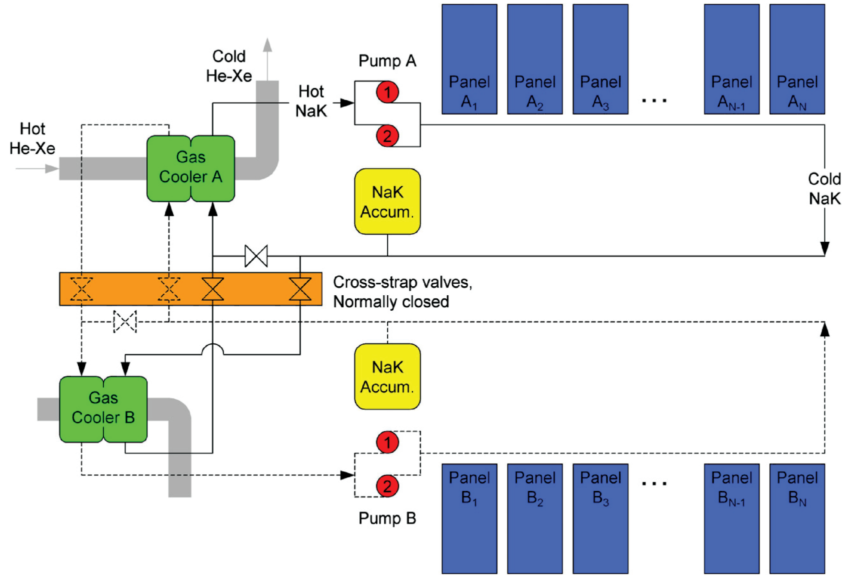

Fig. 7 Radiator heat-transport loop.

temperature of 1450 K would provide a 20% reduction in mass and a 55% reduction in radiator area relative to the 1150 K reference.

Heat-Rejection Subsystem

The HRS dominates the NEP vehicle layout because of the large size of the radiator surface. However, a precedent exists for large space radiators with the International Space Station (ISS) photovoltaic radiator (PVR).[†] The PVR is a pumped ammonia heat-rejection system with deployable radiator panels. A radiator assembly includes seven two-sided panels in series, each measuring 1.82 by 3.35 m, for a total surface area of approximately 85 m^2. The aluminum honeycomb radiator panels are deployed using a scissor mechanism, and the total heat-rejection (panels, fluid loop, deployment mechanism) areal-mass is 8.8 kg/m^2 (based on total surface area). The individual radiator panels are approximately 1.8 cm thick with an areal mass of about 2.75 kg/m^2 (based on total surface area).

During the SP-100 Space Reactor Program,[5] advanced radiator studies were performed by four different contractor teams. The studies addressed radiator designs for operating temperatures of 600 and 875 K. One contractor completed a successful fabrication and test of a high-temperature radiator element utilizing a potassium heat pipe and carbon-carbon fin structure.[6] The condensing section was approximately 91 cm long and 7.5 cm wide with a 2.5 cm diameter Nb-1Zr heat pipe. The integrated heat-pipe and fin assembly had an areal mass of 2.1 kg/m^2 (based on total surface area).

The HRS for the NEP concept study included heat transport, radiator panels, and deployment mechanism. Both the ISS radiator and the SP-100 advanced radiator studies were leveraged in arriving at the design concept. Some of the HRS design trades are discussed next.

Heat-Transport Approach

A significant challenge for the heat-rejection subsystem was to develop a heat-transport approach to accommodate the dual-redundant Brayton power converter architecture. To maintain fail-op redundancy in the conversion system and avoid the need to carry twice the required radiator area, a cross-strapped pumped heat-transport loop was devised as shown in Fig. 7. The two Brayton gas coolers serve as the thermal interface to the coolant loops. Each coolant loop has dual redundant electromagnetic pumps. Each gas cooler includes two independent liquid passages, or cores, and one gas

[†]Data available online at http://www.missiles and fire control.com/our_products/product development/SPACE STATION/product-space station.html [cited Nov. 2002].

