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SPACE SHUTTLE

AUXILIARY PROPULSION SYSTEM

DESIGN STUDY

PROGRAM PLAN

Submitted under Contract NAS9-12013

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY - EAST

MCDONNELL DOUGLAS CORPORATION

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SPACE SHUTTLE AUXILIARY PROPULSION SYSTEM DESIGN STUDY

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PROGRAM PLAN

Prepared by: P.J. Kelly, Program Manager

Submitted under Contract NAS9-12013

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PREFACE

This document presents the plan for implementing the Space Shuttle Auxiliary Propulsion System Design Study, covered by National Aeronautics and Space Administration (NASA) Contract NAS9-12013. All effort described herein is in accordance with the McDonnell Douglas Proposal MDC E0374 (Reference a), submitted to the NASA Manned Spacecraft Center 21 May 1971.

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1. STUDY OBJECTIVES

The objectives of this study effort are, first, to develop design and programatic data, for competitive, Space Shuttle reaction control systems (RCS) and integrated RCS/orbit maneuvering systems (OMS), in sufficient detail that a selection can be made between the various concepts and, second, for the selected concept, to define system and component performance over the full range of operation.

To attain these objectives, a five phase program, conducted in three distinct steps, has been outlined. The first step, Phase A, is the definition of RCS/OMS requirements. Results from this phase will define the number, location, and thrust level of the RCS thrusters and orbit maneuver engines, based on vehicle acceleration requirements, failure criteria, and abort requirements. APS total impulse requirements, thrust vector control requirements, and component environment will also have been determined from mission time lines and vehicle configurations.

The next step is to define fully the competing auxiliary propulsion system (APS) concepts (RCS and OMS). Phase B will examine each of the three candidate RCS concepts delineated in Reference (b), a system optimization will be conducted to establish preliminary RCS operating points, and RCS sensitivity to design requirements and component performance, for both Orbiters and Boosters. Once this preliminary operating point is established the many possible RCS control concepts will be reduced to a few high value approaches. The approach to be taken for this is to consider first the control of individual parameters independently, evaluating control merit on the basis of accuracy, technology, and complexity. Using the previously determined RCS design and operating sensitivities, the order of preference for methods of controlling conditioner pressure, temperature, and flow rate will be determined. These methods will then be used to evaluate control of conditioner parameters, singly and in combinations, with and without mass flow controllers, comparing control benefits, in terms of system weight, versus increased control complexity and cost. It is anticipated that for each candidate RCS, these results will identify two or three high value control concepts for more detailed study. System design, transient, and operating analyses will be conducted for each selected RCS/control concept. These data will define component requirements for formulation of component designs, component development plans, and development costs. Based on transient, operational, and component data, the system design will be finalized and a system development plan will be constructed and used as the basis for estimating system development cost. Phase B will provide the data required to compare performance factors, operational factors, development risk, and cost, for the three candidate systems with their selected control options.

Phase C considers only the Shuttle Orbiter. RCS/OMS integration options, ranging from a fully integrated system to a system in which only propellant storage is integrated, will be evaluated to determine the proper compromise between performance and operating requirements, and between system/vehicle development risk and cost. Preparatory to evaluating integration options, OMS engine physical and performance characteristics will be established, methods of pump and line chilldown selected, and the preliminary system design point and control options defined. Using the same general approach as in Phase B, control and design options for the RCS/OMS will be evaluated at different levels of integration and the most promising concept for each level selected on the basis of performance advantages versus complexity and development risk. Detailed transient and operating performance analyses will be conducted for each of the RCS/OMS integration options. Component design requirements will be defined, preliminary design of components established, component development plans created and cost determined. Based on transient analyses, operational analyses, and component design, the system design point will be reevaluated and finalized. System development programs will be established, and system development costs estimated.

In Phase D, the two special system approaches, which eliminate requirements for turbopumps and/or heat exchangers, will be evaluated, making maximum use of the analytical techniques developed under NAS 8-26248. Pressurization, storage, acquisition, and distribution features which are critical to the feasibility of the systems will be evaluated. Existing component models will be modified as required and, where needed, models of components unique to these systems will be provided. Preliminary transient analyses will be conducted to establish system operation. Using these data, optimum design points will be determined and system sensitivities developed. The results of this phase will constitute an evaluation of the overall viability of the systems, as determined by a comparison with the systems of Phase B.

Phases B and C will provide the data required for comparison of separate and integrated RCS/OMS options on the basis of weight, performance, technology, reliability, flexibility, maintainability, development risk, cost, and other factors pertinent to selection of the preferred approach.

The final step of the design study (Phase E) is to evaluate further the system selected from Phases B, C, or D by conducting a detailed dynamic performance analysis. It is anticipated that the vehicle configuration will be updated at this point in the study to reflect the most current Space Shuttle configuration. Consequently, the requirements of Phase A and the design point of the selected system will be updated. The transient analysis computer model will be updated to reflect the final APS design and will be modified to incorporate any refinements or additional sophistication that is indicated to be desirable by experience gained in the study. The controls required, together with their sensors and sensor locations, will be reassessed, and control loop, logic and gains will be tailored to best satisfy all system criteria. Operation of the system over a complete range of nominal and off-nominal conditions will be evaluated, including simulation of individual and combined malfunctions. Based on these data, the system design point, and the system schematic and its performance will be thoroughly assessed for adequacy or recommended design alterations.

2. SCHEDULE AND MILESTONES

Five major milestones plus deliverables are identified for the study. These milestones, in the form of program reviews, are scheduled at significant decision points in the progress of the program and give NASA the opportunity to review, approve, and ammend the program. The purpose and significance of each milestone is discussed below. Schedules are shown on the program master schedule of Figure 1.

2.1 Requirements Definition Review - This informal review is scheduled at the conclusion of Phase A. Its purpose is to provide, for NASA review and approval, the vehicle data and RCS/OMS requirements to be used in subsequent study phases. As a minimum, the following data (together with the rationale for their recommendation) will be provided: number of RCS and OMS engines; engine thrust levels and locations; maximum sustained and peak RCS thrust levels; RCS and OMS total impulse and impulse histories; penalties for booster-orbiter hardware commonality; gimbal and RCS control requirements during OMS firing; and definition of the system thermal environment.

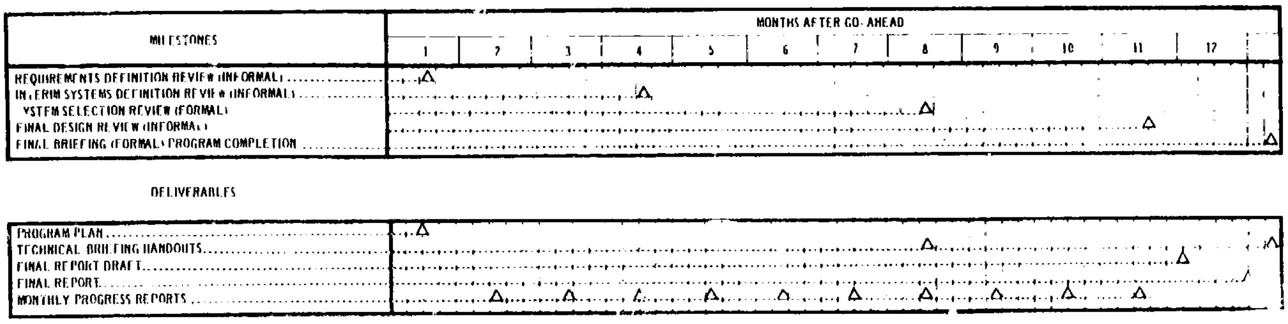
2.2 Interim Systems Definition Review - The schedule of this informal review corresponds to a key decision point in the study, that being the selection of control concepts for detailed comparison. Design and control alternatives will have been developed and evaluated for each RCS and for each level of RCS/OMS integration. The design options or control concepts which provide the most favorable balance between performance and other pertinent selection criteria will have been established. Results of this effort, together with appropriate system recommendations, will be presented for NASA concurrence at this review. Out of this review will come a definition of systems for detailed comparison. Nominally, two control alternates for each of the candidate RCS concepts, and a single candidate for each RCS/OMS integration level will be defined for continued study. Also at this review, ground rules in the form of test criteria for subsequent development planning will be submitted for review and approval.

