OPTIONS AND RISK FOR QUALIFICATION OF ELECTRIC PROPULSION SYSTEMS

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Introduction

As Electric Propulsion (EP) increases in recognition as a means of spacecraft primary propulsion and orbit maintenance, more complex spacecraft using EP will be produced. With the proven adage, test what we fly and fly what we test, the ground and on-orbit verification programs for those spacecraft utilizing EP for primary propulsion also increases in complexity. While EP systems have been tested for decades, this paper will seek to address the options associated with the verification/qualification of entire spacecraft utilizing Electric Propulsion systems powered by nuclear and nonnuclear sources.

Electric propulsion offers the technical advantage of allowing for thruster exit velocities on the order of 10-20 km/sec. This provides a significant advantage over traditional storable chemical propellants. Electric propulsion has traditionally been divided into three classes; Electrothermal, Electrostatic and Electromagnetic. Within each of these categories there exist further subgroups based on the techniques utilized for ion production or method of propellant heating. Table 1 illustrates these subdivisions. Each of these forms of propulsion offers differing challenges from a testing and verification standpoint.

Electrostatic	Electromagnetic	Electrothermal
Ion Bombardment	Magnetoplasmadynamic	Resistojet
Field Emission	Pulsed Plasma	Arcjet
Plasma Seperation Ion	Helicon Plasma	Electrothermal Hydrazine
Hall Effect	Inductive pulsed plasma	Microwave Electrothermal

Table 1 Electric Propulsion Options

The primary effects introduced by the functioning of electric propulsion include:

1) Physical: erosion, deposition of material on all surfaces impacted by the plasma and redeposition of eroded materials on the surrounding surfaces
2) Mechanical: perturbation torque due to impact of beam on spacecraft surfaces and thrust vector variations due to instabilities or divergence of the beam.
3) Thermal: increment of surface temperature
4) Electrical: surface potential charges due to the operation of a plasma beam; electromagnetic effects due to the on-off thruster operation and RF interference with spacecraft systems.[1]

[1] Electrical Propulsion/Spacecraft Interaction Assessment: Modeling and Testing; J. Gonzales, ESA-ESTEC, Electric Propulsion Section

Electrical Propulsion Verification Needs

Chemical power systems consist of battery systems and fuel cell systems. These systems produce electric power via a chemical reaction and in their pure state are time-limited systems. Both batteries and fuel cells can be configured for high power demand systems. Fuel cells utilizing cryogenic effluents are effectively limited to missions of less than 30 days duration. Battery systems can also be coupled with solar, magnetic or nuclear systems to allow of a long duration recharge capability.

Tethers

Magnetic systems, such as tether systems, can be effective for power production in low earth orbit. Such systems are often mechanically complicated and in application have encountered environmental problems. From a verification standpoint these systems also cannot be effectively tested on the ground. Orbital demonstration testing is often limited in scope and extremely costly.

Solar Electric Propulsion

Photovoltaic solar-based systems have the greatest orbital operations history and have proven effective for both low earth obit operations and deep space operations. The solar array systems also suffer from complex mechanisms and the problem of orbital degradation over time. Recent improvements in cell technology have improved power output performance and produced a more robust system.

Nuclear Electric Propulsion

There has recently emerged a renewed interest within the United States space community concerning the utilization of nuclear power for space applications. The advantages of nuclear power for deep space probes and potential extended manned missions have been known for decades, however, a combination of factors, technical and political, have served to restrict development of these systems. The potential now exists to pursue the design and development of this form of space power. One of the major problems to be overcome is the manner and method by which these systems will be verified. The verification of systems designed for long periods of space operation is never easy and, couple with that the application of a nuclear power source, and the problem is compounded. Nuclear can include radioactive decay and fission reactors. For the purposes of this paper, we shall limit our consideration to closed cycle fission nuclear systems coupled with generators to produce electrical current.

The elements of a spacecraft nuclear-based electric propulsion system are depicted in Figure 1. The reactor under consideration is a standard fission based system utilizing liquid metal cooling. Heat transfer is via a conventional heat exchanger transfer system. Heat rejection is via deployable radiators. Verification of reactor performance requires dedicated and unique facilities with increased cost and safety considerations. Integrated systems testing involving thermal vacuum operations becomes extremely complicated and costly when involving nuclear based power systems. Practical considerations require that vehicle reactor operations not be initiated until the vehicle has been deployed in space. Control systems would utilize a secondary battery/chemical based power source for startup and for contingency operations. Verification of startup, emergency shutdown and contingency restart with the flight type hardware and software are critical to understanding the operational characteristics of the vehicle. The risk to vehicle operations increases with each system operational configuration change with steady state operations providing the least risk.

