Systems Engineering of a NEP Rocket to The Moon and Mars

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Abstract: This paper discusses the makeup of a Nuclear Electric Propulsion Rocket and the system engineering considerations which must be made in order to optimize the overall system. Examples of tradeoffs which must be made in the efficiency of various subsystems for the benefit of the overall system efficiency are presented.

Introduction:

The United States has embarked on an extensive evaluation of the processes and technologies to augment current manned exploration of space, with primary interest in establishing an outpost on the moon and exploration of Mars. The program to accomplish these goals is massive compared to the Apollo program of the 1960's and requires major new developments in technology and equipment. For the transit times needed and the tremendous amount of material which must be transported, it has become evident in most circles that some form of nuclear propulsion will be required. The use of nuclear reactors for exploration of space has brought the United States Department of Energy (DOE) into a close working relationship with NASA on the program. The program will involve all the NASA and DOE laboratories, industry and universities, and potentially international partners, as various expertise and capabilities are brought to bear on this project.

There are several sound options for consideration, including Nuclear Thermal Rocket (NTR-with high thrust and short burn time), a Nuclear Electric Propulsion system (NEP-with much lower thrust and longer burn time), or a combination of the two (NTR for astronauts and NEP for cargo) as being the best for the missions envisioned. This paper will discuss the mission options and requirements, from a systems standpoint, in the design of a NEP system.

Missions:

This section briefly describes the mission parameters available using a NEP system, considering a range of power levels and system specific mass. Figure 1 shows the spread of mission times for a round trip to Mars, starting with an initial mass in low earth orbit (IMLEO) of around 500 tonnes, as a function of power level and specific mass. As noted in Figure 1, and stated by Hack, et. al. , "In order for the trip time (all up mission) to approach one year, the system specific mass needs to be reduced to below 4 kg/kWe". Changes in mission design, such as going to a split sprint mission, wherein crew and cargo are transported in separate vehicles, may allow comparable piloted trip times for less aggressive technology assumptions (7.3 kg/kWe). This one year requirement, or desire, is important in a manned mission, but is of less importance in a cargo mission or a mission in which the NEP system (at least a portion of it) could end up as an extraterrestrial surface power unit. Regardless of the mission, however, the lighter the system can be made, the more enhancing it is to any mission.

There are missions, and portions of missions, which are enabled by the closed cycle portion of a NEP system. These missions being surface power, 100 kW class precursor planetary flights, and high mass, long duration cargo shuttle operations.

System Requirements:

For a manned mission, or even for a cargo mission on which the future safety and well being
of a crew may hinge, safety and reliability are of primary importance. Again, where humans are in the loop, time to accomplish the mission is of concern, so a system of sufficient power is required to keep transit times within the limits of human endurance and safe working capabilities. Practical matters such as economics require that a system be as light as possible, because of the tremendous cost of getting mass into low earth orbit.

**Systems and Components:**

The major components of a NEP system are; a nuclear reactor supplying heat to some form of thermodynamic cycle; a power conversion unit which extracts the energy from a working fluid and converts the mechanical energy into electrical energy; a power conditioning unit which delivers the electrical energy, in an appropriate form and process, to an electric thruster; an electric thruster which uses the electric energy to propel some form of on-board mass at a very high specific impulse; and finally, a heat rejection unit(s) to dump waste heat from the system into space. There are several technological candidates for each of these units or subsystems, and each has its advantages and disadvantages. The systems engineering task required for the design is to put together a package which optimizes the system, but does not necessarily optimize a subsystem.

**Reactor**

The Department of Energy, NASA, and the Department of Defense have been cooperating on development of the SP-100 space reactor power system for several years\(^4\), and this reactor system is a good candidate for NEP powered missions in the 10's to 100's kW e range. The SP-100, shown in Figure 2, could be used in the present configuration, supplying power from its thermoelectric devices, or, with a more efficient secondary system such as a liquid metal Rankine system for higher power applications.

From the work done in the late 1980's on Multimegawatt Space Power sources for the Strategic Defense Initiative\(^4\), two reactor systems/cycles emerged as the most fitting for high power space applications - Brayton and Rankine cycles (closed cycles for NEP applications).

The Brayton cycle reactors, using high temperature, coated particles or pellet fuels heating a helium/xenon gas, are simple machines which, when combined with gas foil bearings for the rotating machinery, offer potential high safety, reliability, and a long operating life. Brayton machines have a disadvantage, relative to Rankine machines, in that their heat rejection temperatures are lower, requiring larger and heavier heat rejection units. Figures 3 & 4 show the Particle Bed Reactor (PBR) designed by the Brookhaven National Laboratory\(^5\).
and heat rejection subsystems. Figure 5 shows the cross section of a liquid metal Rankine system reactor developed by Rockwell International.

