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**Multimegawatt Space
Nuclear Power Supply
Phase I Final Report
Volume II-Phase II Plan
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Phase I Multimegawatt Space Nuclear Power Supply Documentation Flow

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GLOSSARY

ACRR	Annular Core Research Reactor
ACS	attitude control system
ALS	Advanced Launch System
ALV	advanced launch vehicle
ARCB	autonomous reactor core booster
AS	Allied Signal
BA	Boeing Aerospace
CBGS	confinement by ground surface
CBM	confinement by missile
DBTT	ductile to brittle transition temperature
DDT&E	design, development, test, and evaluation
DIDO	(research reactor at UKEAE - Harwell)
DIPS	dynamic isotope power subsystem
DOD	Department of Defense
EM	electromagnetic
EPS	electrical power system
F&OR	functional and operational requirements
FBR	fast breeder reactor
FET	field effect transistor
FFTF	fast flux test facility
FSAR	final safety analysis report
GCFR	gas cooled fast reactor
HIF	Horizontal Impact Facility
ICS	instrumentation and control system
ICWG	interface control working group
INSRP	Interagency Nuclear Safety Review Panel
IOCC	integrated operations control center
LANL	Los Alamos National Laboratories
LCU	local control units
LEO	low earth orbit
LIM	linear induction motor
LIMRV	LIM research vehicle
LLO	low lunar orbit
LRU	line replaceable unit

MSNPS	Multimegawatt Space Nuclear Power Supply
MTR	materials test reactor
MURAL	(computer code)
NEP	nuclear-electric propulsion
NPS	Nuclear Power Supply
NTR	nuclear thermal rocket
OSTP	Office of Science and Technology Policy
PCM	parametric cost model
PFR	prototype fast reactor
PLR	parasitic load resistor
PRA	probabilistic risk analysis
PSAR	preliminary safety analysis report
PSICS	power system instrument and control subsystem
PSP	power system processor
PV	photovoltaic
RFLSS	radiofrequency laser subsystem
R/M	reliability/maintainability
RRR	Rolls-Royce and Associates
RTG	radioisotope thermoelectric generator
SAE	Science and Engineering
SAR	safety analysis report
SBFEL	space-based free electron laser
SDI	Space Defense Initiative
SER	safety evaluation report
SNAP	Space Nuclear Auxillary Power
SPA	space processor array
SSEPS	space station electrical power system
STEM	(computer code)
STS	Space Transportation System
UC	uranium carbide
UK	United Kingdom
UKAEA	United Kingdom Atomic Energy Authority
UN	uranium nitride
USAR	updated safety analysis report
WBS	work breakdown structure
WIMS	(computer code)

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Functional and Operational Requirements Cross-Reference Matrix

MMW-Phase II-U90004-7-R4

1.0 INTRODUCTION

Our phase II program objectives are to (1) demonstrate concept feasibility, (2) develop a preliminary design, and (3) complete phase III engineering development and ground test plans.

Our approach to accomplish these objectives is to prove technical feasibility of our baseline design early in the program while maintaining flexibility to easily respond to changing requirements and advances in technology. This approach recognizes that technology is advancing rapidly while the operational phase of MSNPS is 15 to 20 years in the future. This plan further recognizes that the weapons platform and Advanced Launch System (ALS) are in very early program definition stages; consequently, their requirements, interfaces, and technological basis will evolve.

To implement our approach we will focus resources early in the program on feasibility studies supported by selective feasibility testing, while avoiding expenditures on detailed engineering likely to be superseded by significant changes in requirements, technology, or MSNPS interfaces. Feasibility and development issues identified during phase I are addressed in Section 3. New development issues may arise during phase II as a result of new or changing requirements and evolution of the platform and launch vehicle interfaces. If such issues arise, we will prepare a plan of resolution and present this plan to DOE for review and approval. Our plan of resolution will define the impact on our conceptual design, define resolution options, and present a preferred option along with rationale for its selection.

Our phase II plan has been structured to complete the six major tasks identified in the Statement of Work (SOW). In addition to the six major RFP tasks, we plan to investigate additional mission applications during phase II to exploit the high-dual mode potential of our design concept for propulsion, and combined power and propulsion applications. This work will be performed only to the extent approved by DOE, and according to DOE guidelines.

A top-level task flow summary outlining the six major SOW tasks is shown in figure 1.0-1. This task flow spans a 5-year period beginning with phase II contract award, and ending with delivery of the phase II final report to DOE. Inputs to phase II include the requirements baseline (F&OR), our phase I final report, our phase II plan, and our phase I conceptual design baseline. Task 4.0 (refine design concept) is the primary task of phase II and is shown as proceeding through stages--from refinement of our phase I conceptual design baseline to completion of conceptual design, and progressing finally to a preliminary design point including selection of specific components. The process of

Figure 1.0-1 Work Plan Showing Six Major Statement of Work Tasks

design improvement and component selection is supported by results of feasibility studies and testing (task 2.0), safety assessment (task 1.0), and cost trades involving life cycle cost analysis (task 4.0). The process of design concept refinement is iterative in that assessments such as life cycle cost, reliability, and safety will lead to design concept changes that in turn call for new performance assessments. Other design changes will be dictated by new and evolving requirements and incorporation of new ideas and new technology. Task 5.0 (prepare engineering development plan) and task 6.0 (prepare ground test plan) will be based on the preliminary design baseline, and will take place largely during the last years of phase II.

Our schedule for phase II is shown as figure 1.0-2. This schedule involves a 5-year program based on contract award in July 1989. Major milestones and reports to DOE are shown in the top schedule bar.

A complete plan for preliminary safety assessment is provided in section 2.0. The few remaining technical feasibility issues are discussed in section 3.0. The reader is referred to the phase II proposal to access the classified information contained in section 3. Section 4 covers all Boeing's plans for concept refinement during phase II. Life cycle cost tasks are outlined in section 5, and engineering development and ground engineering tests are discussed in sections 6 and 7. Finally, the statement of work is provided in section 8.

Figure 1.0-2 Phase II MSNPS Master Schedule (Sheet 1 of 2)

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Figure 1.0-2 Phase II MSNPS
Master Schedule
(Sheet 2 of 2)

2.0 COMPLETE PRELIMINARY SAFETY ASSESSMENT

This section describes the aerospace and nuclear assessments that are to be performed in phase II of the MSNPS program. In addition, the subsystem and overall safety assessment process is described in section 2.3. Section 2.3 also details specific responsibilities of the system safety program. Finally, section 2.4 discusses the safety certification plan. Due to the overlap of aerospace and overall system safety with subsystem safety, both sections 2.1 and 2.3 cover varied portions of aerospace safety.

This section starts with the goals of the program followed by descriptions of the nuclear safety policy, safety review process, and safety criteria. It also describes the safety plan and safety analysis reports that comprise an integrated safety assessment activity. The methodology for accident analysis, safety development logic, and general design considerations are addressed in detail. This methodology is followed by a description of the analysis that is to be performed on the overall safety and reliability of the system.

The goal in phase II is to complete the preliminary safety assessment. The assessment constitutes the safety requirements basis from which detailed design of the MSNPS will proceed. This section, which is an abbreviated safety plan, could be used as a phase II system safety statement of work. A formal system safety program plan will be written in accordance with Boeing Aerospace command media after contract award.

2.1 AEROSPACE SAFETY AND NUCLEAR SAFETY ASSESSMENT (WBS 2.3 and 1.2)

The MSNPS system safety program will be implemented in accordance with DOE 5480.1B. Phase II of the MSNPS is a continuation and refinement of the work begun during phase I. The engineering tasks will consist of a conceptual design function including system engineering and tradeoff studies, characterization of design performance, specific component selection, and detailed configuration layout. Research and testing required to resolve feasibility issues will be completed. The system safety effort will track with the engineering effort, building on the preliminary assessment work performed in phase I and culminating in a preliminary safety assessment report at the end of the phase.

The philosophy of the Boeing system safety team is to ensure the protection of the environment, the safety and health of the public, and Government and private property against accidental loss and damage through the combined efforts of system safety engineering and system safety management.

- a. System safety engineering analyses reveal the hazards inherent in the system or operation, and are also used to document the process of mishap risk removal, mitigation, and/or control. Residual risks in product designs and related operations are identified and assessed as the end-product of this analytical process.
- b. System safety program management techniques are used to provide continuing management visibility of the mishap risks inherent in the system and in related operations. The program manager is responsible for ensuring that action is taken to eliminate, mitigate, and/or control identified mishap risks. He must ensure that any residual risks are brought to the attention of, and are accepted by, both the customer and the BA team. Design features, operating limitations, or other measures imposed to control identified residual risks must fulfill Boeing's moral, legal, and contractual obligations.

The purpose of the system safety effort in phase II is to identify and evaluate all hazards associated with the MSNPS and its total life cycle including development, fabrication, testing, storage, transportation, launch, operation, and ultimate disposal. The scope of the system safety effort must track with the program; as the design matures in definition and complexity, so must the safety analysis, providing timely identification of system safety design and operational requirements.

Summary of System Safety Tasks. We will perform the following tasks to ensure that hazards associated with the MSNPS are identified for assessment, elimination/control, and management:

- a. Provide day-to-day safety consultation to MSNPS design activities.
 1. Provide technical consultation on safety related problems.
 2. Provide and interpret safety requirements, specifications, and standards.
 3. Document the risk impact on design decisions for risk management.
 4. Provide continuous surveillance of the developing conceptual design to ensure timely identification of hazards, potential causes, and controlling requirements, and coordinate these findings with design.
- b. Participate in design team process, providing real-time input and evaluation to the design effort. System safety is a full member of the design team, but retains the independent safety assessment authority delegated by the program manager.
- c. Produce an integrated preliminary safety assessment.
- d. Provide documentation and support to program reviews and meetings.
- e. Participate in development test planning and accomplishment.

2.2 NUCLEAR SAFETY (WBS 1.2)

Nuclear Safety Policy. The policy of the United States for all U.S. nuclear power sources in space is to ensure that the probability of release of radioactive material and the amounts released are such that an undue risk is not presented, while considering the benefits of the mission. The U.S. approach to nuclear safety has been detailed in several documents, e.g., 10CFR20 notes that in accordance with recommendations of the Federal Radiation Council, approved by the President, persons engaged in licensed activities should "make every reasonable effort to maintain radiation exposures, and releases of radioactive material in effluents to unrestricted areas, as low as is reasonable achievable taking into account the state of technology and the economics of improvement and other factors." DOE Order 5480.1A states that it is the policy of the DOE to "assure protection of the environment, the safety and health of the public, and Government property against accidental loss and damage." In a U.S. working paper submitted to the U.N. Working Group on the Use of Nuclear Power Sources in Outer Space (Paper A/AC.105/C..1/WG.V/L.8, dated 23 January 1980), it is stated that "the primary safety design objective is to minimize the potential interactions of the radioactive materials with the populace and the environments so that exposure levels are within limits established by international standards."

Nuclear Safety Review/Approval Process. The required approval steps to launch a space nuclear system are shown in figure 2.2-1. Both the Department of Energy (DOE) and the Interagency Nuclear Safety Review Panel (INSRP) are involved early in the process. DOE's involvement is obvious because, by law, it is responsible for nuclear safety. The role of INSRP in the nuclear safety review and approval process is discussed below.

INSRP Process. Working under Presidential Directive NSC/25 and the various agency guidelines, the INSRP conducts an independent safety review of each proposed nuclear-powered space mission prior to launch. It provides the necessary independent risk evaluation that will be used by decision makers who must weigh the benefits of the mission against potential risks. Figure 2.2-2 shows the structure of INSRP as it was established for the Galileo mission and the Ulysses mission, the two currently committed U.S. space-nuclear-powered missions.

Space Nuclear Safety Review Process. The formal safety review process begins with the submission of a preliminary safety analysis report (PSAR) by the DOE NPS program office. The generic logic flow for the space nuclear safety review and launch approval process is shown in figure 2.2-3.

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Figure 2.2-1 Nuclear Safety Approval Steps and Documentation

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Figure 2.2-2 Structure of the Interagency Nuclear Safety Review Panel

Note: For existing nuclear systems, the PSAR may not be needed.

PSAR = Preliminary Safety Analysis Report

USAR = Updated Safety Analysis Report

FSAR = Final Safety Analysis Report

SER = Safety Evaluation Report

INSRP = Interagency Nuclear Safety Review Panel

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Figure 2.2-3 Flight Safety Review and Launch Approval Process for Space Nuclear Power Systems

However the INSRP panel should be involved at an earlier program stage because of its experience, the valuable data it possesses, and the contribution it can make to forming a nuclear safety program.

The second formal safety report will be the updated safety analysis report (USAR). This report will be issued as soon as practical after the power system design freeze. The USAR will include updated information on the mission, failure modes analysis, and radiological risk assessment and any required safety tests and data. The final safety analysis report (FSAR) will normally be issued about 1 year before the scheduled launch. The contractors' safety analysis reports (SAR) will not be the only inputs to the INSRP. The INSRP has members not only from DOD, NASA, and DOE, but also from various active working groups. Approximately 1200 scientists and engineers from a number of Government agencies, laboratories, and universities will assist in the review. These specialists will evaluate the SARs and provide independent calculations and tests as required by the INSRP.

After the FSAR has been reviewed, INSRP prepares a Safety Evaluation Report (SER) that provides their independent assessment of the risks. The SER is submitted to the heads of the three agencies for their use in the launch approval request process. When the two supporting agency heads are satisfied, they submit letters of concurrence to the user agency. The user agency will then submit a letter and a copy of the SER to the Office of Science and Technology Policy (OSTP), within the Office of the President, requesting launch approval. The director of OSTP is empowered to approve the launch; however, consultation and deferral to the President for launch approval can also occur. Recommendation for flight approval constitutes the affirmative judgment of the U.S. Government based on an overall risk-benefit evaluation.

Safety Criteria and Technical Specifications. The first document needed early in any space reactor power system is the "Nuclear Safety Criteria and Specifications" (see fig. 2.2-1). It is clear that timely considerations of safety requires an early specification of the criteria that must be met to implement U.S. safety policy. These criteria provide the basis for decisions on the acceptability of specific mission and reactor design proposals.

DOE has provided the following general safety concerns that should be precluded or their risk should be minimized to acceptable levels:

- a. Potential for exposure to ionizing radiation, including the potential for inadvertent criticality as a subset.
- b. Potential for exposure to toxic materials.

- c. Potential for the contamination of the environment through the release of toxic and/or radioactive materials.
- d. Potential for failure to physically control or to protect the system or its special nuclear materials.
- e. Potential for failure of the MSNPS to perform as intended, which could affect safety at any time during the life cycle.

Furthermore, the critical technical specifications or requirements specified for the MSNPS program are from the F&OR document. Briefly the safety technical specifications include:

- a. Intact Reentry: The reactor core shall remain intact during inadvertent reentry.
- b. Reactor Cooling: Reliable reactor cooling shall be provided for all normal and credible accidents to prevent core disruption or structural degradation.
- c. Reactor Power Control: The control system will reliably control the reactor power to prevent core disruption or structural degradation.
- d. Subcriticality: The reactor will remain subcritical for credible initiating events.
- e. Toxic Materials Control: The reactor will minimize the use of toxic materials and limit their spread for normal and accidents conditions.
- f. Benign Fuel: The reactor fuel will remain benign until a stable orbit is achieved.
- g. Transfer to Storage Orbit: The system will achieve a safe orbit at the end of its useful life.

These safety criteria and technical specifications will be incorporated into the more specific design specifications that will be developed for our project to guide the design. They will be updated and augmented as the design matures.

Program Safety Plan. The program safety plan will be a key safety document (fig. 2.2-1) and will require high-level attention early in the MSNPS development. The safety plan will not only provide complete safety planning but also will be useful in providing early comment from INSRP as to the adequacy of the program.

The purpose of the program safety plan will be to provide an overall plan for formulating, integrating, and achieving all necessary safety elements of the program required to meet safety objectives and eventually to obtain flight approval. More specifically, it will provide the logic and strategy for safety assessment, analysis, and tests in support of critical safety technology developments (fig. 2.2-4). After defining the safety needs of the program, analytical and experimental studies would be carried out during phases II and III of the project. These studies would include failure mode

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Figure 2.2-4 Safety Flow Chart

analysis, accident consequence studies, experiments on the reactivity effectiveness of anticriticality systems, and tests of fire-resistant containers if needed. These on-going studies would be continually updated and redefined where necessary. Results from the analytical study program would also be used to modify the experimental program direction where appropriate and vice-versa. We will use the SP-100 safety plan as the starting point for the MMW safety plan.

Results from the analytical and experimental programs would serve as inputs to the formulation of safety analysis reports including the PSAR, USAR, and FSAR.

The event tree referred to in figure 2.2-4 should cover all phases of MSNPS life cycle:

- a. Development, fabrication, manufacture, testing, and storage.
- b. Transport of the reactor to the launch site.
- c. Prelaunch and launch operations.
- d. Ascent.
- e. Orbit.
- f. Disposal.