2.3 System Selection Review - This formal review is scheduled for the end of the study Phases B, C and D. Data relating the system concepts on the basis of component and system technology requirements; complexity; weight and volume; flexibility to mission changes; development program requirements and cost; system performance levels and variations; operational considerations; reliability, safety and maintainability; and sensitivity of results to ground rules will be presented. All study results will be correlated for comparison of alternate systems. NASA will select the system to be subjected to final analyses. In addition, a matrix of nominal, off-nominal and malfunction conditions to be analyzed in the final system analysis phase will be provided for NASA review and approval.

2.4 Final Design Review - This informal review is scheduled at the end of Phase E. The purpose of the review is to present to NASA the results of final, detailed system design and dynamic analyses. The data provided at this review will describe the system design as modified to satisfy updated VDRD requirements, together with results of detailed control, sensor, and reliability/malfunction studies. Included will be data defining system performance over the complete matrix of conditions approved at the System Selection Review.

2.5 Final Briefing - This formal review is scheduled after completion of study documentation, as prescribed in the RFP. At this review a complete summary of the study will be provided, covering data and rationale leading to definition of the RCS and RCS/OMS and their control options, data and rationale used to compare the candidate systems, and final system analyses results. This last element will be emphasized, since these data will have the greatest bearing on subsequent vehicle and component design effort.

Master Schedule



Task Schedule

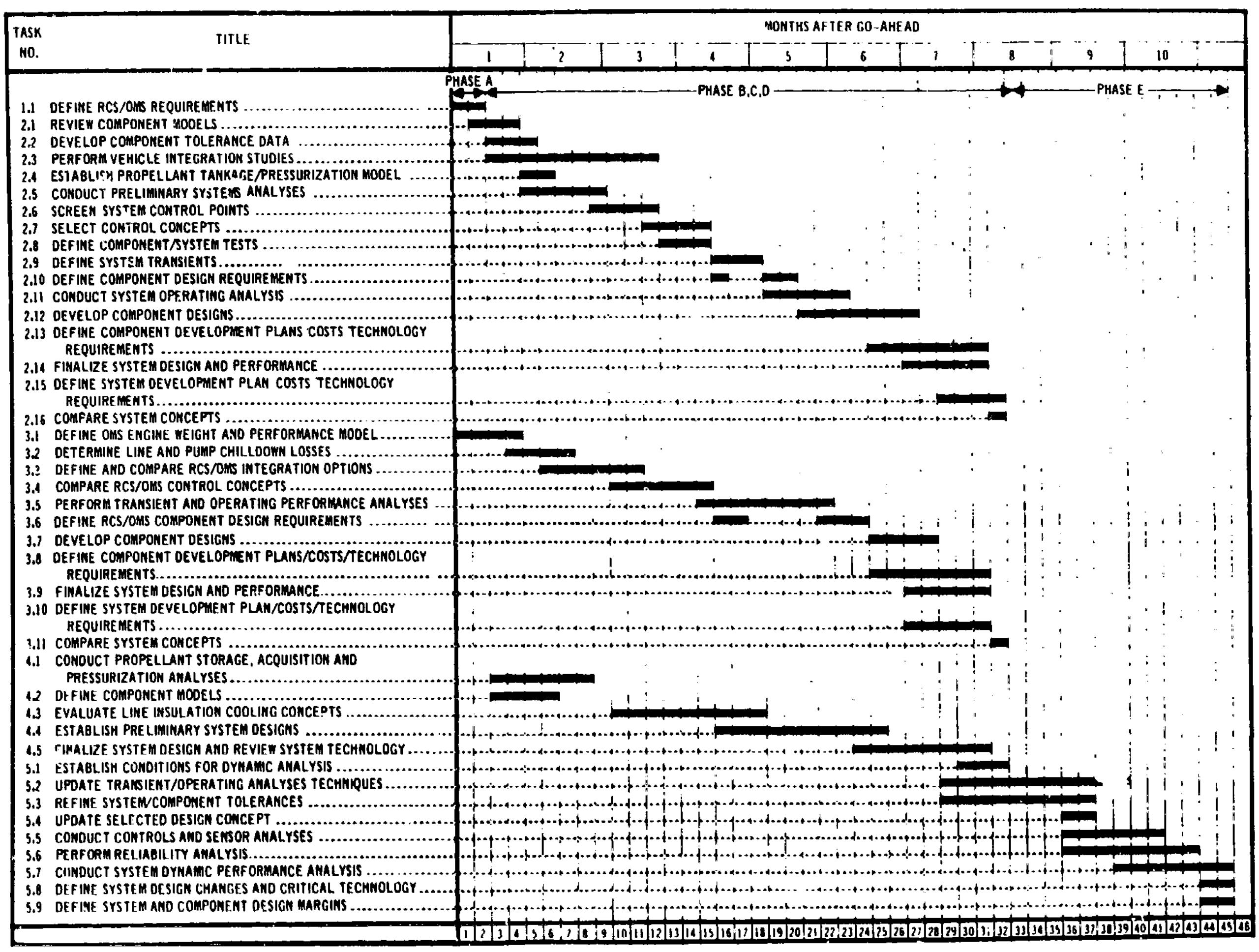


FIGURE 1 PROGRAM SCHEDULE

3. PROGRAM TASKS

To select between RCS and RCS/OMS concepts of near parity, the program tasks defined in this paragraph emphasize evaluation of detail system characteristics, such as system controls and transients. The tasks are organized to address, individually, each of the study phases outlined in paragraph 1. Flow charts identifying relationships between tasks are presented in Figure 2. Phase A, Requirements Definition, serves to develop and compile orbiter and booster characteristics for definition of RCS and OMS requirements for use in Phases B, C and D which are concurrent efforts. Phases B and C are organized along similar lines, and are scheduled so that common tasks will be of maximum utility for each phase. The general approach is to develop design points for each RCS and RCS/OMS being considered. In both phases, possible methods of control are screened to define systems worthy of more concentrated effort at the earliest possible time. The true significance of increased system complexity/technology is assessed in terms of increased development scope and cost, to provide the most realistic possible basis for concept selection. Study Phase D does not include the detail of the other phases. The goal of this phase is to evaluate the principal design features of the special systems and to develop for these systems sufficient data to assess their merit and competitiveness with the other concepts prior to making a judgement regarding continued effort. The final program phase (Phase E) is organized to establish in detail the performance of the selected concept under nominal, off-nominal and malfunction conditions, over its complete operating spectrum (including steady-state and transient conditions).

The five program phases defined in Paragraph 1 are addressed sequentially in Paragraphs 3.1 through 3.5 below. All task references noted in the following paragraphs refer to tasks defined in this program plan. Figure 3 provides the estimated expenditure history of program manhours corresponding to the task descriptions and schedule of Figure 1.

3.1 Task 1 - Phase A: Requirements Definition

Task 1.1 - Define RCS/OMS Requirements

Objective - To define orbiter RCS/OMS and booster RCS vehicle/mission requirements and component packaging constraints upon which system concept evaluation and detailed design studies will be based.