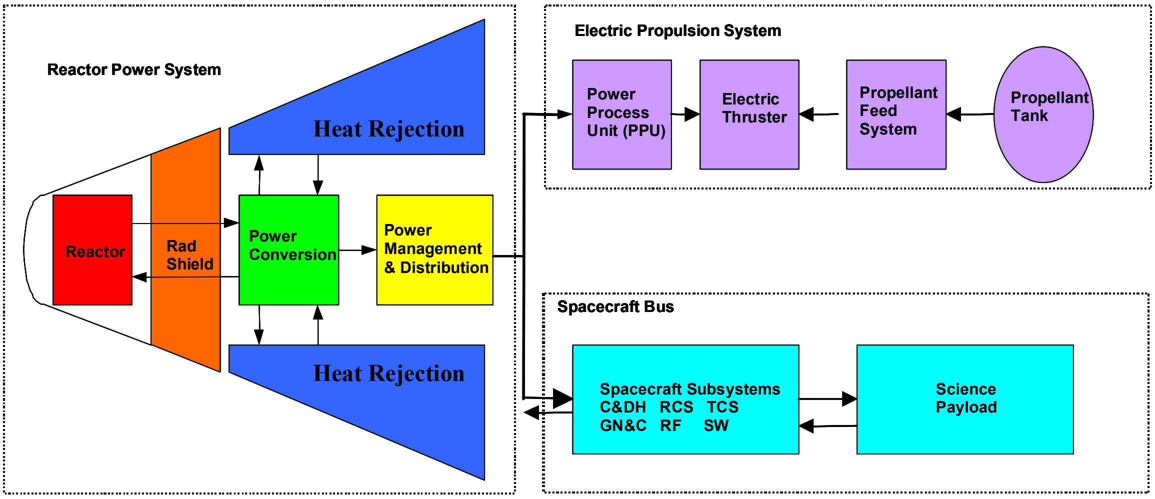

Figure 1 Nuclear Electric Powered Vehicle

Based on the above considerations a target vehicle configuration for an unmanned planetary science mission shall be developed. The vehicle shall consist of the following basic system groups: the vehicle electric propulsion system (assumed to be an electrostatic system), the vehicle primary and secondary electrical power source, the vehicle thermal control, the vehicle avionics, GN&C, vehicle data management, vehicle structure and mechanisms, environmental protection systems, vehicle communications system and the science package.

Alternatives for Verification/Qualification

Electric Thrusters

The interactive effects of electric propulsion systems and other space systems can be represented by a high fidelity model anchored in test data; for example, the beam characteristics of the particular thrusters being utilized impact other spacecraft systems. The thruster ground test data must come from a vacuum test in a facility large enough and with sufficient provisions as to minimize the effects of variations in vacuum and chamber walls effects on the observed test results.

If the chamber is too small, its boundaries can affect measurements by altering the flowfield or by introducing contaminants due to tank wall erosion. The electrical conductivity of the tank walls has been shown to influence the electric field in the plume and the plume flow field. If the tank pressure is too high, thruster operation may be influenced by ingestion of the background chamber molecules.[2] Many chambers exist for thruster testing in government and industry laboratories. Some examples include the European Space Agency's (ESA's) Electric Propulsion Laboratory which has performed endurance testing on thrusters with the main intent of assessing erosion back-flow contamination and performance stability. Electric ion propulsion satellite thrusters can be tested in Arnold Air Force Base's Arnold Engineering Development Center (AEDC). NASA's Glenn Research Center (GRC) is home to the Electric Propulsion Laboratory with several environmental chambers. Keldysh Research Center in Russia has a large cryogenic test facility for testing electric propulsion systems.

A number of electric propulsion thrusters have received extensive testing; such as xenon-fueled Hall thrusters which have been tested with input powers ranging from 0.2 to 8 kW. And, another thruster was tested at Fakel in Russia and JPL to examine wear over time. The integrated spacecraft model must allow for the unique nature of the electric propulsion system with regard to the geometry of the vehicle and the operating parameters of the other systems. Elements of the various spacecraft systems are tested and qualified for the particular operating environment that will be encountered. It is important to ensure that the

[2] Characterizing Vacuum Facility Backpressure Effects on the Performance of a Hall Thruster, Hofer, Peterson & Gallimore, IEPC-01-045

systems are designed to the tolerant to the impacts for the electric propulsion system or to be isolated from them.

