The Challenge of Space Nuclear Propulsion and Power Systems Reliability

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SUMMARY & CONCLUSIONS

In October of 2002, The Power and Propulsion Office and The Risk Management Office of NASA Glenn Research Center in Cleveland Ohio began developing the Reliability, Availability, and Maintainability (RAM) engineering approach for the Space Nuclear Propulsion and Power Systems Project. The objective of the Space Nuclear Power and Propulsion Project is to provide safe and reliable propulsion and power systems for planetary missions. The safety of the crew, ground personnel, and the public has to be the highest priority of the RAM engineering approach for nuclear powered space systems. The Project will require a top level reliability goal for substantial mission success in the range from 0.95 to 0.98. In addition, the probability of safe operation without loss of crew, vehicle, or danger to the public, cannot be less than 0.9999. (See Note 1)

The achievement of these operational goals will require the combined application of many RAM engineering techniques. These include: advanced Reliability, Availability, and Maintainability Analysis, Probabilistic Risk Assessment that includes hardware, software, and human induced faults, Accelerated Life Testing, Parts Stress Analysis, and selective End to End Sub-System Testing. Design strategy must involve the selection of parts and materials specifically to withstand the stresses of prolonged operation in the space and planetary environments with a wide design margin. Interplanetary distances and resulting signal time delay drive the need for autonomous control of major system functions including redundancy management.

1. INTRODUCTION

An important advancement in space propulsion for manned missions to Mars, or unmanned missions to distant planets such as Jupiter, or Neptune, would be a propulsion technology that could provide an enormous energy per unit mass of fuel. Such technologies exist and are called Nuclear Thermal and Nuclear Electric Propulsion. Research on Nuclear Thermal Propulsion (NTP) has been active for nearly 50 years. In particular, the Rover/NERVA program which lasted about 12 years resulted in the development of actual Nuclear Thermal Propulsion (NTP) engines. Nearly 20 of these reactor/rocket engines were designed, built, and tested. However, renewed interest in nuclear propulsion has lead to new efforts to evaluate these propulsion technologies in order

to develop preliminary system designs for planetary missions. NTP utilizes a heat-exchanger nuclear reactor. Liquid hydrogen is pumped through reactor components to provide cooling. After all of the components have been cooled, the liquid hydrogen is pumped right through the core of the nuclear reactor. Here, it is heated to a rather high temperature of approximately 2500 degrees K and is thermally accelerated through (and out) of the reactor producing high thrust. [1] The typical application of NTP would be to provide the high thrust for a spacecraft to escape the gravitational field of the earth from orbital position and for subsequent acceleration. This would be followed by a long term mission phase of low thrust providing continuous acceleration. In this second phase, Nuclear Electric Propulsion (NEP) could be used. [2] Thermal energy from the same nuclear reactor would be converted to electricity by a Brayton-Cycle convertor in order to power electric propulsion engines that accelerate charged particles producing low thrust. [3] The Brayton-Cycle convertor utilizes a single phase working fluid and is a Turbine-compressor-alternator unit. It takes advantage of a thermodynamic work cycle where the hot side of the convertor (from the interface with the reactor) and its cold side (interface to the radiator) temperature differences provide shaft rotation in order to produce electric power from an alternator. This design concept involving the application of NTP technology for high thrust and applying NEP technology for low thrust is called *Hybrid Bimodal Nuclear Thermal and Electric Propulsion*. (See Figure 1 on page 3)

What are the advantages of NTP and NEP technologies? A practical way of relating the thrust of a rocket engine to the mass of propellant flow is by using a figure of merit called the *specific impulse*. The thrust per unit flow rate of propellant is the specific impulse. (expressed in units of seconds) Specific impulse is really a measure of the efficiency of a propulsion system. As a comparison, the maximum specific impulse of a chemical rocket is approximately 450 seconds, whereas a rocket utilizing nuclear thermal propulsion may have a specific impulse as high as 850 to 1000 seconds. Nuclear propulsion systems will contain propellants with low molecular weights and that increases the propulsive force per unit propellant flow. This means that more of the total spacecraft mass can be dedicated to payload (for the crew and for science) and less to propellant that is needed for propulsion. Nuclear

propulsion systems will also enable a spacecraft to attain higher transfer orbits and that minimizes the travel time to the destination. Shorter round trip times on a planetary mission means less exposure to micro-gravity, solar wind, planetary and cosmic radiation, and micro-meteors. It means increased time spent at the planet or planetary moon destination for exploring and scientific observation.

