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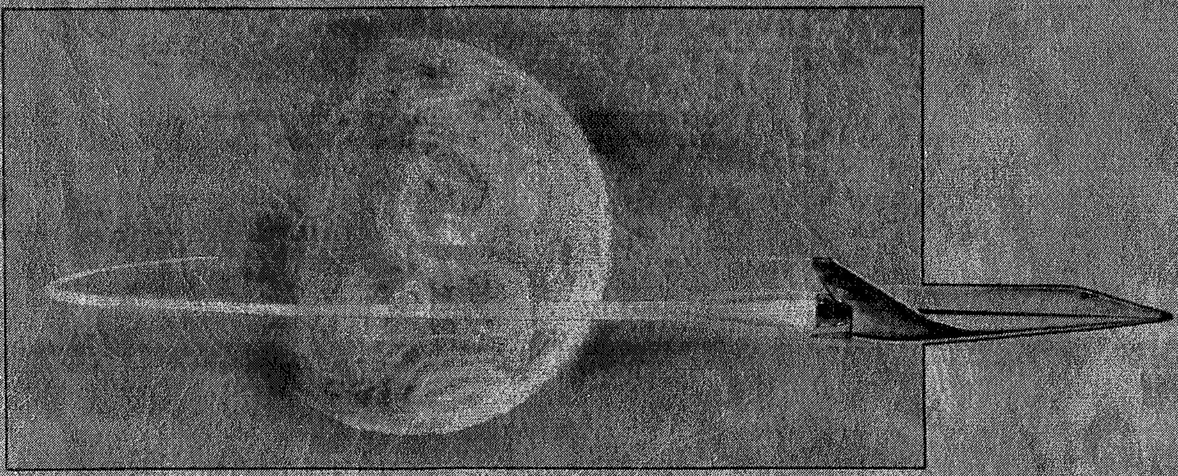

LOCKHEED
LMSC
SPACE SYSTEMS
DIVISION

INTEGRAL LAUNCH AND REENTRY VEHICLE

VOLUME II
TECHNOLOGY IDENTIFICATION

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LMSC-A959837
Vol. II

FINAL REPORT

INTEGRAL LAUNCH AND REENTRY VEHICLE

Volume II

Technology Identification

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FOREWORD

This final report for the Integral Launch and Reentry Vehicle (ILRV) Study, conducted under Contract NAS9-9206 by Lockheed Missiles & Space Company under direction of the NASA Marshall Space Flight Center, is presented in three volumes. Volume I, Configuration Definition and Planning, contains results of the preliminary cost analyses, conceptual design, mission analyses, program planning, cost and schedule analyses, and sensitivity analyses, accomplished under Tasks 1 through 6. Volume II covers Task 7, Technology Identification, and Volume III contains results of the Special Studies conducted under Task 8.

Principal LMSC task leaders and contributors in performance of this study include:

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The three volumes are organized as follows:

Volume I - Configuration Definition and Planning

Volume II - Technology Identification

Section

Volume III - Special Studies

Section

CONTENTS

Section 1
INTRODUCTION AND SUMMARY

In compliance with Task 7 (Technology Identification) of the ILRV study, technologies that are pertinent to the development of the Space Shuttle system have been identified.

These key technologies, presented in this separate volume for utility, are briefly summarized below and described in greater depth in Sections 2 through 7. Technology program schedules and cost estimates are summarized in Section 8.

1.1 PROPULSION SYSTEM TECHNOLOGY

A major portion of the propulsion system technology recommendations are directed at the oxygen/hydrogen integrated reaction control system. Technology advancements are necessary for development of the thrusters, propellant feed systems, and propellant orientation system for the oxygen/hydrogen reaction control system. Another technology program recommendation of major importance is the oxygen/hydrogen auxiliary power unit development. This program would require the development of a rather large oxygen/hydrogen turbine-driven unit.

Leakage detection and location, considered to be a major problem in the Space Shuttle propulsion systems, entails an advancement in techniques. Major weight savings were identified in the elimination of residual propellants through improved instrumentation.

A detailed investigation to determine the desirability of and problems related to the development of hydrogen-fueled, airbreathing engines is also recommended.

1.2 AERODYNAMICS TECHNOLOGY

Although the aerodynamic effort required to develop the proposed Space Shuttle will be considerable, the basic aerodynamic technology exists. The items expected to represent major development effort are subsonic vehicle development, subsonic analytical techniques, hypersonic viscous effects on vehicle performance and control, plumeinduced phenomena, composite launch vehicle interference effects, and staging and abort feasibility studies. In addition, tasks more common to existing airplane and missile systems will be exercised.

1.3 AEROTHERMODYNAMICS TECHNOLOGY

Listed below are key technology issues related to prediction of aerodynamic heating distributions and resulting surface temperatures:

- Prediction of flow field and laminar and turbulent heat transfer distributions (Wind tunnel tests should be conducted to resolve the discrepancies among various flow field and heating prediction techniques.)
- Prediction of boundary layer transition (Experimental boundary layer transition studies should be conducted for each candidate configuration.)
- Evaluation of heat transfer increase due to surface irregularities
- Evaluation of location and heat transfer increases associated with shock wave/boundary layer interactions
- Prediction of base heating rates (Scale model tests of the booster/orbiter configuration employing nozzle hot flow could provide necessary convective and radiative heat transfer design data.)

1.4 STRUCTURES TECHNOLOGY

The development of technology relating to vehicle structure is fundamental to all development approaches for the Space Shuttle booster and orbiter. The driving functions for low structural weight are thermal protection systems and efficient propellant packaging. Consequently, primary technology areas requiring additional investigation or basic research are reusable thermal protection systems (which can maintain their orbital thermal properties) and their interfaces and efficient joining techniques, along with adequate analytical methods.

Specific areas discussed in this volume under Structures Technology include materials; thermal protection systems; joining methods; movable elements in a high-temperature environment, such as control surfaces; structural mechanics analysis; cryogenic technology (particularly reusable insulation development like "breathing" multilayer systems); and orbital vehicle surface thermal properties.

1.5 AVIONICS TECHNOLOGY

Avionics requirements for the Space Shuttle do not indicate the need for a breakthrough in technology; however, improvements in technology are required to achieve the objective of a low-cost transportation vehicle. Integration of the avionics functions is the primary technique to be used in significantly reducing system weight, power, and cost.

The two most challenging areas are in the development of survivable antennas and a link for communications via a relay satellite. Both may require advancement in the state-of-the-art.

The technology plan will require an extensive simulation test program, both ground and airborne, to validate design integrity of the integrated system. These tests should occupy the span from mid-1970 through 1971. It would be desirable to introduce critical Space Shuttle communications equipment on the AAP/ATS-F relay link experiment to provide experience and confidence in the design early in Phase D of the shuttle development program.

1.6 BIOASTRONAUTICS

1.6.1 ECS/LSS Technology

Seven environmental control/life support system technology areas have been identified as being desirable for expansion or refinement to meet the needs of the Space Shuttle. These are radiator design, noise control, chemical oxygen systems, waste management and personal hygiene, reusable ECS, multimode ECS, suit-loop elimination, and equipment temperature control system design. It is recommended that future development of these items be considered.

1.6.2 Crew Systems Technology

Technological problems that must be solved in the course of developing an effective and reliable crew system for the Space Shuttle have been identified. These study areas include a determination of vehicle flying qualities by simulation techniques, assessment of crew visibility requirements for various mission phases along with empirical evaluations of alternative visibility provisions, development and evaluation of candidate crew safety and escape features for crew and passengers, assessment of crew workload distribution and validation of the ability of the specified two-man crew to accomplish all assigned mission activities, and human factors effectiveness evaluations of novel integrated display concepts to allow the crew to exercise a manual override and takeover function.

Section 2

PROPULSION SYSTEM TECHNOLOGY

When the evaluation of the propulsion system was initiated, there was considerable concern regarding the reusability of components. Evaluations were made on the basis of a considerable quantity of information obtained from studies of existing hardware produced in the Reusable Subsystems Design/Analysis Study (Reference 2-1). The general conclusion was that a large percentage of the components have sufficient inherent lifetime for a number of flights. Some of the components that are most likely to entail lifetime problems are the following:

- Check valves
- Instrumentation, such as liquid level devices
- Attitude control thrusters
- Integrated attitude control components, such as pumps, check valves, and heat exchangers

It was concluded that some of the more conventional problems, such as contamination and corrosion, would be major factors influencing reusability.

Advancements in technology considered necessary or desirable are discussed in the following paragraphs.

2.1 OXYGEN/HYDROGEN ATTITUDE CONTROL SYSTEM THRUSTERS

As indicated in the description of the oxygen/hydrogen attitude control system in Volume I of this report, Lockheed has determined that two levels of thrusters are desirable to reduce the propellant requirements for limit cycling. These thrust levels appear to be approximately 100 pounds and 3,000 to 4,000 pounds, respectively. The upper thrust level is highly dependent upon the present ground-rule requirements for acceleration of up to 1.5 ft/sec^2.

Minimum impulse bit is an important consideration in the development of the thrusters.

Only very little development has been accomplished on oxygen/hydrogen attitude control and other cryogenic thrusters. A summary of some of this work is presented in References 2-2 through 2-12.

It is recommended that a program be initiated to evaluate the engineering design problems associated with the gaseous oxygen/hydrogen thrusters and to conduct the necessary component tests on ignition systems, cooling, valving, and materials to develop the required response time and service life.

Prototype thrusters should be fabricated.

2.2 OXYGEN/HYDROGEN ATTITUDE CONTROL PROPELLANT FEED SYSTEM

The oxygen/hydrogen attitude control feed system, described in Volume I of this report, represents a relatively complex cryogenic system for increasing the pressure and converting cryogenic liquids to gas. The number of components in this system and the possible approaches indicate that several major alternate development paths should be followed to assure the success of the program.

Systems using oxygen and hydrogen have not been previously studied, so it is recommended that several technology programs be pursued to develop alternate approaches to integrated attitude control feed systems. The emphasis should be to fabricate and test various design concepts on liquid and gaseous pumping, gas conversion, and duty-cycle effects. The systems should be developed at approximately the required sizes to allow a rapid development of flight hardware suitable for space shuttle application.

2.3 PROPELLANT ORIENTATION FOR ATTITUDE CONTROL SYSTEM PROPELLANTS

The attitude control system as conceived by LMSC should operate with liquid propellant fed from the main propellant tanks. There should be a minimum of two-phase flow to prevent instability in the feed system. (The use of residual gas rather than liquid from the main tanks is believed to represent even more difficult problems in propellant orientation, i.e., the problem of keeping liquid from being vented.) The propellant orientation system in the main tanks must be capable of being refilled and must supply propellants at relatively high rates.