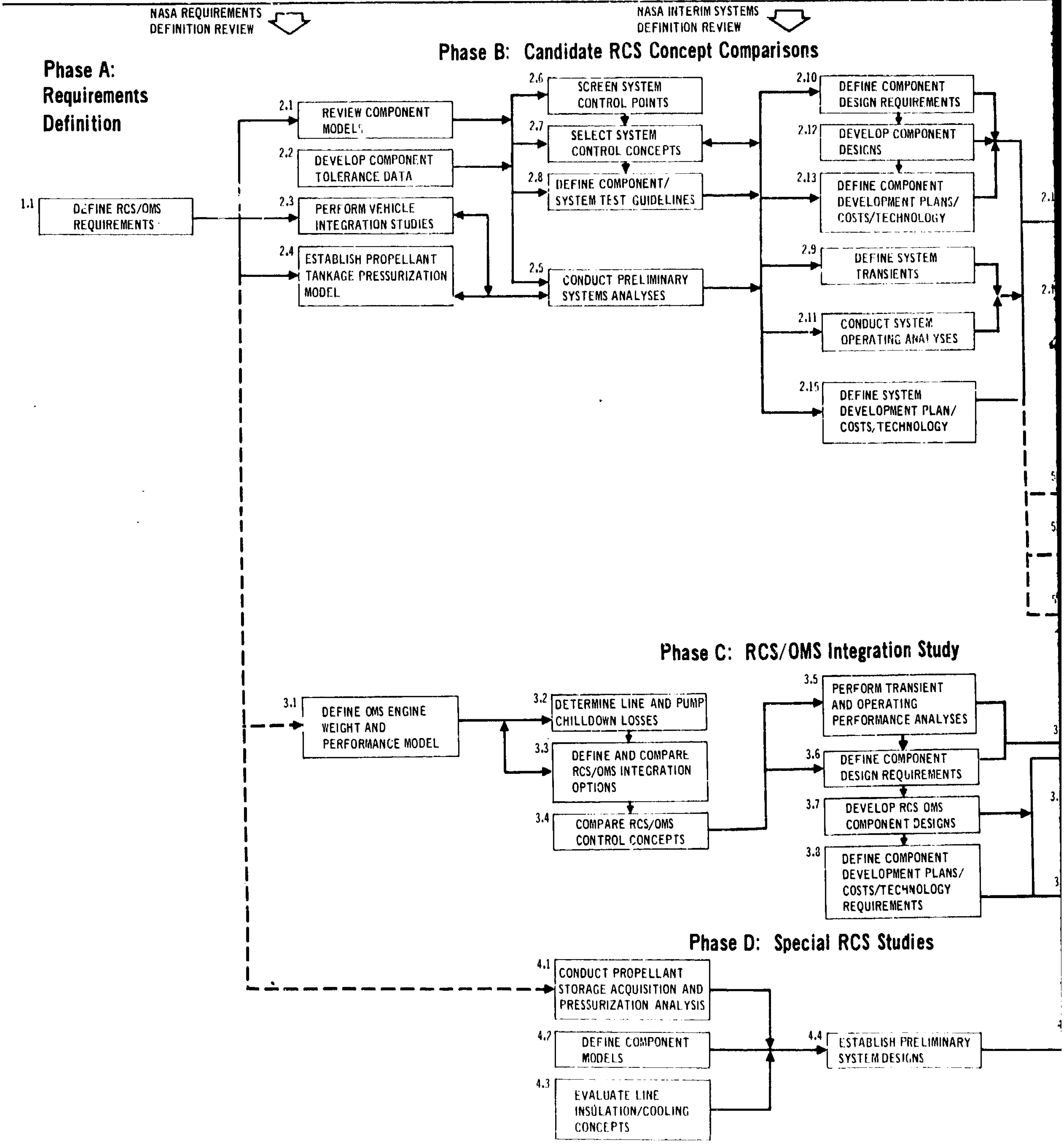
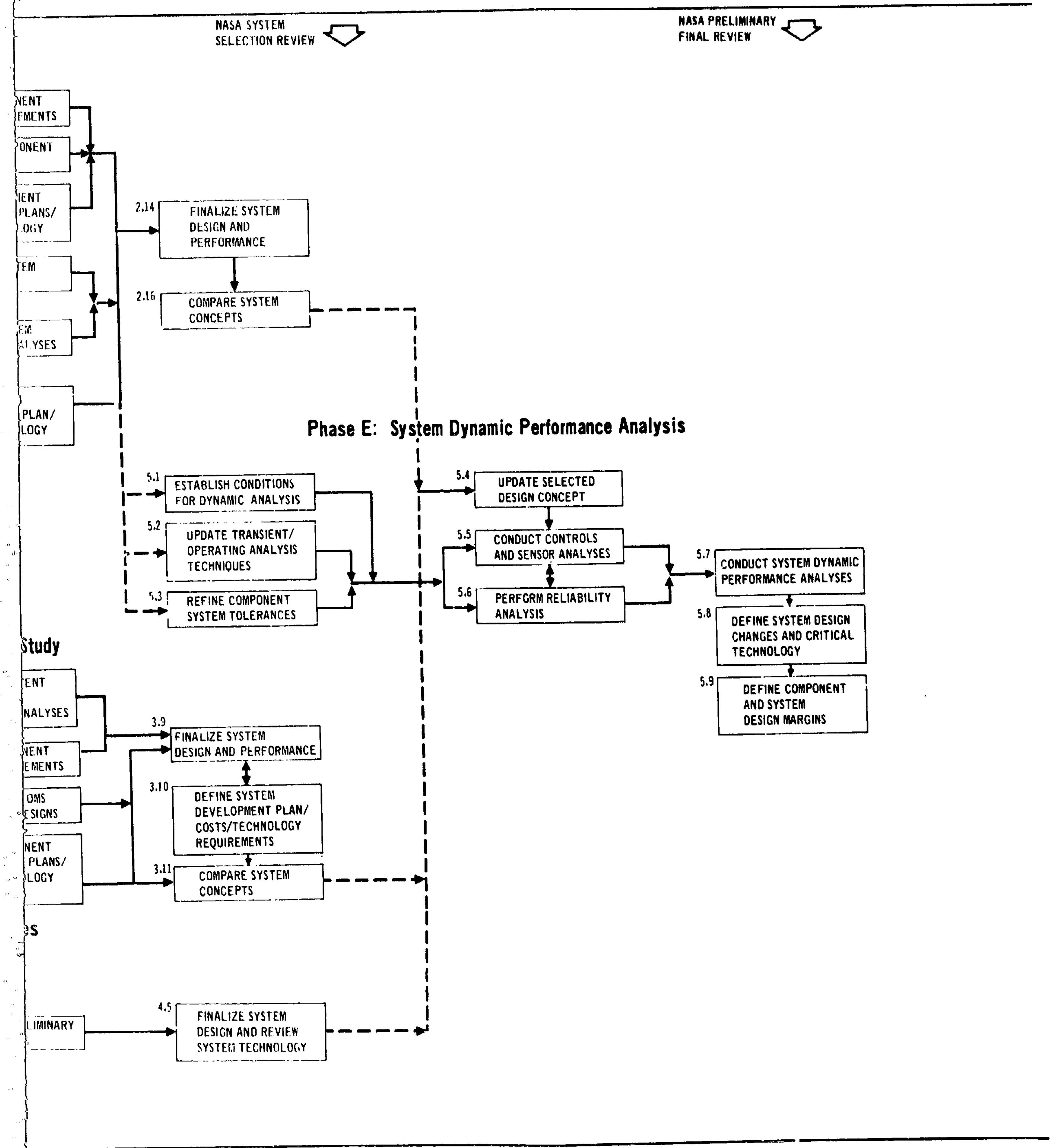


