FIRST INTERIM BRIEFING NUCLEAR SHUTTLE DEFINITION STUDY, PHASE III

PREPARED FOR NASA-MSFC UNDER CONTRACT NAS8-24714
DRL NO. MSFC-DRL-196, LINE ITEM NO. 2

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

MASTER

MDC G0671
2 SEPTEMBER 1970

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MCDONNELL DOUGLAS ASTRONAUTICS COMPANY - WEST

5301 Bolsa Avenue, Huntington Beach, CA 92647

PHASE III FIRST INTERIM BRIEFING REUSABLE NUCLEAR STAGE CONCEPTS

NUCLEAR SHUTTLE SYSTEM DEFINITION STUDY

CONTRACT NAS 8-24714

SEPTEMBER 2, 1970

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NUCLEAR SHUTTLE SYSTEM DEFINITION STUDY

During Phase I and Phase II of the Nuclear Flight System Definition Study, the contracted effort: (1) evaluated three classes of reusable nuclear shuttle concepts which could efficiently perform missions from low earth orbit to either lunar orbit or synchronous earth orbit, and perform planetary missions in the shuttle mode, (2) identified system element characteristics which have major impact on the economics of the nuclear shuttle operations, and (3) defined nuclear stage characteristics. At the conclusion of this phase, it was decided to proceed with a Phase A conceptual definition for two variations of the reusable nuclear shuttle: (1) a 33-ft-diameter load-carrying tank which could be launched to earth orbit by the Intermediate-21 (Int-21) launch vehicle, and (2) propellant modules which are delivered to low earth orbit within the cargo hold of the Space Shuttle.

The objectives of this study are to define the reusable nuclear stage concepts more completely and establish integrated test, manufacturing, facility and equipment, and supporting research and technology plans in order that a preliminary technical plan, a development schedule, and program costs can be identified for each of these concepts. A comparison between the two classes of RNS vehicles will be made at the conclusion of this study.

NUCLEAR SHUTTLE SYSTEM DEFINITION STUDY

11634

- OVERALL OBJECTIVE
 - ESTABLISH PHASE A CONCEPTUAL DEFINITION FOR TWO VERSIONS OF REUSABLE NUCLEAR SHUTTLE
 - 33 FT DIAMETER DERIVATIVE
 - EOS COMPATIBLE
- SPECIFIC OBJECTIVES
 - COMPLETE PRELIMINARY TECHNICAL DEFINITION OF THE RNS CONCEPTS
 - ESTABLISH INTEGRATED PROGRAM REQUIREMENTS FOR THE SELECTED RNS CONCEPTS
 - CONDUCT SPECIALIZED ANALYTICAL STUDIES
 - PROVIDE MISSION AND PERFORMANCE ANALYSES DATA
 - IDENTIFY PHYSICAL AND FUNCTIONAL INTERFACES WITH OTHER SYSTEM ELEMENTS

STUDY ORGANIZATION

The Nuclear Shuttle System Definition Study organization is shown here. The study tasks have been organized into two major areas of activities as indicated in the accompanying figure. Primary responsibilities for study tasks are noted.

STUDY ORGANIZATION

11635

DIRECTOR, ADVANCE SYSTEMS AND TECHNOLOGY-N.T. WEILER

BRIEFING SCHEDULE

The organization of the briefing and the speakers are as shown in the accompanying figure.

BRIEFING SCHEDULE

EXECUTIVE SUMMARY

S. GRONICH

MISSION PERFORMANCE AND DESIGN
REQUIREMENTS

R.G. RIEDESEL

ASSEMBLY, RESUPPLY AND
MAINTENANCE

R.J. HOLL

RNS OPERATIONS

K.P. JOHNSON

DYNAMIC ANALYSIS

R. VAN'T RIET

DESIGN SUMMARY AND FUTURE WORK

S. GRONICH

CONCEPTS EVALUATED

The Class 1 and 3 RNS concepts are shown in the accompanying figure. At the conclusion of Phase II, the Class 1 Hybrid, which consisted of a small propellant run tank and engine, delivered within the cargo hold of the Space Shuttle and a 33-ft-diameter propellant module delivered by the INT-21 launch vehicle, was adopted as a primary baseline. Specific design analyses of a standard configuration with a 10-degree conical aft dome would also be studied to a depth sufficient to define major technical problems. The aft angle for the Class 1 Hybrid configuration will also be a simulated 10-degree angle in order to optimize the shield/tank configuration of the overall system. The propellant tank for the Class 1 Hybrid is fabricated from 2014-T6 aluminum alloy and integrally stiffened cylindrical section. The small propellant run tank is of a monocoque construction, and the total capacity of both tanks is about 300,000 lb propellant. Fiber glass heat blocks and high performance insulation which can be compressed during launch are used to thermally protect the propellant tanks. A fiber glass bumper and foam are used for the basic meteoroid protection system.

RNS equipment was placed in the forward skirt area; a modular configuration of the subsystems was devised to provide for maintainability.

The planar configuration of the Class 3 system was selected at the conclusion of Phase II. An integral number of propellant modules was selected with a total capacity slightly greater than 300,000 lb. This represented a configuration with eight modules. The propellant modules would be of aluminum monocoque construction, and all of the other subsystems would be similar to that described for the Class 1 Hybrid concept. The Class 3 functional subsystems would be packaged in a command and control module. Scheduled maintenance in this concept would be achieved by removal of the entire command and control module.

CONCEPTS EVALUATED

STUDY SCHEDULE

The schedule identifies the tasks to be performed under the Nuclear Shuttle Study and indicates the current status of each of the individual efforts. The study is broken into three phases which consist of about 3-1/2 months each: (1) concept definition and evaluation, (2) system trade studies, and (3) program and system definition. As indicated on the schedule, the tasks initiated during the first phase were: mission capability analysis, operations requirements and systems definition of specific subsystems in order to perform preliminary configuration definition, and engine/stage interface definition. In addition, engineering trade studies such as engine/stage vehicle dynamics and engineering support activities (Task 9) were initiated during this phase of the study. Integrated program plan related tasks will be initiated during the second phase.

STUDY SCHEDULE

RNS STUDY PHASE III TASKS

The major outputs of the study phases indicated on the schedule are shown on the accompanying figure. Mission performance and capability of the RNS would be further updated for the specific concepts defined previously for four missions: (1) a lunar orbit-to-orbit shuttle, (2) a geosynchronous orbit-to-orbit shuttle, (3) unmanned planetary probes, and (4) manned planetary missions. Specific preliminary operational requirements, functional analyses, and a reliability improvement plan which impact the concepts definition and their evaluation would be generated during the first phase. Subsystem analyses and trade studies were also conducted in the phase. During the second phase alternative RNS systems and subsystem designs would be updated to reflect the operational requirements, reliability improvements, thermodynamic analyses, new radiation environments, and NERVA/RNS interface definition. The intent of the activity would be to present alternative RNS designs for final review at the end of 7 months. During this phase of the study, test, facility and GSE requirements, and manufacturing techniques would be identified.

In the last phase, a final RNS system description would be prepared, including hardware trees, design details, and system specifications. Complete functional analyses, reliability allocation sheets, safety contingency plans, and interface requirements would be identified. Lastly, the integrated program would be formulated and an overall program cost would be established.

RNS STUDY PHASE III TASKS

CONCEPT DEFINITION AND EVALUATION

- **MISSION PERFORMANCE AND TIMELINES**
- **RELIABILITY IMPROVEMENT PLAN**
- **OPERATIONS ANALYSIS**
- **SUBSYSTEM DESIGN REQUIREMENTS**

SYSTEM TRADE STUDIES

- **SUBSYSTEM DESIGN**
- **UPDATE FLIGHT SYSTEM DEFINITION**
- **INITIATE PROGRAM PLANS**

PROGRAM AND SYSTEM DEFINITION

- **FINALIZE REQUIREMENTS DEFINITION**
- **DOCUMENT BASELINE SYSTEM DEFINITIONS**
- **COMPLETE INTEGRATED PROGRAM PLANS**
- **PREPARE INTERFACE RECOMMENDATIONS**

TRADE STUDY SUMMARY

Twelve major trade studies were identified in order to perform the concept definition and evaluation previously delineated. The first study is associated with evaluating the reliability of the reusable nuclear stage and recommending design changes as required to eliminate single points of failure. The second study is to evaluate specific design criteria which would have a major impact upon the weight of the nuclear stage. The next two studies are associated with prelaunch and launch operations of the nuclear stage, followed by the next four which are associated with important orbital operations that affect subsystem design, vehicle configuration and propellant tank sizing. The next two deal with RNS operations which have a major impact upon the propellant control subsystem design, and the last two are associated with the vehicle dynamics.

The briefing, to a large extent, has been organized around these 12 major trade studies.

TRADE STUDY SUMMARY

- RELIABILITY IMPROVEMENT PLAN
- METEOROID PROTECTION DESIGN CRITERIA
- PRELAUNCH AND LAUNCH NUCLEAR SAFETY
- INTEGRAL LAUNCH OF CLASS 1 HYBRID
- RNS CLASS 3 ASSEMBLY
- RNS CLASS 1 HYBRID MAINTENANCE
- RNS CLASS 3 SUPPORT AND DEPLOYMENT
- PROPELLANT RESUPPLY SYSTEM
- PROPELLANT/PROPULSION MODULE OPERATION
- AFTERCOOLING SYSTEM
- CLASS 3 CONTROLLABILITY
- ENGINE/STAGE STRUCTURAL DYNAMICS

RELIABILITY IMPROVEMENT PLAN

The overall objectives of the reliability improvement trade study are to improve the reliability and safety of the RNS. This is accomplished by the elimination of as many single-point failures as possible, the reduction of the probability of occurrence of the remaining single-point failures to an acceptable level, and the elimination or reduction of credible multiple failures. The approach that will be used to accomplish this integrated reliability and safety effort has multiple stages, including: (1) reliability analyses investigating mission success with utilization of Failure Mode Effects and criticality Analyses (FMEA) and the identification of single failure items, (2) fault tree analyses to identify credible multiple failures, (3) contingency planning analyses to eliminate or reduce the probability of single failures and to identify monitoring and operational requirements, and (4) availability analysis to maximize the probability of the RNS availability to perform the required missions.

The current phase of this overall program is composed of: (1) a preliminary FMEA to tentatively identify the functional (operating) flight-critical failure modes (single failure items) and the structural item failures (such as leakage, burnthrough, burst, etc.), and (2) recommendations for design changes to eliminate the functional flight-critical failure modes in preparation for the formal FMEA. This phase of the overall program has been accomplished. The next phase will consist of the formal FMEA, the fault tree analysis, and the availability analysis, followed by the contingency planning analysis.

The subsystem design used for the initial preliminary effort was primarily for the design at the end of the Phase II effort, and was reported in the Final Report. The initial effort concentrated on the identification and elimination of the functional flight critical failure modes and reserved for future analysis the structural failure modes and nonmission (availability) failure modes.

The propellant management system prior to and after the design iteration is shown for the Class 1 Hybrid RNS. The modifications include:

- A. Addition of a third shutoff valve in the pressurization line of both modules to eliminate the fail to open failure mode.
- B. Addition of a second flow control valve in the fill system of the propulsion module and a second propellant isolation valve in the propellant module to

RELIABILITY IMPROVEMENT PLAN

OBJECTIVES:

- FORMULATE RELIABILITY IMPROVEMENT PLAN
- REVISE SUBSYSTEM DESIGNS

RESULTS:

- ALL NON-STRUCTURAL SINGLE FAILURE MODES HAVE BEEN ELIMINATED
- NEW STAGE RELIABILITIES:
 CLASS 1 HYBRID - .96
 CLASS 3 1-8-1 - .93

BLANK

RELIABILITY IMPROVEMENT PLAN (Cont)

eliminate the fail to open failure mode. The two propellant isolation valves in the propellant module and the two flow control valves in the propulsion module form a quad system to eliminate the failure to close failure mode.

- C. A quad valve system has been substituted for the single shutoff valve in the prepressurization system.

Additional investigations of auxiliary propulsion systems (APS) and astrionic subsystems led to completely redundant APS, and partially redundant electrical power, gyros, and digital computers and controllers. The resultant stage reliabilities associated with mission success are 0.96 and 0.93 for the Class 1 Hybrid and Class 3 systems.

METEOROID PROTECTION

During Phase II the meteoroid protection subsystem was designed to meet the reliability allocation imposed upon it. As part of the Phase III study, reliability allocations are being reassessed. The meteoroid protection subsystem will be optimized according to economic considerations as well as safety. For this briefing the results of such optimization will be shown for the RNS Class 3 vehicle.

Application of Phase III guidelines requires a revision of the meteoroid protection subsystem in order to accommodate the new meteoroid environment given in the NASA document shown in the accompanying illustration. Additional ground rules, building upon Phase II test and analysis results, were selected with the concurrence of the COR. The variation in meteoroid armor for this analysis is kept within the regime for which Phase II test results are applicable.

Four criteria were evaluated:

- A. Survival of all modules for full mission cycle.
- B. Survival of only active modules for full mission cycle.
- C. Survival of active modules away from earth orbit.
- D. Survival of active modules in transit.

Applying these factors, an optimum was found for meteoroid armor weight of about 8,400 lb. The resultant criteria are: 0.990 for B, 0.995 for C and 0.9975 for D.

METEOROID PROTECTION

OBJECTIVES:

ESTABLISH NEW DESIGN CRITERIA
ON BASIS OF ECONOMIC
OPTIMIZATION

CONCLUSIONS:

USE 0.990 SURVIVAL PROBABILITY
FOR MISSION SUCCESS
0.995 FOR MISSION SUCCESS/SAFETY
0.9975 FOR INTRANSIT AND
OPERATIONS
RECOMMEND 8,400 LB METEOROID
PROTECTION SYSTEM FOR CLASS 3

ASSEMBLY

The accompanying illustration lists the objectives for the orbital assembly trade study. The first objective is to define the vehicle configuration; that is, location of all modules in the vehicle. Following this, assembly operation will be analyzed in detail, concentrating particularly on the sequence of the module assembly and the support element requirements, such as number and capability of space tugs, rendezvous radar, etc. Finally, the RNS subsystems will be defined to meet the assembly operations requirements. Of major import here will be the rendezvous and docking subsystems, the clustering mechanisms, deployment and coupling of the fluid lines, and the flexible elements employed in the feed system such that they accommodate the assembly deployment and tolerances as well as the operational deflections caused by pressure and temperature changes during the mission.

Two planar arrays were evaluated. In the first array, columnar sets of outboard modules are assembled to the cluster. In the latter, only individual modules are assembled to the vehicle. The former method results in five module types, requires column subassembly, maximum assembly and operational tolerances and deflections, and minimum inboard-outboard connections. Although the latter avoids some of these problems and has only three module types, it requires self-driven rotation assembly modes due to lack of space between outboard modules.

The cruciform cluster seems to combine the advantages of both concepts, requiring three module types and two tug assembly operations, and resulting in minimum tolerances and deflections.

ASSEMBLY

CLASS 3

OBJECTIVES:

- SELECT VEHICLE CONFIGURATION
- SURVEY ASSEMBLY OPERATIONS
- DEFINE FLUID LINE HOOK UPS AND STRUCTURAL SUPPORT

CONCLUSIONS:

- RECOMMEND CRUCIFORM CONFIGURATION
- USE 2 TUGS FOR ASSEMBLY

MAINTENANCE LEVEL

The initial maintainability trade study focused on the definition of the maintenance level for the 33-ft diameter RNS. The objective of this trade study was to select a strategy for orbital maintenance and replenishment and determine the level of replacement or repair that would be utilized in maintaining the RNS in earth orbit.

The candidates fall into three categories:

- A. Multiple replacement modules of various configurations derived from the MDAC Phase II RNS study.
- B. A single command and control module analogous to the baseline selected for the RNS Class 3 in the Phase II study.
- C. In-situ maintenance using the capabilities of man in orbit for replacements, and repair. Consistent with this concept, in-place replenishment in either an automatic (unmanned) or manually assisted context is considered.

Within each of these categories multiple candidates have been identified. This trade study first selected the most attractive candidate in each category based on minimum complexity, weight, reliability, and handling requirements, both in orbit and on the ground. The selected candidates for each category were then compared and a selection made based on technical feasibility, complexity of operations, support requirements, weight, and effectiveness. Effectiveness includes the portion of RNS unreliability maintained, reliability of accomplishing repair and replenishment, and the impact on RNS reliability.

The single command and control unit is selected on the basis of weight, highest reliability of operations, and lowest impact on RNS reliability. Weight was 459 lb compared to 505 lb and 714 lb for modular and in-situ repair, respectively. With this concept there would be a minimum number of module replacements, no fluid line connections and disconnections, and least complications which would be associated with EVA.

MAINTENANCE LEVEL

CLASS 1 HYBRID

14931

OBJECTIVES:

- COMPARE CANDIDATE CONFIGURATIONS
MULTIPLE REPLACEMENT MODULES
SINGLE COMMAND AND CONTROL
MODULE
IN SITU REPAIR
- ASSESS OPERATIONS, SUPPORT AND
RELIABILITY

CONCLUSIONS:

- RECOMMEND SINGLE COMMAND AND
CONTROL UNIT

PROPELLANT PROPULSION MODULE OPERATION AND CONTROL

The objectives of the propellant/propulsion module control trade study are identified in the accompanying illustration. In order to select the controller/sensor concept, seven alternative control/sensor systems were evaluated for five system requirements: (1) startup and shutdown ramps, (2) refill run tank after startup ramp, (3) adjustment to acceleration head changes, (4) response to NERVA emergency mode, and (5) control fluctuations at steady state. Only control concept No. 1, shown schematically, displayed a capability to operate during transient and steady-state conditions, and had capacity for independent run tank operation, independent operation of tank pressures, and simplified orbital checkout and ground simulation tests. On this basis, it was selected as the baseline configuration, and further studies were performed to establish effects of the equipment bands and responses on the operation of the system and also to establish the operating penalties for the system.

During startup, the engine run tank is depleted as the larger propellant module is pressurized and would therefore have to be refilled to minimize radiation levels at the top of the run tank and be ready for the next startup. In addition, the liquid operating level would be determined by the radiation environment at the top of the small run tank. Utilizing these constraints, it was determined that a controller with a plus or minus 40 percent on the flow range would be adequate to refill the tank. The system displays excellent self-regulating characteristics. Also shown in the figure is the slug of liquid which enters the run tank due to an impedance change. The effect is seen to be damped out by 10 seconds for ullage volumes ranging from full to nearly empty.

The evaluation of the pressure schedule for the system indicates the desire to minimize the control bands. This would be achieved by employing accurate pressure sensors to operate bang-bang controllers for pressurization and venting. Strain gage transducers were identified as a leading candidate for this capability. Optical point level liquid sensors would provide compatible accuracy in the control of the liquid level in the propulsion module. Regulation of the flow rate within the respective module pressure bands indicated the need for a buffer pressure drop between the tanks. With accurate system hardware, this could be reduced to the level of the feed system friction losses less acceleration head.

PROPELLANT – PROPULSION MODULE OPERATION AND CONTROL

OBJECTIVES:

- DEFINE SENSITIVITIES
- SELECT CONTROLLER/SENSOR CONCEPT
- ESTABLISH EQUIPMENT BANDS AND RESPONSES
- ESTABLISH OPERATING PENALTIES

CONCLUSIONS:

- SELECT VALVE CONTROLLER AND
- LIQUID LEVEL SENSOR
- USE ACCURATE STRAIN GAGE
- PRESSURE SENSORS
- SYSTEM DISPLAYS SELF REGULATING
- CHARACTERISTICS

AFTERCOOLING SYSTEM CONCEPT

Because of the long times and large number of pulses involved in providing cooldown during a mission, the requirement to provide propellant to NERVA at specified conditions during aftercooling can impose severe penalties for propellant settling and/or pressurization with a major impact on the RNS design. Therefore, a trade study was initiated to determine the most effective means for providing LH₂ to NERVA at the required conditions. The previous engine requirement for LH₂ pressurized to 30 psia with 0 percent vapor during cooldown was applied as a baseline. The trade study has entailed definition and evaluation of a variety of aftercooling system concepts to fulfill this requirement. Also, the sensitivity to NERVA requirements was evaluated, considering both the radiated power level and the aftercooling operating pressure, to provide greater visibility for selection of aftercooling system concepts and to identify desirable improvements in the NERVA requirements.

Eight aftercooling concepts were evaluated. Three classes of concepts are distinguished by the techniques used for propellant control. A weight breakdown for the different aftercooling system concepts is shown in this table. The hardware breakdown is differentiated between the pressurization system weight penalty and fixed weight penalties, such as screens, electrodes, etc. The continuous settling mode is heavy because of the long aftercooling duration. However the settling penalty is reduced due to a lower Bond number (10) being acceptable for already settled propellant. Rotation or DEP with ullage control and the burp tank concepts are the most favorable. The system weight penalties for the other concepts are similar and excessive.

The effect of increasing the NERVA radiated power level to greater than 25 kw would decrease the penalty for the rotation concept to 1,000 lb. If only saturated propellant conditions were required, a surface tension pulse basket could be used with a minimum weight assessment of less than 100 lb. Therefore, applying the recommended changes in NERVA groundrules results in a major system weight savings and the least complicated system.

AFTERCOOLING SYSTEM CONCEPT

OBJECTIVES:

- DEFINE CANDIDATE AFTERCOOLING CONCEPTS
- SELECT SYSTEM CONCEPTS ON BASIS OF CURRENT ENGINE REQUIREMENTS
- RECOMMEND NEW DESIGN REQUIREMENTS

CONCLUSIONS

- CARRY STAGE ROTATION AND BURP TANK CONCEPTS TO FURTHER DEFINITION
- INCREASE ENGINE RADIATION LEVEL AND DECREASE A/C PRESSURE REQUIREMENTS
- SURFACE TENSION SCREEN PREFERRED FOR REDUCED PRESSURE REQUIREMENT

WEIGHT BREAKDOWN

LUNAR SHUTTLE MISSION
NERVA PASSIVE COOLING < 5 KW

	SETTLING PROPELLANT (LB)	PRESSURANT (LB)	HARDWARE (LB)	TOTAL (LB)
1 PROPELLANT SETTLING				
● CONTINUOUS ($B_0 = 10$)	3,560	790	2,370	6,720
● PULSED	5,143	1,945	5,835	12,923
● HYBRID	4,752	1,592	4,774	11,118
● ROTATION	128	790	2,370	3,288
2 SURFACE TENSION				
● BURP TANK	475		3,015	3,490
● PULSE BASKET		1,945	5,909	7,854
3 DIELECTROPHORESIS				
● ULLAGE CONTROL		790	2,720	3,510
● PULSE BASKET		1,945	6,185	8,130

RNS CLASS 3 STABILITY

Analyses have been conducted to establish the structural stability and controllability of candidate RNS Class 3 modular configurations. These configurations are based on a 15-ft-diameter by 60-ft-long EOS cargo hold. With this high length-to-diameter ratio for the basic module, an assembled vehicle consisting of many modules could be highly flexible. A tandem assembly of modules would be more flexible than a clustered array. However, it would be desirable for assembly operations and fluid line hookups. Configurations which were considered include: (1) the baseline cruciform cluster, (2) planar array, and (3) tandem array. All these configurations were found to have good rigid body control characteristics. However, vehicle flexibility could be a problem, especially for the tandem configuration. Flexibility could adversely affect the vehicle through (1) interaction with the powered flight control system and (2) interaction of the axial acceleration with the structure.