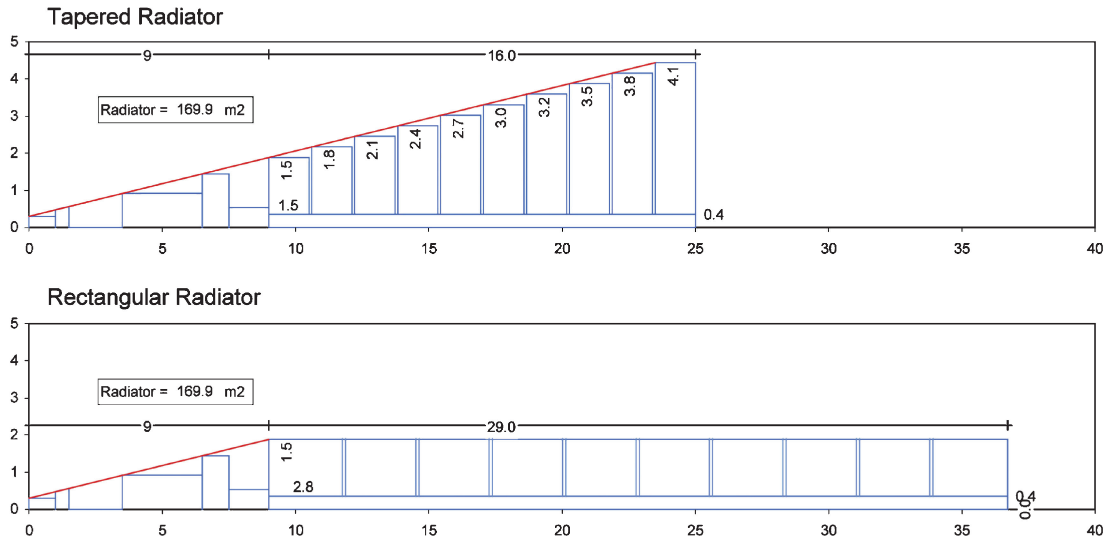

Fig. 8 Radiator geometry options.

passage. During nominal operation, when both Brayton units are operating at 50% power, the liquid coolant flows through one of the liquid passages where the full waste heat load is transferred to the coolant. The coolant is then pumped through manifolds along a series of interconnected radiator panels, forming a radiator wing assembly. The waste heat is transferred through heat pipes to the two-sided radiator surface where it is rejected to space. Each radiator wing assembly is sized to reject one-half of the total waste heat load.

In the event of a converter outage, the two pumped coolant loops continue to operate as before: coolant flow rates and operating temperatures are maintained at near-nominal conditions. However, a series of cross-strapping valves are actuated that allow both coolant loops to service the remaining gas cooler. The gas cooler heat load is increased by approximately a factor of two as the operating converter's power output is doubled to maintain full system power. Both coolant loops continue to transfer the heat to their respective radiator assemblies, which continue to dissipate one-half of the total waste heat load.

Fluids and Materials

The reference HRS design uses NaK coolant and water heat-pipe radiator panels. NaK provides a high specific heat coolant over a wide temperature band suitable to the Brayton cycle conditions. Alternative coolant options include hydrocarbons, fluorocarbons, organics, and water. The coolant loop containment material is stainless steel. The water heat pipes interface to the NaK coolant through evaporator sections that are contained in the fluid loop. Heat pipes provide an efficient means of spreading the heat across the radiator surface with minimal temperature drop. The heat pipes also provide greater fault tolerance than a system with pumped loop radiator panels because the failure of an individual heat-pipe would have minimal system performance impacts. The use of high-pressure water as the heat-pipe fluid provides good heat transfer at suitable temperatures with relatively low risk. The heat-pipe fluid containment material is stainless or nickel-based.

The radiator panels are constructed of a composite material such as carbon-carbon. Composite materials provide low mass, high conductivity, and reasonable stiffness. The assumed areal mass of the heat-pipe radiator panels was 2.75 kg/m^2 (based on total surface area). The total HRS areal mass including radiator panels, pumped coolant loop, and deployment system was 5 kg/m^2 (based on total surface area). The mass of the pumped coolant loop was calculated based on estimates for piping lengths, pump capacity, accumulator size, and fluid volume. The mass of the deployment system was calculated based on 30% of the radiator panel mass.

Radiator Geometry and Deployment

The main power conversion radiators have a total surface area of 170 m^2. Several options were considered in packaging the radiators on the NEP vehicle as shown in Fig. 8 (dimensions in meters). An important constraint is the reactor radiation shield cone angle. Components that are outside the shielded cone are subjected to considerably higher induced radiation levels. Because the radiators are expected to have materials and fluids that might degrade from radiation, a decision was made to maintain the full radiator surface within the shield cone angle. Maintaining the radiator panels within the cone angle also reduces the potential for reactor radiation scattering at the payload end of the vehicle.