FIGURE 2 TASK DESCRIPTION FLOW CHART

FOLDOUT FRAME 2



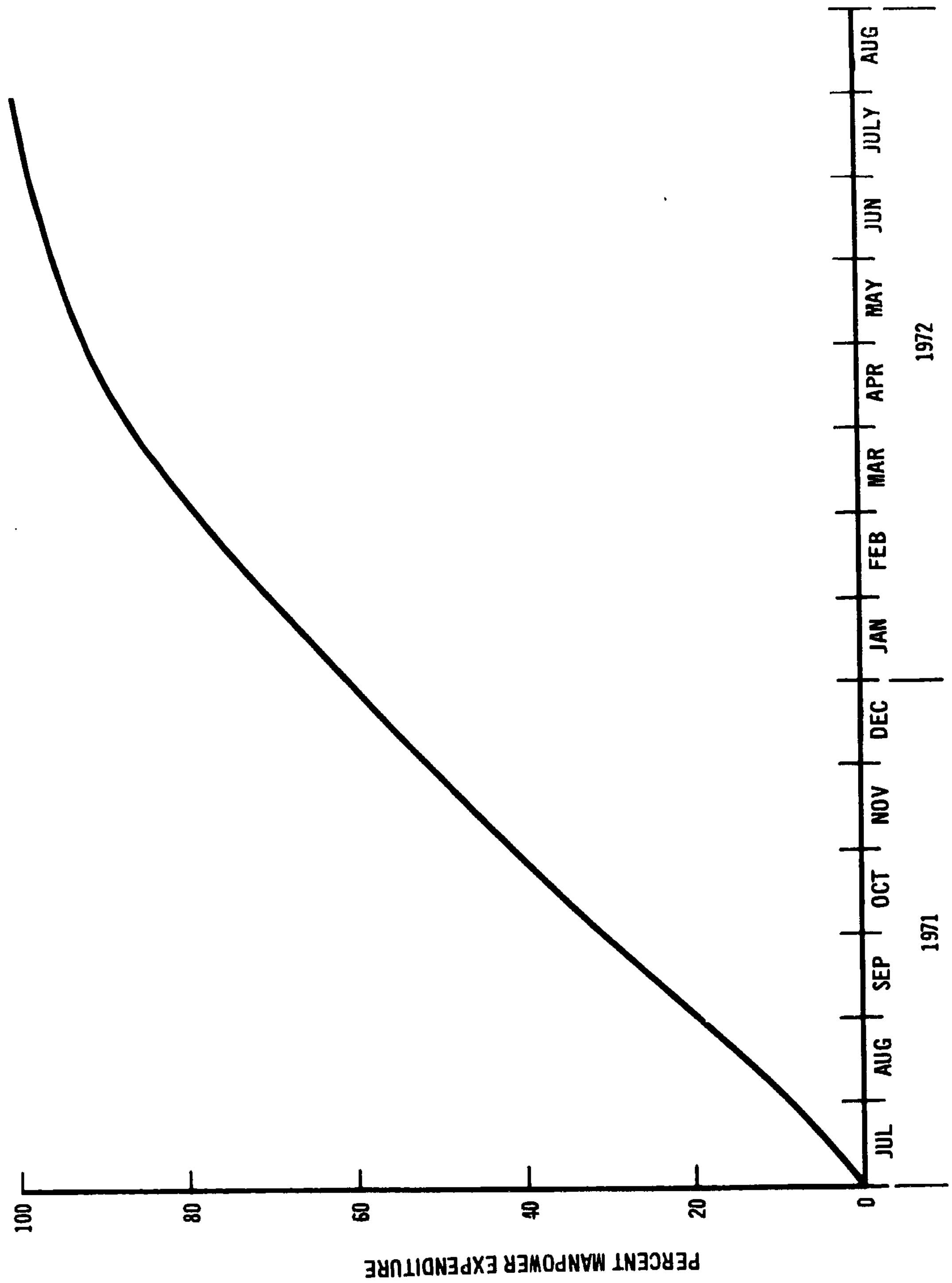


FIGURE 3 PROJECTED MANPOWER EXPENDITURE
CONTRACT NAS9-12013

Approach - Applying vehicle mass properties (cg, mass, and inertia), control acceleration requirements, geometry, and general equipment arrangements specified in the VDRD, engine thrust levels, locations, and number of engines at each location will be defined for the orbiter and booster RCS. This definition will be based on thruster and conditioner component commonality between the orbiter and booster. Associated penalties to both orbiter and booster RCS will be specified. RCS thruster minimum impulse-bit will be determined and used in conjunction with deadband requirements to establish limit cycle total impulse. Combined with maneuver requirements, these will establish impulse histories and total impulse required for the study missions. The maximum number of thrusters firing, and thus maximum conditioner propellant flow rates, will be defined for system sizing (Tasks 2.5, 3.3 and 4.4).

Engine dynamic envelope constraints, failure criteria, abort requirements, and total impulse sensitivity to OMS thrust-to-weight ratio will be considered in establishing required thrust and number of OMS engines. Vehicle cg histories, and thrust vector alignment uncertainties, will be applied to determine OMS gimbal and control impulse requirements. The effect of varying impulse allocations between the OMS and RCS will be determined.

Finally, vehicle internal thermal environments will be defined to permit calculation of RCS/OMS heat leaks. A summary of resultant RCS/OMS requirements will be prepared for NASA scrutiny at the Requirements Definition Review.

3.2 Task 2 - Phase B: Candidate RCS Concept Comparisons

Task 2.1 - Review Component Models

Objective - To update system component models, describing weight, size, and performance over a range of conditions applicable to both separate RCS and integrated RCS/OMS.

Approach - Analytical models developed in the previous APS Definition Study (NAS8-26248) and used for computing weight, size, and performance of gas generators, turbopump assemblies, tube-and-shell heat exchangers, film cooled engine assemblies, and associated controls will be reviewed and changed as needed to reflect design refinements and corrections indicated by technology developments occurring after their original formulation. In addition to weight and performance, pertinent component design characteristics such as cycle life constraints, required NPSP, propellant conditioning temperature constraints, pump and turbine efficiencies, and engine flim cooling requirements, etc., will be reevaluated to ensure valid control concept comparisons (Tasks 2.6 and 2.7). The results of this effort will be submitted informally for NASA review prior to the Interim System Definition Review. These results will clearly delineate any significant changes that were made and will be modified subsequently to incorporate NASA recommendations regarding the component models.

Task 2.2 - Develop Component Tolerance Data

Objective - To generate operating component performance tolerances and sensor accuracies based either on run-to-run variations or, for those component variances which cannot be trimmed, unit-to-unit variations.

Approach - Historical data for component performance tolerances and sensor accuracies will be reviewed and summarized. Component performance and response tolerances affecting flow rates, combustion temperatures, and turbopump efficiencies and sensor accuracies for measurement of temperatures, pressures, flow rates, positions, etc., will be established through literature surveys and inputs from component manufacturers. Tolerances which cannot be thus defined will be estimated based on tolerances of representative components and then related to performance parameters. Tolerances and accuracies will be expressed in terms of maximum and standard deviations about the nominal design points, and will be applied to overall steady-state and transient performance to define variations for each system concept (Tasks 2.5, 2.9, and 3.5). The initial assessment of tolerances and accuracies will be refined and extended in Task 5.3, prior to final dynamic performance analyses of the selected system.

Task 2.3 - Perform Vehicle Integration Studies

Objective - To develop configuration and installation data required for design of RCS and RCS/OMS candidates to be considered in Tasks 2 through 4.

Approach - System installation drawings showing component locations and line routings will be prepared for each RCS and RCS/OMS candidate of Tasks 2 through 4. Recommended installations will be based upon system maintainability considerations, vehicle moldlines, and general equipment locations specified in the VDRD. Also considered will be such design factors as OMS line and turbopump chilldown requirements (Task 3.2), and vehicle thermal environments defined in Task 1.1. These installation details will provide feedline lengths required for the system operating and transient analyses (Tasks 2-9, 2-11 and 3.5) and envelope constraints for primary components (Tasks 2.10 and 3.6). Design criteria for assessment of features, such as the effect of additional OMS engines, the effect of component relocation in partially integrated RCS/OMS will be determined from the layouts.

Task 2.4 - Establish Propellant Tankage and Pressurization Models

Objective - To determine weight sensitivities of propellant storage, acquisition, and pressurization assemblies.

Approach - Separate and integrated RCS/OMS propellant storage, acquisition, and pressurization assembly designs were investigated in depth during the previous APS definition studies. Models of these designs will be refined as required and used to describe sensitivities of assembly weight, volume, expulsion efficiency, and cooling requirements, to variables such as usable propellant weight, mixture ratio, pump NPSP, and environment heating rate. Consistent with the RFP, common pressurization approaches will be used for concept comparisons. It is recommended that cold helium pressurization be assumed for study Tasks 2 and 3, to minimize the effect of pressurization on concept performance evaluations. Separate RCS propellant storage tanks will be baselined for the Task 2 study, and fully integrated storage tanks will be baselined for Task 3. These assumptions will be reassessed during Tasks 2.16 and 3.11 by comparing separate, refillable, and fully integrated tankage, and by evaluating autogenous pressurization.

Task 2.5 - Conduct Preliminary System Analyses

Objective - To establish RCS schematics, preliminary operating conditions, flow balances, and weight sensitivities to design and mission requirements.

Approach - Detailed system schematics will be prepared for each of the three candidate RCS concepts defined in the RFP. These schematics will include the component redundancy required to satisfy Space Shuttle reliability criteria. Preliminary conditioner transients will be determined using the Conditioner Assembly Transient Program; the System Design and Sizing Program will be utilized to develop RCS weight sensitivities to system design variables (i.e., mixture ratio, expansion ratio, chamber pressure, accumulator pressure ratios, accumulator cycles, propellant conditioning temperatures, conditioner response time pump NPSP, head rise, gas generator combustion temperature, etc.) and to mission requirements (total impulse, thrust, maximum number of engines firing, etc.). Preliminary system design points will be selected based on the best compromise between system weight and technology requirements. Component requirements and system pressures, temperatures, and flow rates will then be defined at the selected system design points.