To assess these potential problems, studies were performed in areas of: (1) powered flight attitude control system stability and (2) axial acceleration interaction with structural flexibility.

Powered flight control system stability margins obtained from the (open loop actuator command) frequency responses study are shown in the accompanying illustration. These margins demonstrate the stability of the control system. These margins are for the cruciform cluster Class 3 RNS for the loading conditions shown. A conventional controller similar to that of the Saturn S-IVB was used in obtaining the system responses and attendant stability margins. Necessary system compensation was provided using conventional shaping networks in the attitude feedbacks.

To assess the structural stability margin of the Class 3 RNS, a worst case approach was employed. Because the tandem configuration would be more susceptible to structural instability it was studied. It was shown that the NERVA thrust level (75,000 lbf) could be tripled before structural instability would be approached. Extrapolating this result to the shorter, less flexible clustered arrays would indicate an even greater margin for those configurations.

RNS CLASS 3 STABILITY SUMMARY

OBJECTIVES:

VERIFY

- CONTROLLABILITY
- STRUCTURAL STABILITY
DURING NERVA THRUSTING

CONCLUSIONS :

- ALL CONFIGURATIONS ARE
CONTROLLABLE WITH ADEQUATE
MARGINS USING A CONVENTIONAL
CONTROLLER
- ALL CONFIGURATIONS ARE
STRUCTURALLY STABLE AT
THE NERVA THRUST LEVEL

CONTROLLABILITY MARGINS (CRUCIFORM)

CONDITION	PHASE (DEG)	GAIN (%)	BENDING LOOP (%)
FULL	35.0	12.6	22.0
HALF FULL	38.0	15.8	17.8
EMPTY	30.0	7.9	31.6

THRUST LEVEL MARGIN

- FACTOR OF THREE MINIMUM

BASELINE SYSTEM DESIGN CHANGES - CLASS 1 HYBRID

The baseline system design changes from the Phase II reference designs are indicated on the accompanying chart for the Class 1 Hybrid. Three alternative maintenance concepts were studied. A single command and control module which would be removed after each mission for replenishment and repair was selected over the previous design, which used modular construction and replaced only those elements which had to have expendables replenished or repaired.

An evaluation of the economic impact of meteoroid protection requirements led to the development of a set of new criteria which are dependent upon achieving different reliability goals for different mission strategies, i. e., mission success, crew safety, and system reliability. On the basis of the analyses conducted, lesser design criteria were found to be more economical than those originally allocated. The evaluation of the propellant/propulsion module control characteristics led to the inclusion of a controlling valve between the modules and a conversion from a bang-bang system to a strain gage/bang-bang in order to maintain proper pressure tolerances without excessive weight penalties.

More changes to functional systems were incorporated as a result of the reliability improvement program. These included adding parallel feed valves, fill valves and propellant control valves, a third set of gyros, 50 percent redundancy in battery capacity, 100 percent redundancy power for flight critical items and other changes documented elsewhere. These changes were incorporated to remove single flight critical failure modes of functional elements from the stage design.

BASELINE SYSTEM DESIGN CHANGES

CLASS 1 HYBRID

SUBSYSTEM FEATURE

- **COMMAND AND CONTROL MODULE**
- **METEOROID PROTECTION**
- **PROPELLANT/PROPULSION
MODULE CONTROL**
- **FUNCTIONAL**

CHANGE

- **SINGLE MAINTENANCE UNIT**
- **ADJUST TO NEW CRITERIA**
- **ADD CONTROLLER, USE
STRAIN GAGE/BANG-BANG**
- **ADD PARALLEL VALVING AND
ASTRIONIC SUBSYSTEMS AS
SPECIFIED BY RELIABILITY PLAN**

BASELINE SYSTEM DESIGN CHANGES – CLASS 3

A major activity of this study was to evaluate assembly techniques and to evaluate the impact this would have upon the configuration of the multimodule system. Because it was possible to utilize two tugs without interference during assembly of outboard modules, and minimize fluid line tolerances and deflections, the cruciform configuration was selected. Other techniques which utilized a columnar assembly approach of outboard modules were rejected on the basis of tolerances built up on the system, as well as the alternative individual modules planar approach which required self-actuating rotation of the modules. In addition, the detailed evaluation of the assembly and feed systems led to modifications in fluid line deployment. In the new concept, a sump is used at the bottom of the tank and off-center plumbing is used to enter the top of the next tank in line. The description of the flexible elements to absorb relative motion between module elements and docking and clustering mechanisms was further refined in this phase of the study. The meteoroid protection, propellant/propulsion module control, and functional subsystem changes were similar to those delineated on the previous illustration of the Class I Hybrid.

BASELINE SYSTEM DESIGN CHANGES

CLASS 3

SUBSYSTEM FEATURE	CHANGE
<ul style="list-style-type: none">• CONFIGURATION• ASSEMBLY AND FEED	<ul style="list-style-type: none">• CRUCIFORM• FLUID LINE DEPLOYMENT, FLEXIBLE ELEMENTS, DOCKING AND CLUSTERING MECHANISMS
<ul style="list-style-type: none">• METEOROID PROTECTION• PROPELLANT/PROPULSION MODULE CONTROL• FUNCTIONAL	<ul style="list-style-type: none">• ADJUST TO NEW CRITERIA• ADD CONTROLLER, USE BANG-BANG• ADD PARALLEL VALVING AND ASTRIONIC SUBSYSTEMS AS SPECIFIED BY RELIABILITY PLAN

WEIGHT STATEMENT - CLASS 1 HYBRID

The weight statement for the Class 1 Hybrid is shown on the accompanying illustration. The weight differences from the previous baseline systems defined in Phase II are due primarily to the addition of a new command and control assembly and its associated packaging arrangement, and to the decrease in the meteoroid protection criteria and the additional subsystems which are now required to remove the single points of failure within the design.

WEIGHT STATEMENT (LB)

14867

CLASS 1 HYBRID

	MODULES			
	PROPELLANT	PROPULSION	CONTROL AND ASS'Y	TOTAL
STRUCTURE	24,400	1,200	390	25,990
METEOROID/THERMAL PROTECTION	7,110	660		7,770
DOCKING/CLUSTERING	160	200	280	640
MAIN PROPULSION	515	30,745	35	31,295
AUXILIARY PROPULSION		160	850	1,010
ASTRIONICS	185	75	2,935	3,195
<hr/>				
SUBTOTAL	32,370	33,040	4,490	69,900
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RCS PROPELLANT	0	70	1,780	1,850
RESIDUAL PROPELLANT	9,320	420		9,740
RESERVE				1,700
<hr/>				
TOTAL	41,690	33,530	6,270	83,190
<hr/>				
IMPULSE PROPELLANT				288,560
<hr/>				
λ'				.78

WEIGHT STATEMENT – CLASS 3

The weight statement for the Class 3 configuration is shown on the accompanying illustration. There is a significant decrease in the weight of this configuration as compared to the Phase II result due to the change in the meteoroid protection criteria. Other design changes which were delineated previously were reflected in the weight statement for this configuration. It is interesting to note that the overall weight of the Class 3 system is now about the same as that for the Class 1 Hybrid when the new meteoroid protection design criteria are used.

WEIGHT STATEMENT (LB)

15192

CLASS 3

MODULES

	PROPELLANT	PROPULSION	CONTROL AND ASS'Y	TOTAL
STRUCTURE	3,580	880	330	29,850
METEOROID/THERMAL PROTECTION	1,000	400	0	8,400
DOCKING/CLUSTERING	360	200	280	3,360
MAIN PROPULSION	410	28,155	35	31,470
AUXILIARY PROPULSION		160	850	1,010
ASTRIONICS	55	75	2,935	3,450
<hr/> SUBTOTAL	<hr/> 5,405	<hr/> 29,870	<hr/> 4,430	<hr/> 77,540
RCS PROPELLANT	10	70	1,290	1,360
RESIDUAL PROPELLANT RESERVE	260	230	0	2,310
<hr/> TOTAL	<hr/> 5,675	<hr/> 30,170	<hr/> 5,720	<hr/> 82,910
IMPULSE PROPELLANT				297,020
λ'				.78

LUNAR SHUTTLE PERFORMANCE

Performance of the Class 1 Hybrid RNS is shown for both single and triple-impulse lunar departure and arrival operating modes. The single-impulse departure and arrival (four-burn) is representative of the coplanar mission model, repeating once each 54.6 days. This profile is used for operations and cost analyses. The three-impulse departure and arrival case (six-burn) reflects a design condition. Performance for this case assumes that the NERVA idle mode is applied for outbound and inbound mid-course maneuvers, as well as for the 30-degree plane change requirement during lunar approach and lunar departure. Thus, only six full thrust engine operations are required. As is shown elsewhere, this is not optimum from a performance standpoint. NERVA performance is based on a steady-state specific impulse value of 825 sec and a thrust level of 75,000 lb. The actual time-averaged level of specific impulse varies as the duration of the burn due to the overall degradation in performance associated with the thrust buildup and shutdown of a given engine operation. These values, as well as the ideal mission velocity requirements, are summarized below.

Maneuver	Six-Burn		Four-Burn	
	ΔV (fps)	Isp (sec)	ΔV (fps)	Isp (sec)
Leave Earth	10,372	818	10,372	818.2
Midcourse	50	450	50	450
Arrive Moon	3,150	--	2,760	808
1	(929)	788	--	-
2 (idle mode)	(390)	450	--	-
3	(1,831)	800.5	--	-
Leave Moon	3,590	--	3,200	801
1	(1,831)	790	--	-
2 (idle mode)	(390)	450	--	-
3	(1,369)	777	--	-
Midcourse	50	450	50	450
Arrive Earth	10,454	811.8	10,454	811.8
Totals	27,666	--	26,886	-

The performance data shown are conservative in the sense that impulse derived due to the aftercooling is not credited toward the overall mission velocity requirement. Return payload (PL_R) is defined as the total payload carried above the RNS on the transearth leg of the mission while, correspondingly, delivered payload (PL_D) is defined as the total payload carried above the RNS on the translunar leg of the mission.

LUNAR-SHUTTLE PERFORMANCE

14836

CLASS 1 HYBRID RNS

GEOSYNCHRONOUS SHUTTLE PERFORMANCE

Mission performance for the geosynchronous mission is shown in the accompanying illustration based on a minimum velocity sum for the two primary transfer maneuvers between the low 260-nmi (31.5-degree inclination) orbit, and the geosynchronous equatorial orbit. NERVA performance is based on a steady-state specific impulse value of 825 sec at a thrust level of 75,000 lb. Maneuver velocity requirements and the time-averaged level of specific impulse for each of the mission maneuvers is as follows:

Maneuver	ΔV (fps)	Isp (sec)
Lv 260-nmi*	7,885	817.2
Midcourse	50	450
Arv Geosynchronous**	6,014	814.5
Lv Geosynchronous**	6,014	809.3
Midcourse	50	450
Arv 260-nmi*	7,885	809
Total	27,898	--

*2.4-degree plane change

**29.1-degree plane change

Return payload is defined as the total payload above the RNS on the descent leg of the mission, while delivered payload is defined as the total payload forward of the RNS on the ascent leg of the mission. The performance data shown are conservative in the sense that impulse derived from the aftercooling is not credited toward the overall mission velocity requirement.

GEOSYNCHRONOUS SHUTTLE PERFORMANCE

CLASS 1 HYBRID RNS

PLANETARY MISSION PERFORMANCE 1986 OPPOSITION (OUTBOUND VENUS SWINGBY MODE)

The accompanying illustration shows the heliocentric profile for the 1986 outbound Venus swingby manned planetary mission. Mission maneuver ideal velocity and propellant requirements are also shown. Mission velocity and phase time requirements for manned planetary missions were extracted from MSFC memorandum PD-DO-SI-70-8, "Parking Orbit Selection to Support Planetary Missions," by A. C. Young, dated February 16, 1970. The launch date (24 May 1985), 640-day total trip time, and 24 December 1986 earth arrival date are based on the optimum earth departure date. The profile used in this reference memorandum is optimum in the sense that initial mass in earth orbit is minimized when it is based on an orbital launch vehicle configured for retrieval of the two leave- earth stages. Propellant requirements and the velocities shown are the most severe at each phase associated with a 30-day earth launch window, based on a fixed Mars arrival date. The propellant requirements include a three-quarter of one percent equivalent velocity reserve. Midcourse and Mars orbit trim propulsion maneuvers are assumed to be performed with the NERVA operating in the idle mode. Weight characteristics (lb) of the mission spacecraft are as follows:

Planetary Mission Module	Mars Excursion Module	Mars Probes	Venus Probes	MEM/Probe Compartment	Total
150,000	100,000	30,000	6,000	5,500	291,500

All spacecraft weight elements are assumed jettisoned in Mars orbit with the exception of the planetary mission module, which is returned to earth orbit, and the 6,000-lb Venus probe complement, which is jettisoned during Venus passage. The mission module weight is assumed to diminish at the rate of 13 lb per day, reflecting jettisonable expendable items. Earth departure is from a 260-nmi circular orbit. Mars capture occurs in a 270-nmi (periapsis altitude) by 9,700-nmi (apoapsis altitude) elliptical orbit, and earth return occurs in an elliptical orbit with a perigee altitude of 270 nmi, and an apogee altitude of 38,420 nmi. The leave- earth maneuver requires approximately four propellant modules in addition to about 150,000 lb of propellant from the planetary vehicle. Two outboard propellant modules are jettisoned at hyperbolic speeds during the approach maneuver to Mars, thereby not presenting a disposal problem. The remaining mission maneuvers are performed by a single planetary nuclear propulsion system. If retrieval of the two leave-earth propulsion modules is required, the number of propellant modules needed for trans-Mars injection is increased from four to five.

$$P_{1/2} = (2 \times 10^5) \times 10^6 / (2.2 + 3 + 2(2.2)) \times 10^6 \cdot 10^5 / 3 = .05 \text{ Lb} \cdot \text{sec}$$

PLANETARY MISSION PERFORMANCE

1986 OPPOSITION (OUTBOUND VENUS SWINGBY MODE)

MANEUVER	ΔV (1000 FPS)	W_p (1000 LB)
LV-EARTH	14.08	1222*
MIDCOURSE	0.50	39
ARV-MARS	11.05	431
ORBIT TRIM	0.15	6
LV-MARS	6.88	113
MIDCOURSE	0.50	11
ARV-EARTH	8.95	101
TOTAL	42.11	1923*

*FOR RETRIEVAL OF LV-EARTH STAGES, PROPELLANT = 1,493,000 LB, TOTAL IS 2,194,000 LB

PLANETARY MISSION PERFORMANCE - 1990 CONJUNCTION

A heliocentric flight profile is shown for the 1990 conjunction manned planetary mission opportunity, indicating trajectory phase times, planetary nuclear propulsion system propellant requirements, and ideal mission velocity requirements. The launch date (12 August 1990), 1005 - day total trip time, and 13 May 1993 earth arrival date, are based on the optimum earth departure date. The profile is optimum in the sense that initial mass in earth orbit is minimized based on a propulsion vehicle configured for retrieval of the leave- earth Stages. Propellant requirements and the velocities shown are the most severe at each phase associated with a 30-day launch window. Weight characteristics (lb) of the mission spacecraft are as follows:

Planetary Mission Module	2 Mars Excursion Modules	Probes	MEM/Probe Compartment	Total
170,000	200,000	30,000	11,500	411,500

The planetary mission module is assumed carried throughout the entire mission through return to earth orbit, while all other items are assumed jettisoned while in Mars orbit. The planetary mission module weight is assumed to diminish at the rate of 13 lb per day which reflects jettisoned expendables. Earth departure is from a 260-nmi circular orbit. The 12-hour-period Mars orbit has a periapsis altitude of 270 nmi and an apoapsis altitude of 9,700 nmi, and the earth-arrival orbit (24-hr period) has a perigee altitude of 270 nmi, and an apogee altitude of 38,420 nmi.

The leave- earth maneuver requires expenditure of two nuclear stages in addition to approximately 500,000 lb of propellant out of the planetary vehicle stages. Two outboard propellant modules are assumed jettisoned during the Mars arrival maneuver at hyperbolic speeds relative to Mars, thereby presenting no disposal problem. The single remaining propulsion module completes all subsequent mission maneuvers through earth-orbit capture. Leave- earth propellant requirements are increased from approximately 876,000 lb to 949,000 lb by adding the requirement for return to low circular orbit of the two leave- earth stages. Of this 73,000-lb increase, approximately 39,000 lb is used for the actual return maneuver. The remainder is the penalty imposed during trans-Mars injection for carrying this added propellant.

PLANETARY MISSION PERFORMANCE

1990 CONJUNCTION

MANEUVER	ΔV (1000 FPS)	W_P (1000 LB)
LV-EARTH	13.72	876*
MIDCOURSE	0.50	31
ARV-MARS	4.71	151
ORBIT TRIM	0.15	7
LV-MARS	6.55	98
MIDCOURSE	0.50	10
ARV-EARTH	5.42	59
TOTAL	31.55	1,232*

*FOR RETRIEVAL OF LV-EARTH
STAGES, PROPELLANT = 949,000 LB,
TOTAL IS 1,305,000 LB

ARV-MARS (12-HR ORBIT)

ORBIT TRIM

ARV-EARTH

LV-EARTH
(8-12-90) (260-NMI)

ALTERNATE LUNAR PLANE CHANGE OPERATING MODES

The accompanying illustration summarizes the impact on the delivered payload derived from altering the NERVA engine operating mode when performing the incoming and outgoing 30-deg plane change maneuvers. This maneuver requirement is associated with the design three-impulse lunar arrival and departure mission profile. The powered idle mode (zero payload input) was used as the reference case for this trade study. As is seen, each of the alternate modes considered result in improved performance. Since the full-thrust case did not use the aftercooling for useful thrust, it is conservative. Desirability of a given mode would have to be weighed against its resultant impact on mission success probabilities and stage reliability. The reference RNS configuration used for the analysis is the Class 1 Hybrid, 300,000-lb propellant capacity shuttle.

ALTERNATE LUNAR PLANE CHANGE OPERATING MODES

ALTERNATE NERVA OPERATING MODES	*THRUST (LB)	*ISP (SEC)	** ΔPL_D (LB)
1 POWERED IDLE	10,000	450	0
2 EMERGENCY	30,000	500	+2,200
3 IDLE	1,000	510	+2,600
4 FULL THRUST	75,000	825	+8,300

- * STEADY-STATE LEVELS
 ** IMPACT ON PAYLOAD DELIVERY
 CAPABILITY TO LUNAR ORBIT
- PLANE CHANGE AT LUNAR ARRIVAL
AND LUNAR DEPARTURE
 - RNS PROP. CAPACITY - 300,000 LB

LUNAR SHUTTLE MISSION TIMELINE - EARTH ORBIT TURNAROUND

The accompanying illustration identifies major activities occurring between earth orbit insertion (EOI) following a lunar shuttle mission and subsequent departure on another mission. The 29-day total turnaround time is based on the assumption that the larger of two coplanar round-trip mission opportunities (of the 54.6-day cycle) is used. Due to the time requirements of the various operations, primarily propellant resupply of the RNS, it would not be possible to take advantage of the shorter (4.5 day) lunar orbit stay of the two opportunities as well, due to the small period of time (3 days) allowed following earth return to prepare for the next mission opportunity. It was assumed for this timeline that no operations are conducted until cooldown is completed following the EOI maneuver. The major factor in determining the total duration required to turn around the RNS is the assumed launch rate of the Space Shuttle of one launch per two days. A total of twelve Space Shuttle launches is required to complete the required activities; eight launches to fuel the RNS, one to launch the command and control module, and three for payload. In order to facilitate efficient use of each of the shuttle launches, the lunar mission crew is assumed launched with the command and control module. The command and control module is assumed replaced following loading of the liquid hydrogen in order to minimize the required stay time of the mission crew in earth orbit. The 14 days for LH₂ transfer can also be used for other operations since only 3 to 5 hours per two days are required for orbital tanking. A total of 24 days is required for turnaround, leaving a five-day contingency.

LUNAR-SHUTTLE MISSION TIMELINE

EARTH ORBIT TURNAROUND

LUNAR SHUTTLE MISSION TIMELINE - LUNAR ORBIT OPERATIONS

The accompanying illustration identifies major mission operations from, and including, translunar injection through earth orbit injection of the RNS for the lunar shuttle mission, highlighting lunar orbit operations. Main stage propellant requirements (excluding after-cooling) are shown for each of the main mission maneuvers. The profile is based on a four-burn coplanar operational mode which repeats every 54.6 days. The propellant requirements are based upon using a 300,000-lb capacity Class 1 Hybrid RNS.

No lunar orbit operations are assumed to be conducted until completion of cooldown following the lunar orbit injection (LOI) maneuver. Thus, the timeline could be compressed if necessary by accomplishing rendezvous and docking between pulses once the no-pulse duration becomes sufficiently large. For example, a 1-hour spacing between pulses occurs 8 hours following lunar orbit injection, and a 2-hour spacing is available 13 hours following LOI. The time allowed for payload deployment and exchange (0.5 hours) is considered representative in the case that the cargo delivered is palletized, requiring no EVA. A substantial contingency is seen even for the 4.5 day lunar orbit stay, which is the shorter of the two coplanar mission opportunities occurring during the 54.6 day cycle, thus giving confidence that both opportunities are available for missions.

LUNAR-SHUTTLE MISSION TIMELINE

NUCLEAR SHUTTLE REFERENCE PROGRAM MISSION MODEL

The program mission model shown in the accompanying illustration was supplied by MSFC for use in performing the RNS Phase III Study. It provides the basis for the operations analysis and program development requirements tasks, and is based on an initial operational capability (IOC) date of 1980. The crew rotation requirement for the geosynchronous orbit station is once each 90 days, or four flights per year minimum. The tour of duty for the lunar vicinity (orbit or surface base) was assumed to be 6 months, with the assumption that personnel may be rotated between the surface base and the orbit station to provide all personnel with work in a gravity environment for some portion of their tour of duty.

NUCLEAR SHUTTLE REFERENCE PROGRAM MISSION MODEL

	YR	'80	'81	'82	'83	'84	'85	'86	'87	'88	'89
LUNAR	LUNAR ORBIT STATION										
	6 MEN / 12 MEN										
	3	2	2	2	2	3	3	3	3	3	
	LUNAR SURFACE BASE										
	6 MEN / 12 MEN / 18 MEN / 24 MEN										
	5	6	6	9	12	12	12	12	12	12	
EARTH ORBITAL	GEOSYNCHRONOUS ORBIT STATION										
	6 MEN / 12 MEN										
	2	4	4	4	4	4	4	4	4	4	
PLANETARY	UNMANNED PLANETARY										
	2	2	-	2	1	-	-	-	-	-	
	MANNED PLANETARY										
									8	-	
TOTAL RNS FLIGHTS		5	9	10	14	16	19	19	19	27	19

RNS UTILIZATION SCHEDULE

A program timeline of RNS operations is shown here for the first half of calendar year 1986, with the type and number of missions based upon the MSFC reference program mission model provided for use in the Phase III Nuclear Shuttle System Definition Study. The mission timelines for the lunar shuttle consider operation in a coplanar transfer mode, which provides two opportunities every 54.6 days. RNS No. 1 is shown to operate on a schedule which utilizes the opportunity with the longer (18 days) lunar stay, while RNS No. 2 operates on a schedule compatible with the short (4.5 day) lunar stay. A preliminary lunar orbit operations timeline analysis indicates that a turnaround can be performed in lunar orbit in 4.5 days with contingency allowable, so operations with the short lunar stay should not prove to be a problem.