As an aid in preparing the program logic, a table similar to that shown in figure 2.2-5 should be prepared. For each phase from factory through flight, this table will give the safety objectives, potential environments, and the methods to meet the safety objectives. Such a table will serve to focus planning on the safety objectives and how they can be met. Analyses to define the response of the reactor to these environments will then provide more detailed input to the safety specification.

From the event tree analysis and safety objectives, a time-phased program diagram would be developed. The logic diagram would show how the program elements feed into each other showing how tests support analysis. Any items that represent potential critical technology issues would be clearly identified.

Safety Analysis Reports. The analysis of the potential radiological risk of a given mission is documented in the SARs. These safety analyses begin at the initiation of the design concept and continue through the safety evaluation and launch approval process. For new concepts, it is often advisable to prepare an initial safety assessment report prior to the completion of the conceptual design in order to focus design activities on specific mission scenarios that may impact safety.

As noted earlier, three SARs are usually issued. The PSAR is issued soon after a design concept is selected for a given mission. The PSAR includes a description of the NPS and the mission as well as probabilistic radiological risk assessments as supported by

Phase	Safety objectives	Environments	Methods to meet objectives
Ground handling and transportation	<ul style="list-style-type: none"> • Maintain subcriticality • Prevent dispersal of toxic chemicals • Prevent dispersal of fuel 	<ul style="list-style-type: none"> • Water immersion • Nearness of humans • Fire • Dropping • Puncture 	
Prelaunch and launch	<ul style="list-style-type: none"> • Maintain subcriticality • Prevent dispersal of toxic chemicals • Prevent dispersal of fuel 	<ul style="list-style-type: none"> • Overpressure • Fireball • Shrapnel • Impact • Afterfire (liquid and solid propellant) • Thermochemical reactions • Postimpact water immersion 	
Ascent	<ul style="list-style-type: none"> • Maintain subcriticality • Prevent dispersal of toxic chemicals • Facility recovery 	<ul style="list-style-type: none"> • Fire • Explosion • Shrapnel 	
Orbital	<ul style="list-style-type: none"> • Minimize biosphere and space contamination • Maintain subcriticality on reentry and impact 	<ul style="list-style-type: none"> • Reentry/impact • Post impact • Reentry/impact 	

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Figure 2.2-5 Safety Objectives

the available conceptual design database. The second report, the USAR, is issued as soon as practical after the power system design freeze. The USAR includes updated information on the mission, the failure modes analysis, and the radiological risk assessment plus any safety tests and data required. The third report, the FSAR, is normally issued about 1 year before the scheduled launch. The FSAR provides a description of the final design of the system, the mission, and radiological safety assessment data including the results of the safety tests.

The PSAR usually consists of two volumes: a reference design document and an accident model document. The USAR (if sufficient information is available) and the FSAR include these two plus a third volume called the nuclear risk analysis document. Below is an outline of the contents of these three documents:

- a. Reference design document.
 - 1. Mission/flight system summary.
 - 2. Nuclear power source description.
 - 3. Spacecraft/launch vehicle/trajectory description.
 - 4. Launch site/range safety/radiological safety data.
- b. Accident model document.
 - 1. Models/data.
 - 2. Event tree analyses.
 - 3. Nuclear power source response.
- c. Nuclear risk analysis document (describing probabilistic risk).

In general, the safety analysis reports consider the following types of accident environments (categorized by mission phase):

Prelaunch, Launch, and Ascent Phases

- a. Explosion overpressure.
- b. Projectile impact.
- c. Land or water impact.
- d. Liquid-propellant fire.
- e. Solid-propellant fire.
- f. Sequential combinations of the above.

Orbit and/or Flight Trajectory Phases

- a. Reentry.
- b. Land or water impact.

c. Postimpact environment (land or water).

On-orbit contingency options (including retrieval) are considered as appropriate.

From the foregoing it is clear that there must be a close working relationship between the launching/using agency and the DOE if a meaningful and realistic safety analysis is to be undertaken. Generally, the interagency agreement defines the responsibilities of the two agencies, with the launching/using agency being responsible for providing information about the mission, including nominal and off-nominal events with probabilities and environments. DOE is responsible for determining, through tests and/or analyses, how the NPS will respond. All of this information is summarized in the SARs.

Risk Analysis. Because even the most reliable systems pose a finite failure probability, there is a requirement for safety analyses of NPS. Since the mid-1960s these safety analyses have been based upon probabilistic risk assessments. In fact, the U.S. space nuclear safety program pioneered the use of probabilistic risk analysis techniques to assess the safety of NPS. Risk analysis, as used in this context, refers to a quantitative assessment of the potential for human exposure to radiation resulting from the use of a NPS in a space application. (Exposure in this context refers to radiation exposure in excess of natural background radiation.)

The conduct of a risk analysis for a space mission using nuclear power requires--

- a. Definition of potential mission accidents and probabilities.
- b. Determination of the types and severity of the resulting accident environments or stresses on the nuclear system.
- c. Testing and/or analysis of the nuclear system to determine responses to the various accident environments.
- d. Organization of the information on accidents, probabilities, and system responses into event trees for each mission phase (phases oriented to the potential for human risk).
- e. Analysis of radiological risk using radionuclide environmental pathway and dose models and worldwide databases.
- f. Appropriate emergency planning, launch safety preparations, and real-time accident analysis and recovery capability.

For any given mission or mission phase it is possible to postulate a spectrum of accidents some of which may lead to deleterious consequences. The objective of a risk analysis is to put all the accident scenarios and their potential consequences into

perspective; therefore, individual accidents, mission phases, and the overall mission can be evaluated in terms of risk, and those accidents leading to the highest risk are identified.

Methodology for Accident Analysis. An illustrative example is launch explosion. The project would establish methods for predicting surface blast conditions and thermal environments for a missile or space vehicle systems for a range of potential failure modes.

Experimental databases of explosions of liquid propellants will be consulted for different boundary conditions such as confinement by missile (CBM) and confinement by ground surface (CBGS).

Blast data for 25,000 lbs LH₂/LOX is:

Maximum impulse = 2.002 psi msec

12.8 ft from ground zero on pad

CBGS - vertical tests

Overpressure = 208 lb/in²

To characterize the thermal environment, the following fireball parameters are needed: heat flux, size, and duration. Heat transfer from the fireball is principally radiative transfer. Below are some measured heat flux values for 25,000 lbs LH₂/LOX:

Maximum = 259 W/cm²

t > 1 sec - 100 W/cm²

t > 3.55 - 50 W/cm²

Max fireball duration before liftoff = 9.6 sec

Max heating during = 0.4 sec.

The fireball diameter (D) is correlated to propellant weight (W) by the following relationship:

$$D = {}_1 W {}_2$$

where ${}_1$ and ${}_2$ are empirical constants.

To calculate the loads on the system from a detonation, a hydrodynamics code would be utilized. One such code is the HULL hydrodynamics computer code with the following features:

- a. 1st or 2nd order differencing.
- b. Eulerian mesh.
- c. 2D or 3D.

- d. Cartesian or cylindrical geometry.
- e. Multimaterial capability.
- f. Nonreaching structures.
- g. Extensive plotting capabilities.

Other analysis tools for accident analysis are listed below:

- a. Heat transfer:
 - 1. TOPAZ 2D.
 - 2. TOPAZ 3D.
 - 3. RAVEN (BDM).
 - 4. BLAP (Boeing).
 - 5. CHAP (Boeing).
- b. Hydrodynamics:
 - 1. NIKE 2D.
 - 2. NIKE 3D.
- c. Neutronics:
 - 1. ANISN.
 - 2. DOT.
 - 3. MCNP.
 - 4. MORSE.
 - 5. VEGAS.
- d. Consequence calculations:
 - 1. CRAC2.
 - 2. MACCS.
- e. Nuclide buildup-decay:
 - 1. ORIGEN2.
- f. Launch, ascent, reentry:
 - 1. HART.
- g. Structural:
 - 1. NASTRAN.
- h. Event trees:
 - 1. EVNTRE.
- i. Trajectory mission:
 - 1. MODEC.
 - 2. TRJ (BDM).
 - 3. POST.

- 4. OTIS (Boeing).
- j. Thermal hydraulics:
 - 1. COMMIX.
 - 2. FTHP (BDM).
 - 3. RELAP5.
 - 4. THERMIT.
 - 5. CONTAIN.
- k. Kinetics:
 - 1. KINET (BDM).

A potential code to analyze the thermal environment in launch pad fire is TOPAZ which has the following features:

- a. Detailed system model.
- b. Radiation and convection boundary conditions.
- c. Enclosure radiation.
- d. Temperature dependent.
 - 1. Material properties.
 - 2. Heat transfer coefficient.
 - 3. Emissivities, absorptivities.
- e. View factors computed.
- f. Specially dependent heat source.

The overall analysis methodology is shown in figure 2.2-6.

Safety Development Logic. MSNPS safety development program would include both experimental as well as analytical efforts as discussed previously. Representative tasks for the four of the phases of the space MSNPS are shown below:

Safety Program Task Listing Ground Handling Transport Phase Task

- a. Ground handling and transport accident analysis (e.g., types, shock loads, fire and water conditions).
- b. Critical experiments on nuclear effects of ground handling/transport accidents (e.g., water immersion, nearness of humans, crushing/compacting of reflector).
- c. Critical experiments on nuclear effectiveness for fast reactor safety systems (wings, safety control rods).
- d. Mechanical and thermal analyses and tests of fire resistant shipping container.

Figure 2.2-6 Methodology and Approach to Resolution

- e. Analyses and tests of transport fire control systems.
- f. Chemical interactions analyses.
- g. Radiological and chemical consequences analyses of handling/transport accidents.
- h. Manuals, procedures, and safeguards for handling and transport.
- i. Coordinate reactor shipment with regulatory agencies.

Safety Program Task Listing - Prelaunch and Launch Phase
Task

- a. Launch site survey and meteorology.
- b. Vehicle failure analysis.
- c. Prelaunch/launch accident analyses.
- d. Reactor impact tests.
- e. Mechanical and thermal analyses and tests of fire resistant launch container.
- f. Thermochemical effect analyses.
- g. Analyses of seawater interactions and release effects.
- h. Radiological and chemical consequences analyses of prelaunch/launch accidents.
- i. Manuals, procedures, and training for prelaunch/launch operations.
- j. Coordinate nuclear operations with launch site, state, and local public officials.

Safety Program Task Listing - Ascent Phase
Task

- a. Down range survey and meteorology.
- b. Vehicle failure analysis.
- c. Ascent accident analyses.
- d. Radiological and chemical consequences analyses of ascent accidents.
- e. Manuals, procedures and training for ascent operations.
- f. Coordinate with Coast Guard, State Department, and international groups.

Safety Program Task Listing - Orbital Phase
Task

- a. Permissible orbit analysis.
- b. Orbit failure analyses (e.g., debris impact, failure to achieve orbit).
- c. Shutdown system failure analyses.
- d. Coolant system failure analyses.
- e. Reentry/impact analyses.
- f. Safety shutdown system component tests.

- g. Radiological and chemical consequences of orbital accidents.
- h. Manuals, procedures, and training for orbital operations.

Tasks for the Ground Engineering System (GES) tests:

- a. Ground GES site survey and meteorology.
- b. Critical experiments on nuclear effectiveness of GES safety systems.
- c. Critical experiments on nuclear effects of accident environments on GES reactor.
- d. Criticality (explosion, earthquake, etc.).
- e. Failure mode analysis of GES safety shutdown and coolant systems.
- f. Tests of GES safety shutdown systems.
- g. Tests of GES emergency cooling system.
- h. Analyses of radiological and chemical consequences of GES accidents.
- i. Preparation of PSAR.
- j. Preparation of FSAR.

Of the experiments, potential critical path tasks are the initial experiments on (1) the reactivity effectiveness of safety systems and (2) the reactivity effects of accident environments. Taken together, these two tasks define the range of reactivity accidents to be considered in safety analysis and are needed for both the GES and MSNPS. Tests of safety and fire control systems will follow along later in the program and will primarily confirm the subsystem designs. The reactor impact tests will investigate the nature of reactor damage for conditions similar to those used in the failure mode analysis.

For the analytical safety studies, the critical path elements are the failure mode analysis and accident consequences studies. These studies will involve input from the safety experiments as well as the rest of the development program. Results of these studies will be used to help design the MSNPS and its safety systems, and to evaluate risks.

General Design Considerations. In order to most effectively reduce the potential sources of risk discussed above, the following considerations will be factored into the design:

a. Shutdown System

An essential key to any safe reactor system is a highly reliable shutdown system. This aspect includes not only the shutdown devices but also all of the related instrumentation and sensors. Whether redundant and diverse systems (as is the direction for commercial power reactors) are required is not clear but should be established by appropriate probabilistic risk analysis (PRA). There is probably a high

incentive to avoid spurious scrams, and this avoidance should be factored into the design of the shutdown system.

b. Decay Heat Removal System

A highly reliable decay heat removal system is central to a safe system. Some redundancy and diversity may be required, but needs to be established by PRA analyses. It is essential that the decay heat removal system be assured. The best systems are passive ones (do not need any power).

c. Control System

Because of the required rapid startup (for at least some of the missions) and the possibility of associated malfunctions, significant reliability must be built into the control system.

d. Reactivity Coefficients

Attention must be given to the reactivity coefficients, particularly the ones that come into play during a rapid startup, to ensure that no autocatalytic phenomena could arise. These phenomena primarily relate to the temperature and power coefficients. One would have to ensure that no phenomena (e.g., bowing of fast reactor fuel elements) introduce such autocatalytic behavior.

e. Launch Stresses

Appropriate structural analysis would have to be performed to ensure that the stresses occurring during launch do not fail (or weaken leading to later failures) any of the key components or structures.

f. Avoidance of Criticality on Flooding

In order to ensure that the system cannot go critical on flooding (in the event of splashdown after a failed launch), it may be necessary to introduce specific reactivity-reducing features.

g. Focus on Inherency

With respect to some of the previous design considerations, and more generally on all safety-related aspects of the design, it is a highly desirable objective to place as much emphasis as possible on inherent passive safety, i.e., safety that does not depend on active design features, but rather depends on passive features of the system.

Program management acceptance of risk will be based upon informed trades considering the magnitude of risk, as a function of both probability of occurrence and severity of the consequences, compared with the impact of compensating for the risk. Risks which are not totally controllable by design action because of impact

on cost, performance, or schedule, will be dealt with at the highest feasible level based on the following order of precedence:

1. Design for minimum hazards--to produce a system with inherent safety features through appropriate design.
2. Use safety devices--these may include, but not be limited to, such items as mechanical barriers or inhibiting mechanisms.
3. Use protective systems--these could include fire suppression, radiation shielding, or explosion blast shields.

h. Ability to Test

It is highly desirable to incorporate system features that allow testing of the continuing operability of the various safety features of the system.

2.3 SAFETY ASSESSMENT OF OTHER SUBSYSTEMS AND OVERALL SYSTEM

This section discusses other important aspects of the MSNPS safety program which will contribute to the acceptance of the MSNPS on a boost vehicle at a chosen test range. Analyses will cover the entire MSNPS and its spacecraft and boost vehicle interfaces during all operational phases, including ground processing, test, launch, on-orbit operations, end of life shutdown and disposal, and contingencies. Some of these activities will begin in phase II; others will be undertaken in subsequent phases.

The primary area of safety emphasis outside of the reactor subsystem will be the autonomous reactor core booster (ARCB). This subsystem is intended to separate the reactor core from the rest of the system and boost it into a safe storage orbit at the end of the reactor's useful life. It would also be used if there is potential for the spacecraft to reenter the Earth's atmosphere. The ARCB is a near state-of-the-art subsystem that includes propellants (both solid and liquid), separation devices, pressure vessels, sealed containers and batteries. An initial safety assessment of this subsystem has been performed and is discussed in the Safety Assessment Supplement. During phase II, this assessment will be expanded as the concept of the ARCB is definitized and the design begins to take form.

The primary sources of safety requirements for the ARCB will be the Air Force and NASA safety directives. MIL-STD-1574A is a top-level system safety directive from the Air Force Systems Command's Space Division. It is primarily a system safety management directive, but it does prescribe failure-tolerance criteria. These criteria describe the minimum number of failures or operator errors that must be tolerated before occurrences of specified types of mishaps can occur.

For ground and launch operations, ESMCR 127-1, WSMCR 127-1 or SAMTO HB S-100/KHB 1700.7 provide detailed requirements depending on where the launch takes place and whether the launch uses an unmanned booster or the STS. NHB-1700.7A provides very detailed STS payload safety requirements. BA has extensive experience in the application of these directives. The Inertial Upper Stage (IUS) is a large space booster which serves a similar purpose as the ARCB does: it delivers spacecraft from low Earth orbit to a variety of Earth orbits or interplanetary trajectories. It has been launched using unmanned boosters and also the STS. The major differences between the IUS and the ARCB is that the IUS transports payloads of much greater mass than the ARCB and must also provide payload services such as providing power and safety-critical commands to the spacecraft. Many of the analyses regarding the ARCB, however, will parallel those already completed for the IUS; this experience will be a great advantage for the BA team.

Overall System Safety and Reliability Assessment. Almost all the safety and reliability analysis performed so far in phase I has been limited exclusively to the MSNPS system with limited attention to the launch vehicle. In phase II we propose to address the consequences of launch vehicle failure on the total system.