Space Nuclear Reactors

While electric thrusters have received extensive attention in ground testing, large-scale space nuclear reactors have not had the same level of development. The former Soviet Union has the greatest practical applications for space nuclear power. Both the United States and European governments have been reluctant to fund space nuclear power systems. As one would expect, government facilities are the primary locations for testing of nuclear power systems and DOE and Naval facilities are primary among those in the United States. Changes in current policy within the United States space community have revitalized considerations for the use of space nuclear power. This will require the development of specific verification facilities to support space nuclear power systems.

Limitations of Terrestrial Testing

While it may be possible to run integrated vehicle testing within a thermal vacuum facility on small spacecraft, such a test on larger spacecraft is not feasible. Additionally, integrated vehicle testing is late in the development cycle and extremely costly. Therefore, for most applications, the most practical alternative is a high fidelity system model. Figure 2 illustrates the systems associated with a common 'unmanned' spacecraft.

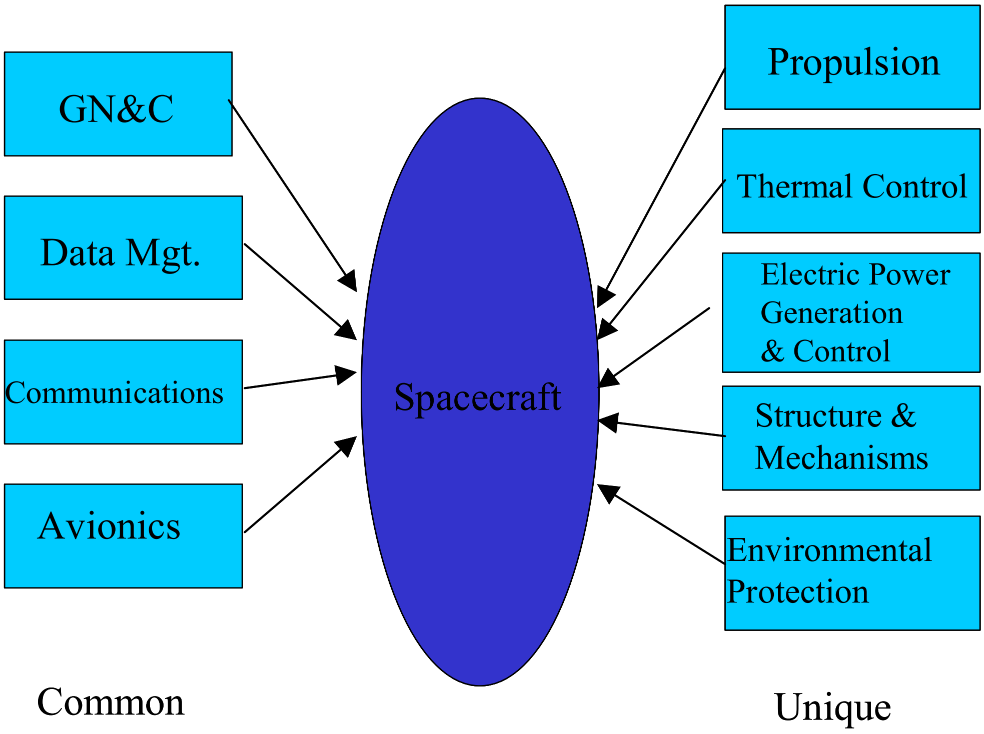

Figure 2 Spacecraft Systems

The spacecraft is launched with a conventional chemical engine booster and the electric propulsion becomes operational only after orbital deployment. For the purposes of this paper we will consider chemical, magnetic, solar and nuclear power sources for both the spacecraft operating power and for the electric propulsion.

Verification/Validation Program

The ultimate objective of any verification/qualification program is to increase the confidence that the spacecraft will be capable of accomplishing its intended mission. The process is always a trade-off of what can be done, what needs to be done, what is the level of risk involved and what is the cost of reducing that risk. These parameters are always actively traded within a world governed by finite constraints. NASA's International Space Station Program utilizes a five-step verification process that is repeatable at each level of verification: component, element, segment, and system. This process is illustrated in Figure 3.