RNS No. 1 and RNS No. 2 are envisioned here to be operating to and from a 260-nmi circular earth orbit inclined at 31.5 degrees, while RNS No. 3 operates from an identical orbit with the line of nodes rotated 90 degrees from the other operational orbit for the case shown. This geometry of earth orbit and lunar orbit also provides two coplanar transfer opportunities every 54.6 days, with the effect of nodal point movement being a displacement of the cycle in time, relative to the other orbit. RNS No. 3 is used to perform two geosynchronous shuttle missions and one lunar shuttle mission. The stay time allocated for turnaround operations in geosynchronous orbit was 6 days; however, a timeline analysis would very probably indicate that less time is required.

The use of a second earth orbit does provide additional flexibility for RNS operations, although it will impose a requirement for an additional set of orbital support systems, such as a space tug or propellant storage facility, if required. The most important aspect of the operational phasing of RNS systems is the staggering of earth turnaround activities to minimize the time of overlap when space shuttles will be required to service more than one RNS. A less ambitious program model would alleviate this problem.

RNS UTILIZATION SCHEDULE

FIRST HALF OF 1986 - MSFC PROGRAM MODEL

*SECOND EARTH-ORBITAL PLANE UTILIZED

RELIABILITY IMPROVEMENT TRADE STUDY

The overall objectives of the reliability improvement trade study are to improve the reliability and the safety of the RNS. This is accomplished by the elimination of as many single-point failures as possible, the reduction of the probability of occurrence of the remaining single-point failures to an acceptable level, and the elimination or reduction of credible multiple failures. The approach that will be used to accomplish this integrated reliability and safety effort has multiple stages, including (1) reliability analyses investigating mission success with utilization of Failure Mode Effects and criticality Analyses (FMEA) and the identification of single failure items, (2) fault tree analyses to identify credible multiple failures, (3) contingency planning analyses to eliminate or reduce the probability of single failures and to identify monitoring and operational requirements, and (4) availability analysis to maximize the probability of the RNS availability to perform the required missions.

The current phase of this overall program is composed of (1) a preliminary FMEA to tentatively identify the functional (operating) flight critical failure modes (single-failure items) and the structural items (including failures such as leakage, burn-through, burst, etc.) and (2) recommendations for design changes to eliminate the functional flight critical failure modes in preparation for the formal FMEA. This phase of the overall program has been accomplished. The next phase will consist of the formal FMEA, the fault tree analysis, and the availability analysis, followed by the contingency planning analysis.

RELIABILITY IMPROVEMENT TRADE STUDY

OBJECTIVES

- ELIMINATE SINGLE POINT FAILURES
- IMPROVE MISSION RELIABILITY
- IMPROVE FLIGHT SAFETY
- IMPROVE MISSION AVAILABILITY

APPROACH

- PERFORM PRELIMINARY FMEA
- IDENTIFY FUNCTIONAL FLIGHT CRITICAL-FAILURE MODES
- PROPOSE DESIGN CHANGES/INCORPORATE DESIGN CHANGES
- PERFORM FORMAL RELIABILITY/SAFETY/AVAILABILITY ANALYSIS
- PERFORM DESIGN ITERATIONS

RELIABILITY IMPROVEMENT TRADE STUDY

The subsystem design used for this initial preliminary effort was primarily the design at the end of the Phase II effort and reported in the Final Report. The initial effort concentrated on the identification and elimination of the functional flight critical failure modes and reserved for future analysis the structural failure modes and non-mission (availability) failure modes.

Several minor assumptions were made in the analysis, i. e., required power levels, requirement for two pressurization valves, etc. and at least one major assumption -- the astronics system is completely autonomous in that it contains all of the capability required to navigate, guide, and control the stage without outside assistance from the payload, ground, or space facilities.

The milestones for this initial study envision a double iteration on the system design where reliability improvements will be incorporated. The initial FMEA and the first design iteration have been accomplished. A reevaluation of the reliability allocations for the several subsystems will be performed, followed by the formal FMEA and the second design iteration.

RELIABILITY IMPROVEMENT TRADE STUDY

ASSUMPTIONS

- ANALYSIS BASED ON RNS SYSTEM DESIGN FROM PHASE II
- INITIAL FMEA AND DESIGN ITERATION LIMITED TO:
FLIGHT-CRITICAL FAILURE MODES OF ACTIVE SYSTEMS
IN-TRANSIT PHASES OF LUNAR SHUTTLE MISSION
- ASTRIONICS SYSTEM IS AUTONOMOUS

MILESTONES

- ✓ • FORMULATE RELIABILITY IMPROVEMENT PLAN
- ✓ • REVISE SUBSYSTEM DESIGN
- REVIEW AND REVISE RELIABILITY ALLOCATIONS
- PERFORM FMEA AND CRITICALITY CALCULATIONS FOR REVISED DESIGN
- FINAL REVIEW, RELIABILITY RECOMMENDATIONS, AND DESIGN REVISIONS

PROPELLANT MANAGEMENT SYSTEM SCHEMATIC - CLASS 1 HYBRID RNS

The propellant management system prior to and after the design iteration is shown for the Class 1 Hybrid RNS, with the shaded elements indicating the design changes. The modifications include:

- A. Addition of a third shutoff valve in the pressurization line of both modules to eliminate the fail-to-open failure mode.
- B. Addition of a second flow control valve in the fill system of the propulsion module and a second propellant isolation valve in the propellant module to eliminate the fail-to-open failure mode. The two propellant isolation valves in the propellant module and the two flow control valves in the propulsion module form a quad system to eliminate the failure-to-close failure mode.
- C. A quad valve system has been substituted for the single shutoff valve in the prepressurization system.

PROPELLANT MANAGEMENT SYSTEM SCHEMATIC

CLASS 1 HYBRID RNS

14856

CRITICALITIES AND RELIABILITIES - CLASS 1 HYBRID

The criticality and reliability values before and after incorporation of the reliability improvement recommendations are shown here for the Class 1 Hybrid RNS. Criticality is defined here as the probability of loss of the RNS $\times 10^6$.

The data here indicate the criticality and reliability of the propellant management system for the Class 1 Hybrid design. As stated previously, the thrust of this initial phase of the study was to eliminate as many functional single failures as possible; reduction of the structural single failures (leakage, burnthrough, etc.) will be pursued later. This logic sometimes presented a paradox in that the calculated reliability actually decreased in the attempt to eliminate single failure items. An example is shown in the accompanying illustration, which shows the criticality of the pressurization subsystem of the propellant module increasing from 2,225 units to 3,212 units when the third pressurization valve was added. The reason for this increase is the additional leak path created by the third valve. This paradox will be corrected when specific attention is devoted to reduction of the leakage failure mode.

CRITICALITIES AND RELIABILITIES

CLASS 1 HYBRID RNS

SYSTEM	BEFORE		AFTER	
	CRITICALITY	RELIABILITY	CRITICALITY	RELIABILITY
• PROPELLANT MODULE		0.9927		0.9924
PROPELLANT FEED	662		35	
PRESSURIZATION	3,550		4,536	
FILL AND DRAIN/ ORBITAL REFUELING	654		654	
FLIGHT VENT	2,426		2,426	
• PROPULSION MODULE		0.9878		0.9938
PRESSURIZATION	2,225		3,211	
PREPRESSURIZATION	6,093		2,235	
FILL AND DRAIN/ ORBIT REFUELING	2,590		437	
FLIGHT VENT	1,391		1,391	

PROPELLANT MANAGEMENT SYSTEM SCHEMATIC - CLASS 3 RNS

The propellant management system schematic before and after the design iteration is shown for the Class 3 RNS, with the shaded elements indicating the design changes. The modifications include:

- A. Addition of a third shutoff valve in the pressurization line of the propulsion module and all propellant modules to eliminate the fail-to-open failure mode.
- B. Addition of a second flow control valve in the fill system of the propulsion module to eliminate the fail-to-open failure mode.
- C. Addition of a second propellant isolation valve in the feed system of each propellant module to eliminate the fail-to-open failure mode.
- D. A quad valve system has been substituted for the single shutoff valve in the prepressurization system.

PROPELLANT MANAGEMENT SYSTEM SCHEMATIC

14855

CLASS 3 RNS

CRITICALITIES AND RELIABILITIES - CLASS 3 RNS

The criticality and reliability values for the propellant management system of the Class 3 RNS propellant and propulsion modules are tabulated to show the effect of incorporating reliability improvement recommendations. There were no design changes to the fill and drain/orbital refueling and flight vent systems of the propellant module and the flight vent system of the propulsion module; therefore, the criticality values of these systems remained constant. The values shown for the propellant module represent only one of the eight propellant modules used in the Class 3 RNS. For this preliminary analysis it was assumed that the propellant modules were identical in design and operation. This assumption will be modified later in a more detailed analysis.

CRITICALITIES AND RELIABILITIES

CLASS 3 RNS

SYSTEM	BEFORE		AFTER	
	CRITICALITY	RELIABILITY	CRITICALITY	RELIABILITY
• PROPELLANT MODULE		0.9945		0.9941
PROPELLANT FEED	631		4	
PRESSURIZATION	2,229		3,215	
FILL AND DRAIN/ ORBITAL REFUELING	1,281		1,281	
FLIGHT VENT	1,391		1,391	
• PROPULSION MODULE		0.9878		0.9938
PRESSURIZATION	2,225		3,211	
PREPRESSURIZATION	6,093		2,235	
FILL AND DRAIN/ ORBITAL REFUELING	2,590		437	
FLIGHT VENT	1,391		1,391	

AUXILIARY PROPULSION SYSTEM SCHEMATIC

A schematic diagram of the cryogenic auxiliary propulsion system used in the reliability improvement effort is shown here. It is applicable to either the Class 1 Hybrid or Class 3 RNS, since the APS systems are functionally identical for the two configurations. The number and placement of valves, regulators, etc. shown here reflect the definition of the system as derived during the Phase II study. The reliability analysis was directed toward elimination of all single point failures of operating components in this system.

The reliability analysis resulted in the recommendation of two alternatives, namely, incorporation of a large number of changes in the single system to eliminate single point failures, or addition of another totally separate system to provide the required redundancy. The current recommendation is the use of two separate auxiliary propulsion systems; however, additional analyses will be performed in future phases of the study to evaluate the relative weights and system design concepts for using a single system with redundancy as compared to the redundant system approach.

AUXILIARY PROPULSION SYSTEM SCHEMATIC

CLASS 1 HYBRID OR CLASS 3 RNS

ELECTRICAL POWER SYSTEM SCHEMATIC

The electrical power system schematic used for the reliability improvement trade study is shown here, as defined during the Phase II Study and after incorporation of reliability improvement recommendations. The design was based upon use of three fuel cells, each with five-kw capacity and fed from a single oxygen and hydrogen supply. The reliability improvement design review resulted in selection of two fuel cell units, each sized to provide the full power load required for flight critical items and with each fuel cell supplied from a separate source of oxygen and hydrogen. Additionally, a separate voltage control and voltage limiter sensor has been incorporated to provide two autonomous power systems. The reduction from three fuel cells, each sized to provide 50 percent of the full power load, to two units, each with a 100 percent capability to provide full power for flight critical items, results in a higher contingency power capability, as well as a simpler system, as denoted by the deletions that are effected. The batteries, which are used to satisfy short-term peak power demands, have also been reduced from four to three in number as a result of a decision to reduce redundancy from 100 percent to 50 percent as a means of saving weight. The final approach taken will be dependent upon the architecture of the battery systems, in terms of number of cells per battery and the interaction, if any, between cells.

ELECTRICAL POWER SYSTEM SCHEMATIC

CLASS 1 HYBRID OR CLASS 3 RNS

ASTRIONICS SYSTEM SCHEMATIC

The astrionics system concept used in the reliability improvement analysis is depicted here. The system is the same for both Class 1 hybrid and Class 3 concepts. As stated previously, a number of assumptions were made regarding the astrionics system, most significant of which was that it is autonomous, with the tracking function and uplink from the ground required only as a backup and possibly for override functions.

The reliability improvement design review resulted in the use of triply redundant systems to protect against the erroneous output type of failure mode. Doubly redundant systems are adequate for failure modes such as failure to operate, but would not protect against the case where the component is putting out a signal that is erroneous. The triply redundant system approach would provide a voting logic to ascertain which of two differing output signals is correct. Self-diagnosis capability of astrionics components is probably realistic in the projected time frame of application; however, the triply redundant approach was adopted as a current baseline to facilitate analysis. This approach requires additional components as indicated by the shaded areas on the figure. In addition, reverse current protection, e.g., diodes, was included for the power supplies to protect against short circuits. While not shown, the power supply provides power for all of the astrionics components and subsystems drawn here. The power distribution network was omitted in order to simplify the system schematic.

ASTRIONICS SYSTEM SCHEMATIC

CLASS 1 HYBRID OR CLASS 3 RNS

CRITICALITIES AND RELIABILITIES - CLASS 1 HYBRID & CLASS 3 RNS

The criticalities of the various subsystems in the command and control module, which is common to the Class 1 Hybrid and Class 3 RNS concepts, are tabulated to show the effect of incorporating reliability improvement recommendations. The overall module reliabilities are also shown. The major systems involved are the astrionics, electrical power, and the auxiliary propulsion systems. The modifications to the electrical power and astrionics systems were on an individual item basis, but a completely separate and redundant auxiliary propulsion system was added. As a result of this design decision, the only remaining flight critical items in the auxiliary propulsion system are those which could cause structural failure of the other auxiliary propulsion systems or of the critical items on the RNS. The two items identified are the APS engines and the gas generators, both of which have a burnthrough failure mode.

The current level of analysis, which is preliminary in the area of astrionics, resulted in the elimination of all single-failure items in this system. This results in a zero criticality number for GN&C and the command and control subsystems in the current single-failure analysis. It is assumed that this condition will change as more detailed analyses are performed on the subsystems during remaining phases of the study.

While the command and control unit remains the most unreliable module, this exercise greatly increased the overall reliability (from 0.60 to 0.98).

CRITICALITIES AND RELIABILITIES

CLASS 1 HYBRID AND CLASS 3 RNS

SYSTEM	BEFORE		AFTER	
	CRITICALITY	RELIABILITY	CRITICALITY	RELIABILITY
• COMMAND AND CONTROL MODULE		0.6025		0.9778
ENGINE SUBSYSTEM, APS	42,761		11,954	
PROPELLANT MANAGEMENT, APS	98,485		4,288	
PROPELLANT STORAGE, APS	13,843		0*	
PRESSURIZATION, APS	30,237		0	
GUIDANCE, NAVIGATION, AND CONTROL	85,632		0	
COMMAND AND CONTROL SUBSYSTEM	184,877		0	
ELECTRICAL POWER	20,452		6,021	

*-CURRENT LEVEL OF ANALYSIS HAS
ELIMINATED ALL SINGLE POINT FAILURES

RELIABILITY IMPROVEMENT SUMMARY

The current status of the reliability estimates for the Class 1 Hybrid and the Class 3 RNS is tabulated here by module, as well as for structure, the engine, and the total system. The values shown for the propulsion modules are exclusive of the NERVA. The value shown for the Class 3 propellant module represents a single module. The total reliability value for the Class 3 RNS represents a vehicle which utilizes eight propellant modules, one propulsion module and one command and control module. These values compare with an assumed goal of 0.975 per mission.

RELIABILITY IMPROVEMENT SUMMARY

SYSTEM	CURRENT VALUES	
	CLASS 1 HYBRID RNS	CLASS 3 RNS
PROPELLANT MODULE	0.9924	0.9941
PROPULSION MODULE	0.9938	0.9938
COMMAND AND CONTROL MODULE	0.9778	0.9778
STRUCTURES	0.9962	0.9965
ENGINE	0.995	0.995
TOTAL RNS	0.96	0.93 *

*- 8-1-1 CONFIGURATION

METEOROID PROTECTION ANALYSIS

During Phase II the meteoroid protection subsystem was designed to meet the reliability allocation imposed on it. As part of the Phase III study, reliability allocations are being reassessed. The meteoroid protection subsystem will be optimized according to economic considerations as well as safety. For this briefing the results of this optimization will be shown for the RNS Class 3 vehicle.

Application of Phase III guidelines requires a revision of the meteoroid protection subsystem in order to accommodate the new meteoroid environment given in the NASA document shown in the chart. Additional ground rules, building upon Phase II test and analysis results, were selected with the concurrence of the COR. The variation in meteoroid armor for this analysis is kept within the regime for which Phase II test results are applicable.

METEOROID PROTECTION ANALYSES

OBJECTIVE

- **PERFORM ECONOMIC OPTIMIZATION OF RNS CLASS 3 ARMOR**

GROUND RULES

- **NEW METEOROID ENVIRONMENT-NASA TMX-53957**
- **PHASE II TEST RESULTS FOR PENETRATION**

EXTRAPOLATION ACCORDING TO NASA TMX-53798

- **DAMAGE CRITERION - NO DAMAGE TO TANK**
- **UNIFORM ARMOR DISTRIBUTION**
- **SHIELDING BY ADJACENT MODULES**

METEOROID SURVIVAL CRITERIA

CLASS 3 - RNS

Four criteria which are relevant to this analysis are shown on the accompanying illustration. Criterion A provides survival for all modules through the full 54.6 day mission cycle. Since penetration of spent modules during the mission or following the mission in earth orbit will not affect mission success or safety, this is clearly an economic criterion. Criterion B provides for survival of active modules, that is, those containing propellant and required for completion of the mission, for the full mission duration including a 9-day period in earth orbit for tanking and preparation for the mission. This criterion represents mission success in the broadest manner. Criterion C, which provides for the survival of active modules away from earth orbit, that is, after the mission is committed, represents a more restrictive criterion of mission success or could have an impact on safety. Criterion D, which provides for survival of the active modules during transit between earth and lunar orbits and during all operations including multiburn maneuvers to arrive and depart from lunar orbit and aftercooling operations, can be considered to represent a safety criterion, since a meteoroid penetration would require an abort or emergency action in order to ensure astronaut safety. This criterion presumes that life support for the astronauts exists in earth orbit and lunar orbit so that module penetration does not jeopardize their survival.

METEOROID SURVIVAL CRITERIA

CLASS 3 RNS

- A- SURVIVAL OF ALL MODULES FOR FULL MISSION CYCLE
(ECONOMIC)
- B- SURVIVAL OF ACTIVE MODULES FOR FULL MISSION
(MISSION SUCCESS)
- C- SURVIVAL OF ACTIVE MODULES AWAY FROM EARTH ORBIT
(MISSION SUCCESS/SAFETY)
- D- SURVIVAL OF ACTIVE MODULES DURING TRANSIT AND OPERATIONS
(SAFETY)

METEOROID ARMOR WEIGHT

CLASS 3 - RNS

The accompanying illustration shows meteoroid armor weight as a function of the survival probability for each of the four criteria defined on the preceding chart. The ground rules cited were used for the analysis. Armor was distributed uniformly over all of the eight propellant modules. The propulsion module was protected with maximum armor which was not varied. Propellant depletion during the mission and mutual shielding between propellant modules in a cruciform cluster configuration were used to define effective vulnerable area as a function of mission phase. For comparison purposes the criteria used during Phase II was a survival probability of 0.9975 according to criterion B. According to the accompanying illustration the meteoroid armor weight would be 12,800 lb to meet this criterion. This is a reduction of about 2,000 lb from the Phase II result which is attributed solely to the change in meteoroid flux model for Phase III.

METEOROID ARMOR WEIGHT

CLASS 3 RNS

METEOROID ARMOR OPTIMIZATION

The combination of the weights and probabilities shown on the preceding chart with their economic impact are used for the economic optimization shown on the accompanying illustration. The cost increment shown on the ordinate is normalized to each roundtrip mission.

The economic penalty imposed for meteoroid armor weight is based on the cost of hydrogen required to transport the armor on the roundtrip mission together with the additional tankage required. A liquid hydrogen cost of \$136 per lb in earth orbit, which will be shown in a subsequent trade study, was used for this analysis. A mission performance sensitivity factor of 2.3 for the partial of propellant weight with respect to stage weight was used together with a stage scaling factor of 0.17 lb of stage weight per lb of propellant. Combining these yielded an overall penalty of \$516 per lb of meteoroid armor for its transportation cost. Criterion A was assessed on the basis of replacing an individual propellant module at a cost of \$4 million, representing \$1 million for the hardware cost, \$1 million for the prorata launch cost of the module (the other \$4 million of the launch is chargeable to the useful propellant), and a \$2 million operations cost for removal and replacement of the module in orbit. Mission success was evaluated according to Criterion B which is the most restrictive basis. A cost of \$80 million was assessed for the mission representing the prorata cost for the RNS hardware and launch together with the full propellant loading. Applying these factors an optimum is found for meteoroid armor weight of about 8,400 lb. Alternatively assessing mission loss according to Criterion C or charging mission loss at a lesser rate would move the optimum to lower meteoroid armor weights. For these cases the knee of the curve still occurs around 8,400 lb. Therefore, at this time it is recommended that this be selected as the baseline meteoroid armor protection assuming uniform armor distribution. However, it is planned to evaluate non-uniform armor distribution, keeping within three module types which will be defined in a subsequent trade study. This should reduce the armor weight for the criteria selected here. The values are: 0.990 for Criterion B, 0.995 for Criterion C, and 0.9975 for Criterion D.