Liquid metal cooled, fast neutron spectrum reactors in the megawatt power range can be remarkably small (<0.5 m) in diameter and the benefits of this small size is reflected in the size and weight of the shadow shield required. This is an important system consideration since the weight of these shields, especially those capable of protecting astronauts, can be relatively massive. Brayton cycle reactors are at a disadvantage in the shield area, since they tend to be larger for the same power level due to lower heat transfer rates to gas, and thus require larger shadow shields to protect the payload.

![Figure 4 PBR Axial Section](image)

This reactor is fueled by coated UO2, UN, or UC particles on the order of 500 microns in diameter. The particles are contained within inner and outer frits through which the coolant flows and is heated. The small particles have a very large surface area for their volume, providing excellent heat transfer, and the small particles are very rugged with respect to long term structural stability and fission gas retention.

The Particle Bed Reactor is only one of many reactor types which can be used for Brayton cycle machines. The Westinghouse NERVA derivative reactor, tested in the 1960's at the multimegawatt level in an open cycle system, uses prismatic graphite rods containing pelletized fissile material. Ceramic (used in the PLUTO reactor) and Cermet (ceramic-metal oxide mixture) fueled reactors also offer the potential for high temperature, long life, and robust cores for use in Nuclear Electric Propulsion machines. All of these machines have advantages and disadvantages which must be considered in the tradeoffs between weight, complexity, safety, control, and reliability.

Rankine cycle reactors using liquid metals as heat transfer media offer, for their power, small volumes, low masses, and high operating and heat rejection temperatures. These advantages are reflected in lighter weights for power conversion and heat rejection subsystems. Figure 5 shows the cross section of a liquid metal Rankine system reactor developed by Rockwell International.

![Figure 5 Liquid Metal Rankine Reactor](image)

**Power Conversion and Power Conditioning**

Once the energy of a reactor system has been taken out of the flow stream by a turbine, the system(s) to convert and condition that energy is relatively independent of the driving system. The systems engineering effort now must be directed toward generating and supplying power to the thruster in the most effective manner.

Rankine systems pay for their efficiency with a system complexity involving the many pipes, pumps, valves, boilers (for two loop systems), and condensers required for system operation. The operational reliability of these subsystems (together with the tendency of liquid metals to freeze in space) must be considered in the overall system requirements of safety and reliability.

Two mass efficient generators, a superconducting and a hyperconducting unit, were proposed as part
of the MMW program. The hyperconducting unit, using ultra pure aluminum and operating at ~20 K, and the superconducting unit, operating at liquid He temperature, both relied on having a large supply of liquid hydrogen to either supply or augment the cooling required. If, for example, a thruster concept is selected (such as a magnetoplasma dynamic (MPD) unit) which uses liquid hydrogen as a propellant, there may be some system benefits to pursuing this advanced technology. If, however, a separate cooling system is required to keep the generator cooled, the mass advantage may be lost.

Once the power is produced in a generator or alternator, it must be supplied to the thruster at a location and in a form usable to generate thrust. The MPD thruster requires tens of kiloamps (steady state) at hundreds of volts and there are several cyclotron type thrusters which require steady state microwave/radiofrequency input. An ion thruster would require kilovolts and tens to hundreds of amps. Therefore, the choice of a thruster immediately places a heavy requirement (in technological terms as well as mass) on either the cables to carry this power and/or the power electronics to condition the power.

High power cables can generate enormous magnetic fields and if the thruster is very far from the generator/power conditioning unit, the mass of these cables alone can be significant. Some of the proposed designs of Mars transit vehicles have the reactor(s) placed on long booms (127 meters in one design) from the thrusters. Cabling and its insulation for these lengths are significant mass items. Moving the thrusters and their controls closer to the reactor and the power conversion equipment reduces this weight penalty, but also moves these components into a higher radiation field with a possible effect on required shield mass.

High levels of radio-frequency or microwave power, pulsed or steady state, brings another systems consideration to the forefront, that being heat dissipation from the power electronics. Even at high efficiencies, there are 10's to 100's of kilowatts to be dissipated. The present maximum operating temperature for most power electronic components is only around 300 °C. Radiating this waste heat to space with such a low radiator temperature can result in power electronic radiators of a size and mass comparable to the reactor system radiators.

Power can be generated at one point, rectified to an efficiently transportable form to cut down on cable size/weight, and reconditioned at the thruster for its use. This efficiency, however, must be weighed against the reliability of very high voltage conductors in space. A small break in the insulation by a micro-meteoroid can cause a conductor to self destruct.

System considerations dictate that we either concentrate effort in the direction of higher temperature and more radiation hardened electronics in order to keep the weight and complexity of the system down, look at thrusters which require a minimum of power transmission and conditioning between the point of generation and the point of use, or an integrated unit which does away with most of the interconnections and sinks the waste heat to the propellant.