In addition to the need for highly efficient propulsion there is also a need for a highly reliable source of thermal energy for power generation. Advanced thermal-to-electric energy conversion technologies being developed by the DOE, NASA, and DOD, are essential to producing lighter and more efficient nuclear power sources. Nuclear power is the enabling technology for outer-planet missions where there is very little sunlight. [4].

1.1 Glossary

- Autonomous Monitoring and Control: Processor control and monitoring of real time operations and functions with the capability for issuing recovery commands without initiation by the earth based operations center.
- Bimodal: Functioning as both a propulsion and power generating system.
- Hybrid Bimodal Nuclear Thermal and Electric Propulsion: A Propulsion system methodology that combines nuclear thermal and nuclear electric propulsion technologies and provides power for on-board applications.
- Brayton Cycle Convertor: An energy convertor that utilizes a single phase working fluid. It is a Turbine-compressor-alternator unit. It utilizes a thermodynamic work cycle where the temperature differences between its hot side interfacing with a reactor and its cold side interfacing to a radiator provides shaft rotation to produce electric power from an alternator.
- Failure Tolerance: Built-in capability of a system to perform as intended in the presence of specified hardware or software failures. [5]
- Failure Tolerant Design: A design that possesses a degree of failure tolerance to assure the continuation of safety and/or mission critical functions. [5]
- Fail Operational: Ability to sustain a failure and retain full operational capability. [5]
- Fail Safe: Ability to sustain a failure and retain the capability to safely terminate or control the operation. [5]
- Functional Interrupt: A radiation induced event requiring a software reboot or a power cycle.
- Nuclear-Electric Propulsion: Converting thermal energy from a nuclear reactor into electricity that powers a device creating charged particles which are accelerated to produce thrust.

- Nuclear-Thermal Propulsion: Utilizing thermal energy from a nuclear reactor to heat, expand, and accelerate a low molecular weight fuel such as hydrogen in order to produce thrust.

- Operational Availability: The probability at any given point in time during a mission that a system will be operational and successfully conducting its intended functions. Operational availability depends upon the reliability and maintainability designed into a system and the resources to carry out preventative and corrective maintenance actions.

- Probabilistic Risk Assessment: The application of analytical methodologies in order to evaluate the risk associated with undesired End-State events that usually pertain to the safety and reliability of a system.

- Radiation Design Margin (RDM): The ratio of the part or component radiation tolerance capability in a given application to the expected radiation environment at the part or component location during the mission. [6]

- Single Event Upset (SEU): A radiation induced event resulting in a data error.

- Single Event Latch up (SEL): An event where a device has an abnormal conduction path established by ionizing radiation that may be indicated by a primary power supply current change. Power must be re-cycled to regain control and/or save the device from destruction.

- Single Event Burnout (SEB): An event where a device has an abnormal conduction path established by ionizing radiation and is destroyed nearly immediately.

- System Effectiveness: The probability that a system can *safely* and *successfully* meet its operational demands over a given mission time when operated under specified conditions. (See Note 2)

1.2 Acronyms

The following are acronyms:

BNTR/EP	Bimodal Nuclear Thermal Rocket with Electric Propulsion Option
FIs-	Functional Interrupts
HeXe	Helium and Xenon
NEP -	Nuclear Electric Propulsion
NERVA-	Nuclear Engine for Rocket Vehicle Applications
NTP-	Nuclear Thermal Propulsion
PRA -	Probabilistic Risk Assessment
RDM -	Radiation Design Margin
SEUs -	Single Event Upsets
SEs -	Single Event Latch-ups
SEBs -	Single Event Burnouts
WCCA -	Worst Case Circuit Analysis

Figure 1 : A Diagram of a Conceptual Bimodal Nuclear Propulsion System

2. WHAT ARE SOME OF THE MAJOR CHALLENGES TO ACHIEVE HIGH RELIABILITY?

One of the greatest challenges of Space Nuclear Propulsion and Power Systems Reliability Engineering and systems engineering will be to attain the extremely high reliability required for safety and mission critical functions. This must be achieved with limited resources over a mission time that could be as high as 15 years. The Hybrid Bimodal Nuclear Thermal and Electric rocket will have to contend with the environmental threats that were encountered by the Voyager, Galileo, and Cassini missions. Nuclear power systems subjected to the planetary surface environment such as the Martian surface will have to survive. NASA has learned from JPL interplanetary missions that *a major design strategy for high reliability and long life missions must be to design a system that withstands all of the deep space, orbital, and planetary surface environments*. This is a major challenge since nuclear systems will be complex and there are many environmental threats such as ionizing radiation, space charging effects, micro-meteoroids, space debris, planetary surface erosion, contamination, and temperature extremes.