System reliability will be integrated with the safety assessment process to ensure comprehensive coverage of the failure studies. This integrated approach should facilitate design tradeoffs of design options that can affect both system safety and system reliability.

Strategy. To ensure a comprehensive and structured safety and reliability study, the assessment will be developed in compliance with existing safety and environmental standards for the system.

Compliance With Required Safety, Reliability, and Environmental Standards. In addition to compliance with DOE 5480.1B, specific safety criteria will be derived from several reference documents and project safety criteria defined. While reactor safety is an area of major emphasis, operational safety of the overall system must also be considered. Depending on the mode of launch of the MSNPS, there are Air Force and/or NASA safety requirements which must be met for both the prelaunch, ground operations, and for the flight itself. BA is intimately familiar with both the safety requirements documents and the process for obtaining safety approval to launch payloads with either an unmanned vehicle such as the advanced launch system or with the space transportation system (STS). We have also had experience with ground and flight nuclear safety through our integration of the BA Inertial Upper Stage (IUS) with the Galileo and Ulysses spacecraft which both use radioisotope thermoelectric generators. Furthermore,

Boeing and some contractors has participated in the Interagency Nuclear Safety Review Panel (INSRP) review for the Galileo and Ulysses missions. The relevant documents are shown below:

AFR 122-15 Air Force Nuclear Power System Safety Reviews and Surveys

AFR 122-16 Air Force Nuclear Safety Review Procedures for Space or Missile Use of
Radioactive Sources

MIL-STD-1574A System Safety Program for Space and Missile Systems.

DOD-HDBK-343 Design, Construction, and Testing Requirements for One of a Kind
Equipment

MIL-STD-1522A Standard General Requirements for Safety Design and Operation of
Pressurized Missile and Space Systems

WSMCR 127-1 (Range Safety)

MIL-STD-1543A (Reliability)

In addition to the IUS program-specific data, BA operates an experience analysis center to collect, store, and retrieve past design experience including safety-related problems. All SAFE-ALERTS distributed by the Government-industry data exchange program are provided to the appropriate system safety personnel.

Through participation in ongoing space programs, BA maintains coordination with the DOD safety review team and the NASA flight and ground payload safety review panels. This participation will ensure that the BA team is up to date on the latest lessons learned and policy changes in the space flight community.

Methodology. In general, the methods to be used in phase II of the assessment will be similar but more complex and expanded to the methods used in phase I. A probabilistic approach will be undertaken using standard PRA techniques to evaluate the likelihood of any particular hazardous event and its resulting consequences. Probabilistic analysis is used to estimate risk and to identify any potential weakness in the design that might lead to undue contribution to risk. Nevertheless, determining analysis will be used to address specific safety or reliability concerns.

Key Safety and Reliability Tasks. The key system safety tasks are:

- a. Safety program plan*.
- b. Preliminary hazard analysis*.
- c. Subsystem/operating/test safety/software/interface hazard analyses.
- d. Preliminary safety assessment report.

*A preliminary version has been completed in phase I for MSNPS subsystem.

The reliability tasks are:

- a. System-level FMEA.
- b. Subsystem level FMEA*.
- c. Reliability projections*.
- d. Parts selection and derating.
- e. Detailed fault tree analysis.
- f. Environmental suitability analysis.
- g. Failure reporting and corrective action.

*A preliminary version has been completed for the MSNPS subsystem in phase I.

Both the safety and reliability tasks will be performed during the next design phase.

The purpose of performing system level FMEA is to define worst-case impact on safety and mission success for subsystem functional failures such as loss of reactor control or loss of downlink. The system-level FMEA is to be used to evaluate mission profile, contingency modes of operation, and to establish a fault tolerance approach. It also serves as a basis for reliability mission success model and identification of safety hazards.

The safety process leading to hazard control and verification is shown in figure 2.3-1 for the proposed preliminary hazard analysis. The objectives of the hazard analysis are to identify all hazards involved in the life cycle of the MSNPS, to identify the factors that would result in these hazards causing a mishap, to evaluate the effect of the mishap on the system, and to identify, to a level commensurate with the maturity of the design, the requirements for the elimination or control of hazard.

As an example of this procedure we discussed ground and flight operations below.

Ground Operations. The term "ground operations" is used here to include production, testing, transportation, storage, and launch preparation of the MSNPS. Specific areas of safety awareness are:

- a. Development and testing of the ground engineering system. This is discussed in section 7.
- b. Production and testing of flight hardware. This activity will take place in later phases (see the following discussion of operating hazard analyses). Production safety will be in accordance with company, state, and national policy for the protection of personnel. Hardware protection will be in accordance with company requirements.
- c. Ground transportation of flight hardware will be in accordance with Department of Transportation and DOE requirements, and will be subject to operating hazard analyses.

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Figure 2.3-1 Preliminary Hazard Analysis Process

- d. Storage of flight hardware will be in accordance with DOE and test-range requirements and will be subject to operating-hazard analyses.
- e. Launch-pad handling of flight hardware. The national test ranges have very detailed safety requirements and established procedure approval practices. The BA team has extensive experience in this process.
- f. Use of hazardous and toxic materials. The use of radioactive materials and beryllium is addressed in volume 1, section 9; additional hazardous materials will potentially be present within the autonomous core reactor booster in the form of propellants. The hazards involved in the use of any such materials will be included in the preliminary risk assessment for risk management in subsequent phases.
- g. Fail safe systems. Wherever possible, systems will be designed to react to a component failure by switching to, or maintaining, a safe operating mode which could possibly include system shutdown. Volume 1, section 9.1 discusses design features presently planned.
- h. Safeguards requirements are discussed in volume 1, section 9.1.
- i. Loss of coolant is discussed in volume 1, section 9.1.

Other safety requirements regarding ground operations which drive the design are included in volume 1, section 9.1 and the safety assessment supplement.

In phase III, as the hardware design becomes firm, operating hazard analyses (OHA) will be prepared for ground (and flight) operations. The OHAs will be based on the preliminary safety assessment, review of proposed time lines, and applicable directives. The OHAs are task and sequence oriented and present both the hazards and the safety requirements applicable to the operations being analyzed. The safety requirements generated by the OHA are used in two ways. First, the procedure writers will use these data and incorporate the requirements into the procedures as caution or warning notes or as procedural steps. The requirements will also be included in the hazard reports to ensure that the incorporation of the requirements is tracked. System safety personnel will verify the procedures as part of their review and approval process.

Flight Operations. Specific areas of safety awareness with respect to flight operations follow.

- a. Launch dynamics and consequences of launch vehicle failure. This area will be subject to an iterative safety analysis effort, beginning in phase II and progressing on out through presentation to the INSRP. In phase II, these analyses will be very preliminary in nature and intended to point out areas of weakness in the concepts,

- providing early warning of potential problems. As the program progresses, the complexity and fidelity of the analyses will increase.
- b. On-station operation. This area is a function of both design and procedures. Preliminary design requirements have been discussed in volume 1, section 9.1. In-flight operations will be subject to similar operating hazard analyses as were discussed with respect to ground operations. BA is very experienced in these activities, having participated in flight operations/malfunction/contingency planning with NASA for the IUS.
 - c. Safe operation in the absence of housekeeping power is discussed in volume 1, section 9.1.
 - d. End of life shutdown and disposal is discussed in volume 1, section 9.1.
 - e. Inadvertent reentry. In the planetary mission safety analysis discussed earlier, extensive analyses were performed for considerations such as IUS program regarding orbital decay, errant reentry, damage to nuclear devices due to nearby explosion, and collision. This background will be extremely valuable in evaluating in-flight anomalies involving the MSNPS.

Safety and Environmental Issues to be Resolved. At this point in the program there are many issues to be resolved which impact the safety of the system. The safety program to date has been concerned with the identification of hazards in any and all phases of the system's life and the appropriate safety requirements to eliminate or control those hazards to an acceptable level. The exact means of implementing those requirements have not, in most cases, been devised and have certainly not been the subject of detailed design. The key at this stage of the program is to ensure that the basic hazards are identified and that the design organizations are aware of the safety requirements. Tracking and verification of design action is discussed in the next subparagraph as it will apply in subsequent phases of the program.

In phase III, the preliminary hazard analysis will be documented in the form of hazard reports to track the completion of hazard control action as the design progresses. The hazard reports provide a closed-loop verification of positive action on the part of the design activity through reference to completed and implemented engineering drawings, successful test accomplishment or approved and completed procedures, etc., which demonstrate proper application of the safety requirements. Closure of the hazard reports will provide traceability that all required control action has been accomplished and approved by the system safety manager and the program manager. Ultimately, these closed hazard reports will be used to obtain MSNPS safety certification.

Overall Safety Management Structure and Responsibilities. The responsibilities of system safety management, engineering, support organizations, and subcontractors are detailed in this section.

a. System Safety Program Management

The BA MSNPS program manager has overall responsibility for the safety of the program. The program manager has delegated system safety management authority to the system safety manager with direct access back to the program manager for coordination of system safety matters, resolution of problem areas and reporting safety program status. Figure 2.3-2 shows the interfaces within the team and with DOE. Boeing's safety capabilities will be augmented by the quality and experience of the subcontractors. BDM is responsible for supporting Boeing by coordinating the safety activities of the contractors as well as performing safety analysis and checks on all computational methods. BDM has significant experience in space power safety. Rolls Royce and Associates, has the responsibility for the reactor and the generator turbine. Rolls Royce has extensive experience both in nuclear reactors and high reliability, long-life aircraft engines. Their reactor safety analyses constituted a major part of the phase I safety effort. Rocketdyne is responsible for power conditioning and turbopumps. They also bring a rich background of space safety experience to the program. Allied-Signal has responsibility for the generators. Science Engineering Associates will write the safety certification plan which will be incorporated into the overall system safety program plan prior to phase III. The MSNPS system safety responsibilities of subcontractors are controlled by specific requirements in the applicable statements of work. Subcontractor safety assessments will be reviewed by the BA MSNPS system safety organization. Potential hazards identified by subcontractors will be included in the integrated preliminary safety assessment.

b. System Safety Manager

The system safety manager will maintain surveillance over all program safety efforts, providing guidance and assistance as required. The system safety manager will, in addition to implementing the overall safety program, be specifically responsible for the following tasks:

1. Act as the focal point for all MSNPS system safety contractual matters within BA and with the customer. Contractual direction will flow to the system safety manager through program Contracts personnel and the program manager.

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Figure 2.3-2 MSNPS Contractor System Safety Interface with DOE

2. Ensure the integrated and coordinated inclusion of subcontractor system safety efforts into the overall system safety program. Also ensure that system safety requirements and tasks are properly levied on subcontractors.
3. Ensure an integrated and coordinated system safety approach
4. Be the BA safety approval authority for system safety-critical portions of program documentation.
5. Provide system safety input to program reviews, technical interchange meetings, and working groups.
6. Review all trade studies and identify those which have a system safety impact. Provide participation in all system-safety-related trades to ensure proper consideration of accident risk.
7. Coordinate system safety activities with program management and program functional organizations.
8. Be responsible for ensuring that test safety and accident/incident reports are initiated and investigations are conducted, as required.
9. Provide support to the DOE Safety Working Group.

c. System Safety Engineering

The technical aspects of the safety program are the responsibility of each lead engineer under the overall direction of the system safety manager. System safety engineering will be specifically responsible for the following tasks:

1. Provide ongoing system safety support to program personnel by interpretation of safety requirements and evaluation of proposed design approaches.
2. Performance of those system safety analyses required by the contract and/or deemed necessary to ensure the safety of personnel, equipment, or the environment.
3. Prepare system safety data for submittal to the prime contractor or customer as required by the contract.
4. Coordinate with other BA/subcontractor safety organizations to ensure proper use of "lessons learned."
5. Perform system safety review and provide comments, as required, on program data.
6. Provide additional system safety support as required by the system safety manager.

Additionally, BA system safety engineering will perform review of subcontractor safety analyses and integration of subcontractor safety analyses into the system assessment.

d. Supporting Safety Organizations

The following BA organizations have supporting roles in the MSNPS system safety program.

1. BA System Safety Engineering and Management.

The BA system safety engineering and management (SSE&M) organization provides managerial and technical guidance on system safety matters to all BA programs including the MSNPS. The manager of SSE&M also conducts independent management reviews and audits of program system safety activities.

2. Radiation Health Protection

Radiation health protection will support the MSNPS safety program in the identification and analysis of radiation hazards and in the interpretation and implementation of associated controls as required by company, contract, state, and federal requirements.

2.4 SAFETY CERTIFICATION PLAN

During the first period of phase II, the draft system safety program plan, which was written in phase I, will be updated and expanded to cover the integrated work of the MSNPS system safety team. This document will be a detailed description of roles and responsibilities involving system safety engineering and management of both the prime and the subcontractors. It will be an expansion of the processes and tasks described within this section 2 as modified or further defined by the customer in contract negotiation. It is intended to be a living document, maintained and upgraded as the program progresses through its phases toward nuclear and flight safety certification and, finally, operation. The plan will be provided to the customer at the first midterm review.

One of our team members, Science Engineering Associates, will write the nuclear safety certification plan which will be incorporated into the overall system safety program plan in an update prior to entering phase III.

3.0 RESOLVE TECHNICAL FEASIBILITY ISSUES

See supplement to Phase I Final Report, section 1.

4.0 REFINE DESIGN CONCEPT

Our Phase II design objectives are to demonstrate concept feasibility and develop a preliminary design that meets the phase I F&OR (rev. 1). Our approach to meeting these objectives is to prove the feasibility of our baseline design early in the program while maintaining the flexibility to easily respond to changing requirements and technical advancements. This approach recognizes that power output requirements and platform interface requirements will remain fluid for the foreseeable future. In addition, technological advances and new ideas will lead to design changes and improvements to our conceptual design baseline as we proceed to preliminary design and detailed design in later phases of the program. This approach is illustrated in the task flow diagram in figure 4.0-1. In addition, a Statement of Work (SOW) for this task is provided in figure 4.0-2. Each subsection (4.1 through 4.10) contains a schedule for the SOW subtasks.

A number of feasibility studies, concept design evaluation steps, and system design trades will be performed to move the program from the conceptual design of phase I to a validated preliminary design in phase II. Developmental issues and key system design uncertainties (described in vol. I sec. 11.0) will be resolved during the first 3 years of phase II. Solutions to these issues will be used to guide our trades and refine our designs. This work will be accompanied by concept evaluation activities such as design concept safety assessment, reliability and availability assessment, life cycle cost assessment, and system performance evaluation during the first 3 years of phase II to identify desirable changes to our conceptual design. Our system and subsystem trades will lead to the selection of the desired system concept and components for the MSNPS. These data, along with updated functional requirements and the results of feasibility investigations, will form the basis for proceeding to the completion of the phase II preliminary design.

4.1 SYSTEMS ENGINEERING

In our role as prime integrating contractor, Boeing Aerospace will employ system engineering processes and techniques developed over several decades of work on complex space systems such as MSNPS. These techniques have been refined through use on hundreds of highly complex major programs and products. Our system engineering plan for phase II is shown in figure 4.1-1. The scope and depth of the subtasks shown will be governed by the needs of the program and program funding constraints. Figure 4.1-2 shows a schedule of the subtasks to be performed.

Our system engineering plan for phase II is based on the view that phase II is fundamentally a technical feasibility and concept verification phase, followed by

Figure 4.0-1 Refine Design Concept Task Flow

SOW	Reference to cost estimate in Volume I	Deliverables
2.2.3 Refine design concept	3.3.2	Design drawings
2.2.3.1 Perform systems engineering	3.3.2	Analysis, trades reports
2.2.3.2 Perform reliability/availability	3.3.2	Reliability, availability approach
2.2.3.3 Develop additional mission applications	3.3.2	Additional missions descriptions
2.2.3.3 Refine reactor concept	3.3.2	Reactor design drawing and reports
2.2.3.5 Refine turbine concept	3.3.2	Turbine design drawings and reports
2.2.3.6 Refine power conversion concept	3.3.2	Drawings and report
2.2.3.7 Refine power conditioning concept	3.3.2	Drawings and report
2.2.3.8 Refine development of instrumentation and control	3.3.2	LCS design drawings and report
2.2.3.9 Refine turbopump subsystem	3.3.2	Design drawings and reports
2.2.3.10 Identify survivability issues	3.3.2	Survivability report

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Figure 4.0-2 SOW for Refining Design Concept Task

Figure 4.1-1 Phase II System Engineering Plan

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Figure 4.1-2 Systems Engineering Schedule

engineering development and a ground test program. Our plan further recognizes key systems requirements will be evolving, and critical interfaces such as the launch vehicle and weapon platform are "soft" interfaces. Additionally, results of technical feasibility investigations and technology advancements will need to be reflected in our system design, while funding constraints will place limits on the type and amount of testing that can be performed.