The layouts in Fig. 8 assume a 10-deg shield half-angle and a 9-m total axial length for the forward equipment: reactor, shield, Brayton units, coolant pumps and accumulators, and truss canister. The deployable truss has a square cross section with a 0.7-m side. The upper layout was selected for the reference concept. This configuration uses a "staircase" geometry consisting of 10 1.5-m panels per wing with a 10-cm gap between panels. The first panel has a deployed height of 1.5 m, whereas the last panel has a deployed height of about 4.1 m. The advantage of this geometry is the relatively short overall length of the radiator panels (16 m), which helps to reduce the mass of the radiator piping, truss, and power cabling.

The lower layout utilizes 10 identical 1.5×2.8 m panels per wing. This geometry offers greater simplicity in panel fabrication and radiator deployment, but results in a significantly greater overall radiator length (29 m).

Deployment of the panels is accomplished with a scissor mechanism, similar to the ISS radiators, that is attached to the panels along the truss edge. Each radiator wing is assumed to have its own deployment mechanism, allowing the wings to be deployed separately and independently from the truss. The separate radiator deployment permits greater flexibility for power system startup, as described earlier. It also removes the complexity of coincident truss deployment and reactor startup.

Figure 9 shows the effect of shield half-angle on radiator length and relative shield mass for a range of radiator areas from 100 to 250 m^2. The curves assume a 9-m forward equipment length and the staircase radiator geometry with 10 panels per wing. An increase in the shield half angle from 10 to 15 deg would reduce the overall radiator length by about 25%. However, the relative shield mass would increase by about 50%.

Power Management and Distribution

The PMAD subsystem is an often overlooked, but highly critical element of the reactor power system. This is particularly true for NEP systems that include high-voltage electric thruster loads. The

PMAD subsystem accepts the electrical output of the converters, modifies it as required by the bus, and distributes the power to the loads. In addition, PMAD provides control and health monitoring for the power conversion subsystem.

Similarly to the HRS, the International Space Station provides a useful reference for the PMAD concept. The ISS represents the largest power system ever developed for space, with power levels approaching 100 kWe at assembly complete. The ISS uses a 120-Vdc primary bus architecture with modular channels. The ISS PMAD system includes several components that provide a notional starting point for NEP designs, including remote power controllers, switchgear, and shunts. Additional PMAD technology efforts are pursuing higher-voltage space-rated electronic components including relays, fuses, and switchgear for 270 Vdc.

A significant challenge for the PMAD subsystem for the JIMO mission is the reactor-induced radiation environment, coupled with the severe natural radiation environment at Jupiter. The contribution of the reactor to the total dose levels anticipated at the electronics is 25 krads-Si and 1×10^{11} neutrons/cm^2 as mentioned earlier. Total cumulative gamma dose at the electronics dose plane for the approximate 12-year JIMO mission is estimated at 4.3 Mrads-Si, whereas total neutron fluence is estimated at 6×10^{12} neutrons/cm^2 based on 1-MeV equivalent silicon damage and 100-mil aluminum shielding of the electronics. This radiation exposure is well beyond the present state of the art in radiation tolerant high-power PMAD components.

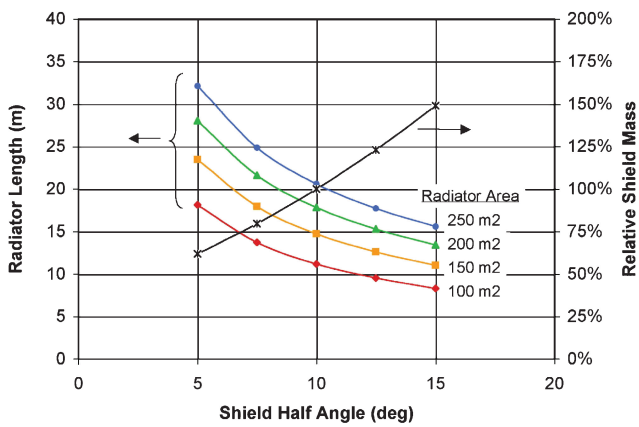

Fig. 9 Shield half-angle sensitivities.