There are many other challenges within system design that must be met for Nuclear Thermal and Nuclear Electric engines. Loss of thrust or thrust control is safety critical for manned missions. In particular, the exposure of system control electronics and critical engine components to external radiation or to residual reactor radiation must be a key consideration in the design.

It is understood clearly that a radioisotope is a highly reliable source of thermal energy for any energy conversion technology that requires thermal energy. NTP and NEP propulsion and planetary surface power facilities utilize a radioisotope. While the design process is striving to attain a highly reliable propulsion design, a crucial objective must be *highly reliable containment and control* of the radioactive material in the reactor core. In addition, the probability of catastrophic failure for the launch vehicle that will be used to transport the radioactive payload into earth orbit must be extremely low. *Design for Reliability cannot be a process with goals that are disconnected from the safety engineering process. The key to achieving success in NTP and NEP safety and reliability will be an integrated approach with the underlying philosophy of minimizing risk.*

3. THE INTEGRATED APPROACH

In order to develop an integrated approach for Nuclear Propulsion and Power Systems Reliability, we can start with a broad definition of the *System*. The *System* is composed of all necessary hardware, firmware, software, and humans. Attention must be given to the successful execution of all the specific functions and actions that must be carried out to achieve mission objectives. The system must include a *carefully defined boundary*. [7] It also includes *interaction and interdependency* between its internal components, crew, and ground support. Interaction with the environment that lies outside the boundary must be considered. *Connectedness and transfer of energy and information between the system components and with their environment must be considered in the system analysis*.

Using a very precise definition of the System would lead to a definition of system effectiveness that encompasses multiple areas of design requirements. System Effectiveness would be defined as the probability that a system can *safely* and *successfully* meet its operational demands over a given mission time when operated under specified conditions. The required System Effectiveness would drive the following types of requirements:

1. Safety Design Requirements
2. Operational Readiness
3. Software Reliability and Maintainability
4. System Design Rules
5. Survivability in planetary, orbital & space environments
6. Human Reliability

Figure 2: System Effectiveness for Nuclear Propulsion and Power Systems

4. DESIGN STRATEGY

What will be some of the major design strategies to achieve high system reliability? A robust design for the Nuclear subsystem, all control electronics, and the Command Data Management subsystem is needed. Components must utilize materials and designs to withstand the stresses of prolonged operation with extra design margin. Internal failure tolerant design for high reliability processors, electro-mechanical devices, and software will have to be implemented to protect from and contend with radiation induced SEUs, FIs, SELs, and SEBs. Where possible and practical, electronic parts must be selected to assure a RDM of at least 2. [6] In order to detect, isolate, and recover from anomalies or faults during a long life mission that involves vast interplanetary distances (where signal time delay is significant) autonomous monitoring and control of complex system interactions must be built in. In addition, self-healing materials may have to be used for safety critical structure and other applications.

Due to the severity of potential catastrophic events and the importance of scientific success for NTP, NEP, and space nuclear power systems, the RAM program must include the combined application of various analyses, practices, and testing. Many of these are noted in the chart below:

Reliability, Availability, and Maintainability (RAM) Analyses for System Design	Reliability Practices (Examples)
<ul style="list-style-type: none"> Setting Reliability Goals RAM Allocations Trade Studies and Predictions Failure Modes and Effects PRA: Includes Mission Event Tree and Fault Trees Human Error Risk Assessment Worst Case Circuit Analysis Parts Stress Analysis Performance Trending Limited Life Items Corrective and Preventative Maintenance Fault Detection & Isolation Sparing and Logistics Operational Availability 	<ul style="list-style-type: none"> Supplier Screening, Supplier Quality Assurance Testing: Thermal cycle, Vibration, and Burn-in Minimize EMI susceptibility Selection of parts for high quality level and radiation hardness to meet or exceed reliability allocations Thermo-graphic Mapping of circuit cards Problem/Failure Reporting and Corrective Action System (PRACA/FRACAS)