Thrusters

Several thruster concepts can provide 5000 to 10,000 seconds specific impulse at power levels required for NEP systems. The most mature concepts are magnetoplasma dynamic (MPD) thrusters and inert gas ion thrusters (Figs. 6, 7). Ion thrusters have demonstrated high performance and long life at low power levels (1 to 5 kW), and MPD thrusters have demonstrated high power capability (0.1 to 0.6 MW for short periods of time).
More than six ion propulsion systems and two pulsed MPD arcjets have been qualified for flight at power levels less than 2 kW\textsuperscript{16}. High power electrodeless thrusters are also candidates for NEP systems, and such devices will be evaluated under innovative technology programs.

Ion propulsion components and systems have been ground and flight tested worldwide for three decades. Mercury ion thrusters were tested at beam power levels of 20 to 200 kW more than 20 years ago\textsuperscript{17}. Due to the prospects of modest space power capability, most subsequent ion thruster research has been conducted at power levels less than 5 kW.

Present programs at NASA Lewis involve the development of a 10 to 45 kW, 50 cm diameter ion thruster capable of delivering 5000 to 10,000 seconds specific impulse using krypton and argon propellants\textsuperscript{17}. While the high thrust efficiency and specific impulse of ion thrusters are well known, the scalability, lifetime, and power processing issues for power thrust systems will be the focal point of early development efforts.

Steady state MPD thrusters have typically been operated at power levels from 30 to 600 kW, while quasi-steady MPD devices have been run at powers exceeding 1 MW\textsuperscript{18}. The most promising propellants are hydrogen and lithium. Steady state operation with hydrogen at low power has yielded about 3500 seconds specific impulse and a thrust efficiency of nearly 40 percent. Thruster lifetimes have been limited by cathode erosion, although an applied field MPD thruster operating at 25 kW delivered a total impulse of 1M N-s. Vigorous efforts to develop the technology of steady state MPD thrusters are now ongoing in the United States, Europe, and Japan\textsuperscript{15}.

The thruster component and subsystem technology will be developed in phases with each phase building towards the next. The feasibility and practicality of high power thrusters, along with the power processors, will initially be assessed for applications involving 100 kW class robotic precursors, building to megawatt-class cargo vehicles, and multimegawatt piloted vehicle applications. Ten to fifty kilowatt krypton or argon ion thrusters are the strongest candidates for the early robotic precursor applications since high thruster performance is easily attained. Major products of focused technology programs would be low thruster/power processor specific mass, low risk, 5000 to 10,000 hour lifetime, and detailed definition of critical thruster systems interfaces.

High power electric thrusters must interface with power processing, propellant management, thermal control, and thrust vector control systems. The power processor unit (PPU) is usually the most massive and most expensive thrust subsystem component. The thrusters will likely require dedicated PPU's whose technology focus will be on low component mass, high efficiency, low parts count, radiation resistance, and high temperature components. Argon and hydrogen electric thrusters will require cryogenic storage of propellant in order to minimize system mass. Such propellant management and distribution system technologies are very similar to those now being carried out for liquid hydrogen and oxygen systems for chemical rockets. A thruster gimbal system will likely be required to accomplish small thrust vector changes needed during a given mission. Thrust vector control is considered a mature technology for low power systems. Gimbal system mass for a 3 kW thruster was about one-third of the thruster mass. Another critical interface involves the flow-field characterizations of emitted ions, propellant neutrals, and sputtered flux. The effects of electromagnetic radiated emissions and static/dynamic magnetic fields on spacecraft systems will also have to be addressed. In-space and ground integration tests have been successfully conducted for a variety of low power electric propulsion systems.
Heat Rejection

Heat rejection requirements for a multimegawatt power source in space result in the largest single component (area, volume, and sometimes mass) of a NEP system. High temperature, liquid metal, refractory metal and carbon-carbon clad heat pipes offer the possibility of bringing these system weights down, but with any system, this subsystem is going to be a large and massive item.

There have been a number of innovative heat rejection subsystems proposed over the years, such as liquid droplet, liquid sheet, solid ribbons, rotating balloons, Curie point magnetic particles, and various forms of heat pipe radiators. All of the dynamic systems have raised questions about their operational behavior during start-up, shutdown, spacecraft maneuvering, and thermal load transients.

The simple heat pipe, usually with fins to augment the heat transfer area, appears to be the best candidate to quietly perform its required function in a safe, reliable manner. Liquid metal, foil heat pipes (<0.005 inch wall thickness) have been fabricated and tested by deploying them from a rolled configuration and then operating them at over 1000 K. The ability to deploy and operate such a significant subsystem in this manner has a very positive system benefit, not only in operation, but in launch volume and in-orbit assembly of a large space transportation vehicle.