The PMAD subsystem concept was developed from a bottoms-up approach. The study included analysis of power electronics, switchgear, electrical control, thermal control, and power cabling. The proceeding sections describe some of the PMAD-specific trades conducted during the study.

PMAD Architecture

Before any comparative analysis could be performed on the PMAD subsystem, an electrical architecture was required. Figure 10 shows the resulting block diagram. Each of the two Brayton alternators has its own dedicated PMAD module, sized for 100 kWe. The alternator power is delivered to a 400-Vac, 1-kHz PMAD bus within the PMAD module. A buck transformer is provided at the input of the PMAD bus to reduce alternator voltage from 600 to 400 Vac, for the off-nominal case when a single alternator is providing the full 100-kWe system power. Additional work is needed to assess the PMAD performance for the minimum power coast mode condition, with two Brayton units at 10 kWe each.

From the PMAD bus, power is distributed to switchgear for the electric thruster power processing units (PPUs), the spacecraft bus, the PLR controller, and the power system auxiliary loads. The PMAD module also includes a start inverter for motoring the alternator during startup and a computer processor for overall PMAD control. A 333 K cold plate provides a thermal control interface for the PMAD radiator.

The electric-propulsion (EP) system includes 10 PPUs and two ion thrusters per PPU. The PPU power distribution approach provides considerable redundancy and fault tolerance. The EP design concept includes a complete second set of thrusters to accommodate wear-out of the first set and two redundant thrusters per set. A maximum of eight thrusters can be operated at any one time. A single PMAD module provides power switching to all 10 PPUs at 400 Vac and 12.5 kWe per channel. During full power EP operation (i.e., 100 kWe) with both Brayton units operating at 50 kWe, each PMAD module powers only four of the 10 PPU channels. If a single Brayton unit is operating at 100 kWe, eight of the 10 PPU channels are powered. The PPU converts the 400 Vac to approximately 4000 Vdc via a transformer/rectifier/filter for the main beam power supply load. Lower power ancillary thruster loads (cathodes, heaters, etc.) are supplied via a 120 Vdc ac-dc converter in the PPU.

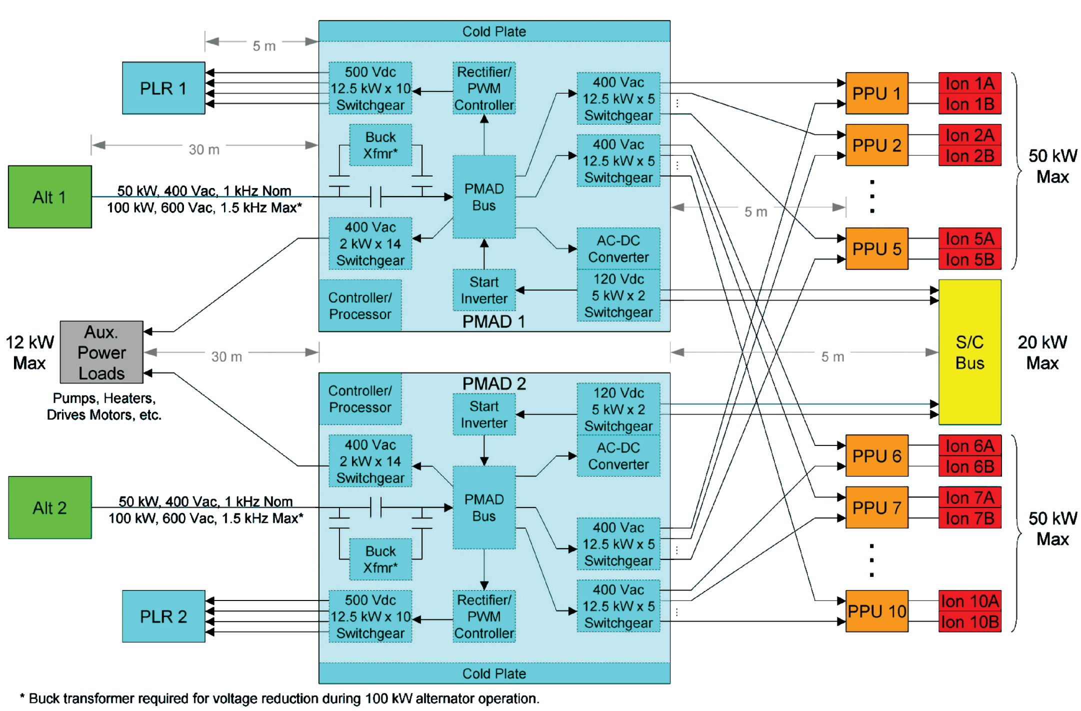

Fig. 10 PMAD architecture.