Prior programs related to propellant orientation devices are presented in References 2-13 through 2-31.

A program is needed to analyze propellant orientation system approaches, to perform the necessary engineering designs, and to construct and test model hardware. Required testing should be performed under low-g (drop towers and orbital experiments), progressing to the compilation of design information that can be used to design hardware suitable for Space Shuttle application.

2.4 LEAKAGE DETECTION TECHNIQUES

Leakage detection and the monitoring of leakage rates will be an important aspect of reusable vehicle operation and checkout. The complex subsystems will make these measurements extremely difficult. Improvements in detection and measurement must be developed.

Previous leakage studies are presented in References 2-32 through 2-36.

Approaches to determining the existence, location,and rates of leakage in reusable vehicle propulsion subsystems should be investigated. Evaluations should be conducted with advanced detection techniques, such as the use of krypton 85 gas.

The tests should be conducted on simulated mockups of the propulsion subsystem lines and valves.

2.5 REDUCTION OF RESIDUAL PROPELLANTS

Improvements in the overall propellant management system are required to reduce the penalties entailed by residuals. Instrumentation required increases confidence in the propellant utilization and reserves.

Specific technology in this area has not been developed under an integrated program. Related efforts are discussed in References 2-37 through 2-44.

The purpose of additional effort in this area should be to devise techniques and instrumentation to minimize residuals. Scale-model testing and intermediate size testing is considered essential, and a cryogenic vacuum flight simulator is required.

2.6 OXYGEN/HYDROGEN AUXILIARY POWER UNITS

The described auxiliary power supply system utilizes the rocket engine and the jet engines to supply power whenever these engines are operating. During reentry, the power requirements are relatively high; so an auxiliary power unit is required. The logical energy source for this unit is oxygen and hydrogen.

There has been only limited effort concerned with development of oxygen/hydrogen turbines of the size required for auxiliary power units, and these efforts have been only of a feasibility nature. Therefore, engineering and development programs are needed to produce suitable oxygen/hydrogen auxiliary power units of the required power output.

2.7 HYDROGEN-FUELED AIRBREATHING ENGINES

Airbreathing propulsion systems are likely required to fulfill flyback, ferry, and go-around capabilities. Comparisons are shown in Volume I regarding the propulsion system weight requirements as a function of subsonic cruise duration. These studies indicate the possibility of reducing the required weights by employing hydrogen as the fuel for the engines. This would require storage of the liquid hydrogen in the atmosphere; and this introduces a number of cryogenic storage problems, as well as engine development considerations.

Some development work has been performed with a goal of employing liquid hydrogen-fueled engines for military and commercial applications. However, in light of the magnitude of a program related to the development of a hydrogen-fueled engine, it is recommended that a detailed investigation be made of the related problems and a development program planned prior to the initiation of hardware development.

The technology study should include investigation of the various tradeoffs associated with the employment of a hydrogen-fueled engine, including such factors as propellant storage, fuel consumption, engine design, and risk assessment. The recommendations from this program should then be evaluated to determine whether a hydrogen engine program is justified.

REFERENCES - SECTION 2

Ref.	Program	Contractor	Government Cognizance	Contract No.	Duration
2-1	Reusable Subsystems Design/Analysis Study	Lockheed Missiles & Space Company	USAF Rocket Propulsion Laboratory	F04611-69-C0041	12/68- 11/69
2-2	Demonstration of Advanced Attitude Control System	Bell Aerosystems Company	USAF Rocket Propulsion Laboratory		1969-
2-3	Investigation of Thrusters for Cryogenic Reaction Control System	TRW Systems Group	NASA Lewis Research Center	NAS3-11227	1968-
2-4	Development and Demonstration of an Advanced Attitude Control System	Bell Aerosystems Company	USAF Rocket Propulsion Laboratory	F04611-68-C0072	1968-
2-5	Radiosotope-Heated Reaction Control System	TRW Systems Group	USAF Rocket Propulsion Laboratory	AF04(611)-11536	3/66-
2-6	Pyrolytic Graphite Reaction Control Engines for Use with Fluorine Oxidizers	Curtiss-Wright Corporation, Wright Aeronautical Division	NASA Manned Spacecraft Center		1966-
2-7	Evaluation and Demonstration of the Use of Cryogenic Propellants for Reaction Control Systems	North American-Rockwell Corporation, Rocketdyne Division	NASA Lewis Research Center	NAS3-7941	6/65-
2-8	Feasibility Demonstration of Advanced Attitude Control Systems	Bell Aerosystems Company	USAF Rocket Propulsion Laboratory	AF04(611)-10818	1965-

REFERENCES - SECTION 2 (Cont'd.)

Ref.	Program	Contractor	Government Cognizance	Contract No.	Duration
2-9	Design, Fabrication, and Test of Pyrolytic-Graphite Wedge Heat-Sink Nozzles	Curtiss-Wright Corporation, Wright Aeronautical Division	USAF Rocket Propulsion Laboratory	AF04(611)-9365	2/66
2-10	Experimental Evaluation of Gaseous Hydrogen as a Monopropellant	Lockheed Missiles & Space Company	NASA Marshall Space Flight Center	NAS8-9500 (Subtask 1.5)	5/64 9/64
2-11	Catalytically Ignited Oxygen/Hydrogen Attitude Control Systems	North American-Rockwell Corporation, Rocketdyne Division	NASA Lewis Research Center	NAS3-4185	6/64-
2-12	Catalytic Ignition of Hydrogen and Oxygen	North American-Rockwell Corporation, Rocketdyne Division	NASA Lewis Research Center	NAS3-2565	6/63-
2-13	Investigation of Space Storable Propellant Acquisition Devices	Martin-Marietta Corporation, Denver Division	NASA Pasadena Office	NAS7-754	7/69 10/70
2-14	Low-Gravity Propellant Control Using Capillary Devices in Large Scale Cryogenic Tanks	General Dynamics/Convair	NASA Marshall Space Flight Center	NAS8-21465	1968- 1969
2-15	Experimental Investigation of Capillary Propellant Control Devices for Low-Gravity Environments	Martin-Marietta Corporation, Denver Division	NASA Marshall Space Flight Center	NAS8-21259	1968- 1969
2-16	Design of Advanced Propellant Management System	Martin-Marietta Corporation, Denver Division	NASA Manned Spacecraft Center		1968-

REFERENCES - SECTION 2 (Cont'd.)

Ref.	Program	Contractor	Government Cognizance	Contract No.	Duration
2-17	Study of Long Term Effects of High Energy Propellants on Fine Micronic Stainless Steel Used in Surface Tension Devices	Western Filter Company	USAF Rocket Propulsion Laboratory	F04611-68-C0064	7/68
2-18	Design, Fabrication, and Testing of Subscale Propellant Tanks with Capillary Tank Traps	Martin-Marietta Corporation, Denver Division	NASA Marshall Space Flight Center	NAS8-20837	6/67-
2-19	In-space Propellant Orientation and Venting Experiments	Lockheed Missiles & Space Company	USAF Rocket Propulsion Laboratory	AF04(611)-11403	3/66- 4/68
2-20	Propellant Orientation and Venting System for Zero-G Applications	Bell Aerosystems Company	USAF Rocket Propulsion Laboratory	AF04(611)9901	6/64-
2-21	Propellant Expulsion and Orientation Systems for Advanced Liquid-Rocket Propulsion Systems	Bell Aerosystems Company	USAF Rocket Propulsion Laboratory	AF04(611)-8200	6/62- 7/63
2-22	Cycle Testing of Cryogenic Expulsion Bellows to Evaluate Cycling Performance in Liquid Fluorine	Martin-Marietta Corporation, Denver Division	NASA Lewis Research Center	NAS3-12053	6/69-
2-23	Propellant Expulsion System for Missiles	International Harvester Company, Solar Division	US Army Picatinny Arsenal	DAA21-68-C0809	1968- 1969
2-24	Cryogenic Metallic Positive Expulsion Bellows Evaluation	Martin-Marietta Corporation, Denver Division	NASA Lewis Research Center	NAS3-12017	6/68- 3/69

REFERENCES - SECTION 2 (cont'd)

Ref.	Program	Contractor	Government Cognizance	Contract No.	Duration
2-25	Metallic Expulsion Bellows Design	Bell Aerosystems Company	NASA Pasadena Office	NAS7-385	
2-26	Liquid Hydrogen Expulsion Bellows	International Harvester Company Solar Division	NASA Lewis Research Center	NAS3-11755	1968
2-27	Improved Welded Bellows Design	Battelle Memorial Institute	USAF Rocket Propulsion Laboratory	F 04611-68-C0031	
2-28	Propellant Expulsion System for Spacecraft	International Harvester Company Solar Division	NASA Pasadena Office	NAS7-100	1967-1968
2-29	Subcritical Cryogenic Positive Expulsion System	Arde, Inc.	USAF Aero Propulsion Laboratory	AF 33(615)-2827	Jun 1965 Mar 1968
2-30	Development of Techniques for Bellows and Diaphragm Design	Battelle Memorial Institute	USAF Rocket Propulsion Laboratory	AF 04(611)-10532	Mar 1965 Mar 1968
2-31	Low Pressure Cryogenic Storage and Expulsion System	Arde, Inc.	USAF Aero Propulsion Laboratory	AF 33(657)-11314	Jun 1963- Sep 1967
2-32	Leakage Testing Handbook Project	General Electric Company	NASA	NAS7-396	- 1967
2-33	Study of Propellant Valve Leakage in a Vacuum	Atlantic Research Corporation	NASA Manned Spacecraft Center	NAS9-4494	Jun 1965 Apr 1968

REFERENCES - SECTION 2 (cont'd)