These analyses will be performed for both orbiter and booster RCS. The selected system design and operating points will consider thruster and conditioner component commonality between the orbiter and booster. Weight and complexity penalties attributed to commonality will be identified. The system Operating Performance Program will be used to establish propellant weight sensitivity to conditioner performance variations.

System design and operational data developed in this task will form the basis for subsequent control point screening and control concept comparisons in Tasks 2.6 and 2.7, and will define tankage and component sizing data for Tasks 2.3 and 2.4.

Task 2.6 - Screen System Control Points

Objective - To define the best means of controlling individual conditioner interface parameters (i.e., conditioner pressure, temperature, and flow rate).

Approach - Numerous control point options exist for controlling each of the conditioner interface parameters. These options will be evaluated and compared, for the RCS designs established in Task 2.5, to identify an order of preference for control of each conditioner interface parameter (pressure, temperature, flow rate). The relative merit of each option will be assessed in terms of control complexity and accuracy. To accomplish this, a matrix of possible control points will be established for each RCS concept. System analyses will be performed to define the interdependence and interactions between the interface parameters for each RCS. Reference open-loop accuracy will be established using the tolerance data of Task 2.2. Then, for each parameter the accuracy achievable at each control point and the resultant change in the accuracy of the other interface parameters will be assessed. All control points will be evaluated for each interface parameter and their order of preference established comparing the benefits derived from control with complexity and technology requirements. Favored control points will be selected for controlling conditioner interface pressures, temperatures, and flow rates. Control of multiple interface parameters will be assessed in Task 2.7.

Task 2.7 - Select Control Concepts

Objective - To select preferred methods of conditioner control for each candidate RCS concept.

Approach - Prerequisite to this effort, preliminary analyses (including system transient and operating performance analyses) will be conducted, as required to establish all necessary controls for system operation, malfunction and/or safety (such as gas generator mixture ratio controls). These will establish the reference system controls and, if suitable, they will also be considered for operational control. Using both design and operational RCS sensitivities developed in Task 2.5, comparison of the benefits accruing from, and the complexity associated with, alternate control concepts will be evaluated. The order of control point preference established in Task 2.6 will then be used to evaluate single and multiple interface parameter control combinations. Open loop system operation will serve as a reference for this evaluation. Transient analysis will be conducted as required. Typically, progressive controls build-up (from open loop) will begin with only one parameter, e.g., mass flow control; define the benefits; compound this parameter with another; e.g., temperature control; define the benefit; etc. The effort will conclude with a comparison of control benefits versus complexity and technology, allowing selection of the preferred control concepts for each RCS. Selection and rationale will be presented to NASA at the Interim Systems Definition Review for concurrence. The most suitable control approaches for each candidate RCS concept will be defined for subsequent, more detailed, comparisons.

Task 2.8 - Define Component/System Tests

Objective - To establish guidelines to be followed in the formulation to RCS and RCS/OMS development plans for use in Tasks 2.13, 2.15, 3.8 and 3.10.

Approach - A definitive matrix of development test criteria and objectives, number and types of tests to be performed, and schedules consistent with overall Space Shuttle goals, will be prepared and submitted for NASA evaluation and approval at the Interim Systems Definition Review. Specifically, the test guidelines will include a description and recommended number of component and system life tests, off-nominal (limits) tests, environmental simulations, and vehicle integration tests to be used for development planning and cost estimating.

Task 2.9 - Define System Transients

Objective - To evaluate nominal and off-nominal conditioner assembly transient characteristics for each candidate RCS concept.

Approach - Applying the nominal design points established in Task 2.5, conditioner assembly transient performance analyses will be conducted using the Conditioner Assembly Transient Program. Preliminary conditioner start-up response determined in Task 2.5 will be refined to reflect control differences and off-nominal effects. Conditioner shutdown lags will be determined, and component transient flow rate, pressure, and temperature characteristics developed. In addition, control tailoring such as pump bleed-in, ramped turbine power profiles, and recharge control options, will be evaluated to tailor the operation of each RCS/control option. These analyses will start with the component descriptions of Task 2.5 and will conclude with descriptions of components that reflect design changes induced by these analyses and parallel component preliminary design effort (Task 2.12). Based on the results from this evaluation, component design points established in Task 2.5 will be modified to reflect margins required for conditions encountered during transients. For off-nominal conditioner transient analyses, the component and sensor tolerance data established in Task 2.2 will be statistically (RSS) applied. At the conclusion of this task, data which allow comparison of the different RCS/control concepts on the basis of their performance and on the basis of differences in component requirements during transient operation, will have been developed. These will be compiled for use in concept comparison.

<u>Task 2.10 - Define Component Design Requirements</u>

<u>Objective</u> - To establish requirements for component preliminary designs.

Approach - Nominal component requirements and transient performance boundaries developed in Tasks 2.5 and 2.9 will be delineated for each component. These requirements will be used by ALRC to initiate preliminary component designs in Tasks 2.12. It is anticipated that iterations will occur between this task and Tasks 2.9 and 2.11.

<u>Task 2.11 - Conduct System Operating Analyses</u>

<u>Objective</u> - To evaluate overall system performance during simulated missions.

<u>Approach</u> - Using conditioner assembly characteristics as defined by the transient analyses conducted in Task 2.9, overall system performance during mission operation will be simulated using the system Operating Performance Program. As with the transient analyses of Task 2.9, both nominal and off-nominal conditioner component performance will be simulated. Program output will provide time histories of system flow rates, pressures, temperatures, and mixture ratios for each RCS concept. From these results, dispersions in system total impulse and mixture ratio will be established, defining required propellant margins, propellant utilization, conditioner operating cycles per mission and component life requirements. Based on the results of this task, design requirements of Task 2.10 will be modified.

Task 2.12 - Develop Component Designs

Objective - To prepare preliminary designs for thruster and conditioner components and associated controls.

Approach - Based on the detailed component requirements defined in Task 2.10, preliminary component designs will be developed including conceptual layout drawings, weights, operating and performance characteristics, maintainability, and replacement features. Thruster assembly components will include propellant valves, injector, igniter, thrust chamber, and nozzle. Control components will include pressure regulators or mass flow controllers, isolation valves, and instrumentation. Conditioner assembly components will include pumps, turbines, gas generators, and heat exchangers. Component designs will be developed in sufficient detail to permit definition of development plans, costs, and technology. Where possible these designs will reflect configuration, design, and performance details of concurrent component technology programs.

Task 2.13 - Define Component Development Plan/Costs/Technology Requirements

Objective - To formulate component development plans, development costs, and identify technology requirements.

Approach - For each component identified in Task 2.12, detailed development plans will be formulated consistent with the guidelines specified in Task 2.8. The development plans will form the basis for estimating development risk and cost differences between RCS/control concepts, and will include schedules (by task) for component design, tooling, fabrication, number and types of development and qualification tests, test setups, instrumentation requirements, data analyses, documentation, and component hardware deliveries. Historic data will be used to guide assessments of component costs. In addition, the technology extensions required and their associated impact on costs in terms of additional tests and schedule contingencies will be identified. It is planned that detailed development plans will be prepared for the components in the parallel-flow RCS concept. For the other concepts, this plan will simply be verniered to account for differences in requirements and design. The results of this task will provide a concrete assessment of development differences between the alternate concepts and clear definition of why such differences exist.

Task 2.14 - Finalize System Design and Performance

Objective - To update and summarize system designs, operation, and performance.

Approach - Based on the component designs developed in Task 2.12 system design, operation and performance will be updated and a complete system technical description summary will be prepared for each of the RCS concepts. This summary will include.

(1) final system schematics, installation and component layout drawings
(2) steady state system flow rates, temperatures, pressures, and mixture ratios, thruster and system specific impulse and thrust
(3) conditioner transient startup and shutdown performance profiles (flow rates, temperatures, pressures)
(4) system sensitivities to mission requirements (total impulse, total thrust) and design guidelines (booster-orbiter hardware commonality, separate propellant tanks, failure criteria)
(5) number and types of control, and control accuracies
(6) system operating sequence and chilldown procedures
(7) system safety and maintainability considerations

To complete this summary, a failure mode and effects analysis will be performed to define system reliability and component maintenance schedules for use as selection criteria in the final concept comparison.