The PMAD subsystem delivers 120 Vdc and up to 20 kWe to the spacecraft bus. Each PMAD module can provide up to 10 kWe in two 5-kWe channels. The spacecraft bus delivers secondary power, at lower voltages if necessary, to all of the vehicle subsystems (e.g., communications, avionics, etc.) and to the science instrument payload. The 400-Vac PMAD bus power is converted to 120 Vdc via an ac-dc converter. The PMAD switchgear interface with the spacecraft bus also serves as a power feed to the start inverter for alternator motor startup.

The PLR controller provides pulse-width modulated switching of the PLR resistor elements to maintain constant alternator speed and load regardless of external power demands. This approach has been successfully implemented on previous Brayton systems.[7] Each PMAD module includes a dedicated 500-Vdc PLR load bank sized to dissipate up to 100 kWe at 773 K.

The power system auxiliary load bus provides electrical power for coolant pumps, heaters, drive motors, and instrumentation using a 400-Vac distribution system. The switchgear and cabling was sized for as many as fourteen 2-kWe loads, assumed to be located in the general vicinity of the Brayton units.

Equipment Layout and Cabling Distance

The cabling distances indicated in Fig. 10 represent a reference power distribution layout for the study. The reference layout has the PMAD subsystem located at the payload end of the vehicle, with 30 m of cabling provided between the Brayton alternators and PMAD. The PMAD modules are within close proximity (∼5 m) of the electric thruster PPUs, spacecraft bus, and PLR. The auxiliary load bus is colocated with the Brayton units at the reactor end of the vehicle. The location of the PMAD modules at the payload end of the vehicle allows the electronic equipment to share shielding with other electrical systems. This helps to minimize the spot shielding required for vehicle electronics.

The power cabling assumed for the study was tin-coated, copper conductor with Tefzel insulation, similar to what is used on the ISS, rated for 600 V and 150°C. Table 3 provides a summary of the cable sizes. All of the cables were derated for current-carrying capacity per MIL-STD-975L, for operating temperature, and for bundling. The total power cabling mass for the five cable assemblies (alternator-to-PMAD, PMAD-to-PPU, PMAD-to-bus, PMAD-to-PLR, and PMAD-to-aux) associated with one PMAD module was 77 kg. Prior to arriving at the final power distribution layout, several alternatives were considered including locating the PMAD near the Brayton alternators. The cabling mass penalty was relatively small at about 10%, but the radiation shielding mass penalty was projected to be significant.

Table 3 PMAD cable sizing

Cable	P, kW	Volts	Ncond	Amps	AWG	L, m
Alt-PMAD	100	600 Vac	6	53	4	30
PMAD-PPU	125	400 Vac	30	20	10	5
PMAD-Bus	10	120 Vdc	4	42	6	5
PMAD-PLR	125	500 Vdc	20	25	6	5
PMAD-Aux	28	400 Vac	42	3	20	30

Alternator Voltage

The alternator-to-PMAD cable represents the heaviest of the cable assemblies because of its long length and large wire size. The alternator power and operating voltage dictates the conductor current rating. For a given power level, higher alternator voltage results in a lower current rating and mass for the power cabling. However, the higher alternator voltage creates other concerns relative to space-rated electronic parts availability (switchgear, etc.) and corona discharge.

Figure 11 shows alternator-to-PMAD cable mass as a function of alternator voltage assuming 100-kWe distribution and 30-m transmission distance. The reference case at 600-Vac alternator output is shown at the "knee" of the cable mass curve. A 100-Vac alternator voltage would result in a 260-kg cable mass penalty. If the alternator voltage were doubled to 1200 Vac, the resulting cable savings would only be 24 kg, and additional concerns would be raised with respect to corona and parts availability.