Mission Analysis. We plan to use the results of our extensive contract work on SDI missions and work closely with DOE to define requirements for the primary MSNPS mission, particularly those that will drive the MSNPS and weapon system interface design. In addition, we will use the results of past and present DOD and NASA contract work to define applications and requirements for additional MSNPS missions. Examples include operating as a Nuclear Thermal Rocket (NTR) or as a Nuclear Electric Propulsion (NEP) unit to propel interplanetary spacecraft, or operation as a fixed power plant and production heat source on the surface of the moon. For further discussion on additional mission applications, see volume I section 14.

Systems Requirements and Design Constraints. Using the Functional and Operational Requirements as a top-level system specification, we will work closely with DOE to identify key missing requirements and requirements that excessively drive cost or system complexity. Additional work will be performed to identify key system design constraints such as those imposed by the launch vehicle interface or safety regulations.

We recognize that the requirements of the weapons platform will drive the detailed requirements and preliminary design of the MSNPS. Consequently, the beginning of phase II we will (1) address the weapon platform integration issues identified in figure 2.3-1 of volume I section 2.0 and (2) analyze the requirements at the MSNPS/platform interface. Where specific quantitative point values cannot be defined due to uncertainties associated with the weapons platform, we will examine the likely range of values and perform parametric studies to evaluate the ability of our concept to meet high, low, and likely values. Examples of key platform interface requirements to be defined include the following:

- a. Amount of hydrogen available from the weapons platform, and the temperature at which it will be provided to MSNPS.
- b. Control commands to be issued by the weapons platform to MSNPS, along with their data rates and message format.
- c. Status reports to be provided by MSNPS to the weapons platform.
- d. Allowable limits on radiation and electromagnetic interference (EMI) from MSNPS to the weapons platform and vice versa.

- e. Allowable limits on vibration and power switching transients from MSNPS to the weapons platform.
- f. Structural loads at the weapons platform/MSNPS interface.
- g. Characteristics of the power to be supplied to the weapons platform.
- h. Test commands to be issued by the weapons platform, and test responses to be implemented by MSNPS.

These requirements, as well as several others, will be addressed by the collaboration of engineers from Boeing and Rockwell SDI programs, and engineers involved with the MSNPS. These requirements will be defined to the level of detail permitted by the developmental state of the weapons platform and MSNPS. In some cases, we expect that it will not be possible to include quantitative data in the requirement, i.e., the requirement will be a qualitative statement such as a command to be issued or a need for status to be determined and reported.

In addition to important interface requirements with the weapons platform, launch vehicles, and stationkeeping power system, our requirements analysis work will address the requirements imposed on MSNPS design by the space environment in which it must function, and the handling and launch conditions that must be sustained without damage, e.g., launch vibration requirements to be survived by the reactor.

Requirement Allocations and Systems Support Functions. Our established functional analysis and requirement allocation techniques will be used to allocate top-level system requirements to major subsystems or major components such as turbines or generators. Allocation of system-level reliability and availability requirements to establish reliability and availability requirements for turbines, generators, and power-conditioning components is an example of this process. System support requirements such as ground handling equipment, test support equipment and facilities, and space support requirements will be identified by first identifying the system support functions, and then analyzing these functions to identify equipment requirements, facility requirements, and necessary procedures.

The functional analysis and requirement allocation process will be supported by studies and allocation trades. These supporting studies will be selected to address important uncertainties and critical questions that must be resolved in order to establish realistic requirements and cost-effective designs to meet them. Additional data to support requirements definition and allocation will be provided by phase II test activities. Supporting studies and allocation trades during phase II are expected to include the following.

- a. Safety regulations and requirements (to be performed under safety assessment task).
- b. Environmental conditions and requirements.
- c. Survivability requirements, allocations, and alternative solution trades.
- d. Reliability requirements and allocation study.
- e. Control system requirements and design trades.
- f. Status reporting and monitoring requirements.
- g. Structural requirements, and structural design trades.
- h. Launch vehicle interface requirements.
- i. Radiation shielding requirements and radiation protection options.
- j. Mass and volume design constraints and weight reduction options.
- k. EMI design constraints and EMI suppression options.
- l. Platform stability and directional control requirements, and resulting design constraints on MSNPS design.

The results of these studies and others, along with test results, will be used to establish a design requirements baseline. These requirements will form the basis for design refinements and improvements during phase II. It will also be a baseline for evaluating the impact of new and evolving functional and operational requirements established by DOE.

Operating Concept Studies. The operating concept studies of phase I will be continued to greater depth in phase II to develop an understanding of how the system will be operated by the user in each operating mode, and in each mission phase. These studies will encompass ground transportation and handling, ground test, packaging and handling for launch, launch operations, system startup and operation in space, and system shutdown and disposal. These studies will include the operational trade studies and analysis identified in figure 13.0-2 of volume I section 13.0.

External Interface Definition. Our system engineering and integration work will involve representatives from the Advanced Launch System (ALS) program, our MSNPS contractor team, and weapons platform contractor to coordinate and define the MSNPS external interfaces. Interface data will be documented in the form of preliminary interface control drawings (ICD) as these data evolve. In later program stages, Boeing will request formation of a more formal Interface Control Working Group (ICWG).

Trade Studies and Sensitivity Analysis. Our system engineering plan includes several subsystem design trade studies in addition to those trade studies associated with developing system operating concepts and those in support of system requirements

definition and system design. Subsystems design trades are discussed in section 3.2 (reactor), 4.2 (turbines), 5.2 (power conversion), and 6.2 (power conditioning) of volume I.

As a part of our design evaluation and refinement task, sensitivity analyses and parametric studies will be performed to reduce weight and cost and to examine the impact of variations in critical parameters. The results of these analyses will be used to determine the degree of flexibility in our design before encountering major cost cliffs or large development risks. These studies will also be used to optimize our preliminary design and to identify where major improvements can be achieved with new technology.

System Design Concept Assessment Studies. During phase II, significant emphasis will be placed on design concept assessment and evaluation. The most important of these is our task of verifying the reliability and availability of our design. Detailed reliability assessments will be made of all elements of our system, and the need for diverse redundant systems will be examined as part of these analyses. Failure mode and effects analysis techniques used on all major Boeing programs will be used to examine all failure modes and their consequences with particular emphasis on those failures that could result in safety hazards.

Additional system design assessments will be made to evaluate overall system performance versus functional and operational requirements, total system life cycle cost, and system weight and size parameters versus design goals.

System Design Refinement. We will examine the top three levels of the total system design and perform concept trades and analyses to resolve the derived and evolving issues.

The first level involves the interface between the complete weapon system (NPB, MSNPS, and SP-100) and the various launch platforms. We will work with the ALS and NPB Boeing design teams and the SP-100 to update these interface issues and evolve an MSNPS system design that will best fulfill the interface requirements.

The second level of design trades and analyses involves the interfaces between (1) MSNPS and NPB and (2) MSNPS and SP-100. Again, we will work with the Boeing NPB design team and the SP-100 to address the evolving interface issues and develop MSNPS configurations through trades and analysis to best meet these interface requirements.

The third level involves the MSNPS platform and the integration of its components. We will perform design trades and analyses to resolve the evolving design issues and those stated in section 2.3 of volume I as deemed appropriate. We will work with the component design members of our team as their systems are developed and issues resolved in an effort to ensure the compatibility of the individual components, one with

another. For example, we will analyze the thermonuclear radiation from the reactor and perform trades to ensure compatibility of other components. We will examine effects of reducing radiation from the reactor, shielding the reactor, shielding components, thermonuclear hardening of components, and relocating components. These and other trades and analyses will be performed to achieve an integrated, compact, cost-effective, and safe system.

4.2 RELIABILITY, AVAILABILITY, AND MAINTAINABILITY

In phase I we emphasized reliability and availability in the system design concept, which led to the present configuration. An assessment of this configuration indicated the feasibility of achieving very high inherent reliability (0.96) throughout the operational life of the system and the duty cycles, without depending upon maintenance and repair except as might be required to provide sufficient operational availability.

Phase I also revealed reliability design issues requiring further study (vol. I sec. 12.0). In addition, there are issues related to the reliability analysis process itself, to be resolved in phase II, as discussed herein. A schedule illustrating the reliability subtasks is shown in figure 4.2-1.

Integration of a structured reliability and maintainability (R&M) design process into the design and test program, as described below, aids in development of the optimum preliminary design. In support of the R&M preliminary tasks, advanced computer-aided tools for R&M analyses are available for the MSNPS application.

R&M Objectives and Issues. For phase II, our R&M program is a blend of traditional methodology together with special engineering analyses which address the R&M issues specific to MSNPS, and are suited to the level of design detail for phase II.

Because of unique operational requirements and lack of related experience-based design data, a major objective is to ensure compatibility of materials, parts, and processes with MSNPS environmental and operating conditions. The problems to be overcome in meeting this objective are:

- a. Uncertainty of engineering properties in environments.
- b. Unusual operating conditions in terms of active/dormant states; long life.
- c. Lack of data on reliability of new materials and reliability of components in space environments and dormant operating conditions.
- d. Unavailability of procedures customarily used to sustain reliability and obtain availability (e.g., maintenance).

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Figure 4.2-1 Reliability Schedule

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The second major objective is to assess the capability of meeting the quantitative reliability and availability requirements. These are:

- a. Ninety-five percent (95%) overall probability of success under the operational conditions, for 10 years, composed of:
 - 1. Ninety-six percent (96%) inherent operational reliability.
 - 2. Ninety-nine percent (99%) survival of natural threats.
- b. Ninety-nine percent (99%) availability for use at any given time.

We will expand the reliability studies conducted during phase I to provide more complete and thorough assessments in order to increase confidence in the predictions and supporting data; to support design trade studies, and, if necessary, to increase the reliability over present values. Ways by which the R&M assessment process will be further expanded and improved are:

- a. Improving the reliability database for space components, particularly for components that are in standby for long periods.
- b. Using more detailed reliability models.
- c. Optimizing the degree of redundancy that should be incorporated in control systems in order to achieve the required levels of reliability.
- d. Assessing the system availability.
- e. Assessing the system reliability under natural threats.
- f. Reviewing whether space based maintenance is a cost-effective option.
- g. Implementing probabilistic risk assessment.

Approach to R&M. In summary, our R&M approach is to--

- a. Determine through analysis, the extremes of environment and operation stress conditions on components.
- b. Using FMEA, determine failure modes and the operational/environmental conditions which tend to induce them.
- c. Develop component quantitative reliability values and uncertainty ranges by estimating impact of operational and environmental conditions on present levels of reliability in conventional and space applications.
- d. Apply traditional reliability analysis and prediction methods to quantify reliability, maintainability, and availability, and enable trade studies of design alternatives for achieving high reliability and availability. In this area, emphasis will be upon--
 - 1. Failure modes and effects analysis to support reliability, risk, and maintenance-planning analyses.

2. Probabilistic risk assessment to identify failure modes uncertainties and to support trade studies.
3. Impacts and alternatives due to changing R&M requirements.
4. Maintenance and logistics planning.

Figure 4.2-2 shows an overview of the Boeing Aerospace reliability and maintainability program. Sections of this diagram have been highlighted to show the major thrusts of R&M engineering during phase II of MSNPS.

In phase II, the reliability program primarily is aimed at developing the requirements and criteria for parts and materials evaluation. Computer analysis and simulation programs will be used to support this activity. An example is the 'SABER' program, which can be used for FMEA and for fault detection/isolation analysis at high levels of the system as well as at low levels of indenture. SABER (Analogy, Inc., Beaverton, Oregon) provides time, frequency, and other analyses of entire linear and nonlinear systems. These analyses include mixed-level component descriptions (behavioral, functional, and primitive) and mixed-technology parts (electrical, mechanical, chemical, optical and more). SABER also has the ability to include time-varying and logical elements in a single analysis.

Design Analysis. The engineering design analyses and R&M assessments are integrated with other elements of the design and development process, as shown in figure 4.2-3. Use of computer-aided R&M analysis tools as an integral part of the computer-aided design process is illustrated in figure 4.2-4. Of particular importance to the phase II MSNPS are failure modes and effects analysis (FMEA), and probabilistic risk assessment (PRA).

The FMEA will be structured to provide the following information:

- a. Identification of single points of failure, to ensure that all of them are included in the reliability predictions.
- b. Accuracy of system fault detection and identification, needed to evaluate adequacy of the reconfiguration process in fault-tolerant subsystems and to assess maintainability of the system.
- c. Causes and effects of induced failures, providing input to PRA and to the evaluation of reliability under natural threats.
- d. Identification of critical failure modes and effects, used in reliability-centered maintenance planning, as an input to probabilistic risk assessment (PRA), and to direct test planning for later program phases.

Figure 4.2-2 Reliability and Maintainability Integrated Into Design Process

Figure 4.2-3 Integration of a Structured Reliability and Maintainability Design Process Into the Design and Test Program

Figure 4.2-4 Reliability and Maintainability Computer-Aided Tools Integrated With ECAD and MCAD Design and Analysis Tools

Probabilistic risk assessment (PRA) was applied to the reactor during phase I, and was carried out at the subsystem level. During phase II, the scope of PRA will be broadened to include other selected subsystem, on which it will be used at the major component level. PRA primarily is used as a management technique to ensure that reliability, availability, and safety analyses are conducted systematically and thoroughly. The MSNPS PRA will ensure identification of significant consequences of failure, and of the failure causes. The likelihood of critical failures will be assessed using all available data. Where reliability data are limited in amount or relevancy, PRA techniques quantify the degree of uncertainty in the risk probabilities. The integrated reliability risk assessment software (IRRAS) will be used in PRA studies.

Data Sources. As previously mentioned, it is necessary to build up our database on performance of MSNPS-similar components in space applications. In addition, the database must be extended to lower level component parts to support the more detailed reliability models necessary to determine the amount and location of redundancies that should be incorporated in the system.

Available data will be obtained on reliability for long life and for long-time dormant conditions; and for resistance to the space environment including radiation and other natural threats. Sources of such data are:

- a. NASA analyses of spacecraft performance, reliability, and failure modes during orbital life.
- b. Ballistic missile storage data (NASA, Air Force, Army, Navy).
- c. Operational test data on attack missiles such as Boeing/Air Force SRAM (Short-Range Attack Missile).
- d. Storage data on other complex expendables used by the armed forces.

Sources of these data include the Boeing experience analysis center, which collects data from Air Force and Navy R&M databases. However, additional data, of the type described above, will have to be obtained from Government sources. Specific needs will be identified as early as possible in phase II.

In cases where reliability data are of limited applicability to MSNPS components, engineering estimates of reliability will be made, based upon study of differences between MSNPS components and similar equipment for which data are available. The adjustments of reliability data in these cases will require technical information about the similar equipment. DOE's help in obtaining these data may also be needed.

Maintainability. The MSNPS design concept incorporates maintenance concept to the extent that it is both cost effective and operationally effective. During phase II,

these design concepts will be refined to define specific requirements for fault detection and diagnostics, installation provisions and modularity, and robotic repair. Associated trade studies may indicate that additional redundancy is desirable. Boeing's space logistics support simulation model will be used in support of these studies, and the FMEA will be structured to ensure that it provides information needed for reliability-centered maintenance planning. The Boeing satellite support simulation model was developed for performing allocations, tradeoffs, and sensitivity analyses of satellite support systems and supportability features. Performance is measured in terms of availability and support costs. The model is particularly useful as an allocation tool during conceptual design analysis. We plan to use the model to derive requirements for redundancy types, redundancy management, accessibility, time between false alarms, false-alarm resolution, fault detection, and fault isolation. As the design progresses, and as we are able to estimate maintainability characteristics with the required confidence, we will use the model in trade studies.

R&M in the Design Process. Phase II efforts will focus on developing an MSNPS design that is inherently reliable, remotely maintainable, and cost effective through the iteration of the systematic R&M process.

Beginning in phase II, Boeing team members and product designers will be provided with the following R&M resources: R&M allocations; design guidelines and rules; parts, materials, and processes requirements; and R&M computer-aided tools and online access to the Experience Analysis Center; and a companywide R&M experience database.

The evolving MSNPS system design will be subjected to R&M design analysis to develop and flow down R&M design requirements to major components.

The MSNPS R&M program for phase II (fig. 4.2-3) begins with development of a reliable and maintainable system architecture followed by subsystem R&M design and analyses at the equipment level. One key feature of the R&M program is integration of R&M design in the phase II design process through involvement of all system development team members so that R&M, as well as operability and cost considerations are reflected in the MSNPS design from the outset.

The system analysis process elements of figure 4.2-3 will be used to develop a reliable and maintainable architecture. Candidate architectures WILL BE developed from system analysis and flowdown of the system requirements from the F&OR document. System and subsystem trade studies will be conducted to evaluate architectures for configuration optimization. The derived requirements then will be allocated downward (initial allocations are shown in fig. 12.1-1 in vol. I). The allocations along with the R&M controls and guidelines drive the design. R&M design analysis

techniques (fig. 4.2-3) will be used to develop R&M characteristics in the preliminary design to satisfy the allocated requirements, controls, and guidelines. This effort will initially focus on the system and later on the subsystem and lower levels for the designated design.