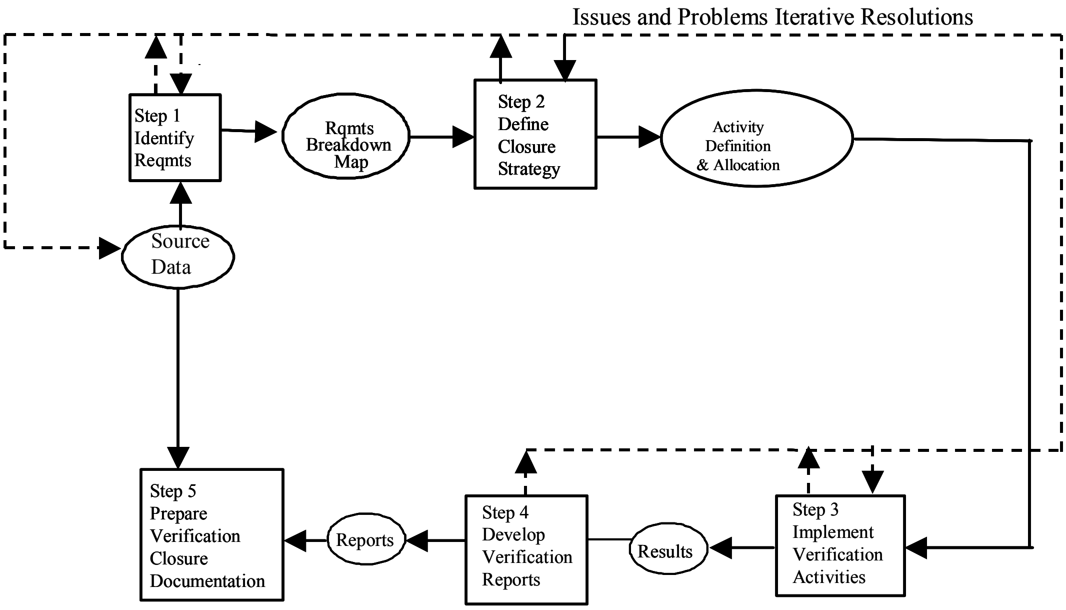

Figure 3 ISS Five-step Verification Process[3]

At the extreme with regard to risk reduction and cost impact is the integrated vehicle qualification article. This a physical and functional copy of the flight vehicle built to flight specifications. While this 'Hanger Queen' provides the highest fidelity of vehicle system interaction and timeline testing, this testing is of necessity late in the development flow and changes to vehicle designs resulting from this activity are always costly. The method is frequently referred to as "prototype". This level of testing does little to reduce the lower levels of component and subsystem testing. However, this level of testing is extremely helpful in identifying and isolating manufacturing/workmanship problems. Most vehicle cost environments will not allow for this level of testing and therefore a high fidelity vehicle model anchored in lower level testing would be utilized. This method is frequently referred to as "protoflight". Table 2 identifies some of the parameters of prototype and protoflight developments.

Prototype Development	**Protoflight Development**
Dedicated Qualification Article	Flight Article Only
Full Limit Qualification Testing	Limited Vehicle Level Qual Testing
Component, Subsystem and Vehicle Qual Testing	Component/Subsystem Qual Articles
Increased Cost	Reduced Cost
Reduced Risk	Increased Risk

Table 2 Prototype vs Protoflight

While the requirements on a program flow from the top down, the verification program flows from the bottom up. The first level of verification/qualification is at the component level. It is assumed that all parts are procured to an acceptable quality standard/specification and have been analyzed for the intended application. At the component/box level all units shall be subjected to functional, environmental and vibration testing at the appropriate levels for the intended application. This characterization requires that the vehicle mission be analyzed to establish the limits that the components will see in operation.

[3] Program Master Integration and Verification Plan, D684-10020-1, Jan 8, 1998.

The next level of analysis is to establish the critical interfaces within the spacecraft. This can be accomplished via a network on event trees that establish dependence relationships for all components. This analysis can then the scaled into a subsystem functional dependence diagram and ultimately expanded to a vehicle level network. An example of this approach can be seen in Figure 4.