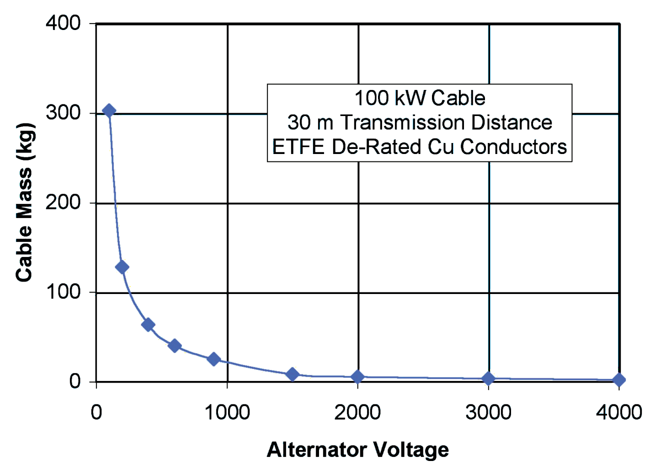

Fig. 11 Cable mass vs alternator voltage.

Table 4 Power conversion mass list

Power conversion mass, kg	Location	No. units	Unit mass	Total mass	Comments
Brayton converter subsystem	——	——	——	1280	1.2 × 1.4 × 6 m total assembly
Turboalternators	Forebody	2	136	272	50 kWe nominal, 100 kWe max. per unit
Recuperators	Forebody	2	243	486	HeXe to HeXe, counterflow, Hastelloy
Gas coolers	Forebody	2	178	355	HeXe to NaK, cross-counterflow, stainless steel
Gas ducting	Forebody	——	15%	167	15% of components, Hatelloy and stainless steel
Heat-rejection subsystem	——	——	——	854	
Main radiator wings	Truss	2	234	468	2-sided, 85 m^2 per wing, C-C panels w/ HPs, 2.75 kg/m^2
Radiator fluid pumps	Forebody	4	24	96	2-string, redundant EM pumps
Radiator plumbing	Truss	2	75	150	NaK-78, stainless-steel piping, accumulator
Deployment mech. and structure	Truss	——	30%	140	30% of panels, scissor mechanism (i.e., ISS)
Power mgmt. and dist. subsystem	——	——	——	684	
Controls, electronics, switchgear	Aftbody	2	193	386	2 channels in one 50 × 50 × 75 cm box
Parasitic load radiator	Aftbody	2	36	72	6.0 m^2 total surface area, 500°C
Alt to PMAD cabling	Truss	2	44	88	100 kW, 600 Vac, 30 m (incl cntl, ground wires)
PMAD to PPU cabling	Aftbody	2	7	14	125 kW, 400 Vac, 10 ch, 5m
PMAD to Bus cabling	Aftbody	2	3	6	10 kW, 120 Vdc, 5m
PMAD to PLR cabling	Aftbody	2	14	28	125 kW, 500 Vdc, 5m
PMAD to Aux cabling	Truss	2	9	18	28 kW, 400 Vac, 30 m (pumps, heaters, motors)
PMAD radiator	Aftbody	2	36	72	6.4 m^2 total surface area, 60°C

Mass and Equipment List

Table 4 presents the power conversion mass and equipment list. The total mass was 2818 kg or 28 kg/kWe. The mass fractions for the Brayton units, HRS, and PMAD are approximately 45, 30, and 25%, respectively. The reactor and shield subsystem adds about 1300 kg for a total power system mass of 4115 kg or 41 kg/kWe. The table shows the approximate location of the equipment on the vehicle: forebody (reactor end), truss, or aftbody (payload end). A short description of the equipment is provided in the right-hand column.

Conclusions

The Jupiter Icy Moons Orbiter (JIMO) mission is currently under study by the Office of Exploration Systems under the Project Prometheus Program. JIMO is examining the use of nuclear electric propulsion to carry scientific payloads to three Jovian moons. A potential power system concept includes dual 100-kWe Brayton converters, a deployable pumped loop heat-rejection subsystem, and a 400-Vac PMAD bus. Many trades were performed in arriving at this candidate power system concept. System-level studies examined design and off-design operating modes, determined startup requirements, evaluated subsystem redundancy options, and quantified the mass and radiator area of reactor power systems from 20 to 200 kWe. In the Brayton converter subsystem, studies were performed to investigate converter packaging options and assess the induced torque effects on spacecraft dynamics caused by rotating machinery. In the HRS, design trades were conducted on heat-transport approaches, material and fluid options, and deployed radiator geometries. In the PMAD subsystem, the overall electrical architecture was defined, and trade studies examined distribution approaches, voltage levels, and cabling options.

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