R&M Computer-Aided Tools for Design Use. R&M computer-aided tools will be integrated on electrical and mechanical computer-aided design (ECAD and MCAD) workstations as previously shown in figure 4.2-4. These tools will allow the designers to give R&M timely consideration throughout the design process. R&M requirements and allocations will be stored in the engineering design database for the system level and down to the lowest level of individual design responsibility, that is, the designer and supplier levels. A design will be captured on the workstation and stored in the database. As part of the capture process, it is checked against the design rules and the user is notified of rule violations. Electrical, thermal, and mechanical analyses are performed and stored. These data are then extracted from the database by the R&M tools, evaluated, and compared to requirements. The results are supplied to the workstation user and then stored. If the design does not meet requirements, the user can perform the sensitivity analysis provided by the tools or revise the design and rerun the analysis. The process continues until requirements are met and provides for timely design process iteration. At any time, program and engineering management personnel can query the database to determine design status.

Most of the R&M tools have broad program application. For example, the failure modes and effects analysis tool (SABER) is supplied with behavioral models of the product design. It is used from the start of the design process beginning with top-level models describing the MSNPS. As the design progresses, lower level models are added. Faults are inserted in the models at any level, and the simulation determines the effect at all levels of definition. All R&M tools will be used as the preliminary design is detailed. The benefits of each R&M computer-aided tool are shown in figure 4.2-5.

Tool name	Reliability and maintainability (R&M) application and benefits	Inputs	Outputs
Single-thread reliability optimization program (STROP)	Optimize reliability via redundancy, in concept definition phases	<ul style="list-style-type: none"> • Single-thread elements • Mean time between failure of elements • Element optimization parameter (e.g., weight) 	<ul style="list-style-type: none"> • Optimized set of added redundant elements • Sensitivity data
Computer-aided reliability modeling analysis (CARMA)	Mission reliability modeling and prediction on nonstate-dependent redundant configurations	<ul style="list-style-type: none"> • System configuration • Mission phases • Duty cycles • Failure rates • Fault-detection coverage 	<ul style="list-style-type: none"> • Mission reliability • Sensitivity data
CEPFRA, SURE, HARP, CARE III	Reliability/availability evaluation of configuration models which are formulated as Markov processes	<ul style="list-style-type: none"> • Transition matrix • Failure rates • Initial conditions • Mission time 	<ul style="list-style-type: none"> • System reliability • State probabilities • Availability
RELALC	MIL-HDBK-217 part types/stresses failure rate prediction	<ul style="list-style-type: none"> • Parts list • Parts characteristics • Application stress data 	<ul style="list-style-type: none"> • Unit MTBF • Failure rates of parts • Sensitivity data
QUICKFAULT	Digital circuit fault detection and isolation, evaluation, and generation of manufacturing tests	<ul style="list-style-type: none"> • Circuit model • Part models • Circuit inputs • Faults 	<ul style="list-style-type: none"> • Fault dictionary • Faults detected/not detected • Faults isolated/level • Test vectors
SABER	Analog circuit fault detection/isolation evaluation and top-down failure mode and effects analysis	<ul style="list-style-type: none"> • System description (high or low level network or behavioral) 	<ul style="list-style-type: none"> • Operating points • Outputs versus frequency • Transient response • Sensitivity data • (Fault analysis in development)
Event Tree Network Analysis	Safety and reliability analysis Evaluate large fault/event trees, uncertainty analysis, common-mode failure analysis	<ul style="list-style-type: none"> • Events • Event rates • Fault/nsk propagation logic 	<ul style="list-style-type: none"> • Ranked nsk sequences • Ranked significant events • Failure probability distributions
Failure Analysis Diagnostics Expert System	Safety and reliability analysis Fault analysis of complex systems during design	<ul style="list-style-type: none"> • Qualitative description of system 	<ul style="list-style-type: none"> • System failure modes and effects • Fault tree logic • Fault diagnostics rules
Automated Maintainability Analysis Program (AMAP)	Corrective maintenance calculations in MIL-HDBK-72 format	<ul style="list-style-type: none"> • Parts list • Maintenance tasks and times 	<ul style="list-style-type: none"> • Mean time to repair (MTTR) • Maximum maintenance time (MMT) • Timeline chart
Crewchief	Evaluate maintainability of design in terms of maintenance technology anthropometry, body positions, strength, hand tools, clothing, vision, and interference	<ul style="list-style-type: none"> • Design description • Work area description • Maintenance technical characteristics • Tools • Tasks 	<ul style="list-style-type: none"> • Interactive simulation of maintenance actions with display of successful outcome of problems
Satellite Support Simulation Model	Determine support feature enhancing reliability, maintainability and availability by performing allocations, tradeoffs and sensitivity analyses of satellite support systems and supportability features	<ul style="list-style-type: none"> • Constellation data • Support concept • Launch vehicle data • Orbital transfer data • Subsystem data • Component data <ul style="list-style-type: none"> Reliability Maintainability Fault detection • Maintenance action times • Spares turnaround times • Recoverability factors 	<ul style="list-style-type: none"> • Observed availability • Actual availability • Effective availability • Non-recurring costs • Recurring costs • R M&A statistics
Integrated Reliability and Risk Analysis System (IRRAS)	Support probabilistic nsk assessment (PRA) by creating reducing and analyzing fault trees	<ul style="list-style-type: none"> • Fault tree events • Fault tree logic • Basic event probabilities 	<ul style="list-style-type: none"> • Outsets • Importance • Sensitivity • Fault tree graphics

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Figure 4 2-5 Selected Reliability and Maintainability Computer-Aided Tools Available for MSNPS Use

4.3 DEVELOP ADDITIONAL MISSION APPLICATIONS

Following the signing of the Presidential Directive on National Space Policy in January 1988, NASA announced that it was pursuing a long-range goal "to expand human presence and activity beyond Earth orbit into the solar system." NASA then established the Office of Exploration (OEXP), which defines human exploration missions and evolutionary expansion scenarios that meet the criteria set forth in the directive. These studies provide an excellent source on the requirements to develop additional MSNPS missions.

We plan to analyze alternative SDIO missions and the NASA Human Exploration missions to define propulsion and power applications suitable for the MSNPS. We will then perform preliminary design and mission analysis to size a variant of the MSNPS to perform each of the applicable missions. Figure 4.3-1 contains the schedule for this task. Comparing the mission cost with the MSNPS to the cost with the current baseline systems will show economic leverage, a key issue for determining system design requirements.

The Boeing team MSNPS concept offers several advantages, but the major one is flexibility. We are proposing one development which satisfies both the major propulsion and power generating requirements for all lunar and Mars exploration and evolutionary development missions. It performs both high thrust and low thrust missions as a propulsive element and can be delivered to the surface of either the moon or Mars to serve as a fixed powerplant after its propulsive duties are completed. Our conservative design approach, combined with clad fuel elements, also offers major cost savings during development.

Propulsive Applications. The current Mars mission scenarios have requirements for a spacecraft to transport an eight-crew transit habitat module after the Mars Crew Sortie vehicle from low earth orbit (LEO) to the moon Phobos in Mars orbit using a conjunction class high-thrust trajectory. These same scenarios specify that a nuclear-electric propulsion stage will be used as the cargo spacecraft used to deliver to Phobos the supplies and equipment needed to develop a permanent manned base, and that a nuclear-electric propulsion stage will be used for cargo delivery from LEO to low lunar orbit (LLO) in the latter years of lunar base development.

The following is an example of the analysis we will perform in this task. Using the MSNPS in a Mars delivery spacecraft, as a reusable Nuclear Thermal Rocket with an exit temperature of 2000 degrees K, the additional specific impulse saves 113 tons of initial spacecraft mass required in LEO, relative to conventional chemical propellants (fig. 4.3-2). This is equivalent to saving one Heavy Lift Launch per Mars mission at \$100

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Figure 4.3-1 Additional Mission Applications Development Schedule

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Figure 4.3-2. Use of NTR Saves Two Heavy Lift Vehicle Launches On Each Mars Mission

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million each. Configured as a NEP, operating at 1200 degrees K (fig. 4.3-3), the RRA/BA MMW completes the same Mars mission for an initial mass in LEO of 540 tons, which saves 470 tons relative to the chemical system. Note, that 540 tons is an entire year's worth of launch budget for the Human Exploration Program. Hence, development of NEP can be construed as an enabling technology for the Manned Planetary Program.

Additional applications that will be analyzed are as the rocket motor in a Mars lander and ascent vehicle, where the MSNPS capability to operate with multiple gaseous coolants will allow serious consideration of using in-situ produced propellants at the Mars base.

Power Applications. The evolutionary missions currently planned aggressively develop resources found in-situ: on the surface of the moon; on Phobos, Mars' inner moon; and on the surface of Mars. These resource developments will eventually all require large amounts (greater than one MW) of readily available long-term power. We will analyze the power design requirements of these missions and define variants of our MSNPS design suitable for each application. Key issues are power level, duty cycle, system lifetime, and synergism with the material processing production process. The first issue to be addressed is which nuclear cycle is best for these particular applications. The advantages of the Boeing team Brayton cycle under these conditions are: safe shutdown and cold storage (no fluids to freeze), high-efficiency operation (less waste heat to disturb neighboring operations), and the ability to generate large amounts of very hot hydrogen gas, the primary ingredient for in-situ materials processing.

Combined Power/Propulsion Applications. The best application for the dual-mode (open/closed cycle) reactors is to self-deliver powerplants to the surface of a planet. Using the reactor first as an NTR provides relatively high impulse to reduce delivery launch costs, then using its high thrust capability to land on a planet simplifies the number of systems required and reduces propellant consumption. A schematic drawing of a potential combined power/propulsion unit for lunar applications is shown in figure 4.3-4. We will examine the possible applications for dual-mode MSNPS systems within the current NASA scenarios and define variants of our current design with capability to complete mission requirements. These results will be documented and become part of the data base used to recommend MSNPS design variables.

4.4 REACTOR CONCEPT

See Supplement to Phase I Final Report, section 1.

Figure 4.3-3 Use of NEP Saves 5 or 6 Heavy-Lift Vehicle Launches on Each Mars Mission

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Figure 4.3-4 Dual-Mode Nuclear Rocket Used to Self-Deliver Lunar Power Plant

4.5 TURBINE CONCEPT

We will refine the turbine design concept in the following subtasks: continuing trade studies, continuing the design beyond the present concept stage, and aerodynamic testing (see fig. 4.5-1). We will be continuing studies in the following areas that will be funded by other programs: EM bearings, and blisk materials and fabrication. A schedule for this task is shown in figure 4.5-2. This information will be made available to this program while preserving the proprietary nature of the material. This material will be used to assess the feasibility of this program. Specific trades and design tasks are described below.

We will carry out a trade study on the effect of reducing the turbine inlet temperature, considering the turbine design, the reactor power and performance, and materials benefits in both reactor and turbine.

We will produce the following during phase II:

- a. Preliminary turbine assembly drawing, showing overall dimensions, interface positions, and overall weight.
- b. Preliminary drawings of major components of the turbine will also be prepared. The components to be drawn include:
 1. Disks and blades.
 2. Gas entry scroll/casing and bearing supports.
 3. Main HP and LP casings.
 4. Intermediate casing and bearing supports.
 5. Exhaust volute/casing and bearing supports.
- c. Preliminary blade and nozzle shapes, and the complete turbine annulus. These designs will be refined based upon data acquired from the cascade tests.
- d. Interface data to enable the design of other components and assemblies to proceed. This would include:
 1. Mounting torque reaction and vibration loads.
 2. Shaft inertias and weights.
 3. Shaft lateral and torsional stiffness data.
 4. Gas entry pipe (main flow and auxiliary cooling flows) position, mechanical loading and size data.
 5. Main gas exhaust position, mechanical loading and size data.
- e. Turbine sealing arrangements, anticipating the positions and likely flow rates of any leakages and bleeds not entrained in the main exhaust flow.

Figure 4.5-1 Turbine Concept Task Flow

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Figure 4.5-2 Turbine Concept Schedule

- f. Outline drawings of the main exhaust ducting and final nozzles to space. The bulk of the design activity on the main exchange duct and final nozzles will be deferred to phase III.

The ongoing proprietary developments at RRA in blisk will be periodically assessed. If a high level of confidence can be demonstrated, then dual-alloy blisk technology will be adopted in order to save weight and cost and to further improve reliability.

During phase II we will perform a cascade test of the turbine blading. This is a low-cost means of experimentally verifying aerodynamic performance. There are two particular features of the proposed turbine which make this physical demonstration necessary:

- a. The first stages of the blading have very low aspect ratios and high hub:tip ratios. This means that the secondary flows associated with annulus boundary layers and the ends of the blades will have a significant effect on stage performance and gas exit conditions.
- b. From an aerodynamic standpoint, the two spools act as a single light-stage turbine. The gas exit conditions from each stage are not modified by the nozzle guide vanes of the next stage. Hence, even small deviations from calculated stage performance would accumulate through the turbine, which could result in large gas incidence angles in the latter stages, causing a reduction in stage power output.

Using existing Rolls Royce computer programs, we will design the turbine nozzle guide vanes and blades. These produce an aerodynamic flow model using finite element techniques based both on aerodynamic theory and on empirical data gathered over many years of hardware testing. The test data have been used, in effect, to calibrate the theoretical model by the introduction of various correction factors. The proposed cascade test for this turbine will confirm that the assumed values of these correction factors, interpolated or extrapolated from previous test data, are correct. It is thus not necessary to cascade test every stage; a test on one blade row only will give the required confirmation.

The test geometry will be subjected to a range of entry conditions; experience indicates that six to eight test conditions will suffice. The effects of gas entry angle, velocity, and boundary layer thickness will be investigated. At each condition, aerodynamic performance will be assessed by means of static pressure measurement on the aerofoil surfaces, and by entry and exit plane velocity traverse measurement.

4.6 POWER CONVERSION CONCEPT

This section describes subtasks that will be performed in phase II of the MSNPS program to refine the alternator baseline design resulting from the phase I study. These tasks, which are discussed below, include bearing type selection studies, and alternator development and testing to resolve alternator design issues as shown in figure 4.6-1. Figure 4.6-2 contains a schedule of the subtasks performed.

Bearing Type Selection Study. The two bearing types that are considered viable for the MSNPS application are the foil gas bearing and the electromagnetic bearing. Both types are used in this application. The foil gas bearing type is currently selected for the alternator baseline design, and Rolls Royce has used the electromagnetic type in the turbine design. The foil gas bearing type, unlike the electromagnetic type that requires controls by means of electronics, provides simplicity of design and high reliability. The foil gas bearing type, however, has two drawbacks, and those are hydrogen coolant leakage, which may cause excessive coolant loss, and bearing losses due to friction even during standby operation. These drawbacks may adversely affect the turbine and cooling system designs. Evaluations of both types will be performed in phase II to determine the optimum bearing type for the MSNPS application. Airesearch of Allied-Signal will conduct study and testing of foil gas bearings, and Rolls Royce will be responsible for assessment of electromagnetic bearings. The results of both the foil gas bearing and electromagnetic bearing studies will be evaluated by Boeing, who then will select the single optimum bearing concept for both the alternator and the turbine designs.

Alternator Development and Testing. The following paragraphs give detail discussions of the alternator designs issues that have been identified in the power conversion section of the phase I final report.

Foil Bearings. The feasibility of foil bearings used in this application will depend on two criteria relating to the low leakage requirement in the standby condition. First, if a closed system can be used, heat generated by bearing drag and rotor windage must be transferred through the housing to the outer environment. A heat transfer model is required to ensure temperature limits are not exceeded. Second, if an open system is required, seals must be designed and tested to meet leakage and life requirements. In addition, bearing cavity pressure may have to be minimized to reduce leakage. Reducing the cavity pressure adversely affects bearing load capacity. Therefore, bearing tests would be run to determine the minimum allowable cavity pressure.

Effects of Hydrogen on Alternator Materials. Hydrogen is used to cool both the alternator stator and rotor. Interactions between hydrogen and different materials of alternator including the copper windings, the stator laminations made of electrical steel,

Figure 4.6-1 Power Conversion Concept Task Flow

Figure 4.6-2 Power Conversion Concept Schedule

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and the rotor forging of high-strength steel may lead to problems. The most common problem of hydrogen in steels is hydrogen embrittlement, which can be either a loss of ductility or a cracking phenomenon. The parameters that affect the hydrogen problems are pressure and temperature of the coolant. In this application the hydrogen coolant is supplied to the alternator at 35K and 150 psia. The result of preliminary investigation shows no problems of hydrogen in steel at such low pressure and temperature. Further study, however, will be conducted to confirm this. Also a detail thermal model of the alternator will be constructed and used to accurately predict the pressures and temperatures of the hydrogen coolant in the alternator assembly.

Characteristics of Alternator Magnetic Materials at Low Temperatures. With low cooling temperature, the alternator will be designed to operate in low temperature environment for maximum efficiency and reliability. Magnetic B-H, and loss characteristics of the stator and rotor materials at low operating temperatures are required to guide the alternator design. Research and material testing, therefore, will be conducted for various stator and rotor materials to determine their properties and capabilities at low operating temperatures.