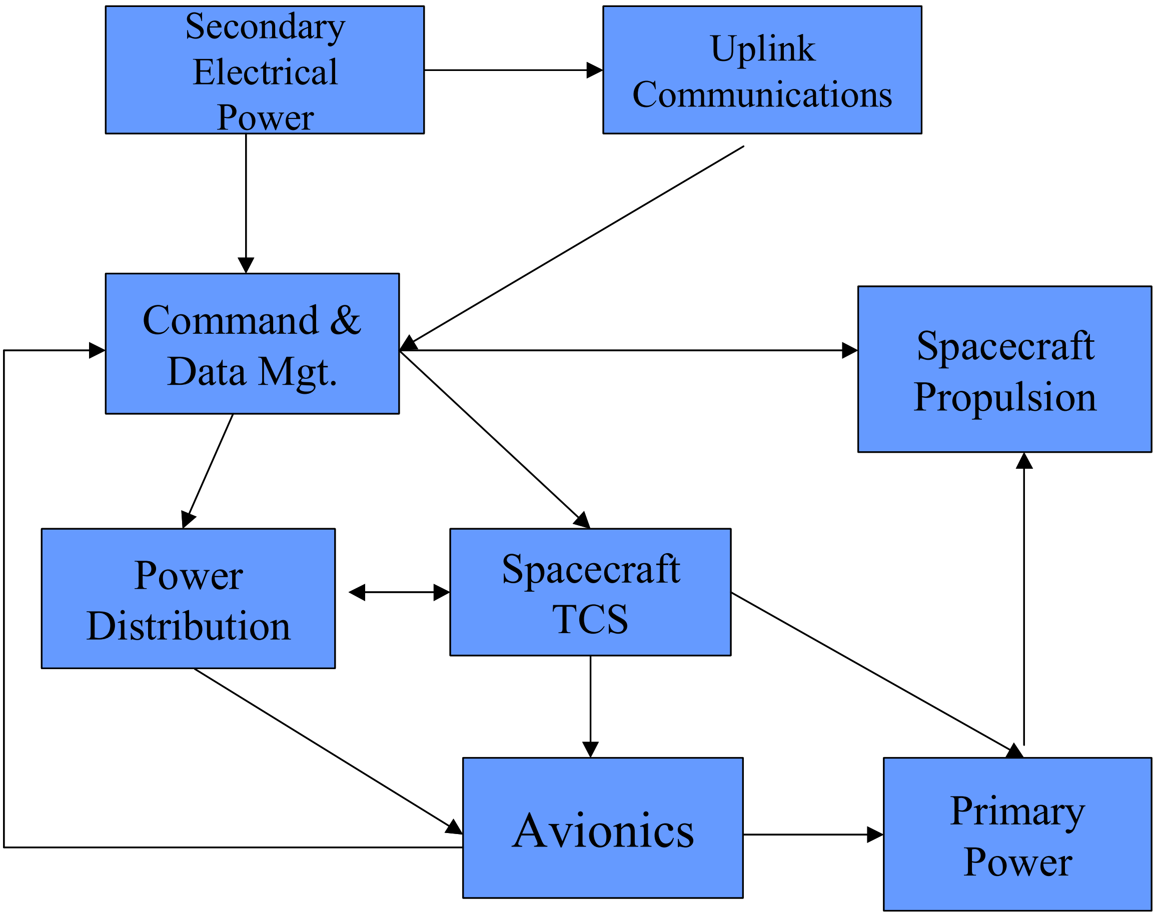

Figure 4 Spacecraft Event Tree

The purpose of this analysis is to establish the critical interfaces and to make an informed decision and to which of these should be verified by test as apposed to analysis. This interface analysis should be coupled with a Failure Modes Effect Analysis (FMEA) or fault tree to establish critical fault events and their associated impacts. The integrated listing of critical functions constitutes the second level of testing within the verification structure. Again at each stage there should be a trade of the risk reduction vs. the cost of the specific test.

The next level of analysis overlays the operational timelines for the mission to identify the critical mission events and to establish those vehicle subsystems and components that are involved in these sequences of events. Events such as vehicle start up, vehicle shut down, emergency operations, changes in flight/operating modes become prime candidates for consideration of integrated testing. This testing brings together the flight hardware and the flight software both having completed lower level verification. As a general rule it is desirable to have the flight code successfully through Validation and Verification prior to the application of that code to the flight article. However, practical considerations of development and verification timing may preclude this.

The avionics, communication, data management, and GN&C for the Electric Propulsion Spacecraft are common with that of a conventional chemical powered vehicle. The electric power generation, management and distribution, the structures and mechanisms, the environmental protection and the electric propulsion are the unique areas of the spacecraft and dependent on the type of EP utilized.