Ref.	Program	Contractor	Government Cognizance	Contract No.	Duration
2-34	Space Effects on Propulsion Components	Aerospace Corporation	USAF Systems Command, Space and Missile Systems Organization	AF 04(695)-469	- Oct. 1964
2-35	Analytical Techniques for the Design of Seals for use in Rocket Propulsion Systems	Illinois Institute of Technology	USAF Rocket Propulsion Laboratory	AF 04(611)-8020	Feb 1962 - Nov 1963
2-36	Zero-Leakage Connectors for Launch Vehicles	General Electric Company, Missile & Space Division	NASA Marshall Space Flight Center	NAS 8-4012	Mar 1962
2-37	Evaluation and Application of Data from Low Gravity Orbital Experiment	General Dynamics/ Convair	NASA Marshall Space Flight Center	NAS8-21291	1969
2-38	Orbital Refueling and Checkout Study	Lockheed Missiles & Space Company	NASA Kennedy Space Center	NAS10-4606	Mar 1967- Feb. 1968
2-39	Earth Orbital Experiments for Low-Gravity Fluid Dynamics (Project THERMO)	McDonnell Douglas Astronautics Company	NASA Marshall Space Flight Center	NAS8-18053 & NAS8-21129	Aug 1966
2-40	Response of Liquid-Fueled Space Vehicles to Low G	General Dynamics/ Convair	NASA Marshall Space Flight Center	NAS8-20356	1966
2-41	Residual Crogenic Propellant Behavior in Orbital Vehicles	General Dynamics/ Convair	NASA Marshall Space Flight Center	NAS8-20165	Jun 1965 Nov 1967

REFERENCES - SECTION 2 (cont'd)

Ref.	Program	Contractor	Government Cognizance	Contract No.	Duration
2-42	Cryogenic Liquid Experiments in Orbit	Martin-Marietta Corporation, Denver Division	NASA Marshall Space Flight Center	NAS8-11328	Sep 1964
2-43	Terminal Draining for Liquid Oxygen and Liquid Hydrogen Propellants	Martin-Marietta Corporation, Denver Division	NASA Marshall Space Flight Center	NAS8-5417	Aug 1964.
2-44	Geysering of Cryogenics	Martin-Marietta Corporation, Denver Division	NASA Marshall Space Flight Center	NAS8-5418	Jun 1963-Mar 1965

Section 3

AERODYNAMICS TECHNOLOGY

The aerodynamic effort required to develop the Space Shuttle system will be considerably greater than that for existing manned lifting-body vehicles. Since the basic aerodynamic technology has already been developed, emphasis here is placed on the aerodynamic tasks for which a major development effort is anticipated. Nevertheless, the more classical problems shall not be overlooked.

One of the significant requirements is an accurate substantiation of aerodynamic characteristics of the orbiter, the return booster, and the composite launch configurations over the subsonic through hypersonic speed regimes.

A major portion of the system study effort should be concentrated on the subsonic speed regime, where performance, stability, and handling characteristics are particularly important. For example, assessment of the effects of auxiliary landing aids, such as jet engines, and the problems of self-ferry is necessary to the development of a subsonic cruise vehicle capable of airplane-type operation.

Reliable theoretical or empirical techniques for predicting low-speed aerodynamic characteristics of the arbitrary body shapes being investigated for the Space Shuttle are noticeably absent. Consequently, there is currently a heavy reliance on subsonic data from experimental sources, particularly wind tunnel facilities. Also, there are no reliable solutions for iterating configuration variables without costly and time-consuming experimental investigation; so theoretical/analytical methods must be developed to provide this capability. As always, such methods must be substantiated in wind-tunnel investigations and finally in full-scale flight.

A wide spectrum of hypersonic entry attitudes investigated have ranged from L/D_{max} to CL_{max} (15 and 55 degrees angle of attack, respectively). An existing LMSC computerized technique for analyzing hypersonic arbitrary bodies appears to be sufficiently accurate as an engineering tool. The viscous effects associated with this speed regime cannot be accurately predicted from scale model testing, so considerable verification will be required in flight testing to assess these viscous effects on vehicle performance and controllability.

Flow separation, induced from rocket exhaust pluming, can seriously affect the hypersonic aerodynamic characteristics. Synergetic plane change requirements,cross-range capabilities, etc., make a method for accurate assessment of rocket plume effects essential. Unfortunately, minimal information is available on this subject; however, recent interest has prompted some investigation. Considerable wind tunnel testing will be required.

A comprehensive aerodynamic study of the launch configurations will be required. The orbiter and booster composite arrangement may produce extensive regions of aerodynamic uncertainties, particularly in regard to flow separation effects associated with the proximity of the two vehicles.

Atmospheric staging and abort dynamics are critical areas on which the feasibility of any two-stage reusable launch system hinges. Aside from the aerodynamic coefficients of both vehicles on various relative positions, it is necessary to know the transients of such coefficients experienced during staging. A free-trajectory wind tunnel simulation of the three-dimensional stage separation problem is required as soon as possible to refine the concepts.

Section 4

AEROTHERMODYNAMICS TECHNOLOGY

Accurate prediction of aerodynamic heating distributions and resulting surface temperatures is necessary to ensure adequate design of the Space Shuttle thermal protection system. Key issues are as follows:

- Prediction of flow field and laminar and turbulent heat transfer distributions
- Prediction of boundary layer transition
- Identification of heat transfer increase due to surface irregularities, protuberances, control surface, etc.
- Identification of location and heat transfer increases associated with shockwave-boundary layer interactions
- Prediction of base heating rates

4.1 PREDICTION OF FLOW FIELD AND HEATING DISTRIBUTIONS

Limited experimental flight data are available to aid in selecting appropriate analytical methods for predicting flow field and heating distributions on Space Shuttle configurations. The ASSET and SV-5 programs provided most of the applicable data, but these programs were limited in scope and failed to provide the quantity and quality of data essential to establish appropriate flow field and heating prediction techniques. Of particular concern is the large discrepancy among various turbulent heating theories. LMSC has selected the rho-mu turbulent heat transfer methods, which was used during the X-20 (Dyna-Soar) program for use on Space Shuttle studies. However, as indicated in Volume III, Section 3, the orbiter entry corridor would be reduced by as much as 12,000 feet if the reference enthalpy method were selected and increased by as much as 10,000 feet if the Spalding-Chi method were selected. A similar problem exists with prediction of local flow properties. The orbiter entry corridor would be increased by as much as 22,000 feet if the lower surface boundary layer edge entropy were the normal shock, rather than oblique shock, value.

Because of the large discrepancies among various flow field and heating prediction techniques and their resulting impact on thermal protection requirements, extensive analytical and experimental studies must be conducted in these areas. The uncertainties regarding local flow properties can be reduced by test and analysis; however, the appropriate turbulent heating theory can be established only through a flight test program. Wind tunnel tests should be conducted on each candidate configuration to obtain pressure data and laminar and turbulent heat transfer distributions. Caution should be exercised in extrapolating the wind tunnel results to flight heating predictions to avoid less than conservative estimates.

4.2 PREDICTION OF BOUNDARY LAYER TRANSITION

The location of boundary layer transition greatly influences the orbiter entry corridor. Analytical and experimental studies have shown transition to be influenced by many variables, including Reynolds number, unit Reynolds number, Mach number, roughness, wall cooling, freestream turbulence, etc. In addition, it has been shown that noise generated by the turbulent boundary layer on wind tunnel walls has a significant influence on the location of transition on test models. Experience has shown, however, that the transition Reynolds number on a full-scale flight vehicle is generally larger than that measured on a wind tunnel model.

Experimental boundary layer transition studies should be conducted for each candidate Space Shuttle configuration, with particular emphasis on the orbiters. Tests should be conducted over a range of Reynolds numbers for various angles of attack. It is recommended that the transition locations be identified from heating distributions obtained through temperature sensitive coating tests. This technique will yield maximum detail regarding the transition patterns.

4.3 IDENTIFICATION OF HEAT TRANSFER INCREASE DUE TO SURFACE IRREGULARITIES, ETC.

Surface irregularities, protuberances, and control surfaces are unavoidable disruptions to normally smooth external surfaces and generally create localized heating problems. Considerable data from wind tunnel and flight tests are available to estimate local heating increases associated with a variety of surface irregularities and protuberances. However, if unusual shapes are involved or a protuberance must be located in a high heating region on the Space Shuttle, tests must be conducted to determine the magnitude of the local heating increase. In addition, the effect of surface irregularities due to normal manufacturing tolerances should be included in the heating predictions.

4.4 IDENTIFICATION OF LOCATION AND HEAT TRANSFER INCREASES ASSOCIATED WITH SHOCKWAVE-BOUNDARY LAYER INTERACTIONS

The heating and pressure increases associated with interaction of a shockwave and boundary layer have been the subject of numerous analytical and experimental investigations. All of the candidate Space Shuttle configurations entail shockwave-boundary layer interaction problems. For example, a sizable heating increase will occur where the orbiter bow shock impinges on the booster upper fuselage of the LMSC Two-Stage launch configuration. During the NASA Reusable Orbital Transport study, Lockheed conducted Mach 8 wind tunnel tests on a similar two-stage configuration and measured interference heating rates of 5 to 10 times the undisturbed value along the booster upper surface. The reduction in view factor to space resulting from the presence of the adjacent vehicle complicates the problem for a radiation cooled structure. Additional shockwave-boundary layer interactions would occur on the MSC fixed wing configuration, where the bow shock impinges on the wing and the wing shock interacts with the fuselage boundary layer.

Because shockwave-boundary layer interaction effects are highly geometry dependent, extensive testing will be required to determine appropriate interference heating factors for each candidate configuration. These effects are localized; consequently, it is recommended that the heating distributions be obtained from temperature-sensitive paint tests to assure that the peak values and extent of the affected region are properly defined.

4.5 PREDICTION OF BASE HEATING RATES

The base region of the booster and the orbiter will be subjected to convective and radiative heating from the engine exhaust plume and recirculating flow. Considerable base heating data applicable to multiengine clusters have been obtained from the Fleet Ballistic Missile and from Saturn and Minuteman. Regions of flow separation provide for recirculation of fuel rich nozzle exhaust, with resultant localized burning and associated heat transfer. For asymmetrical vehicles (mated booster and orbiter), large separated regions could exist between the booster and the orbiter forward of the base region, particularly at angle of attack; thus, combustion effects may not be restricted to the base regions of the booster and the orbiter. The combustion-contributed heating environment may provide significant heat-rate levels in relation to the normal plume interaction reverse flow convective and radiative heat transfer.

Scale model tests of the booster/orbiter configuration employing nozzle hot flow provide necessary convective and radiative heat transfer design data regarding plume interaction effects. Suitable simulation of the combustion phenomenon is not possible from small scale model tests. Only a qualitative evaluation of the combustion contributed heating environment is possible with a partial definition of the region of influence. Unfortunately, scale model tests under estimate the inflight combustion effects; therefore, it is essential that a conservative design approach be used until data are obtained from the prototype.