METEOROID ARMOR OPTIMIZATION

NUCLEAR SHUTTLE DESIGN REQUIREMENTS SUMMARY

Design requirements for the nuclear shuttle include a stage lifetime of up to 3 years in space, with the capability for maintenance in earth orbit. This design lifetime requirement was stipulated in the guidelines and constraints document furnished by MSFC. The nominal number of missions used for the lunar shuttle and geosynchronous shuttle is 10, based on a NERVA design lifetime goal of 10 hours and an engine operating time of approximately 1 hour per mission. This number of missions is currently being used to determine the operating cycles through which the RNS subsystems must be designed to operate. The mission durations shown are times away from low earth orbit, with the range for unmanned planetary missions indicating the effects of expending or retrieving the RNS. Meteoroid shielding requirements will be highest for the manned planetary missions due to the longer exposure time, with some potential differences between the Class 1 hybrid and Class 3 as a function of their respective configurations. Clustering will be a design requirement for all mission class applications of the Class 3 RNS, whereas the Class 1 hybrid concept will be clustered only for the manned planetary missions. The propellant module for the Class 1 hybrid will have to be designed to withstand launch loads created by the INT-21 vehicle, whereas the propulsion module and all elements of the Class 3 RNS will be subjected to the loads created by the launch of a space shuttle carrying the payload internally. The amount of radiation shielding required will vary between mission classes, and will of course be a function of the specific configuration and dose criteria being considered. Replacement of total modules, e.g., the command and control unit, in earth orbit is envisioned as the method of maintenance for the RNS when considering the Class I and Class II missions; however, the Class III (manned planetary) missions will very probably require additional in-transit maintenance in order to raise the mission success probability to an acceptable level. In this event, the replacement of smaller modules, e.g., electronic gear, is a likely requirement. The number of engine full-power operations required on each mission varies from a minimum of one for performing an unmanned planetary injection mission in an expendable mode to eight for a lunar shuttle mission when accomplishing lunar plane change maneuvers at full power. The manned planetary mission will require at least two engines, depending upon the operating profile, whereas one engine is sufficient for performing each of the remaining mission classes. There will also be requirements for providing in-flight checkout capability of the RNS, which has design implications for the astrionics subsystems, as well as other functional subsystems within the stage. Additionally, all mission classes pose design requirements for providing a rendezvous and docking capability, as this function is fundamental to the operation of the system.

NUCLEAR SHUTTLE DESIGN REQUIREMENTS SUMMARY

	LUNAR SHUTTLE	MANNED PLANETARY	GEOSYN- CHRONOUS	UNMANNED PLANETARY
STAGE LIFETIME	3 YR	3 YR	3 YR	—
NUMBER OF MISSIONS	10	1	10	—
MAXIMUM DURATION	30 DAYS	1.75 YR (SWINGBY) 2.9 YR (CONJUNCTION)	30 DAYS	1 HR - 2 DAYS
METEOROID SHIELDING	MODERATE	HIGH	MODERATE	LOW
CLUSTERING	CLASS 3 ONLY	YES	CLASS 3 ONLY	CLASS 3 ONLY
STRUCTURAL LOADING	CLASS 1H - SAT V INT-21 CLASS 3 - SPACE SHUTTLE (INTERNAL)			
RADIATION SHIELDING	YES	YES	YES	NO
METHOD OF MAINTENANCE	EARTH ORBIT REPLACEMENT	IN-FLIGHT MODULES REPLACEMENT	EARTH ORBIT REPLACEMENT	EARTH ORBIT REPLACEMENT
NUMBER OF MANEUVERS	6 TO 8	5 TO 7	4	1 TO 3
NUMBER OF ENGINES	1	2 OR MORE	1	1
IN-FLIGHT CHECKOUT	YES	YES	YES	—
RENDEZVOUS AND DOCKING	YES	YES	YES	YES

ASSEMBLY, MAINTENANCE AND RESUPPLY

This section will cover three trade studies associated with orbital operations providing assembly of the RNS Class 3 vehicle, orbital maintenance of the Class 1 hybrid, and propellant resupply for both RNS concepts. The RNS Class 3 assembly trade study will review the vehicle configuration selected in Phase II in terms of the detailed operations required for assembly. Additionally, these assembly operations will be defined and the corresponding RNS subsystem design features defined to meet these requirements. The orbital maintenance trade study will be directed toward selecting the level of maintenance and replenishment to be used. The candidates are listed as multiple modules, single module, and in-situ. The propellant resupply trade study will reassess the selections made in Phase II in terms of the Phase III ground rules. Candidate concepts will be integral tanker, deployed tanker, and replacement tankage for the Class 3 vehicle.

ASSEMBLY MAINTENANCE AND RESUPPLY

ASSEMBLY-CLASS 3

- VEHICLE CONFIGURATION
- ORBITAL OPERATIONS
- RNS SUBSYSTEM REQUIREMENTS

ORBITAL MAINTENANCE--CLASS 1 HYBRID

- LEVEL OF MAINTENANCE AND REPLENISHMENT
 - MULTIPLE MODULES
 - SINGLE MODULE
 - IN-SITU

PROPELLANT RESUPPLY

- INTEGRAL TANKER
- DEPLOYED TANKER
- REPLACEMENT TANKAGE--CLASS 3 ONLY

ORBITAL ASSEMBLY - RNS CLASS 3

TRADE STUDY OBJECTIVES

The accompanying illustration lists the objectives for the orbital assembly trade study. The first objective is to define the vehicle configuration. That is, location of all modules in the vehicle. Following this, assembly operation will be analyzed in detail concentrating particularly on the sequence of the module assembly and the support element requirements, such as number and capability of space tugs, rendezvous radar, etc. Finally, the RNS subsystems will be defined to meet the assembly operations requirements. Of major import here will be the rendezvous and docking subsystems, the clustering mechanisms, deployment and coupling of the fluid lines, and the flexible elements employed in the feed system such that they accommodate the assembly deployment and tolerances as well as the operational deflections caused by pressure and temperature changes during the mission.

ORBITAL ASSEMBLY--RNS CLASS 3

TRADE STUDY OBJECTIVES

VEHICLE CONFIGURATION

ASSEMBLY OPERATIONS

- SEQUENCE OF MODULE ASSEMBLY
- SUPPORT ELEMENT REQUIREMENTS

RNS SUBSYSTEM DESIGN

- RENDEZVOUS AND DOCKING
- CLUSTERING
- FLUID LINE DEPLOYMENT AND COUPLING
- FLEXIBLE ELEMENTS--FEED SYSTEM
 - ASSEMBLY DEPLOYMENT AND TOLERANCES
 - OPERATIONAL DEFLECTIONS

RNS CLASS 3 CONFIGURATION CANDIDATES

The candidate propellant feed system schematics for the Class 3 RNS are shown. The first concept of the planar configuration provides structural and functional assembly within columns prior to vehicle assembly. The second candidate depicts a planar configuration that would employ structural and functional assembly of outboard modules to the adjacent inboard module. The third sketch shows a cruciform cluster configuration which maintains the advantages of individual module assembly while relieving the clearance problem between tandem outboard modules during assembly or operation. Propellant feed system deflections between inboard and outboard modules for the cruciform cluster configuration are the same as the second planar configuration. The planar-columnar configuration has twice the longitudinal deflections of the other two assemblies.

RNS CLASS 3 CONFIGURATION CANDIDATES

COLUMNAR ASSEMBLY
PLANAR CONFIGURATION

INDIVIDUAL MODULE
ASSEMBLY
PLANAR CONFIGURATION

CRUCIFORM
CLUSTER

RNS CLASS 3 CLUSTERING METHODS

The three RNS Class 3 candidate configurations shown on the preceding chart have significantly different implications with respect to their orbital assembly. The first configuration, that of the columnar assembly planar configuration, requires subassembly within columns prior to vehicle assembly. This is shown schematically in the first sketch of the accompanying illustration. Two-tug assembly can be employed to accomplish the rotation of the columns. However, it is clear that assembly tolerances will accumulate for the entire column of modules. The second candidate, the individual module assembly planar configuration, employs assembly of outboard modules directly to the adjacent inboard module. Because of clearance constraints with the adjacent module in the outboard column, two space tugs cannot be employed for the entire rotation and clustering operation. This concept requires self-driven form of rotation as well as provision of clearance between adjacent outboard modules. The third concept, that of the cruciform cluster, limits the assembly of all outboard modules to a single tier. This eliminates clearance problems between outboard modules and allows for two tug assembly.

RNS CLASS 3 CLUSTERING METHODS

CONFIGURATION EVALUATION

The accompanying illustration summarizes the main considerations utilized in comparing the candidate Class 3 vehicle configurations. The major characteristics of the planar array - columnar are shown. The five module types are defined according to plumbing and structural characteristics required for clustering. Orbital subassembly intercolumns is required prior to vehicle assembly. This imposes a greater demand upon the orbital support system. Additionally, the columnar subassembly increases all assembly and operational tolerances. When the columns are assembled structurally with each column individually, deflections between columns will sum over the entire column length rather than merely over an individual adjacent module. The major advantage of this configuration is that there are minimum connections in order to connect the inboard and outboard modules. The planar array - individual requires only three module types, and tolerances and deflections only occur between adjacent modules. The major characteristic of this configuration, however, is the requirement for self-driven rotation of the outboard modules. The third candidate, the cruciform cluster, seems to combine the advantages of both of the above, requiring only three module types, being able to utilize a two-tug assembly operation, and with minimum tolerances and deflections. Group variations employing more than eight propellant modules could utilize a cluster containing six outboard modules and a second tier of one, and provide three- and four-tier totals respectively for nine and ten modules. For these reasons the cruciform cluster configuration is selected for the RNS Class 3 vehicle configuration and will be used for subsequent operations analysis. This configuration also minimizes the number of difficult-to-reach modules to one.

CONFIGURATION EVALUATION

- PLANAR ARRAY--COLUMNAR
 - 5 MODULE TYPES
 - REQUIRES COLUMN SUBASSEMBLY
 - SUMS ASSEMBLY AND OPERATIONAL TOLERANCES AND DEFLECTIONS
 - MINIMUM INBOARD/OUTBOARD CONNECTIONS
- PLANAR ARRAY--INDIVIDUAL
 - 3 MODULE TYPES
 - REQUIRES SELF-DRIVEN ROTATION
- ✓ ● CRUCIFORM CLUSTER
 - COMBINES ADVANTAGES OF BOTH
 - 3 MODULE TYPES
 - 2 TUG ASSEMBLY OPERATIONS
 - MINIMUM TOLERANCES AND DEFLECTIONS
 - USE 6 OUTBOARD MODULE CLUSTER FOR GROWTH

RNS CLASS 3 ORBITAL OPERATIONS

A summary of the orbital operations required for assembly of a RNS Class 3 vehicle are shown schematically in the accompanying illustration. All modules are brought to the earth orbit by the space shuttle. The orbiter cargo compartment contains the 15-ft by 60-ft modules. The first figure shows the module being rotated out of the orbiter. The work tug is approaching. Tug docking will follow. The module is released from the orbiter and the tug transports the module to the vehicle being assembled. The next figure shows the tug and module rendezvousing with the partially assembled vehicle. The final sketch illustrates the assembly and hookup of the vehicle.

These operational phases will be the bases for subsequent operations analysis and RNS subsystem requirements definition.

RNS CLASS 3 ORBITAL OPERATIONS

MODULE DEPLOYMENT

RENDEZVOUS AND DOCK

ASSEMBLY AND HOOKUP

PROPELLANT MODULE DEPLOYMENT

The accompanying illustration depicts both propellant module support and deployment from the shuttle cargo bay. The figure at the upper right shows the module (1) stowed, (2) initially deployed (linear), and (3) fully erected.

The propellant module is loaded into the cargo bay and latched to forward and aft deployment rings of the space shuttle. The forward deployment ring is latched to the forward bulkhead of the cargo bay and transmits propellant module longitudinal, lateral and vertical loads to the shuttle. This ring has trunnions that attach to a set of tracks mounted on the bulkhead. The aft deployment ring also has trunnions that attach to tracks mounted on the cargo bay aft bulkhead. The trunnion pickup points in the aft tracks are slotted and only transmit lateral and vertical loads to the shuttle. A thermal contraction of 2.16 in. caused by propellant loading and an expansion of 1.37 in. resulting from pressurization are compensated for by movement of the trunnion in the slot.

Module deployment is effected by actuation of both the forward and aft sets of telescoping tracks. Each track consists of three sections. The tracks are deployed by a cable system operated off a single drum and motor.

After the module is deployed, a motorized drive is deployed from the shuttle and engages the forward deployment ring. The aft deployment ring latches are then released and the module rotated to the erected position. The hinge or pivot is built into the forward tracks. In order to stabilize the stage in the erected position a probe is extended from the orbiter; it contacts and latches to one of the propellant module docking drogues. A tug then docks to the free end of the module, the forward deployment ring latches are released, and the module is transported to its staging area. The deployment mechanism is retracted into the shuttle by a method of operation which is the reverse of deployment.

In order to accommodate the tracks and deployment rings the shuttle cargo bay would have to be at least 11 in. longer than the propellant module. This would permit 5 in. at the forward end and 6 in. at the aft end for installation of these components. Three inches of clearance was allowed on the propellant module outside diameter. This resulted in cargo bay that was 731 in. long and had a diameter of 186 in.

PROPELLANT MODULE DEPLOYMENT

LASER RADAR RENDEZVOUS AND DOCKING SYSTEM

A configuration for a laser radar rendezvous and docking system, which shows the location of active and passive elements, is depicted in the accompanying illustration. This system is derived from characteristics of the scanning laser radar system currently being developed for NASA by ITT. The equipment located on the chaser or active vehicle consists of a transmitter and receiver and scanners which position these components. The transmitter is a semiconductor laser. The equipment located on the passive vehicle consists of a corner cube reflector. These elements are located in arrays around the circumference of the vehicle to establish the geometry. Employing the space tug for assembly operations, the location of active and passive elements on the modules is shown for the initial clustering operations, including the sequence of assembly and for the complete assembly of the vehicle. Both inboard and outboard locations are indicated. It is seen that all of the propellant modules and the propulsion modules are passive and only the space tug and command control module contain active laser radar elements. The system can be used to acquire and track the target for rendezvous with a range of about 75 miles. The high accuracy provided by the system as shown in the illustration would provide a great advantage for the RNS assembly operations. Using the multiple laser radar unit array provides system redundancy without using the backup of a different technology system such as conventional radar or TV.

LASER RADAR RENDEZVOUS AND DOCKING SYSTEM

INITIAL CLUSTERING

SYMBOLS

- A - ACTIVE ELEMENT:
LASER RADAR AND
RECEIVER
- P - PASSIVE ELEMENT:
CORNER CUBE

COMPLETE ASSEMBLY

- ALL MODULES PASSIVE, EXCEPT SPACE TUG AND CCM

- CORNER CUBE ARRAY

- RANGE : 75 MI

- DOCKING ACCURACY

$\pm 10 \text{ CM}$

$\pm 0.5 \text{ CM/SEC}$

$\pm 0.05^\circ$

- REDUNDANCY PROVIDED WITH SAME TECHNOLOGY SYSTEM

ASSEMBLY SEQUENCE

The next three illustrations show the assembly operations of the baseline RNS Class 3 Cruciform Configuration. Two tugs are used to perform the assembly. Tug A is utilized in a stabilization mode. Tug B is the active assembly element. The module assembly sequence is denoted by the numbering system shown on the propellant modules. An assessment of the operational requirements shows that both the stabilizing and working tugs require electrical hookup with the RNS modules during assembly to provide power and control signals, and to obtain sensor data.

The format of the illustrations shows the starting configuration on the left, identifies operations, and illustrates the final configurations on the right. This, then, becomes the starting point for the operations listed on the next illustration.

ASSEMBLY SEQUENCE

- DOCK
- DEPLOY HINGES
- RELEASE LATCHES
- ALIGN HINGES
- DEPLOY SIDE PROBE
- ROTATE
- IMPACT AND CAPTURE
- STRUCTURAL LATCH
- DEPLOY FLUID LINES
- COUPLE FLUID LINES
- DEPLOY AND CONNECT ELECTRICAL PANEL
- TRANSFER ALL CONTROL TO TUG A
- UNDOCK TUG B
- REPEAT FOR MODULES 3, 4, AND 5

ASSEMBLY SEQUENCE (CONT)

- DOCK 6 FORWARD OF 1
 - STRUCTURAL LATCH
 - COUPLE FLUID LINES
 - DEPLOY AND CONNECT ELECTRICAL PANEL
 - TRANSFER CONTROL TO TUG A
 - UNDOCK TUG B
 - REPEAT TO ASSEMBLE 7 FORWARD OF 6
 - REPEAT TO ASSEMBLE CCM FORWARD OF 7
 - TRANSFER CONTROL TO TUG B
- UNDOCK TUG A

ASSEMBLY SEQUENCE (CONT)

- DOCK AND LATCH 8 AFT OF 1
- FLUID AND ELEC COUPLING
- TUG A POSITIONS PROPULSION MODULE
- PROPULSION MODULE SELF STABILIZED
- UNDOCK TUG A
- DOCK ASSEMBLY TO PROPULSION MODULE
- FLUID AND ELECTRICAL COUPLING
- TRANSFER CONTROL TO CCM
- TUG B DEPARTS
- INITIATE ORBITAL CHECKOUT

DOCKING DROGUE AND PROBE ASSEMBLY

The multiple probe/drogue docking system defined in Phase II was modified as shown in the accompanying illustration. The upper half of the sectional view depicts the assembly in the latched position and the lower half shows the retracted or launch position. Modifications from Phase II include:

- A. Redesign of the probe capture mechanism located in the vertex of the guide cone. With this scheme capture is accomplished by the probe riding up the inclined plane, latching cams which are spring-loaded closed and probe-deflected open to accomplish the catch. Probe release is effected by actuating the four pull-solenoids to retract the cams.
- B. Addition of a resilient wire mesh pad to provide a soft contact surface for the probe. This prevents marring of the cone during docking.
- C. Incorporation of a flange on the probe housing that makes contact with the cone assembly outer lip. This flange provides a better draw up load path and increases both stability and tolerance absorption capability.
- D. Installation of probe support struts, a deactuating ratchet solenoid, and the main drive motor.

DOCKING DROGUE AND PROBE ASSEMBLY

DEPLOYABLE HINGE SYSTEM

The hinge mechanism used to permit rotation of a module from the inline docked position to the outboard position is shown in the accompanying illustration. The system is shown fully engaged after rotation has been completed. During launch and docking the hinges are retracted within the 15-ft-diameter envelope constraint of the EOS. The mechanism used for deployment is a basic quadric chain. The drive link is rotated by a motor driven screw jack, pivoting in a circular arc about its vehicle mounted rotational center. This rotation causes the idler link (center link) to fold in, in a scissor-type motion. The pivot on the other end of the idler is connected to the hinge link. The hinge link then moves through its 90 degrees of travel.

The triangular hinge link is a forged aluminum frame supported to the stage by two clevis connections. The upper clevis is a close fit to facilitate alignment. The outer end of the hinge link contains a shear pin with a pilot end. This pin engages the bushing located on the mating hinge. Two pairs of the above hinges constitute the upper rotational support system. System operational sequence is as follows: After inline docking and latching has been completed, the lower module hinges are deployed. These hinges contain a female mono-ball type fitting. Upper module hinges are now deployed. Deployment continues until the primary pilot of the shear pins engage their mating bushing ends. At this time docking latching is released in order to facilitate proper engagement and alignment. Final hinge deployment is completed permitting a close tolerance shear pin fit-up.

DEPLOYABLE HINGE SYSTEM

DEPLOYMENT AND COUPLING MECHANISM

The deployment and coupling mechanisms used for the outboard module feed duct is shown in the accompanying illustration. The upper half of the sectional view shows the duct in the normal position after the outboard module is rotated into position. The lower section shows the duct deployed and the coupling made. This is accomplished in two steps, first deployment, then coupling. The linear deployment mechanism is located on the compensator feed duct for the outboard module. The coupling mechanism is located on the inboard module. The outboard module feed duct flange is attached to the handling frame with a floating cross-member. This arrangement permits flange freedom for tolerance absorption during the deployment and coupling operations. The flange contains two alignment pilots that engage conical guides located on the inboard module feed duct flange. The frame corner fitting contains the ball bearing loading nuts that accept the four drive screws. The drive screw assembly is hard mounted to the structure. When the threaded drive screws are rotated, the frame assembly is extended linearly the deployment distance of 3 in. as shown. The screws are chain driven by a worm wheel gearing system. An electric motor is used as the prime mover.

DEPLOYMENT AND COUPLING MECHANISMS

ALIGNMENT AND COUPLING MECHANISM DETAILS

The coupling mechanism located on the inboard module feed duct is shown in the accompanying illustration. The automatic coupling operation is initiated after the deployment operations are completed for clustering, or directly for tandem assembly. This mechanism consists of two V-coupling sections that are supported and operated by left- and right-hand threaded drive screws. The drive screws are chain driven by the a worm wheel gearing system. Sealing is accomplished by dual metallic pressure-actuated seals.

Section A-A is a detail of the floating cross-frame described in the deployment mechanism.

ALIGNMENT AND COUPLING MECHANISM DETAILS

SECTION A-A

FLANGE COUPLING MECHANISM

PROPELLANT FEED SYSTEM INTERFACES

The three basic propellant fuel system interfaces are the cross-feed, tandem propellant, and tandem propulsion. The feed system tank exit is common for all modules. It consists of a manhole access flange located in the aft dome. A tank sump is bolted to this flange. This fitting provides for maximum tank depletion efficiency, is a uniform low weight tank penetration design, and allows the space required for a straight line, side ducting configuration. The sump fitting which bolts to the tank manhole flange uses a static-pressure-actuated dual seal. This fitting has configured exit ports to reduce module-to-module differences.

The cross-feed ducting from both outboard modules to the center inboard module are identical in configuration. These ducts are deployed 3 in. linearly after the outboard modules are swung into the assembled position and latched. The configuration shown in the accompanying illustration is an inline, direct routed system using a pressure compensator as the prime flexible element. The compensator in conjunction with two inline gimbal joints provide the linear, offset and angulation requirements of the system.

The cross-feed inboard ducting is passive in the assembly operation. This system contains two gimbal joints and a tolerance compensator. The tolerance compensator will absorb manufacturing tolerances and directional operational tolerances.

The tandem propellant module contains an inline compensator, two-gimbal joint feed duct. A fish mouth tank exit fitting provides the maximum length needed with minimum module-to-module spacing. The feed duct flange is aligned for automatic coupling by the final latching operation. No independent linear deployment mechanism is required at this interface.

The cross-feed portion of the tandem propulsion to propellant module is identical for all three of the basic interfaces. The propulsion module tandem feed duct uses a three-gimbal tensile system. This system is compatible with the routing requirement established by the difference in tank diameters. This feed duct is aligned in the linear direction by final latching in the docking operation. Automatic coupling is then accomplished with the baseline mechanism.

PROPELLANT FEED SYSTEM INTERFACES

PROPELLANT FEED SYSTEM FLEXIBLE ELEMENTS

The three basic flexible elements that were used for the Class 3 RNS propellant feed system interfaces are: pressure volume compensator, tolerance compensator, and gimbal joints.

The cross-feed system on the inboard module contains two inline gimbal joints and a tolerance compensator. The tolerance compensator provides for both installation tolerances and directional operational deflections in the axial direction. Outside constraint of the bellows eliminates squirm problems, and pressure loads are transmitted through the outer collar. The two end gimbals provide the parallel offset deflections required during operation. The tied gimbal transmits tensile loading with a predictable angular spring rate.

The cross feed system on the outboard module contains two inline gimbal joints separated by the pressure volume compensator. This interface requires the largest linear deployment motions. The compensator provides the axial motion without excessive end loading. All bellows sections can be internally lined and are of multi-ply design to reduce pressure drop and flow-induced vibration problems. The two end gimbal joints provide the parallel offset motion and flange angulation requirements. The system is envelope efficient and is compatible with the automatic coupling mechanisms.

The tandem feed system between propellant modules has the same configuration as the outboard cross-feed system-two gimbals and a pressure volume compensator. This selection is based on providing maximum deflection capability within the minimum length available between propellant modules.