The electric power for the target vehicle for the remainder this paper shall be assumed to be a closed system nuclear fission reactor. This system is coupled with an electrical power generation capability as depicted in Figure 1.

Risk and Implications of Ground Testing vs. Orbital Demonstration Testing

End-to-end system level testing is always desired of a development program; however, it is usually not deemed a practical enterprise. Some programs have attempted some levels of integrated testing, such as the ISS Multi-Element Integrated Testing (MEIT). In this example, some of the ISS elements are placed within proximity of each other and soft connections made while functional testing is performed. This has proved quite costly, although it does provide a valuable method of identifying anomalies prior to flight.

Ground Verification Program

As stated previously, the reactor is assumed to be off-line until the spacecraft has been deployed to orbit. The reactor startup activity would be a function of onboard software or, where time lag permits, ground in the loop processing. Verification of the reactor operations would be performed within a special facility that would provide the degree of safety required for ground operations. All critical interface functions and critical timing operations would be verified within this test environment. Critical interfaces would utilize flight type hardware and software as part of the verification process. Additionally, this testing would be utilized to verify a high fidelity simulation of the performance and interface characteristics of the reactor system. This high fidelity simulation would later be utilized to drive emulators for electric propulsion testing. This testing would also form the basis for characterizing the degree of isolation of the reactor from other critical spacecraft systems.

Likewise the electric propulsion system will be verified qualified at the thruster level within a special vacuum facility. The characteristics of the thruster performance will be utilized to anchor and integrated model of the spacecraft propulsion system. This testing will also be used to characterize the interactive effects of the electric propulsion system on the overall spacecraft environment. These characterizations will form the basis for the inputs to the environmental requirements for the other subsystem of the spacecraft.

The spacecraft thermal protection system will be composed of both active and passive elements. The passive elements will consist of Multi-layer Insulation and coating associated with the secondary structure and other exposed surfaces. The active thermal control system will be associated with the maintenance of operating systems within the prescribed thermal limits. This type of active system may involve both heating and cooling functions. The primary cooling mechanism is some form of liquid loop heat transport and rejection system. The primary method of heat rejection is some form of deployable radiator. The mechanism portion of this system must be verified in an appropriate thermal vacuum facility. Heat rejection/transfer can be verified at the panel level and then expanded analytically to the entire radiator level. Integrated system flow characteristics can be modeled at the system level and anchored in component performance testing.

Environmental protection systems will be unique to the vehicle environment with micrometeorite shielding being tested at the panel level and analytically to the vehicle geometry. The overall risk to the vehicle is a function of the environment, the flight attitude, the mission duration and the capability of the protection system.

Structural elements will be designed with appropriate safety factors. A finite element model of the vehicle structure would be anchored in testing at the structural element level. The unique impacts of the electric propulsion system with respect to plume impact on vehicle structure would be modeled based on the plume characterization identified out of the propulsion test. The passive shielding would be modeled based on the characterization from the reactor testing.

This testing flow is illustrated in Figure 5.