Small Hollow Conductor Fabrication and Manufacturing. To keep weight to a minimum, very high current densities in the range of tens of million amps/square-meter, were designed into the rotor and stator windings. The design also incorporated hollow conductor cooling for maximum cooling effectiveness. With high current densities, the design requires the use of hollow conductors of small sizes, which may present manufacturing problems. Research into small-size hollow conductors that are practical to manufacture, therefore, is needed to guide the alternator design.

Rotor Conductor Insulation. The rotor slot configuration is shown in figure 4.6-3. The radial insulation separating adjacent rotor field conductors will sustain high compressive loading, particularly at the upper slot section. While a mica cell insulation can easily sustain the value of compressive loading necessary, in this case the combined effects of thermal expansion and spin cycling with high compressive loading could lead to eventual wear of the separator. Accordingly, tests and evaluation of candidate separator materials, including (1) standard mica cell separators with various coatings and composite (layer) additions and (2) boron nitride both alone and in combination with mica and other materials need to be conducted. The process for construction and installation of cell separators also requires investigation.

Figure 4 6-3 Rotor Slot Configuration

4.7 POWER CONDITIONING CONCEPT

The power conditioning system will be refined during phase II through the use of trade studies, further design and analysis. The phase II analysis will develop initial construction tolerances, define the thermal management system, and characterize initial electrical operating parameters. During this period, the development issues will be addressed and resolved to result in a preliminary design, suitable for the phase III final design. Figure 4.7-1 shows the interrelationships of the component and system analysis to arrive at a preliminary design. Utilizing information obtained from Rocketdyne's Space Power Electronics Laboratory (SPEL) in conjunction with analysis, various power transistors will be studied to ensure that multiple switches can be precisely synchronized to meet the inverter reliability and survivability criteria. A preliminary power conditioning system design will then be developed utilizing analysis techniques to study the effects of cryogenic cooling. This design will be further refined by analyzing the output waveform characteristics and studying various PLR and dummy load configurations. A schedule for these subtasks is shown in figure 4.7-2.

High Voltage Power Transmission. The transmission of high voltage power in a space environment is extremely difficult due to plasma arcing and corona discharge effects. Cables insulated with solid insulations, such as Kapton, may become very large in diameter, making them inflexible and unwieldy. Using insulating gases, such as sulfur-hexafluoride (SF₆), may reduce cable diameters and improve flexibility: but it introduces gas containment problems and complicates cable terminations. We will closely monitor DOE contract #DE-AC-03-SF15933, Vapor Mist Insulation to ensure that new conductor developments are incorporated into the power conditioning system, thus reducing the cost for the MSNPS customer.

Inverter Switch Analysis. We will analyze the proposed MSNPS inverter switch configuration, while following developments obtained from Rocketdyne's SPEL, to verify the reliable synchronized operation of multiple transistor switches. Current inverters are about one-tenth the power rating required for the MSNPS. This is considered the practical 20 kHz inverter size limit with present technology due to the difficulty of precisely switching multiple paralleled transistors efficiently and reliably.

New transistor switch configurations are currently being developed to meet the demand for future high power, high frequency switches criteria. The most recent of these are metal-oxide semiconductor controlled thyristors (MCTs). MCTs are being developed for the main inverter units contained in the space station electrical power system (EPS). In support of the space station EPS, MCTs will be studied by Rocketdyne.

Figure 4.7-1. Preliminary Power Conditioning Design Development

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Figure 4.7-2 Power Conditioning Concept Schedule

These results will be available to MSNPS and they will be combined with proprietary analysis codes to verify the inverter operation.

Filter Design Considerations. The current power conditioning system utilizes the inductive and capacitive effects present in the cabling at the ripple frequency to meet the ripple requirements specified in the F&OR. This premise is justified since the inherent filtering present in the cables at 20 kHz is high. Since the cable filtering is proportional to frequency, high ripple frequencies will be attenuated even further. If this technique does not yield adequate filtering, the filtering needs can be reduced by going to a six-phase inverter. The circuit configuration for a six-phase inverter permits the elimination of most of the lower harmonics and reduces transients. During phase II, an analysis of the output waveform will be conducted to determine the inherent system filtering utilizing codes developed for the space station EPS. Since the inherent filtering of the cable system is dependent on the final system configuration, these analysis routines will be updated throughout the design to ensure that the final filter configuration meets the specified ripple and harmonic requirements.

Low Temperature Operation. We will evaluate the effects of cryogenic cooling during phase II. Electrical, thermal and stress analyses will be conducted on the conceptual design components to define their performance at cryogenic temperatures and select an optimum operating temperature range. The functioning of a high power, high voltage power conditioning system for the mission lifetime is currently considered a developmental issue to be resolved through detailed analysis and trade studies. Materials will be selected on the basis of thermal conductivity, thermal expansion, and electrical conductivity properties. The preliminary design will ensure that a good thermal conduction path exists for each component, since thermal interfaces are considered the greatest challenge in a space environment. These units will be fully analyzed to determine the effects of cryogenics on the operation, reliability and availability of the component for the mission life.

Parasitic Load Resistor and Dummy Load Design. Another key task conducted during phase II will be the development of a conceptual design for a parasitic load resistor (PLR) and dummy load. The PLR is designed to test the operation of the power conditioning system. In conjunction with the PLR design, a dummy load design will be developed. The driving requirement for the dummy load is the ability to accept 100% of the electrical power generated by the power system if it is rejected by the load. In addition, the dummy load will be used during startup and power rundown to provide system stability. Ideally, the PLR would be an integral part of the dummy load. A trade

study will be conducted during phase II to yield the minimum mass for the dummy load and PLR.

The trade study will consider three possible dummy load and PLR types: resistive, induction heating, and arc discharge. The placement of the dummy load and the cooling for both the dummy load and the PLR will be studied during this trade study. If a resistive dummy load and PLR are selected, the power (I^2R) losses must be maximized by utilizing a high current. This favors placement of the dummy load directly after the alternator. The cooling of the dummy load and the PLR are also important considerations. The selection of the cooling fluid temperature, cryogenic or 800K, affects the selection of materials. These factors will be considered during the design to optimize the thermal, electrical and heat transfer properties, and minimize the cost of these units.

After completion of the trade study, Boeing will construct a dummy load development model. If a modular dummy load design is selected, only one module will be constructed. This module will be tested to evaluate the cooling method employed, its electrical properties, and its structural integrity. This model will be constructed by the Boeing environmental laboratory because they have extensive space-related experience and modern facilities for the fabrication of space-related hardware.

The studies, analysis and tests conducted during phase II will enable the development of preliminary design layout drawings for the rectifier, inverter/transformer, dummy load and PLR. The results of later analyses will be used to revise the drawings on an orderly basis. These layout drawings will be used for design reviews and included in the final report.

4.8 DEVELOPMENT OF INSTRUMENTATION AND CONTROL SYSTEM

There are five major areas that we will address in phase II concerning the instrumentation and control system. These are (1) reliability and redundancy management for the impact on logic design and on instrumentation quantities and types; (2) specific definition of the ICS modules required (e.g., data requirements, power, weight, volume, and compatibility control measures); (3) thermal and threat protection integration; (4) verification of control approach through simulation; and (5) application of expert system technology for autonomous control. These are organized into two major tasks as illustrated in figure 4.8-1. The schedule for WBS 3.8 is shown in figure 4.8-2. WBS 3.8.1 covers the aspects of the design that ensure high reliability and WBS 3.8.2 address integrated simulation of the ICS with incorporation of expert system technology. These are discussed below.

Figure 4.8-1 Task Flow Diagram for Phase II Development of Instrumentation and Control System

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Figure 4.8-2 Instrumentation and Control System Development Schedule

Development of High Reliability Instrumentation and Control Subsystem (WBS 3.8.1)

The initial effort of task 3.8.1 will include a confirmation of the Phase I baseline approach using the system engineering process outlined in figure 4.1-1, updated as necessary to evolving F&ORs.

Reliability and Redundancy Management. To ensure safe operation of the MSNPS throughout all phases of the mission, the ICS must be fault tolerant. For instrumentation such as thermocouples, this requires physical redundancy in place. For signal conditioners and processors, we will develop appropriate sparing concepts. One particularly attractive concept that can be easily implemented with the space processor array (see vol. I sec. 8.1) is pooled sparing. Circuit switching allows failed modules to be eliminated from the network and operational modules from a spares pool to be incorporated into the active set. We will use failure modes and effects analyses and reliability design tools described in section 4.2 to complete the ICS reliability and redundancy management approach.

The output of this task using the developed logic design will include (1) refinement of the overall architecture, (2) identification of required instrumentation and processors, (3) a preliminary configuration layout, (4) a failure modes and effects analysis, and (5) reliability/availability estimates.

ICS Module Definition and Compatibility Control. Based on the quantities of the processing components and the cycle time required for processing, we will develop specifications for needed instruction execution rates, data transmission rates, and other performance parameters. In conjunction with the developers of the space processor array (SPA) (Boeing Electronics and Control Data), we will use the specifications to define specific modules and interconnections as a basis for refined estimates for mass, volume, and power requirements for use in overall spacecraft integration. We will institute a compatibility control program to ensure that electrical bonding, susceptibility, and emissions from components do not adversely affect overall system operation.

Thermal and Threat Protection Integration. Safe operating temperatures for electronics usually fall in the -40°C to 75°C range. To maintain this operating envelope through all orbital environments and system operation and test phases requires careful thermal integration. We will refine the thermal protection design for the overall configuration and verify through analysis that there is sufficient thermal isolation from the high temperature components and that the chosen radiator design can provide appropriate temperature control for the mounted electronics. We will monitor the

technology progress of the SUPER program and incorporate appropriate features combining thermal and threat protection. The primary output of this task will be a verified physical configuration layout.

ICS Simulation (WBS 3.8.2)

Control Simulation. To ensure the coordinated operation of all the spacecraft systems, it is important in phase II to further develop the simulation of the control system. We plan for RRA and the UKAEA to continue to develop the reactor control simulation for the evolving mission requirements. As part of phase II we will investigate incorporating the reactor control simulation into an overall spacecraft simulator to model the coordinated operation of the power system processor and the lower-tier local control units. Boeing has experience analyzing dynamic interactions using the NPB vehicle simulation model NPBSIM (developed for AFWAL by RDA, Contract F29601-85-C-0135) and we will augment the model with the power system parameters if we determine that this is the most cost-effective approach. To aid in our continuing development of overall simulation capability we will consult with the Boeing Electrical Power Conditioning and Control Technology group that developed an autonomous power system testbed simulating operation and control of large space-based power systems such as for the Space Station.

Expert System Application. Due to potential of multiple spacecraft, the involvement of ground support personnel in operation and troubleshooting must be minimized. Incorporation of an expert system for autonomous control appears attractive from this viewpoint. The expert system allows different levels of autonomous operation and man-machine interface. Specific roles of the expert system would include fault identification, fault recovery, performance prediction, and trend analysis. The power system simulation program referred to above has incorporated an expert system for control using the power system simulator as the testbed. Using the involved personnel as a resource, we will evaluate specific areas of the MSNPS for application of expert system technology to our instrumentation and control system, and develop a simulation shell for autonomous operations and fault management as appropriate.

4.9 TURBOPUMP SUBSYSTEM

The requirements for the conceptual design of the turbopumps are defined in volume I section 2.2 and by the system flow schematic, volume I, figure 2.2-5. They are also shown in tabular form in volume I figure 2.2-6. During phase I, the conceptual design with two turbopumps was selected as the baseline feed system.

As noted, the overall system flow schematic shows a series flow of hot gases through two turbopump turbines. This makes it feasible to integrate the two turbopumps into a single assembly wherein the turbines are coaxial and adjacent. By doing this, the interconnecting hot gas ducting with its weight and volume requirements is eliminated and overall turbopump drive gas is reduced. This arrangement, illustrated in figure 4.9-1, also allows the turbines to rotate in opposite directions, thereby minimizing the torque/inertia effects of the turbopumps on the platform.

An alternative to the integration of the two turbopumps is a single turbopump with two separate pumps and a single drive turbine, illustrated in figure 4.9-2. In this concept fewer bearings, shafts, and turbines are needed, therefore, the system could potentially involve lower cost, lower weight, and more reliability than two turbopumps with separate shafts. However, the drawback of the single shaft turbopump is that the pumping system has less flexibility in operation (i.e., a single shaft speed for both pumps) and would not have torque cancellation.

If appropriate, during phase II we will compare the two separate turbopump configurations with the integrated turbopump designs shown in figures 4.9-1 and 4.9-2. Figure 4.9-3 illustrates the subtasks that will be performed and figure 4.9-4 shows a schedule.

We will consider turbopump weight, volume, reliability, maintainability, and system factors such as drive gas consumption, MSNPS platform integration, and startup in the selection during the trade study. To obtain weight, volume, drive gas consumption, and related information (i.e., shaft speed, suction parameter information, and shaft power), we will make conceptual designs to each turbopump configuration. With these data, we will make an engineering judgment to select the best configuration for the baseline turbopump. The basis for the engineering judgment is the experience gained from rocket engine programs such as NERVA, SSME, and J-2.

An objective/goal of the phase II turbopump trade studies is to enhance the overall MSNPS reliability using a minimum of equipment weight, volume, and turbopump drive gas. A turbopump failure constitutes a system failure, and turbopump weights are modest compared with the weights of the primary components such as the reactor and turbogenerator, therefore, it is reasonable to consider redundant turbopumps. We will perform a second trade study to select a single set versus a dual set of turbopumps for the system. The prime consideration in the study will be the relative reliability of the two options. Secondary trade factors will be performance (turbine drive gas requirements), weight, and volume.

Figure 4.9-1 Two Turbo Pumps in Single Assembly

Figure 4.9-2 Single Turbo Pump: Two Pump, One Turbine

Figure 4.9-3 Turbopump Subsystem Trade Studies Task Flow

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Figure 4.9-4 Turbopump Subsystem Schedule

4.10 IDENTIFICATION OF SURVIVABILITY ISSUES

Survivability is the ability of a system or component to continue to function or recover sufficiently to complete its mission after being physically attacked by a belligerent force, introduced to a natural, hostile, electromagnetic, or nuclear environment.

Figure 4.10-1 shows the natural, self-induced, and hostile environments the system may encounter. These environments are described in details in the supplement to the final report, section 2.

Figure 4.10-2 shows the effect of environment and threat on components. The vulnerability of a spacecraft system depends on its susceptibility, feasibility concerns, and its accessibility. The options for survival include proliferate, mask, decoy, evade, and harden. The survivability effort necessary to ensure a particular level of survivability for a nuclear reactor space power system includes identification of the system susceptibility and threat capabilities--determining the areas where the threat exceeds the system susceptibility and developing an optimum set of design and platform enhancements which maximizes survivability.

Figure 4.10-3 shows the impact of the environment on Boeing's MSNPS and a qualitative description of the protective measures. While the survivability strategy is simple in concept, the development of a survivable power system must be performed in the context of a total system design. The survivability of this whole system is affected by the design choices in individual subsystems. Similarly, the survivability design choices for the power system may affect the mission performance of the payload.

The overall preliminary survivability approach is shown in figure 4.10-4. The schedule detailing our approach is in figure 4.10-5. The initial step in the development of a survivable power system is defining the environment in which the system must survive. By combining the total environment list with the mission parameters, constellation size, altitude, orbital inclination, etc., the applicable threat environments can be identified. The next step is determining the power system susceptibility to the threats on this reduced list of threat environments. For the Boeing MSNPS, the reduced list of threat environments are given in section 2 of the supplement to the final report of this proposal. The susceptibilities are then compared to the capabilities of the various threats to determine where there are gaps in the survivability of the power system. A model is used to measure the benefits and costs for various combinations of survivability enhancements. Finally, the resultant survivability predictions must be validated. To perform various steps in this approach requires data collection, analysis, and testing at many different levels of integration.

Natural environment	Self-induced environment	Hostile environment
<ul style="list-style-type: none"> • Solar flux • Trapped and solar charged particles • Space plasma • Micrometeoroids and debris • Atomic oxygen 	<ul style="list-style-type: none"> • System outgassing • Electric and magnetic fields • Thermal • Neutron and gamma radiation • Effluents 	<ul style="list-style-type: none"> • Nuclear <ul style="list-style-type: none"> • X-ray • Neutron and gamma • Enhanced trap particles • Directed energy <ul style="list-style-type: none"> • Microwaves <ul style="list-style-type: none"> — Ground — Space • Lasers <ul style="list-style-type: none"> — Ground pluse — Long — Short — Space <ul style="list-style-type: none"> — CW — Pulse <ul style="list-style-type: none"> — Long — Short • Kinetic energy <ul style="list-style-type: none"> • Projectile • Pellets

Figure 4.10-1 Threat Environment

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Environment and threat	Source			Susceptible elements	Effect
	Natural	Self-induced	Hostile		
Nuclear and space radiation	●	●	●	Electronics	Performance degradation, upset, burnout
Thermal (nuclear, laser, etc.)			●	Materials and/or structure	Pyrolysis, melting, vaporization, thermal shock, spallation
DEMP/SGEMP			●	Electronics	Upset and/or burnout
Debris and pellets	●		●	Materials and/or structure	Impact damage
Effluent		●		Sensors and neutral particle beams	Sensor performance degradation and beam ionization

Figure 4.10-2 Effect of Environment and Threat on Components

Environment	Impact	Component
Natural environment	Electronics degradation Ionization of effluent Single point failure of pipes, tank, etc.	Hardened electronics Add protective bumper material to pipes, tanks, etc.
Effluent	High voltage breakdown Beam interference Spacecraft charging RF propagation interference	Prevent exposed high voltage fields, electric insulation, redundant links to ground/space
Nuclear	Ionization of effluent Degradation of electronics EMP current coupling	RAD hard parts shielding, transmission line shielding Evasion
Laser	Cryogen loss	Hardened insulation, high temperature material Evasion
Kinetic	Puncture, loss of coolant, fracture or rupture of tank	Defensive shield, evasion

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Figure 4.10-3 Impact of Environment on Space Power System Components

A description of the Boeing approach, the operating environments, system consequences, and results of preliminary investigations is detailed in section 2 of the supplement of the proposal.