The tandem feed system from the propellant module to the propulsion module is a three-gimbal joint tensile system. Three gimbals provide the 5-degrees-of-freedom motion capability of the compensator-2 gimbal configurations with pure angular deflections. Linear extension motion is reduced below that of the compensator configuration, but is adequate for this interface. The dogleg duct routing for this system efficiently utilizes the tank diameter differences of these two modules.

PROPELLENT FEED SYSTEM FLEXIBLE ELEMENTS

RNS CLASS 3 CRUCIFORM CLUSTER

INTERFACE	DESIGN REQUIREMENTS			FLEXIBLE ELEMENTS SELECTED
	EXTENTION (IN.)	PARALLEL OFFSET (IN.)	ANGULATION (DEG)	
CROSS FEED				
INBOARD MODULE	± 0.350	± 0.500	± 3	TOLERANCE COMPENSATOR 2-GIMBAL
OUTBOARD MODULE	± 2.50	± 2.00	± 5	PRESSURE COMPENSATOR 2-GIMBAL
TANDEM FEED				
PROPELLANT MODULE	± 0.650	± 0.500	± 4	PRESSURE COMPENSATOR 2-GIMBAL
PROPULSION MODULE	± 0.400	± 0.550	± 1-1/2	3-GIMBAL

MAINTENANCE LEVEL TRADE STUDY

The initial maintainability trade study focused on the definition of the maintenance level for the 33-ft-diameter RNS. The objective of this trade study was to select a strategy for orbital maintenance and replenishment and determine the level of replacement or repair that would be utilized in maintaining the RNS in earth orbit.

The candidates fall into three categories:

- A. Multiple replacement modules of various configurations derived from the MDAC Phase II RNS study.
- B. A single command and control module analogous to the baseline selected for the RNS Class 3 in the Phase II study.
- C. In-situ maintenance using the capabilities of man in orbit for replacements and repair. Consistant with this concept, in-place replenishment in either an automatic (unmanned) or manually assisted context is considered.

Within each of these categories multiple candidates have been identified. This trade study first selected the most attractive candidate in each category based on minimum complexity, weight, reliability, and handling requirements, both in orbit and on the ground. The selected candidates for each category were then compared and a selection made based on technical feasibility, complexity of operations, support requirements, weight, and effectiveness. Effectiveness includes the portion of RNS unreliability covered, reliability of accomplishing repair and replenishment, and the impact on RNS reliability.

MAINTENANCE LEVEL TRADE STUDY

CLASS 1 HYBRID

- OBJECTIVE - - SELECT STRATEGY FOR ORBITAL MAINTENANCE AND REPLENISHMENT
- CANDIDATES
 - MULTIPLE REPLACEMENT MODULES (PHASE II DERIVATIVE)
 - SINGLE COMMAND AND CONTROL MODULE (ANALOG TO CLASS 3)
 - IN-SITU
- EVALUATION
 - OPTIMIZE CONFIGURATION FOR EACH CANDIDATE
 - COMPARE CANDIDATES

MAINTENANCE LEVEL CANDIDATES

Within each category the basic characteristics are common:

Multiple Replacement Modules — All planned operations are accomplished without EVA using the space tug as an orbital support element. Maintenance consists of the replacement of a relatively large module at the forward end of the RNS. The RNS consumables will be replenished by replacement of a like module each round trip. Consumables include the APS and fuel cell reactants and pressurants. The onboard checkout system must be able to isolate faults only to the level of the candidate replacement module to determine which module must be replaced. Although this substantially reduces the potential onboard checkout requirements, the onboard checkout system still must verify the operational readiness of the RNS prior to mission initiation.

Single Command and Control Module — All functional components and consumables are packaged in a single module which will be replaced each round trip using unmanned orbital support for both maintenance and replenishment. In order to minimize the system, subsystem, and component requirements, all operations that are required each round trip will be attributed to the ground recycle procedure. The entire command and control module, replenished and qualified, would then be replaced on the RNS and the next mission initiated. Characteristically, this module has a simple interface with the balance of the RNS. A standard docking structure and procedure is used for all orbital operations, including payload attachment and refueling. No fluid connections are made or broken in orbit to recycle the module, and the electrical connections between replaceable modules are reduced to zero.

In-Situ — This category is represented by manned replacement of relatively small modules as required. All hardware, including fluid and electrical couplings, is so mounted that it is accessible for manned operations. Appropriate hand holds and restraining devices are used to help with connections or component removals and replacements. Manned orbital operations require that pressures are reduced to a safe level and hydrogen and oxygen mixtures are precluded. This implies a requirement for passivation of storable elements prior to manned maintenance operations. The onboard checkout system must be able to isolate faults to the line replaceable unit (LRU). Maintenance operations can then be performed by replacement of the LRU. Consistent with the in-situ concept of maintenance, replenishment in place will be considered for expendables. Hydrogen and oxygen would be tanked separately based on safety requirements. Fluid disconnects can be made either automatically or utilizing manual assistance.

MAINTENANCE LEVEL CANDIDATES

- MULTIPLE REPLACEMENT MODULES
 - UNMANNED OPERATIONS
 - REPLENISH BY REPLACEMENT
 - FAULT ISOLATION TO REPLACEMENT MODULE
- SINGLE COMMAND AND CONTROL MODULE
 - REPLACED EACH MISSION
 - GROUND RECYCLE
 - SIMPLE INTERFACE WITH STAGE
 - STANDARD DOCKING
 - NO FLUID AND MINIMUM ELECTRICAL CONNECTORS
- IN-SITU
 - MANNED OPERATIONS
 - ACCESSIBILITY
 - PASSIVATION
 - IN-PLACE REPLENISHMENT
 - FAULT ISOLATION TO LOWEST LEVEL

MULTIPLE MODULE CANDIDATES

DISCRETE REPLACEMENT MODULES

The candidates for the multiple replacement module category include the eight replacement modules defined at the conclusion of Phase II. These modules are listed in the accompanying illustration. The current study has identified other candidates which appear attractive. In addition to reconfiguration of RNS baseline subsystem design, the consideration of potential redundancy requirements based on preliminary reliability estimates were included in the definition of candidates. Candidates added to those considered in the Phase II study are: (1) configuring the APS as autonomous pods with self-contained tankage and (2) upward integration of all equipment which does not require replenishment into a single module and integration of all consumables into a second replacement module.

The Phase II baseline requires a minimum of two module replacements per round trip based on replenishment requirements. Reconfiguration of the APS to autonomous pods would result in three module replacements and reduce the number of fluid disconnects to zero. Reliability analysis indicates that a redundant APS subsystem is likely to be required. Two autonomous pods 180 degrees apart, each containing functional redundancy, were selected as a representative subcandidate. Consideration of upward integration of nonconsuming equipment and integration of all consumables into a single replacement module (centralized replenishment) provides a continuous range of candidates between the Phase II baseline and the single command and control module.

MULTIPLE MODULE CANDIDATES

DISCRETE REPLACEMENT MODULES

	<u>PHASE II BASELINE</u>	<u>AUTONOMOUS APS PODS</u>	<u>CENTRALIZED REPLENISHMENT</u>
POWER		X	ONE MODULE FOR REPLENISHMENT
APS TANKAGE		} 2 PODS	
(2) APS ENGINES			
PROPELLANT MANAGEMENT		X	ONE MODULE FOR MAINTENANCE
FLIGHT CONTROL		X	
OPTICAL SENSOR		X	
INSTRUMENTATION		X	
TOTAL MODULES	8	7	2
REPLACE EACH MISSION	2	3	1

MULTIPLE MODULE EVALUATION

Three candidates are compared to determine which would best represent the multiple maintenance module category. This evaluation consisted of three specific aspects: (1) the weight penalty incurred for packaging the various module approaches, (2) the total number of functional disconnects (both fluid and electrical) required to be designed and the total number of disconnects to be made and broken each round trip, and (3) orbital support requirements.

The weight penalty shown for the Phase II Baseline includes 267 lb of aluminum structure for packaging the eight modules, 53 lb for eight fluid disconnects, and 71 lb for electrical panels and connectors. For the autonomous APS pods, 27 lb of disconnects can be saved, however, an additional packaging penalty of 50 lb and a propellant residual and valving penalty of 90 lb were assigned. Largely because of the requirement of an additional standard docking structure, the centralized replenishment candidate shows a substantially higher weight.

The eight fluid disconnects represent four APS connections which must be broken each round trip unless autonomous pods are provided, and two pressurization lines plus the vent and fill line which would be broken only for specific maintenance operations after a component failure.

Because the centralized replenishment candidate has only a standard docking structure interface, only the space tug is required for orbital support. The other two candidates require a maintenance unit to adapt the module interface to the space tug.

Based largely upon the reduced number of disconnects required and nominal weight penalty, the autonomous APS pod approach was selected to represent this category.

MULTIPLE MODULE EVALUATION

	<u>PHASE II BASELINE</u>	<u>AUTONOMOUS APS PODS</u>	<u>CENTRALIZED REPLENISHMENT</u>
WEIGHT PENALTY (LB)	391	505	956
FUNCTIONAL DISCONNECTS EACH MISSION:			
FLUID	4	0	4
ELECTRICAL	4	4	2
TOTAL:			
FLUID	8	4	8
ELECTRICAL	11	10	5
ORBITAL SUPPORT	TUG + MAINTENANCE UNIT	TUG + MAINTENANCE UNIT	TUG ONLY

SELECTION--AUTONOMOUS APS PODS

SINGLE COMMAND AND CONTROL MODULE CANDIDATES

Two command and control module (CCM) candidates identical in concept but of different physical configuration were considered: (1) the wafer configuration and (2) the outrigger configuration. Implicit in the outrigger configuration is space shuttle compatibility with the docking structure facing the cargo bay opening, providing for easy removal by a space tug. The wafer configuration, on the other hand, has the potential of maintaining the 15-ft-diameter constraint of the space shuttle when mounted with the docking structure in plane with the forward bulkhead, thus efficiently utilizing the space shuttle cargo bay. It is likely, however, that this configuration with fixed APS nozzles and consideration given to removal from the space shuttle would also be carried with the docking structure directly accessible. The primary concern motivating a candidate other than the wafer configuration was to avoid the potential plume impingement problems resulting from APS firings. In the wafer configuration the required cant angle is 29 degrees for the center of thrust to avoid impinging the RNS forward dome. For the outrigger configuration this angle can be reduced to zero.

SINGLE COMMAND AND CONTROL MODULE CANDIDATES

SINGLE COMMAND AND CONTROL MODULE SELECTION

An analysis was performed to determine the APS nozzle cant angle required for various outrigger configurations to reduce heating of structures due to impingement to an acceptable level. This was translated to an APS propellant and structural weight penalties for various lengths of outrigger arms. Based on 1,200 lb of APS aft nozzle propellant usage and 16 lb/ft of outrigger length, a relatively constant total weight penalty of between 133 and 150 lb occurs corresponding to the optimum range of 2- to 7-ft outrigger lengths. Three-foot outriggers with a structural weight of 68 lb were selected corresponding to a cant angle (θ) of 20 degrees. The APS propellant weight penalty, W_p is:

$$W_p = 1,200 \text{ lb} (1 - \cos \theta)$$

$$W_p = 72 \text{ lb}$$

SINGLE COMMAND AND CONTROL MODULE SELECTION

- HYBRID CONFIGURATION SELECTED
 - EQUIPMENT CONTAINED IN WAFER
 - OUTBOARD APS PODS
 - 3 FT EACH SIDE
 - TRANSVERSE ORIENTATION IN SPACE SHUTTLE
- WEIGHT PENALTY -- 459 LB

IN-SITU MAINTENANCE CANDIDATES

The in-situ maintenance category using manual replacement and inplace replenishment is represented by two candidates. The first candidate utilizes a pressurized forward skirt which would enable shirtsleeve maintenance operations when supported by an orbital workshop type airlock. Maintenance operations would be effected by a man at a low replacement level (black box or valve assembly). The second candidate would require backpack EVA and consist of accessible equipment mounted in the forward portion of the RNS. An estimated 80 line replaceable units (LRU) would be replaceable in either candidate.

IN-SITU MAINTENANCE CANDIDATES

IN-SITU EVALUATION

The major weight differential for the two candidates is based on the structural elements required to provide a shirt-sleeve environment. 840 lb of structure and mounting equipment is assigned to achieve a shirt-sleeve environment. Only 90 lb of mounting equipment would be required for EVA due to the essentially free mounting structure available on the forward thrust structure. Based on orbital workshop experience, 180 and 244 lb, respectively are assigned to astronaut aids and fluid and electrical disconnects. Instrumentation and display penalties of 240 and 380 lb, respectively, are assessed based on the requirement to fault isolate to the LRU in orbit.

Although a shirt-sleeve environment provides substantially greater capability for diagnostics, repair and calibration, it also has the highest passivation requirement and potentially offers some serious safety problems. Additionally, an air lock would be required as an orbital support element. Backpack EVA offers somewhat less hazard than the shirt-sleeve environment but does require life support and generates maximum impact on the various subsystem designs.

Backpack EVA was selected as the representative for this category based on the substantial weight advantage and minimal hazard.

IN-SITU EVALUATION

SHIRT SLEEVE ENVIRONMENT

- 1260 LB
- GREATER CAPABILITY
 - DIAGNOSTICS
 - REPAIR
 - CALIBRATION
- HIGHEST PASSIVATION
AND SAFETY REQUIREMENTS
- AIRLOCK ORBITAL SUPPORT

EVA

- 714 LB
- MAXIMUM IMPACT ON SUBSYSTEMS
- LESS HAZARDS
- LIFE SUPPORT FOR EVA

SELECTION -- EVA

MAINTENANCE LEVEL EVALUATION

The representative candidates of the three categories were compared to determine the maintenance level. The accompanying illustration summarizes the evaluation results. The RNS offers essentially free mounting structure for in-situ maintenance conveniently located on the forward thrust structure. A weight penalty for instrumentation was assessed to allow for orbital display and fault isolation to the LRU. Additionally, a small weight penalty was assessed to provide for the electrical and fluid disconnects to facilitate removal of the anticipated 80 LRU's. This accounts for a slight weight penalty for in-situ compared to the other two candidates. Although the weight penalty to provide thermal and meteoroid protection was not quantified, the single command and control module would seem to offer some advantages over the other two candidates.

Assuming the engine module is replaceable in all cases, all three candidates are able to maintain the equipment to which greater than 99 percent of the RNS unreliability is attributed. For the three candidates, the single command and control module requires the minimum number of orbital operations both each round trip and on an unscheduled basis.

With a minimum number of operations and a single repetitive operation each round trip, the single command and control module was assessed to have the highest reliability of operations. Because of the extensive EVA and the relative unpredictability of successful manned operations, the reliability of performing operations successfully with an in-situ maintenance policy was assessed to be lower. Because of the large number of disconnects that would have to be incorporated into the subsystem design, an in-situ maintenance policy would impact the reliability of the RNS unfavorably. The ability to test the refurbished command and control module on the ground with relatively unlimited support and the potential of using a minimum number of disconnects both within and external to subsystems resulted in a minimum impact assessment to RNS reliability for a single command and control module concept.

Based on these considerations, the single command and control module is selected for the orbital maintenance level in this trade study.

MAINTENANCE LEVEL EVALUATION

	<u>MULTIPLE MODULES</u>	<u>SINGLE COMMAND AND CONTROL MODULE</u>	<u>IN-SITU</u>
WEIGHT PENALTY (LB)	505	459	714
RNS UNRELIABILITY COVERED	0.992	0.990	0.996
OPERATIONS-EACH TRIP	REPLACE 3 MODULES (1 DOCKING OPERATION)	REPLACE 1 MODULE	REPLENISH BY TANKING EVA EXPECTED FOR REPLACEMENTS
- AS REQUIRED	REPLACE 4 MODULES	NONE	EXTENSIVE EVA
RELIABILITY OF OPERATION	NOMINAL	HIGHEST	LOWEST
IMPACT ON RNS RELIABILITY	NOMINAL	MINIMUM	MAXIMUM
SUPPORT REQUIRED	TUG + MAINTENANCE UNIT	TUG ONLY	TUG + CREW MODULES

SELECTION -- SINGLE CCM

COMMAND AND CONTROL MODULE

CLASS 1 HYBRID

The selected candidate of the maintenance level trade study is detailed. The central wafer contains essentially all the functional components and consumables. The 3-ft outriggers support redundant APS nozzles so canted that the heating rates from the exhausts of the aft nozzles do not exceed the material limits in the forward dome area. The standard probe/drogue docking structure is utilized.

The cylindrical section of the command and control module employs two integrally stiffened (60-degree waffle pattern) segments with a membrane thickness of 0.025 in., a rib height of 0.420 in., a rib thickness of 0.050 in., and a rib length of 4 in. The outrigger arms are fabricated from aluminum angles. The integral shroud concept is utilized for meteoroid protection. It consists of a 1-in.-thick layer of rigid foam and a 0.020-in.-thick fiber glass shell.

COMMAND AND CONTROL MODULE

CLASS 1 HYBRID

14916

PROPELLANT RESUPPLY

Because propellant resupply accounts for a major portion of the RNS transportation system costs, an economical resupply concept is essential. Candidate concepts are identified in the accompanying illustration. In each case the RNS propellant is resupplied at the 260-nmi, 31.5-degree inclination operational orbit. For the integral tanker concept, the LH₂ is delivered directly by the space shuttle and propellant transfer occurs between the space shuttle and the RNS. For the deployed tanker concept, the space shuttle can deploy the tank at a lower orbit and the space tug can pick it up, take it to the 260-nmi orbit, and return it to the space shuttle after its propellant has been depleted. Similar operations would be employed for replacement tankage except that depleted RNS tanks would be replaced by identical loaded modules and recycled. In the analysis the deployment altitude was optimized for each case.

Tanks for the three concepts were sized to occupy a 15-ft-diameter by 60-ft volume in the space shuttle cargo bay. Note that an optimized integral tanker design could utilize the space and clearance between the cargo bay and nominal payload dimensions. The nominal space shuttle performance to the operational orbit is indicated for the equal payload up and down case as 33,000 lb according to MSFC guidelines. A trade factor for weight of payload up divided by weight of payload down of -0.27 was used as a baseline obtained from the Integral Launch and Reentry Vehicle system studies, representing an optimized vehicle design for propellant resupply. Sensitivities to these space shuttle performance factors were evaluated. The MSFC guideline space tug has a gross weight of 60,000 lb and a 450-sec specific impulse. However, a number of alternate tugs were also evaluated to optimize performance.

PROPELLANT RESUPPLY

CANDIDATES

- INTEGRAL TANKER
- DEPLOYED TANKER
 - SPACE SHUTTLE TO LOW EARTH ORBIT
 - SPACE TUG TO OPERATIONAL ORBIT
- REPLACEMENT TANKAGE
 - SAME MODE AS DEPLOYED TANKER

STUDY GUIDELINES

- SPACE SHUTTLE PAYLOAD PERFORMANCE
 - 33,000 LB UP AND DOWN (260 NM, 31.5°)
 - -0.27 LB UP/LB DOWN TRADE FACTOR
- SPACE TUG PM/PPE
 - 60,000 LB GROSS WEIGHT
 - $I_{SP} = 450$ SEC

PROPELLANT RESUPPLY EVALUATION

The integral tank was designed for 20 psia. It requires no meteoroid protection and little thermal insulation because it is inside the space shuttle, and requires no docking structure because the space shuttle docking structure is utilized. It incorporates a propellant transfer system. The inert weight including residuals is 4,200 lb, and when fully loaded it can contain 40,300 lb of useable LH₂. The deployed tanks are designed for 32 psia and provide both thermal and meteoroid protection and docking structure. The tanks' inert weight is 7,400 lb, and when fully loaded they contain 36,600 lb usable LH₂. The replacement tank is identical to the deployed tank except the inert weight is 1,200 lb lower.

Several propellant resupply system performance sensitivities are depicted in the accompanying illustration. The first graph shows the performance of the space shuttle for equal payloads up and down and applying the baseline payload trade factor for a 7,400-lb deployed tank. The points on the curve show where 16 psia saturated liquid or 100 percent solid hydrogen would become a volume- or weight- limited payload for the deployed tank. The useable payload to orbit is reduced below these values by the amount of the tank inert weight and the propellant loading for the space tug to transfer between the space shuttle and the RNS. The single point of an integral tanker is also shown.

The cost of propellant in orbit was assessed including the \$5 million launch cost of the space shuttle, the amortized cost of the propellant tanks, and the estimated cost of using a tug. Tanks were prorated over 100 reuses and the tug was prorated over 10 refuelings with additional \$1 million cost for checkout after refueling. Tug use was idealized, neglecting velocity penalties for orbit phasing, and the cost of additional orbital operations (including reassembly). The nominal propellant delivery cost with the integral tanker is \$137 per lb.

The cost sensitivity data show the integral tanker to be more economical than an idealized deployed tank with the reference tug over the range of space shuttle payload up vs down trade factors. A non-optimum space shuttle design which could not benefit from reduced payload return to the ground with a tanker would represent a 14 percent penalty on the delivered cost of LH₂. The effect of hydrogen density on the transportation cost to orbit is shown, including the range of slush. For the baseline system performance, the deployed tank becomes competitive with the integral tanker only for

PROPELLANT RESUPPLY EVALUATION

BLANK

PROPELLANT RESUPPLY EVALUATION (Cont)

delivery of slush. However, the integral tanker is weight-limited, so it could benefit from use of slush only with improved space shuttle performance. Finally, the hydrogen resupply cost is shown as a function of the space shuttle payload to orbit (equal up and down capability). The deployed tank does not benefit significantly from performance gains because it becomes volume-limited. However, the integral tanker could achieve meaningful cost reductions with improved performance. Reduction of space shuttle performance below the current groundrule would jeopardize delivery of the NERVA to orbit.

PROPELLANT RESUPPLY CONCLUSIONS

Based on these evaluations the integral tanker mode is recommended as the most economical propellant resupply mode. It is favored for an optimized space shuttle for any tug size. It represents the minimum set of orbital operations compared to either the deployed tanker or replacement mode. Because it is weight-limited under the current space shuttle performance ground rules, it will benefit the most from improved space shuttle performance. Slush was found to reduce the propellant delivery costs for the integral tanker mode only with improved space shuttle performance.

The idealized deployed tankage evaluation indicates that there was no economic advantage for the idealized replacement tankage mode. Furthermore, replacement of tankage for each mission would incur excessive operations not only for delivery of the propellant tanks to the RNS, but also because of the complications associated with vehicle disassembly and assembly.

PROPELLANT RESUPPLY CONCLUSIONS

RECOMMENDED MODE -- INTEGRAL TANKER

- SUPERIOR PERFORMANCE
- MINIMUM OPERATIONS
- WILL BENEFIT MOST FROM IMPROVED SPACE SHUTTLE PERFORMANCE

SLUSH IS ONLY ATTRACTIVE WITH IMPROVED SPACE SHUTTLE PERFORMANCE

REPLACEMENT TANKAGE INCURS EXCESSIVE OPERATIONS

- DELIVERY
- VEHICLE DISASSEMBLY AND ASSEMBLY

PROPELLANT-PROPULSION MODULE CONTROL TRADE STUDY

The run tank of the NERVA propulsion module serves a number of useful purposes in the operation of the RNS. It facilitates engine removal and replacement and greatly simplifies provision of NERVA propellant condition requirements for startup and aftercooling transients. During steady-state operation it acts as a surge tank. A control system is required to regulate the pressures in both the run tank and the main propellant tank(s). In addition, the control system must reduce the flow rate of LH_2 into the run tank when it becomes too full and must increase the flow rate when it becomes too empty. The objectives of the propellant-propulsion module control trade study are identified in the accompanying illustration.