Figure 3: Elements of the RAM Program for NTP, NEP, and Space Power Systems

There are many more analyses discussed in NASA Technical Standard NASA-STD-8729.1 that can also be applied to a space propulsion and power project but are not listed in figure 3. [8] In addition, an integrated approach can be adopted that includes the consideration of hardware, software and human induced failures. A Software Hazard Risk Analysis is an initial software risk assessment that considers the potential hazard severity and the degree of control which the software exercises. A Software hazard or failure modes analysis can be performed and the failure effects can be classified in terms of Hazard Severity and Probability. A numerical scale of probabilities can be used to define what is meant by frequent, probable, occasional, remote, and improbable. Integrated Hardware-Software-Human Response Fault Tree Analysis would include basic events that are hardware failures, software induced faults, and human errors. [9] There are many specific technical benefits to the integrated analysis approach. Some of these benefits will be listed here. These are:

1. Determining the design-to targets for major sub-systems and components to drive the design for Reliability.
2. Optimizing performance and reliability with resource constraints.
3. Finding Safety and Mission critical failure modes and fault propagation paths to enable improved design, risk reduction and risk mitigation.
4. Designing to operate under worst case stresses and accomplish the mission.
5. Selecting parts to meet or exceed the mission reliability requirement
6. Maximizing total system reliability at the minimum mass for the power System.

The value of applying all these types of analyses, practices, and testing has been demonstrated by JPL interplanetary mission experience with Voyager and Galileo. [10]

Throughout the development process for the Nuclear Propulsion and Power system project, the tendency to segregate human, hardware, and software supported functions must be resisted. [11] Humans are "in the loop." It is necessary to realize that errors in design, manufacturing, testing, operation, and maintenance can have quite adverse effects on any complex system. Thus, it may be very beneficial to do an analysis to find the possible sources of human error *that are unique to* this nuclear propulsion and power program by performing a Human Error Risk Assessment. Such an analysis may have as its qualitative foundation a Failure Modes and Effects Analysis, an Event Tree or Fault Tree Analysis of Human supported functions and planned program activities for each phase of development. The analysis would include possible failure propagation scenarios, the anticipated worst case severity of human failure effects and their associated probability of occurrence. Risks

could be estimated and better understood so that serious problems may be avoided.

5. CLOSING REMARKS

Hybrid Bimodal Nuclear Thermal and Electric Propulsion would provide a great advancement in propulsion technology for planetary missions. Extremely high system Reliability is needed to support mission critical and safety critical functions. *Reliability requirements are a design criteria that will have to be equal in importance to any other design criteria.*

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NOTES

Note (1)-This corresponds to a probability of failure that must be less than 1×10^{-4} . This goal was estimated by using "The NASA Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners," Version 1.1 dated August 2002, Section 2.3 (Societal Risk Acceptance), Table 2-1, pg.7. In addition, the confidence interval for this goal must also be established.

Note (2)- MIL-HDBK-338B, Section 10 titled "Systems Reliability" illustrated three models for system effectiveness: The ARINC model, the WSEIAC model, and the Navy model. All of these are excellent. However, in this paper, the authors are proposing a fourth concept that they believe is tailored for application to the Nuclear Space Propulsion and Power Systems.

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Ed earned his MS degree in Physics from the Cleveland State University and worked as a Quality Assurance Engineer for the Technicare Division of Johnson & Johnson. Ed became interested in Reliability during the early 1980s when he had the opportunity to work with EIMAC Division of Varian on X-ray tubes. In 1987, Ed had the privilege to join NASA. He supported many Space Flight and Research projects. Ed is proud of a pilot application project with R.O.S.E. Informatik GmbH utilizing the model based reasoning tool called RODON. He was also a theory analyst for the NASA Breakthrough Propulsion Physics Project and has an enduring life interest in Relativity and relativistic theories of gravitation.

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Bob earned his BSEE and MSIE from Cleveland State University and has worked in the power systems field for both terrestrial and space energy storage technology. He has lead various power system studies for human exploration missions of the Moon and Mars. He authored the power system sections for the NASA Special Publication 6107, *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team*, July, 1997. Bob is interested in the techniques of predicting space power system design life and how limited resources can be utilized to test and validate the design life. He is concerned about how the problem of long life design and verification couples with the special requirements of human space flight and nuclear systems.