Task 2.15 - Define System Development Plan/Costs/Technology Requirements

Objective - To formulate system development plans, define development costs, and identify technology requirements.

Approach - For each of the candidate RCS concepts, detailed development plans will be formulated consistent with the guidelines approved by NASA (Task 2.8). These development plans will form the basis for estimating development costs and will include specific schedules for system design, fabrication, system development and qualification tests, environmental simulation tests, data analysis and documentation, preinstallation acceptance tests, system verification tests, and system deliveries. As in the component effort in Task 2.13, the parallel flow system will be examined in detail and other concepts will be verniered about this reference. Again, as in 2.13, historic cost data will be used to guide assessment of overall system development costs. Technology requirements associated with each system concept will be identified and reflected in the development plans in terms of schedule and test contingencies. The results of this task will reflect differences in development scope associated with the three basic RCS and with differences in complexity (control concepts).

Task 2.16 - Compare System Concepts

Objective - To compare the candidate RCS/control concepts.

Approach - Applying the technical description summaries prepared in Task 2.14 and development plan/costs/technology requirements defined in Task 2.15, the candidate RCS concepts will be compared and rated. System ratings will be based on:

(1) system weight and volume
(2) system complexity (number, types and kinds of components and controls)
(3) flexibility to mission total impulse and number of starts
(4) system maintainability/maintenance requirements
(5) development program scope and cost
(6) safety and reliability
(7) component and system technology status

Confidence levels for each of these comparison criteria will be estimated and the result of the comparisons presented to the NASA at the Concept Selection Review.

3.3 Task 3 - Phase C: RCS/OMS Integration Study

Task 3.1 - Define OMS Engine Weight and Performance Model

Objective - To define parametrically the weight, size, and performance of an LH_2/LO_2 regeneratively fuel cooled engine assembly for variations in design thrust, expansion ratio, and chamber pressure.

Approach - OMS engine parametric weight and performance data will be defined in curve and equation form to allow inclusion into the system design and sizing model. The regenerative cooled engine model will largely be based on previous ALRC analyses of similar engines using accepted industry standards for performance calculations. Typical structure/component weight calculations will be used for weight estimates and incremental weights for gimbal mounts will be defined. Also, criteria for hydrogen and oxygen pressure balances, and the criteria for such limitations on propellant inlet conditions as changes in propellant quality, density, pressure, or temperature will be determined. The parametric weight and performance data will be defined over a thrust range sufficient to include the liquid RCS thrusters to be considered in Task 4. These data will be used to develop RCS/OMS design points and to establish system weight.

Task 3.2 - Determine Line and Pump Childown Losses

Objective - To determine the method of providing childown for pumps and propellant distribution lines, and to provide design criteria for the definition of component locations determined in Task 2.3.

Approach - To obtain an accurate evaluation of line losses for both the OMS and the liquid distribution subsystem of Task 4, an analytical model defining liquid cooling/heating and thermal transients within the liquid feedlines will be developed. This model will be used in conjunction with line lengths and routings defined in Task 2.3 and the thermal environment from Task 1.1 to determine optimum pump locations and associated propellant losses. Using the program, various childown techniques such as refrigeration (thermodynamic vent) and bleed cycles for the OMS turbopumps will be investigated. The preferred methods for the different OMS integration concepts will be identified. The line cooling model will be compatible with the Conditioner Assembly Transient Program to allow investigation of conditioner sequencing for integrated RCS/OMS engine start and preconditioning analysis.

Task 3.3 - Define and Compare RCS/OMS Integration Options

Objective - To define the RCS/OMS design options and to develop system schematics, system design points, and methods of providing control.

Approach - While many RCS/OMS integration options are possible there are four basic levels that can be used, covering the spectrum from full integration to separate systems with only a common propellant supply. With a fully integrated RCS/OMS, there are three major interactions, resulting from integration, that must be resolved either by control, design point changes or RCS conditioner reimplementation. Specifically these interactions are RCS/OMS mixture ratio differences, RCS constraints on OMS burn time and simultaneous sequencing of OMS engine propellant during startup. The successive levels of deviation from full integration (e.g., separate pumps, separate pumps and gas generator, etc.) inherently resolve one or more of these interactions but compromise hardware commonality. For each of the four RCS/OMS options the preferred means of resolving their interactions must be defined (i.e., design point change, reimplementation or controls). This task will develop the design data and weight sensitivities necessary for evaluation of design point change and/or reimplementation. These results will be used in Task 3.4 for comparison with controls required to resolve the interactions. Design data resulting from Task 2.7 will be used to the fullest extent possible and any additional data and sensitivities necessary for RCS/OMS design definition will be developed.

To accomplish this definition, the System Design and Sizing Program will be modified to incorporate the OMS engine model from Task 3.1. Using this program, sensitivity studies will be conducted to determine preliminary design points (e.g., chamber pressure, mixture ratio, etc.) for each RCS/OMS option. The schematics used for these analyses will reflect the redundancy necessary to satisfy failure criteria. Weight sensitivity to design and operating points for each of the RCS/OMS integration options will be developed for comparison between design and control solutions in Task 3.4.

Task 3.4 - Compare RCS/OMS Control Concepts

Objective - To select the method of control to be used for each candidate RCS/OMS configuration.

Approach - For each of the four basic RCS/OMS configurations there are a number of methods available for their implementation. However, all are not worthy of detailed investigation and it is therefore desirable to screen their number so as to allow the analyses depth needed in subsequent control/operation analysis. The intent of this task is to compare the options and arrive at preferred design/control approaches for each of the four levels of RCS/OMS integration. Like the previous task, this task will utilize companion RCS controls and design analyses from Task 2. For each of the candidate RCS/OMS concepts, methods to provide mixture ratio control for both systems, to sustain OMS burn duration and to provide acceptable start sequencing will be investigated. For mixture ratio control, this will typically compare several means of providing bilevel pump operation such as by turbine power control or liquid throttling. The preferred control approaches will be selected. Control complexity and performance will be compared to solutions relying on system design changes, e.g., comparison of bilevel pump controls to design of the RCS for high mixture ratio operation.

Design concepts which show the best compromise between weight, complexity, and development risk will be identified for each integration option. It is anticipated that there will be sufficient similarity between the design and control selections or an outstanding RCS/OMS integration option of sufficient merit to allow concentration of subsequent effort on a primary choice with the remaining options being largely a vernier of its results. The rationale for these selections, and substantiating data,will be presented for NASA review and concurrence at the Interim Systems Definition Review.

Task 3.5 - Perform Transient and Operating Performance Analyses

Objective - To evaluate transient characteristics of the RCS/OMS components and conditioning assembly and to evaluate system performance during simulated flight operation with nominal and off-nominal component performance.

Approach - Some of the principal differences between RCS/OMS integration options will be system transient response characteristics, system sequencing for start up, and control during operation.

These analyses will use a version of the Conditioner Assembly Transient Program, which couples the liquid supply line thermal model developed in Task 3.2 to the start transient/sequencing analyses, to evaluate the effects of different component locations defined in Task 2.3.

Specific data generated in this task will be startup and shutdown response times, and transient flow, pressure, and temperature histories. Following evaluation of nominal operation, component design or control adjustments will be made as required, and the analysis will be repeated for off-nominal component performance and mission requirements. The operation of the systems will then be evaluated to provide a definition of required overall system performance and margins (thrust, propellant outage, system total impulse, etc.). Component requirements, as influenced by the transients, will be defined. These data will be compiled as part of the selection criteria for comparison of separate and independent systems at the conclusion of Task 3.

Task 3.6 - Define RCS/OMS Component Design Requirements

Objective - To define component design and performance requirements for component preliminary design.

Approach - The component requirements reflecting the results of the steady state sizing analysis of Task 3.3 and the transient analysis of Task 3.5 will be summarized for use by ALRC in the preliminary component design effort in Task 3.7.

Task 3.7 - Develop RCS/OMS Component Designs

Objective - To prepare preliminary designs for the integrated RCS/OMS conditioning assembly components and for the feed subsystem and OMS components.