PROPELLANT-PROPULSION MODULE CONTROL TRADE STUDY

14932

OBJECTIVES

- **DEFINE AND EVALUATE PRESSURE AND FLOW CONTROL SYSTEMS**
- **SELECT BASELINE CONTROL CONCEPT AND OPERATIONS**
- **ESTABLISH CONTROLLER BANDS AND RESPONSES**
- **ESTABLISH OPERATING PENALTIES**
 - **TANK PRESSURE LEVELS**
 - **PROPELLANT VENTED**

PROPELLANT FLOW HISTORY AND REQUIREMENTS

The accompanying illustration depicts a model for the NERVA flow rate, run tank propellant loading, run tank pressure, and propellant tank pressure for the startup ramp and full power operation. NERVA flow rate goes through the bootstrap and ramp-up phases reaching a steady state full power flowrate of 91.9 lb per sec after 56 sec. The shortest full power burn times are indicated on the graph: transearth injection for the four-burn lunar shuttle mission profile; and transearth injection (third impulse) and lunar orbit injection (first impulse) for the six-burn lunar shuttle mission profile, which incorporates plane changes and elliptic phasing orbits at the moon.

During the 56-sec startup ramp, the run tank propellant loading declines from a nominal initial loading of 9,500 lb LH₂ to 8,470 lb. If the run tank were not replenished from the associated propellant tank(s), it would be depleted in 150 sec total time (92 sec of full power operation). This indicates that it will be necessary to bring the propellant tank on line quickly. The dashed line in the figure shows an example of refilling the run tank and returning it to a steady-state operating level. An index of relative radiation dose rate at the top of the run tank is shown alongside the run tank propellant loading. For example, maintaining a steady state 8,000-lb LH₂ loading would result in a 40 percent higher dose rate than the 9,500-lb LH₂ loading. A desire to maintain the dose rate within a 5 percent band would require control of the LH₂ loading to within 250 lb.

The pressure level in the run tank is also depicted with regimes where a range of pressurant flow rates would apply. The run tank is prepressurized during the bootstrap period from 16 to 26 psia to be ready for the ramp-up period. When the propellant tank has been brought on line, the steady-state run tank pressurant flow rate is 0. The propellant tank pressure history is also shown. It is prepressurized during the time after full power has been achieved and prior to the time when the run tank propellant loading has reached the selected minimum level. A pressurant flow rate larger than required for steady-state expulsion is employed while refilling the run tank, which is vented simultaneously.

The numbers selected for the examples in this figure are not specific design requirements or selected modes of operation. Rather, they are intended to illuminate the system operations and their relationships. These include a desire to minimize the propellant drop in the run tank and to refill it quickly, with the consequent desire to have the propellant tank pressurized early in the operating phase. This can amplify the pressurant flow demand on NERVA.

PROPELLANT FLOW HISTORY AND REQUIREMENTS

CONTROL STUDY ELEMENTS

The accompanying illustration identifies the three parameters which are sensed for control of the system and identifies the controllers which can be operated from the sensed parameters to achieve desired design conditions. The control system must be able to: regulate the startup and shutdown ramp; refill the run tank after startup when the propellant module has been brought on line; adjust to acceleration head changes during burn, including switching between tanks in the Class 3 RNS; respond to flow rate changes for the NERVA emergency mode operation at 60 percent of full power; and control fluctuations within controller hardware pressure bands at steady state.

CONTROL STUDY ELEMENTS

SENSED PARAMETERS

- PROPELLANT TANK ULLAGE PRESSURE
- RUN TANK ULLAGE PRESSURE
- RUN TANK LIQUID LEVEL

CONTROLLERS

- PROPELLANT TANK PRESSURANT FLOW RATE
- RUN TANK PRESSURANT - VENT FLOW RATES
- PROPELLANT TANK - RUN TANK LH₂ FEED VALVE

SYSTEM REQUIREMENTS

- STARTUP AND SHUTDOWN RAMPS
- REFILL RUN TANK AFTER STARTUP RAMP
- ADJUST TO ACCELERATION HEAD CHANGES DURING BURN
- RESPOND TO NERVA EMERGENCY MODE
- CONTROL FLUCTUATIONS WITHIN CONTROLLER BANDS AT STEADY STATE

CANDIDATE PROPELLANT-PROPULSION MODULE CONTROL SYSTEMS

A variety of concepts for connecting the control sensors and controllers which were considered are shown in the accompanying illustration. Control systems 1 through 6 are characterized by connecting a single sensor to each controller. Candidate No. 7 has the two sensors on the propulsion module connected to a single controller. The gross characteristics of these control system concepts will be described and compared in the next illustration.

CANDIDATE PROPELLANT-PROPULSION MODULE CONTROL SYSTEMS

CONTROL SYSTEM NO. 5

CONTROL SYSTEM NO. 6

CONTROL SYSTEM NO. 7

CONTROL SYSTEM NO. 1

CONTROL SYSTEM NO. 2

CONTROL SYSTEM NO. 3

CONTROL SYSTEM NO. 4

COMPARISON OF CONTROL SYSTEM CANDIDATES

Control system concepts 1, 2, and 7 are characterized by independent pressure control on each tank. This permits prepressurization or pressurant makeup as required in any tank and accommodates different thermodynamic states in each tank. Control system No. 1 is the only one which is suitable for startup and shutdown ramps to bring the propellant tank on line. It is seen that several of the concepts are subject to wide variations of control response in the coupling of the run tank liquid level to the large pressurized volume of the propellant tank.

Independent operation of the run tank would be desirable. Orbital checkout would be simplified because it would be on a discrete module basis compatible with the module assembly and replacement concept. Ground test simulation would also be simplified because the run tank could be connected to arbitrary tankage configurations and still demonstrate operation on an integral run tank. These would provide significant economic benefits to the program. The control system would be applicable to either a Class 1 or a Class 3 RNS and would permit an arbitrary multiple tank buildup between missions. Concepts 1 and 7 have the additional feature of providing direct control of tank pressure for NERVA. Control system concepts No. 1, 2, and 7 were therefore considered to be the most attractive, while the other four concepts were considered inconsistent with the simplified RNS module replacement concept.

Since control system No. 1 accommodates startup and shutdown ramps and also permits refilling the run tank with minimum additional pressure head built into the system, it was selected as the baseline for further evaluation. The latter consideration reflects a tank weight penalty of 500 lb per psia which is charged at \$5,000 per lb for 10 reuses on the lunar shuttle mission.

COMPARISON OF CONTROL SYSTEM CANDIDATES

CANDIDATE CONCEPT	TANK PRESSURES	CONTROLLER RESPONSE VARIATION	RUN TANK OPERATION	ORBITAL C/O AND GROUND SIMULATION
✓ 1	INDEPENDENT	MODERATE	INDEPENDENT	SIMPLE
2	INDEPENDENT	MODERATE	INDEPENDENT, STEADY STATE	SIMPLE
3	RUN TANK INDEPENDENT	EXTREME	COUPLED, STEADY STATE	COMPLEX
4	Δp CONTROL	EXTREME, INDIRECT CONTROL	COUPLED, STEADY STATE	COMPLEX
5	Δp CONTROL	EXTREME, INDIRECT RUN TANK p	COUPLED STEADY STATE	COMPLEX
6	Δp CONTROL	EXTREME	COUPLED, STEADY STATE	COMPLEX
7	INDEPENDENT	MODERATE	INDEPENDENT, STEADY STATE	SIMPLE

RESPONSE TO VALVE IMPEDANCE CHANGE

A variety of actions can be taken with the control system in order to accomplish an operational requirement such as refilling the run tank or maintaining tank pressure within a control band. In order to understand the behavior of the coupled system it is useful to investigate the response of the system parameters to a variety of single controller actions. Any control action affects all of the sensed parameters simultaneously. A series of representative actions which would be associated with fluctuations within control bands will be described.

The first case considered is response of the system parameters to a change in valve impedance amounting to a 10 percent reduction of the run tank feed system impedance. A steady-state feed system pressure drop of 1 psia is used and the propellant tank volume, $V_1 = 34,750 \text{ ft}^3$, corresponds to a half-full Class 1-H propellant tank. A range of run tank ullage volumes is shown here: $V_2 = 2,270 \text{ ft}^3$, empty; $V_2 = 1,435 \text{ ft}^3$, 3,500 lb-LH₂; and $V_2 = 113 \text{ ft}^3$, full (9,500 lb-LH₂) with 5 percent ullage. The perturbation of the flow rate ($\dot{m}'$) above the steady state value of 91.9 lb per sec is shown as a function of time. The flow rate perturbation is quickly damped out and the system returns to its steady state flow rate. The incremental propellant (Δm) which would change the run tank liquid level from the steady state is indicated. The valve impedance reduction resulted in only a small slug of propellant being added to the run tank loading.

The perturbations of the pressure from the steady-state value in the propellant tank (P_1') and the run tank (P_2') are also shown. It is seen that the reduction of the valve impedance led to an increase of the pressure in the run tank and a small reduction of the pressure in the propellant tank. These pressure changes balanced the change of the feed system impedance, thereby restoring the steady-state flow rate. The run tank sustained a modest pressure rise, less than 0.2 psia.

RESPONSE TO VALVE IMPEDANCE CHANGE

10% REDUCTION ($V_1 = 34,750 \text{ FT}^3$)

RESPONSE TO PROPELLANT TANK PRESSURIZATION

Another typical single controller action is to pressurize the propellant tank by increasing the pressurant flow rate above the steady-state expulsion flow rate. The example shown here is for an incremental pressurant flow rate of 0.035 lb per sec, or somewhat less than 10 percent of the steady-state value. The same system parameters are used as in the preceding case. It is seen that a small increase in the flow rate from the propellant tank into the run tank is achieved. However, the increment is too small to fill the tank rapidly. The pressure perturbations in the run tank (P_2') and propellant tank (P_1') are also shown. After an initial phase lag, the pressures become closely coupled and rise at a constant and identical rate. Thus, the system would require a continuous increase of the pressure in order to refill with a substantial amount of LH_2 .

RESPONSE TO PROPELLANT TANK PRESSURIZATION

10 % INCREASE ($V_1 = 34,750$)

14946

RESPONSE TO RUN TANK VENTING

Another single controller action is to vent the run tank. The example shown here is for a vent rate of 0.035 lb per sec, or somewhat less than 10 percent of the steady-state expulsion pressurant flow rate in the propellant tank. The other system parameters are the same as previously. An increment of the flow rate above the steady-state value is achieved, and the magnitude is somewhat larger than for the case of pressurizing the propellant tank. The pressure in the propellant tank is closely coupled to that in the run tank, and after the initial phase lag, a constant incremental pressure drop is maintained. The LH₂ loading change is comparable to that for the valve impedance change, or less than 50 lb before steady state is achieved.

RESPONSE TO RUN TANK VENTING

10% OF EXPULSION PRESSURANT FLOW ($V_1 = 34,750$)

RESPONSE TO EMERGENCY POWER MODE -- 0.6 FULL FLOW

The accompanying illustration shows the response of the system without control actions to a step change in the flow rate out of the run tank to 0.6 full flow for the emergency power mode. The reduction of the flow rate from the initial value is shown, together with the increase in the propellant loading of the run tank which occurs while the inflow rate exceeds the outflow rate before steady state has been achieved. The pressures in the run tank and propellant tank increase during this process. If the pressure control band on the run tank were small, as would be expected in practice, the run tank would need to be vented before this response pattern were permitted to complete its development. Similarly, the expulsion pressurant flow rate would need to be reduced to match the new expulsion rate, or the propellant tank pressure would continue to rise.

RESPONSE TO EMERGENCY POWER MODE - 0.6 FULL POWER

($V_1 = 34,750 \text{ FT}^3$)

14948

CONTROL SYSTEM OPERATION ASSESSMENT

The examples presented show that the system is highly self-regulating and seeks to return to steady state. Additional variations of the parameters over ranges of interest were investigated. Single controller action is inefficient for filling the run tank, imposing multiple cycles, venting, and slow implementation on the system. Instead, the system would be used in a mode with the simultaneous action of three controllers to refill the run tank: run tank feed impedance variation, pressurization of the propellant tank, and venting of the run tank. This implies tight sensor hardware control bands.

The controller responses shown indicate that a small deadband would be permitted between pressurization and vent bands in each of the tanks. The incremental pressurant and vent flow examples led to less than 0.2 psia run tank pressure changes for 10 percent variations of the gas flow rate. Similarly, a 10 percent feed valve impedance change resulted in less than 0.2 psia run tank pressure change. While the emergency mode transient can be accommodated by the system, a desire to use small pressure control bands would impose a requirement to vent the run tank for the emergency transient. The associated requirements on the vent system are reasonable. The LH₂ loading fluctuations can probably be limited to 100 lb.

CONTROL SYSTEM OPERATION ASSESSMENT

SYSTEM HIGHLY SELF-REGULATING

USE COMBINED ACTION OF THREE CONTROLLERS (TIGHT BANDS) FOR LIQUID LEVEL CONTROL

SMALL DEADBAND PERMITTED BETWEEN PRESSURIZATION AND VENT BANDS

- INCREMENTAL PRESSURANT OR VENT FLOW AT 10% OF EXPULSION PRESSURANT FLOW RATE YIELDS < 0.2 PSIA RUN TANK PRESSURE CHANGE
- 10% FEED VALVE IMPEDANCE CHANGE YIELDS < 0.2 PSIA RUN TANK PRESSURE CHANGE

EMERGENCY MODE TRANSIENT ACCOMMODATED

- REQUIRED RUN TANK VENT
 - ~ 0.1 SEC RESPONSE FOR 0.2 PSIA DEADBAND
 - ~ 0.12 LB/SEC VENT

ACCELERATION HEAD AND PRESSURE DROP TO RUN TANK FEED CONTROL

The acceleration head and line loss pressure drop from the propellant tank to the run tank feed control valve will influence the separation of the design pressures in the run tank and propellant tank(s). These are depicted here for the lunar shuttle mission for both the Class 1 and Class 3 RNS, together with their difference, which is the net ΔP built into the system. It is seen that the Class 3 RNS will impose a larger pressure differential and also undergoes some significant transients during steady-state operation as the propellant supply system switches from tank to tank. These effects must be accommodated in the design of the control system.

ACCELERATION HEAD AND PRESSURE DROP TO RUN TANK FEED CONTROL LUNAR SHUTTLE MISSION

14949

CLASS 1-H

CLASS 3

PROPELLANT-PROPULSION MODULE PRESSURE SCHEDULES

The accompanying illustration depicts a typical relationship between various pressure bands in the propulsion and propellant modules. A deadband for steady state operation is provided between the pressurization and vent bands within each module. Based on the preceding evaluation, this was selected as 0.2 psia to permit the control system to undertake isolated corrective actions one at a time with minimum excitation of the system. The pressure schedules for the propulsion module and propellant module are separated as indicated by the feed system pressure drop. A buffer pressure drop is built into the pressure schedule between the propulsion and propellant modules. This will be discussed on the subsequent illustration.

The pressure schedules are developed for the tolerances associated with three hardware options. The pressure switch sensor operated in conjunction with bang-bang valves, used for pressurization on S-IVB, results in the largest pressurization and vent bands. A regulator system with a back pressure regulator vent is also evaluated. The final candidate is a strain gage sensor coupled to a bang-bang valve operation, which would be the most accurate system. The bands identified are considered to be a reasonable assessment of the tolerance capabilities of these systems, but would impose high cycle-life capabilities on the components. Additional strategies could be employed to develop these bands, utilizing desired hardware characteristics such as variable flow rates. These deserve further investigation.

As discussed in the subsequent chart, the buffer ΔP imposed in the schedule is taken as equal to the hardware band, consisting of the sum of pressurization, vent, and module deadband. In view of the 500 lb per psia tank weight penalty, it is evident that the most accurate control concept would be desired. That could reduce the penalty for more complex control strategies, such as multiple expulsion pressurant flow rates.

The run tank LH_2 loading varies 614 lb/ft. Optical point liquid level sensors have an accuracy of ± 0.01 in., corresponding to 0.05 lb- LH_2 . Thus, liquid level control does not appear limiting for control system accuracy.

PROPELLANT-PROPULSION MODULE PRESSURE SCHEDULES

14939

IMPLICATIONS OF PRESSURE DIFFERENTIALS BETWEEN MODULES

The flow rate ($\dot{m}$) into the run tank varies as the square root of the pressure drop across the run tank feed system. The pressures in the run tank and propellant tank can vary within the ranges of their hardware deadbands. Consequently, for a fixed impedance, a wide variation from the steady state flow rate $\dot{m}_0$ could be incurred. A buffer ΔP is desired in order to minimize the magnitude of the allowed fluctuation. The impact of the buffer ΔP on the magnitude of the fluctuations is shown in the associated graph. The hardware ΔP is defined to consist of the sum of the pressurization and vent bands and module deadband. The reference used in establishing the representative pressure schedules was to set the buffer ΔP equal to the hardware ΔP , resulting in a 22 percent maximum flow increase and a 30 percent flow decrement.

The dependence of the incremental flow rate for refilling the run tank on the nominal feed system pressure drop (line losses) and the flow control valve impedance is shown. Thus, a rapid refill rate imposes higher operating pressures on the system.

IMPLICATIONS OF PRESSURE DIFFERENTIALS BETWEEN MODULES

14940

TIME TO REACH STEADY STATE VS RUN TANK ULLAGE VOLUME

The transient behavior of the system to controller action for a number of circumstances including those already discussed is shown in the accompanying illustration. The time to reach steady state is given as a function of the ullage volume, V_2 , of the run tank. These data indicate that the larger run tank ullage volumes result in slower transients, and consequently, a more easily controlled and less excited system.

However, the previous analysis of the propellant flow history and requirements indicated that a low liquid level in the run tank would result in increased radiation dose rates. This contrary desire probably will prove to be more significant. Prepressurization of the run tank would also favor a smaller initial ullage volume, but that includes consideration of operations which are not as yet fully defined.

Considering these factors, a nominal steady-state run tank liquid level of 8,000 lb LH_2 was selected. This would result in an ullage volume of about 450 cu ft, which would appear to provide a reasonably well controlled transient behavior while incurring a 40 percent increase in radiation dose rate as compared to a full (9,500 lb LH_2) run tank during steady state.

TIME TO REACH STEADY STATE VS RUN TANK ULLAGE VOLUME 14950

LH₂ FLOW RATE CONTROL ASSESSMENT

The accompanying illustration shows a number of factors bearing on the flow rate control range of the run tank feed system. The variations of acceleration head and pressure drop associated with changing tanks (Class 3), which influence the feed system pressure drop, are identified together with the resulting flow rate responses. The pressure controller bands and their flow rate responses are also indicated for the selected buffer, ΔP . Another factor in the flow response is the requirement to accommodate the NERVA emergency mode. Representative run tank refill times are indicated for flow control ranges comparable to those of the other factors cited. The requirement to refill the run tank rapidly would be the dominant consideration for increase of flow rate and the emergency mode response represents the design point for flow reduction. Thus, a baseline flow rate control range of ± 40 percent is considered, leaving open the possibility that subsequent analysis of alternative strategies associated with refilling the tank could lead to a desire for a larger flow rate increase or refill. Since the flow control margin for the favored strain gage/bang-bang system was 0 psi with the reference buffer ΔP , the buffer would then need to be increased by the indicated control margin. Propellant tank design pressures were calculated accordingly.

LH₂ FLOW RATE CONTROL ASSESSMENT

14951

	CLASS 1-H	CLASS 3
NOMINAL FEED SYSTEM ΔP	1.2 PSIA	2.0 PSIA
<ul style="list-style-type: none"> VARIATIONS: (1) ACCELERATION (2) CHANGE TANKS 	0.4 PSIA	1.0 PSIA
<ul style="list-style-type: none"> FLOW RATE RESPONSES 	22%	0.73 PSIA 41%
PRESSURE CONTROLLER BANDS		
<ul style="list-style-type: none"> VARIATIONS 		0.6 PSIA
<ul style="list-style-type: none"> FLOW RATE RESPONSES 		+22% -30%
EMERGENCY MODE FLOW RATE RESPONSE		-40%
REFILL RUN TANK		
<ul style="list-style-type: none"> FLOW CONTROL RANGE 		20 TO 40%
<ul style="list-style-type: none"> TIME TO REFILL 3,000 LB-LH₂ 		160 TO 80 SEC
BASELINE FLOW RATE CONTROL RANGE		$\pm 40\%$
REQUIRED FLOW CONTROL MARGIN	CLASS 1-H:	1.2 PSIA
	CLASS 3:	2.0 PSIA

PROPELLANT-PROPULSION MODULE CONTROL CONCLUSIONS

Control system No. 1 was selected from the candidates identified. It employs independent control of the module pressures. The liquid level is controlled with the feed valve between the propellant and propulsion modules, maintaining tight bands on the tank pressures. This implies simultaneous pressurization of the propellant module and venting of the propulsion module, while reducing the feed valve impedance for a refill operation. This approach permits a rapid refill without increasing the pressure drop across the feed system.

Investigation of transient effects indicates that the system is highly damped and self-controlled. This permits applying tight dead bands between the pressurization and vent hardware bands on each module while minimizing the excitation of the control system.

Accurate pressure sensors are desired to operate bang-bang controllers for pressurization and venting. Strain gage transducers are a leading candidate for this capability. Optical point level liquid sensors would provide compatible accuracy in the control of the liquid level in the propulsion module. Regulation of the flow rate within the respective module pressure bands required a buffer pressure drop between the tanks, which is minimized by accurate pressure sensors.

Tank design pressures for the baseline control system are shown for two possible NERVA design pressures: 26 psia represents a new design goal, and 30 psia is the original steady-state design requirement.

It is desired to minimize the time to refill the propulsion module during the initial phase of operation. Further evaluation of the strategies for bringing the propellant module on line are warranted. These will impact NERVA both through the pressurant bleed requirements and possible shaping of the startup transients. A steady-state liquid level of about 8,000 lb LH_2 would appear to be reasonable, balancing the desire to have a large ullage volume to slow down the system transients and the desire to provide radiation shielding to equipment at the top of the run tank. The well behaved nature of the system, including moderately slow transients and narrow bands, indicates that the propellant which would be vented from the propulsion module would be dominated by the initial refill operation, and consequently, would be limited to the range of 10 lb per burn. Further evaluation of the approach for refilling the propulsion module after NERVA cooldown and the aftercoolant propellant has been expelled from the run tank is warranted. The approach would need to be consistent with the aftercooling system operation requirements, discussed in another trade study in this report, and the overall mission timeline for providing acceleration levels.

PROPELLANT PROPULSION MODULE CONTROL CONCLUSIONS

SELECT CONTROL SYSTEM NO. 1

- INDEPENDENT CONTROL OF MODULE PRESSURES
- CONTROL LIQUID LEVEL WITH FEED VALVE - TIGHT BANDS ON TANK PRESSURES
- PERMITS RAPID REFILL WITHOUT INCREASING PRESSURE DROP

SYSTEM HIGHLY DAMPED AND SELF-CONTROLLED

- MINIMIZE CONTROL BANDS
 - ACCURATE PRESSURE SENSORS - STRAIN GAGE
 - POINT LIQUID LEVEL SENSORS - OPTICAL
- BUFFER ΔP BETWEEN TANKS

DESIGN PRESSURES (PSIA)

• NERVA		26	30
• PROPULSION MODULE		26.6	30.6
• PROPELLANT	CLASS 1-H:	29.0	33.0
MODULE	CLASS 3:	29.8	33.8

PROPULSION MODULE OPERATION

- MINIMIZE TIME TO REFILL - NERVA IMPACT ✓
- STEADY STATE LEVEL - $\sim 8,000$ LB-LH₂
- PROPELLANT VENTED DOMINATED BY REFILL ~ 10 LB
- EVALUATE REFILL AFTER NERVA COOLDOWN

AFTERCOOLING SYSTEM TRADE STUDY

At the inception of the nuclear stage design studies, NERVA reference data were provided for the hot bleed cycle engine in two documents: (1) "NERVA-Engine Briefing to Marshall Space Flight Center," AGC Report No. RN-PA-0019, dated June 24, 1969, and (2) "NERVA Reference Data," AGC Report No. RN-S-0526, dated August 1969. These documents establish rated conditions for NERVA operation as 30 psia liquid hydrogen at the tank outlet with provision of a bootstrap startup from 24 to 30 psia. They also identify a requirement for the stage to be capable of providing liquid hydrogen pressurized to 30 psia at its outlet with 0 percent vapor at all times during engine operation, including cooldown. A subsequent updating of NERVA data was provided in the report "NERVA Reference Data (Full-Flow Engine)," S-130, AGC Report No. S-130-CP-090290-F1-PREL, dated April 1970. This document identified cooldown propellant requirements and operating phase times for the new full flow design, but left the propellant conditioning requirements unspecified for all phases of engine operation. This report indicates that active cooling will be required, employing the pulse mode, until the fission product inventory decay power has been reduced to a 5-kw power level.

Because of the long times and large number of pulses involved in providing cooldown during a mission, the requirement to provide propellant to NERVA at specified conditions during aftercooling can impose severe penalties for propellant settling and/or pressurization, with a major impact on the RNS design. Thus, a trade study was initiated to determine the most effective means for providing LH_2 to NERVA at the required conditions. The previous engine requirement for LH_2 pressurized to 30 psia with 0 percent vapor during cooldown was applied as a baseline. The trade study has entailed definition and evaluation of a variety of aftercooling system concepts to fulfill this requirement. Also, the sensitivity to NERVA requirements was evaluated, considering both the radiated power level and the aftercooling operating pressure, to provide greater visibility for selection of aftercooling system concepts and to identify desirable improvements in the NERVA requirements.

AFTERCOOLING SYSTEM TRADE STUDY

RNS DESIGN REQUIREMENT:

- PROVIDE LH_2 AT NERVA CONDITIONING REQUIREMENT FOR PULSES
 - NOMINAL CONDITIONS: 30 PSIA
0 % VAPOR
- ACTIVE COOLING UNTIL DECAY TO 5 KW POWER LEVEL

TRADE STUDY OBJECTIVES

- DEFINE AND EVALUATE AFTERCOOLING SYSTEM CONCEPTS
- EVALUATE SENSITIVITY TO NERVA REQUIREMENTS
 - RADIATED POWER LEVEL
 - AFTERCOOLING OPERATING PRESSURE

NERVA AFTERCOOLING PARAMETERS

This chart summarizes the relevant NERVA aftercooling parameters for a representative four-burn reference mission used to evaluate the aftercooling system concepts. The characteristics identified include steady-state propellant consumed for each burn, the steady-state burn time, the aftercooling propellant, the total aftercooling time, the continuous flow duration portion of the aftercooling, and the total number of aftercooling pulses. The total aftercoolant propellant exceeds 5 percent of the steady-state propellant. Changes in the mission profile, including additional lunar orbit burns, would not change the conclusions of the trade study. During the initial portion of the cooldown a continuous trickle flow at 0.4 lb per second is maintained between pulses. The resulting 186-lb thrust level is sufficient for settling, but it makes a negligible contribution to the overall settling requirement because it is active for only 0.4 percent of the total cooldown time. Thus, additional functional requirements are imposed on the RNS to settle propellant. The requirement for active aftercooling of NERVA down to a power level of 5 kw results in very long aftercooling durations, particularly for the leave-earth burn.

The 8,000-lb aftercoolant requirement for the leave-earth burn is compatible with the propellant capacity of the run tank on the propulsion module. The Class 1 RNS propulsion module has a run tank with a 9,700-lb LH_2 capacity, which will be used as a baseline for this study. The portion of the leave-earth cooldown in the pulsed mode without trickle flow amounts to 5,950 lb. Operations are simplified by providing propellant conditions only in the run tank and not transferring propellant from an LH_2 tank to the run tank during pulsed cooldown. Also, the small volume of the run tank reduces pressurization and settling penalties compared to those which would be incurred if the large (Class 1 or Class 3) propellant modules were utilized.

NERVA AFTERCOOLING PARAMETERS **REFERENCE LUNAR SHUTTLE MISSION**

MISSION PHASE	STEADY STATE PROPELLANT (LB)	BURN TIME (SEC)	AFTERCOOLING PROPELLANT (LB)	TOTAL AFTERCOOLING TIME (SEC)	TOTAL AFTERCOOLING TIME (HR)	CONTINUOUS FLOW DURATION (SEC)	NUMBER OF PULSES
LEAVE EARTH	178,100	1,940	8,000	480,000	139	1,825	182
ARRIVE MOON	45,510	496	2,900	168,000	46.7	1,180	67
LEAVE MOON	16,490	180	1,400	87,000	24.2	880	34
ARRIVE EARTH	41,460	450	2,700	157,000	43.6	1,130	63
TOTAL	281,560	3,066	15,000	892,000	253.5	5,015	346

NERVA AFTERCOOLING PULSE PARAMETERS

The accompanying illustration summarizes NERVA reference data on aftercooling pulses showing the time between pulses and the duration of pulses for a range of burn times. The reference burn times for the system evaluation are indicated in the illustration. After a period of time, the duration of the aftercooling pulse decays to approximately 40 seconds per pulse. The flowrate is 0.7 lb per sec during each pulse, so that the terminal pulses consume 28 lb of LH_2 per pulse. The time between pulses increases rapidly, reaching several hours for the terminal pulses. The large number of pulses complicates operation of the RNS systems to provide propellant conditions for each pulse. On the other hand, the long cooldown duration and the long time between pulses complicates maintaining propellant conditions continuously throughout the mission.

NERVA AFTERCOOLING PULSE PARAMETERS

AFTERCOOLING SYSTEM CONCEPT DEFINITION

The aftercooling system concepts which were evaluated are defined in the accompanying illustration, which identifies principle features of the concepts. Three classes of concepts are distinguished by the technique used for propellant control: settling by acceleration, surface tension, and dielectrophoresis. The design criteria, characteristics, and operations of these systems concepts will be described briefly to indicate the basis for the system weight penalties assessed.

The propellant settling concepts employ low acceleration to locate the propellant at the bottom of the run tank. A settling criterion of Bond number equals 100 is applied, which is conservative but confirmed by S-IVB experience. This results in an acceleration level requirement of 6.73×10^{-5} g's for the Class 1 run tank, corresponding to a thrust level of 20 lb for cooldown after earth departure and reduced to 7 lb after earth arrival.

For the continuous settling concept, the acceleration level would be provided continuously for the duration of cooldown, and makeup pressurant would be added to the run tank as required to counteract the effects of ullage gas cooldown and condensation. For the pulsed settling concept, a settling impulse would be applied before each cooldown pulse cycle and a prepressurization of the run tank would be accomplished. A factor of safety of 2 times the time to relocate the propellant from the top to the bottom of the run tank was applied, resulting in a settling time of 280 sec for the reference acceleration level in the run tank. The hybrid settling system is an optimum combination of continuous and pulsed settling. Continuous settling is maintained until the time between pulses exceeds the settling time. Then settling is applied prior to each pulse. Settling propellant consumption was assessed on the basis of a 300-sec specific impulse. The rotational concept could satisfy the acceleration requirements with an end-over-end tumbling of the stage at a very low rotation rate, about one revolution every 1,000 sec. The impact of this on other operations has not been fully assessed, but it is considered that such a slow rotation, of the order of attitude limit cycling, would be tolerable.

The surface tension and dielectrophoresis concepts will be described in the subsequent illustrations.

AFTERCOOLING SYSTEM CONCEPT DEFINITION

CONCEPT	PRINCIPAL FEATURES 5415
1 PROPELLANT SETTLING A CONTINUOUS B PULSED C HYBRID D ROTATION <i>(end of end run - 1600sec)</i>	RUN TANK LH ₂ SETTLED -- BOND NO. = 100 <ul style="list-style-type: none"> • USE APS FOR DURATION OF AFTERCOOLING • USE APS PRIOR TO EACH PULSE • INITIALLY CONTINUOUS, SWITCH TO PULSED • CONTINUOUS END OVER END TUMBLING
2 SURFACE TENSION A BURP TANK B PULSE BASKET	COLLECT PULSE LIQUID WITH SCREENS <ul style="list-style-type: none"> • DISCRETE, PRESSURIZED TANK, REFILL AFTER PULSE USING APS • COLLECT LH₂ TO SETTLE, THEN PRESSURIZE
3 DIELECTROPHORESIS A ULLAGE CONTROL B PULSE BASKET	COLLECT LIQUID WITH ELECTRODES <ul style="list-style-type: none"> • ORIENT LIQUID TO MAINTAIN ULLAGE PRESSURE • COLLECT LH₂ TO SETTLE, THEN PRESSURIZE

SURFACE TENSION CONCEPTS

Two aftercooling system concepts employing surface tension for collection of LH_2 are shown schematically in the accompanying illustration.

The surface tension burp tank concept employs a small, discrete tank in the bottom of the run tank which contains LH_2 , surface tension screens to collect LH_2 , and its own pressurization system. The burp tank is isolated from the run tank at the beginning of a pulse and it is pressurized separately with cold (LH_2 temperature) helium to 30 psia. The system would operate efficiently only if the aftercooling pulse were modified to permit a lower flow rate (0.2 lb/sec) so as to provide sufficient time to settle the run tank propellant for subsequent refilling of the burp tank. A settling impulse is applied by the APS upon completion of the aftercooling pulse to refill the depleted burp tank. The burp tank is then vented and refilled while maintaining the settled propellant in the run tank. The only pressurization requirement is for burp tank expulsion, and the run tank is not pressurized. For the vent and refill operation on the burp tank 60 sec was allocated. Because of the wide variation in pulse duration, the burp tank was designed to provide single pulses during the beginning of pulsed aftercooling and two to three pulses during the later period. An alternative operation of the burp tank which avoided separate settling impulse but required run tank pressurization was evaluated but found to be less efficient.

The surface tension pulse basket concept employs a set of screens to collect sufficient LH_2 for an aftercooling pulse. The main tank screen retains liquid at the end of the tank near the pulse basket, thereby reducing settling time to refill the basket during a pulse. The concept would not fully satisfy NERVA pressure requirements, in the sense that it could only be used to guarantee 100 percent liquid but not the pressure level. Thus, an effective bootstrap approach would be required, initially settling the LH_2 in the run tank and then prepressurizing the run tank to achieve the required operating pressure after the initial portion of the cooldown pulse.

SURFACE TENSION CONCEPTS

DIELECTROPHORESIS CONCEPTS

Another alternative for control of the liquid and ullage locations in the run tank is to employ a dielectrophoretic (DEP) propellant collection concept. Two representative concepts are depicted in the accompanying illustration.

A preliminary definition of a concept to provide ullage location control is shown. A set of ribbon electrodes is located adjacent to the tank walls, and spike electrodes are located within the volume of the tank. Such a configuration could locate an ullage bubble near the top of the tank so that only makeup pressurant would be required to maintain the required propellant conditions. The peak electrode voltages would be about 100 kv, and negligible power (less than 1 watt) would be consumed to operate the device.

The pulse basket concept shown would function in a manner similar to that of the surface tension pulse basket concept, but substituting an electrode grid for surface tension screens.

DIELECTROPHORESIS CONCEPTS

WEIGHT BREAKDOWN FOR AFTERCOOLING SYSTEM CONCEPTS

A weight breakdown for the different aftercooling system concepts is shown in this table. The hardware breakdown is differentiated between the pressurization system weight penalty and fixed weight penalties such as screens, electrodes, etc. The continuous settling mode is excessively heavy because of the long aftercooling duration, although the settling penalty would be reduced if a lower Bond number were acceptable. Rotation or DEP with ullage control and the burp tank concepts are the most favorable. The system weight penalties for the other concepts are similar and excessive.

The pressurization penalties assessed need further clarification. For continuously settled or controlled LH₂, a makeup pressurization system is required to counteract the combined effects of ullage gas cooldown and condensation. The pressure decay rate for this case was estimated utilizing NASA data (TND-3219) as about 3.4 psia per hour. Pressurant was then added to the run tank to counteract the pressure loss and maintain a constant tank pressure. Alternatively, in systems where the propellant orientation is not controlled between pulses, it is assumed that the ullage collapses to the liquid temperature. A prepressurization is then required to provide the proper pressure. This was based on a 5 percent initial ullage in the run tank, initial pressures of 16, 18, 24, and 30 psia for the four mission legs corresponding to the pressure profile for the baseline insulation system, and a final pressure of 30 psia. The baseline operational prepressurization system concept stores ambient hydrogen in rechargeable bottles on the run tank, which are recharged during engine operation. This approach cannot be used economically to provide multiple prepressurizations or makeup pressurant for aftercooling, because the turbopump is not operating and the high pressure required to recharge the ambient H₂ bottles is not available. Therefore, prepressurization and makeup pressurant system weight penalties were assessed for this comparison employing an H₂/O₂ combustor system, which has previously been found to be lighter than most conventional systems (stored gas, heated helium, etc.).

WEIGHT BREAKDOWN FOR AFTERCOOLING SYSTEM CONCEPTS

LUNAR-SHUTTLE MISSION

NERVA PASSIVE COOLING BELOW 5 KW

AFTERCOOLING CONCEPT	SETTLING PROPELLANT	MAKEUP PRESSURANT	PREPRESS- URIZATION	HARDWARE (INCL He PRESSURANTS AND COMBUSTANTS)	TOTAL
1. PROPELLANT SETTLING					
A CONTINUOUS ($B_o = 100$)	35,610	790		2,370*	39,770
($B_o = 10$)	3,560	790		2,370*	6,720
B PULSED	5,143		1,945	5,835*	12,923
C HYBRID	4,752	32	1,560	4,774*	11,118
D ROTATION	128	790		2,370*	3,288
2. SURFACE TENSION					
A BURP TANK	475			3,015	3,490
B PULSE BASKET			1,945	{ 74 5,835*	7,854
3. DIELECTROPHORESIS					
A ULLAGE CONTROL		790		{ 350 2,370*	3,510
B PULSE BASKET			1,945	{ 350 5,835*	8,130

*PRESSURIZATION SYSTEM WEIGHT PENALTY

AFTERCOOLING SYSTEM WEIGHTS

The influence of NERVA radiated power level on the aftercooling system weight penalty is shown here. At high power levels, the continuous settling concept becomes more favorable than those concepts requiring prepressurization for each pulse. The DEP concept with ullage control and the rotation concept, both of which employ only makeup pressurization, remain the most favorable. The burp tank shows less advantage at higher power levels because the reduction in pulses is less than the reduction of time. It is seen that substantial weight improvements can be gained for NERVA radiated power levels as high as 50 kw.

AFTERCOOLING SYSTEM WEIGHTS

NERVA AFTERCOOLING PARAMETERS - RADIATED POWER EFFECTS

The substantial system weight penalties incurred for aftercooling are partially a result of the large number of coolant pulses and long aftercooling duration associated with the baseline 5-kw radiated power level for NERVA. The effect of increasing the radiated power level of NERVA on aftercooling duration and number of pulses is shown in the accompanying illustration, accumulated for the full mission. Significant reductions are evident. The implications of these effects were evaluated for the candidate aftercooling system concepts.

NERVA AFTERCOOLING PARAMETERS RADIATED POWER EFFECTS

TOTAL AFTERCOOLING PENALTY

The total aftercooling penalty includes the propellant wastefully expended during pulsed aftercooling operations, as well as the system requirements of the RNS to provide NERVA propellant conditions. This figure shows the total aftercoolant consumed for the reference mission as a function of the radiated power level. A minimum aftercoolant penalty is also identified based on an average aftercoolant Isp of 430 sec compared to an average steady-state Isp of 815 sec. This is the minimum penalty on the aftercooling propellant consumption if all of it is usefully employed. Because of the prolonged cooldown times, this would not be achieved in practice. This penalty will be clarified further in subsequent studies. The system weight penalties incurred for various aftercooling systems are added to the minimum aftercoolant penalty and shown in the accompanying illustration for attractive systems. Substantial gains are obtained for the rotation and DEP concepts if the radiated power can be increased to 25 kw or more. As can be seen, the major portion of the benefit is attributed to the aftercooling system concept, and the advantage from reducing propellant consumption is relatively small.

TOTAL AFTERCOOLING PENALTY

14853

AFTERCOOLING SYSTEM WEIGHTS

A review of the weight breakdown comparison for the aftercooling system concepts indicates that, even for the most favorable concepts, the major portion of the system weight penalty is attributed to the pressurization system requirement. This chart shows the sensitivity of the aftercooling system weight to the tank pressure required during aftercooling pulses. The rotation concept is representative of the continuous makeup pressurization system. The improvement of that concept with reduced tank pressure is minimal so long as it is necessary to operate with subcooled liquid. Since the burp tank concept employs pressurized helium expulsion, the gains with this system are modest also. The most substantial benefits are obtained for the surface tension pulse basket concept, which is the best of the systems employing a prepressurization for each pulse. The data shown for that system are based on providing equal pressures during steady state and aftercooling. A small reduction in system weight below about 24 psi would occur with this approach if 30 psia was required during steady state.

While reduction in the tank pressure requirement does show a benefit, major operational penalties are incurred as long as it is necessary to pressurize above the liquid saturation pressure in the run tank. Thus, the major advantage of reduced pressure would be obtained only if NERVA could operate with saturated liquid at arbitrary pressures. Because the aftercoolant pulse flow bypasses the turbo pumps and only flows through piping, this should be attainable in the engine design regardless of the power level at which aftercooling is terminated, although it might be necessary to accept reduced flow-rates. It would be desirable to adopt such a capability as a baseline for future RNS studies.

AFTERCOOLING SYSTEM WEIGHTS

TANK PRESSURE EFFECTS

AFTERCOOLING SYSTEM CONCLUSIONS

The conclusions and recommendations of the trade study are shown in the accompanying illustration. The rotation and burp tank concepts are most favorable for current groundrules, but result in weight penalties of 3,300 and 3,500 lb, respectively to provide after-coolant. The rotation concept is less reliable (0.894 without redundancy, 0.985 with redundancy) and imposes a long lifetime requirement (>180 hr per mission) on the burner pressurization system. The burp tank concept has better reliability (0.935 without redundancy, 0.999 with redundancy). Demonstration of the concept would probably require an orbital experiment.

Applying the recommended changes in NERVA groundrules results in a major system weight savings and the least complicated system, a surface tension pulse basket, having no moving parts or expendables to replenish.

AFTERCOOLING SYSTEM CONCLUSIONS

RECOMMENDED SYSTEMS WITH CURRENT GROUND RULES

- ROTATION WITH PRESSURANT MAKEUP ~ 3,300 LB
 - IMPROVES WITH INCREASED RADIATED POWER
 - ACCELERATION MINIMIZES STRATIFICATION
- BURP TANK ~ 3,500 LB
 - IMPROVES WITH REDUCED PRESSURE REQUIREMENT

RECOMMENDED CHANGES IN NERVA AFTERCOOLING REQUIREMENTS

- PROPELLANT CONDITIONS: >16 PSIA, 0% VAPOR
- RADIATED POWER: > 25 KW

PREFERRED SYSTEM WITH RECOMMENDED GROUND RULES

- SURFACE TENSION PULSE BASKET < 100 LB
 - SIMPLEST SYSTEM

RNS CLASS 3 STABILITY

Analyses have been conducted to establish the structural stability and controllability of candidate RNS Class 3 modular configurations. These configurations are based on a 15-ft-diameter by 60-ft-long EOS cargo hold. With this high length-to-diameter ratio for the basic module, an assembled vehicle consisting of many modules could be highly flexible. A tandem assembly of modules would be a longer and more flexible configuration than a clustered array. A tandem configuration, however, would be desirable for assembly operations and fluid line hookups. With these tradeoffs and assembly options, many RNS configurations were considered. These configurations include: (1) cruciform cluster, (2) planar array, and (3) tandem array. All these configurations were found to have good rigid body control characteristics with the engine located on the centerline and a distance between the cg and engine of over 90 ft. However, vehicle flexibility could be a problem, especially for the tandem configuration. Flexibility could adversely affect the vehicle in three ways:

- A. Interaction with the powered flight control system through the rough sensor pickup.
- B. Interaction of the axial acceleration with the structure—the so-called "garden hose effect."
- C. Dynamic loading of the structure caused by response of the flexible vehicle to disturbances.

To assess these potential problems, analyses were performed in the following areas: (1) modal studies, (2) powered flight attitude control system stability, and (3) axial acceleration interaction with the structural flexibility.

RNS CLASS 3 STABILITY

OBJECTIVE

- ASSURE STABILITY AND CONTROLLABILITY OF CLASS 3 CONFIGURATION(S)

ANALYSES

- MODAL STUDIES
- CONTROL SYSTEM STABILITY
 - ASTRIONICS IN CCM
- GARDEN-HOSE EFFECT
 - CRITICAL THRUST LEVEL

MODAL ANALYSES

Modal properties have been determined for a number of RNS configurations, including (1) cruciform cluster, (2) planar array, and (3) tandem array. The accompanying illustration shows the first and second mode bending frequencies for these configurations. These frequencies are for the fully loaded, 300,000-lb LH₂ capacity RNS, assuming a payload of 116,000-lb. For the tandem configuration, the two different values shown are for: (1) the fiber glass truss interstages designed by flight loads and (2) interstages between propellant modules as stiff as the propellant modules. These two cases bracket the possible interstage stiffnesses and attendant bending frequencies. The vehicle length is shown for comparison. In addition to modal frequencies, the analysis also provided the bending deflections, slopes, moments, and internal shears. This analysis was conducted for various propellant loading conditions.