Section 5

STRUCTURES TECHNOLOGY

Technology relating to vehicle structure and thermal protection systems is fundamental. Basic information must be available during the vehicle definition phase to permit evaluation of structural-thermal concepts. Areas requiring additional investigation or basic research include the following:

- Materials
- Thermal protection systems
- Movable elements in a high-temperature environment
- Efficient and low-cost joining methods
- Structural mechanics, including loads, structural and environmental dynamics, and separation mechanics

5.1 MATERIALS

Past government and company-funded development programs have demonstrated that a state-of-art has been established to design and construct a single-mission lifting reentry space vehicle. Current advanced technology programs indicate that multimission capabilities are practical through improved materials systems and the application of improved manufacturing technology. Contemporary design concepts now require multimission capabilities, which impose relatively long-life requirements on current material systems. The suitability of these materials and material systems has not been adequately demonstrated by environmental evaluation of cyclic entry conditions, i.e., time, temperature, and pressure, nor have refurbishment guidelines been established.

Definition of the cyclic and mission-peculiar environment is required so that existing, flight-proven and improved advanced materials may be analyzed for applicability to Space Shuttle design. It is recognized that the stringent requirements of launch-ascent, orbit, entry, cruise, and landing are superimposed upon one another and thereby generate performance requirements not previously required.

In general, materials and application processes require evaluation to establish behavior and limits of state-of-art concepts under Space Shuttle environmental profile conditions and to explore improvement of those less than optimal materials. The behavior and effects of interrelationships of launch, ascent, orbit, entry, cruise, and landing conditions on materials must be verified. Specific development activities necessary to meet design constraints imposed by mission requirements are as follows:

- The thoria dispersion-strengthened alloy, TD-NiCr, has been a leading candidate material for many design applications involving heat shields and leading edges. This nickel-chromium base alloy, which has outstanding oxidation resistance, structural stability, and moderate strength up to 2400°F, is strengthened by a microscopic and uniform dispersion of thoria (ThO_2). Primary development was for long service in severe applications at temperature ranges served by superalloys and coated refractory metals. TD-NiCr, however, has not been produced in large quantities, and reproducibility of alloying and material behavior requires further verification. The alloy also exhibits property loss if severely worked in the recrystallized condition. Basic fabrication characteristics must be developed consistent with projected design considerations. Although oxidation resistance appears outstanding, further verification of this resistance is necessary, under cyclic low-pressure conditions.

  Environmental parameters influencing the application of materials in hypersonic and reentry vehicles have been defined by Lockheed and by various Government agencies. Lockheed has recently designed and evaluated a test simulator capable of operating simultaneously under programmed loads and reduced pressures and temperatures for unlimited lapsed-time cycles. Complex specimens with dimensions up to 5-1/2 by 10 inches can be cyclic loaded and exposed to flight profiles. This equipment provides a test facility for evaluation of TD-NiCr alloy and coated refractory alloys under environmental reentry conditions of pressure, temperature, and loads.

On the basis of available data, columbium alloy, Cb 752, in the single-annealed heat treatment condition is the most promising candidate of the second-generation columbium alloys. Severe losses in ductility after exposures to a 1700°-2100°F temperature range have been experienced with duplex-annealed material. The more temperature-stable single-annealed condition is more promising where a reusable structure stressed at or near room temperature is required. Evaluation and verification of behavior for coated columbium alloys are necessary to ensure desirable mechanical properties and ductility after fabrication, welding, coating, and flight simulation. Also, the creep characteristics of Cb 752 must be fully defined.

- High-temperature/refractory material protection systems capable of withstanding the high-temperature, low-pressure oxidizing environment must be investigated or developed to ensure optimum integrity, reliability and reusability.

- High-temperatures generated in entry necessitate further investigation of ablative materials for use in areas such as the nose cone, removable doors, accesses, and heat shields. Ease and cost of refurbishment or replacement are prime considerations.

- The design of an efficient structure dictates the use of advanced fibrous composite materials, such as boron and graphite in metallic and organic matrix materials. Physical and mechanical properties, coupled with forecasts of decreased material and fabrication costs, make these items especially attractive. Lockheed has been engaged in programs to develop proficiency in the design, application, manufacture, and test of hardware, using boron/epoxy, graphite/epoxy, and boron/aluminum composites. These programs include boron/epoxy (Air Force contract) used in the design, fabrication, and test of a C-5 aircraft wing slat. A removable door panel for a spacecraft equipment section is now being fabricated from high-modulus, graphite/epoxy, corrugation-stiffened material. Also, a spacecraft design that makes use of fibrous composites is nearing completion; and Lockheed is conducting a continuing IRAD program to develop boron/aluminum composite materials. Planned work by Lockheed will include an investigation of attachment methods for typical spacecraft and aircraft. High-temperature matrix materials, such as the polyimides and polybenzimidizoles, appear as prime areas for continuing development of both graphite and boron reinforced composites for Space Shuttle structural application where temperatures in the 500°F range are anticipated. Localized strengthening of aluminum structure with tapes of advanced composites will be used to advantage where environmental and compatibility considerations dictate other than purely composite structure.

Current and future programs should develop the design and materials data, manufacturing and inspection/test technology, and the confidence required to use the advanced composite materials in the Space Shuttle.

- The temperature extremes to be encountered require improvements in sealants, adhesives, coatings, lubricants, and plastic materials. The ability to endure the repetitive long-duration space and earth environmental exposure, compatibility with liquid and gaseous propellants, and flammability must also be investigated.

- Electrical insulations and terminations require improvements. Flammability, durability, weight considerations, and electrical integrity are controlling requirements.

- Various thermal insulations such as LI-1500, microquartz, dynaflex, cellular organics, and multilayer systems need to be fully developed for internal tankage installation, external insulation, and locations below heat shields and structure. Performance must be evaluated, application methods improved, inspection procedures devised, and refurbishment or repair techniques analyzed.
- Thermal analysis of attachment techniques for insulation systems (e.g., multilayer, LI-1500) must be initiated; material type and thickness must be predicated, in part, upon effect of heat leaks due to method of attachment to vehicle surfaces.
- Thermophysical properties (solar absorptance, infrared emittance, and thermal conductivity) of materials to be used as insulators, ablators, or passive thermal control must be established. Effects of prelaunch, ascent, stationkeeping, and reentry environments, must be determined in order to predict operating temperatures for the Space Shuttle. Ability of such materials to withstand thermal cycling and reentry conditions will dictate reusability/refurbishment requirements.

5.2 THERMAL PROTECTION SYSTEMS

The thermal protection system, which will be a major portion of the vehicle structure, is considered to be one of the key technical areas. Both the basic material and unique structural-thermal concepts evaluation is necessary. Several thermal protection systems, including metallic, nonmetallic and ablators, exist; however, additional testing and design studies in which such factors as reliability, reusability, structural efficiency, refurbishment, inspection, cost, and development and refurbishment time are considered, are required before the final selection is made.

5.2.1 Metallic Heat Shields

Shielding requirements of reusable reentry vehicles make further development in **superalloy** and refractory metal shields necessary. Problems to be encountered in reuse require definition before solution.

LMSC is currently conducting an ID program to develop superalloy/refractory metal heat shield capability from analysis design and manufacturing technologies. Damage tolerant designs exceeding current state-of-the-art are receiving major emphasis. An environmental test apparatus being calibrated is capable of duplicating realtime thermal, stress, and atmospheric conditions to investigate the capabilities of refractory metals and proposed joining methods. The coating sensitivity to low pressure is a key factor.

Full-scale large-panel tests duplicating the entire flight environment are required. Flight loadings, consisting of air, thermal, acoustic, and dynamic factors, must be duplicated; and investigations of existence and effect of local hot spots on shielding metals must be conducted. The cumulative effects and possible repair associated with recycling of environments compatible with this intended flight usage must be investigated.

5.2.2 Nonmetallic Heat Shields

Current lightweight, rigid, high-performance materials appear to be promising as a thermal protection system.

During the past few years LMSC has been developing such a material system, identified as LI-1500. This is a rigid silica system weighing 15 lb/ft^3. Considerable elemental testing, including thermal, mechanical, and environmental, has been conducted on LI-1500. Results indicate that this material system has significant merit in weight and cost savings and in design simplification, relative to existing metallic reradiative heat shields or ablative systems.

Additional LI-1500 panel and component testing is required to establish compatability with the substructure, attachment methods, joining techniques, RF transparency, and overall design criteria.

5.2.3 Ablative Thermal Protection Systems

The following developments are necessary:

- Ablator designs that are readily refurbished with a minimum of cost, equipment, and time
- A suitable ablative material with predictable properties for long heating periods during lifting entry
- An ablator that has adequate physical properties and is compatible with the load-carrying structure

The thermal environment for lifting reentry trajectories suggests ablators with the following characteristics:

- Low density
- Small char formation with high char strength
- Minimum char recession (spallation or oxidation)
- Thermal conductivity to limit heat conducted to substructure

The prime consideration for long entry time environments is the thickness of char formed and the amount lost through chemical oxidation and mechanical erosion. Thick char layers formed during long entry time and low heat rate environments experience thermal stresses that could cause spallation and precipitate mechanical erosion. The material system to be chosen must have char layers that resist spallation and exhibit good resistance to oxidation. For panel applications, current methods to reduce char erosion of silicone materials make use of glass fibers or a phenolic honeycomb encasing the basic silicone material. Another reinforcement method with good erosion resistance, but developed only to laboratory level, involves the use of a rigid felt or rigid fiber reinforcement.

Sustained heating produces hot melt layer over deep char. The char becomes progressively thicker and more porous. Longer heating also increases time for silica/char reactions, further weakening the surface char zone. Net effect is a char that becomes increasingly less insulative and progressively more susceptible to mechanical spallation. If deep char is thus removed, the remaining virgin material overheats, allowing bondline failure and loss of substructure strength.

The temperatures associated with long thermal soak cause expansion problems that can further aggravate mechanical integrity, especially in the pyrolysis zone, where expansion reversals occur. This internal expansion can open gaps between ablator and substructure and between ablator and radiative structure.

Ablative panels are made up of two basic components - an ablative stratum and a substrate to facilitate mounting. The feasibility of total or partial reuse of each panel must be considered. Definitive refurbishing techniques will depend on the specific design of the panel as well as the condition and characteristics of the material at the time of refurbishment.

Since the substrate generally encounters no temperature that could degrade its mechanical and physical properties, any refurbishment consideration will be governed by the characteristics of its interface to the ablative stratum. However, if under operational conditions, the substrate should be damaged to such an extent as to require refurbishing, the panel design should be questioned. It is anticipated that properly designed installation and removal methods for the panel assembly will meet any refurbishment requirement.

Several possible refurbishment considerations and their respective potentials applicable to orbiter vehicle application are presented in Table 5-1. For simplicity, a glass honeycomb reinforced silicone elastomer system is considered to be representative.

To evaluate the merits of refurbishment, the exact behaviors of the ablative material on various degrees of exposure must be determined. This can be accomplished by simulated entry environment testing, after which the handling characteristics of the degraded system as well as the boundary line of the virgin material **are** established. Techniques for refurbishment must vary with the panel shape.

The use of a rigid felt or fiber reinforcement, such as LI-1500, shows considerable promise for simple refurbishment by employing subliming resins as coolants in an LI-1500 matrix (passive transpiration system). This system

Table 5-1

POTENTIAL SCHEMES FOR REFURBISHING ABLATIVE STRATUM

Scheme	Advantages	Disadvantages	Potential for Orbiter Application
Trim off affected layer and replace with new layer	Applicable to all conditions Controllable process Total removal of consumed material Rebuildable with virgin material Surface finish controlled Easily inspected In-position refurbishment possible (but difficult)	Reinstallation variables New interface layer Density deviation possible Reinformcement continuous in thickness direction	Best
Replace entire ablative layer (ablative not permanently affixed to substrate)	Accomplished in-position Short installation time Identical to original condition	Feasible only for a specific attachment method Geometric restriction	Moderate
Refill and revitalize consumed area	Unknown	Only for specific operation condition Complete removal of old material not possible Duplication of original material not possible Skill required Complicated process Difficult to control High cost	Worst

may be refilled after entry exposure by a simple immersion in the thermally efficient resin and reconstituted for reuse.

Employment of combined ablative and radiative panels as a heat protective system with the ablative panels located upstream of the radiative panels introduces complex design interface problems and possible chemical reaction of ablator decomposition products with a refractory metal protective coating.

5.3 MOVABLE THERMAL HINGES

It is necessary to establish the structural-thermal integrity of movable surfaces of a lifting reentry body. Examples of these surfaces are aerodynamic control surfaces, landing gear doors, and payload compartment doors. The basic problem is to develop satisfactory bearings or hinges for attaching 2000°F movable surfaces to 150°F primary structure. Such bearings are not presently available.

An LMSC ID program has been initiated to define workable design concepts for reentry body hot movable surfaces with adequate thermal-structural integrity. The program includes preliminary structural and thermal analyses, preliminary design, and fabrication of a functional demonstration model. High-temperature lubricants and bearing materials and joints providing rotation through elastic flexural or torsional deflections are being considered.

Detail analysis, design, development, and structural and functional testing under simulated flight environment will be required to solve the hot movable surface problem.

5.4 RESISTANCE WELDED AND BONDED STRUCTURE

Most of the problems associated with the technique of resistance welding through an adhesive lie, as with all new developments, in establishing adequate quality assurance techniques. Techniques proposed and tested include x-ray, ultrasonic, electroinductive, and radioactive isotope testing. Of these, the ultrasonic technique seems to offer the most promising results.

LMSC has fabricated a series of liquid hydrogen tanks with the spot-bonded joint technology. These tanks were cycled, leak tested, and burst; the adhesive retained adequate ductility to provide a seal without crazing or cracking down at temperatures of -423°F.

A wealth of uncorrelated information exists on the strength of resistance welded adhesive joints. Much of the earliest work was done by the Russians, who have used this method for both primary and secondary structural applications in aircraft since 1956. Lockheed-Georgia Company has performed lap shear, tension shear interaction, and fatigue tests on this process, dating back to 1966. At LMSC some work has been initiated on determining suitability for application as tank joints. This joining method should be pursued further.

5.5 STRUCTURAL MECHANICS

To design optimum structural load-carrying elements and to minimize excessive weight penalties, a thorough understanding of total loading environments and their effects on the structural design and integrity of the vehicle is required. Many of the elements contributing to the loads are readily identifiable, and their effects on the vehicle can be adequately treated with current technological methods. On the other hand, aspects of the environment require more in-depth consideration and advancement of technology to ensure that accurate techniques are available to account for their effects in vehicle design. Among these are the dynamic and aeroelastic aspects of the loads, the acoustic environment, and the unsteady aerodynamics. In addition, accurate modeling of highly complex structures having widely varying stiffness and mass properties, nonlinear elements, and vastly different damping characteristics is required to define the structural response for the many loading conditions.

5.5.1 Problem Areas

Specific areas requiring solution or technology development are as follows:

- Vibro acoustic environmental definition and simulation - Definition of the acoustic environmental characteristics is necessary to ensure adequacy of the structure, proper definition of the fatigue life of various elements or panels, reliability of components, crew protection and to determine demands on ground support equipment. Acoustic vibration qualification test procedures must be optimized to eliminate substantial overtest and resultant weight penalties. Fatigue resistance of composites, laminates, and other structural elements subjected simultaneously or successively to high acoustic and thermal cyclic environments must be investigated.
- Unsteady aerodynamic effects - It is necessary to understand the unsteady aerodynamic effects over wide Mach number ranges for adequate analysis to be performed in the areas of buffet response, staging dynamics, panel flutter, etc. Oscillating shocks and local flow conditions in this area of radical body shape changes can cause severe surface and internal vibration problems. Unsteady flow (vortexing effect) associated with ground winds could impose serious loading conditions. Experimental data should be acquired to prevent costly redesign or the weight penalties of over design.
- Structural dynamic modeling and response analysis - Accurate dynamic modeling to determine dynamic response characteristics is required to define response due to transient loading effects (engine forces, winds, unsteady aerodynamic effects, POGO oscillation effects, etc.) Current techniques for handling the damping characteristics of the various structural components are not sufficiently systematized to provide rapid parametric evaluation of their effects on vehicle response. Modularized or model synthesis approaches can provide an improved technique in the final analysis in order to make full use of the computer capability.
- Aeroelastic effects - Aeroelastic characteristics of such primary Space Shuttle elements as the wings, fins, control surfaces, and panel elements must be established for varying flight regimes,

ranging from subsonic to hypersonic and including reentry flight oscillating shock and separated flow effects. Also, fatigue effects of low-amplitude flutter must be well defined.

5.5.2 Current State-of-the-Art and Technology

Considerable acoustic data are available from Saturn and other large propulsive vehicles. Data are presently being compiled and organized to compare with analytical predictions. Near and far field acoustic environments for candidate Space Shuttle engines are presently being studied by means of analytical techniques, based on specific impulse values, nozzle diameters, flow velocities, etc. Information regarding damping characteristics of candidate thermal protection surfaces is being compiled.

In the absence of wind tunnel data for the configuration considered, maximum use will have to be made to scale past tunnel testing of various booster and aircraft vehicle shapes; however, it is believed that this data will be of only limited use because of the complex flow patterns that will be generated by body interaction effects. Ground wind effects will most certainly have to be determined by wind tunnel testing or application of conservative design philosophy.

Finite element modeling techniques are well developed and have direct application to the Space Shuttle. Both LMSC's REXBAT and NASA's NASTRAN computer codes are usable for dynamic modeling of the individual vehicles and the combined vehicles. Development will be required in the representation of some vehicle elements, representation of nonlinear elements, response and structural interaction effects of liquid filled tanks, damping representation in components of the structure, and modal synthesis techniques.

5.5.3 Technology Development Requirements

- Environment definition and simulation - Methods must be developed for empirically predicting the response of typical panel structures and structural elements to acoustic environments. Predictions of these responses must be correlated with realtime data obtained through comprehensive laboratory testing. Dynamic scale model testing of the advanced propulsion systems must also be conducted. This should include measure of acoustic spectrums and spatial correlation effects for near and far field and determination of effects of mixed flow from adjacent engine patterns, correlated with predictive techniques.

To determine acoustic and vibration environments and surface pressure distribution due to inflight separated flow effects, it will be necessary to conduct wind tunnel tests to obtain amplitude and correlation data over a wide range of Mach numbers, angles of attack, and dynamic pressures covering ascent and reentry phases. These data are not available through means other than tunnel testing. Comprehensive laboratory test programs are needed to determine most optimum methods of test to simulate in-flight **acoustic and vibration environments.**

- Unsteady ærodynamics - Techniques to predict fluctuating pressure distributions and spatial correlation effects are needed. Also, scale model wind tunnel tests of each separate body and combined vehicle configuration must be conducted at various angles of attack, Mach numbers, and dynamic pressures, with fluctuating pressure distributions measured and effects correlated. Problems of scaling and interaction of flow effects with tunnel surfaces must be solved. **Extensive wind tunnel test data must be acquired for the booster and orbiter vehicles in various stages of separation, including control force and engine plume force effects. Data must be acquired at various Mach numbers, under various dynamic pressures, and at different angles of attack as a function of time or separation distance in order to define the complex aerodynamic flow fields and interaction effects. The repeatability of these data as a result of changes in parameters must also be established in order for credibility to be attached to separation analyses conducted.**

- Structural dynamic modeling - Continual development and improvement of methods in finite element modeling and computer codes to handle wider variety of structural elements is needed. Also needed are methods to handle dynamic response problems, including nonlinear effects and varying values of damping for different structural elements. Capabilities should be increased in areas of determination of total vehicle model properties by component mode analysis. Study must determine which model properties are critical and how boundary conditions can be adequately handled.

  Capabilities must be developed through model testing and analysis to enable proper dynamic representation of liquid filled tanks. Line-loss characteristics and propellant feed system parameters (pump characteristics) must be determined so that adequate analytical representation of the interaction between the propulsion system and structural properties (POGO effect) can be obtained. A computer program is needed for solving the response of two docking bodies when the input parameters are body flexibility characteristics, different orientations of the two body axes, and differences in the velocities,translations and roll motions.
- Aeroelastic effects - Wind tunnel tests over varying Mach number and angle-of-attack combination must be conducted to determine total vehicle and control surface aeroelastic stability effects for the individual vehicles and for the combined vehicle configuration during the exit phase of flight. This testing should be conducted in phases, with the first phase occurring early enough in the program and accomplished with a simlified dynamically representative model in order to identify any prior stability or flutter problems and to correlate with analytical representation. Final phase testing should be conducted with sophisticated models to demonstrate flutter-free design and to determine magnitude (if any) of limited amplitude flutter in order that fatigue effects can be properly identified.

5.6 CRYOGENICS

5.6.1 Reusable High-Performance Cryogenic Insulation

The tanks required for orbital transfer, maneuver, and retro in Space Shuttle must be insulated with high-performance, multilayer insulation. The multilayer insulation must be purged with helium during ground hold and the insulation is vented to vacuum during ascent. The purge is accomplished through theuse of an external purge bag over the insulation.

With the insulation under vacuum before reentry, the atmosphere will enter the insulation, resulting in water vapor condensation and other contamination. It is therefore desirable to maintain a slight positive pressure within the purge bag during reentry and this requires a differential pressure regulator and a suitable purge bag system surrounding the propellant tank insulation.

The accomplishment of these requirements necessitates the development of a "breathing" insulation system.

No programs have been conducted to accomplish this specific goal. However, extensive work has been done in the development of cryogenic thermal protection systems for space vehicles; and some past effort has been completed in the development of thermal protection systems for cryogenic hypersonic vehicles. Summaries of these programs are presented in References 5-1 through 5-30.

The recommended approach is to establish an orderly experimental program from laboratory to moderately large ground tests. Laboratory test and small-scale environmental tests would be conducted to develop the materials and methods.

The most promising concept would be selected, and a detailed design of this system would be made. A large-scale test article would consist of a liquid hydrogen tank (5 feet in diameter or larger), the selected thermal protection system, and a simulated propellant bay wall. Flight simulations would be performed in a cryogenic vacuum flight simulator through the sequences of environments paralleling those of an actual mission. The insulation would be developed to a flight application status.

5.6.2 Reusable Foam-Type Insulation Systems

The propellant tanks of the booster and the ascent tanks of the orbiter are proposed to be foam insulated. It is likely that protective purging and possibly purge bag protection will be required for the foam-type insulations.

Foam-type insulations have been used extensively in reusable ground systems, but not under the environments to be experienced by the Space Shuttle. Work is presented in References 5-31 through 5-34.

The objective of the test programs would be to determine the effects of the Space Shuttle mission profiles on foam insulation systems. The steps in the program would involve laboratory testing and scaled tank testing. The laboratory program would principally involve the effects on various foam systems from repeated cycling through the ground hold, ascent, vacuum, and reentry atmospheric conditions to which the insulations would be subjected. Both thermal and physical properties should be investigated.

Following laboratory testing, scaled tank tests should be conducted, with 5-feet or larger diameter tanks used. (This testing would require use of a cryogenic flight simulator.) Any necessary modificiations to the insulation system would be developed in these scaled tests.

5.6.3 Fracture Mechanics in Cryogenic Propellant Tankage

The principal problem in the development of cryogenic tankage for reusable vehicles is the required sustained loading, rather than the pressure cycling. Only meager information is available on the fracture mechanics of aluminum alloys and welded joints under sustained loading in contact with cryogenic propellants. Also, only a limited amount of data are available on tankage materials, such as 2219 aluminum and 2021 aluminum. Prior programs are listed in References 5-35 through 5-50.

The purpose of new programs would be to establish the parameters related to the fracture mechanics of propellant tank materials when exposed to extended loading conditions in contact with liquid hydrogen and liquid oxygen.

The programs would involve mechanical properties testing of candidate tank materials (aluminum and titanium alloys). Notched and unnotched specimens of base material and weldments would be used. Tests required in the expected environments include:

- Extended cyclic testing
- Testing with the material exposed to liquid oxygen and liquid hydrogen propellants

On the basis of the test results, the threshold stress intensity factors for each tank material will be determined for each propellant exposure.

REFERENCES - SECTION 5.6

References	Program	Contractor	Government Cognizance	Contract No.	Duration
5-1	Space Storable Propellant Module Environmental Control Technology	TRW Systems Group	NASA Pasadena Office	NAS7-750	Sep 1969-
5-2	Application of High-Performance Insulation to Large Conical Support Structures	Goodyear Aerospace Corporation	NASA Marshall Space Flight Center	NAS8-24884	Jun 1969- Jan 1970
5-3	Cryogenic Tank Support Evaluation	Lockheed Missiles & Space Company	NASA Lewis Research Center	NAS3-7979	Apr 1967- Jun 1969
5-4	Advanced Studies on Multilayer Insulation	Arthur D. Little, Inc.	NASA Lewis Research Center	NAS3-7974	Jan 1967- Jan 1968
5-5	Tank Mounted Insulation Program	McDonnell Douglas Astronautics Company	USAF Rocket Propulsion Laboratory	F04611-67-C0015	Oct 1966- Apr 1967
5-6	Nonmetallic Parts for Launch-Vehicle and Spacecraft Structures	Boeing Company, Aerospace Group	NASA Marshall Space Flight Center	NAS8-18037 Mar 1968	Jun 1966-
5-7	Lightweight Multilayer Insulation System	Union Carbide Corporation, Linde Division	NASA Lewis Research Center	NAS3-7953	Jun 1966- Feb 1968
5-8	Cryogenic Insulation Development	General Dynamics/ Convair	NASA Marshall Space Flight Center	NAS8-18021	Jun 1966- 1968

REFERENCES - SECTION 5.6 (continued)

References	Program	Contractor	Government Cognizance	Contract No.	Duration
5-9	Study of High-Performance Insulation Thermal Design Criteria	Lockheed Missiles & Space Company	NASA Marshall Space Flight Center	NAS8-20353	Mar 1966- Jun 1967
5-10	Fiberglas Supports for Cryogenic Tanks	Lockheed Missiles & Space Company	NASA Lewis Research Center	NAS3-12037	May 1969- Sep 1970
5-11	Lightweight Modular Multilayer Insulation	Union Carbide Corporation Linde Division	NASA Lewis Research Center	NAS3-12045	May 1969-
5-12	Analytical and Experimental Investigation into Problems Associated with Application of High Performance Insulation System Required for Modular Nuclear Vehicle	McDonnel Douglas Astronautics Company	NASA Marshall Space Flight Center	NAS8-21400	Jan 1969- Oct 1970
5-13	Thermal Performance of Multilayer Insulation	Lockheed Missiles & Space Company	NASA Lewis Research Center	NAS3-12025	Jun 1968 Oct 1970
5-14	Propulsion System Thermal Design Study	TRW Systems Group	NASA Pasadena Office	NAS7-711	1968
5-15	Investigations Regarding Development of a High Performance Insulation System	Lockheed Missiles & Space Company	NASA Marshall Space Flight Center	NAS8-20758	Jun 1967 Jul 1968
5-16	Partitioned Centaur Tank	General Dynamics/ Convair	USAF Rocket Propulsion Laboratory	F04611-67-C-C0004	1966- 1967

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References	Program	Contractor	Government Cognizance	Contract No.	Duration
5-17	System Effects on Cryogenic Propellant Storability and Vehicle Performance	McDonnell Douglas Astronautics Company	USAF Rocket Propulsion Laboratory	AF 04(611)-10750	Mar 1965-
5-18	Lightweight Self-Evacuating Prefabricated Multilayer Insulation System for Cryogenic Space Propulsion Stages	Union Carbide Corporation Linde Division	NASA Lewis Research Center	NAS3-6289	Jun 1965- Jul 1966
5-19	Thermal Protection System for a Cryogenic Spacecraft Propulsion Module	Lockheed Missiles & Space Company	NASA Lewis Research Center	NAS3-4199	Jun 1964- Dec 1965
5-20	Cryogenic Insulation Research	Martin-Marietta Corporation, Baltimore Division	NASA Marshall Space Flight Center	NAS8-11397	Jun 1964- Aug 1965
5-21	Design of High-Performance Insulation Systems	Lockheed Missiles & Space Company	NASA Marshall Space Flight Center	NAS8-11347	Jun 1964- Aug 1965
5-22	Development of Materials and Materials Application Concepts for Joint use as Cryogenic Insulation and Micrometeoroid Bumpers	Goodyear Aerospace Corporation	NASA Marshall Space Flight Center	NAS8-11747	Jun 1964-

REFERENCES - SECTION 5.6 (continued)

Reference	Program	Contractor	Government Cognizance	Contract No.	Duration
5-23	Development of a Lightweight Cryogenic Insulating System	Goodyear Aerospace Corporation	NASA Marshall Space Flight Center	NAS8-11761	Jun 1964 May 1966
5-24	Advanced Studies on Multilayer Insulation Systems	Arthur D. Little, Inc.	NASA Lewis Research Center	NAS3-6283	Mar 1964 Jun 1966
5-25	Basic Investigations of Multilayer Insulation Systems	Arthur D. Little, Inc.	NASA Lewis Research Center	NAS3-4181	Dec 1963 Oct 1964
5-26	Structure/Cryogenic-Insulation Integration	Martin-Marietta Corporation Baltimore Division	NASA Marshall Space Flight Center	NAS8-5300	Jun 1963 May 1964
5-27	Structure/Cryogenic-Insulation Integration	North American Rockwell Corporation	NASA Marshall Space Flight Center	NAS8-5268	Jun 1963 May 1964
5-28	Propellant Storability in Space	General Electric Company, Missile & Space Division	USAF Rocket Propulsion Laboratory	AF 04(611)-9078	May 1963- Jun 1964
5-29	Liquid Propellant Losses During Space Flight	Arthur D. Little, Inc.	NASA Headquarters	NASw-615	Dec 1962- Sep 1963
5-30	Liquid Propellant Losses During Space Flight	Arthur D. Little,	NASA Headquarters	NAS5-664	Sep 1960- Nov 1962

REFERENCES - SECTION 5.6 (continued)

Reference	Program	Contractor	Government Cognizance	Contract No.	Duration
5-31	Insulation System for Liquid Methane Fuel Tanks for Supersonic Cruise Aircraft	Martin-Marietta Corporation Denver Division	NASA Lewis Research Center	NAS3-12425	Apr 1969 Feb 1971
5-32	Thermal Protection System for Liquid Hydrogen Fuel Tanks in High-Speed, Long Range Aircraft	Rand Corporation	USAF	AF 49(638)-66-C0001	Oct 1965
5-33	Hydrogen Tankage Application to Manned Aerospace Systems	General Dynamics/ Convair	USAF Systems Command, Research and Technology Div.	AF 33(615)-2048	Sep 1964-1967
5-34	Research on Hydrogen Fueled Hypersonic Vehicles	General Dynamics/ Convair	NASA Langley Research Center	NAS1-4017	May 1964- Dec 1964

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5.7 THERMAL CONTROL SURFACE DEFINITION AND DEVELOPMENT

The average temperature of a spacecraft on orbit is a function of several parameters; two of the most important are the ratio and external surface solar absorptivity to infrared emittance (α/ϵ) and the internally generated power level. Spacecraft systems are normally provided with a specific surface coating capable of withstanding the ascent and orbit environments. Any coating applied to external surface of the Space Shuttle must either survive reentry or be re-applied between flights. If the inherent characteristics of the external skin are adequate for orbit temperature control (without a special coating), the system reusability is greatly enhanced.

The proposed effort will involve the measurement of α and ϵ for candidate external surfaces. Measurements will be made to establish nominal values, tolerances and the effects of repeated use.

The applicability of these properties will be established by analysis to determine resulting on-orbit temperature levels. Should it be determined that inherent characteristics of candidate skins are not adequate, a development program for a specific surface coating or treatment will be prepared.

Section 6
AVIONICS TECHNOLOGY

Avionic requirements for the Space Shuttle do not entail the need for a breakthrough in technology; however, improvements in technology are required. Integration of avionics functions is the primary technique for significantly reducing system weight, power, and cost. Required improvements in technology at the subsystem and system level are identified in the following paragraphs.

6.1 ELECTRICAL SYSTEMS

The Space Shuttle has several requirements that affect electrical system development technology. For example, the 1-hour entry period following deorbit imposes a nonradiative cooling problem on both the primary and standby power systems. Fuel cells, the leading candidate as a primary source of power for the orbiter, will require open-cycle operation or possibly evaporative cooling. Also, the standby battery system will have to be actively cooled. Lightweight, high-efficiency, power control and distribution systems will be required because of the wide dispersement of electrical user equipment throughout the vehicle. The short turnaround time will require repairable or replaceable hardware units.

In the past, a valuable design tool has been the spacecraft or aircraft electrical mockup. On vehicles of the size and complexity of the Space Shuttle, however, the cost of construction and use of such a mockup would be prohibitive. The use of flat conductor cabling with its predictable characteristics makes it possible to consider some type of simulation techniques that would provide all the practical test data of a full-size electrical mockup with much lower cost and facility requirements. In addition to the wiring, a simulation technique must be developed for loads and power sources. Once developed, such a power system simulation technique could be used for Space Station as well as Space Shuttle or other advanced spacecraft design.

Specific developments for power sources, power distribution, and power conditioning are presented below.

6.1.1 Power Sources

6.1.1.1 Fuel Cells. The present limit of 2000 to 3000 hours of life should be increased toward a goal of 10,000 hours. This increase applies to the fuel cell system and includes pumps and valves.

Electrochemistry improvements would contribute to reduced weights, improved performance, and longer life. Attainment of improved control of electrolyte position, of cell voltage closer to theoretical, and of less voltage drop with increased load and operating time is desirable.

Easy servicing of fuel cell system components is required to reduce operating costs. Access to and ease of removal of modular components is also desirable. Aircraft maintenance should be allowed for in the design to help attain the increased life goal.

To allow increased current densities, methods of high rate heat removal should be developed. These methods include water injection and boiling and the application of heat pipe technology.

The use of the Space Shuttle H_2 and O_2 propellants for fuel cell reactants is a desirable integration method. Methods for conditioning these materials to remove carbon-bearing impurities and for using low-pressure reactants must also be developed.

6.1.1.2 Chemical Turbine-Driven Alternators. Effort in this area has been essentially dormant since the Dyna-Soar program. The use of the Space Shuttle propellants for power generation requires advances in H_2-O_2 combustor design and control and the application of advances in turbine design and materials to a long-life H_2-O_2 turbine system.

6.1.1.3 Batteries. To reduce the cost of high-rate emergency batteries that are not normally used, long stand life and fast battery activation technology requires continued development.

The short-duration booster mission can be reliably powered by a battery system. The development of high-rate, low-weight battery systems with adequate cooling and the highest possible degree of reusability is required to reduce costs.

6.1.1.4 Cruise Engine Power Takeoff. Significant reductions in generator system weight can be achieved through eliminating constant-speed drives with variable speed, constant-frequency generator technology development.

6.1.2 Power Distribution

6.1.2.1 Distribution Voltage. Up to the present, distribution of primary power at 28 vdc and 115-v 400 Hz ac has been adequate for most spacecraft. However, because of its size and complexity, the Space Shuttle requires optimum power distribution voltages. A study must be made to determine the optimum voltage, with attention given to the magnitude and location of major power loads, the overall power distribution concept(centralized versus decentralized or isolated power sources), the aircraft/spacecraft operational phases, the cost of redesign and requalification of components if a new operating voltage is selected, and reliability and crew safety. This study must have high priority because of potential impact on the development of both power sources and major power-using subsystem components.

6.1.2.2 Lighweight Circuit Components. Concurrent with the voltage optimization study, work must continue on the development of lightweight wiring (flat conductor cable, ribbon cable, and aluminum wire) for spacecraft power and signal distribution. Also, the development of lightweight solid-state circuit breakers to meet the Space Shuttle power switching requirements and match the integrated avionics and power control and protection concepts must be initiated. One desirable development in the use of multiconductor wiring would be a computer program to aid cable design and routing. Such a program would save many manhours of design time.

Lockheed is active in both of these areas. Flat conductor cable is being used on one Agena flight program and is being designed for another. The Lockheed S-3A aircraft will employ this technique extensively. A solid-state switch has been developed for deep submergence vehicle use. Additional development and testing of this device would be required for space use.

6.1.3 Power Conditioning

Excellent progress has been made recently in solid-state inverter technology with the development of the harmonic stepped wave inverter by Engineered Magnetics Division of Gulton Industries. When an optimum Space Shuttle distribution voltage is selected, this technique could be used to develop a lightweight high-power static inverter.

6.2 HIGH-SPEED DATA BUS SYSTEMS

Traditionally, information transfer between avionic items has been accomplished by multiconductor cable. With the advent of integrated circuits, signal multiplexing as a means of reducing the cabling weight has become feasible. Transmission of data over a single coaxial cable at rates of 1 to 6 megabits per second can be considered. Further improvement can be achieved by the use of a standard interface unit between the avionics equipment and the data bus.

Improvements in the Apollo modem processors and command systems, which interface with the data bus, are necessary to meet Space Shuttle requirements. Significant development will be required to achieve redundant, fail-safe, and self-test operations, as well as increased reliability. The command system must have the increased capability to meet the requirements for rendezvous, docking, and earth landing.

A mincom system involving time division multiplexing has been considered for the Lockheed S-3A aircraft. An overall wiring weight reduction of 422 pounds is achievable. Design of a suitable standard interface unit is underway. One task in the 1969 LMSC microelectronic independent development program is the design and fabrication of a 16-channel multiplexer and a family of hybrid circuits suitable for digital data processing.

There is considerable interest in ultrasonic and optical signal processing to permit the simultaneous handling of a large number of signals. LMSC has included this task as part of the independent research program for the past 2 years.

The LMSC independent development program has also funded several tasks in the laser communications field. These could provide a background of knowledge and capability applicable to high data rate systems. One task is devoted to the determination of optimum design and characteristics of solid-state lasers for use in wideband communication systems. A second task is conducting research on techniques for modulating lasers emitting in the visible spectrum, with the specific aim of reaching information bandwidths of 1 GHz, with 20 to 40 percent depth of modulation. A third task is devoted to the determination of the most suitable modulation system and format for use in a wideband laser communication system. This study will also provide data needed for overall system design and performance analysis.

6.3 ELECTRONIC CONTROLS AND DISPLAYS

An all-electronic flight and status display and a heads-up display used in conjunction with the command control devices (namely, the electronic system inputs, such as solid-state switching, stick, throttle, and keyboard, etc.) warrant a significant development program. Cathode ray tubes (CRT), programmable and controllable, are expected to represent the primary media for displaying single or simultaneous multiple events. Selection of single versus multiple gun, color versus black and white, or even three-dimensional CRTS require study.

The following hardware developments should be investigated:

- Electronic attitude indicator
- Electroluminescent status displays
- Digital event time control and display
- Multiparameter display
- Plasma displays
- Space-qualified version of the CRT

The advantages of solid-state control/display devices for space application are well known. LMSC recognized the importance of this technology in 1965 and produced a number of electroluminescent bar graph meters. Considerable research was conducted concerning element thickness, phosphor composition, drive voltage, brightness, manufacturing and packaging, power consumption, weight, and useful life. A human factors evaluation was performed in the LMSC Space Station simulator to obtain knowledge in the integration of such devices into the crew station.

The complexity of the Space Shuttle causes a shift in the evaluation weighting and in favor of the solid-state devices. Current LMSC evaluations of electroluminescent displays in conjunction with CRTs currently available tend to show that major electroluminescent use will be for dedicated displays such as caution and warning functions or critical information displays, which require continuous and specific information availability to the crewmen. The wide flexibility of the CRT for alpha numerics and graphics as well as color make it a more attractive device for integrated display.

Lockheed has made extensive evaluations of tactical CRT display systems for use in the S-3A aircraft. Control and display studies for use in the Lockheed 1011 Tristar also involved evaluation of the electronic attitude director indicator as well as CRTs for general-purpose readout. These study results are being incorporated into LMSC design considerations. Breadboard simulation studies are planned at LMSC to investigate instrument configurations, data presentation format and symbol designs, compatibility with keyboards and other input devices, etc., with parameters specific to the Space Shuttle used.

6.4 SELF-TEST AND WARNING SYSTEMS

In the manned spacecraft program, checkout has been conducted in detail as a ground function. During flight, status has been monitored by ground controllers with caution and warning information provided onboard to the crew. A self-test and warning system is required to provide checkout from the factory build-up and throughout the operational life of the Space Shuttle. The system must be highly reliable and must possess a high degree of flexibility to meet the diverse vehicle test requirements. Current systems are not capable of meeting Space Shuttle requirements; therefore, a technology program must be initiated.

A system concept must be established well in advance of spacecraft subsystem design, since techniques that depend on the development of self-test within each equipment or subsystem are preferred. Furthermore, standardized interfaces are desirable.

The primary area that requires development effort is the signal conditioning system. A highly reliable microelectronic system, in which the system itself and its companion transducers are operated from programmed power, is desirable.

6.5 CONFIGURATION AND SEQUENCING CONTROL

A configuration and sequencing control system will perform automatically the checklist function to establish the required system configuration and verify status for a go condition. A completely automatic onboard system has never been used on manned vehicles. A technology program is needed to define system concepts. In addition, development of electronically controlled fuses, relays, and circuit breakers and switches is required.

As part of its independent development program, LMSC has conducted studies on solid-state switching devices, with an objective of developing basic circuit designs for high-reliability, low-weight switches for satellite applications.