System Relations

We engineers tend to be specialists in our fields, and advocates of our specialities. This situation does not lend itself well to viewing the big picture and seeing many of the programs we are involved in as large systems, sometimes with our speciality item as only a small part of that system, and often controlled by requirements that push our speciality item down into the mélange of the system. A prime example of this is the recuperator on a Brayton cycle power system. Recuperators are used to enhance the thermodynamic efficiency of a Brayton cycle. Recuperators are, however, rather heavy and when it comes to putting a Brayton system in orbit, it is cheaper to put a little extra fissile material in the core and accept the slightly lower operating efficiency of the system.

Initial mass in Low Earth Orbit (IMLEO) is a big driver in the cost and mission performance of a system, given the high per pound launch cost of present and projected launch systems and impact of specific mass on mission time. Figure 8 shows the specific mass breakdown of Brayton and Rankine systems at various power levels. The reader sees that the reactor can be a minor part of this important system parameter relative to the heat rejection, power conversion, and power conditioning subsystems.

Figure 8 Brayton & Rankine Sp. Mass

A number of system related decisions, or at least points for consideration, can be derived from Figure 8. First, from a system power level standpoint, not a lot is gained in specific mass by going beyond a 5 - 10 MWe unit, and there is a lot to be gained in safety and reliability (from redundancy) with multiple units. Therefore, multiple 5 - 10 MWe units should be considered for the 20 - 40 MWe power level missions. In addition, a single 5 MWe unit has a number of potential missions in the cargo and surface power applications. Second, from a system technology payoff position, effort directed toward a light weight, high temperature radiator for a Brayton, or a better power conversion subsystem for a Rankine, will yield more payback per percentage performance increase than effort directed toward the reactor. In addition, benefits gained by a Brayton cycle from a better radiator are also applicable to a Rankine cycle, although not to as large an effect. Directing a significant effort...
toward something as mundane as a radiator may be difficult to sell when we are bouyed up by the excitement of "Going to Mars on a Nuclear Rocket", but from a systems standpoint, the radiator is an important part of the trip. The reader can see from Figure 8, that if a significant improvement is made in the radiator portion of the specific mass, the system specific mass is well below the 7.3 kg/kWe stated by Hack, et. al. as being needed for a one year split mission, and is close to the 4 kg/kWe needed for an all up mission.

A major space power systems consideration that should be kept in mind at this time is the future use of the closed cycle technology required for a NEP propulsion system in the closely related application of surface power. The same basic requirements of a propulsion power plant are needed in a surface power plant - safety, reliability, and low mass. Extraterrestrial surface power has an even more stringent requirement on mass than a propulsion unit, namely, that one must not only get it into orbit around the earth, but one must also pay the energy bill for taking it out of orbit around another body and deploying it on the surface. In addition to the mass issue, the set-up and operational requirements of a surface power system must be very simple and the system itself should be a safe, rugged, maintenance free design because of the limited time and personnel available to deal with problems.

In the Multimegawatt Space Power program, activities were directed toward the development of reduced mass components in heat pipe radiators, power generation, and power conditioning. High temperature (>than 1000 K) foil heat pipe radiators were produced and tested at Los Alamos National Laboratory, showing promise of producing space radiator subsystems of less than 1 kg/m². Superconducting and hyperconducting generators were being proposed in the multimegawatt range by General Electric and Westinghouse and high temperature power electronics were being pursued at Sandia. With the scaling back and changing direction of the Strategic Defense Initiative, the need for these components has lessened and their development has suffered accordingly. The emphasis on development of these mass efficient components should be increased as part of the Space Exploration Initiative because of their contribution to the system, as shown in Figure 8.

Summary

In order to arrive at a safe, reliable, mass efficient NEP system, it is imperative that a broad, systems approach be taken in the overall design and the selection of individual components for the system. The stringent requirements of manned space travel, particularly safety, reliability, and low mass to orbit, are not as familiar ground to power reactor engineers as it is to the aerospace engineers who have been launching hardware for decades. Reactor power engineers must be ready, even eager, to back away from maximum cycle efficiency if it benefits weight, do away with valves for the benefit of reliability, and concentrate on those portions of the system with the most gains to be made in safety, reliability, and mass reduction.

The approach to an optimum NEP system will, and probably should, be an evolutionary process in which modest powered reactors, such as the SP-100, are coupled with low power thrusters and used in precursor planetary exploration and light cargo roles. The experience gained from the construction of these machines, and integration of components which make them up, will be the base on which effective system engineering of larger machines will be made.

Development of a NEP system should have a systems engineering and evaluation group as an integral part of the project team, with the task of continually evaluating the system for balance, fidelity to the requirements, and directions for development which will enhance the system. This group should be part of the project team in order to minimize the bias that is inherent in suppliers of systems and components.

References: