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**NUCLEAR SHUTTLE
SYSTEM DEFINITION STUDY, PHASE III
FINAL REPORT**

PREPARED FOR NASA-MSFC
UNDER CONTRACT NAS8-24714
DRL NO. MSFC-DRL-196,
LINE ITEM 3

**VOLUME II
Concept and Feasibility Analysis
PART B
Class 3 RNS
BOOK 2
System Definition**

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5301 Bolsa Avenue, Huntington Beach, CA 92647

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FOREWORD

This document contains the results of the system design definition effort, including the stage/engine interface, performed during the Phase III Nuclear Shuttle Definition Study for the Class 3 Reusable Nuclear Stage (RNS) concept. This work was accomplished for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama, under Contract NAS8-24714. The final report was generated to fulfill the requirements of DRL No. MSFC-DRL-196, Line Item 3, and it covers the period from May 1, 1970 to May 1, 1971.

The study effort described in this volume was performed under the direction of Dr. R. J. Holl and Dr. K. P. Johnson, with responsibility for specific activities as follows:

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PREFACE

The material contained in this document represents a portion of the final report documentation for the Phase III Nuclear Shuttle System Definition Study. The study effort was performed as a 12-month extension to the existing Nuclear Flight System Definition Study Contract (NAS8-24714), with the objective of establishing Phase A conceptual definition for two classes of reusable nuclear shuttle concepts. The first concept class is characterized as a 33 ft diameter configuration that is launched integrally to orbit by a Saturn V INT-21 vehicle. The second concept class is characterized as a modular configuration which is assembled in earth orbit from modules carried to orbit in a space shuttle.

The final report documentation has been organized to provide separable information for the two concepts, where appropriate, and to combine report material common to both concepts in singular documents. The total documentation for the study is listed below, with this document identified in the left margin.

- o Volume I: Executive Summary
- Volume II: Concept and Feasibility Analysis
  - Part A—Class 1 Hybrid RNS
  - o Book 1—System Analysis and Operations
  - o Book 2—System Definition
  - Part B—Class 3 RNS
  - o Book 1—System Analysis and Operations
  - Book 2—System Definition
- Volume III: Program Support Requirements
  - o Part A—Class 1 Hybrid RNS
  - o Part B—Class 3 RNS
  - o Part C—Test Program Analyses and SRT Requirements
- Volume IV: Cost Data
  - o Part A—Class 1 Hybrid RNS
  - o Part B—Class 3 RNS
- o Volume V: Schedules, Milestones, and Networks
- o Volume VI: Reliability and Safety Analysis
- o Volume VII: RNS Project Requirements

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Section 1

DESIGN SUMMARY

This section contains a brief description of the reusable nuclear stage (RNS) Class 3 concept. The vehicle is based in low earth orbit (260-nmi altitude, 31.5 degree inclination) and provides transportation in a shuttle mode to more distant destinations. Its design mission is a round trip to 60-nmi lunar polar orbit. It is launched, maintained, and replenished in earth orbit by the space shuttle.

A sketch of the baseline configuration is shown in Figure 1-1. It consists of three distinct types of modules designed for launch to orbit inside the 15-ft diameter by 60-ft cargo bay of the space shuttle, and which can be assembled and disassembled in space. The propulsion module contains NERVA and a small run tank of propellant. This facilitates replacement of NERVA, as might be required because of failure or to extend the lifetime of the RNS beyond that of the engine. Primary propellant is contained in the multiple tanks shown, which are designated as propellant modules. These contain minimal propellant management subsystems. At the forward end of the stage is a command and control module (CCM) which contains most of the functional equipment and all of the expendables except main stage LH_2 . This module is replaced between missions in earth orbit, thereby effecting a replenishment of expendables and all scheduled maintenance. The main feed system, providing communication from any propellant module to the run tank on the propulsion module, is shown in this figure. The RNS is resupplied with LH_2 in earth orbit by the space shuttle between missions.

The vehicle configuration was selected to optimize the combined effects of biological shield weight, which favors maximum vehicle length; maximum stability and controllability, which favors minimum length; and minimum assembly operations from the fewest outboard modules. The baseline configuration shown employs four tandem propellant modules which, in conjunction with the small solid angle subtended by the run tank on the

Figure 1-1 CLASS 3 RNS

propulsion module, precludes the requirement for any biological shield. A fully adequate margin of safety is maintained for vehicle stability and controllability. The cruciform array of outboard propellant modules simplifies assembly and clustering operations.

The RNS design and operations concept minimizes orbital support requirements. The space shuttle is utilized to deliver replacement modules and to resupply propellant. A space tug is utilized to support assembly and replacement of modules and to safely dispose of expended propulsion modules. No permanent, manned, orbital facilities are required for maintenance or propellant resupply.

A detailed weight statement for the RNS Class 3 vehicle is given in Table 1-1. Entries are shown for each of the modules as well as for the total vehicle. The system description contained in the work breakdown structure, provided as part of the study guidelines, is used with additional items added to cover unique components.

Table 1-1
WEIGHT SUMMARY OF CLASS 3 RNS

Code	Description	Modules Weight (lb)			Total Vehicle Weight (lb)
		Pro-pellant	Pro-pulsion	Command and Control	
2.00	Structure	(3, 560)	(1, 300)	(690)	(30, 470)
2.01	Propellant tank assembly	2, 370	570	---	
2.02	Engine thrust structure	---	170	---	
2.03	Forward skirt	370	250	---	
2.04	Aft skirt	390	---	---	
2.05	Tunnel and fairings	---	---	---	
2.06	Exterior finish and sealer	60	20	---	
2.07	Antislosh baffles	Avg 70	60	---	
2.08	Equipment support structure	170	160	360	
2.09	Equipment module structure	---	---	330	
2.10	Additional structure--access	130	70		
3.00	Meteoroid/thermal protection	(1, 240)	(710)	(120)	(10, 750)
3.01	Insulation	Avg 470	430	---	
3.02	Meteoroid protection	770	280	120	
4.00	Docking/clustering	(370)	(80)	(280)	3, 320)
4.01	Forward docking structure	Avg 140	80	80	
4.02	Aft docking structure	Avg 140	---	200	
4.03	Clustering structure (4 sets at 180)	Avg 90	---	---	
5.00	Main propulsion	(510)	(27, 730)	(540)	(32, 350)
5.01	NERVA engine	---	27, 730	500	
5.02	External disc shield for NERVA	---	---	---	
5.03	Purge system	---	---	---	
5.04	Propellant scavenging system and sensors	---	---	---	
5.05	Propellant feed system	260	140	---	
5.06	Pressurization system	60	60	---	
5.07	Prepressurization system	---	---	---	
5.08	Pneumatic system	---	---	---	
5.09	Fill and drain/orbit refueling	50	60	40	

Table 1-1 (Continued)

Code	Description	Modules Weight (lb)			Total Vehicle Weight (lb)
		Pro-pellant	Pro-pulsion	Command and Control	
5.10	Ground and emergency vent	80	---	---	
5.11	Flight vent	60	50	---	
5.12	Integrated chilldown system	---	70	---	
5.13	Refill system	---	50	---	
6.00	Auxiliary propulsion	---	(160)	(950)	(1,110)
6.01	Reaction control system	---	160	950	
6.02	Retro system	---	---	---	
6.03	Ullage system	---	---	---	
7.00	Astrionic system/ astrionics	(115)	(345)	(1,905)	(3,170)
7.01	Guidance navigation and control	---	20	310	
7.02	Instrumentation	15	15	210	
7.03	Command and control	5	10	140	
7.04	Electrical power	Avg 15	130	785	
7.05	Electrical networks	Avg 70	150	85	
7.06	Environmental control	---	---	---	
7.07	Propellant management	---	10	---	
7.08	Onboard checkout	5	5	60	
7.09	Data management	5	5	315	
8.00	Safety/ordnance system	---	---	---	---
8.01	Safety system	---	---	---	
8.02	Ordnance system	---	---	---	
9.00	Contingency	(280)	(200)	(200)	(2,590)
	Subtotal	6,075	30,475	4,685	83,760
10.00	RCS propellant	---	---	(1,250)	(1,250)
11.00	Residual propellant	(465)	(440)	---	(4,160)
11.01	Liquid propellant	100	100	---	
11.02	Vapor vented	280	---	---	
11.03	Vapor	85	340	---	
12.00	Reserve flight performance				(1,700)
13.00	Propellant boiloff	---	---	---	---

Table 1-1 (Continued)

Code	Description	Modules Weight (lb)			Total Vehicle Weight (lb)
		Pro-pellant	Pro-pulsion	Command and Control	
14.00	Impulse propellant				(296,990)
14.01	Leave Earth				179,240
14.02	Arrive moon				39,040
14.03	Leave moon				26,920
14.04	Arrive earth				51,790
	Total	NA	NA	NA	387,860

Section 2

SYSTEM REQUIREMENTS

The analyses of the design and operations of the RNS are contained in Book 1 of this volume. A brief summary of the system requirements established in that document is provided in this section to complement the system definition.

2.1 MISSION APPLICATIONS

Three classes of missions are proposed for the RNS: interorbital shuttle (lunar and geosynchronous), unmanned planetary, and manned planetary. These are all performed in a reusable shuttle mode. The design implications of these are presented in Section 2 of Book 1 and more detailed mission descriptions and performance data are documented in the Mission Planning Handbook (MDC G0595).

The lunar shuttle mission provides the basis for RNS design requirements in this study. This mission entails transfer of cargo and men to and from a 60-nmi polar lunar orbit, operating from a low circular earth orbit at 260 nmi and 31.5-degree inclination. The design mission consists of eight main stage burns, which provides for plane rotation at lunar orbit injection and transearth injection. Mission timelines are based on a 54.6-day repeating cycle. The top level mission timeline is shown in Table 2.1-1. This mission is used for design purposes only; a 4-burn mission, without the plane change maneuvers in lunar orbit, is considered nominal for performance purposes.

2.2 RNS OPERATIONS

The prelaunch, launch, and mission phases of the RNS system operations are analyzed in Section 3 of Book 1 to establish a basis for the RNS design. The functional flow of operations and method of reporting is summarized in Figure 2.2-1 for major categories of operations which have been abstracted from the top and first level functional flow diagrams reported in Volume VII.

Table 2.1-1
MISSION TIMELINE

Event	Initiation Time (hr)	Impulse Propellant ¹ (lb)	Cooldown Propellant (lb)	Propulsion Parameters		Cooldown Time ² (hr)
				Steady-State Time (sec)	Total Run Time ¹ (sec)	
TLI	0	171,020	7,500	1,800	2,780	108
Midcourse ³	15,37,67 (typ)	1,060	--	530	530	-
LOI-1	108	11,080	790	74	335	12
LOI-2 ⁴	120	5,500	450	28	260	12
LOI-3	132	19,860	1,390	165	470	32
TEI-1	518	12,460	890	88	350	12
TEI-2 ⁴	530	4,100	300	0	230	5
TEI-3	542	8,600	630	47	300	11
Midcourse ³	552,577,595 (typ)	510	--	255	255	-
EOI	614	48,440	2,410	475	940	45
Total		(282,630)	(14,360)			

Notes:

¹Including chilldown (56 sec) through PSOV closure.

²Or time to next maneuver, whichever is less.

³Idle mode operation.

⁴Throttle mode operation, 30-degree plane change.

TLI Translunar injection

LOI-1 Lunar orbit injection (into 24-hr elliptical capture orbit)

LOI-2 30-degree plane change maneuver

LOI-3 Circularization maneuver at 60 nmi

TEI-1 Injection maneuver to elliptical departure orbit

TEI-2 30-degree plane change maneuver

TEI-3 Transearth injection

EOI Earth orbit injection (260 nmi)

Figure 2.2-1 RNS OPERATIONS SUMMARY

The entries in Figure 2.2-1 are indexed according to the functional flow designation, "FF," the MSFC study task numbers, "T," and the report sections in Book 1, "S." Major features of these operations and their implications for the RNS design are summarized here.

The Class 3 propellant module is assembled at Huntington Beach and subjected to cold-flow testing at Sacramento. The propulsion module run tank will be assembled at Huntington Beach and subjected to cold-flow testing with an engine simulator at Sacramento. Engine mating and interface verification tests will be conducted at KSC. The CCM is assembled and checked out at Huntington Beach. Propellant modules, the propulsion module run tank, and CCM are transported by air (Super Guppy). Clusters of six propellant modules are transported by barge.

A space tug is utilized to accomplish assembly of the Class 3 propellant modules providing both stabilization and module clustering operations. The propulsion module is launched last, and the space tug docks the RNS assembly to it. The propulsion module is self-stabilized for the assembly operation. Fluid and electrical interfaces are accomplished in orbit using remote assembly mechanisms.

Propellant resupply is a major orbital support operation. Selection of RNS fleet size and missions scheduling obviates the requirement for an additional reservoir of propellant tankage in orbit as a tank farm. The space shuttle delivers LH_2 directly to the RNS performing a propellant transfer under linear acceleration provided by the space shuttle. Prior to initiating the mission, propellant is vented to reject the heat from propellant tank chill-down and orbital heating during refueling. The tank is subsequently topped off to begin the mission with propellant at 16 psia.

Checkout of orbital assembly interfaces is provided by the CCM or space tug during the assembly operations. The RNS performs autonomous onboard checkout for the orbital countdown. Component functional check is utilized to avoid the consumption of expendables and NERVA criticality associated with simulated operations. A nominal processor requirement of 8,200 equivalent adds per sec and 25,000 words of storage has been identified for

onboard checkout. Except for a small increase in instrumentation, no additional components or subsystems are required to accomplish RNS checkout.

The ground will monitor the RNS performance and intermittently provide information to the RNS via uplink as required. Ground processing will be performed for fault prediction and trend analysis evaluation between missions. The primary RNS data interface is to the ground utilizing an estimated transmission rate over ground stations of only 8,500 bits/sec. Hence no requirement for communication satellite relay is anticipated.

The RNS will be oriented in the gravity-gradient-stable, local-vertical orientation during long-term coast phases in earth and lunar orbits. This precludes the need for active attitude control. The RNS will operate in a limit cycle mode during the translunar and transearth coast periods, and during both of the 24-hour lunar phasing orbits. The navigation and guidance subsystem will remain dormant during the gravity gradient stabilized periods; 36 attitude maneuvers have been imposed to establish vehicle attitude for RNS operations. A separation maneuver is also performed by the APS before translunar injection or transearth injection to permit the RNS to leave the vicinity of the space station before initiating full thrust NERVA operation.

The propellant utilization and NERVA thrust modes were defined for the reference lunar shuttle mission profile in Table 2.1 -1. Six burns are performed using NERVA at full thrust. A throttle mode (45,000-lb thrust) is employed for the two lunar orbit plane change maneuvers. NERVA idle mode operation is used for midcourse maneuvers. The RNS propulsion module operates autonomously to provide aftercooling propellant to NERVA after all burns and to accomplish throttle mode maneuvers and midcourse corrections. The run tank is refilled before each full-thrust operation.

The startup operations have been defined for the RNS. These begin with propellant settling provided at a 3.2-lb thrust level by the APS (this results in accelerations less than 2×10^{-5} g). Settling is completed at high thrust

using the NERVA startup thrust ramp. A thrust hold is integrated into the startup ramp at the throttle point to permit completion of propellant settling and propellant module pressurization. The propellant feed system is chilled down during the initial phase of propellant settling and the run tank is refilled before initiating the NERVA thrust ramp. The run tank operates autonomously during the startup operation and uses NERVA bleed gas for an autogenous bootstrap startup. The propellant tank is pressurized and brought on-line to restore the steady-state propellant level in the run tank before its level has dropped below 5,000-lb LH_2 .

Use of the navigation and guidance system with two star trackers and a strapdown inertial measuring unit provides adequate trajectory accuracy for an autonomous navigation and guidance approach.

During the steady-state operation, the run tank in the propulsion module acts as a surge tank. A control system was defined to regulate the pressures in both the run tank and main propellant tank in addition to the LH_2 level in the run tank. This propellant management control system has been simulated to demonstrate its capability to regulate the startup and shutdown ramp, to refill the run tank after shutdown when the propellant module has been brought on-line, to adjust to acceleration head changes during burn, and to respond to flow rate changes for the NERVA emergency mode operation.

Simulations of thrust vector control have established engine gimbal requirements and determined the attitude excursions following startup both with and without pretrimming the NERVA thrust vector prior to startup. The advantages of the initial trim operations were established.

RNS operations for shutdown and aftercooling have been defined. Because of the long times and large number of pulses involved in providing cooldown during a mission, the requirements to provide propellant to NERVA at specified conditions during aftercooling can impose severe penalties on the RNS design. The recommended approach uses a surface tension device to provide saturated LH_2 from the run tank for aftercooling pulses. The mission performance implications of aftercooling were established. The payload

delivery to lunar orbit was increased by 8,400 lb by crediting the cooldown contribution to mission velocity. A potential payload gain of 23,540 lb was identified if cooldown could be eliminated entirely using passive heat rejection. Trajectories have been defined for orbital injection accounting for dispersions in cooldown propellant which permit reaching the final target orbit without imposing additional impulsive requirements on the RNS. The desirability of trimming the engine thrust vector through the vehicle cg has been identified to reduce attitude disturbances during pulsed aftercooling as well as prior to startup as described earlier.

The requirements for trajectory midcourse correction were evaluated. It was found that multiple impulsive midcourse maneuvers or a single impulsive correction early in the trajectory are preferable to a single impulse maneuver at the end of the cooldown phase. Trajectory correction utilizing vectored cooldown thrust is also considered competitive with early impulsive corrections.

RNS maintenance is accomplished by module replacement at the assembly level. The CCM containing the functional subsystems is recycled to the ground each mission for maintenance and replenishment of expendables. The Phase III maintenance study considering multiple replacement modules, a single CCM and in-situ maintenance has reaffirmed the advantages of the CCM concept and its minimal orbital support requirement. At the end of NERVA life, it is recommended that the propulsion module be disposed of from earth orbit (or from lunar orbit in the event of a failure) by a reusable chemical tug and propellant modules recycled on an unscheduled basis.

The evaluation of RNS operations and interfaces with other candidate system elements has indicated that RNS operations require minimal orbital support. Elements considered and found to be unnecessary include an orbital propellant depot, an orbital maintenance facility, communications satellites, and remote manipulator units. The space tug can be used to support RNS assembly, although its functions could be adequately provided by a CCM from the RNS. A lunar-lander-size tug is utilized for NERVA disposal. Thus, the major support systems for the RNS are the space shuttle which

provides initial delivery of RNS modules to orbit and subsequent propellant resupply as a tanker vehicle and a space tug for RNS assembly and NERVA disposal operations.

2.3 DESIGN CRITERIA

The design criteria for each of the major subsystems used as a basis for the design analysis are presented in the various subsections of Section 4 in Book 1. The major considerations and sources of data for these will be summarized here.

The basis for structural design criteria is contained in "Guidelines for Strength Analysis Test and Assessment Requirements," MSFC Memorandum S&E-ASTN-AS-70-55, dated June 5, 1970. This memorandum defines terminology and data sources. The principal source of material properties is "Metallic Materials and Elements for Aerospace Vehicle Structures," MIL-HDBK-5A, February 8, 1966. Space shuttle load factors are defined by MSFC Memo PD-SA-70-269, dated November 13, 1970. The space shuttle launch is manned. All RNS pressure vessels are designed such that pressure stabilization is not required for any ground launch or mission operation. The propulsion module run tank is launched dry and unpressurized.

The space meteoroid environment is defined in "Natural Environment Criteria for the NASA Station," D. K. Weidner, Editor, NASA TMX-53865 dated October 31, 1969. The damage criterion for tankage is that there will be no penetration of the tank wall. Experimental test data are used for armor effectiveness. The thermal environment is defined by two documents: "Terrestrial Environment (Climatic) Criteria Guidelines for Use In Space Vehicle Development," NASA-TMX-53872, September 1970; and "Space Environment Criteria Guidelines For Use in Space Vehicle Development," (1969 Revision) NASA-TMX-53957, October 1969. High-performance insulation characteristics have been established using test data obtained from Contract NAS8-21400. Hypervelocity test results were used for meteoroid armor effectiveness. The thermal and meteoroid protection systems impose no requirements for vehicle orientation during any operations or mission phases.

The docking and clustering mechanism designs accommodate tolerances established with reference to an ITT laser radar system performance and considers the resultant of a 10 lb-sec impulse for maneuvering an empty propellant module. Docking courses are not used to actuate or to lock the latching mechanisms. The RNS or its separate modules, except the CCM, will be passive for all docking operations while providing functions to permit automatic rendezvous and docking.

Main propulsion system design criteria are established for the NERVA engine in the following documents: "NERVA Program Requirements Document," SNPO-NPRD-1, January 19, 1970; "NERVA Reference Data (Full Flow Engine)," AGC Report S-130-CP-090290-FL-Preliminary, April 1970. Propellant conditions are derived from AGC Letter 7410:1075, July 15, 1970 which includes a steady-state operating pressure of 26 psi saturated liquid with zero NPSP. Reduced flow rates are permitted at zero NPSP and saturated liquid for saturation pressures below 26 psi to provide autogenous start capability. The RNS will provide propellant conditions for a NERVA malfunction mode; however, the total pressure need not exceed 26 psi for such a mode. During pulsed aftercooling the RNS will provide saturated liquid to the bypass line at a pressure exceeding 16 psia. The NERVA engine will provide pressurant flow as required for all RNS operations except during pulsed aftercooling. Fluid line interfaces will provide for assembly and disassembly in orbit.

The auxiliary propulsion system is located in the CCM and provides thrust for: (1) attitude control during coast phases, (2) attitude maneuvers, (3) attitude control during cooldown thrusting, (4) separation maneuvers, (5) roll control during main engine burns, (6) rendezvous maneuvers, and (7) propellant settling. The APS motor configuration is designed to fail operational with subsequent failure accommodated by the use of alternate engines for a particular maneuver.

The RNS has capability for navigation and guidance, data management, command and control, and power functions independent of payload. The RNS provides autonomous capability for orbital checkout, fault isolation and

detection, and emergency detection. Uplink and downlink capability for data and control will be provided with the ground in necessary support system elements. The RNS navigation and guidance policy will provide for maximum practical utilization of aftercooling pulses for final velocity attainment, mid-course correction, and/or rendezvous maneuvers. Electronic technology expected in the 1974 time period is utilized. The NERVA power requirements are defined by the NERVA documents cited previously.

Data on NERVA and its radiation sources are based on "NERVA Flight Engine Common Radiation Analysis Model," AGC Report RN-TN-0583, May 1969. The fundamental radiation and criterion was a dose of 10 rem per mission to a manned capsule located 11 ft ahead of the RNS. Radiation damage to materials is established from multiple data sources contained in the open literature; however, the Radiation Effects Information Center (REIC) operated by Battelle Memorial Institute is considered as the primary source.

The RNS will have a capability of performing 10 missions over a period of 3 years. It will be designed to achieve a reliability at 0.975 with a confidence level of 90 percent for the in-transit phases of the mission. No single failure will cause loss of mission. Accordingly, the functional subsystems of the RNS are designed to fail operational.

Section 3

RNS SYSTEM DEFINITION

This section contains an overall description of the Class 3 RNS vehicle. Detailed hardware trees for each module are given in the following sections.

3.1 VEHICLE CONFIGURATION

Figure 3.1-1 is an inboard profile drawing of the assembled Class 3 RNS vehicle. This RNS configuration contains three major types of modules: the propulsion module contains the NERVA engine and a run tank; eight similar propellant modules characterized by location as outboard modules, tandem modules and a core module; and the CCM. All of the modules are launched by the space shuttle. The size of each one is therefore governed by the 15 by 60 ft cargo compartment of the shuttle. The interfaces between modules which represent orbital assembly planes are indicated on the drawing. The main propellant feed subsystem supplies liquid hydrogen to the engine from the run tank via two separate 10-in. -diameter tank outlets. The NERVA-supplied pump shutoff valves interface at these run tank outlet penetrations. At rated thrust conditions, the combined outflow from both of these ducts totals 91.9 lb/sec of hydrogen at a pump inlet pressure of 26 psia.

Antivortexing and filtration screens are located inside the tank around each of the feed duct outlet penetrations. Due to the spacing of the NERVA dual pump locations, two individual screens will be used, one over each exit port. These screens will provide 100-micron filtration. Because of the chilldown conditioning requirement for the NERVA engine, provision is made to open the antivortexing and filtration screens during the chill and before initiation of engine prestart. Propellant inflow to the propulsion run tank is accomplished by a 12-in. -diameter internal tank feed line extending the length of the tank. This duct, which is designed for collapse pressure, contains two 8-in. flow control valves located at the tank bottom. These two motor-driven control valves are actuated through the data management subsystem by liquid level sensors located in the run tank. The system is utilized to

maintain a constant liquid level in the run tank during steady-state engine operation.

At the forward penetration of the run tank, the feed duct exits and is routed up to the interface plane. The section of ducting from the dome penetration to the interface plane is a linear section of stainless steel ducting utilizing a compensator and two gimbal joints. This system of flexible elements will provide the linear deployment required to perform the automatic coupling of the feed duct at this interface. The 12-in.-diameter internal feed line is fabricated from aluminum alloy. Bolted connections are used at the stainless steel transition sections containing the 12-in.-diameter gimbal joints utilized as flexible elements. Dual pressure actuated static seals are used in the feed system with automatic leak check capability.

Propellant is supplied to the NERVA engine during full-thrust operation by a tap-off expulsion pressurization system. A control system is provided for this purpose in each one of the propellant modules as well as the propulsion module run tank. The pressurant gas used for expulsion is obtained from the NERVA engine tap-off located downstream of the turbine. The engine will supply a duct from the turbine tap-off to the engine/stage connect panel. This panel is mounted to the propulsion module thrust structure. The 1-1/4-in. -diameter pressurization duct will run along the outside of the run tank covered by insulation and meteoroid armor. Pressurization control valves are located external to the tank in the forward dome area. The 1/2-in. -diameter penetration will enter the forward ullage space and terminate in a diffuser to prevent ullage collapse. A tee is provided in the pressurization system and the line is run from the tee to the interface plane. The pressurization duct, using a conventional quick-disconnect coupling, is routed to the electrical connect panel located at the interface. Deployment and coupling of the pressurization duct will utilize the deployment mechanism for the electrical coupling panel. These are the only fluid couplings crossing the interface plane between the propulsion module and the propellant module.

The flight vent is located in the forward region of the propulsion module run tank. This system utilizes quad redundant valving and two positive propulsive vent nozzles located 180 degrees apart in the forward skirt region and

Figure 3.1-1. Inboard Profile (Sheet 1 of 3)

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Figure 3.1-1. Inboard Profile (Sheet 2 of 3)

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is used for both command flight venting and for emergency flight relief. The nozzles point aft to aid in propellant settling during venting. The vent system extends into the forward dome ullage space using a single penetration. System control is via the data management subsystem operating on information from pressure sensing strain gage transducers located in the ullage.

The propulsion module also contains an ambient gas auxiliary propulsion system. It is used to stabilize the module during the assembly sequence with control provided by a local gyro package. This system is located in the forward skirt region of the run tank and uses a 25-in.-diameter titanium sphere for gas storage and two sets of nozzles, three per cluster, located 180 degrees apart on the outer surface of the run tank forward structure. Recharge of the sphere is accomplished from the NERVA engine by tapping off from the pressurization line in the forward skirt of the propulsion module.

The run tank is refilled with propellant from any one of the eight propellant modules before every full-thrust operation. The refill system consists of two parallel mounted submerged ac-motor-driven pumps. These pumps are mounted in a manifold which is identical to the manifold used for the two 8-in. -diameter flow control valves. The pumps intake from this main feed manifold and discharge via control valving to the 4-in. -diameter line that runs to the ullage of the run tank. The pumps accomplish the transfer against a pressure head between the two tanks.

Orbital refill, performed every round trip, utilizes the tanker as the active element. The run tank refueling operation is accomplished without the use of the motor driven pump system. Fluid is transferred through the main feed system and discharges through the spray nozzle into the ullage space of the run tank.

The propulsion module contains an integrated stage/engine recirculating chilldown system. This system conditions the NERVA engine inlet ducting, turbo pumps and related engine valving. It contains two parallel mounted ac-motor-driven pumps that are submerged at the bottom of the run tank. These pumps discharge to a single line which penetrates the run tank and

then separates into two ducts which are routed to the engine inlet ducting downstream of the pump shutoff valves. As presently conceived, the PSOV's will contain a boss for each of these lines to provide the engine-to-stage interface connection. During the chilldown cycle, the PSOV's are closed and flow proceeds downstream into the feed ducts and through the engine turbo-pumps. The engine will supply a chilldown return line that will run from the customer connect panel to the discharge side of both pumps. The stage will return the chilldown flow via a set of quad-redundant valves back into the run tank. This closed-loop system will provide conditioning for all of the NERVA inlet hardware to ensure a reliable start.

In addition to performing engine preconditioning, this system also provides conditioning for the feed ducting between the propulsion module and the desired propellant module. This is accomplished by first closing the blocking valve in the propellant module to be conditioned. Next the module's two tank isolation valves are opened. Pump discharge flow is then routed into the main feed duct manifold and proceeds up the 12-in. -diameter run tank feed line to the first tandem module sump. Entrance to the propellant module is through the two 8-in. -diameter tank isolation valves. This is the typical operational flow sequence for conditioning any of the propellant modules. The chilldown return line valves associated with this system will be mounted to the run tank thrust structure.

The propellant feed system, commencing at the interface of the first tandem propellant module with the propulsion module, contains a 12-in. -diameter line that extends the full length internal to that module and continues to the forward tandem modules. This system utilizes gimbal joints and pressure volume compensators as flexible elements. All internal ducting will be fabricated from aluminum employing external rigidization designed based on collapse conditions. Where flexible elements are required in the internal duct runs, stainless steel ducting with bolted static connections will be utilized. Internal ducting will be supported off the tank wall by sliding type vibration mounts. Feed line blocking valves (12-in. -diameter) which permit isolation of the module during the chilldown cycle are located in the forward dome region of each propellant module. The forward interfaces of the

three in-line modules will contain the baseline compensator two-gimbal flexible element system. This duct will be deployed after docking and latching is accomplished.

The four outboard propellant modules attach to the central feed system at the inboard module sump. Each of the four 8-in. -diameter ducts located on the inboard module contain two gimbal joints. They are automatically coupled to the four outboard propellant feed ducts which contain automatically deployed compensator gimbaled ducting. Coupling is accomplished by mechanisms mounted to the inboard module.

Each propellant module contains a flight vent system which is sized at a 2-1/2-in. -diameter and contains a set of quad redundant, on-off type control valves and discharges through nozzles located 180 degrees apart. This system, which is strain-gage pressure sensor controlled for the flight relief function, can be commanded to operate for venting. In order to accommodate ground fueling and ground safety requirements, each propellant module also contains a ground vent and relief system. This system is utilized during the ground fill operation and also in the event of inadvertent pressure buildup in the tank. It consists of a vent and relief valve close coupled in the forward skirt region and a 6-in. -diameter duct running from the valve mounting to a penetration in the forward dome. The flight vent system tees into the ground vent and relief system downstream of the ground vent and relief valve. Thus, both the ground vent and relief, and the flight vent and relief systems utilize a single tank penetration.

Ground fill of each of the propellant tanks is accomplished through the feed system. Each of the propellant modules contains an in-flight refueling system which consists of a set of quad-redundant control valves, an antiback-flow check valve and a spray nozzle. The system tees in upstream of the blocking valve for each of the in-line modules. In the case of the outboard modules a 4-in. dia line extends the full length of the tank originating at the the sump and terminating in a spray nozzle located in the ullage region.

The pressurization system for the propellant modules and the propulsion module consists of a two flow loop system with four quad-redundant valves

per loop. Each module contains its own independent control and the on-off type system is controlled by pressure sensors located in the ullage region of the tanks. Pressurant gas is manifolded and distributed to each of the propellant tanks through 1/2-in. -diameter external stainless steel lines that run the entire length of the tank. These lines are covered by the thermal/meteoroid protection subsystem. Quick-disconnect couplings located at the interfaces on the electrical connect panels are utilized for pressurization line hookups. Each pressurization duct terminates in a diffuser to prevent ullage collapse. Ground pressurization is accomplished by the flight interface quick disconnect.

A 4-in. -diameter refueling connection is made at the command and control module interface with the forward tandem propellant module. The CCM contains a straight section of 4-in. -diameter ducting. This duct contains a section of untied convoluted bellows to accommodate thermal and pressure deflections. The automatic flange coupling mechanism utilizing dual static seals is located on CCM refueling duct. This section of feedthrough ducting in the CCM enables refueling of the propellant modules and the propulsion module with the CCM in place.

The CCM also contains the cryogenic auxiliary propulsion system for vehicle control. This system utilizes central tankage that feeds two sets of thruster pods located 180 degrees apart. The thruster as shown is located on the interior surface of the command and control module. Centralized propellant storage for the APS and fuel cells is located in the command and control module. This tankage consists of low-pressure storage spheres, a turbo-pump system, and high-pressure hot-gas storage accumulators.

Sheet 2 shows the automatic coupling mechanism that is used for the large diameter feed ducting between the propulsion module and the aft propellant module. The upper half of this sectional view shows the duct in the normal position after docking and latching have been accomplished. The lower section shows the duct deployed with the coupling made. This is accomplished in two discrete steps: deployment and then coupling. A linear deployment mechanism is located on the lower module feed duct and the

coupling mechanism is located on the upper module feed duct. The lower module feed duct flange is attached to the handling frame of 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 propellant 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 propellant module upper thrust structure. When the threaded drive screws are rotated, the frame assembly is extended linearly the deployment distance of 1-1/2 in. as shown. The screws are chain driven by a worm wheel gearing system using an electric motor drive. The coupling mechanism located on the propellant module feed duct is shown on sheet 3. The automatic coupling operation is initiated after the deployment operation is completed. This mechanism consists of two V-couplings. The coupling sections are supported and operated by left- and right-hand threaded drive screws. The drive screws are chain driven by the same worm wheel gearing system. Sealing is accomplished by the dual propellant pressure actuator seals as shown on sheet 2.

The feed duct coupling from the outboard propellant modules is accomplished in exactly the same manner. The linear deployment mechanism is located on the feed duct of the outboard module with the coupling mechanism located on the central propellant module. A deployment distance of three inches is used in this case.

The method used for connection of the electrical panels module interfaces is shown on Section F-F of sheet 1. The initial alignment motion is supplied by structural docking and latching. Ball bearing screw jacks which are chain driven via electric motors raise the lower panel to the first engaged position. This aligns the connectors with their mating almost to within pin engagement tolerances without actually engaging the pins. Position switch talkback is obtained before the final pin engagement stroke is initiated. This will prevent pin binding and result in reliable mating and demating. The ball and

jack drive screws and motor driving mechanisms are similar to that described for the duct deployment system.

3.2 STRUCTURES

A summary of the RNS structural design is contained in this subsection.

3.2.1 Loading Summary

The Class 3 cruciform configuration bending moment and axial load diagrams are shown in Figures 3.2-1 and 3.2-2 for mission operation with the engine gimbaled hardover at 5.7 degrees under full thrust (75,000 lb). These represent limit load conditions and were generated by the MDAC SB-15 computer program. They are for the case with all modules full, which is the most severe case. In the figures, the gimbal point is at station 4963.5 and the forward end of the CCM is at station 1664.5. These loads designed the CCM and the skirts and thrust structure of the propellant and propulsion modules.

Figure 3.2-1 LIMIT BENDING MOMENT DISTRIBUTION, ENGINE OPERATION

Figure 3.2-2 LIMIT AXIAL LOAD DISTRIBUTION, ENGINE OPERATION

At the launch release transient, the tankage limit loads are:

Moment	1.07×10^7 in. -lb
Axial	17,700 lb Compression

This assumed that the module was simply supported at each end of the shuttle cargo bay. The tankage sidewall stiffening was determined by these loads. The design burst pressure for the tankage membranes was 30 psi.

3.2.2 Structural Description

A layout of the structural configuration for the Class 3 cruciform is shown in Figure 3.2-3, the layout is contained on 10 sheets located at the end of this description so that the sheets can be folded out while reading the text. The configuration consists of eight propellant modules, a propulsion module, and a CCM.

3.2.2.1 Propellant Modules

There are three classes of propellant modules tandem (3 required), core (1 required), and outboard (4 required). The modules are virtually identical

structurally. Tankage reinforcement was determined by the shuttle launch condition. All skirts were designed for the highest combined loading. The only difference between modules is the addition of four clustering systems to the core module and one system to each of the outboard modules.

The overall dimensions of the propellant module (main view sheet 1) were governed by the 15-ft diameter, 60-ft-long constraints of the shuttle cargo bay. The overall length of the tank was determined by the distance required between tanks for the docking structure and the propellant transfer lines, while the determining factor for the tank diameter was the diameter of shuttle cargo bay reduced by the total thickness required for the thermal/meteoroid protection system. These two constraints produced a tank with a capacity of 36,500 lb of LH₂ with a 5 percent ullage volume. The tank, fabricated from 2014-T6 aluminum alloy, consists of two hemispherical domes and integrally stiffened cylindrical section, all fusion butt-welded. To compensate for manufacturing tolerances, 0.005 in. was added to the theoretical membrane thicknesses to arrive at all final thicknesses. The weld land thickness was held constant throughout the tank to avoid tapered welds.

The one-piece domes are of monocoque construction fabricated from a forging. Integrally machined attach lugs, shown in views AA-AA and AC-AC on sheet 5, are provided on the domes for attachment of the skirts. Pads are incorporated around the lugs to reduce the stress level for the point loads which are introduced tangentially to the dome surface. Plumbing penetrations are integrally reinforced and pads are provided for plumbing line support attachment. Because of the angle the feed duct penetrates the dome, a precision casting was employed as its feedthrough. This casting has a 30-in. -diameter flange which is welded normally to the dome surface. It has cast in stubs to which the feed duct attaches. The outside stub incorporates a static seal bolted flange while the inside joint is welded. A manhole with a bolt on cover is provided at the pole of the forward dome. Provisions for attachment of a sump shown in views on sheet 5 are incorporated in the pole of the aft dome.

The tank cylindrical section is comprised of three segments which employ an isogrid stiffening pattern. This pattern, shown in view T on sheet 5, consists of a gridwork of equilateral triangles over the wall surface with a rib height of 0.615 in., a rib thickness of 0.035 in., and a rib length of 8.10 in. The membrane thickness is 0.055 in. The fill and drain supports attach to inserts which are installed in the nodes of the isogrid pattern.

Two slosh baffles and a geysering baffle are incorporated in the core and tandem module tankage design. Their location is shown in the main view on sheet 1. The outboard modules have only one slosh baffle and a geysering baffle. The purpose of the baffles is to improve the efficiency of propellant settling. All three baffles lie in a station plane with the membranes of the slosh baffles attaching directly to the tank walls while the membrane of the octagon-shaped geysering baffle (view Y-Y sheet 5) is centrally located. The membranes of the slosh baffles tie to rings which are supported by struts. The struts which incorporate self-aligning bearings attach to fittings mounted to node inserts at 16 equally spaced peripheral locations around the tank. Nylon cord is used to tie the membranes to both the rings and the tank. It is also used as an edge member for the geysering baffle membrane and to attach the baffle to fittings mounted to node points in the tank side-walls at eight equally spaced peripheral locations.

The forward and aft skirts must keep the heat flow into the propellant tank low compared to the heat flow through the insulation blanket (i. e. thermal conductance (<1 Btu/hr/°F)). Therefore, fiber glass was selected for their construction. These components are protected from the atmospheric environment during boost by the shuttle cargo, so an open-type truss is employed for their configuration to take advantage of light weight, low heat transfer and easy accessibility to internal installations. The laminated strut arrangements consist of X-member subassemblies (view U on sheet 6) comprised of a central tubular cast titanium fitting to which four laminated tubes with tapered titanium end fittings are installed. A self-aligning bearing is provided in each end fitting to minimize alignment problems. The laminated struts are designed so that the longitudinal fibers resist the axial loads, with internal and external radial plies providing reinforcement in the circumferential direction.

Closing frames, which are basically channel sections (view S on sheet 5), are provided at the ends of the skirts to resist the strut-induced radial or kick loads and to provide support for the docking system. The propellant transfer line coupling and handling frame as well as the electrical interface panel are mounted to these frames. Each of these components is stabilized by a pair of struts fabricated from 6061-T6 aluminum alloy tubing that attach either to fiber glass struts or the strut titanium splice members. Attach lugs for the skirt struts and support points for the structural latches are machined into the frames. These are depicted in view AL-AL and section W-W on sheet 8. The aft skirt is approximately 10 in. longer than the forward skirt because of space requirements for the propellant feed line as it exits the aft dome.

3.2.2.2 Propulsion Module

The maximum size of the propulsion module was also governed by the 15-ft-diameter, 60-ft-long shuttle cargo bay. The tank length was determined by engine length and space allocations for the docking system and the propellant transfer lines. The diameter was defined by the radiation-shield zone. The shadow shield zone half-angle of 10 degrees was generated by extending a line from the aft outboard corner of the engine reactor through a point tangent to the aft dome of the outboard propellant tank. These two constraints produced a tank with a capacity of 10,850 lb of LH_2 with a 5 percent ullage volume. The tank is fabricated from 2014-T6 aluminum alloy and consists of two hemispherical domes and an integrally stiffened cylindrical section, all fusion butt-welded. To compensate for manufacturing tolerances, 0.005 in. was added to the theoretical thickness to arrive at all final membrane thicknesses. Weld land thickness was held constant throughout the tank to avoid tapered welds.

The one-piece domes are of monocoque construction, fabricated from a forging. Integrally machined attach lugs, shown in views B-B of sheet 3 and section F-F of sheet 2, are provided on the domes for skirt and thrust structure attachment. Pads are incorporated around the lugs to reduce the stress level for the point loads which are introduced tangentially to the dome surface. Plumbing, astrionic probe support points and penetrations are

integrally reinforced. Access to the tank interior is provided through a manhole shown in view C-C of sheet 4 with a bolt cover at the pole of the forward dome. An isogrid pattern (view R on sheet 3) which has a rib height of 0.560 in., a rib thickness of 0.035 in. and a rib length of 10.130 in. is employed to stiffen the cylindrical section of the tank. The membrane thickness is 0.051 in. The point level support system and the fill and drain line supports are attached to inserts installed in the nodes of the isogrid pattern. Two slosh baffles and a geysering baffle (view D of sheet 2) are installed inside the tankage. Their location is shown in the main view on sheet 1. Except for size, the slosh baffle design, location, level, and method of attachment are identical to the baffles in the propellant modules. The geysering baffle is a scaled-down version of those in the propellant modules.

Since there is a low thermal conductance requirement for the thrust structure (view A-A on sheet 2) and forward skirt and these components are protected from the launch environment during boost by the shuttle cargo bay, a truss-work of struts (view P-P on sheet 4) fabricated from fiber glass was selected for their configuration. Except for physical dimensions, the design is identical to that employed for the propellant module skirts. A ring frame shown in view C-C on sheet 4 is provided at the forward end of the skirt to resist the strut-induced radial or kick loads and to support the docking probes. The propellant feed line disconnect and the electrical interface panel are also mounted on this frame. Each component is stabilized by a pair of struts (view P-P on sheet 4) fabricated from 6061-T6 aluminum alloy tubing that attach to the fiber glass struts. Attach lugs shown in view Q on sheet 4 for the skirt struts and support points for the structural latches are machined into the ring frame which is basically a channel section. The thrust structure closing frame (view A-A sheet 2) was designed to pick up the 12 equally spaced 3/4-in.-diameter attach points on the 56-in.-diameter bolt circle of the engine upper-thrust structure (UTS). This is a mastered hole pattern. In order to provide the most direct load path, the thrust structure struts attach to the interface ring at these bolt locations. Cutouts are incorporated in the ring to provide clearance for the propellant inlet lines. Electrical wiring harnesses are supported off the UTS as they

traverse the interface plane. Integrally machined lugs for attachment of the thrust structure struts are incorporated in the design of the frame which is basically a channel section.

3.2.2.3 Command and Control Module

The CCM shown in view Z-Z on sheet 9 consists of a cylindrical section plus a pair of closing frames. The cylindrical section is fabricated from two 180-degree segments which are integrally stiffened with an isogrid pattern (View AM-AM on sheet 9) which has a rib height of 0.420 in., a rib thickness of 0.050 in., and a rib length of 4 in. The membrane thickness is 0.025 in. Lips which are shown in Section AN-AN on sheet 9 are machined into the panel edges for segment joining with mechanical fasteners. Astrionic equipment panels and APS pressure bottle and accumulator supports attach to inserts installed in nodes of the grid pattern. The integrally machined closing frames are channel sections but include provisions for attaching docking cones to the forward frame and docking probes to the aft frame. The probes and cones are stabilized by pairs of struts which attach to the segment gridwork nodes. The electrical interface panels, and the propellant in-flight refill line coupling and handling frame also mount to the frames. They are stabilized in the same manner as the docking probes and cones. The APS units are mounted inside the cylinder. Each unit is supported by a pair of stub frames that attach to the module sidewalls and to a pair of beams extending the full length of the module. The beams attach to the closing frames and to nodes of the sidewall gridwork. Blast shields are provided from the nozzle ends to the exterior surface of the module. Meteoroid protection is furnished by a one-in. layer of rigid foam and an external fiber glass cover sheet. The foam is bonded to the outside surface of the module.

The docking subsystem shown in view AO on sheet 10 consists of four cylindrical probe assemblies (including shock absorbers and pull-in mechanisms) located on one module, and a mating set of drogue cones mounted on the other module. The extended portions of the probes have a flexible section at the tip, which is deflected along the cone surface and

enters a latch pocket at the vertex. The latch pocket contains inclined plane latching cams which are spring loaded closed and probe deflected open to accomplish the catch. Probe release is effected by actuating four pull-solenoids to retract the cams. The flexible sections are then retracted, pulling the rigid sections of the probes into the cones, to align the modules. Further retraction of the probe mechanisms draws the aligned modules into contact. Structural latches are actuated to provide a rigid connection between modules.

The probe components are the probe casing and flange, the hard probe, retractor, flexible probe, probe screw jack, actuator, helical springs, and solenoid-deactuating operated ratchet. The hard probe and retractor are concentric within the casing. The flexible probe is attached to the outer end of the retractor. One spring is located between the casing and the hard probe; the other is positioned between the hard probe and the retractor. The springs tend to hold the hard probe and flexible probe in the extended position, but may be compressed either by the screw jack (to retract) or by forces due to docking impact. The ratchet detent prevents rebound.

Operation of the main drive retractor motor is initiated when the extended flexible probe tip is captured by the latch at the vertex of the cone. The (weaker) retractor spring is compressed first, drawing the rigid probe into the vertex of the cone. Continued rotation of the screw jack retracts the hard probe into the casing to pull the modules together.

The central tier of five modules has supports (view X on sheet 7) machined in the skirt frames for the hinge mechanisms (view AJ-AJ on sheet 7) and structural latches required for clustering. During launch and docking the hinges located in the forward skirt area are retracted within the 15-ft-diameter envelope of the shuttle. 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 center. Two pairs of hinges constitute the forward rotational support system for each of the outboard modules and the core module.

The aft portion of the core and the outboard module support system is located in the aft skirt area and is shown in views V, AH-AH, and AI-AI on sheet 6. The system must be capable of absorbing module rotational impulse and then structurally latching. Impulse is absorbed by a probe shock absorber which contacts a cone mounted to the inboard module. The cone (view AG-AG on sheet 6) is mounted on four sets of track roller bearings. This permits the cone to move along stage longitudinal axis to absorb assembly tolerances and operational deflections after latching. This system is a scaled down version of the main docking system. Both the probe and the cone are mounted to supports that attach to the skirt closing frame and to the struts.

The structural latching system shown in View AL-AL and Section W-W of sheet 8 is actuated after the docking system has aligned and joined the two modules. The hook-type latches are located at 12 points around the interface frame adjacent to the truss skirts structure attach points. They are all activated simultaneously by a single cable driven by a reversible drum and motor assembly. A braking system incorporated in the motor holds the latches in either the closed, over-center or open positions.

The latch and link assemblies are attached to machined supports in the aft module interface frame with the axes lying in a radial plane of the frame. Each assembly consists of a hook and four links. Motion of the hook is controlled by a pin riding in a machined slot in the frame. Upon actuation, the hook travels through clearance holes in the mating frames and engages an adjustable striker plate mounted on the opposite frame. The frames are locked as the links are rotated to their over center position. Unlatching is accomplished by reversing the direction of cable travel which returns the hook to its normal unlocked position. A shear pin is provided at each latch for alignment and transfer of shear loads between modules.

3.2.3 Mass and Dynamic Properties

Rigid and flexible body properties were prepared for structural dynamics and powered flight attitude control analyses. These properties were determined using MDAC computer program DA02, "Determination of Vibration

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Figure 3.2-3. Structural Configuration (Sheet 2 of 10)

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Figure 3.2-3. Structural Configuration (Sheet 3 of 10)

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Figure 3.2-3. Structural Configuration (Sheet 4 of 10)

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Figure 3.2-3. Structural Configuration (Sheet 5 of 10)

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Figure 3.2-3. Structural Configuration (Sheet 6 of 10)

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Figure 3.2-3. Structural Configuration (Sheet 7 of 10)

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Figure 3.2-3. Structural Configuration (Sheet 8 of 10)

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Figure 3.2-3. Structural Configuration (Sheet 9 of 10)

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Figure 3.2-3. Structural Configuration (Sheet 10 of 10)

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Modes by K-Matrix Displacement Method." This program provides the normalized bending deflection, slope, bending moments, and shears. Rigid body mass, center of mass, and inertia are also generated. Variation of these characteristics throughout the mission have been established. A lunar delivery payload model of 98,000 lb in weight, 140 ft long, and of uniform mass distribution was assumed in these calculations. The return payload used was uniform and 15,000 lb in weight and 20 ft long. Table 3.2-1 summarizes the rigid and flexible body properties obtained for the Class 3 cruciform configuration. Also shown in this table are the control arms for a forward and aft auxiliary propulsion system (APS) location. The forward location of the APS would be in the CCM with the aft location on the forward part of the run tank.

Figures 3.2-4, 3.2-5, and 3.2-6 present the bending deflections for the first three modes. These relative deflections are normalized to a value of unity at the NERVA gimbal point (Station 100). The attitude and attitude rate gyros would be located in the CCM Station 3199. Plots for normalized bending moments and shears and the other loading condition are also available.

3.3 METEOROID/THERMAL PROTECTION

This subsection identifies the design conditions and describes the subsystems for meteoroid and thermal protection.

3.3.1 Design Conditions

The meteoroid protection system of the RNS provides a 0.995 probability of no tank penetration in active modules in one lunar mission. The mission duration is 27.5 days embedded within a 54.6-day repeating cycle measured from initial RNS startup in earth orbit to completion of aftercooling upon return to earth orbit. Based on the analysis described in Section 4.3.3 of Book 1, the following criteria are established:

<u>Criterion</u>	<u>Survival Probability</u>
Full cycle (54.6 days)	0.976
Lunar mission (27.5 days)	0.995
Lunar mission during transit (9.5 days)	0.9975

Table 3.2-1
RNS CLASS 3 MASS DATA

Vehicle Loading Condition	Vehicle Mass Lb-Sec ² In. ⁻¹	Vehicle C.G. Location Station Number*	Vehicle Inertia About C.G. Lb-Sec ² In.	Engine Gimbal Control Arm In.	First Mode Body Bending Freq. Hz	First Modal Mass Lb-In. ⁻¹ Sec ²	Second Mode Body Bending Freq. Hz	Second Modal Mass Lb-In. ⁻¹ Sec ²	Third Mode Body Bending Freq. Hz	Third Modal Mass Lb-In. ⁻¹ Sec ²	APS Control Arm	
											Forward Location In	Aft Location In
All Modules Full 98 K Lb Payload	1,253	2,046	2.02 x 10 ⁹	1,946	0.274	253	0.676	617	1.38	4,032	1,189	1,646
Outside Cluster Modules Empty 98 K Lb Payload	870	2,307	1.80 x 10 ⁹	2,207	0.292	323	0.766	700	1.53	9,120	928	1,907
Outside Cluster and 1st Forward Module Empty, 98 K Lb Payload	776	2,239	1.77 x 10 ⁹	2,139	0.311	295	0.850	905	1.55	9,982	996	1,839
Outside Cluster and 1st Two Forward Modules Empty, 15 K Lb Payload	466	1,328	4.72 x 10 ⁸	1,228	0.550	331	1.64	12,454	3.40	1,621	1,907	928
Outside Cluster and 1st Three Forward Modules Empty, 15 K Lb Payload	335	1,372	4.46 x 10 ⁸	1,272	0.623	396	1.93	40,839	3.89	608	1,863	927
All Modules Empty, 15 K Lb Payload	274	1,485	4.27 x 10 ⁸	1,385	0.658	619	2.37	1,605	3.95	455	1,750	1,085

* Gimbal Point = 100

Figure 3.2-4 FIRST MODE BENDING DEFLECTION

Figure 3.2-5 SECOND MODE BENDING DEFLECTION

Figure 3.2-6 THIRD MODE BENDING DEFLECTION

An average mission surface temperature of 370°F was adopted for thermal protection system design. Surface coatings are considered degraded by the space environment and a value of 0.32 is used for absorptivity and 0.96 is used for emissivity. The thermal conductivity for DAM/dacron net, high-performance insulation is 2.0×10^{-5} Btu/hr-ft-°R for a mission temperature range of 400 to 40°F. The natural layer density of 96 layers/in. is utilized. The density of the blanket is 4.1 lb/ft³, exclusive of installation. The heat input to the tank is based on the propellant utilization history during the mission and considers the reduced heat capacity of offloaded tanks. The resulting equivalent times are defined in Section 4.3.7 of Book 1 considering pre-mission and mission phases. The analysis in Section 4.3.11 of Book 1 indicates that it is most economical to vent the tank in earth orbit prior to the mission. The tank must then be topped off with the initial condition for the propellant in the outboard module, being approximately 16 psia, which is the condition of the delivered propellant. The inboard modules are sub-cooled. The thermal protection system design parameters are summarized as follows:

	<u>Inboard Propellant Module</u>	<u>Outboard Propellant Module</u>	<u>Run Tank</u>
Tank volume (ft ³)	8,710	8,710	2,590
Tank surface area (ft ²)	2,630	2,630	964
Heat short insulated area (ft ²)	270	126	230
Propellant loading (lb LH ₂)	36,400	36,400	10,850
LH ₂ saturation pressure after topping off	16	16	16
Full tank equivalent time (hours):			
Before mission	430	430	430
During mission	695	1	1,092
Total	1,125	431	1,522

3.3.2 Subsystem Description

The integral thermal/meteoroid protection system is shown in Figure 3.3-1 on 7 sheets. This figure identifies the insulation and meteoroid protection components that make up the complete system. It is located at the end of this subsection to facilitate reference while reading the text. Thermal protection for the stage is provided by three blankets of HPI, and meteoroid protection is furnished by a layer of polyurethane foam encased by a fiber glass shroud.

View AA on sheet 2 shows the manhole cover insulation and the forward dome insulation which is made up of 12 pie-shaped segments. The three blankets that make up each segment are staggered as shown and are supported at the periphery of the manhole cover by nylon studs. The outer edges of the uppermost blankets are laced to each other to hold the entire assembly in the proper position. Each blanket of the manhole cover insulation is installed separately, and the cover of the outer manhole cover insulation blanket is laced to the outer cover of the forward dome insulation. Three concentric gas inlet rings supply helium purge gas to the manhole and forward dome HPI blankets. These rings are attached to studs which are supported by fiber glass rings. The insulation covers are laced together as shown in View K on sheet 2.

A typical sidewall thermal/meteoroid protection panel and the insulation joints are shown in Views D and E on sheets 3 and 4. As shown in the main view on the first sheet, the sidewall insulation is divided into three tiers, each of which is divided circumferentially into 12 panels. Each panel is approximately 48 in. wide by 175 in. long and is composed of three HPI blankets, a layer of foam, and the fiber glass shroud. Each core and tandem module blanket contains 16 layers of doubly aluminized mylar with net separator, sandwiched between two face nets. The only difference for the outboard modules is that their blankets contain only 10 layers.

The fiber glass shroud with its inner and outer connector strips riveted to the shroud is shown in View E on sheet 4. The reason the shroud is 6 in. narrower than the insulation blankets is for installation of the shroud splice. As shown in the lower view, which is a typical longitudinal joint, a 6-in. section of flexible foam is installed between shroud panels and a fiber glass splice section riveted to adjoining outer sheets. The thermal blankets are staggered in the splice area.

The face nets shown in View D on sheet 3 have border and longitudinal reinforcing strips, 12 in. center-to-center formed by impregnating the net with resin. Each blanket is held together by small nylon studs and buttons located 12 in. on center in the longitudinal and lateral directions. The inboard cover net of each blanket has four tabs at each end. At the forward end, these tabs support the blanket via four fiber glass inner connector strips which attach to studs on the tank wall. The inner strips continue aft and outboard, through the HPI and foam, to the forward end of the fiber glass shroud. Here they are attached to and support the shroud. Four fiber glass outer connector strips are also provided for insulation support. These are riveted to the tabs that are located on the aft ends of the cover sheets and extend outboard and aft, through the foam, to anchor the aft ends of the panels to the fiber glass shroud.

The lower view shows a section through the circumferential joint. Each of the three blankets is tapered at the ends to make a lap joint which is approximately 12 in. wide. The inner surface of the foam contains a grid-work of pumpout channels, 6 in. apart, extending axially the length of the sidewall and circumferentially around the tank. These channels intersect

MAIN VIEW

Figure 3.3-1. Thermal/Meteoroid Protection System (Sheet 1 of 7)

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MANHOLE COVER INSULATION

Figure 3.3-1. Thermal/Meteoroid Protection System (Sheet 2 of 7)

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FIBER GLASS SHROUD

Figure 3.3-1. Thermal/Meteoroid Protection System (Sheet 4 of 7)

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Figure 3.3-1. Thermal/Meteoroid Protection System (Sheet 5 of 7)

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STRUT INSULATION CLOSE OUT

Figure 3.3-1. Thermal/Meteoroid Protection System (Sheet 6 of 7)

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VIEW **S**

COMPENSATED BELLOWS INSULATION

Figure 3.3-1. Thermal/Meteoroid Protection System (Sheet 7 of 7)

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larger-area headers at the panel joints which, in turn, connect with vent ports in the fiber glass shroud.

Insulation of the compensated bellows sections is shown in View S on sheet 7. The insulation is retained by channel sections welded to the duct. A small tube is manifolded into the forward channel to purge the insulation during ground hold. The insulation blanket is wrapped around the gimbals, pressure volume compensator bellows and finally takes a U-configuration and attaches to the aft channel manifold. The U-overlap will accommodate the linear deployment motion required for the duct. The entire outer surface of the insulation is encased in a polyethylene purge sleeve.

The insulation concept for the struts of the intermodular thrust structure is shown in Views F and G on sheets 5 and 6. The dome thermal/meteoroid composite is cut out in a triangular pattern at the strut intersection points with the thermal blanket cutouts staggered. Insulation blankets are laid up around the struts in a square pattern with their edges staggered to match those of the dome thermal blankets. A V-shaped fiber glass/foam cover with the legs of the V having a square cross-section is installed over the insulated struts. It is riveted to the dome fiber glass shroud. The foam terminates at the edge of the fiber glass cover. This is also the transition juncture where insulation necks down in order to be wrapped around the struts. The blanket assemblies are retained by lacing the outer blankets in a manner similar to that shown in View K on sheet 2. The blankets terminate in a staggered configuration at the opposite end as shown in View G on sheet 6. The inboard cover net of each blanket has three tabs that attach to studs bonded to the struts. A plastic purge sleeve encases the insulated strut.

The prelaunch helium purge concept is shown in the main view which is on the first sheet of Figure 3.3-1. It is integrated with the structural and meteoroid/thermal protection systems. Purge gas flow, indicated by the arrows, is in the direction of gravity, for the most effective displacement of the higher-density residuals by helium. The outer fiber glass shroud forms the purge gas container for the modules. The exterior joints of the shroud are sealed, and the vent ports are closed by means of burst diaphragms during prelaunch.

3.4 MAIN PROPULSION

This subsection defines the operating conditions and describes the main propulsion subsystems.

3.4.1 Operating Conditions

The ANSC fluid line interfaces with the RNS consists of: (1) feed duct, 2 required, 10.5-in. diameter, (2) aftercooling bypass line, 3-in. diameter, and (3) pressurant line, 2 in. diameter. The isolation valves for these lines are currently located on the engine side of the engine/stage interface.

NERVA LH_2 flow rate requirements for nominal performance are: (1) 91.9 lb/sec for full power and (2) 0.7 lb/sec during aftercooling pulses. The steady-state operating pressure is 26 psia saturated liquid with zero NPSP. Reduced flow rates are permitted at zero NPSP and saturated liquid according to Figure 4.5-2 in Book 1 to provide autogenous start capability. The RNS also provides propellant conditions for a NERVA malfunction mode at a maximum pressure of 26 psia. Saturated liquid is provided to the bypass line for aftercooling at a pressure exceeding 16 psia.

The NERVA and stage LH_2 feed system is chilled down prior to operation. Tank pressures are regulated by a propellant management control system according to the pressure schedule defined in Section 3.12.2 in Book 1. The nominal tank pressures for this schedule are 26.3 psia in the propulsion module and 29.7 psia in the propellant module. The vent settings permit this nominal level to be exceeded by 0.3 psia. A 30 percent increase in the main feed system flow rate is permitted to refill the run tank during full power operation. Separate expulsion and control pressurization functions are provided at 0.4 and 0.6 lb/sec of GH_2 for use subject to the requirements of the propellant management control system. A flight vent flow rate of 0.6 lb/sec is provided. Pressurant is delivered to the module pressurization systems at the NERVA tap-off pressure of 850 psia. Ground vent and relief functions are provided in multiple modes with a maximum flow rate of 10 lb/sec provided. A maximum flow rate for orbital refueling of 2,000 gpm is provided.

3.4.2 Schematic

A schematic of the overall propulsion system for the Class 3 RNS vehicle is shown in Figure 3.4-1. This schematic shows the three module types that constitute the Class 3 configuration: the propulsion module, eight similar propellant modules, and the CCM. In the left-hand portion of the drawing, a typical propellant module is outlined with dotted lines which indicates where remote couplings are made to adjacent modules. In the case of this typical module, two main feed duct connections are made and also a pressurization duct. The eight propellant modules employed in this configuration utilize three configurations: the central core module, outboard modules, and tandem inboard modules. The outboard modules are connected to the central core module in this cruciform cluster configuration. The tandem propellant module is only assembled to adjacent in-line modules. Each of these propellant modules contains the following subsystems: a propellant feed system, a ground vent and relief system, a flight vent and relief system, a flight expulsion pressurization system, and an in-flight refueling system. The propellant feed system contains two normally closed, motor-driven shutoff valves located in the sump of each propellant module. These valves are 8 in. in nominal diameter and are parallel manifolded. Tank outflow is introduced to the valve inlet via a filtration and antivortex screening device. During full power operation both valves handle a total of 91.9 lb/sec of liquid hydrogen at a NERVA pressure of 26 psia. These valves are mounted from a 12-in. -diameter feed duct running the entire length of the propellant module. At the forward end of the feed duct is a 12-in., motor-operated blocking valve. Closure of this valve will permit feed duct conditioning prior to transfer and main NERVA engine burn operations. This will be covered in detail in the chilldown conditioning system description.

Each propellant module contains the baseline inflight refueling system. This system tees into the feed duct riser upstream of the 12-in. -diameter blocking valve. This system consists of a quad-redundant set of binary type motor-driven control valves, a flow meter, an antibackflow check valve, and finally a spray nozzle. The system is located in the forward ullage space of each propellant tank. This system is 4-in. -diameter in nominal size, has a capacity of 3,000 gpm maximum flow rate. This system is utilized for propellant module refueling after every round trip. Flow is introduced into the tank via the spray nozzle to prevent pressure surges and

Figure 3.4-1. Propulsion System Schematic

possible overpressurization of the propellant tank. Refueling is accomplished with the vehicle in a settled mode. The check valve located in the system prevents disturbances from being propagated back through the refueling system and eliminates excessive surges and interrupted flow.

Each propellant module contains a flight vent and relief system. This system contains four normally closed, 2-1/2-in. -diameter, pilot-operated solenoid valves located in a quad-redundant set. These valves are designed for a maximum pressurant inflow of 0.6 lb/sec. The valves are located external from the propellant tank and terminate in two propulsive vent nozzles routed 180 degrees apart on the outer surface of the upper structure of the propellant module. These vent valves are commanded by the data management subsystem using information from strain-gage pressure sensors located in the propellant tank. An emergency relief mode is provided by the emergency detection system.

The propellant module is launched in a wet condition. Thus, requirements are established for both a ground vent and relief system and a ground fill function. The ground fill function will utilize the two 8-in. -diameter tank isolation valves located in the sump of the propellant tank. Fill will be accomplished by an umbilical panel hookup to the main feed hookup for this ground only operation. The utilization of the flight feed system for ground fill and drain does not require the addition of a ground only fill system in this configuration. In order to accomplish the fill operation, a ground vent and relief system is required. This system consists of a vent and relief valve that is a combination pneumatically controlled vent valve and an absolute pressure relief valve utilizing a single flow path. Pneumatic control is a ground only function. These valves are used to permit venting of the hydrogen tank during fill and also to provide a primary safety device in the event of inadvertent pressure buildup. A 6-in. -diameter duct runs from both the vent and relief valve to a disconnect located in the forward region of the propellant module. In addition, the 1/4-in. -diameter pneumatic control line is also run to the vent and relief valve. This line provides the 475 psig helium control pressure for command ground venting. The ground vent and relief system is sized to accommodate the maximum fill flow rate of 3,000 gpm of hydrogen at a supply pressure of 50 psig, assuming a warm propellant tank.

Expulsion pressurization for all of the propellant modules and the propulsion modules is accomplished by a tap-off system which obtains 850 psia gaseous hydrogen at 230°R from the NERVA turbine discharge. This gas is run through a 1/2-in. -diameter duct across the interface plane routed up along the outside of each propellant module to the forward skirt region of that module. At each of the propellant modules and the run tank of the propulsion module, a two flow rate pressurant control system is utilized. The rates are: an expulsion flow rate of 0.6 lb/sec, and a control flow rate of 0.4 lb/sec. Control is accomplished with an on-off-type strain gage pressure sensing control system. This system provides the pressurant flow into the ullage of the run tanks of the tanks via two control orifices. The system utilizes a set of quad-redundant, 1/2-in. -diameter, direct-acting solenoids in each of the two control legs. The valves are normally controlled poppet-type solenoids, normally closed. These control valves are located external to the tank in the forward dome region in all cases. For the prelaunch ground-only pressurization function, the normal in-flight automatic pressurization coupling is used. In the case of the propulsion module the baseline is a dry launch and no ground pressurization is required.

The pressurization system of the propulsion module is identical to that contained in each one of the propellant modules and was covered above. The main feed system in the propulsion module run tank operates in conjunction with the two 8-in. -diameter tank isolation valves in the propellant modules. Flow is introduced to the valve inlet of the propellant module on line and proceeds through the 12-in. -diameter ducting systems at a flow rate of 91.9 lb/sec and a design pressure of 26 psi, and into the propulsion module run tank. Internal of the propulsion module run tank the 12-in. -diameter duct tees into two 8-in. -diameter ducts each terminating in an 8-in. -diameter propellant flow control valve. These valves are analog-type, motor-driven valves that are controlled by information from redundant liquid level sensors that are located in the propulsion module run tank. This system enables the propulsion module run tank to be maintained at a constant level throughout the NERVA engine burn. Propellant outflow from the run tank to the NERVA engine is accomplished by two separate tank bottom outlets. These 10-in. -diameter outlets exit the tank and close coupled to these outlets are the two NERVA engine PSOV shutoff valves. These valves are open during engine burn. Flow proceeds through the shutoff valves

down to the NERVA main turbopump inlet. The two tank isolation valves in the operating propellant module in conjunction with the two propulsion module control valves result in an effective quad redundancy.

The propulsion module run tank contains a flight vent and relief system which is identical to that described for each of the propellant modules. The propulsion module run tank contains the baseline in-flight refueling system, although it has been integrated with the propulsion module run tank refill system. The upper portion on the right hand corner of the schematic is an exploded view of the run tank depicting all of the subsystems that are internal of the run tank. The refill system is noted in this schematic. The refill system is primarily utilized after every NERVA engine burn to refill the propulsion tank utilizing propellant from any one of the eight propellant tanks. The system operates in the following manner: two submerged, parallel-mounted, motor-driven centrifugal pumps in the run tank, discharge through two antiflow check valves into the baseline spray fill refueling system, which contains the quad-redundant control valves, flow meter, check valve, and spray nozzle. The spray nozzle sprays hydrogen into the ullage of the run tank. Fluid is obtained from the 12-in. -diameter main feed duct through the two 8-in. -diameter propellant shutoff valves located in the propellant tank from which the transfer is to be accomplished. Antibackflow check valves are incorporated at both pump discharges and also in the propellant line tap-off. These check valves prevent pump surges and back flow and permit independent pump operation in the event of a single pump failure.

The propulsion module run tank also contains an integrated engine/stage chilldown conditioning system. This is a closed-loop recirculation system using two submerged ac-motor-driven centrifugal pumps located in the bottom of the run tank. These pumps intake from the run tank and discharge through two antibackflow check valves into a 2-in. -diameter duct that exits the tank and tees to the two main NERVA pump inlet ducts. These lines enter below the PSOV's. In the conditioning operation the PSOV's are closed and a flow rate of 1.5 lb/sec per pump is injected into each duct. This flow proceeds through the main feed duct to the NERVA turbopumps. Upstream of these valves the tap-off takes the return flow manifolded from both engine pumps to a common return line. The return line crosses the gimbal plane and flow is introduced back into the run tank via a set of quad redundant shutoff valves located on the propulsion module. This flow system accom-

plishes NERVA engine conditioning. In addition, flow is also introduced into the main feed duct riser and directed forward into the stage main propellant feed ducting and up to the blocking valve internal of each of the modules. The blocking valves are closed during this operation, thus enabling a conditioning of the feed system from the propulsion module run to the propellant module that is going to be operated. Return flow for the stage portion of the conditioning system is not returned to the run tank in the closed loop, as is the engine conditioning, but is accomplished by actuating the spray refueling system thus enabling return flow to be introduced into the next propellant module. Each of the ac motor driven centrifugal pumps has a nominal capacity of 2 lb/sec against a pressure head of 3.5 psia.

The propulsion module contains a simplified gas attitude control system that is used for stabilization during orbital assembly of the vehicle. This system is depicted in the lower-right-hand corner of the schematic. The system consists of a one gas storage system utilizing hydrogen gas from the NERVA engine. The tap-off is accomplished in the same manner that expulsion pressurant gas is utilized. This gas is in the 300-degree range and approximately 850 psi. It is stored in a 25-in. -diameter titanium sphere. The system is basically a blowdown-type system which permits high-pressure stored gas to be vented over to any one of six nozzles located 180 degrees apart in clusters of three on the outer diameter of the propulsion module. Each of these nozzles is controlled by a set of quad-redundant, normally closed solenoids; 1/4-in. nominal sizing is used for the solenoids. The system is armed by opening two parallel mounted 1/2-in. -diameter solenoid valves on the storage tank discharge. This system has provisions for initial ground loading via a ground disconnect and a normally closed ground fill valve. The storage sphere is provided with emergency relief provisions for ground as well as flight utilization. A set of quad-redundant recharge direct-acting solenoids connect the sphere to the NERVA engine pressurant tap-off. These valves are actuated to accomplish the recharge operation.

3.5 AUXILIARY PROPULSION

The APS described in this section is located in the CCM and provides all APS functions during RNS operation. The stabilization system located on the propulsion module is only used during vehicle assembly and disassembly

and was described in the last subsection together with the propulsion system schematic.

3.5.1 Design Conditions

The APS provides thrust for: (1) attitude control during coast phases, (2) attitude maneuvers, (3) attitude control during cooldown thrusting, (4) separation maneuvers, (5) roll control during main engine burns, (6) rendezvous maneuvers, and (7) propellant settling. Common storage of propellant for the cryogenic fuel cells and APS is utilized. Long-term orbital storage of the RNS will be in the local vertical, gravity gradient, stable orientation to minimize attitude control impulse requirements.

The impulse budget for attitude control, maneuvers, and propellant settling is shown in Table 3.5-1. The associated thrust level requirements are 100 lb for pitch, roll, and yaw; 200 lb for longitudinal maneuvers; and 3.2 lb for propellant settling. The 100-lb thrust level requirement, combined with a minimum valve operating time of 30 msec, yields a 3 lb-sec minimum impulse bit.

Table 3.5-1
APS ATTITUDE CONTROL IMPULSE BUDGET

Maneuver	Impulse (lb-sec)
Coast attitude control	1,800
Attitude maneuvers	145,000
Attitude control for aftercooling	38,800
Separation	49,400
Roll control	11,300
Rendezvous	108,000
Propellant settling	40,000
Subtotal	394,300
Contingency (15%)	58,700
Total	453,000

The APS motor configuration selected in Section 4.6.2 of Book 1 contains a total of ten 50-lb thrust motors in each of two pods. Rationale for this selection and contingency operating modes are presented in that section. In the normal operating mode, two of the 50-lb motors are used to obtain the 100-lb thrust level. In addition to the ten attitude control motors, an 1.6-lb thrust propellant settling motor will be provided in each pod.

3.5.2 Schematic

The baseline cryogenic LO_2/LH_2 APS system contains two thruster module pods and a central propellant supply. The thruster pods are located 180 degrees apart mounted on the CCM skin. Each pod contains 11 thrusters, as discussed in the previous subsection. Each thruster contains quad-redundant control valving. High chamber pressure thrusters are utilized with film cooling for the nozzles.

The cryogenic APS system schematic and integrated propellant storage for fuel cells are shown in Figure 3.5-1. Gaseous hydrogen and oxygen in the temperature ranges of 200° to 300°R is supplied to the thrusters and fuel cells from a central propellant conditioning system which uses low pressure liquid storage for both fluids. Gas-driven centrifugal pumps are utilized in conjunction with heat exchangers to supply the high-pressure, warm gas required for thruster operation. The gas is then stored in accumulators at 1000 psia. Thrusters operate from the accumulator in a pressure-fed mode. The fuel cells will also obtain their reactants in a pressure-fed mode from these accumulators. Redundant pressure regulator to reduce the pressure to 100 psia are provided for fuel cell operation. The system operation is described as follows: Liquid hydrogen and liquid oxygen are each stored in low-pressure tanks at about 20 psia. Propellant orientation and acquisition in these tanks are provided by a surface tension system. Each of the propellant tanks contains a ground-fill system for reactant replenishment. Each propellant tank contains a series of quad-redundant valves that are pressure-sense actuated to provide the ground vent and relief requirements during fill. As a backup flight relief system, a combination burst disc relief valve is provided in the accumulator system to compensate for any

Figure 3.5-1. Auxiliary Propulsion System

overpressure in the accumulator. This uses a pressure-driven piston which forces a cutting edge through the burst disc. The burst disc is backed up with a relief valve. The propellant tanks also contain an expulsion pressurization system which utilizes pressurant obtained by tapping off from the accumulators in the system. Control is provided by a bang-bang pressure sensor control system. A quad set of valves is utilized for this function.

The basic propellant conditioning loop operates as follows: Low-pressure propellant is expelled from the storage tank through a shutoff valve to the turbopump inlet. The turbo portion of the pump is driven by the exhaust gas products of a gas generator. The gas generator has two control valves and obtains its propellants by tapping off from the accumulators. The gas generator is igniter actuated. High-pressure liquid then leaves the turbopumps via an antibackflow check valve, which prevents disturbances from being related back to the pump, and flows through a heat exchanger which is an integral part on the gas generator. This heat exchanger provides the high-temperature gas required to be stored in the accumulator. The LO_2 and hydrogen systems each have a completely redundant propellant conditioning loop. The redundant loop is a standby loop. Any failure in the primary operational loop is detected by the inability of the accumulator in that loop to be able to be recharged to the required pressure. In the event of this type of failure, the active loop is then isolated by squib operated isolation valves and the second or standby loop is activated.

The accumulators discharge through isolation valves and then pressure regulators to a central manifold that supplies the reactants at the proper pressure for all thruster operations. The thruster system and the fuel cells operate in a pressure-fed mode using the regulated gaseous propellants from the accumulator. When the accumulator pressure drops below a preset level, the conditioning system is turned on, gas generator ignitors actuated, and a recharge of the accumulator is initiated. Propellant is admitted to the gas generator providing the energy to start the turbopump and to warm the heat exchanger. When the pump and heat exchanger have reached operating condition, propellant is admitted to the conditioning system from the pressure storage tank. The conditioning system continues to operate until the

predetermined upper pressure level is reached in the accumulator. The system has been sized for the total RNS impulse requirement 455,000 lb-sec utilizing an Isp of 365 sec and a mixture ratio of 4. To satisfy this total impulse, 1250 lb of propellant are required: 260 lb of hydrogen and 1000 lb of oxygen. The 256 lb of propellant is provided (28 lb of hydrogen, 228 lb of oxygen) for the fuel cell requirement. This brings the total requirement to 278 lb of hydrogen and 1,228 lb of oxygen.

The storage tanks were designed to a 30-psia pressure. The accumulators were sized to handle the 16,400 lb-sec impulse, sufficient for two of the largest attitude maneuvers in sequence. The propellant conditioning system is sized to operate on a continuous makeup basis.

3.6 ASTRIONICS

A block diagram of the astrionics system is shown in Figure 3.6-1. Capability is provided for autonomous mission performance, including navigation, guidance, control, electrical power, and emergency fault detection. The system architecture is characterized by the use of a data bus for intermodule and intersubsystem communication. A data bus terminal dedicated to NDICE components on the propulsion module uses the stage data bus to communicate with the NDICE processor located forward in the command and control module.

Each subsystem function is controlled via signal sent through the data bus which are locally decoded. Data required for checkout and operation of the subsystem is accumulated through the normal RNS instrumentation channels and routed to the processor in encoded form to provide monitoring and control. For the operational RNS a requirement has been established for 732 channels of instrumentation (including NERVA) with a frequency response of 8,800 samples per second. Development vehicles would use 1152 channels and about a 5 fold increase in frequency response. Data to be sent to ground is routed through the command and control data bus terminal to the PCM encoder where addressing and framing is accomplished prior to PSK modulated transmission on the 1.024-MHz telemetry subcarrier of an S-band channel like the 2,287.5 MHz carrier. In earth orbit the data are

Figure 3.6-1. Astrionics Block Diagram

stored between ground stations and dumped at a minimum rate of 8.3×10^3 bits/sec based on 160 minutes per day viewing time. At lunar distances, the continuous minimum rate is 900 bits/sec. The transponder responds to interrogations from the ground and utilizes the antenna components in the command and control subsystem. Uplink commands received from the ground are decoded and routed to central processor for action.

The emergency detection system (EDS) processor accepts hardline signals from each of the critical functions in the various modules and has the capability of independently providing controlling signals to correct situations without assistance of the central processor. The action taken is communicated to the central processor in the form of an alert. Control is effected by the EDS using direct action through the controllers in the various modules. Crew control can be exercised through the EDS for manned missions.

3.6.1 Navigation and Guidance

The autonomous baseline navigation and guidance subsystem for the RNS is shown in Figure 3.6-2. An unknown landmark tracker is used as the primary navigation sensor in conjunction with a strapdown IMU. This sensor and associated electronics are capable of landmark selection and tracking including correlation of intensity pattern and generation of scanning signals. The indication of landmark acquisition and gimbal angles at the time of acquisition can be stored in the optical buffer until the processor is ready for that information. The processor determines navigation parameters from this data.

A horizon sensor of the conical scanning type is used for coarse navigation, backup attitude control, and initial orbit determination after wakeup. Two rotating sensor heads are utilized. The entire sensor is mounted on gimbals permitting easier acquisition of the earth during a wakeup phase of operation. The time of crossings of the horizon sensor line of sight of the earth horizon are used to accomplish the estimate of the local vertical direction. This information can be read into the optical buffer where it is prepared for the data bus transfer to the RNS processor.

Figure 3.6-2 NAVIGATION AND GUIDANCE BLOCK DIAGRAM

Accelerometers are used to update orbit parameters, determine the guidance commands, and for impulse management. Two ranges are provided to allow for measurements at both full thrust and during aftercooling. The accelerometers are rebalanced by electronics located on or adjacent to the sensor. The rebalance pulses are accumulated in an IMU buffer, which communicates with the central processor through the data bus.

Star trackers are used as the primary attitude sensor. Two star trackers are included as a part of the autonomous system. Each is mounted on a set of gimbals. The star tracking optics and detector provide an error signal to torque the gimbals. The intensity of the star being tracked is also measured. The gimbal angles and star signal intensity can be read by the optical input/output buffer, and stored until the processor is ready for the information. Search commands are generated in the processor and sent to the star tracker gimbals where the commands are reduced to gimbal angle signals for the star tracker gimbals. Ball-bearing gyros are used for short

term attitude reference. The gyros are rebalanced by the electronics which are mounted on or near the gyro sensor. The gyro rebalance pulses are accumulated in the IMU buffer. The gyros (and accelerometers) are mounted in a redundant dodecahedron strapdown configuration.

A transponder and receiver are included to allow for ground tracking and ground commands, and dual-scanning, laser radar systems provide range, range rate, and orientation data for active rendezvous and docking operations. A minimum stabilization and control capability is provided as part of the propulsion module to provide stable RNS orientation during assembly and CCM replacement. This consists of 3 gyros and the associated control package for the ambient gas APS.

3.6.2 Electrical Power

Redundant fuel cells supply 28-vdc primary power for the RNS. Two regulated capillary matrix-type alkaline cells of 2-kw capacity each have been selected consistent with the space shuttle fuel cell to be developed. Secondary power is supplied by rechargeable Ag Zn batteries. AC power requirements are satisfied by the use of inverters.

The fuel cells, control, and rechargeable peaking batteries are located in the CCM. The reactant storage is shared with the cryogenic APS. The tapoff from the APS accumulators which stores gas at 1,000 psi and 300°R, will be regulated to about 100 psi and conditioned by the fuel cell to between 460 and 620°R. A battery is located on the propulsion module to regulate module power and satisfy peak module demands during engine operation. During refurbishment, when the CCM is not attached to the RNS, this battery supplies power to monitor, command, and control the RNS or the propulsion module.

A block diagram of the electrical power subsystem is shown in Figure 3.6-3.

3.6.3 Data Management

A centralized processor approach using a data bus concept and an autonomous engine control processor was selected for this subsystem. The RNS

Figure 3.6-3 ELECTRIC POWER BLOCK DIAGRAM

processor system architecture utilizes redundant processors in a 1 + 1 configuration. The failure of the primary processor allows for the switchover to the secondary processor without loss of mission objectives. The primary responsibility of the secondary processor is to remain in synchronization to allow for an efficient transfer of control. The processor and data bus configuration is shown in Figure 3.6-4. A shared section of memory is provided in order to insure switchover to the secondary computer. Bulk storage capability is also allowed for. The radiation environment is not constraining for the processors which will be located forward in the CCM.

The instrumentation subsystem provides the primary source of data for all mission operations and checkout. This is accomplished by the use of local signal conditioning in each module and a group of 16 channel multiplexers with a digitizer associated with each multiplexer. Once digitized, the data is put on the data bus for use by the central processor. The generation of commands throughout the vehicle is accomplished by encoded signals sent on the data bus and decoded locally in each module. The decode logic then drives a controller which act as power amplifiers that have the capability of energizing the function to be controlled. Should it be required to hold a particular function, the controller will provide memory or latching and a second command will be required to unlatch the function. This approach is standardized throughout the vehicle and localized to each module.

The limiting requirement for the RNS data management function appears to be the reliability of the processor and the ability to provide for an efficient switchover to a backup processor.

3.6.3.1 Processor Requirements

Each processor has a reliability requirement of about 38,500 hours mean time before failure. This likely will require internal redundancy. The total peak processing requirements for the RNS are about 241,000 equivalent adds/sec exclusive of engine control. This corresponds to a 4- μ sec add time.

Figure 3.6-4 DATA MANAGEMENT BLOCK DIAGRAM

The high speed, random-access storage requirement is about 32,000 words which provides about 5,000 words of procedure in dynamic storage. The bulk storage requirement is 70,000 words; however, the sensitivity to this requirement is small as a magnetic tape or similar high-capacity storage device is postulated.

The major requirements for the RNS processor are for data compression, navigation, guidance and control, and the overhead for the executive functions. The early estimates of the NERVA engine control processing requirements to meet present specifications are substantially above the present stage requirements.

3.6.3.2 Data Bus

The selected data bus concept is fundamentally the time sharing of a single digital line to transmit data between modules and subsystems. Several data bus approaches are presently under development. A data bus concept compatible with the space tug and space shuttle is required because of physical interconnection during assembly and maintenance operations. The present developmental efforts use from 1 to 3 lines and have transfer rates from 1 to 5 MHz with either Manchester or bipolar formats.

Any of the data bus implementations presently under development would satisfy the requirement of the RNS based on the requirement for the RNS developmental vehicle of 0.5×10^6 bits/sec. It is expected that the data bus concept selected for the leading programs such as the space shuttle will be used for the RNS. Eight data bus terminals are required. Although the data bus controller can be implemented in either hardware or software, the processing requirements for the RNS assumed software as the worst case.

3.7 RADIATION ENVIRONMENT

The radiation environment was defined during engine operation and after shutdown. These results were applied for: (1) radiation effects on the materials, components, and subsystems in the RNS, (2) nuclear heating of the propellant, and (3) orbital maintenance operations.

The PATCH point kernel code described in Section 4.5.11 of Book 1 was used in the definition of the radiation levels exterior to the engine. Data on engine radiation sources during reactor operation were based on the May 1969 Common Radiation Analysis Model (Reference 1) as modified by Reference 2.

Figure 3.7-1 shows the time to accumulate a dose of rem at 2 different times after final shutdown. This is used to assess the constraints imposed on orbital operations by the residual radiation levels.

Figure 3.7-1 RADIATION ENVIRONMENT AFTER SHUTDOWN

1. A.D. Wilcox, B.A. Lindsey and M.A. Capo (WANL), "NERVA-Flight-Engine Common Radiation-Analysis Model," RN-TM-0583, Aerojet General Corporation (May 1969).
2. "Final Report of Shield System Trade Study," S054-023, Volume I, Book 2, Aerojet Nuclear Systems Co. (July 1970).

A schematic representation of radiation exposure to RNS equipment over 10 missions is shown in Figure 3.7-2. Subsystems were evaluated for the levels shown in the different zones without regard for the detailed layout. The maximum level in each zone is shown on the figure.

3.8 RELIABILITY ANALYSIS

The reliability analysis for this phase of the RNS project consisted of a failure mode effects analysis followed by a criticality analysis. The overall results produced a reliability prediction of 0.9552 for the Class 3 RNS compared with a 0.9750 reliability goal. Values are for the active portions of the mission which are the sum of (1) the time from the initiation of engine operation for the translunar injection burn to the completion of cooldown in lunar orbit and (2) the time from the initiation of engine operation for the first burn of the transearth transfer maneuver to the completion of cooldown in earth orbit. These predictions must be considered preliminary at this point in the design cycle. The predictions are based on a single failure analysis, some designs are not sufficiently detailed to do a detail reliability analysis. Adequate failure rates are lacking for some components and some specific failure modes are questionable.

The reliability allocations for the Class 3 RNS modules, systems, and subsystems are shown in Table 3.8-1. The equivalent reliability predictions are given in Table 3.8-2. In several areas the reliability allocations were used as the prediction—structure, safety and a prediction of 0.9950 was used for the NERVA. The NSF in the table indicates that there are no identifiable single failures in the corresponding subsystem.

The detailed reliability and safety analyses with the specific failure mode effects analysis worksheets and the specifics on the criticality analysis (prediction analysis) are given in Volume VI.

Figure 3.7-2 RADIATION EXPOSURE TO RNS EQUIPMENT (10 MISSIONS)

Table 3.8-1
RELIABILITY ALLOCATION—CLASS 3

System	System Totals (1-8-1)	CCM	Propellant Module	Propulsion Module
2.0 Structure	0.9987	0.99996	0.99986	0.99986
3.0 Meteoroid	0.9975	0.9999	0.999725	0.9998
5.0 Main Propulsion	0.9848	-- --	0.99891	0.99352
5.01 NERVA	0.9950	--	--	0.9950
5.05 Propellant Feed	0.99598	--	0.99956	0.9995
5.06 Pressurization	0.9955	--	0.9995	0.9995
5.09 Fill	0.9993	--	0.99996	0.99962
5.10 Ground Vent	0.99992	--	0.99999	--
5.11 Flight Vent	0.9991	--	0.9999	0.9999
6.0 Auxiliary Propulsion	0.9982	0.9983	--	0.9999
7.0 Astrionics	0.9960	0.9967	0.99993	0.99986
7.01 Guid, Nav, and Control	0.9992	0.9994	0.99998	0.99996
7.04 Electrical Power	0.9985	0.9985	--	--
7.05 Electrical Networks	0.9993	0.9998	0.99995	0.9999
7.09 Data Management	0.9990	0.9990	--	--
8.0 Safety	0.9998	0.9999	0.99999	0.99998
Totals 1-1-1	--	0.99476	0.998415	0.99292
1-8-1	0.9750	0.99476	0.98732	0.99292

Table 3.8-2

RELIABILITY PREDICTION—CLASS 3

System	System Totals (1-8-1)	CCM	Propellant Module	Propulsion Module
2.0 Structure	0.9987	0.99996	0.99986	0.99986
3.0 Meteoroid	0.9950	0.9999+	0.99939	0.9999
5.0 Main Propulsion	0.9895	--	0.9992	0.9937
5.01 NERVA	0.9950		--	0.9950
5.05 Propellant Feed	0.99587		0.99918	NSF
5.06 Pressurization	NSF		NSF	NSF
5.09 Fill	0.99872		NSF	0.99872
5.10 Ground Vent	0.99992		0.99998	--
5.11 Flight Vent	NSF		NSF	NSF
6.0 Auxiliary Propulsion	0.9721	0.9722	--	0.9999
7.0 Astrionics	0.9970	0.9977	0.99993	0.99986
7.01 Guid, Nav, and Control	0.9992	0.9994	0.99998	0.99996
7.04 Electrical Power	0.9995	0.9995	--	--
7.05 Electrical Networks	0.9993	0.9998	0.99995	0.9999
7.09 Data Management	0.9990	0.9990	--	--
8.0 Safety	0.9998	0.9999	0.99999	0.99998
Totals 1-1-1	--	0.9698	0.99847	0.9932
1-8-1	0.9527	0.9698	--	0.9932

NSF—No single failure

Section 4

PROPULSION MODULE

This section contains a description of the propulsion module starting with a summary of the overall module configuration and concluding with a listing of the module hardware organized according to the system provided in the study guidelines.

4.1 CONFIGURATION

The propulsion module consists of the NERVA plus a run tank together with subsystems to perform docking, module latching, propellant feed, flight vent, pressurization, orbital refueling, engine-stage chardown, and attitude control.

The module shown in Figure 4.1-1 is transported to earth orbit by the shuttle. After it is deployed it utilizes its attitude control system for stabilization while being docked with the aft tandem propellant module. Docking drogues (cones) and structural latches are incorporated in the forward skirt. Power for docking and latching is supplied by a low-capacity AgZn battery which is recharged by the fuel cells contained in the CCM.

The tank diameter was defined by the radiation shield zone. The shadow shield zone half angle of 10 degrees was generated by extending a line from the aft outboard corner of the engine reactor through a point tangent to the aft dome of the outboard propellant tank. The tank sidewalls are integrally reinforced with an isotropic grid pattern to prevent buckling during engine operation. The domes are hemispherical with the feed line offset a maximum in order to obtain the longest tank while still penetrating the dome normal to its surface. Lugs are machined in the domes for attachment of the thrust structure and forward skirt fiber glass X-member strut assemblies. Fiber glass was utilized to minimize heat flow into the propellant tank. Thermal protection of the tank is provided by three blankets of DAM/net insulation. Meteoroid protection is provided by a 2-in. layer of foam encased by a 0.010-in. -thick fiber glass shroud.

Figure 4.1-1. Propulsion Module

The main feed duct originates at the module interface and contains two gimbal joints, a pressure volume compensator and has capability for linear deployment to accomplish automatic assembly. The 12-in. feed duct penetrates the forward dome, runs the entire length of the tank and terminates with two 8-in.-diameter control valves. Propellant outlet is through two 10-in.-diameter ducts to which the NERVA PSOV's are mounted. Inlet to these lines is through an antivortexing filtration screen. The flight vent system penetrates the tank in the ullage region and has its quad-redundant valving mounted to the forward skirt. The external pressurization line runs the full length of the tank and has a conventional quick-disconnect coupling at the aft end which mounts to customer connect panel at the NERVA interface. The forward end of the line penetrates the dome in the ullage region and terminates in a pressurant diffuser which utilizes a nylon bag to prevent pressurant impingement and ullage collapse.

A two level flow control pressurization system is employed which contains separate sets of quad-redundant valves mounted to the forward skirt. The integrated engine/stage chilldown conditioning system is submerged in the aft dome region of the tank. It consists of two parallel motor-driven pumps whose discharge is routed to both the NERVA interface and the RNS feed system. Two additional motor-driven centrifugal pumps are mounted in the tank bottom. They are utilized in conjunction with the orbital refueling system to enable refilling of the run tank from the aft tandem propellant module. The details of all cross interface plumbing from the NERVA to the propulsion module are defined in Section 9 (NERVA interface).

The module contains a simplified gas attitude control system which is recharged by hydrogen gas from the NERVA engine. Tapoff is accomplished in the same manner as the expulsion pressurant gas. The system is basically a blowdown-type system which permits high-pressure gas to be vented to any of the attitude control nozzles. The system is armed by opening two parallel-mounted solenoid valves on the storage tank discharge. A simple control system incorporating gyros and control logic is provided.

The astrionic equipment is effectively shielded from the radiation environment by the run tank. Signal conditioning, multiplexing and digitizing of instrumentation, command decode, drivers and data bus terminals are physically mounted on this module. Flight readiness of the module is determined utilizing the capability of the onboard checkout system in the CCM via the data bus. Since the propulsion module is a space resident element, fault prediction sensors are included and replacement is on an unscheduled basis only upon the occurrence of a failure. Additionally, the NERVA engine checkout will be performed by NDICE. The data bus transfers instrumentation and command information in digital form between the CCM and the propulsion module. DC primary power is distributed and used in the module for electro-mechanical functions. Local inverters are used for ac-motor-driven valves. EDS is used to gather information on critical parameters and distribute safing commands. Parallel wiring systems are employed with flat cable used for the majority of functions carried between the PVARA and the top of the run tank. Round ribbon cable is employed for functions in the engine area. An external tunnel is provided along the run tank.

4.2 HARDWARE TREE

A description of the equipment contained in the propulsion module, including the specific design conditions and the weight is contained in this subsection. The organization and numbering is that given in the study guidelines.

PROPULSION MODULE HARDWARE TREE

Description	Design Conditions/ Requirements	Weight (lb)
2.00 Structure		
2.01 Propellant Tank-2014-T6 Aluminum		
Forward Dome—hemispherical, monocoque construction, 0.029 in. thick by 160 in. dia by 80 in. long, one piece dome, forging	30 psia at end of burn	570
Aft Dome—same as forward dome	30 psia at end of burn	

PROPULSION MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
● Cylinder—integrally stiffened 60°waffle, membrane thickness 0.051 in., rib height 0.561 in., rib length 10.13 in., rib thickness 0.035 in., 160 in. dia by 116 in. long, 2 segments, each segment fabricates from 0.750 in. x 10 ft x 22 ft plate. ● 103 ft of welding	Membrane — 30 psia end of burn Stiffeners—engine operation, gimbaled hardover (336 lb/in.)	
2.02 Engine Thrust Structure—fiber glass, space truss truncated cone, aft dia 60 in., forward dia 45 in., length 45 in., 24 tubular struts fabricated into 12 X-member subassemblies, 3.75 in. dia by 0.065 in. wall by 58.8 in. long struts	Engine operation, gimbaled hard-over (12,540 lb/strut), minimize heat short to tank	170
2.03 Forward Skirt—fiber glass, space truss truncated cone, forward dia 174 in., aft dia 160 in., length 70 in., same configuration and number of struts as engine thrust structure, 4.25 in. dia by 0.065 in. wall by 81.3 in. long struts	Engine operation, gimbaled hard-over (9,460 lb/strut), minimize heat short to tank	250
2.06 Exterior Finish and Sealer	Prevention of corrosion	20
2.07 Baffles ● Antislosh—2 reqd, 120 in., and 150 in. dia rings fabricated from 2.0 in. dia by 0.049 in. wall 6061-T6 Al tubing, ring support struts—16 reqd per baffle, fabricated from 1.5 in. dia by 0.035 in. wall 6061-T6 Al tubing, nylon cloth (0.375 lb/sq yd) membranes	Propellant settling	60

PROPULSION MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
Geysering—1 reqd, octagon, 53 in. across flats, nylon cloth (0.375 lb/sq yd) membrane, nylon chord edge member and tension tie		
2.08 Equipment Support Structure—7025-T73 Al alloy sheet metal and machined brackets	Maximum acceleration and vibration	160
2.10 Additional Structure—Provisions for cutouts and doors	Access	70
3.00 Thermal/Meteoroid Protection		
3.01 Insulation—Tank Area 960 ft ²	Tank heat input (90 BTU/hr), pressure in space (10 ⁻⁴ torr)	430
Blanket—Sidewall - 96 layers 0.00015 in. double aluminized mylar with dacron net spacers, 3 blankets of 32 layers each, 4 ft x 12.5 ft panels, total insulation thickness 1.0 in.		
Blanket—Forward and aft dome Same as sidewall except pie-shaped panels		
Blanket Attachment—fiber glass straps 0.015 in. x 4 in. x 24 in., nylon tank attach studs 0.5 in. dia x 0.4 in. long		
Purge System—gas manifold system, mylar shroud	He atmosphere prior to launch	

PROPULSION MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
3.02 Meteoroid Protection - Flexible Foam Blanket—outside of insulation 2 in. thick, density 1.2 lb/ft³ - Shroud—outside of foam 0.010 fiber glass laminate, 4 ft x 12.5 ft panels	RNS P(0) = 0.995 baseline lunar mission away from earth (27 days)	280
4.00 Docking/Clustering		
4.01 Forward Docking Structure—cone assemblies, 4 reqd 14 in. dia x 45° cone, integrally stiffened, aluminum support struts and attach hardware, solenoid driven, spring-loaded latching assembly	Longitudinal position ±5 in., lateral position ±5 in., angle, pitch or roll ±3°, longitudinal velocity ±0.1 ft/sec, lateral velocity ±0.1 ft., pitch angular velocity ±0.2 deg/sec, roll angular velocity ±0.02 deg/sec, maximum relative impact velocity 0.2 ft/sec	80
5.00 Main Propulsion		
5.01 NERVA Engine (less 500 lb for NDICE in CCM)		27,300
5.05 Propellant Feed System 8 in. dia throttle valves—2 reqd, motor-drive (120 Vac 400 Hz), planetary gear transmission, full flow analog visor type, metallic main gate seal opening motion—linear seal withdrawal 90° rotational.	91.9 lb/sec LH₂, flow at 30 psia	140

PROPULSION MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
• Feed duct—12 in. dia ducting stainless steel 0.035 in. x 54 in. long • 12 in. nominal dia pressure volume compensator • 12 in. nominal dia gimbal joints—2 reqd • 12 in. nominal automatic coupling and deployment assy including deployment rack and motor • Fuel feed line—12 in. internal ducting 6061-T6 aluminum 0.035 in. x 276 in. long • Bolted flange connection at run tank, 2 segment coupling at interface, dual static seal configuration both ends	30 psia operating pressure ±1.00 in. extension ±8 degree angulation ±1.00 in. extension collapse pressure automatic leak check, maximum leakage 10⁻⁵ sccm	
5.06 Pressurization System • 1-1/4 in. dia disconnect, normally open • 1/2 in. 24 vdc dia direct acting solenoids, 8 reqd • 1-1/4 in. dia stainless steel ducting 0.017 x 325 in. long • 1-1/4 in. dia metallic flexible braided hose sections • Bolted flange connections at ends with dual static seals and welded intermediate joint	4 lb/sec GH₂ p = 850 psia T = 225°R 0.6 lb/sec GH₂ p = 850 psia at T = 225°R p = 850 psia p = 850 psia maximum leakage 10⁻⁵ sccm	60

PROPULSION MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
5.09 Orbit Refueling		
4 in. dia spray bypass valve—4 required, planetary gear transmission, full flow visor type, metallic main gate seal, open motion—linear seal, withdrawal, 90° rotational, mechanical spring loaded, override—normally closed, ac motor driven (120 vac, 400 Hz) 4 in. dia normally open disconnect 4 in. dia check valve flapper type (2 sections) 4 in. dia stainless steel ducting, 0.035 x 300 in. long 4 in. nominal dia gimbal joints - Bolted flange connections with dual static seal ends and intermediate welded joints	3,000 gpm p = 40 psia T = 40°R p = 45 psia p = 45 psia maximum leakage 10⁻⁵ sccm	60
5.11 Flight Vent		50
2-1/2 in. dia pilot operated quad blowdown valves—4 reqd 2-1/2 in. dia x 0.016 in. stainless steel ducting - Bolted flange connections with dual static seal ends and intermediate welded joints	0.6 lb/sec GH₂ at 29 psia T = 40°R p = 29 psia maximum leakage 10⁻⁵ sccm	

✓

PROPULSION MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
5.12 Integrated Chillover System		70
Centrifugal Pumps—motor driven (120 vac, 400 Hz), submerged in run tank—2 reqd	2 lb/sec LH ₂ at 3.5 psia	
2 in. dia check valves—flapper type (split design) 5 reqd	2 lb/sec LH ₂	
2 in. dia shutoff valves—normally closed, pilot operated solenoid type—4 reqd	2 lb/sec LH ₂	
2 in. dia x 0.035 in. stainless steel ducting		
2 in. dia (nominal) gimbal joints		
Bolted flange connections with dual static seals at ends and intermediate welded joints		
5.13 Refill System		50
Centrifugal pumps ac-motor driven (120 vac, 400 Hz) submerged in run tank—2 reqd	5 lb/sec LH ₂ at 3 psia	
3.25 in. dia check valves—flapper type (split design) 2 reqd	5 lb/sec	
3.25 in. dia x 0.035 in. stainless steel ducting		
3.25 in. dia (nominal gimbal joints)		
Bolted flange connections with dual static seals at flanges at ends and intermediate welded	maximum leakage 10 ⁻⁵ sccm	

PROPULSION MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
• 2 in. dia (nominal) gimbal joints • Bolted flange connections with dual static seals at flanges at ends and intermediate welded joints	maximum leakage 10^{-5} sccm	
6.00 Auxiliary Propulsion		
6.01 Reaction Control System	Module stabilization during assembly and maintenance	160
• Gaseous hydrogen storage sphere, 25 in. dia, titanium, 2 reqd	p = 1200 psia	
✓ • 1/2 solenoid valves direct acting—2 reqd		
• 1/4 in. fill disconnect		
✓ • 1/2 in. relief valve		
• 1/4 in. nozzle control solenoids directing acting—24 reqd		
• Tubing—welded joints		
7.00 Astrionics		
7.01 Navigation Guidance and Control		20
• 3 gyros and electronic package to generate ambient gas APS commands at required	Maintain stable attitude during assembly and maintenance. Drift rate ≤ 0.5 degree/hr	
• Optical corner cubes	Cooperative target for docking operations	

PROPULSION MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
7.02 Instrumentation (exclusive of engine) 18 transducers for sensing 10 channels of signal conditioning 2 analog multiplexers—MSI, 16 channel 2 analog to digital converters 10 bit resolution	80% of analog channels 60% of analog channels 1 part in 1024 resolution, 0.1% accuracy, 1 per multiplexer for encoding analog data	15
7.03 Command and Control - Logic decoder - Controllers with memory as required	Accept serial input instructions from data bus terminal Accept decided signals and drive controllable functions—up to 10 amps (those with memory—turned off by separate command)	10
7.04 Electric Power 2 AgZn batteries with 1.7 kwh capacity each - Power management cabling and distribution package	Supply peaking power, discharge to 50% or less Power distribution, switching and battery recharge	130

PROPULSION MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
- Power distribution 2 inverters frequency—400 Hz voltage—120 vrms	Round conductor wiring, all Polyimide insulation, copper conductors Redundant power to drive 2 chill-down pumps and 2 refill pumps	
7.05 Electrical Networks - Emergency detection, data bus, manual control, and engine function cabling between station O and top of run tank - Connectorless terminations for engine stage interface - Module interface connectors and blind mating panel	Flat conductor cables, all Polyimide insulation copper conductors 3,000 lines, increased reliability by eliminating socket/pin connections Motor driven	150
7.06 Environmental Control Controlled emissivity coatings and internal electrical heaters as required by each subsystem	Included in each subsystem	--
7.07 Propellant Management 3 redundant probes with discrete point level sensors		10

PROPULSION MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
7.08 Onboard Checkout		5
• Sensors for EDS	EDS monitoring of critical functions	
7.09 Data Management		5
• 2 data bus terminals	NDICE, stage	
Total Dry Weight (including 150 lb contingency)		30,975

$$\begin{array}{r}
 30475 \\
 - 27300 \text{ Engine} \\
 \hline
 3175
 \end{array}$$

570
 170
 250
 20
 60
 160
 70
 430
 280
 80
 27300 - 22800 = 4500
 140
 60
 60
 50
 70
 50
 160
 20
 15
 10
 130
 150
 10
 5
 5

30325
 150 contingency
 30475
 500 NDICE on Fwd Bkhd (see pg 106)
 30975

NOTE
 pg 6 Book #1
 gives 30475
 the total as this
 figure is too high
 by amount of NDICE
 NDICE is included in
 CCM pg 170

Section 5

CORE PROPELLANT MODULE

This section contains a description of the core propellant module, starting with a summary of the overall module configuration and concluding with a listing of the module hardware organized according to the system provided in the study guidelines.

5.1 CONFIGURATION

The core propellant module is located centrally at the second tier of propellant modules. It provides for propellant storage during the mission. No other major function is provided, resulting in a simple module which is passive and responsive to external control. It contains subsystems to perform docking, clustering, module latching, propellant feed, ground vent and relief, flight vent, pressurization, and orbital refueling.

The module shown in Figure 5.1-1 is transported to earth orbit by the shuttle. A tug is utilized to convey the module to the assembly area. Docking probes and four sets of clustering hinges are installed in the forward end of the module. The aft end contains the docking cones and four clustering latches. The latches, conical in configuration, are roller mounted in a track to compensate for relative motion between the core and outboard modules which results from thermal and pressure differentials between the two modules. The tug is utilized to stabilize and provide power to the module while in orbit.

The tank sidewalls are integrally reinforced with an isotropic grid pattern to prevent buckling of the unpressurized tank during boost and to transport thrust loads during engine operation. Hemispherical domes with the propellant feed line offset a maximum from the module centerline proved to be the superior configuration considering propellant capacity, cost, and manufacturing. Lugs are machined in the domes for attachment of the skirt fiber

glass X-member strut assemblies. Fiber glass, because of its low thermal conductivity, was utilized in order to minimize heat flow into the propellant tank. Thermal protection of tank is provided by three blankets of DAM/net insulation. Meteoroid protection requirements are identical for all propellant modules except for the core module which is protected by the outboard modules. However, it proved cost effective to maintain the same foam and fiber glass thickness for all modules and meteoroid protection is provided by a 2-in. layer of flexible foam encased by a 0.010-in. -thick fiber glass shroud. A sump is incorporated in the design to minimize residuals.

The external section of the feed system originates at the module forward interface and consists of a section of 12-in. -diameter ducting with the baseline two-gimbal compensator joint, and an automatic deployment mechanism. Entrance to the tank is through a bolted dual seal flange. The internal duct terminates at the sump and is rigidized for collapse pressure. It is supported off the tank wall by sliding type vibration mounts. A blocking valve is included at the forward end of the run to precondition the tank feed system. Upstream of the blocking valve is the 4 in. -diameter bypass system which is utilized for flight refueling. This system contains quad-redundant control valves, a check valve and terminates in a spray nozzle which injects LH_2 into the ullage. The spray nozzle prevents pressure surges while refueling.

Two tank discharge isolation valves are housed in the sump. Inlet to the valves is through an antivortexing, filtration screen. Four sections of ducting, one 12-in. -diameter and three 8-in. -diameter attach to the sump. Each contains two gimbal joints for deflection absorption. The 12-in. -diameter leg is the full flow leg. The 8-in. -diameter legs couple with the outboard modules. Automatic coupling mechanisms are contained in these legs. Both the ground vent and relief, and the flight vent systems are located in the ullage region of the tank. The systems are integrated and require a single tank penetration only. The external pressurization line runs the full length of the tank and has a conventional quick disconnect coupling at the aft end which mounts to the electrical connector deployment

Figure 5.1-1. Core Propellant Module

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CORE PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
● Cylinder—integrally stiffened 60° waffle, membrane thickness 0.055 in., rib height 0.615 in., rib length 8.10 in., rib thickness 0.035 in., 174 in. dia by 519 in. long 3 segments, each segment fabricated from 0.75 in. x 15.5 ft x 44 ft plate ● 221 ft of welding	Membrane—end of burn (30 psi) Stiffeners—launch release transient (710 lb/in.)	
2.03 Forward Skirt—Fiber glass, space truss cylinder, 174 in. dia by 85 in. long, 24 tubular struts fabricated into 12 X-member sub-assemblies, 5.75 in. dia by 0.075 in. wall by 96.2 in. long struts	Engine operation, gimbaled hardover (17,790 lb/strut), minimize heat short to tank	370
2.04 Aft Skirt—Same as forward skirt except space truss cylinder is 95.4 in. long and strut length is 105.3 in.	Same as forward skirt	390
2.06 Exterior Finish and Sealer	Prevention of corrosion	60
2.07 Baffles ● Antislosh—<u>2 reqd</u>, 156 in. dia rings fabricated from 2.0 in. dia by 0.046 in. wall 6061-T6 Al tubing, ring support struts 16 reqd, fabricated from 1.5 in. dia by 0.035 in. wall 6061-T6 Al tubing, nylon cloth (0.375 lb/sq yd) membranes ● Geysering—1 reqd, octagon, 80 in. across flats, nylon cloth (0.375 lb/sq yd) membrane, nylon cord edge member and tension tie	Propellant settling	80

CORE PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
2.08 Equipment Support Structure— 7075-T73 Al alloy sheet metal and machined brackets	Maximum acceleration and vibration	170
2.10 Additional Structure— Provisions for cutouts and doors	Access	130
3.00 Thermal/Meteoroid Protection		
3.01 Insulation—Tank area 2,630 ft ² ● Blanket—Sidewall—48 layers 0.00015 in. double aluminized mylar with dacron net spacers, 3 blankets of 16 layers each, 4 x 14.5 ft panels, total insulation thickness 0.49 in. ● Blanket—Forward and Aft Dome Same as sidewall except pie- shaped panels ● Blanket Attachment—Fiber glass straps 0.015 x 4 x 24 in., nylon tank attach studs 0.5 in. dia x 0.4 in. long ● Purge System—Gas manifold system, mylar shroud	Tank heat input (470 Btu/hr), pressure in space (10 ⁻⁴ torr), inert gas atmosphere, no cryopumping (prelaunch)	560
3.02 Meteoroid Protection ● Flexible Foam Blanket— outside of insulation 2 in. thick, density 1.2 lb/ft³ ● Shroud—outside of foam 0.010 fiber glass laminate, 4 ft x 14.5 ft panels	RNS P(0) = 0.995 baseline lunar mission away from earth (27 days)	770

CORE PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
4.00 Docking/Clustering		
4.01 Forward Docking Structure—cone assemblies, 4 reqd, 14 in. dia x 45° cone, integrally stiffened, aluminum support struts and attach hardware solenoid driven, spring loaded latching assy.	Longitudinal position ±5 in., lateral position ±5 in., angle pitch or roll ±3°, longitudinal velocity ±0.1 ft/sec, lateral velocity ±0.1 ft, pitch angular velocity ±0.2 deg/sec, roll angular velocity ±0.02 deg/sec, maximum relative impact velocity 0.2 ft/sec	80
4.02 Aft Docking Structure—probe assemblies, 4 reqd, 5 in. dia x 23 in. long, aluminum support struts and attach hardware		200
4.03 Clustering Structure—7075-T73 Aluminum, machined hinges, idlers, and drive links, motor driven screw jacks, 4 sets reqd 10 in. dia x 45° cone, integrally stiffened four sets track roller bearings, 4 reqd	Maximum relative impact velocity 0.2 ft/sec, vehicle longitudinal misalignment ±0.5°	360
5.00 Main Propulsion		
5.05 Propellant Feed System	91.9 lb/sec LH ₂ 30 psia	260
• 8 in. dia throttle valves—2 reqd 12 in. dia blocking valve—motor-driven (120 vac, 400 Hz), planetary gear transmission, full flow binary visor type, metallic main gate seal, opening motion—linear seal withdrawal, 90° rotational • 12 in. dia aluminum ducting 720 in. long x 0.035 in.	Collapse	

CORE PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
12 in. dia ducting stainless steel, 0.035 in. x 54 in. long, 2 reqd 12 in. nominal dia gimbal joints - 4 reqd 12 in. dia pressure volume compensator 8 in. dia ducting stainless steel x 0.035 in. 54 in. long - 4 reqd 8 in. dia gimbal joints - 8 reqd - Automatic coupling and deployment assembly with motor and drive screws - 2 reqd - Bolted flange connections at tank sump with dual static seals, 2 segment coupling at interfaces	30 psia operating pressure ±8° angulation ±1 extension ±8° automatic leak check, maximum leakage 10 ⁻⁵ sccm	
5.06 Pressurization System - Expulsion		60
1/2 in. dia quick disconnect, normally closed 1/2 in., 24 vdc dia direct acting solenoids valve - 8 reqd 1/2 in. dia metallic flexible braided hose sections - Bolted flange connections at ends with dual static seals and welded intermediate joints	0.6 lb/sec p = 850 psia T = 225°R 0.6 lb/sec GH ₂ p = 850 psia at T = 225°R maximum leakage 10 ⁻⁵ sccm	

CORE PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
5.09 Orbit Refueling ✓ 4 in. dia spray bypass valve—4 reqd, motor driven (120 vac, 400 Hz), planetary gear transmission, full flow binary visor type, metallic main gate seal, open motion—linear seal, withdrawal, 90° rotational mechanical spring loaded override—normally closed • 4 in. dia disconnect, normally open ✓ 4 in. dia check valve—2 sectioned flapper type ✓ 4 in. dia stainless steel ducting, 0.035 x 50 in. long • 4 in. nominal dia gimbal joints—3 reqd • Bolted flange connections ends with dual static seal configurations and welded intermediate joint	3,000 gpm p = 40 psia T = 40° R p = 45 psia p = 45 psia maximum leakage 10⁻⁵ sccm	50
5.10 Ground and Emergency Vent ✓ 6 in. vent and relief (pneumatically actuated) valve • 6 in. poppet disconnect—normally closed ✓ 4 in. (poppet balanced) relief valve • 1/4 in. 3-way direct acting solenoid valve • 1/4 in. quick disconnect coupling normally closed	11 lb/sec GH₂ at 29 psia 3,000 gpm 2 lb/sec GH₂ at 29 psia 475 psig 475 psig	80

CORE PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
6 in. OD x 0.035 in. stainless steel ducting - Bolted flange connections ends with dual static seals configurations 6 in. and 4 in. dia tubing welded intermediate joints 1/4 in. tubing all welded	maximum leakage 10^{-5} sccm	
5.11 Flight Vent		60
2 1/2 in. dia pilot operated quad blowdown valves -4 reqd 2 1/2 in. dia x 0.016 stainless steel ducting - Bolted flange connections ends with dual static seal configurations, welded intermediate joints	0.6 lb/sec GH ₂ at 29 psia T = 40°R p = 29 psia maximum leakage 10^{-5} sccm	
7.00 Astrionics Systems/Astrionics		
7.01 Guidance, Navigation, and Control		--
Optical corner cubes	Cooperative target for docking operations	
7.02 Instrumentation		15
22 transducers for sensing 17 signal conditioning circuits 2 analog multiplexers -MSI, 16 channels	80% of analog channels 60% of analog channels	

CORE PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
2 analog to digital converter, 10-bit resolution	1 part in 1024 resolution, 0.1% accuracy, 1 per multiplexer	
7.03 Command and Control		5
Logic decoder	Accept serial input instructions from data bus terminal	
Controllers with memory as required	Accept decoded signals and drive controllable functions—up to 10 amps (those with memory—turned off by separate command)	
7.04 Electrical Power		20
Power management, cabling, and distribution assembly	Power distribution and switching	
Power distribution	Round copper conductor wiring—Kapton insulation	
2 inverters Frequency—400 Hz Voltage—120 vrms	Redundant power for ac valve actuation	
7.05 Electrical Networks		170
Emergency detection, data bus, manual control and engine function cabling between station 0 and the top of the run tank.	Flat Conductor cable, polyimide or Kapton insulation, copper conductors	
Outboard module distributors	Core module only	

CORE PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
7.06 Environmental Control		--
Controlled emissivity coatings and internal electrical heaters as required by each subsystem	Included in each subsystem	
7.07 Propellant Management		--
Point level sensors mounted on propellant feed duct		
7.08 Onboard Checkout		5
Sensors for emergency detection	EDS monitoring of critical functions	
7.09 Data Management		5
1 data bus terminals		
Total dry weight (including 280-lb contingency)		6,550

2370
 370
 390
 60
 80
 170
 130
 560
 770
 80
 200
 360
 260
 60
 50
 80
 60
 15
 5
 20
 170
 5
 5

 6270
 280 contingency
 6550

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Section 6

TANDEM PROPELLANT MODULE

This section contains a description of the tandem propellant module, starting with a summary of the overall module configuration and concluding with a listing of the module hardware organized according to the system provided in the study guidelines.

6.1 CONFIGURATION

The tandem propellant module comprises the first, third, and fourth tiers of the clustered cruciform configuration. This module provides for storage of propellants. No other major function is provided, resulting in a simple module which is passive and responsive to external control. It contains subsystems to perform docking, module latching, propellant feed, ground vent and relief, flight vent, and orbital refueling.

The module shown in Figure 6.1-1 is transported to earth orbit by the shuttle. A tug is utilized to convey the module to the assembly area where it is docked to either core or another tandem module. The baseline probe/drogue system is employed for docking. This system has the capability of soft docking whereby the last few inches of drawup can be accomplished by the probe. The module has the drogues mounted forward and the probes aft. Power, guidance, and impulse for docking are supplied by the tug.

The tank sidewalls are integrally reinforced with an isotropic grid pattern to prevent buckling of the unpressurized tank during boost and to transmit thrust loads during engine operation. Hemispherical domes with the propellant feed line offset a maximum from the module centerline proved to be the superior configuration considering propellant capacity, cost, and manufacturing. Lugs are machined in the domes for attachment of the skirt fiber glass X-member strut assemblies. Fiber glass, because of its low thermal

conductivity, was utilized to minimize heat flow into the propellant tank. Thermal protection of tank is provided by three blankets of DAM/net insulation. Meteoroid protection is provided by a 2 in. layer of flexible foam encased by a 0.010-in. -thick fiber glass shroud. A sump is incorporated in the design to minimize residuals.

The external section of the feed system originates at the module forward interface and consists of a section of 12-in. -diameter ducting with the baseline two gimbal compensator joint, and an automatic deployment mechanism. Entrance to the tank is through a bolted dual seal flange. The internal duct terminates at the sump and is rigidized for collapse pressures. It is supported off the tank wall by sliding-type vibration mounts. A blocking valve is included at the forward end of the run to precondition the tank feed system. Upstream of the blocking valve is the 4-in. -diameter bypass system which is utilized for flight refueling. This system contains quad redundant control valves, an antidisturbance check valve and terminates a spray nozzle which injects LH_2 into the ullage. The spray nozzle prevents pressure surges while refueling.

Two tank discharge isolation valves are housed in the sump. Inlet to the valves is through an antivortexing, filtration screen. Exit from the sump is through a 12-in. -diameter duct containing two gimbal joints for deflection absorption. Automatic coupling is provided at the module aft interface. Both the ground vent and relief, and the flight vent systems are located in the ullage region of the tank. The systems are integrated and require a single tank penetration only. The external pressurization line runs the full length of the tank and has a conventional quick disconnect coupling at the aft end which mounts to the electrical connector deployment panel. The forward end of the line penetrates the dome in the ullage region and terminates in a pressurant diffuser which utilizes a nylon bag to prevent pressurant impingement and ullage collapse. Pressurization control valves are mounted external to the tank in the forward skirt region.

Flight readiness of the module is determined utilizing the capability of the onboard checkout system in the CCM. Since the module is a space resident

Figure 6.1-1. Tandem Propellant Module

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element, fault prediction sensors are included. The module is replaced on an unscheduled maintenance basis only upon the occurrence of a failure. The data bus transfers instrumentation and command information in digital form between the CCM and the propellant module. DC primary power is distributed and used in the propellant module for electromechanical functions. The EDS is used to gather information on critical parameters and distribute safing commands from the CCM.

6.2 HARDWARE TREE

A description of the equipment contained in the tandem module, including the specific design conditions and weight is contained in this subsection. The organization and numbering is that given in the study guidelines:

TANDEM PROPELLANT MODULE HARDWARE TREE

Description	Design Conditions/ Requirements	Weight (lb)
2.00 Structure		
2.01 Propellant Tank—2014-T6 Aluminum		2,370
- Forward Dome—hemispherical, monocoque construction, 0.031 in. thick by 174 in. dia by 87 in. long, one-piece dome, forging - Aft Dome—same as forward dome - Cylinder—integrally stiffened 60 degree waffle, membrane thickness 0.055 in., rib height 0.615 in., rib length 8.10 in., rib thickness 0.035 in., 174 in. dia by 519 in. long 3 segments, each segment fabricated from 0.75 in. x 15.5 ft x 44 ft plate 221 ft of welding	30 psia at end of burn 30 psia at end of burn Membrane— 30 psia at end of burn Stiffeners launch release transient (710 lb/in.)	

TANDEM PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
2.03 Forward Skirt—Fiber glass, space truss cylinder, 174 in. dia by 85 in. long, 24 tubular struts fabricated into 12 X-member sub-assemblies, 5.75 in. dia by 0.075 in. wall by 96.2 in. long struts	Engine operation, gimbaled hard-over (17,790 lb/strut), minimize heat short to tank	370
2.04 Aft Skirt—Same as forward skirt except space truss cylinder is 95.4 in. long and strut length is 105.3 in.	Same as forward skirt	390
2.06 Exterior Finish and Sealer	Prevention of corrosion	60
2.07 Baffles - Antislosh—2 reqd, 156 in. dia rings fabricated from 2.0 in. dia by 0.049 in. wall 6061-T6 Al tubing, ring support struts 16 reqd, fabricated from 1.5 in. dia by 0.035 in. wall 6061-T6 Al tubing, nylon cloth (0.375 lb/sq yd) membranes - Geysering—1 reqd, octagon, 80 in. across flats, nylon cloth (0.375 lb/sq yd) membrane, nylon cord edge member and tension tie	Propellant settling	80
2.08 Equipment Support Structure—7075-T73 Al alloy sheet metal and machined brackets	Maximum acceleration and vibration	170
2.10 Additional Structure—Provision for cutouts and doors	Access	130

TANDEM PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
3.00 Thermal/Meteoroid Protection		
3.01 Insulation—Tank area 2,630 ft ²		560
- Blanket—Sidewall—48 layers 0.00015 in. double aluminized mylar with dacron net spacers, 3 blankets of 16 layers each, 4 ft x 14.5 ft panels, total insulation thickness 0.49 in. - Blanket—Forward and Aft Dome same as sidewall except pie-shaped panels - Blanket Attachment—Fiber glass straps 0.015 in. x 4 in. x 24 in., nylon tank attach studs 0.5 in. dia x 0.4 in. long - Purge System—Gas manifold system, mylar shroud	Tank heat input (470 BTU/hr), pressure in space (10 ⁻⁴ torr), inert gas atmosphere, no cryopumping (prelaunch)	
3.02 Meteoroid Protection	RNS P(0) = 0.995	770
- Flexible Foam Blanket—outside of insulation 2 in. thick, density 1.2 lb/ft³ - Shroud—outside of foam 0.010 fiber glass laminate, 4 ft x 14.5 ft panels	baseline lunar mission away from earth (27 days)	

TANDEM PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
4.00 Docking/Clustering		
4.01 Forward Docking Structure—cone assemblies, 4 reqd, 14 in. dia x 45 degree cone, integrally stiffened, aluminum support struts and attach hardware, solenoid driven, spring loaded latching assembly	Longitudinal position ± 5 in., lateral position ± 5 in., angle pitch or roll ± 3 degrees, longitudinal velocity ± 0.1 ft/sec lateral velocity ± 0.1 ft, pitch angular velocity ± 0.2 deg/sec, roll angular velocity ± 0.02 deg/sec, maximum relative impact velocity 0.2 ft/sec	80
4.02 Aft Docking Structure—probe assemblies, 4 reqd, 5 in. dia x 23 in. long, aluminum support struts and attach hardware		200
5.00 Main Propulsion		
5.05 Propellant Feed System	91.9 lb/sec LH ₂ 30 psia	260
8 in. dia throttle valves—2 reqd		
12 in. dia blocking valve, motor-driven (120 vac, 400 Hz), planetary gear transmission, full-flow, binary, visor-type metallic main gate seal opening motion—linear seal withdrawal, 90 degree rotational		
12 in. dia aluminum ducting, 0.035 in. x 720 in. long	Collapse	
12 in. dia ducting stainless steel 0.035 in. x 54 in. long	Operating pressure 30 psia	
12 in. dia pressure volume compensator	± 1 in. extension	

TANDEM PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
12 in. nominal dia gimbal joints—4 reqd - Bolted flange connection at tank with dual static seals and 2 segment coupling at interfaces - Motor and drive screws—2 reqd and automatic deployment and coupling segments assembly	±8 degree angulation Automatic leak check maximum leakage 10^{-5} sccm	
5.06 Pressurization System		60
1/2 in. dia quick disconnect, normally closed 1/2 in. dia 24 Vdc direct acting solenoids—8 reqd 1/2 in. dia metallic flexible braided hose sections - Bolted flange connections at ends with dual static seal and welded intermediate joints	0.6 lb/sec p = 850 psia T = 225°R 0.6 lb/sec GH₂ p = 850 psia at T = 225°R maximum leakage 10^{-5} sccm	
5.09 Orbit Refueling		50
4 in. dia spray bypass valve—4 reqd, motor driven (120 vac, 400 Hz), planetary gear transmission full-flow, binary, visor-type, metallic main gate seal open motion—linear seal, withdrawal, 90 degree rotational, mechanical spring loaded, override—normally closed	3,000 gpm p = 40 psia T = 40°R	

TANDEM PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
• 4 in. dia disconnect normally open • 4 in. dia check valve— 2 sectioned flapper type • 4 in. dia x 0.035 in. stainless steel ducting • 4 in. nominal dia gimbal joints • Bolted flange connections ends with dual static seals and welded intermediate joint	p = 45 psia p = 45 psia maximum leakage 10⁻⁵ sccm	
5.10 Ground and Emergency Vent		80
• 6 in. vent and relief valve (pneumatically actuated) • 6 in. poppet disconnect—normally closed • 4 in. (poppet balanced) relief valve • 1/4 in. 3-way direct acting solenoid valve • 1/4 in. quick disconnect coupling normally closed • 6 in. dia x 0.035 in. stainless steel ducting • Untied metal bellows sections • Bolted flange connections ends with dual static seals and 6 in. and 4 in. dia tubing with welded intermediate joints • 1/4 in. tubing all welded	11 lb/sec GH₂ at 29 psia 3,000 gpm 2 lb/sec GH₂ at 29 psia 475 psig 475 psig maximum leakage 10⁻⁵ sccm	

TANDEM PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
5.11 Flight Vent ✓ 2-1/2 in. dia pilot operated quad blowdown valves—4 reqd 2-1/2 in. dia x 0.016 in. stainless steel ducting - Bolted flange connections with dual static seals and welded intermediate joints	0.6 lb/sec GH₂ at 29 psia T = 40°R p = 29 psia Maximum leakage 10⁻⁵ sccm	60
7.00 Astrionics Systems/Astrionics		
7.01 Guidance, Navigation and Control Optical corner cubes	Cooperative target for docking operations	--
7.02 Instrumentation 22 transducers for sensing 17 signal conditioning circuits 2 analog multiplexers—MSI, 16 channels 2 analog to digital converter, 10 bit resolution	80% of analog channels 60% of analog channels 1 part in 1024 resolution, 0.1% accuracy, 1 per multiplexer	15
7.03 Command and Control Logic decoder	Accept serial input instructions from data bus terminal	5

TANDEM PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
Controllers with memory as required	Accept decoded signals and drive controllable functions—up to 10 amps (those with memory—turned off by separate command)	
7.04 Electrical Power		20
Power management, cabling and distribution assembly	Power distribution and switching	
Power distribution	Round copper conductor wiring—Kapton insulation	
2 inverters Frequency—400 Hz Voltage—120 v rms	Redundant power for ac valve actuation	
7.05 Electrical Networks		110
Emergency detection, data bus manual control, and engine function cabling between station O and the top of the run tank	Flat conductor cable, Polyimide or Kapton insulation, copper conductors	
7.06 Environmental Control		--
Controlled emissivity coatings and internal electrical heaters as required by each subsystem.	Included in each subsystem	
7.07 Propellant Management		--
Point level sensors mounted on propellant feed duct		

TANDEM PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
7.08 Onboard Checkout	EDS monitoring of critical functions	5
Sensors for emergency detection		
7.09 Data Management		5
One data bus terminals		
Total dry weight (including 280-lb contingency)		6,130

all but the same as one propellant module except tandem propellant module does not include item # 4.03 (clustering structure 360#) and item 7.05 electrical network is 60# lighter (110 compared to 170) for a net reduction of 420 #

$$\begin{array}{r}
 6550 \\
 -420 \\
 \hline
 6130
 \end{array}$$

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Section 7

OUTBOARD PROPELLANT MODULE

This section contains a description of the outboard propellant module starting with a summary of the overall module configuration and concluding with a listing of the module hardware organized according to the system provided in the study guidelines.

7.1 CONFIGURATION

The outboard propellant module is located at the second tier of propellant modules. It provides for storage of propellants. No other major function is provided, resulting in a simple module which is passive and responsive to external control. It contains subsystems to perform docking, clustering, propellant feed, ground vent and relief, flight vent, pressurization, and orbital refueling.

The module shown in Figure 7.1-1 is transported to earth orbit by the space shuttle. A tug is utilized to convey the module to the assembly area where it is docked to the core module. The baseline probe/drogue system is employed for docking, however, in this case it is necessary to invert the system with respect to the core module and locate the probes forward and the drogues aft since the modules dock nose to nose. This system has the capability of soft docking, whereby the last few inches of drawup can be accomplished by the probe. The deployable clustering hinges are located at the forward end of the module. After they engage and lock the outboard module is rotated to its side by side position with the core module. Structural latching is accomplished through utilization of a scaled-down version of the probe/drogue docking system mounted to the aft skirts of the module. The probe is contained within the outboard module. For both the docking and clustering operations, power, guidance and impulse is supplied by the tug.

The tank sidewalls are integrally reinforced with an isotropic grid pattern to prevent buckling of the unpressurized tank during boost. The hemispherical dome configuration was maintained to provide commonality of modules. Lugs are machined in the domes for attachment of the skirt fiber glass X-member strut assemblies. Because these modules are depleted first less HPI insulation is required for them and their DAM/net thermal blanket thickness is less than that used on the core and tandem modules. Meteoroid protection is provided by a 2-in. layer of flexible foam encased by a 0.010-in. -thick fiber glass shroud. A sump is incorporated in the design to minimize residuals.

Two 8-in. -diameter tank isolation feed valves are mounted to the base sump. Inlet to the valves is through an antivortexing, filtration screen. Outlet is through an 8-in. -diameter duct which provides the cross flow to the core module. This duct contains the baseline two gimbal compensator system for automatic deployment and hookup. Orbital refueling is accomplished by an internal 4-in. -diameter line terminating in a spray nozzle located in the ullage region. The spray nozzle diffuses the LH_2 during refueling preventing pressure surges. Sliding-type vibration mounts are employed to support the line. Both the ground vent and relief, and the flight vent systems are located in the ullage region of the tank. The systems are integrated and require only a single tank penetration. The external pressurization line runs the full length of the tank and has a conventional quick-disconnect coupling at the aft end which mounts to the electrical connector deployment panel. The forward end of the line penetrates the dome in the ullage region and terminates in a pressurant diffuser which utilizes a nylon bag to prevent pressurant impingement and ullage collapse. Pressurization control valves are mounted external to the tank in the forward skirt region.

Flight readiness of the module is determined utilizing the capability of the onboard checkout system in the CCM. Since the module is a space resident element, fault prediction sensors are included. The module is replaced on an unscheduled maintenance basis only upon the occurrence of a failure. The data bus transfers instrumentation and command information in digital form between the CCM and the propellant module. DC primary power is

Figure 7.1-1. Outboard Propellant Module

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distributed and used in the propellant module for electro-mechanical functions. EDS is used to gather information on critical parameters and distribute safing commands.

7.2 HARDWARE TREE

A description of the equipment contained in the outboard module, including the specific design conditions and weight is contained in this subsection. The organization and numbering is that given in the study guidelines.

OUTBOARD PROPELLANT MODULE HARDWARE TREE

Description	Design Conditions/ Requirements	Weight (lb)
2.00 Structure		
2.01 Propellant Tank—2014-T6 Al		2,370
- Forward Dome—hemispherical monocoque construction, 0.031 in. thick by 174 in. dia by 87 in. long, one-piece dome, forging - Aft Dome—same as forward dome - Cylinder—integrally stiffened 60° waffle, membrane thickness 0.055 in., rib height (0.615 in., rib length 8.10 in., rib thickness 0.035 in., 174 in. dia by 519 in. long 3 segments, each segment fabricated from 0.75 in. x 15.5 ft x 44 ft plate 221 ft of welding	30 psia at end of burn 30 psia at end of burn Membrane—30 psia at end of burn Stiffeners launch release transient (710 lb/in.)	
2.03 Forward Skirt—Fiber glass, space truss cylinder, 174 in. dia by 85 in. long, 24 tubular struts fabricated into 12 X-member sub-assemblies, 5.75 in. dia by 0.075 in. wall by 96.2 in. long struts	Engine operation, gimbaled hard-over (17,790 lb/strut), minimize heat short to tank	370

OUTBOARD PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
2.04 Aft Skirt—Same as forward skirt except space truss cylinder is 95.4 in. long and strut length is 105.3 in.	Same as forward skirt	390
2.06 Exterior Finish and Sealer	Prevention of corrosion	60
2.07 Baffles - Antislosh—1 reqd, 156 in. dia rings fabricated from 2.0 in. dia by 0.049 in. wall 6061-T6 Al tubing, ring support struts 16 reqd, fabricated from 1.5 in. dia by 0.035 in. wall 6061-T6 Al tubing, nylon cloth (0.375 lb/sq yd) membranes - Geysering—1 reqd, octagon, 80 in. across flats, nylon cloth (0.375 lb/sq yd) membrane, nylon chord edge member and tension tie	Propellant settling	60
2.08 Equipment Support Structure—7075-T73 Al alloy sheet metal and machined brackets	Maximum acceleration and vibration	170
2.10 Additional Structure—Provisions for cutouts and doors	Access	130
3.00 Thermal/Meteoroid Protection		
3.01 Insulation—Tank area 2,630 ft ² Blanket—Sidewall—30 layers 0.00015 in. double aluminized mylar with dacron net spacers, 3 blankets of 10 layers each, 4 ft x 14.5 ft panels, total insulation thickness 0.32 in.	Tank heat input (720 Btu/hr), pressure in space (10 ⁻⁴ torr), inert gas atmosphere, no cryo-pumping (prelaunch)	380

OUTBOARD PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
- Blanket—Forward and aft dome same as sidewall except pie-shaped panels - Blanket Attachment—Fiber glass straps 0.015 in. x 4 in. x 24 in., nylon tank attach studs 0.5 in. dia x 0.4 in. long - Purge System—Gas manifold system, mylar shroud		
3.02 Meteoroid Protection - Flexible Foam Blanket—outside of insulation 2 in. thick, density 1.2 lb/ft³ - Shroud—outside of foam 0.010 fiber glass laminate, 14.5 ft panels	RNS P(0) = 0.995 baseline lunar mission away from earth (27 days)	770
4.00 Docking/Clustering		
4.01 Forward Docking Structure—probe assemblies, 4 reqd, 5 in. dia x 23 in. long, aluminum support struts and attach hardware, solenoid driven spring loaded latching assy	Longitudinal position ±5 in., lateral position ±5 in., angle pitch or roll ±3°, longitudinal velocity ±0.1 ft/sec, lateral velocity ±0.1 ft,	200
4.02 Aft Docking Structure—cone assemblies, 4 reqd, 14 in. dia x 45° cone, integrally stiffened, aluminum support struts and attach hardware	pitch angular velocity ±0.2 deg/sec, roll angular velocity ±0.02 deg/sec, maximum relative impact velocity 0.2 ft/sec	80

OUTBOARD PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
4.03 Clustering Structure—7075-T73 aluminum machined hinges, idlers, and drive links, motor driven screw jacks, 1 set reqd, probe assembly—1 reqd, 3 in. dia by 20 in. long, cone assembly—1 reqd	Maximum relative impact velocity 0.2 ft/sec, vehicle longitudinal misalignment ± 0.5 deg	90
5.00 Main Propulsion		
5.05 Propellant Feed System	91.9 lb/sec LH₂ 30 psia	260
8 in. dia throttle valves—2 reqd, motor-driven (120 vac, 400 Hz), planetary gear transmission, full flow binary visor type, metallic main gate seal, opening motion—linear seal withdrawal, 90° rotational		
8 in. dia ducting stainless steel 0.035 in. x 54 in. long	operating pressure 30 psia	
8 in. dia pressure volume compensator		
8 in. nominal dia gimbal joints—2 reqd	$\pm 8^\circ$ angulation	
Motor and drive screws and automatic deployment assembly—2 reqd		
Bolted flange connection at tank with dual static seals	maximum leakage 10^{-5} sccm	
5.06 Pressurization System		60
1/2 in. dia quick disconnect—normally closed	0.6 lb/sec p = 850 psia T = 225°R	

OUTBOARD PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
1/2 in. dia 24 vdc direct acting solenoids—8 reqd 1/2 in. dia metallic flexible braided hose sections - Bolted flange connection at ends with dual static seals and welded intermediate joints	0.6 lb/sec GH₂ p = 850 psia at T = 225°R 10⁻⁵ sccm	
5.09 Orbit Refueling		50
4 in. dia spray bypass valve—4 reqd Motor driven (120 vac, 400 Hz), planetary gear transmission, full flow binary visor type, metallic main gate seal, open motion—linear seal, withdrawal, 90° rotational, mechanical spring loaded, override—normally closed 4 in. dia normally open disconnect 4 in. dia check valve—2 sectioned flapper type 4 in. dia stainless steel ducting—0.035 x 720 in. long 4 in. nominal dia gimbal joints—3 reqd - Bolted flange connections ends with dual static seals and welded intermediate joint	3,000 gpm p = 40 psia T = 40°R p = 45 psia p = 45 psia maximum leakage 10⁻⁵ sccm	

OUTBOARD PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
5.10 Ground and Emergency Vent 6 in. vent and relief valve— (pneumatically actuated) 6 in. poppet disconnect— normally closed 4 in. (poppet balanced) relief valve 1/4 in. 3-way direct acting solenoid valve 1/4 in. quick disconnect coupling—normally closed 6 in. dia x 0.035 in. stain- less steel ducting - Untied metal bellows sections - Bolted flange connections ends with dual static seals and 6 in. and 4 in. dia tubing welded intermediate joints 1/4 in. tubing all welded	11 lb/sec GH₂ at 29 psia 3,000 gpm 2 lb/sec GH₂ at 29 psia 475 psig 475 psig maximum leakage 10⁻⁵ sccm	80
5.11 Flight Vent 2 1/2 in. dia pilot operated quad blowdown valves — 4 reqd 2 1/2 in. dia x 0.016 in. stain- less steel ducting - Bolted flange connections ends with dual static seals and welded intermediate joints	0.6 lb/sec GH₂ at 29 psia T = 40°R p = 29 psia maximum leakage 10⁻⁵ sccm	60

OUTBOARD PROPELLANT MODULE HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
7.00 Astrionics Systems/Astrionics		
7.01 Guidance, Navigation and Control		--
Optical corner cubes	Cooperative target for docking operations	
7.02 Instrumentation		15
22 transducers for sensing	80% of analog channels	
17 signal conditioning circuits	60% of analog channels	
2 analog multiplexers—MSI, 16 channel		
2 analog to digital converter, 10 bit resolution	1 part in 1,024 resolution, 0.1% accuracy, 1 per multiplexer	
7.03 Command and Control		5
Logic decoder	Accept serial input instructions from data bus terminal	
Controllers with memory as required	Accept decoded signals and drive controllable functions—up to 10 amps (those with memory—turned off by separate command)	

OUTBOARD PROPELLANT MODULE HARDWARE TREE (Continued)

*Some are covered
mainly pg 130
but 10 # added
2 2 10 #*

Description	Design Conditions/ Requirements	Weight (lb)
7.04 Electrical Power - Power management, cabling and distribution assembly - Power distribution 2 inverters Frequency—400 Hz Voltage—120 vrms	Power distribution and switching Round copper conductor wiring—Kapton insulation Redundant power for ac valve actuation	10
7.05 Electrical Networks Emergency detection, data bus and manual control cabling	Flat conductor cable, polyimide or kapton insulation, copper conductors	15
7.06 Environmental Control Controlled emissivity coatings and internal electrical heaters as required by each subsystem.	Included in each subsystem	--
7.07 Propellant Management Point level sensors mounted on propellant feed duct		--
7.08 Onboard Checkout Sensors for emergency detection	EDS monitoring of critical functions	5
7.09 Data Management 1 data bus terminals		5
Total dry weight (including 280-lb contingency)		5,915

Section 8

COMMAND AND CONTROL MODULE (CCM)

This section contains a description of the command and control module, starting with a summary of the overall module configuration and concluding with a listing of the module hardware organized according to the system provided in the study guidelines.

8.1 CONFIGURATION

The CCM is located at the forward end of the RNS. It contains the entire navigation and control function including the sensors and processing capability required to implement autonomous navigation. Primary power source and peaking batteries as well as the cryogenic APS are located in the CCM. The major components of the NERVA Digital Instrumentation and Control Electronics (NDICE) are physically contained in the CCM which communicates with the RNS processor via a data bus.

The current RNS operating plan calls for return of the CCM to earth for maintenance and refurbishment subsequent to completion of every mission. The objectives of this plan are: (1) replenishment of consumables, (2) verification of functionality, (3) verification of redundancies, (4) calibration and adjustment of components, and (5) replacement of limited-life hardware. This provides effective maintenance since over 90 percent of potential RNS failures are located on this module. Space shuttle transportation, which provides a protective environment during boost and entry, will be used for recycling. The CCM will include all hardware required to accomplish orbital onboard checkout including recalibration, aided by ground support equipment, prior to each mission phase.

The CCM, shown in Figure 8.1-1, consists of a cylindrical section employing isotropic integrally stiffened skin. The CCM is 15 ft in diameter, 6 ft in length, and weighs 5,935 lb when fully fueled with expendables. The

Figure 8.1-1. Command and Control Module

construction of the integrally machined isogrid structure permits ease of component mounting, since mounting holes at the grid intersections are part of the structure. An integral shroud concept is utilized for meteoroid protection. It consists of a thin layer of rigid foam and a fiber glass shell. The baseline probe/drogue system is utilized for docking. In order to enable refueling of the main propellant tank in orbit with the CCM in place, a feedthrough refueling duct is provided internally to the CCM. This 4-in.-diameter duct contains the automatic coupling mechanism with deployment performed by the mating duct on the most forward tandem propellant module.

Autonomous navigation of the RNS uses a strapdown inertial measuring unit which includes accelerometers, an unknown landmark tracker and a horizon sensor. The horizon sensor also serves as a backup for the primary attitude reference, consisting of two star trackers. All sensors are located within the CCM in close proximity to each other in order to establish close coordination and correlation of data acquired. Provision for receiving ground transmission of uplink data will be made as a backup to the nominal autonomous navigation scheme.

Storage of the propellants for the turbopump augmented cryogenic auxiliary propulsion system (LO_2/LH_2) and the primary power fuel cell system are integrated, using a common storage container. The propellant tankage and conditioning equipment is located circumferentially within the CCM. This equipment consists of (1) hydrogen and LO_2 storage spheres, (2) turbopumps, (3) gas generators, (4) high-pressure accumulators, and (5) propellant control valving. Fluid ducting is run from storage accumulators circumferentially to the APS motors pods located 180 degrees apart. Eleven APS motors are mounted in each pod. These motors consist of ten 50-lb thrust motors, two in each orthogonal plane, and one aft-facing 1.6 lb thrust motor for propellant settling. Deflectors between adjacent motors are provided to protect against burnthrough.

Fuel cell reactants storage is common with the APS propellant. They are tapped off of the high-pressure accumulators. After conditioning, these

reactants are supplied to redundant fuel cells. The fuel cells proposed are of the type currently under development for the space shuttle and space station programs. These cells, generating 2 kw, will be the primary source of vehicle power. Two rechargeable, low weight, AgZn batteries will be provided to supply peaking power.

Redundant processors, capable of satisfying all stage and engine processing requirements, are connected to a central high speed memory to form the RNS processing complex. A bulk storage, auxiliary memory unit holds all operational and checkout procedures and data for fully autonomous functional and checkout operation of the RNS. Communications between these processors and other module subsystems are carried on the data bus under supervision of the data bus controller. The maximum traffic rate anticipated for the development vehicle is about 0.5×10^6 bits/sec. This maximum load is derived primarily from transmission of data from the modules to the data bus controller before the compression operation. An independent hardwired Emergency Detection System providing emergency commands as well as payload display and manual override is provided.

Telemetry and uplink communications are carried out by redundant transmitters and receivers compatible with current space communications networks.

8.2 HARDWARE TREE

A description of the equipment contained in the Command and Control Module, including the specific design conditions and weight is contained in this subsection. The organization and numbering is that given in the study guidelines.

COMMAND AND CONTROL MODULE HARDWARE TREE

Description	Design Conditions/ Requirements	Weight (lb)
2.00 Structure		
2.08 Equipment support structure— 7075-T73 aluminum alloy sheet metal and machined brackets	Maximum accel- eration and vibration	360
2.09 Equipment module structure— 7075-T73 Al alloy plate, integrally stiffened. 60 degree waffle, mem- brane thickness 0.025 in., rib height 0.420 in., rib length 4.00 in., rib thickness 0.050 in., 180 in. dia by 72 in. long, 2 segments, each segment fabricated from 1.0 in. x 6.5 ft x 25 ft plate	Engine operation gimbaled hard- over (225 lb/in. compression) APS operation (100 lb thrust)	330
3.00 Meteoroid/Thermal Protection		
3.02 Meteoroid protection—rigid foam layer 1.00 in. thick, density 2.1 lb/ft ³ , shroud outside foam 0.020 in. fiber glass laminate	RNS P(O) = 0.995 baseline lunar mission away from earth (27 days)	120
4.00 Docking/Clustering		
4.01 Forward docking structure—cone assemblies, 4 reqd, 28 in. dia x 45 degree cone, integrally stiffened, aluminum support struts and attach hardware	Longitudinal posi- tion ±5 in., lateral position ±5 in. angle, pitch or roll ±3 degrees, longi- tudinal velocity ±0.1 ft/sec, lateral velocity ±0.1 ft, pitch angular velocity ±0.2 deg/ sec, roll angular velocity ±0.02 deg/ sec, maximum relative impact velocity 0.2 ft/sec	80
4.02 Aft docking structure—probe assemblies, 4 reqd, 5 in. dia x 40 in. long, aluminum support struts and attach hardware		200
5.00 Main Propulsion		
5.01 NDICE		500

was added in
propulsion module.
(see pg 118)

COMMAND AND CONTROL MODULE
HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
5.09 Orbit Refueling		40
4 in. dia x 0.035 in. stainless steel ducting—length = 48 in. with dual static seal flanges at both ends 2 segment coupling flanges, coupling segments, motor + drive screws 4 in. dia pressure volume compensator 4 in. dia gimbal joints—2 reqd	30 psia 3,000 gpm LH ₂ Maximum leakage 10 ⁻⁵ sccm	
6.00 Auxiliary Propulsion		
6.01 Reaction Control System		950
- Aluminum Spherical Storage Tanks, Al 2014-T6, 0.040 in. Weight oxygen = 1,000 lb Weight LH₂ = 250 lb - Storage High Performance Insulation—DAM/Net - Oxygen Accumulator Sphere, 2014-T6 Al, 1.23 ft dia, 0.53 in. thick - Hydrogen Accumulator Sphere—Ti-6Al-4V, 3.9 ft dia x 0.48 in. thick - Thrustors—high pressure film cooled nozzles—22 reqd	Total impulse 455,000 lb/sec Isp = 365 sec p = 30 psia T = 40°R 3,000 psia T = 360°R S.F. = 2.5 3,000 psia T = 260°R S.F. = 2.5 Thrust 50 lb— 20 reqd Thrust <u>1.3 lb</u> — 2 reqd	

COMMAND AND CONTROL MODULE
HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
● Heat Exchanger – Conditioners Helical tube annular shell, stainless steel, external fiber glass insulation – 2 reqd ● Thrustor Control Valves, direct acting solenoids, normally closed – 48 reqd ● Squib Operated Closed, plunger type isolation valves – 12 reqd ● Regulators – 4 reqd ● Normally Closed Direct Acting Solenoid Valves – 32 reqd ● Normally Open Direct Acting Solenoids – 3 reqd ● Turbine Driven Centrifugal Pumps – 2 reqd ● Burst Disk Relief Valves – 2 reqd ● Check Valves – 4 reqd ● Gas Generators and Igniters – 4 reqd ● Filters – 2 reqd ● Tubing all welded joints except connections at components, dual static seals at ends		
7.00 Astrionics		
7.01 Guidance Navigation and Control		310
● 2 star trackers on gimbal mounts each cover ± 60 degrees conical field of view, each tracker covers 120 degrees of opposite hemispheres	4 arc sec point- ing accuracy	

COMMAND AND CONTROL MODULE
HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
Horizon sensor—160 degree field of view, conical scanning type with two rotating heads—gimbal mounted	0.1 degree pointing accuracy, course attitude determination-backup position, velocity determination	
Landmark tracker on gimbaled mount—120 degree conical field of view	4 arc sec pointing accuracy, determine position and velocity vector during orbital operations	
Inertial measuring unit—6 gyros in strapdown dodecahedron configuration	Determine vehicle attitude in inertial space. Drift rate not to exceed 0.05°/hr	
12 accelerometers—6 high range, 6 low range	High range 1g to 10 ⁻³ g, low range 10 ⁻³ to 10 ⁻⁶ g. Scale factor error not to exceed 0.05%	
2 scanning laser radar systems	120 km range, range accuracy 0.2% or 10 cm, range rate accuracy 1% or 0.5 cm/sec	
Optical corner cubes for rendezvous and docking	Cooperative target for space rendezvous	
7.02 Instrumentation		210
225 transducers—pressure, temperature, flow, voltage, etc.	80% of analog channels	
135 signal conditioning circuits	60% of analog channels	

COMMAND AND CONTROL MODULE
HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
• 18 ea 16-channel MSI analog multiplexers • 18 ea 10-bit analog to digital converters	Data switching and programming 1 part in 1,024 resolution, 0.1% accuracy encoding of analog data, 1 per multiplexer	
7.03 Command and Control		140
• 2 S-band transmitters	Dual redundant. Compatible with DSIF/MSFN	
• 2 receivers and uplink command decoders	Dual redundant. Compatible with DSIF/MSFN	
• Tracking transponder	Allow for ground backup	
• 2 omni antennas, 1 steerable directional antenna	Omnidirectional for near earth, steerable for lunar distances	
• Data programmer to control and sequence instrumentation channels	Capable of reprogramming to multiple modes (estimate 8)	
• PCM encoder to format, address, and tag data blocks	Format compatible with DSIF/MSFN processing capability	
• Logic decoders	Accept serial input instructions from data bus terminal	

COMMAND AND CONTROL MODULE
HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
Controllers with memory as required	Accept decoded signals and drive controllable functions up to 10 amps (those with memory turned off by separate command)	
7.04 Electrical Power		785
2 fuel cells—regulated capillary matrix type with alkaline electrolyte. 2 kw capacity each	Redundant cells—each capable of supplying max aftercooling power of 1.2 kw plus peaking power recharge. 317 kwh total/mission	
Hydrogen and oxygen reactant storage integrated with APS tankage. 300°R and 100 psi from accumulator	250 lb of reactant and 100 lb of tankage included	
2 batteries—AgZn rechargeable. 1.25 kwh capacity each	To provide emergency and peaking power for CCM subsystems, 50% max discharge	
2 inverters frequency—400 Hz voltage—120 vrms	Redundant power for motor driven valves for APS and fuel cell reactant control	
Power management, regulation, and switching assembly. Power distribution busses and cabling	Provide redundant busses for backup components, fault sensing and switching	
Instrumentation reference supply, 5 vdc	0.01% voltage reference	

COMMAND AND CONTROL MODULE
HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
7.05 Electrical Networks		85
Emergency detection, data bus and manual control cabling	Conductor cables, kapton or polyimide insulation, copper conductors	
Power and intersubsystem functional distribution	Round wire copper conductors with kapton insulation	
Module interface connectors and blind mating panel	Mounted on motor driven panel	
7.06 Environmental Control		
Controlled emissivity coatings and internal electrical heaters, as required by each subsystem	Included in each subsystem	
7.07 Propellant Management		
Point level sensors and flow meters in APS tankage	Included in instrumentation	
7.08 Onboard Checkout		60
Procedures stored and executed by DMS	Software	
Emergency detection and command generation logic assembly. 50 functions capacity	Independent detection and safing. Capable of accepting manual inputs from payload	
7.09 Data Management		315
2 processors in 1 + 1 configuration—32 bit word, 4 μsec add, 32,000 word high speed storage	Redundant processors with MTBF of 38,500 hr	

COMMAND AND CONTROL MODULE
HARDWARE TREE (Continued)

Description	Design Conditions/ Requirements	Weight (lb)
- Shared high-speed memory, 8,000 words, 32 bits, 1 μsec cycle time 1 auxiliary memory, 10^6 bit storage capacity - Data bus controller/processor I/O - System time base 4 data bus terminals	Multiple access channels—1 for each processor Bulk storage of all operational and checkout procedures Buffer processor to interfacing circuitry Provide time base data for procedure control NDICE, N&G, C&C, and instrumentation 0.5×10^6 bits/sec data rate	
Total Dry Weight (including 200 lb contingency)		4,685
RCS propellant		1,250
Total Operational Weight		5,935

360
 330
 120
 80
 200
 500
 40
 950
 310
 210
 140
 785
 85
 60
 315

 4485
 200 contingency

 4685 DRY
 1250 RCS

 5935 operational

NDICE (See pg 118) propulsion module is 500 # too heavy

4685
 - 520

 4165

Section 9

NERVA INTERFACE

The NERVA interface section contains the engine description, a description of the functional interfaces between NERVA and the stage, the physical interfaces between NERVA and the stage using an interface control drawing, and a summary of interface recommendations.

The NERVA engine is delivered for assembly to the nuclear stage with the following separate subassemblies: (1) a nuclear engine module assembly, (2) an assembly consisting of the stage-mounted portion of the NERVA digital instrumentation and control electronic system, (3) two PSOV assemblies, and (4) a cooldown supply module (CSM) assembly.

9.1 NERVA ENGINE

This section contains an operational description of the NERVA engine, physical configuration considerations, and NERVA performance summary. The requirements for thrust vector control, cooldown, and engine structural dynamics are reviewed.

9.1.1 Description

The NERVA engine (Figure 9.1-1) utilizes a nuclear reactor to provide heat to liquid-hydrogen propellant in a "full-flow" cycle, thus obtaining a high-specific-impulse propulsive force. Thrust is generated by hydrogen which is heated under pressure in the reactor core and expelled through a De Laval nozzle. The hydrogen is supplied from the tank by means of dual turbopumps and flows through cooling passages in the nozzle wall and reflector before reaching the reactor. Energy transferred to the hydrogen in the cooling passages is extracted by the full-flow turbines to drive the pumps. Bypass valves control the output of the turbopumps and thus regulate chamber pressure. Reactor power is regulated to maintain a desired chamber

Figure 9.1-1 NERVA ENGINE

temperature by control drums and by structural support coolant valves which control the hydrogen density in the reactor support structure.

NERVA performance characteristics are summarized in Table 9.1-1. Two basic elements of engine control are turbine power and reactivity. Both are used in the control of the primary engine variables: chamber temperature and pressure as demanded by the engine programmer. Inputs to the programmer come from the stage or ground-test control and are typically the start command, set points, shutdown, and emergency actions.

The NERVA engine reliability allocation is 0.995 for the 10-hour operating life. The engine will incorporate means of preventing accidental criticality during all ground and space operations.

The engine is being designed for maintainability both on the ground and in space. The fluid flow paths are illustrated in the schematic on Figure 9.1-2. Propellant flows from the propulsion module tank through propellant shutoff valves (PSOV) to the turbopumps. After leaving the turbopumps, the flow divides between the reflector, the structural support system, and structural support bypass flow. Distribution of the flow is determined by the SSCV and the structural support bypass orifice (SSBO). Flow through the structural support system controls the reactivity of the nuclear subsystem in conjunction with the control drums. Structural support bypass flow cools the reactor core support plate but is not used to control reactivity. Flows from the reflector, structural bypass, and structural support system are combined to exit from the pressure vessel into the turbine. Part of the flow is

Table 9.1-1
NERVA ENGINE DESIGN CONDITIONS

Thrust (Vacuum)	75,000 lb
Chamber Pressure	450 psia
Specific Impulse (Vacuum)	825 sec
Chamber Temperature	4,250°R
Life	10 hr, 60 cycles

Figure 9.1-2 NERVA SCHEMATIC

bypassed around the turbine, using the turbine bypass control valve (TBCV) for control of chamber pressure. The flow from the turbine is then reintroduced into the pressure vessel and further heated in the reactor core before exiting from the nozzle. Part of the flow in the turbine exhaust is diverted through the stage pressurant check valve (SPKV) for propulsion and propellant module pressurization. In cooldown, a separate tank fluid line is used, controlled by the cooldown system control valve (CSCV) for removing decay heat from the reactor.

The NERVA interface and the engine overall geometry, including interpump spacing, which affects tank bottom penetration, are primarily dictated by current ground testing removal and replacement constraints. Current ground removal and replacement capabilities, and a ground maintenance policy are not necessarily compatible with desired flight maintenance and flight maintainability capabilities. However, at present, stage design philosophy only constrains the interface between the engine and the run tank by flight constraints. The propulsion module used for the MDAC RNS concept

integrates the engine with a small run tank. This eliminates the requirement for remote engine separation at the run tank engine interface. This interface could therefore be designed with primary flight requirements, namely, closed-space pumps, minimum length ducting, and optimum fluid and electrical connector locations. The only interface that would then be required to have remote capability would be the interface between the propulsion module and the test stand for ground testing.

9.1.2 Thrust Vector Control

Based on a 1.5-deg thrust vector misalignment for the NERVA and stage interface a minimum engine position gimbal limit of ± 3 deg has been established by controls studies. Table 9.1-2 summarizes the engine gimbal requirements.

Studies have shown that it is highly desirable to have the capability of trimming the NERVA prior to start. With this capability the NERVA misalignment would be established during its first use and pretrimmed out for subsequent uses. With the first use being translunar injection, requiring on the order of half an hour of operation, the effect of the relatively short attitude transient on the velocity errors at cutoff will be minimal. For the subsequent NERVA operations, many of very short duration, the vehicle attitude transient could be highly reduced by pretrimming the NERVA.

The engine manufacturer should provide the stage contractor with a log book containing the geometric misalignment of the mounting plane for each engine. Sufficient adjustment should be allowed in the actuator end fitting to adjust the actuator length to account for this misalignment.

Table 9.1-2
ENGINE GIMBAL REQUIREMENTS

Maximum Engine Deflection	± 3 deg
Maximum Engine Rate	0.25 deg/sec
Maximum Engine Acceleration	0.5 deg/sec ²

The NERVA gimbal actuator model being used by MDAC in control system studies was obtained from ANSC letter 7410:1071 dated 10 July 1970. This letter states that the actuator can be thought of as:

- A. Reversible 28v motor.
- B. Multistage gear transmission.
- C. Ball screw mechanism.
- D. Rate and position feedback.
- E. Compensated servopower amplifier.

The letter further states that the actuator will meet or exceed the deflection, rate, and acceleration requirements listed in the table. ANSC is designing the actuator for a maximum force output of 20,000 lb. Preliminary calculation by MDAC indicates that the static load could be greater than the present actuator maximum force capability. Therefore, the design conditions that ANSC is using should be reviewed.

The gimbal actuator transfer function given by ANSC in the referenced letter is:

$$\frac{\theta(s)}{\theta_c(s)} = \frac{8310}{s^3 + 200 s^2 + 1774 s + 8040}$$

where

θ = actuator position

θ_c = commanded actuator position

s = Laplace transform variable

This transfer function has been converted by MDAC for controls studies to

$$\frac{\theta(s)}{\theta_c(s)} = \frac{(6.4)^2}{s^2 + 2(0.695)(6.4)s + (6.4)^2}$$

To obtain the above function, a third order pole at 196 radians was dropped since it will not affect the attitude control system.

Control system studies have indicated that the actuator transfer function is not optimum. In general, the bandwidth of this system is greater than necessary with it contributing very little to the required control system attenuation. It should be possible without sacrificing low-frequency phase lag to obtain a pole-zero configuration which would provide more high frequency attenuation to the total vehicle control loop. In other words, in designing the actuator with its attendant response characteristics the effect on the total vehicle control system should be considered.

9.1.3 Cooldown Thrust

The vehicle orbital attitude disturbances resulting from pulsed aftercooling can be a very significant contribution to total coast attitude control propellant consumption. These disturbances result from, and are proportional to, the thrust vector misalignment. Three alternatives for thrust vectoring during cooldown are possible:

- A. Not controlling the engine angular position
- B. Positioning and maintaining the engine mechanically centered
- C. Trimming the effective thrust vector through the vehicle cg.

The first of these alternatives results in excessive coast attitude control propellant usage and is totally unacceptable. The second is an improvement, but could still result in an excessive requirement. In the third alternative an active control system would be used to periodically retrim the thrust vector. In this approach the disturbances resulting from after cooling would be minimal. The weight saving (in coast attitude control propellant and tankage) will far offset the added complexity of providing for active thrust vector control during coast. The NERVA gimbal actuator should be designed to allow for periodic re-trimming. After trimming the actuator should lock and hold in the last position.

9.1.4 Structural Dynamics

Engine/stage structural dynamic analyses conducted during the Phase III study showed that launch dynamics could be a problem for vehicle configurations where the engine is launched integrally with the Saturn V INT-21.

Although detailed structural dynamics analyses of the space shuttle mode of NERVA transportation have not yet been made, some of the findings of the analyses conducted on the propulsion module for the Class 1 configuration apply. The NERVA dynamic model used in these analyses was obtained from Reference 9.1.1. The free-free data obtained from Reference 9.1.2 for the "B" configuration of the NERVA in the 045 to 225 degree X-Y plane were used. The first six modes of this model (which are not component modes) were used. The resonant frequencies of these engine modes are 3.34, 14.34, 18.14, 36.19, 44.09, and 47.96 Hz.

References

- 9.1.1 Aerojet Nuclear System Company Report S038-CP 090290-F1 dated September 1970 entitled "Dynamics Analysis Report."
- 9.1.2 Aerojet Nuclear System Company Letter 7410:0214 dated 12 Oct 1970 entitled "Structural Information Requested by McDonnell Douglas Corporation."

9.2 RNS/NERVA FUNCTIONAL INTERFACE

This section defines the functional interface between the NERVA engine and the RNS propulsion module. This interface is covered for each of the three technologies: structural, fluid, and electrical.

9.2.1 Structural

Structural attachment is provided between the NERVA engine and the run tank thrust structure. The function of this interface is to transmit all engine gimbal, actuator and inertial loads to the thrust structure which distributes these loads into the propulsion module propellant tank. The most severe design condition for this interface occurs with the engine gimballed hardover at 5.7 degrees (based on $\sqrt{2} \times 3$ deg for control plus 1.5 deg for misalignment) under 75,000 lb of thrust. This condition produced the following ultimate loads:

Moment	1.04×10^6 in - lb
Shear	8,050 lb
Axial	97,500 lb

These ultimate loads resulted in a maximum compressive point load of 25,420 lb at the strut attach points. The engine manufacturer should verify these loads and provide the stage contractor with a loads envelope for the interface plane. The actual actuator location should be reviewed to determine the impact on stage induced loads. These loads should be distributed uniformly by the upper thrust structure and not introduced into one set of struts only.

The NERVA/propulsion module for launch inside the space shuttle cargo bay was investigated, employing the preliminary load factors shown in Table 9.2-1. The NERVA engine was assumed to be supported at the nozzle throat as recommended by the engine manufacturer. The load factors are based on MSFC memo PD-SA-70-269, dated 13 November 1970.

9.2.1.1 Biological (Disk) Shield

The current NERVA design provides for a removable disk shield with a weight of 10,000 lb which can be used to provide biological shielding for manned missions. For the baseline Class 3 configuration, geometry is used to reduce the radiation dose to the payload. There is no requirement for the external shield.

9.2.1.2 Mass Properties

The current calculated weight for the NERVA engine without the external shield in a flight operating condition is 27,728 lb including 500 lb for the stage mounted portion of NDICE. *

The center-of-gravity location without the external shield is at station 128, or 128 in. below the engine/stage interface.

Moment of inertia values for the operating engine (dry) taken about the gimbal point are

Roll axis	3,800 slug-ft ²
Pitch axis	83,618 slug-ft ²
Yaw axis	83,507 slug-ft ²

* ~~27,728~~ used 27300 in
Propulsion Module at Station 128
Pg 111. & pg 5 Book #11
must have had base at 27800 including 500 NDICE

Table 9.2-1
PRELIMINARY ACCELERATION LOAD FACTORS
SPACE SHUTTLE PAYLOAD COMPARTMENT

(Based on payload at cg location. Sign conventions based
on Orbiter Reference datum, Level II requirements)

Mission Phase/Event	Longitudinal (X)		Lateral (Y/Z)	
	Steady (g)	Dynamic (g)	Steady (g)	Dynamic (g)
Launch Release Transient (within 2 sec of release)	+1.5	±2.0	-	±2.0 (Y & Z)
Lift-off + 5 sec	+1.5	±0.25	-	±0.25 (Y & Z)
Max Q-Alpha Region (35 to 55 percent Booster Burn)	+2.0	±0.40	-0.75 (Z)	±1.5 (Y & Z)
Maximum Acceleration (80 to 100 percent Booster Burn)	+3.0	±0.25	-0.5 (Z)	±0.25 (Y & Z)
Cut-off/Separation (Within 2 sec of Booster Cut-off)	-	±3.0	-	±2.0 (Y & Z)
Separation + 5 sec	+1.5	±0.25	-	±0.1 (Y & Z)
Maximum Acceleration (60 to 100 percent Orbiter Burn)	+3.0	±0.25	-	±0.1 (Y & Z)
Reentry	-1.0	-	-4.0 (Z)	±0.1 (Y & Z)
Landing/Taxiing/ Braking	-1.0	-	-2.0 (Z) 0.5 (Y)	±2.0 (Z) ±0.5 (Y)

9.2.1.3 Structural Dynamics

Studies by ANSC and MDAC on launching the NERVA to orbit using an INT-21 have shown that restraint of the NERVA is required to limit NERVA lateral displacements during launch. In general some of the study results also apply to the Class 3 RNS configuration where NERVA is launched in the space shuttle cargo bay. Specifically, the frequencies obtained for the INT-21 integral launch of the propulsion module will be approximately the same as would be obtained in the case of space shuttle transportation of the propulsion module. Table 9.2-2 lists these resonant frequencies.

The launch configuration of the propulsion module is shown in Figure 9.2-1. The propulsion module is deployed in orbit by the space shuttle payload deployment mechanism. The module is launched with its propellant tank dry and unpressurized. Launch and boost loads associated with shuttle launch impose requirements on the propulsion module and NERVA which exceed those anticipated for space operation. Accelerations and load factors for the space shuttle are shown in Table 9.2-1. Based on these loads, and the low unrestrained frequencies shown in Table 9.2-2, the capability of

Table 9.2-2
RESONANT FREQUENCIES
CANTILEVERED PROPULSION MODULE

Mode Number	Without Restraint	10^4 lb/in. Lateral Tie Between The Engine and Shuttle Cargo Bay Floor
1	0.63	2.01
2	2.28	2.47
3	4.66	4.66
4	6.55	6.55
5	9.26	9.26
6	14.25	14.25

Figure 9.2-1 PROPULSION MODULE IN ORBITER CARGO BAY

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providing for engine lateral support such as indicated in Figure 9.2-1 is recommended. This scheme would use retractable structure to allow deployment.

9.2.2 Fluid Conditions

The propellant conditioning requirements for NERVA steady-state, full-power operation are defined by Figures 9.2-2 and 9.2-3 derived from AGC Letter 7410:1075, July 15, 1970, which includes a steady-state operating pressure of 26 psia, saturated liquid, with zero NPSP. Reduced flow rates are permitted at zero NPSP, and saturated liquid for pressures below 26 psia provide autogenous start capability. The RNS design provides for a NERVA malfunction mode. However, the total pressure (saturation pressure plus NPSP) does not exceed 26 psia for such a mode.

During pulsed aftercooling, the RNS provides saturated liquid to the bypass line at a minimum pressure of 16 psia.

Figure 9.2-2 RNS PRESSURE REQUIREMENTS

Figure 9.2-3 NERVA PUMP PERFORMANCE FOR SATURATED LIQUID AND ZERO NPSP

The pressurization system operates with NERVA bleed gas delivered at 225°R. Separate gas storage for prepressurization is not provided. This approach makes full use of NERVA bootstrap startup capability. Stage pressurant demand is summarized in Table 9.2-3 for the various thrust modes and operations.

✓ Prior to startup it is necessary to chilldown the active portion of the RNS feed system to ensure propellant conditions for NERVA and to accomplish a predictable startup operation. The feed system interfaces that require conditioning include the two legs of the NERVA feed system between the turbopump and the run tank, and the ducts between the RNS modules.

These are summarized in Table 9.2-4. All the stage feed ducting uses two basic types of flexible elements—gimbal joints and linear pressure volume compensators—which account for a major portion of the weights of those systems. Chilldown time requirements were based on the minimal permissible time for chilldown of each interface taking into consideration film boiling heat transfer for a duct initially at ambient temperature and providing a margin of safety for flow surges. An integrated stage/engine pump-fed chilldown system which is located in the run tank is employed. Its operation is integrated with the run tank refill function.

Table 9.2-3
RNS PRESSURANT DEMAND

Operation	Flow Rate (lb/sec)
(1) Steady state expulsion (including run tank prepressurization)	0.58
(2) Steady state with pressure control active	0.64
(3) Propellant module pressurization	1.16
(4) Full power run tank refill	0.81
(5) NERVA emergency mode	0.35

Table 9.2-4
RNS CHILLDOWN REQUIREMENTS

Interface	Components	Mass (lb)	Length (ft)	Equivalent Boiloff (lb-LH ₂)	Chill Time (sec)
NERVA (each side)	PSOV 9 in. feed duct* Turbopump PDKVA-valve	973	8.9	92	43
Run Tank/ Propellant Module	12 in. feed duct*	263	11	28	34
Propellant Module/ Propellant Module	12 in. feed duct*	217	10.2	23	24
Outboard/Inboard Propellant Module	8 in. feed duct*	116	11.5	13	17
*Includes gimbal joints.					

Figure 9.2-4 shows a schematic of the integrated system concept compatible with the current NERVA interface. The propulsion module run tank contains redundant submerged ac motor driven centrifugal pumps. An inverter is provided for each motor to utilize the dc power bus. Each pump is sized for full system chilldown capacity. In normal operation at reduced flow the pumps will operate at a higher head. The parallel manifolded pumps discharge via two antibackflow check valves into a header that directs flow forward to the stage main propellant feed ducting and aft to the engine. Return for stage feed duct chilldown is accomplished with the refueling spray nozzle bypass system on the run tank and the duct blocking valves located in each propellant module. This system permits conditioning of propellant module to propellant module external feed ducting. NERVA feed system chilldown concerns the conditioning of the inlet ducting to the NERVA turbopump, the pump, and pump discharge ducting to the location of the

Figure 9.2-4 INTEGRATED CHILLDOWN SYSTEM

✓
pump discharge valve (PDKVA). There are two such sections for the dual turbopump configuration. The pump shutoff valve (PSOV) and pump discharge valve are closed during chilldown.

9.2.3 Electrical

Electrical interfaces between NERVA and RNS subsystems exist both in the CCM and the propulsion module. The interface in the CCM is accomplished by using the stage data bus between the NDICE and the RNS data management subsystem. The stage data bus is shared by NDICE for transmission of multiplexed data from the propulsion module to the CCM where dedicated bus terminals for NDICE are assigned. A battery integral to the stage power subsystem is provided for propulsion module peaking power requirements. Signal conditioning, multiplexing, and digitizing of engine instrumentation, and decode of engine control signals are performed by the NDICE components on the propulsion module prior to (for instrumentation) or subsequent to (for control signals) transmittal on the data bus. Figure 9.2-5 shows the functional interface between stage and engine electronics.

9.2.3.1 Power

The NERVA engine requires 28-vdc power at various power levels, depending on which phase of the mission the engine is executing. Figure 9.2-6 shows an engine power demand profile for a single burn. Two power levels are shown: (1) NDICE power, which is dissipated in the CCM, at 500 w during engine operation, 200 w during cooldown, and 60 w during coast periods; (2) total power at 2,300 w with 3,500 w peaks during engine operation, 200 w with 1,000 w peaks during aftercooling and 60 w during coast. Alternating current power requirements will be satisfied by the use of local inverters in each module. Engine functional requirements will be satisfied by engine inverters. Precision reference instrumentation power supplies will be integral to the local instrumentation package.

Power quality will be 28 ± 4 vdc and will be distributed as required to the engine from the forward portion of the run tank. The vehicle skin will not be used as a return path for power or signals, but will serve as a noncurrent carrying reference. Environmental control will be provided internal to

Figure 9.2-5 ENGINE/STAGE ELECTRICAL INTERFACE

Figure 9.2-6 TYPICAL POWER PROFILE FOR A NERVA BURN

the equipment and use a portion of this power for internal electrical heaters. The 400 Hz ac $\pm$ 1 percent will be available as a reference frequency in the propulsion module, as will the data bus clock of 0.5 MHz.

9.2.3.2 Instrumentation

NERVA instrumentation will be conditioned, multiplexed, and digitized prior to insertion on the RNS data bus. A dedicated data bus terminal is provided on the propulsion module for NERVA instrumentation and control functions. The instrumentation channels will have multiple (eight estimated) internally programmed sequences of sampling which are commanded by a single mode set instruction transmitted on the data bus. Calibration capability will be included on individual instrumentation channels and commanded by an encoded signal from the data bus. Provision is allowed for hardline routing of a limited set of emergency functions to the CCM.

Allowance is made for 266 engine analog instrumentation channels for operational vehicle and 407 channels for development vehicles. Ground test instrumentation is separable and independent of these allowances. The digitizer will encode to 10 bits with an accuracy of 0.1 percent.

9.2.3.3 Control

Control of engine functions will be performed exclusively by NDICE. Control signals will be generated by NDICE components in the CCM and transmitted on the stage data bus to the propulsion module. These commands will be decoded, and appropriate drivers in the NDICE components on the propulsion module will effect control. Provision is made for hardline control of a limited number of emergency functions from the CCM to the NERVA engine. Engine gimbal signals will be supplied by the stage NG&C subsystem and the actuators controlled by stage drivers mounted on the propulsion module.

Engine checkout operations will be performed by procedures stored in NDICE and data for evaluation will be supplied through the operational data channels.

9.2.3.4 Information Transfer

Information will be transferred between the NDICE and the stage data management subsystem in the CCM. Two following classes of data are identified:

- A. Stage Commands to NDICE—Specific commands to control RNS operations will be required to be acted upon by the NDICE. Characteristically these would include: (1) prestart, (2) engine start, (3) set thrust or throttle, (4) shutdown, (5) hold cooldown pulse, (6) checkout, (7) instrumentation mode set, and (8) various emergency commands. These commands will be transmitted in encoded form on the RNS data bus.
- B. Status and Data Messages—Various status and data messages will be transmitted between the NDICE and the stage data management subsystem (DMS). These could include state computation results, health information, estimates of time to next event, processor activity monitors, and specific data. It is expected that a continuous flow of encoded data will cross the RNS data bus between NDICE and the DMS during the mission.

9.2.4 Mission Operations

The RNS mission operations impact the NERVA functional interface through specification of thrust modes for mission maneuvers, steady state operating times, constraints on the startup ramp, and aftercooling utilization. The overall mission timeline was presented in Table 2.1-1 which gives the propellant utilization and operating times for various mission maneuvers. The thrust modes and steady-state operating times associated with this mission timeline are presented in Table 9.2-5. Typically a throttle mode operation is utilized if the steady state burn time at full thrust is very short. Idle mode operations are employed for small impulses in lieu of the APS. Additional idle mode operations are also postulated for separation maneuvers prior to TLI and TEI-1. Idle mode operations for rendezvous maneuvers are also postulated after LOI-3 and EOI. The NERVA parameters characterizing the selected thrust modes and the functional requirements imposed on RNS subsystems are summarized in Table 9.2-6.

Table 9.2-5
NERVA THRUST MODE REQUIREMENTS

Burn	Thrust Mode	Steady-State Time (sec)	Thrust Hold Duration (sec)
TLI	Full thrust	1,800	44
Midcourse	Idle	530	--
LOI-1	Full thrust	74	28
LOI-2	Throttle	28	--
LOI-3	Full thrust	165	27
TEI-1	Full thrust	88	18
TEI-2	Throttle	0	--
TEI-3	Full thrust	47	16
Midcourse	Idle	255	--
EOI	Full thrust	475	14

Table 9.2-6
REQUIREMENTS FOR NERVA THRUST MODES

NERVA Thrust Mode	NERVA Parameters			RNS Functions			
	Thrust (lb)	Flow Rate (lb/sec)	Isp (sec)	Propellant Settling	Feed System Chill-down	Prepressurization	Run Tank Refill
Full Power	75,000	91.9	825	X	X	X	X
Throttle Mode	45,000	55.1	825	X	X		
Idle Mode	1,000	2.0	500				
Aftercooling	300	0.7	430				

X = Required

The RNS startup operations are defined in Section 3.11 of Book 1. Evaluation of the startup operations has identified the need for a thrust hold at the throttle point during the NERVA startup ramp. Since the engine operates at full Isp, payload losses associated with the thrust hold are negligible. The thrust hold will provide time to complete propellant settling prior to prepressurization and increase the time available for prepressurizing the propellant module, thereby reducing pressurant demand from NERVA. The estimated thrust hold durations established in Section 3.11 of Book 1 are summarized in Table 9.2-5. The steady-state operating times associated with these were not increased to reflect the thrust hold duration.

The integration and utilization of aftercooling propellant has a major impact on stage performance. Its implications are discussed in Section 3.13 of Book 1. Accurate N-body trajectory simulations were performed using the ANSC NERVA cooldown data to evaluate the performance implications of aftercooling. Whereas early RNS performance calculations neglected any potential payload gain from utilization of aftercoolant, the benefits have been established in this study. This amounts to a credit to the mission velocity resulting in 8,400 lb of payload delivered to lunar orbit. The amount of aftercooling required represents a degradation of the Isp for the stage. It was established that there would be a potential additional payload gain of 23,500 lb if aftercooling with propellant could be eliminated entirely.

The current NERVA specifications contain an impulse tolerance of $\pm 20,000$ lb/sec. The impact of this tolerance on the translunar trajectory was determined in Section 3.14 of Book 1 for the trajectory simulations as corresponding to 0.6 percent of TLI impulse or less than 12-nmi lunar miss distance. Consequently, it is considered that the tolerance could be relaxed and should be related to the operating time and total impulse.

Evaluation of midcourse correction concepts indicated that multiple impulsive midcourse maneuvers or a single impulsive correction early in the trajectory are preferable to a single impulsive maneuver at the end of the cooldown phase. A simulation indicated that manipulating the vehicle attitude and cooldown impulse during cooldown thrusting is competitive with

an impulsive midcourse correction. It is desirable to develop a method for predicting error early in the cooldown phase. This would permit implementation of a guidance policy to maximize the cooldown utilization as indicated during Phase II (Section 2.3.4, "Nuclear Flight System Definition Study - Final Report, " Volume II, Part 2, MDC G0585, May 1970).

Whereas the nominal NERVA Isp is 825 sec, the actual Isp obtained for the mission operations exclusive of idle mode burn is 790 sec. This imposes a substantial performance penalty as indicated. Therefore, it is desirable to reduce the amount of aftercoolant required by increasing the radiated power level from NERVA. The implications of this were discussed in Section 3.13.3 of Book 1.

Evaluation of the TLI trajectories with N-body trajectory simulations indicated that when using the aftercooling propellant for mission velocity, there is a critical period between 0.8 and 3.2 hours from ignition during which a vehicle abort could result in an earth impact trajectory. This is discussed in Section 3.13 of Book 1. This trajectory results from deflection of the vehicle by the lunar gravitational field. Failures which could lead to such a condition include loss of NERVA operation, loss of attitude control, and destruction of the RNS.

9.3 RNS/NERVA PHYSICAL INTERFACE

This section contains a physical description of the NERVA to RNS propulsion module interface. An interface control drawing is used to document the interface.

9.3.1 Interface Control Drawing

Figure 9.3-1 is the interface control drawing (ICD) for the NERVA engine to the propulsion module run tank. This drawing defines the structural, fluid, and electrical physical interfaces, based on ANSC Engine Layout Drawing 1137400C (9 August 1970) and includes MDAC interface considerations. The main view shows the NERVA engine installed to the run tank. The structural interface occurs at station zero. This is a cut through the thrust structure. The fluid lines that cross this interface plane are the

chilldown return line, pressurization line, and cooldown lines. These are located on the stage/engine customer connect panel. The two main feed duct attachments are detailed in View C. For the electrical cross plane functions, the flat cable routing is depicted. An end view of the propulsion module run tank is shown. This view shows the interface between the propulsion module and subsequent propellant modules in both RNS class vehicles. Depicted in this location are the probe/drogue docking system, the automatic feed duct deployment and coupling mechanisms, and the location of the automatic deployable electrical interface panel. The clocking and location of the harness tunnel area and the general arrangement of all of these subsystems are shown. This drawing will establish the dimensional compatibility between the NERVA engine and the stage.

9.3.2 Structural

The structural attachment for the NERVA engine to the run tank thrust structure occurs at station zero, as shown on the ICD. This station plane is a cut through the thrust structure. The engine side of this interface contains the NERVA upper thrust structure, which is an integral part of the engine. The stage side of this interface consists of a tubular thrust structure which initiates at the run tank and terminates in a thrust structure frame. The interface ring shown is fabricated from a 7075-T73 aluminum plate stock. It has a 58-in diameter at the interface plane and is basically a channel section 6-in deep incorporating integrally machined lugs for attachment of the thrust structure struts. The interface is designed to pick up the 12 equally spaced 3/4-in-diameter attach points on the 56-in-diameter bolt circle of the engine upper-thrust structure (UTS). This is a mastered hole pattern. In order to provide the most direct load path the thrust structure struts attach to the interface ring at these bolt locations. Cutouts are incorporated in the ring to provide clearance for the propellant inlet lines. This stage/engine attachment is a hard attachment and, therefore, it is assumed that the engine supplied gimbal bearing, which is an integral part of the upper thrust structure and the engine lower thrust structure, will have provisions for alignment in two axes during installation.

The separation distance between the pole of the aft dome and the interface plane increased to 30 in. from 23 in. because the POSV's and their flanges

Figure 9.3-1. Interface Control Drawing

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increased in size. The strut configuration was tailored to provide clearance for the POSV's and the engine feed line. Separate fittings are welded in the tank bottom for attachment for the POSV's. These fittings incorporate a flange which has provisions for installation of the Naflex seals. The antivortexing, filtration screens are mounted to the interior surface of these fittings. In order to provide adequate thermal isolation between the run tank and the NERVA the thrust structure struts are fabricated from fiber glass. They are tapered and have a tubular cross-section. Titanium fittings containing self-aligning bearings are installed in the ends of the struts.

The customer connect panel is attached to lugs machined in the closing frame of the thrust structure. It is stabilized by a truss that attaches to the titanium splice members of the thrust structure X-member subassemblies. It is designed to accommodate the gimbal loads induced by the propulsion lines that attach to it. The flat conductor and ribbon cable is also supported off the thrust structure closing frame. The support clamps are bolted to machined faces on the frame.

9.3.3 Fluid

The fluid interface will be described for the four basic stage subsystems: (1) propellant feed, (2) chilldown, (3) aftercooling, and (4) pressurization.

9.3.3.1 Propellant Feed

The feed system from the run tank bottom to the NERVA turbopump inlet consists of the engine supplied propellant shutoff valve which is a 10 in nominal diameter in-line poppet valve. An in-line duct from the PSOV discharge flange to the pump inlet is supplied by the engine manufacturer. The present design indicates that this duct has a section of untied bellows and two tied gimbals. These flexible elements are required to absorb the engine gimbal deflections. The current design deflection is ± 3 degree circular pattern. In addition to the gimbal deflections, this ducting must absorb stage deflection requirements. These requirements are incurred by stage thermal deflections, manufacturing tolerances, tank pressurization deflections, and various load deflections that occur during NERVA operation. In the present design the physical interface is the bolted flange connection on

the PSOV valve. This static connection utilizes a Marman-type conoseal. The maximum flow of hydrogen at this interface is 91.9 lb/sec.

NERVA engine conditioning is accomplished by directing the chilldown pump discharge flow to two lines that tie from the chilldown pump discharge manifold, as shown in ICD. Each line injects flow forward into the NERVA pump inlet duct downstream of the closed PSOV. Check valving located at the injection points prevents surges and disturbances from being transmitted to the adjacent system. This chilldown ducting does not cross the gimbal plane. The present consideration is to inject the supply flow through a boss that is an integral part of the PSOV body casting. Chill flow proceeds through the NERVA pump inlet ducting, turbopump, and down to the pump discharge valves. Upstream of these valves a tap-off takes the return flow manifolded from both engine pumps to a common return line. This return line crosses the gimbal plane and contains three gimbal joints to provide for the required deflection. Return flow is introduced back into the tank via a set of quad-redundant shutoff valves at a location well removed from the chilldown pump location to prevent degrading fluid inlet condition. The interface drawing shows the chilldown supply duct, which does not cross the gimbal plane. This duct will be stage supplied and the interface for this system will be the bosses which are located on the PSOV's. A return duct is required in conjunction with the chilldown conditioning system. This duct taps off from both engine main pump discharge manifolds to a single duct and must be returned to the tank. The engine must provide the pump tapoff manifold and run a 2-in return line back to the engine/stage customer connect panel. Since this line crosses the gimbal axis, gimbal provisions will be an engine requirement. At the customer connect panel, the stage will provide a line back to the run tank for the return of the chill-down conditioning fluid.

9.3.3.2 Aftercooling

The current NERVA design depicts a stage-mounted cooldown supply module located on the run tank lower thrust structure. The module receives hydrogen from the run tank and a single discharge line comes to the

engine gimbal interface. Across the interface a three-gimbal dogleg duct provides for the gimbal deflections. This duct as presently conceived will be part of the NERVA engine.

Details of the engine supplied cooldown module are shown in View BB. This module, which is furnished by the engine manufacturer, contains the quad redundant cooldown valves. It will be mounted on the stage side of the engine interface. In the position shown the module is hard mounted to the tubular thrust structure. This module will obtain hydrogen from the run tank via a 3-in-diameter cooldown supply line. A 3-in-diameter duct will leave the module and run to the customer connect panel. Both legs of this duct, the tank tap-off and the module discharge leg to the customer connect panel, will be stage supplied. From the customer connect panel across the gimbal plane and on to the NERVA engine, this duct will be engine supplied.

The NERVA pressurization system requires a single 1-1/4-in.-diameter line across the interface plane. The configuration of this duct, flexible elements, and position are not defined by current Aerojet interface drawings.

This duct provides the run tank and propellant modules with expulsion pressurant that is tapped off from the engine turbopump discharge side. This duct, to the cooldown supply duct, and the chilldown return line will all cross the interface at the engine-to-stage customer connect panel. View AA, a section through station zero of the structural interface, also depicts this customer connect panel. The hinge panel is attached to the thrust frame as shown. The stage will supply ducting from the run tank to the customer connect panel. Ducting from the panel to the NERVA engine will be engine supplied; this portion of the ducting run will have to absorb gimbaling deflection and other associated operational tolerances. In the right hand portion of the interface control drawing there is a table titled, "Connect Panel Schedule," which codes the customer connect panel fluid functions noted in View BB, with their function, duct diameter, pressure schedule, and flow rate.

It should be noted that all the fluid lines that interface from the NERVA engine to the stage must be reviewed with respect to heat short thermal

conditioning. The main feed inlet ducting is a primary concern, in view of the difficulties involved in defining insulation layup schemes which are compatible with the deflections required of these ducts. This problem also exists for the three other smaller cross-plane ducts.

9.3.4 Electrical

Physical interfaces between stage and engine electrical components exist in three locations in the RNS: (1) at the engine stage interface (Station 0.0), (2) at the forward end of the run tank, and (3) in the CCM.

The baseline Aerojet interface between the engine and stage consists of numerous connectors on a connector panel at Station zero which is mounted to the engine thrust structure. These connectors are located both internal and external to the thrust structure. This type interface is compatible with ground testing. However, there are two significant disadvantages for flight vehicles. The first is the extreme reliability penalty paid by the use of connector systems. The second is the interference problems caused by internally mounted connectors because of the envelope and routing restrictions.

The baseline interface arrived at in the RNS study allows for provision of 3,000 lines to cross this interface. The bulk of these lines represents instrumentation signals. The type of wiring that will cross the interface is anticipated to be combination of flat conductor cable and round conductor wire in a ribbon configuration to be compatible with the parallel conductor system. To enhance reliability, the use of connectorless terminations is recommended at this interface. It is envisioned that once these connections are made at the point of engine run tank assembly, there will be no requirement to disassemble this interface; however, the use of connectorless termination does not preclude this disconnect should maintenance operations be required on the ground prior to launch.

NDICE components are located at the forward end of the run tank. These include a multiplexer and signal conditioning for the engine instrumentation

and the decode for engine control functions. Stage wiring is routed along the side of the run tank to these modules where permanent or connectorless terminations are utilized to connect stage wiring to the NDICE components. These components interface with a dedicated data bus terminal and EDS wiring via stage wiring that terminates in an interface panel at the propulsion module interface. The latter wiring is largely represented by emergency control functions and the stage data bus.

The NDICE components located in the CCM interface with the interface wiring routed to the CCM/propellant module interface and via the data bus to the data management system. The use of permanent or connectorless terminations is recommended in this location also to enhance reliability.

9.4 INTERFACE RECOMMENDATIONS SUMMARY

The preceding sections have contained an extensive discussion of the functional and physical interfaces between the stage and NERVA, including specific changes which are recommended. Also, the RNS design analyses and descriptions contain implicit NERVA interface considerations. These have been collected into Table 9.4-1, which provides a summary of recommended changes to the NERVA interface and identifies aspects of the interface which require future work.

Table 9.4-1
NERVA INTERFACE RECOMMENDATIONS SUMMARY

Requirements	Recommended Interface
1. Mission Operations	
1.1 Thrust Mode	
Translunar injection	Full thrust
Lunar orbit injection	Full thrust
Transearth injection	Full thrust
Earth orbit injection	Full thrust
Lunar orbit plane changes	Throttle (45,000 lb)
Midcourse correction	Idle (~1,000 lb)
Separation maneuver	Idle (~1,000 lb)
Rendezvous maneuver	Idle (~1,000 lb)
	Establish minimum impulse tolerances and cooldown impact for idle mode.
1.2 Aftercooling	
Maximum performance	1. Total utilization of aftercooling impulse—no thrust nulling 2. Increase radiated power level for passive cooling (>100 kw)—potential 24,000 lb or 22% increase of lunar orbit payload High-temperature passive heat rejection from NERVA: at least 1200° to 1500°R.
Impulse tolerance and predictability	Relax ±20,000 lb-sec tolerance—corresponds to 0.6% of TLI impulse or < 12 nmi lunar miss distance Future Work: 1. Relate tolerance to operating time or total impulse 2. Develop method for predicting error early in cooldown 3. Correlate performance to impulse tolerance

Table 9.4-1
NERVA INTERFACE RECOMMENDATIONS SUMMARY
(Continued)

Requirements	Recommended Interface
Trajectory Correction	Regulate impulse for error correction
1.3 Abort	
Inject into safe orbit or trajectory	1. Multiple start capability: single emergency mode operation followed by cooldown and one or two idle mode operations 2. Remove constraint of 5-hour maximum cooldown 3. Determine impact of multiple emergency mode operations and increased Isp on external rescue requirements
2. Structures	
2.1 Engine Attachment	
Transmit all engine, gimbal, and actuator loads to thrust structure	1. Current closing ring in ICD acceptable Provide stage contractor with loads envelope for interface plane: shear, moment, and axial loads for all design conditions. Define bolt pattern tolerances 2. Distribute actuator loads uniformly to stage thrust structure Provide stage contractor with load envelope resulting from actuator operation
2.2 Engine Deflection	
5.7 degrees maximum deflection: ± 3 degrees for TVC (square pattern) and ± 1.5 degrees misalignment	Decrease maximum deflection to reduce loads in intermodule structures Evaluate round pattern Evaluate misalignment requirements

Table 9.4-1

NERVA INTERFACE RECOMMENDATIONS SUMMARY
(Continued)

Requirements	Recommended Interface
2.3 Thrust Structure Configuration Locate struts to provide clearance for PSOV	Define angulation capability of feed duct for installation
2.4 Engine Alignment Lateral motions at interface plane to align engine and tank centerlines	Adjustable gimbal lateral alignment
2.5 Acceptance Test	Install GSE for PSOV and cooldown module to isolate tank and simulate operations Evaluate installation of flight assemblies for some tests
2.6 Customer Connect Panel Location	External to stage thrust structure Provide stage contractor with loads envelope for all design conditions
2.7 Aftercooling Bypass Line Support	Support from thrust structure closing ring Provide stage contractor with loads envelope for all design conditions
3. Structural Dynamics Propulsion module launch to orbit by space shuttle Prevent excessive dynamic loading to NERVA—particularly on nuclear subsystem and gimbal actuators Prevent excessive dynamic loading on stage	1. Stage provides lateral restraint and energy dissipation 2. Tentative ANSC attach points at nozzle throat and NERVA upper thrust structure 3. Design gimbal actuators for flight and accommodate launch by restraint system

Table 9.4-1
NERVA INTERFACE RECOMMENDATIONS SUMMARY
(Continued)

Requirements	Recommended Interface
	Future Work: Establish dynamic environment for: a. Space shuttle cargo bay b. Phase IV selected alternate launch mode Define support, restraint, and possible energy dissipation systems for the above launch modes Clarify dynamic load implications on nuclear subsystem
4. Thrust Vector Control	
4.1 Engine Gimbal Capability	
Deflection: ± 3 deg Rate: 0.25 deg/sec Acceleration: 0.5 deg/sec²	Review periodically as the RNS configuration and mission requirements evolve
4.2 Thrust Vector Alignment	Pretrim prior to restart—reduces attitude transient (essential for short burns). Define tolerance.
4.3 Attitude Control During Aftercooling	
Minimize attitude error impact on APS	Active trimming during aftercooling. Define tolerance.
4.4 Gimbal Actuator Dynamics	
Actuator transfer function	To be determined by stage contractor

Table 9.4-1
NERVA INTERFACE RECOMMENDATIONS SUMMARY
(Continued)

Requirements	Recommended Interface
5. Propellant Management	
5.1 Propellant Conditions	
1. Startup and steady state: total pressure vs flow rate specified by curve in ANSC letter 7410:1075 July, 1970 (includes 26 psia, 0 NPSP for steady state)	1. Satisfactory—permits autogenous startup Reduce steady state requirement to 22 psia, 0 NPSP: stage weight savings of 2,400 lb
2. Malfunction Mode: requires 2 psia increase of total pressure	2. MDAC design based on no increase in total pressure—avoids 1,100 lb penalty Revise malfunction mode requirement to no increase in total pressure
3. Aftercooling: not specified, but originally was identical to steady state requirement	3. Saturated liquid—avoids a pressurization system and >1,000 lb penalty Permit mixed phase or vapor—would permit reduction of gaseous residuals (>2,800 lb)
5.2 Pressurant Demand	
Steady State	0.58 lb/sec
Peak: during propellant tank bootstrap pre-pressurization	1.16 lb/sec Review peak demand as operations evolve
5.3 Thrust Ramp	
Thrust hold at throttle point	1. Integrate propellant settling with NERVA startup ramp 2. Stage commands to hold thrust at throttle and resume thrust buildup

Table 9.4-1
NERVA INTERFACE RECOMMENDATIONS SUMMARY
(Continued)

Requirements	Recommended Interface
5.4 Feed Ducts	Future Work: Orbital experiments on propellant settling
Spacing	Acceptable—a tank sump is not required, and duct spacing does not affect LH₂ residual Future Work: 1. Optimize pump spacing for radiation shielding 2. Review type of flexible element—stage contractor considers untied bellows unreliable
Coupling to Stage	Ground assembly only
Seal	Dual seal flange (metallic seal) with leak detection port—common throughout stage Flange location below PSOV or welded connection would reduce leakage into HPI
Thermal Isolation of Tank	1. Stage HPI extend > 2 ft below PSOV, and possibly to turbopump HPI layup on flexible ducting is not state-of-the-art 2. Install duct HPI integral with tank blanket Evaluate alternate locations of PSOV and flange to accommodate HPI installation
5.5 Other Ducts	
Coupling, seal, and thermal isolation	Analogous to feed duct

Table 9.4-1
NERVA INTERFACE RECOMMENDATIONS SUMMARY
(Continued)

Requirements	Recommended Interface
5.6 Customer Connect Panel Stage supplied ducts from tank to panel; aftercooling via ANSC cooldown module	Engine ducting shall absorb deflections below panel
5.7 Propellant Cleanliness Limit erosion, contamination, and damage: ANSC used MIL-STD1246A, Level 1500; in addition, ANSC limits particulate matter accumulation to 220 gm	Stage will filter particles exceeding 25 microns Review need for stringent ANSC cleanliness requirement
6. Feed System Conditioning Provide saturated liquid in active portion of feed system prior to run tank refill and NERVA startup	Integrated stage/NERVA chilldown system as per MDAC concept: stage ducting to PSOV and PDKV for closed loop Future Work: 1. Review system requirements 2. Orbital experiments on zero-g boiling
7. External Disk Shield 7.1 Baseline Criteria 10 REM to payload Payload attenuation = 3 4.5 deg gimbal deflection	No disk shield is required

Table 9.4-1

NERVA INTERFACE RECOMMENDATIONS SUMMARY
(Continued)

Requirements	Recommended Interface
7.2 Alternate Criteria: Same as above but with no payload attenuation factor	1,700 lb, 2 zone
8. Astrionics and NDICE Interfaces	
8.1 NERVA Power Level and Conditioning Full thrust: 2.3 kw nom, 3.5 kw peak Aftercooling: 0.2 kw nominal (CCM), 1.0 kw peak	- Supplied by stage Refine NERVA power requirements 28 ± 4 vdc and inverters provided by stage - Voltage reference by each contractor.
8.2 Power Source Stage + NERVA: 317 kwh/round trip 1.2 kw nominal	Supplied by stage. Baseline system: fuel cells and secondary batteries, 785 lb total
8.3 Data Management NERVA instrumentation monitored by NDICE	- Stage supplied serial data bus terminals dedicated to NDICE located at CCM and forward of run tank Establish NDICE traffic rates (0.5×10^5 bits/sec for stage) - NDICE digitize to 10 bits - Hardline backup for EDS

Table 9.4-1
NERVA INTERFACE RECOMMENDATIONS SUMMARY
(Continued)

Requirements	Recommended Interface
Autonomous NDICE processor	Communicate with RNS processor via data bus
	Establish NDICE processor requirements
	Evaluate processor integration (2.5×10^5 adds/sec for stage)
Transmission to ground	Stage compression and formatting of all data
8.4 Control	
NERVA control by NDICE	1. Gimbal actuator control from stage N&G 2. Stage commands to NERVA include start, shutdown, hold thrust at throttle point, resume thrust buildup, etc. Establish command repertoire and format Evaluate feasibility of Isp trim signal 3. NDICE provide stage with continuous prediction of aftercooling impulse to permit use of heuristic algorithm by stage N&G Evaluate control of aftercooling impulse Evaluate performance sensitivity to impulse tolerance
Commands	1. Stage supplied serial data bus terminals dedicated to NDICE located at CCM and forward of run tank

Table 9.4-1
 NERVA INTERFACE RECOMMENDATIONS SUMMARY
 (Continued)

Requirements	Recommended Interface
8.5 Cable and Connections 3,000 lines	2. NDICE supply control logic encode and decode 3. Hardline backup for EDS 1. Flat conductor and ribbon cable 2. Polyimide insulation 3. Connectorless terminations