Figure 4.10-4 Survivability Development Flow

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Figure 4.10-5 Identification of Survivability Issues Schedule

5.0 REFINE LIFE CYCLE COSTS

The purpose of the MSNPS program is to develop preliminary designs for a space-based nuclear power system to meet the needs of SDIO missions at an affordable cost. The objective of the cost analysis is to provide credible estimates of these costs. The results of the phase I life cycle costing activity, including associated groundrules and assumptions, can be found in volume I, section 15. We will use this estimate as the baseline, which will be refined during the phase II study (see fig. 5.0-1). Specifically, during phase II we will estimate acquisition costs, refine launch, operations and maintenance, disposal costs, and assess risk, as shown in the statement of work in figure 5.0-2. A schedule for each SOW item is shown in figure 5.0-3 (summary of our schedule).

5.1 ESTIMATE OF ACQUISITION COSTS

The primary tool to be used during phase II for estimating acquisition costs (DDT&E and production) for the MSNPS system is the Boeing-developed parametric cost model (PCM). PCM is structured to represent the aerospace environment, and we will use it to integrate the acquisition portion of the life cycle cost estimate as well as generate most costs for the MSNPS system. We will estimate DDT&E and production transportation costs unique to the MSNPS program using the Boeing Advanced Launch System model designed specifically for such payload requirements.

The information we generate during phase II will be based upon the expansion of the work breakdown structure/equipment list developed during phase I. Due to the early stages of development and hardware definition, costs for phase I were generated primarily at the subsystem level. During phase II, we will provide hardware information at the component LRU level, significantly increasing the absolute cost accuracy of the estimate (fig. 5.1-1).

Figure 5.1-2 illustrates the source, type, and level of information that will be generated for the cost analysis of the MSNPS program in phase II. As depicted in the illustration, the scope of the program has been established by the Department of Energy in cooperation with the Department of Defense, Strategic Defense Initiative Office (SDIO). We will amplify this information to (1) establish the design, test, fabrication, sparing, and maintenance philosophy required to successfully implement the program and (2) interject known costs, GFE costs, and estimates from other sources into the estimating process. We will then assemble and integrate all data, including labor and overhead rates from Finance and technical details from Engineering and Manufacturing, to create a record of programmatic and design choices that ultimately shape program

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Figure 5.0-1 Refinement of Phase I LCC

SOW	Reference to cost estimate in Volume I	Deliverables
2.2.4 Refine life cycle costs 2.2.4.1 Estimate acquisition costs 2.2.4.2 Refine launch costs 2.2.4.3 Refine operation and maintenance costs 2.2.4.4 Refine disposal costs 2.2.4.5 Assess risk	Section 3.3.2	Program estimate will include: <ul style="list-style-type: none">• Life cycle cost• Launch cost• Operation and maintenance costs• Disposal costs

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Figure 5.0-2 SOW for Refining Life Cycle Costs Task

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Figure 5.0-3 Refine Life Cycle Cost Schedule

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Figure 5.1-1 Cost Estimate Accuracy

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Figure 5.1-2 Boeing PCM Model System for Estimating MSNPS Program Costs

cost. Using this approach allows the assembly of a program estimate from the best available source data, whether it be parametric, analogy, vendor quotes, detailed grassroots analysis, or known costs from other sources.

In order to arrive at total acquisition cost, we will estimate the cost of non-hardware-related functions in addition to the hardware elements comprising the system. For example, functions such as system engineering, software, system test, logistics, peculiar support equipment, and program management fall into this category. PCM factors these costs based on aerospace relationships to the hardware design and manufacturing processes. This methodology simulates the actual approach used to develop and produce advanced system hardware in the aerospace environment.

5.2 LAUNCH COSTS

For phase I, launch costs were assumed to be \$500/lb. This assumption, however, does not take into consideration the unique developmental effort for the ALS launch vehicle, and the facilities and site activation required to meet the launch needs of the MSNPS system. Boeing has developed a launch cost model which takes these costs into consideration, and during phase II we will use this model to more accurately reflect the launch cost scenario. An additional benefit of this launch model is that it takes into account the amortization of advanced launch system costs over the design reference missions.

5.3 OPERATIONS AND MAINTENANCE COSTS

In addition, we will further refine the operational scenario for the phase II effort using the Boeing-developed model for transportation costs to estimate launch vehicle operations, payload integration, and launch consumables. We will estimate operations and support costs for the MSNPS system by comparing space EVA/IVA personnel costs with ground command, control and monitoring, control center costs, historical relationships for consumable items such as recurring spares, and a maintenance concept which will ensure continuous uninterrupted operations. In addition to transportation costs, the operations and support elements include space crew personnel, spares, maintenance, material modifications, and indirect support operations.

5.4 DISPOSAL COSTS

In phase I we have developed a means of safe disposal of the MSNPS system. It includes using up the remaining H₂ on board the weapons platform for propulsive means to reach the highest attainable orbit, and then use the autonomous reactor case booster

to separate the reactor and boost it into a nuclear safe orbit. The cost of this booster in phase I was based on analogous historical boosters. In phase II, as the design becomes more refined, we will update cost to reflect specific design requirements for the MSNPS system.

5.5 RISK ASSESSMENT

The PCM model used to generate acquisition costs during phase II will provide a point estimate of cost for the MSNPS system. In order to better quantify the uncertainty surrounding this point estimate, Boeing has developed a computer model called "Ranger" which places approximately three sigma bounds on the cost estimate. The model provides a low, high, and most probable (50-50) value of cost. The model is based on quantifying key factors which have been identified by people experienced in risk analysis which affect the uncertainty of a cost estimate. These major areas of uncertainty include schedule, technical, programmatic, and estimating uncertainty. Assessments are generally made at the subsystem level, with knowledgeable program personnel choosing from a 1-10 scale based on the descriptions illustrated in figure 5.5-1. The output of the model provides a low, high, and 50-50 value of cost for each subsystem, and for the total program figure 5.5-2. Using this model to assess cost uncertainty will identify the areas where excessive costs may exist, and where attention must be given to reduce risk.

	1	2	3	4	5	6	7	8	9	10
SCHEDULE DRIVERS	Appropriate Contingency		Reasonable				Too Long or Short		Too Short	
	Time to Test Interface			Serial Loading			Parallel Load		Out of Sync	
	No Overlap			Minimal Overlap			Some Overlap		Much Overlap	
PROGRAM DEFINITION	Clear		Minimal Ambiguity				Ambiguous		None	
	Clear Command and Well Staffed			Well Staffed			Inadequate Staffing		Conflict	
	Adequate with Reserves				Adequate and Steady		Irregular		Poor	
	Effective Comprehensive			Comprehensive			Incomplete		Dysfunctional	
	Experienced Effective			Experienced			Inexperienced		Disruptive	
TECHNICAL CHALLENGE	OTS		State of the Art			Some Advance		Much Advance		New Tech
	Same Product			Similar Product			New Line Same Tech		New Tech	
	Standard		New Processes			Need Innovation		Complete New Approach		
	Available		Some New		All New				No Standard	
ESTIMATING APPROACH	Extension of Actuals		Firm Quotes			Good Parametrics		Educated Guesses		
	Familiar with Product			Familiar with Similar Product			No Familiarity		Minimal Experience	
	Good Inputs			Uncertain Clear Inputs			Sloppy Minimal Staffing			
	Regular			Ad Hoc				None		

Figure 5.5-1 Uncertainty Factors

Costs to be evaluated			Uncertainty factors				Cost range		
Line item name	\$ estimate with contingency	\$ estimate without contingency	Schedule	Definition	Technical	Estimating	Low	50/50	High
Engineering	105.15	105.15	5	5	4	5	86.75	109.09	131.44
Developmental shop	33.50	33.50	6	5	4	5	27.64	35.59	43.55
Manufacturing	80.30	80.30	5	4	5	5	66.25	83.31	100.37
Purchased equipment	25.50	22.00	5	4	5	6	18.15	22.82	27.50
Subcontract	85.00	76.50	5	4	5	6	63.11	79.37	95.63
Quality control	8.50	8.50	5	5	4	4	7.12	8.87	10.63
Logistics	4.25	4.25	5	5	4	4	3.56	4.44	5.31
Program management	21.35	21.35	5	5	3	3	18.09	22.17	26.69
Program total	363.55	351.55					290.67	402.67	485.22

Figure 5.5-2 Sample Uncertainty Evaluation

6.0 DEFINE THE ENGINEERING DEVELOPMENT PROGRAM

In this task we will (1) identify the MSNPS subsystems, components, and materials requiring demonstration during the engineering development phase; (2) prepare preliminary subsystem and component performance specifications; (3) prepare fabrication plans for the test hardware; (4) establish test plans including the environments; and (5) identify fabrication and test facilities required to complete these tasks. The various subsystems that will be included in this development plan, and the deliverables, are summarized in figure 6.0-1 along with reference to Volume I cost sections for the phase II cost estimates. Figure 6.0-2 shows our approach to performing the tasks required to develop the plans for the engineering development program. Figure 6.0-3 shows the schedule for this task. This task will be led by our system design group with support from subsystems design, systems engineering, test engineering, manufacturing, facilities, and safety functions.

We are initiating fuel and other critical component testing in phase II to minimize any major program risks early in the program and to identify further development testing required in the engineering development phase. We will begin the planning for the engineering development program by reviewing (1) the F&OR requirements, (2) the phase I final report, (3) phase II interim design reports, (4) phase II feasibility and developmental test reports, (5) safety requirements documents, and (6) the allocated subsystem and component performance and reliability requirements. Based on a review of these documents, we will identify the mission environments; critical subsystems, components and materials requiring engineering development and demonstration; and their safety, performance, and reliability requirements. We will then prepare preliminary subsystem and component drawings that will be fabricated and tested during the engineering development phase. The detailed test hardware drawings will be prepared early in phase III. The subsystems will include but not limited to the reactor, turbine, power conditioner, alternator, and instrumentation and control. Components for engineering development will include critical items such as the fuels. We will then define the subsystem/component test, fabrication, and facilities requirements. Subsystem and component test plans, including test environments, number and geometry of test hardware, and acceptance criteria, will then be prepared. Included in the plan will be any pretest analysis required to define the test environments, and post-test correlations required to interpret the test data and to refine the hardware designs.

Also in this task, plans for the test hardware fabrication will be established. We will identify the fabrication and test facilities and prepare a plan for acquiring these. We

SOW	Cost estimate (Volume I)	Deliverables
5.0 Define engineering development program	Section 3.3.2	a) Preliminary prototype component design documents for six subsystems,
5.1 Define reactor subsystem development		b) Component fabrication plan,
5.2 Define turbine system development		c) Facilities plan,
5.3 Define power conversion subsystem development		d) Test plan,
5.4 Define power conditioning subsystem		
5.5 Define development for other subsystems		

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Figure 6.0-1 Engineering Development Program Definition Summary

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Figure 6.0-2 Engineering Development Program Definition Task Flow Diagram

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Figure 6.0-3 Engineering Development Program Definition Schedule

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will review our fabrication and test plans and prepare a preliminary safety assessment of our engineering development program. The output of this task will include (1) test hardware preliminary design drawings, (2) pretest and posttest analysis requirements, (3) fabrication plan, (4) test plan including test environments, (5) facilities plan, and (6) a plan for the incorporation of the test results into system/component designs.

6.1 REACTOR SUBSYSTEM DEVELOPMENT

Rolls Royce and Associates will lead the Boeing team effort to accomplish the reactor development work. We will accomplish all of the reactor feasibility tests and initiate some of the development tests in phase II. The phase II test include two feasibility tests and five developmental tests as described in section 3.0. These tests are comprised of materials tests and critical component tests. We are performing the fuel tests in phase II to achieve early abatement of any serious program risks. We will use these phase II feasibility and developmental test results to identify further development required in phase III for this critical subsystem.

In phase II we will (1) review the F&OR requirements, reactor preliminary designs, performance and safety reports and (2) establish safety, performance, and reliability requirements. We will develop preliminary designs for the reactor hardware, and establish test, fabrication, and facilities requirements. We will then prepare test, fabrication, and facilities plans to meet these requirements. A preliminary safety assessment of the reactor test hardware fabrication and test plans will be made and a safety report will be prepared.

During the engineering development program we will focus on refinement of the reactor detailed design and subsequently the finalization of the reactor subsystem specification. We must recognize the lengthy effort required to finalize the detailed reactor design and the relevant safety documents. Our goal for this program is to be ready to proceed with the fabrication of the reactor subsystem to be used in the ground test program.

The following tasks are examples of phase III reactor development items for which engineering development plans will be prepared in phase II.

Reactor Core. We will build a full-scale mockup core using the correct geometry and materials to validate the computer codes used in the physics design and in the design itself. We will measure power shapes and reactivity worths of control rods and reflector wings, and basic core reactivity--both dry and flooded.

Aerodynamics. We will build an air flow rig to confirm the satisfactory gas flow behavior within the reactor, including flow distributions, and stability.

Control Rod and Reflector Wing Drives. We will build prototypes, confirm satisfactory precision of operation, and undertake endurance and reliability tests (in vacuum if deemed necessary).

Control Algorithm. Following the demonstration of the successful operation of the control system in conjunction with a computer simulation of the reactor, we will carry out proving trials on a test reactor.

Valves. We will fabricate prototype decay heat removal system valves and demonstrate satisfactory performance when initiated over the working temperature range of 35 to 600K. We will check satisfactory closing after passing cryogenic hydrogen.

Reactor Control Unit. We will fabricate a prototype reactor control unit and test it in conjunction with the prototype instrumentation and control system (see sec. 6.2).

6.2 INSTRUMENTATION AND CONTROL SUBSYSTEM

The Boeing team will complete an expert power simulation effort and a study effort to identify a high-reliability computer candidate in phase II as described in section 4.8. The results of the simulation and the computer study will be available along with preliminary design information to begin the engineering development program.

The simulation results, computer study, and preliminary design information will be used to develop a preliminary instrumentation and control subsystem specification and prepare a detailed design of the instrumentation and control prototype. In phase III subsequent to the final design work, a prototype computer will be purchased to support software development and test. In the process of selecting the prototype computer, we will look at the current technology and expected future developments. Because of the rapid advances in computer technology, we intend to allow for the possibility of buying a more advanced computer for instrumentation and control subsystem. We will write a test report to document software test results. We will evaluate the test results to determine if the software design is adequate. If we identify a design deficiency, we will revise the software design and reaccomplish the software tests. When we determine that the software design is satisfactory, we will use the software design to finalize the computer program specification for the instrumentation and control subsystem computer program.

In parallel with computer program development, we will prepare a detailed design for the prototype reactor control unit. Rolls Royce and Associates will fabricate the prototype reactor control unit and test the control units in an actual reactor, for example, at the Sandia facility. Rolls Royce will document the test results in a report

and evaluate the test results to determine if a design deficiency is discovered during the prototype reactor control unit tests. The detailed design will be revised to correct the deficiency. The prototype reactor control units will then be modified to incorporate the design changes and be retested. When the detailed design of the prototype is judged to be satisfactory, then the detailed design will be used along with test results and the software design to finalize the instrumentation and control subsystem specifications.

6.3 TURBINE SUBSYSTEM DEVELOPMENT TEST

We will develop the turbine in close coordination with the reactor and the alternator because of the integral relationship between these three subsystems. In order to optimize the turbine-reactor development, we will assign the lead on turbine development to Rolls Royce and Associates. During phase II, we will accomplish trade studies and scaled-down turbine performance and blisk tests as described in section 4.5. We will make an assessment of the practicality of the electromagnetic bearing based on existing test data available at Rolls Royce and compare the assessment results to the results of the gas-cooled test bearing demonstration, which is to be conducted for alternator development. The intent is to select the same type of bearing for both the turbine and the alternators.

In phase III, in order to test the turbine, we will adapt/build a test loop to operate with hydrogen as the working fluid. This will require approximately A1/0.3 MW of heating and A1 MW of dynamometer capacity, and is therefore a major undertaking. The prototype turbine will be installed in the rig and operated at progressively higher power levels until the design power has been demonstrated. A considerable range of measurements will be made during this process, including:

- a. Gas flow distributions.
- b. Temperature distributions.
- c. Dimensional changes during power changes.
- d. Strains in major components.
- e. Vibration levels.
- f. Power matching between high and low pressure spools.
- g. Response to failure of the electrical supply to the bearings (if the electromagnetic bearing is selected) or response to failure of the gas supply (if the gas bearing is selected).
- h. Response to failures in other components in the reactor system.

The trade studies, test results, and preliminary design will be used to develop a preliminary turbine specification and a detailed design for a prototype turbine. The prototype turbine will be tested in England in the laboratory facilities of Rolls Royce, Plc. A test report will be prepared and the test results will be evaluated to determine the suitability of the prototype design. If the evaluation of the test results reveal deficiencies in the turbine design, the detailed design will be modified to correct the deficiencies. The turbine will be modified to incorporate the design changes and then re-tested. When the evaluation of the test results indicates that the turbine design is satisfactory, the test results and the detailed design will be used to finalize the turbine subsystem specification.

6.4 POWER CONVERSION SUBSYSTEM DEVELOPMENT TEST

Allied-Signal will lead the Boeing team in the development of the power conversion subsystem, of which the alternators are the key component. Section 4.6 describes trade studies, a hydrogen-cooled foil bearing demonstration, an alternator materials test, a test on the effects of cryogenic temperatures on magnetic materials, and a research study on the manufacture of hollow conductors which will be accomplished in phase II. The results of the trade studies, research, tests, and preliminary power conversion subsystem design will be available at the beginning of the engineering development program.

We will use the trade studies, tests, research study, and the preliminary design to develop the preliminary power conversion subsystem specification and detailed prototype alternator design. Then, in phase III, we will build a prototype alternator and test the alternator for performance and reliability testing. We will prepare a test report and evaluate the test results. If the evaluation reveals a deficiency in the alternator design, the prototype alternator detailed design will be modified to correct the deficiency. We will then modify the prototype alternator to eliminate the deficiency and retest. The alternator will be tested in the cryogenic environment similar to the operational environment and will be tested for proper mechanical and electrical operation. When the evaluation of the test results indicate that the alternator design is satisfactory, the detailed prototype alternator design and the test results will be used to finalize the power conversion subsystem specification.

6.5 POWER CONDITIONING SUBSYSTEM TEST

Rockwell-Rocketdyne will lead the Boeing team's work on development of the power conversion subsystem. During phase II, Rocketdyne will complete trade studies to design

the optimum power conditioning subsystem and to define and test the dummy load, and complete the preliminary design of the power conditioning subsystems as described in section 4.7.

At the beginning of the engineering development program, we will use the trade study results, dummy load test results, and the preliminary design work from phase II to develop a preliminary power conditioning subsystem specification and a detailed design for a prototype power conditioning subsystem and prototype dummy load. We will test the prototype module and dummy load for environmental, reliability, mechanical, and electrical performance. We will document the results of tests of the prototypes in a report. We will evaluate the test results to determine if the prototype designs are satisfactory. If a design deficiency is discovered, we will revise the detailed design and the prototype will be modified to incorporate the new design and then retested. When the test results from the test of the prototypes indicate that the design is satisfactory, we will use the test results and detailed prototype design information to finalize the power conditioning subsystem specification.

6.6 DEVELOPMENT TEST OF OTHER SUBSYSTEMS

Turbopump Subsystem Test. Rockwell-Rocketdyne will lead the Boeing team in the development of the turbopump subsystem. During phase II we will refine the design of the turbopump subsystem as indicated in section 4.9. We will prepare a preliminary design to be available at the beginning of the engineering development program.

In phase III we will use the preliminary design information from phase II to develop a preliminary turbopump subsystem specification and a detail prototype turbopump design. When the detailed design is completed, we will fabricate a prototype turbopump and test the turbopump in the environmental laboratory at Boeing for performance and reliability. We will document the test results in a test report and evaluate the test results to determine the suitability of the prototype design. If the results of the test reveal a deficiency in the prototype turbopump design, we will revise the detailed prototype turbopump design and modify the prototype turbopump to incorporate the new design. We will then retest the modified prototype turbopump and evaluate the test results. When the test results indicate that the prototype turbopump design is satisfactory, we will use the test results and the detailed prototype design to finalize the turbopump subsystem specification.

7.0 DEFINE GROUND ENGINEERING TEST PROGRAM

The purpose of this task is described in three parts as follows:

- a. To define a complete system ground engineering test configuration.
- b. To define a test program outline.
- c. To identify preliminary facility requirements.

Because safety is so critical we have defined a fourth part:

- a. Safety assessment.

Figure 7.0-1 shows the work breakdown structure (WBS) cost estimate reference, and the deliverables from this task. The work flow is shown in figure 7.0-2 and the scheduling of the work is shown in figure 7.0-3. The ground engineering test program is expected to be in phase IV, which will follow the engineering development program of phase III. The cost estimate for the definition of the ground test program is based on our experience in other space-related programs and is therefore realistic.

We will begin our task to define the ground engineering test by reviewing the draft preliminary subsystem specifications, the safety assessment report, and proposed schedule to obtain test requirements, safety requirements, schedule requirements, and facility requirements as shown in figure 7.0-2. We will use the requirements to prepare a preliminary test plan draft. One part of the preliminary test plan will be the definition of the ground test configuration. The system design which results from the phase II design refinement will be used as a model for definition of the ground test configurations for phase IV. The subsystems and components will be redesigned as test articles to be compatible with test facilities, but still capable of simulating the real configurations as nearly as possible. Our safety experts and safety experts from a national laboratory (to be designated at a later date) will assess the safety of the planned tests and assist in the resolution of safety problems discovered in the test plan draft. We will then prepare a safety supplement to the test plan to explain safety procedures and safety precautions required for each test. We will also review the draft test plan to identify requirements for both Government and contractor test facilities. As a part of the review, we will determine the most cost-effective facility to be used for each test as well as the availability of each facility in the timeframe the facility is required. If a desired facility is not available for the planned test, we will select the next best facility that meets the requirements. When we have identified suitable available facilities for each test, then we will publish a preliminary test facilities requirements document.

WBS	Cost estimate (Volume I)	Deliverables
6.0 Define test program outline	Section 3.3.2	a) Complete system ground engineering test configuration
6.1 Define program outline		b) Preliminary test plan
6.2 Safety assessment of test program		c) Safety supplement
6.3 Facility requirements		d) Preliminary facilities requirements document

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Figure 7.0-1 Ground Test Program Definition Study

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Figure 7.0-2 Ground Test Program Outline Task Flow

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Figure 7.0-3 Ground Engineering Test Program Definition Schedule

In conjunction with the safety and facilities review we, including subcontractor members of the Boeing team, will review the draft test plan for completeness and accuracy. When we are satisfied that we have a safe, complete, accurate, and achievable plan, we will publish the preliminary test plan. We would expect the ground test plan to be finalized during the engineering development phase in concert with the finalization of the subsystem system specification.

7.1 PROGRAM OUTLINE

The purpose of our ground test program is to provide the means to transition from the engineering development program through (1) the ground subsystem and (2) the weapon system and launch vehicle integration test activities; to the beginning of the system flight test program. A test program safety assessment is discussed in section 7.2. It is also important to identify the requirements for test facilities to ensure that laboratories, national laboratories in particular, are available when needed for tests. Facilities requirements are discussed in section 7.3. The flow diagram shown in figure 7.1-1 shows the hierarchy of tests which are to be accomplished throughout phases II, III, and IV of the project. The program outlined in this section is not yet firm. We intend for the ground test program to remain sufficiently flexible so that tests can be added, modified, or deleted as necessary until the program is finalized, hopefully in phase III.

The ground test phase will begin with the finalization of the detailed subsystem design. We will base the subsystem designs on the subsystem specifications and the detailed prototype designs which were developed and tested during the engineering development program. We will identify subsystem manufacturers early in the engineering development program so that, upon completion of the detailed subsystem designs, manufacturing of the subsystems can begin. We will also finalize test plans and procedures in parallel with the detailed design activity.

Subsystem tests will begin with the completion of the initial checkout and safety assessment for the individual subsystems. Each subsystem will be functionally tested, measured for electromagnetic compatibility, and then performance and reliability tested across a full spectrum of operational scenarios. Upon completion of subsystem tests, we will integrate the instrumentation and control subsystem together with launch vehicle and the weapon system simulators to verify key operational control and safety features. We will also integrate the reactor and instrumentation and control subsystems for both performance and integration tests. For other subsystem tests, interfaces will be simulated. A report will be prepared for each subsystem and integration test. We will evaluate test results and use the results to develop the production design of the MSNPS.

Figure 7.1-1 Feasibility, Development, and Ground Test Flow Diagram

7.2 SAFETY ASSESSMENT OF THE TEST PROGRAM

There are five major areas where safety is a paramount concern during ground engineering tests. The five major areas are: (1) nuclear safety, (2) hydrogen, (3) toxic materials, (4) high voltage, and (5) fragmentation of materials under test. Our safety program will deal with each of the five major areas of safety.

We plan to investigate the feasibility of conducting the reactor tests in the open test range at a chosen test site (for example, INEL or the Nevada Test Site). In figure 7.2-1, the radiological effects of a nuclear incident show that the worst case nuclear incident would be safe on the open range. For example, the dose to red bone marrow and lung tissue in the event of loss of coolant flow caused full cone meltdown and would be well within the allowable 5-REM annual dose for observers only 1/4 km away. The planned open range test will be carefully considered in the safety assessment. The cost savings compared to other approach, which require vacuum chambers or reactor confinement, is clear.

Hydrogen is a safety concern in both the cryogenic and the hot gaseous form. However, by testing on the open air range, the consequences of hydrogen incident is greatly diminished. We will document our procedures to ensure a safe test and an assessment on risk in the safety supplement.

High voltage, toxic materials, and fragmentation of materials under test are all concerns which can be easily dealt with in open or close area with appropriate use of recognized safety procedures. We will address each of these safety concerns whenever they are relevant to a specific test. We will document our proceedings to ensure a safe test in the Safety Supplement.

7.3 FACILITIES REQUIREMENTS

Our plan is to make use of national laboratories, contract, or team-member facilities whenever possible to maintain a cost-effective approach. Our goal is to use established facilities which are manned by experienced technicians and who are capable of performing independent safety assessments. Our projected facilities requirements list for the ground test program are as follows:

Reactor Subsystem/Instrumentation and Control Subsystem. We plan to explore the use of an open test range such as the Idaho National Engineering Laboratory or the Nevada Test Site, as well as potential DOD closed facilities.

Instrumentation and Control Subsystem. We plan to test the instrumentation and control subsystem (I&CS) at the Boeing Environmental Laboratories in Kent, Washington,

before the I&CS is integrated with the reactor, the launch vehicle simulator, and the weapon system simulator for integration tests and the reactor performance and reliability tests.

Turbine Subsystem. We will test turbine subsystem at the Rolls Royce, plc, Ansty facility in England.

Power Conversion Subsystem. We plan to test the power conversion subsystems at Allied-Signal's Los Angeles, California facility.

Power Conditioning Subsystem. We plan to test the power conditioning subsystem at the Boeing Environmental Laboratories in Kent, Washington.

Turbopump Subsystem. We plan to test the turbopump subsystem at the Boeing Environmental Laboratories in Kent, Washington.

Figure 7.2-1 Radiological Chart for MNSRP Reactor Operation

8.0 STATEMENT OF WORK (PHASE II)

The statement of work for phase II is presented in figure 8.0-1.

Work Breakdown Structure (WBS) Elements	Boeing Team									DOE*	
	BOEING	RRA	RRBV	UKAEA	Rkdn	AS	BDM	SEA	PNL	ORNL	
1.0 COMPLETE PRELIMINARY SAFETY ASSESSMENT	●						x				
1.1 Aerospace Safety Assessment	●						x				
1.2 Reactor Subsystem Safety Assessment		●					x				
1.3 Safety Assessment of Other Subsystems			x		x	x	●				
1.4 Safety Certification Plan	x						x	●			
2.0 RESOLVE RESEARCH AND TESTING OF FEASIBILITY ISSUES	●										
2.1 Reactor Issues		●									
2.1.1 Fuel Behavior During Power Ramps				●							
2.1.1.1 Mo/Re Fabrication Development				●							T
2.1.1.2 Enriched Specimen Fabrication				●						T	T
2.1.1.3 Fuel Ramp Test				●							
2.1.1.3.1 Uranium Carbide				●							
2.1.1.3.2 Uranium Nitride	●								T		
2.1.1.4 Post Irradiation Examination				●							
2.1.2 Fuel/Clad Integrity During Launch Vibration				●							
2.1.2.1 Validate Mo/Re Toughness				●							
2.1.2.2 Unfueled 19-pin Bundle Fabrication				●							
2.1.2.3 Vibration Test and Examination				●							
2.2 Other Subsystem Issues	●		x		x	x					
3.0 REFINE DESIGN CONCEPT	●										
3.1 Systems Engineering	●										
3.1.1 Requirements Allocation	●										
3.1.2 Platform Integration	●										
3.1.3 Availability	●										
3.1.4 Maintainability	●										
3.2 Reliability	●						x				
3.3 Develop Additional Mission Applications	●										
3.4 Reactor Concept		●		x						T	
3.4.1 Trade Studies and Design Refinement		●		x							
3.4.2 Fuel-Bundle Compaction testing		x		●							
3.4.2.1 Fuel Bundle		x		●							
3.4.2.2 Compaction test		x		●							
3.4.3 Corrosion and Embrittlement due to H2 Inside Pins				●							
3.4.3.1 Adapt Facility and Perform Safety Assessment				●							
3.4.3.2 Fabricate Specimens				●							
3.4.3.3 Tests and Examination				●							
3.4.3.4 Evaluate Possible MoH Formation				●							
3.4.4 Reactor Physics Experiments				●							
3.4.4.1 Design and Fabricate Demountable Pin Immersion Tests in DIMPLE				●							
3.4.4.2 Experiments and Analysis				●							
3.4.5 Reactor Control During Startup		●									
Boeing Team: BOEING The Boeing Company RRA Rolls Royce & Associates RRBV Rolls Royce Business Ventures Limited UKAEA United Kingdom Atomic Energy Authority Rkdn Rocketdyne Division of Rockwell International									Responsibility Codes: ● Technical Lead x Support T Technology Transfer		
*DOE Technology Transfer: PNL Pacific Northwest Laboratories ORNL Oak Ridge National Laboratory											

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Figure 8.0-1 Assignment of WBS Element Responsibility to Team Members (Sheet 1 of 2)

Work Breakdown Structure (WBS) Elements	Boeing Team										DOE*
	BOEING	RRR	RRBV	UKAEA	Rkdn	AS	BDM	SEA	PNL	ORNL	
3.5 Turbine Concept			●								
3.5.1 Trade Studies and Design Refinement			●								
3.5.2 Turbine Performance Tests			●								
3.5.2.1 Build Cascade Test Section			●								
3.5.2.2 Test and Analysis			●								
3.5.3 Electromagnetic Bearing Assessment			●								
3.6 Power Conversion Concept						●					
3.6.1 Trade Studies and Design Refinement						●					
3.6.2 Gas Bearing Feasibility						●					
3.7 Power Conditioning Concept					●						
3.7.1 Trade Studies and Design Refinement					●						
3.7.2 Operability with Cryogenic Cooling					●						
3.7.3 Dummy Load Development	●										
3.8 Development of Control and Instrumentation	●	x									
3.8.1 High Reliability ICS Development	●	x									
3.8.2 ICS Simulation	●	x									
3.9 Turbopump Subsystem					●						
3.10 Survivability Issues	x						●				T
4.0 REFINE LIFE CYCLE COSTS	●	x									
4.1 Estimate Acquisition Costs	●	x	x	x	x	x					T
4.2 Estimate Launch Costs	●										
4.3 Operation Costs and Maintenance	●										
4.4 Disposal Costs	●										
4.5 Risk Assessment	●										
5.0 DEFINE ENGINEERING DEVELOPMENT PROGRAM	●										
5.1 Reactor Subsystem Development Testing		●		x							
5.2 Turbine Subsystem Development Testing			●								
5.3 Power Conversion Subsystem Development Testing						●					
5.4 Power Conditioning Subsystem Development Testing					●						
5.5 Development Testing of Other Subsystems	●				x						
6.0 DEFINE GROUND ENGINEERING TEST PROGRAM	●										
6.1 Program Outline	●	x	x	x	x	x					T
6.2 Safety Assessment of Test Program	●	x	x	x			x				
6.3 Facility Requirements	●										T
7.0 PREPARE FINAL REPORT											
7.1 Volume I - Concept Design Report											
7.2 Volume II - Preliminary Reliability Analysis											
7.3 Volume III - Preliminary Safety Analysis											
Boeing Team: BOEING The Boeing Company RRA Rolls Royce & Associates RRBV Rolls Royce Business Ventures Limited UKAEA United Kingdom Atomic Energy Authority Rkdn Rocketdyne Division of Rockwell International										Responsibility Codes: ● Technical Lead x Support T Technology Transfer	
*DOE Technology Transfer: PNL Pacific Northwest Laboratories ORNL Oak Ridge National Laboratory											

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Figure 8.0-1 Assignment of WBS Element Responsibility to Team Members (Sheet 2 of 2)