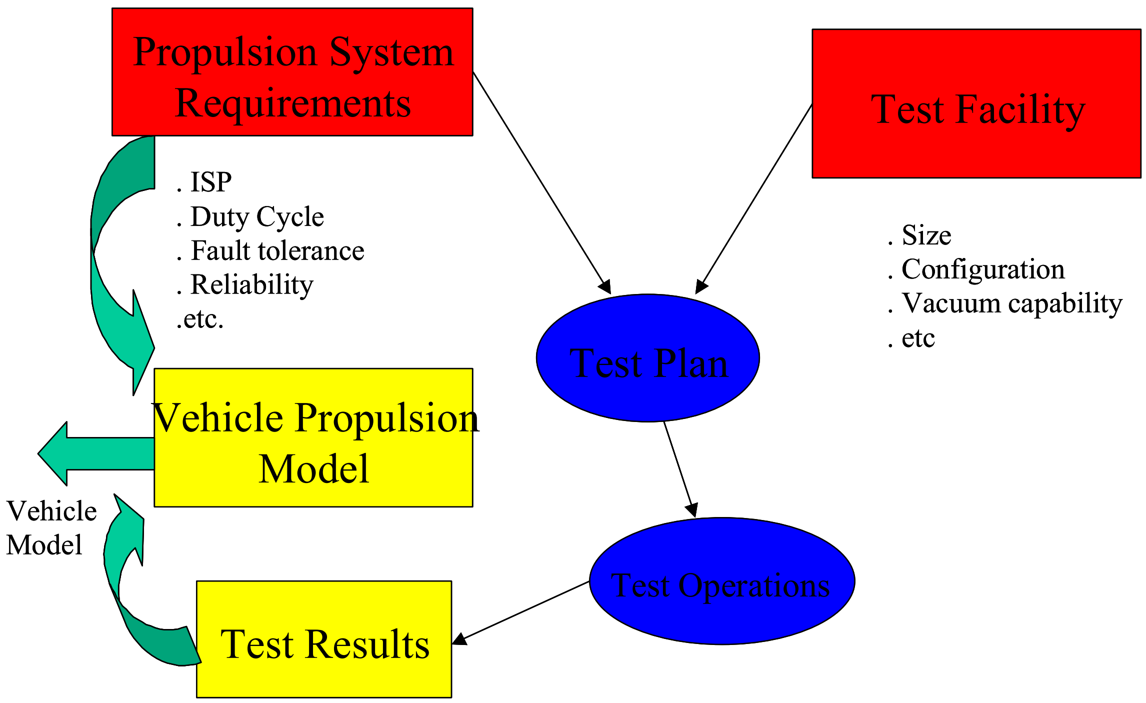

Figure 5 Ground Test Flow

The flow is intended to provide a high fidelity vehicle level model anchored in appropriate component and subsystems testing. For long duration missions, the model needs to address the effects of time and cycle exposure to the various subsystems. This requires an analysis of the design to identify components that are impacted by time and cycle exposure. The limits for these elements must be established and the design must incorporate provisions, redundancy etc., to respond to the impact of time exposure. Critical elements may require accelerated life testing in order to establish operating limits.

On-Orbit Verification Program

The reference spacecraft would be launched into Earth orbit and, potentially, spend a significant period of time spiraling out toward it's destination. Nuclear regulations will probably prohibit the startup of the reactor until some time has been spent reaching a safe distance from Earth orbit. Therefore, a complete systems check-out cannot be performed until well after launch. Additionally, there will always be subsystems that require their intended zero gravity environment for proper operation and will have to be tested on-orbit.

Political and Programmatic Issues

The context of any vehicle development and verification program must always function within the constraints of both the programmatic and political environments. The primary programmatic constraints effecting development and verification options are schedule and resources. Schedule dictates both what can be done and the sequence of events for various activities. Resources are always finite and are often related to schedule. In either case, the available resources will serve to limit what can be done and when it can be done. These programmatic limitations increase the need to identify "high value" elements of the system to which limited resources must be applied. This also mandates that critical technologies necessary for successful system operations be developed consistent with program schedule needs. In the case of electric propulsion these technologies include thrusters, materials and test facilities.

All Programs function within one or more political environments. These environments serve to limit the options available for Program development. The primary constraint to the development of nuclear propulsion within the United States has been the strong political opposition to nuclear power. The majority of the development work on nuclear power for spacecraft was done more than 30 years ago with the intervening time focused on traditional chemical propulsion systems. The recent change in United States Space Policy has allowed for the reconsideration of nuclear power as an option for spacecraft.

Summary

Many aspects of a verification program appropriate for an EP vehicle, or more particularly a NEP vehicle, have been documented and component or system testing is frequently performed. Approaching an EP verification program from a systems perspective and including a space nuclear reactor power system adds complexity to the verification program. The nature of electric propulsion and nuclear power mandates the use of special facilities, which adds cost and complexity to the verification program. The programmatic and political implications of the use of nuclear power for spacecraft further complicates the verification program and limits the options available for the execution of this program. The practical limitations of a nuclear powered electric propulsion spacecraft require that the overall verification will be accomplished via a high fidelity model anchored in selected testing both on the ground, in special facilities, and in orbit which will provide indication of compliance with all program requirements.

Bibliography

"Electric Propulsion", David Y. Oh, Aerospace America, December 2001.

"Electric Propulsion: Which One For My Spacecraft", Ian J. E. Jordan, December 7, 2000.

Program Master Integration and Verification Plan, D684-10020-1, Jan 8, 1998.

"First electric ion propulsion thruster fires at AEDC", Tina Barton, AEDC Public Affairs.

"Advanced Propulsion Concepts", Robert H. Frisbee, JPL.