Approach - Based on the detailed component requirements defined in Task 3.6, preliminary designs for the system components, including conceptual layout drawings, weights, performance, operating and life characteristics, interface definition and maintainability/replacement features will be developed. RCS conditioner components will include those identified in Task 2.12 and it is anticipated that essentially all required design detail on these components will be provided by that effort. In the event that conditioner components differ for integrated systems their design will be verniered as necessary from those developed in Task 2.12. OMS engine assembly components will include propellant valves, mounts, injector, igniter, thrust chamber, and nozzle. The preliminary designs developed will be of sufficient depth to define technology risks. Based on the preliminary designs, development plans and related component costs will be established in Task 3.8.

Task 3.8 - Define Component Development Plans/Costs and Technology Requirements

Objective - To define component development plans and associated costs, and to assess their technology status.

Approach - The components defined in Task 3.7 will be assessed to determine their technology status. Detailed development plans will be formulated based on the test criteria guidelines and schedules developed in Task 2.8. The development plan will be sufficiently detailed to form the basis for cost estimating and will include schedules by task, for component design, tooling, fabrication, number and types of tests, test setups, instrumentation requirements, data analysis, documentation, and hardware deliveries. Required extensions in component technology will be defined in terms of their impact on schedules and number of tests. This effort will use, as a reference, the development planning on the parallel flow RCS conditioner concept so as to provide as much uniformity as possible for comparison of the separate RCS and integrated system approaches. The results of this task will supply the component development aspects required for system selection.

Task 3.9 - Finalize System Design and Performance

Objective - To update system designs, operation, performance and performance sensitivities.

Approach - The detail data generated in the previous tasks will be updated as necessary and a data summary prepared for each of the candidate configurations. This summary will include:

(1) final system schematics, installation and component layout drawings
(2) steady state temperature, pressure and mass flow balances
(3) transient characteristics and startup/shutdown sequences
(4) nominal performance characteristics and sensitivities
(5) number and type of controls and control accuracy
(6) operating characteristics, including childown procedures
(7) system safety/maintenance considerations.

A failure mode and effects analysis will be conducted to define system reliability and component maintenance schedules for final system comparisons.

Task 3.10 - Define System Development Plan/Costs/Technology Requirements

Objective - To prepare system development plans, associated costs and assess technology status for each candidate RCS/OMS configuration.

Approach - The parallel flow conditioner, RCS configuration will be examined in detail in Task 2.15 to define the system development plan, costs and technology status. Results will be used in this task to determine the incremental development scope and costs required to implement the various degrees of RCS/OMS integration. Test criteria, guidelines, and schedules were previously defined in Task 2.8. The system test plan will include design effort; fabrication; pre-installation tests; required environmental simulation and facilities required; instrumentation requirements; number, type and complexity of texts; data analysis; and systems support effort. The development plan will be sufficiently detailed to allow valid cost comparisons reflecting number of components, number of controls and operating modes. Requirements to develop technology will impact schedule and costs by additional tests or by schedule and cost contingencies.

Task 3.11 - Compare System Concepts

Objective - Compare the RCS/OMS options.

Approach - The candidate RCS/OMS options will be evaluated and compared on the basis of:

(1) system weight and volume
(2) system complexity and costs
(3) system flexibility to mission and design requirements
(4) reliability, safety and maintainability
(5) development program requirements (component and system)
(6) technology requirements (component and system)
(7) system performance levels and variations.

System ratings under each of these categories will be summarized and presented to NASA at the Final Systems Definition Review. The result of this effort will constitute a comparison of the merit of various degrees of RCS/OMS integration and the impact of this integration on the RCS.

3.4 Task 4 - Phase D: Special RCS Studies

Task 4.1 - Conduct Propellant Storage, Acquisition and Pressurization Analyses

Objective - To evaluate and compare high pressure propellant storage, acquisition, and pressurization design alternatives.

Approach - The high pressure propellant storage assembly will strongly influence total weight of the special systems. Therefore, special emphasis will be given to alternate propellant storage, acquisition and pressurization design concepts and propellant resupply procedures. Consistent with Task 1 requirements RCS tank capacities will be identified for: (1) propellant resupply during +X and/or reentry maneuvers, and (2) continuous propellant resupply by means of high-head-rise transfer pumps and OMS propellant acquisition devices. Advanced tank materials and fabrication methods will also be evaluated and potential weight savings identified. Alternate pressurization concepts, such as cold helium, heated helium, and autogenous pressurants will be evaluated and their weights defined for blowdown, regulated, and bootstrap control modes. Pressurant boost or amplification schemes, such as motor-compressors and differential area propellant expulsion devices, will be considered for the bootstrap concepts. The relative weight, complexity, and development risk for the various approaches will be assessed, and selections made for subsequent system studies dependent on the criticality of storage to the two different concepts (in terms of storage weight relative to total system weight).

Task 4.2 - Define Component Models

Objective - To develop analytical models for components unique to the special RCS.

Approach - Component analytical models developed for Phases 2 and 3 will be used or modified, as necessary, for system design and sizing. For those components which are peculiar to the special systems, i.e., alternate propellant acquisition devices, propellant transfer pumps, and pressurant compressors, etc., component specialty manufacturers will be surveyed and data assimilated to define component weight, size, and performance. As necessary for subsequent design studies parametric data will be developed over a limited range of flow rates, specific speeds, pressures, temperatures, power requirements, etc. Such pertinent physical and operating characteristics as cooling requirements, suction pressure capabilities, cycle life and number of pump or compressor stages will also be identified.

Task 4.3 - Evaluate Line Insulation/Cooling Concepts

Objectives - To define RCS line routing and line insulation/cooling concepts for liquid propellant distribution systems.

Approach - The impact of line heating on system pressure and temperature balances, thruster cooling requirements and screen acquisition performance is a key element in design of the special system using liquid distribution. Impulse usage histories in conjunction with thermal environment and engine propellant quality requirements will be evaluated and acceptable line heating rates will be defined. This information will then be used to compare and select line materials; e.g., aluminum, stainless steel or composite (fiberglass with thin steel liner); line insulation concepts (uninsulated, purged HPI or vacuum jackets); and line cooling concepts (uncooled, recirculation, or thermodynamic vent). Line diameters will be optimized for each concept, based on the trade between inner line plus insulation and cooling weights versus incremental tank/pressurization weights. Vehicle internal temperature environments (Task 1.1) and line routings (Task 2.3) will be reviewed and line routings modified, as necessary, to reduce heat leaks or total line weights. From this effort, a distribution system concept which is most suitable to the special system will be selected considering system weight, complexity, technology, and maintenance of the distribution system. For the selected approach the size and weight of lines, supports, and compensators will be developed for subsequent design and sizing studies.

Task 4.4 - Establish Preliminary System Design

Objective - To define preliminary design points for each of the special systems.

Approach - For each of the special system concepts, system schematics will be prepared based on reliability studies conducted to define necessary component redundancy. Accumulator pressure-volume relationships will be defined by transient analyses procedures used in Task 2. These data, together with the results from the preceding tasks, will be used to determine sensitivity to such design factors as operating pressures, line pressure drops, engine expansion ratio, and minimum engine inlet temperature; and to determine sensitivity to such requirements as thrust, impulse usage, and total impulse. Rather than develop special procedures for these systems, their analyses will, in general, use data developed by the design and sizing techniques described in Task 2 as a base, and vernier these data to account for system differences. This effort will result in component and system design and operating requirements. The component models will be reviewed with respect to these conditions to ensure validity. The designs will be adjusted to achieve the best balances between system weight and the other RCS selection criteria. The resulting design will be defined for Task 4.5 evaluation and comparison with other RCS concepts.

Task 4.5 - Finalize System Design and Review System Technology

Objective - To perform incremental studies as needed for design evaluation and assessment of system technology.

Approach - The special systems will not be studied to the same depth as those considered in Tasks 2 and 3 but a basis for comparison will be provided by evaluation to the same selection criteria. Hence, Task 2 development plans will be reviewed to evaluate reductions in development requirements due to the elimination of turbopumps, heat exchangers and accumulators. Cost differentials will be established and will include adjustments for variations in system performance and maintenance. Relative complexity and mission flexibility will also be assessed. Finally, critical technology areas will be identified and backup positions determined. System schematics, design and operating points, sensitivities, system performance, and system evaluation criteria will be summarized and presented to NASA at the Systems Selection Review.