MODAL ANALYSES

	VEHICLE LENGTH (FT)	FIRST MODE FREQ (Hz)	SECOND MODE FREQ (Hz)
CRUCIFORM CLUSTER	405		
NOMINAL INTERSTAGES		0.27	0.66
PLANAR ARRAY	405		
NOMINAL INTERSTAGES		0.25	0.68
TANDEM (8 PROPELLANT MOD)	645		
NOMINAL INTERSTAGES		0.12	0.35
FULLY STIFFENED		0.16	0.45

NOTES

- (1) PAYLOAD 140 FT LONG, 116,000 LB
- (2) FREQ SHOWN FOR PROPELLANT
MODULES FULL CONDITION

CONTROL SYSTEM ANALYSES

Control system requirements were based on achievement of: (1) unconditional stability and (2) acceptable attitude transient response following startup. Specifically, adequate gain and phase margins were achieved to ensure system stability. System compensation was provided where necessary to achieve these margins. To limit the attitude excursion (and attendant performance loss) following startup, a lower bound was placed on the rigid body control frequency. Based on previous studies by both IBM and MDAC, a conservative lower bound of 0.01 Hz was chosen. Since this frequency is still approximately a decade above the guidance frequency, satisfactory response to guidance commands should be obtained.

Linear control system design was used in these analyses. MDAC computer program CE06 was used to perform the stability analyses. This program was used to determine the open loop frequency responses of the control system. Gain and phase margins of the control loops were obtained from these frequency responses. A conventional controller similar to the Saturn S-IVB was used in the simulation. Also, when system compensation was necessary, conventional shaping networks were used.

CONTROL SYSTEM ANALYSES

- CONTROL SYSTEM REQUIREMENTS
 - STABILITY
 - ATTITUDE TRANSIENTS
 - LIMIT PERFORMANCE LOSS
 - SATISFACTORY RESPONSE TO GUIDANCE COMMANDS
- APPROACH
 - LINEAR CONTROL SYSTEM DESIGN
 - SYSTEM RESPONSE SIMULATION
 - CONVENTIONAL CONTROLLER USED

CONTROL SYSTEM BLOCK DIAGRAM

The attitude control system chosen for the RNS in this study is a conventional attitude and attitude rate feedback system similar to the Saturn S-IVB. Proportional attitude position and attitude rate feedback is summed with the guidance commands to obtain the actuator command. According to ANSC, the actuator consists of an amplifier, a dc motor, and gears. Position feedback is provided within the actuator to obtain a positioning device. The actuator gimbals the NERVA. The gimbaled NERVA provides a control moment on the vehicle. The block diagram indicates the actuator block as well as the components of the position and rate loops and the vehicle dynamics. The vehicle dynamic terms included were: rigid body; propellant sloshing; first, second, and third mode vehicle bending; and tail-wags-dog. The control sensors are located in the command and control module forward of the first propellant module. These sensors provide vehicle angular position and rate feedback signals. Feedback shaping to compensate for vehicle dynamic effects can be included in either loop.

CONTROL SYSTEM BLOCK DIAGRAM

x_c = GUIDANCE COMMANDS (DEG)

ψ = ATTITUDE ERROR (DEG)

β_c = ACTUATOR COMMAND (DEG)

β = ACTUATOR POSITION (DEG)

$\ddot{\theta}$ = VEHICLE ANGULAR ACCELERATION (DEG/SEC²)

$\dot{\theta}$ = VEHICLE ANGULAR RATE (DEG/SEC)

θ = VEHICLE ANGULAR POSITION (DEG)

a_0 = POSITION LOOP GAIN (DEG/DEG)

a_1 = RATE LOOP GAIN (DEG/DEG/SEC)

FREQUENCY DISTRIBUTION

CRUCIFORM CLUSTER CONFIGURATION

The facing page shows the frequency distribution of the rigid body control system and the vehicle dynamics. The data shown is for the fully loaded propellant tank (initiation of TLI burn) condition. A nominal rigid body control frequency of 0.01 Hz was selected based on previous studies. Considerations included in the control frequency selection were (1) maintaining the control frequency well below the first mode bending frequency to avoid undesirable interaction, (2) maintaining it high enough to prevent interaction between the control and guidance systems, and (3) achievement of satisfactory attitude transient response characteristics and attitude error limitations. The rigid-body closed-loop control frequency is related to the control system natural frequency by the desired system damping ratio. A damping ratio selected for this design is 0.4. This value results in a system natural frequency of 0.013 Hz. By relating the desired control system characteristics to the control loop gains, the value of a_0 was determined to be 0.1 degree/degree, and a_1 was determined to be 0.9 degree per degree/second ($M_\delta = 0.0682$).

The low value of a_0 will require large vehicle attitude errors to compensate for NERVA thrust vector misalignment. Since large attitude errors can have a detrimental effect on the trajectory accuracy, a scheme which biases the TVC to account for most of the misalignment would be highly desirable.

Frequencies are shown for the first, second, and third lateral vehicle bending modes, first mode propellant slosh, NERVA gimbal actuator, and tail-wags-dog dynamics. The tail-wags-dog frequency is defined as the frequency at which no force is applied to the vehicle by engine gimbaling. This frequency is a function of the NERVA thrust and mass characteristics.

A second order transfer function was used to model the NERVA gimbal actuator. The transfer function was derived from ANS data (Reference 7410:1071, dated July 10, 1970). Specifically, the data provided in the reference was factored and the terms resulting in low-frequency effect were retained.

FREQUENCY DISTRIBUTION CRUCIFORM CLUSTER CONFIGURATION

0% BURNTIME

$$M_{\delta} = 0.0682 \text{ 1/SEC}^2$$

$$a_0 = 0.10 \text{ DEG/DEG}$$

$$a_1 = 0.90 \text{ DEG/DEG/SEC}$$

NERVA GIMBAL ACTUATOR TRANSFER FUNCTION

$$\frac{\beta}{\beta_c} = \frac{(6.4)^2}{s^2 + 2(0.695)(6.4)s + (6.4)^2}$$

CONTROL SYSTEM STABILITY—NYQUIST PLOT

An RNS Class 3 control system stability analysis was accomplished by determining open-loop frequency responses. Nyquist plots and the Nyquist's stability criterion were used to establish stability. The open-loop frequency responses evaluated were: (1) the open actuator command loop, (2) the open vehicle attitude loop, and (3) the open vehicle angular rate loop. This analysis was conducted for the cruciform cluster and tandem array configurations of the RNS. Various propellant loading conditions for each configuration were considered.

The plot in the accompanying illustration shows the open actuator loop response Nyquist diagram for the cruciform cluster RNS configuration at the fully loaded (initiation of TLI burn) condition. For this response, an encirclement of the -1.0 point denotes a closed-loop instability. This corresponds to zero db and 180 degrees phase on the db/phase polar plot. The gain and phase margins obtained from this frequency response plot demonstrate the stability of the control system. To obtain these margins, attitude rate feedback compensation was necessary. It was found that, for this case, adequate compensation could be provided by a simple filter which notched at the first node bending frequency and attenuated at higher frequencies.

CONTROL SYSTEM STABILITY NYQUIST PLOT

CRUCIFORM CLUSTER

14930

CONTROL SYSTEM STABILITY MARGIN SUMMARY

Stability margins obtained from the open loop actuator command frequency responses are shown on the facing page. These margins demonstrate the stability of the control system. These margins are for the cruciform cluster and tandem configurations of the Class 3 RNS for the loading conditions shown. In all cases, attitude rate feedback compensation was necessary to attenuate vehicle bending and high frequency dynamics. For the propellant tank empty conditions, position loop compensation was required for stability. This was a result of the high modal gain associated with first bending mode at that condition. In all cases, slosh dynamics did not have an appreciable effect on the control system margins.

The gain margins shown starred for first bending response loop are to the unit circle (i.e., zero-db circle). These loops therefore have unlimited phase margin. The phase margins associated with first mode bending for the tandem configuration indicate that bending is stable. The phase margins indicate the phase shift at the bending frequency that can be allowed before the control system is unstable.

CONTROL SYSTEM STABILITY MARGIN SUMMARY

14929

	RIGID BODY		FIRST MODE BENDING
	PHASE DEG/HZ	GAIN DB/HZ	GAIN DB/HZ
CRUCIFORM CLUSTER			
FULLY LOADED	35/0.016	18.0/0.10	13/0.285*
HALF FULL	38/0.017	16.0/0.09	15/0.30*
EMPTY	30/0.044	22.0/0.21	10.0/0.845*
TANDEM			PHASE DEG/HZ
FULLY LOADED	28/0.021	8/0.048	44/0.135
HALF FULL	29/0.021	9/0.046	50/0.173

*GAIN TO UNIT CIRCLE

GARDEN-HOSE STRUCTURAL STABILITY

An analysis was conducted to assess the "garden hose" structural stability margin of the Class 3 RNS. The so-called "garden hose" effect is a form of a Euler elastic instability with a "follower" force and column mass effects included. That is, the vehicle thrust remains tangential to the deformed axis such that a follower force is realized.

To assess garden hose stability margin of the Class 3 RNS a worst case approach was employed. The tandem configuration of the Class 3 RNS is a longer and more flexible configuration than the baseline clustered array. The tandem configuration would, therefore, be more susceptible to a garden hose instability. If it can be shown that the tandem configuration is stable, the result could be applied to the clustered array by extrapolation.

The accompanying illustration shows the results of a garden hose analysis conducted on the tandem configuration. A plot of lateral bending frequencies versus NERVA thrust level is shown. Data for two limiting cases of interstages between modules are shown: (1) The baseline design of fiber glass truss interstages and (2) an upper bound on stiffness which uses a continuous tank wall EI along the entire RNS length. Both cases are stable against the garden hose phenomenon at the NERVA thrust level of 75,000 lb. As can be seen for the figure, the decrease in the first mode bending frequencies is less than 5 percent at operating thrust, and the thrust could be tripled before the decrease would be excessive.

Extrapolating these results to the shorter, less flexible clustered arrays would indicate an even greater margin for those configurations.

GARDEN-HOSE STRUCTURAL STABILITY EIGHT MODULE TANDEM ARRAY

ENGINE/STAGE STRUCTURAL DYNAMICS

The large mass of the NERVA, combined with the low structural stiffness of some of the engine and stage components, could result in low lateral resonant frequencies. With these low frequencies, coupling with the booster structural dynamics could produce large dynamic displacement of the NERVA and/or stage engine support structure. These displacements could lead to engine clearance problems and excessive structural loads.

Three concepts of transporting the NERVA to earth orbit are currently being considered in this subtask. These concepts are: (1) integral launch with the NERVA attached to a standard thrust cone, (2) integral launch with the NERVA attached to a propulsion module, and (3) EOS launch of the propulsion module with the NERVA attached and orbital assembly with the propellant module. Concepts 1 and 2 are characterized by the Class 1 and Class 1 Hybrid vehicles as defined by the MDAC nomenclature. Concept 3 is the normal mode of NERVA earth orbit transportation for the Class 1 Hybrid and the Class 3 modular RNS. For Concepts 1 and 2, the RNS is boosted into orbit by an Int-21 vehicle. In this subtask, the bulk of the effort will be devoted to transportation concepts employing an Int-21, and only a preliminary assessment of the effects of EOS NERVA transportation will be made.

Restraint of the NERVA to limit displacements and attendant structural loads can be achieved by using lateral and/or longitudinal ties to the stage. Aerojet letter 7840:0399L, dated May 26, 1970 presents possible schemes for the standard thrust cone case. Similar schemes are possible for the Class 1 Hybrid concept. These schemes are currently being evaluated by MDAC. An alternative to restraint stiffening and strengthening in critical areas is being considered. Preliminary assessment of the NFPM during the Phase II study indicated that if the stage structure was stiffened about 35 percent it would withstand the static and dynamic loads.

The study approach consists of: (1) developing an improved dynamic model to include lateral, longitudinal, and torsional modes of the NERVA mounted to the stage; (2) obtaining updated dynamic properties using this model; (3) generating data on the response of the NERVA to stimuli using a MSFC-supplied stimuli model; and (4) conducting restraint tradeoff studies. The study plan includes investigation of the Hybrid integral launch dynamics, employing variations in Class 1 standard parameters, to assess stiffening and lateral restraint requirements.

ENGINE/STAGE STRUCTURAL DYNAMICS

SUBTASK 9.6

PROBLEM

- LOW RESONANT FREQUENCIES OF THE ENGINE/STAGE STRUCTURE
COULD RESULT IN LARGE DISPLACEMENTS AND LOADS

CANDIDATE SOLUTIONS

- RESTRAIN NERVA DURING BOOST
LATERAL
LONGITUDINAL
- STIFFENING AND STRENGTHENING

STUDY APPROACH

- IMPROVED DYNAMIC MODEL
- UPDATED DYNAMIC PROPERTIES
- DYNAMIC RESPONSE DATA
- RESTRAINT TRADEOFFS
- HYBRID TREATED BY PARAMETER VARIATION

ENGINE/STAGE STRUCTURAL DYNAMICS STATUS

The accompanying illustration lists the status of the study. Updated spring rate data have been developed for the standard cone Class 1 vehicle. These data have been provided to ANSC for use in their NERVA dynamics analyses.

Spring rate data are being developed for the Hybrid configuration. Development of these data required the enlargement of a digital computer program. This enlargement was necessitated by the large number of struts used in the truss structure of the propellant module. The enlargement is now complete and the truss structures are being analyzed. The complete spring rate matrix for the propulsion module will be obtained by combining the data for the truss structures and the run tank wall by analytical means.

An improved dynamic model of the NERVA mounted to a standard 10-deg thrust cone has been obtained from ANSC (Ref. 7733:1277L, dated July 31, 1970). The first two resonant frequencies provided by this model are 2.34 and 5.78 Hz. A study is in progress to determine the response of this improved model to transient lateral accelerations of the launch vehicle. The accelerations are being applied to the thrust cone base and are characteristic of release and liftoff. The stimuli model being used to generate the acceleration history was supplied by MSFC in S&E-ASTN-AA-70-42, dated May 12, 1970. This stimuli model has appreciable energy at 2.46, 4.50, 5.37, 7.99, 9.30 and 11.2 Hz.

ENGINE/STAGE STRUCTURAL DYNAMICS

SUBTASK 9.6

STATUS

- UPDATE SPRING RATE DATA HAS BEEN DEVELOPED FOR THE STANDARD 10 DEG THRUST CONE
- SPRING DATA FOR THE HYBRID CONFIGURATION IS BEING DEVELOPED
- AN IMPROVED DYNAMIC MODEL (STANDARD THRUST CONE) HAS BEEN OBTAINED $f_1 = 2.46 \text{ HZ}$, $f_2 = 4.50 \text{ HZ}$
- STUDY TO DETERMINE THE RESPONSE OF IMPROVED MODEL TO TRANSIENT ACCELERATIONS IS IN PROGRESS. S&E-ASTN-AA-70-42 DATA IS BEING USED.

ENGINE/STAGE STRUCTURAL DYNAMICS EXPECTED RESULTS

The accompanying illustration shows the expected study results. These results included dynamic response data with various NERVA lateral and longitudinal support schemes. During the study, the stiffness of various system elements will be varied to reflect possible design modifications. This effort will concentrate on identifying design modifications necessary to present designs so that excessive dynamic coupling with the launch vehicle is avoided. The system elements to be considered are: (1) RNS thrust structure and aft LH₂ tank bulkhead, (2) NERVA thrust structure assembly, and (3) the NERVA gimbal assembly and actuators. The need for lateral restraint of the NERVA will be evaluated in this study. The study output will include the design modifications or support requirements necessary for an integral launch Hybrid configuration. The objective of this effort will be to clarify differences between the standard and Hybrid configurations which could affect support requirements.

ENGINE/STAGE STRUCTURAL DYNAMICS

SUBTASK 9.6

EXPECTED RESULTS

- DYNAMIC RESPONSE DATA WITH VARIOUS NERVA SUPPORT CONCEPTS
- DESIGN MODIFICATIONS REQUIRED TO AVOID EXCESSIVE DYNAMIC COUPLING DURING LAUNCH
 - RNS THRUST STRUCTURE
 - NERVA THRUST STRUCTURE
 - GIMBAL ASSEMBLY AND ACTUATORS
- NEED FOR LATERAL RESTRAINT OF THE NERVA
- DESIGN MODIFICATIONS OR SUPPORT REQUIRED FOR INTEGRAL LAUNCH OF HYBRID CONFIGURATION

INTERFACE AREAS

On the basis of the preliminary evaluations conducted during this phase of the contract, several important interface recommendations are proposed. Several of these pertain to engine design requirements which were identified by the trade studies conducted in this study. Performance penalty was assessed due to the 30-psi design requirement that was stipulated for engine startup. Reducing this requirement not only would decrease the overall weight of the Class 1 Hybrid but also would permit a lesser time for pressurizing the propellant module. This would require less depletion of the run tank propellant during this transient. Secondly, if the 30-psi propellant condition requirement for aftercooling could be reduced to saturated conditions, a less complicated surface tension concept could be utilized with an attendant 3,000-lb weight reduction.

In order to guarantee safe operation regardless of any incident, or avoid requiring the implementation of an anti-criticality destruct system on the shuttle orbiter, all safety wires must be installed in the core. Because, in both the Class 1 Hybrid and the Class 3, the run tank is launched within the cargo hold of the space shuttle (from which the wires can be removed efficiently) it is preferable to be able to remove all safety wires in Earth orbit within the cargo hold of the shuttle. This is more preferable to the current guideline of removing the peripheral wires in the VAB.

To accomplish the mission model which was supplied, a large number of space shuttle launches are required. These exceed current shuttle traffic requirements by about a factor of three. Therefore, investigation of the program model appears warranted in order to establish better compatibility between nuclear stage and shuttle studies.

INTERFACE AREAS

14944

ENGINE DESIGN REQUIREMENTS

- ENGINE START UP PRESSURES
- AFTERCOOLING PRESSURES
- SAFETY WIRES REMOVAL

PROGRAM MODELS

NUMBER OF SPACE SHUTTLE LAUNCHES

FUTURE TASKS-SYSTEM TRADE STUDIES

During the second phase of the study, orbital and flight operational requirements will be further defined. Overall timelines for earth orbital and lunar orbital operations will be defined more explicitly utilizing the operations analyses which were conducted during the first 3 months of this study as a basis. Flight operations will be continued to assess auxiliary propulsion system requirements, propulsion/propellant module control and NERVA transient performance. The latter will be initiated in this period to determine aftercooling impulse utilization and pulse shaping requirements.

Design criteria will be upgraded periodically to reflect new requirements and design data. Subsystem analyses will be updated to account for the additional operational requirements, the reliability improvement plan, thermodynamic analyses, new radiation environment, and NERVA interface support requirements. Contingency planning work sheets and safety tasks will be fully implemented during this period.

Material selections and structural configurations from Phase II will be reviewed. The controllability of the launch of an Int-21 with a nuclear stage will be reviewed. The thermal meteoroid protection system will be reoptimized on the basis of the new design criteria established and compatibility with a more optimum economic criterion. Propellant handling subsystem features will be further refined on the basis of reviewing orbital tanking requirements, new expulsion pressurization system requirements, new radiation environments, and the new subsystem designs defined in the concept definition and evaluation phase of this study. Astrionics subsystem features will be reviewed to assess the effect of the new maintainability concepts proposed and the power systems will be reviewed on the basis of new mission requirements.

A final definition of the flight system will be made in order to make a final review on the basis of the subsystem analyses, interface, and system integration tasks conducted in this study. This review will allow for the selection of the baseline configurations for the Class 1 and Class 3 vehicles which will permit final program definition in the latter portion of the study.

During this phase of the study the program definition tasks associated with test requirements, manufacturing facilities and equipment definition, and supporting research and technology plan will be initiated.

FUTURE TASKS - SYSTEM TRADE STUDIES

SECOND 3-1/2 MONTHS

14942

REQUIREMENTS DEFINITION

CONTINUE OPERATIONS ANALYSES AND TIMELINE DEFINITIONS

**EVALUATE NERVA TRANSIENTS, SUBSYSTEM AND ORBITAL
OPERATION INTERFACES**

FLIGHT SYSTEM DEFINITION

**UPDATE SUBSYSTEMS FOR RELIABILITY IMPROVEMENT PLAN,
OPERATIONS, RADIATION ENVIRONMENT, THERMODYNAMIC
ANALYSIS AND MAINTAINABILITY**

EXTEND DEPTH OF DESIGN ANALYSES

PERFORM FINAL REVIEW OF RNS CONCEPTS

PROGRAM DEFINITION

**INITIATE PLANS FOR: TEST, MANUFACTURING, FACILITIES AND EQUIPMENT,
SRT AND OPERATIONS**

FUTURE TASKS-PROGRAM AND SYSTEM DEFINITION

The Phase A Concept Definition of the Reusable Nuclear Stage (RNS) will be completed during this phase. In this period the requirements definition tasks will define final functional flow diagrams, requirements allocation sheets, reliability requirements and quality assurance plan, and the final safety and contingency plans. Design requirements due to safety and reliability will be coordinated to ensure an integrated approach. Top-level and first-level functional flow diagrams (and second- and third- level where required), and top-level and first-level requirement allocation sheets will be presented at the conclusion of this phase. Recommendations of NERVA stage interfaces and required modifications will be made, as will recommended orbital support system interfaces.

A final description of the nuclear stage, including hardware trees, design details, and system specifications with which to enter Phase B or post-Phase A studies will be generated to a level consistent with preparing the integrated program plan, development schedule, and system costs and SRT program. Two integrated test plans which would determine the ground test and flight test requirements for the two RNS concepts will be formulated. Test hardware will be defined. Alternative test sites will be evaluated and recommendations will be made. The manufacturing and assembly techniques for the two RNS concepts, as well as the requirements for their associated tooling, manufacturing facility capabilities, and GSE will be established in conjunction with the other plans which are being formulated. Final assembly sites and manufacturing plans will be recommended for these concepts. Associated facilities and equipment plan will be defined to assist the manufacturing and operations of the RNS. Supporting research and technology task descriptions, including costs and schedules, will also be presented. The results of the preceding tasks will be integrated into an overall plan including the following elements: system and design engineering, ground and launch operations, safety, maintainability, integrated logistic support reliability, quality assurance, testing, manufacturing facilities, and SRT. Program cost estimates and funding schedules will be identified. During the preceding phases the engine stage interface definition, system engineering support of NERVA, engine stage structural dynamics analyses, and NERVA transient and cooldown studies will be continued.

FUTURE TASKS - PROGRAM AND SYSTEM DEFINITION

FINAL 3-1/2 MONTHS

14943

REQUIREMENTS DEFINITION

PREPARE FINAL FUNCTIONAL FLOW AND REQUIREMENT ALLOCATION SHEETS

PREPARE SAFETY AND CONTINGENCY PLANS

ESTABLISH RELIABILITY AND QUALITY ASSURANCE REQUIREMENTS

RECOMMEND RNS INTERFACES

FLIGHT SYSTEM DEFINITION

PREPARE HARDWARE TREES, DESIGN DETAILS AND SYSTEM SPECIFICATIONS

PROGRAM DEFINITION

PREPARE INTEGRATED PROGRAM PLAN

DOCUMENT MISSION PLANNING HANDBOOK

PREPARE SYSTEM COST ESTIMATES

PREPARE SRT PLAN