3.5 Task 5 - Phase E: System Dynamic Performance Analysis

Task 5.1 - Establish Conditions for Dynamic Analysis

Objective - To delineate, for NASA review and approval, the specific conditions to be evaluated in the dynamic and operating analyses of Tasks 5.5 and 5.7.

Approach - In Tasks 2 and 3, the conditioner assembly, components, controls and sensors, as well as the tolerances associated with system performance, response, and mechanical characteristics were defined. Using these elements, a matrix of transient and steady state operating conditions that fully covers the resulting limits of steady state and transient operations will be established. The matrix will include conditions for evaluation of partial and complete malfunctions, both for individual components and critical component combinations. Typically, conditions will be defined to allow evaluation of the transient and steady state operating variances associated with each individual tolerance and for compounded tolerances, both statistically and in worst-case combinations. Conditions defined for malfunction simulation will follow a similar approach. Total and partial component malfunctions will be defined for individual elements, as will anticipated critical malfunction combinations to confirm sensor types, locations, and control logic. Contingencies, for investigation of additional operating conditions, that are indicated (by subsequent analysis) to be important will be provided.

Task 5.2 - Update Transient/Operating Analyses Techniques

Objective - To provide computer program refinements indicated by Tasks 2 and 3 effort.

Approach - Based on the experience gained through computer program usage in Tasks 2 and 3, the adaptability and accuracy of the programs will be assessed to establish desired refinements. These refinements will ensure that the final system analyses of Tasks 5.5 and 5.7, is performed with programs of maximum accuracy and simulation capability. Component model revisions, to more closely conform to the preliminary designs developed in Tasks 2 or 3, will be accomplished under this task and incorporated into the computer programs. Likewise, experience gained with program usage may indicate that such additional capability as automated tolerance stackups, or development of transient sensitivities on an automated basis, are desirable. Any additional capability that will improve the conduct of final system analyses will be incorporated in both the transient and operational analysis programs under this task effort.

Task 5.3 - Refine System/Component Tolerances

Objective - To extend component tolerance studies and data as required to enable definition of final system operating boundaries in Tasks 5.5 and 5.7.

Approach - All components within the subsystem will be examined to delineate their mechanical, performance, and response tolerances. Tolerances developed in Task 2.2 will be reviewed and, as applicable, will serve as the initial input for this effort. Tolerance data not available from Task 2.2 will be developed using either generic data or analyses of the component preliminary designs. This task will include amplification of conditioner, component, and control tolerance definition, with particular attention to sensors for normal and malfunction operating control. Alternate sensor types will be investigated. Variances in their operating characteristics over the design range, and the effect of design requirements on operation, will be defined. Additionally, the effect of wear on component and sensor operating tolerances will be assessed to define expected increases in operating boundaries with accumulated system life. Also included in this task will be any prerequisite studies of sensor/control loop stability and reliability studies necessary to guide and prepare for final system analyses in subsequent tasks.

Task 5.4 - Update Selected Design Concept

Objective - To establish, for the selected RCS concept, a revised RCS baseline reflecting updated vehicle requirements.

Approach - Revised VDRD requirements will be evaluated and the RCS design will be modified accordingly. Component baselines will be revised as necessary and analyses will be conducted to reestablish and update the RCS design to the level of detail developed in Tasks 2.9, 2.10, 2.11, and 2.14. This revised design will then be used for final system controls analyses in Task 5.5.

Task 5.5 - Conduct Controls and Sensor Analyses

Objective - To establish RCS control, sensor types, and locations, for use in the final RCS analyses of Task 5.7.

Approach - This task will provide a detailed reassessment of controls for the baseline system in conjunction with detail sensor evaluation, definition of control loop logic, gains, and sensor locations. For the baseline RCS concept, open loop operation will be reassessed, and desired/necessary controls established. For the controls defined. alternate control logic schemes will be investigated as will alternate sensor locations for the different approaches. These will be accompanied by controls analyses to tailor the gains within the individual loops such that they provide the necessary accuracy with desired stability margins. These control evaluations will include operating analyses simulations, transient analyses, and input from companion reliability and failure mode analyses in Task 5.6. A matrix of all control options considered together with their respective merit will be prepared, allowing comparison of the approaches and a final controls definition. For the selected control concept, the location, type, response, accuracy, power, and design requirements for all sensors and controls will be defined as baseline characteristics for the final system analyses in Task 5.7.

Task 5.6 - Perform Reliability Analysis

Objective - To establish final sensor, controls, and logic definition for controls studies in Task 5.5 and final system analyses in Task 5.7.

Approach - Reliability flow charts showing component sequencing in the event of failure will be prepared. From these, detection alternatives for various malfunction modes will be defined, as will operating sequences in the presence of malfunction and required sensor redundancy for different control schemes. The best means of implementing sensor redundancies (e.g., averaging, majority vote) will be determined based on sensor malfunction modes and control accuracy/criticality. These results will be used in an iterative manner to support and modify the control-sensor analyses of Task 5.5. The intersystem redundancy necessary to accommodate combined malfunctions will be defined, and the reliability flow charts refined to reflect these second-level system redundancy considerations. For the system description developed in Tasks 5.4 and 5.5 (as supported by this task), final reliability analyses will be conducted to establish both absolute RCS reliability and expected system maintenance requirements.

Task 5.7 - Conduct System Dynamics Performance Analysis

Objective - To document the system operating and performance boundaries under all potential operating conditions, and to confirm the final design and/or define required changes.

Approach - The initial effort in this task will be to support, on an "as required" basis, the control/sensor/reliability design iterations necessary for development of the final system configuration. When the configuration has been established by Task 5.5, analyses will proceed to define nominal, off-nominal, and malfunction characteristics under steady state and transient conditions as defined by the matrix of conditions developed in Task 5.1. Final analutical effort will be initiated by defining sensitivities of system design and performance under both transient and steady state operating conditions, for each individual tolerance in the system. These will be used to define the more critical features of the system. Key tolerance effects then will be combined and reevaluated under steady state and transient conditions, to define the impact of a maximum tolerance stackup within the system. Finally, operating limits based on a statistical combination of tolerances will be defined. From these analyses, system oerformance boundaries will be developed defining the extent of off-nominal operation during the missions. These analyses will also include backup operating modes for ascent abort and deorbit. Control loop stability and accuracy will be confirmed and/or amended if certain operating conditions show such changes to be desirable. Malfunctions, complete and partial, both singularly and in critical combinations, will be simulated to determine the adequacy of system malfunction sensors, controls, and logic. From these studies, final system performance and performance boundaries will be defined.

Task 5.8 - Define System Design Changes and Critical Technology

Objective - To reflect in the study output any design iteration that is indicated to be attractive or necessary by the detailed investigations in Task 5.7.

Approach - The results from Task 5.7 will be reviewed in detail to identify any design/control aspects which offer potential improvements in the RCS design. If indicated, changes will be assessed quantitatively to assure practicality and benefit. The impact of the changes will be assessed as a vernier to the baseline design and a description of the impact together with the rationale for recommendation will be prepared. Additionally, for the baseline system, critical technology areas associated with system/component design, operation, control, sensors, and logic will be identified and backup positions, plus their associated penalties, defined.

Task 5.9 - Define System and Component Design Margins

Objective - To provide the design criteria necessary to allow reflection of study results into later, more refined vehicle designs and component/system hardware development.

Approach - The component requirements resulting from Task 5.4 will be extended to include design criteria in the form of tolerance impacts on system performance. Allowable component tolerances, in terms of their effect on system operation will be defined. Additionally, tolerances which are critical or those which may be deemphasized during development will be determined. The system design margins, in terms of internal operating characteristics, and the system performance boundaries will be defined to aid in subsequent vehicle design and mission planning.

4. REFERENCES

a) McDonnell Douglas Report MDC E0374, "Space Shuttle Auxiliary Propulsion System Design Study", Vol. I Technical Proposal, dated 21 May 1971

b) NASA Request for Proposal RFP MSC-BC421-M68-1-10P, "Space Shuttle Auxiliary Propulsion System Design Study", dated 23 April 1971.