6.6 TRACKERS AND SENSORS

Tracking and sensing aids will be required to assist guidance, control, and navigation in all phases of the mission. Development programs are needed in several equipment areas. Of major importance is a concerted materials program on environmental protection materials for the sensor ports, since the material must be transparent at the operating frequencies.

Several requirements can best be resolved by using radar technology. Satellite tracking, weather avoidance, terrain avoidance, and collision avoidance are tasks that are currently assigned to specialized devices. Since one mode of operation is required at any one time, these tasks could be achieved by using a multimode radar with built-in redundancies to provide reliability. Successful development of this device would be a significant contribution toward providing a low-cost transportation system.

The requirement for an automatic docking device requires development of a suitable docking sensor. Range and range rate during the final docking phase must be extremely precise. Laser technology appears to be attractive; however, operation at short ranges requires further development. Lockheed's independent research on lasers, which is directed at wideband communications applications, could contribute to the solution of the docking problem.

Increased applications for onboard television are required for the Space Shuttle. Improvements are needed in camera life, performance, and size. Specifically, higher resolution, improved motion rendition, and a wider dynamic range to cover a wide range of ambient illumination levels are required.

6.7 COMMUNICATION SUBSYSTEM

Since communication requirements during launch, orbit injection, and landing are no more severe than for present systems, the basic technology exists. However, technological advances are needed in certain areas; and equipment development will be required to achieve an integrated system with the required reliability and maintainability features.

The requirement for communications via a relay satellite during the period from orbit injection to reentry entails technological advances. Also substantial antenna gain is needed for this link. Emphasis should be placed on phased-array technology, including efficient means for generating increased microwave power and for achieving low-noise reception with devices that are integrated with the antenna structure. In addition, means for generating multiple independent beams and for the reduction of beam steering power are necessary.

A significant technological development is required to ensure that antennas survive the thermal effects of the reentry environment.

Laser communication systems offer potential advantages over microwave systems in that extremely high antenna gain may be obtained with very small apertures. Weight and volume requirements could be reduced and structural problems minimized. Also, optical wavelengths are not significantly affected by reentry plasma, thus providing a potential solution to the communication problem. Lockheed's substantial independent research program on lasers is presently directed toward wideband communications between a low-altitude satellite and a synchronous data relay satellite.

Antenna systems are under investigation in several independent development programs. For example, a switched-beam, phased-array system suitable for use with a data relay satellite was started in 1969. This is the initial effort of a 3 year program leading to a demonstration model. A multipurpose satellite antenna under study is an elliptical reflector, which achieves substantial interchannel isolation because of inherent polarization effects in the antenna. A microminiaturized, electronically tunable receiver, which can be integrated physically with an antenna-radiating element for use as part of a phased-array or a repeater system, is also being developed. The design goals include a tuning range from 1.5 to 2.3 GHz and a noise figure of less than 5 db, with an IF bandwidth of 100 MHz. Components have been designed, and the receiver is being fabricated.

Concurrent with antenna systems studies, transmitter and receiver characteristics must be studied to reduce the antenna design problem and to implement an integrated RF system approach. Providing an optimum design for an advanced communication system entails evaluation of many interrelated parameters. In 1968, LMSC devoted a portion of its independent development funds to the development of a computer-aided parametric systems analysis technique for use in evaluating the feasibility of communications systems. The program is now focused on investigating the feasibility of pointing narrow-beam parabolic reflectors, as well as other aspects of satellite relay systems.

Multichannel selectable frequency transmitters/receivers must be developed. The receiver development should follow one of two approaches - use of wideband RF amplifiers and filters or use of a single wideband receiving system with adaptable RF from end stages for different frequencies. Low-noise solid-state preamplifiers also must be developed.

LMSC has recently completed an independent development program to investigate the suitability of microelectronics and miniature components for spacecraft applications and the development of circuitry and techniques leading to a marked reduction in size and weight of superheterodyne receivers. Two prototype receivers were designed, fabricated, and evaluated. Finally, a project is underway to design, develop, and test an S-to-X band repeater suitable for satellite applications.

High-power (approximately 100-watt) transmitters are required for the satellite relay link. Solid-state exciter stages are available; however, development of suitable power amplifiers is required. LMSC has had an independent development program underway since 1968 on solid-state power amplifiers. This current effort is concentrating on the fabrication of amplifiers operating at S band.

6.8 INTEGRATED GUIDANCE, NAVIGATION, AND CONTROL SYSTEMS

Reusable integrated redundant guidance, navigation, and control systems capable of providing the complete mission guidance and control functions from launch through landing must be developed. This entails development in the areas discussed in the following paragraphs.

6.8.1 Integrated Systems Analyses

System requirements and design criteria for all flight phases must be prepared for use in tradeoff studies. Guidance equations to be used in flight path-optimum options to provide a rapid and absolute convergence of all conceivable combinations of system and mission parameters must be studied. The blending of aerodynamic and reaction controls at the entry interface must be studied. The requirements of manned and automatic terminal landing systems must be studied in detail. The blending of manual and automatic control capabilities for all flight phases must be studied.

6.8.2 Unitized Sensor Pointing System

Several instruments to sense the outside world for navigation and control information are required. Precision alignment and alignment stability between the navigational reference and its sensor are required. The development of a concept in which the detection (and transmitting for active sensors) sensor subassemblies would be mounted on a common mounting plate suspended by a single two-axis gimbal structure should be undertaken. This combination of detecting subassemblies and two-axis gimbal mounting constitutes the system. The principal problem to be solved is that of marrying a single servo system to a variety of detection schemes, each possessing its own acquisition strategy and track transfer functions.

6.8.3 Inertial Reference Unit

Parallel evaluation of strapdown and gimbaled all-attitude inertial reference units must be conducted.

6.8.4 Solid-State Hand Controller

A hand controller with solid-state switches rather than the multiple cycle-limited relays must be evaluated.

6.8.5 Redundant CG&N Data Processor

A dedicated redundant CG&N data processor must be evaluated.

6.8.6 Structural Mode Alleviation Systems

The overall performance of an autopilot-controlled vehicle is dependent on an accurate representative of the vehicle's elastic motion. The output of the control systems sensors that are located at various points along the vehicle will contain both local rigid body and elastic information to be fed to the control system. The flexibility effects become important in the overall analysis of the flight characteristics. The need exists to study the structural integrity of the various Space Shuttle configurations with mode alleviation systems to bring to light any structural problems that could affect the selection of the final configuration.

A program is required to establish the mode alleviation system requirements, if any, during the boost and recovery/reentry phase. Both mathematical and analog studies are required.

Associated experience as part of the LMSC independent development program on the following subjects could be useful in the guidance, navigation, and control study programs:

- Dynamic and performance software (reentry and trajectory/performance optimization)
- Strapdown guidance error analysis
- Autonomous guidance for ascent and descent
- Reusable spacecraft stabilization and control hardware
- Control systems for reusable spacecraft

6.9 INTEGRATED ELECTRONIC SYSTEMS

Development programs for avionic subsystems must be keyed to an overall integrated electronics development program. System decisions based on an orderly development program are needed to establish guidelines for subsystem designs. One critical decision is the degree of centralization of computational functions.

System level decisions must be based on adequate test data. Simulation testing is required to ensure compatibility of the individual subsystems. Both ground and airborne simulations are required. Flight and trajectory related forces and loads could be simulated by digital analog hybrid computers. High torque and control element inertias could be mechanically simulated. Actual pilot displays and controls would be used; however, targets such as landing fields, the Space Station, and docking ports would be simulated mechanically, electrically, or optically. The LMSC Space Station simulator would provide an excellent facility for these tests. Flight test simulation would be used to test functional operations for which ground simulation of the flight environment would be too difficult or not sufficiently representative.

The LMSC independent development program has funded two tasks that could provide knowledge and capability applicable to the integrated electronics development effort. The first is the development of a general-purpose digital computer for application to advanced avionics systems. Prototype hardware is being fabricated for test in the LMSC simulation laboratory.

The second is a major program, started in 1968, to design and develop a complete vehicle digital processing and computation system and to demonstrate its capability in a hybrid computer laboratory with simulated realtime inputs from vehicle sensors and a command link. The integrated computer system, under the control of the operational program stored in its memory bank, will perform process algorithms on sensed data. Outputs are directed to a downlink, used for detection of malfunctions or retained as source data for autonomous vehicle operations. The computer employs its stored instructions to solve mathematical equations relating to various navigation and control functions and either stores the solutions for subsequent computations, multiplexes them on the downlink, or outputs low-voltage commands suitable for control of vehicle operations. Many conceptual designs have been evaluated. Detail designs have been completed, and breadboards are being fabricated for use in simulated realtime demonstrations in the hybrid computer laboratory.

Section 7

BIOASTRONAUTICS

7.1 ECS/LSS TECHNOLOGY

Expansion or refinement of technology to meet the needs of the Space Shuttle program is needed in the following areas:

- Radiator
- Noise control
- Chemical oxygen systems
- Waste management and personal hygiene
- Reusable ECS
- Multimode ECS
- Suit loop elimination
- Equipment temperature control system design

7.1.1 Radiator

Various coolants, such as MSC 198, ethylene glycol/water mixtures, or plain water, are used in the present active cooling systems. Water is the ideal coolant because of its high specific heat capacity and incombustible nature. During periods of minimum heat rejection and with the radiator exposed to its coldest conditions, water or other coolants can freeze in the radiator. This may be prevented by incorporating various control techniques, such as freon interchange systems or zone freezing of selected radiator panels. Other approaches should be investigated to determine the optimum radiator configuration for the Space Shuttle.

7.1.2 Noise Control

Present noise levels generated from ECS equipment, such as compressors and pumps, are extremely high. Methods of reducing noise levels through equipment improvements or additions of acoustical insulation are highly desirable.

7.1.3 Chemical Oxygen System

For short duration missions, the conventional approach is to use lithium hydroxide for CO_2 removal and oxygen stored cryogenically or as a high-pressure gas. Cryogenic storage of oxygen is not completely satisfactory for the long hold times that might be encountered during prelaunch or rendezvous and docking, and storing oxygen as a high-pressure gas involves a high weight penalty. The optimum system design would be a simple lightweight O_2 supply and CO_2 removal system. Chemical systems have been investigated for this purpose, with the bulk of these investigations directed towards superoxide systems. Such systems entail low weight, volume, and power; and they are highly storable. On the other hand, they have the disadvantage of system imbalance (O_2 supply vs CO_2 removal) and, more important, the safety hazard of an uncontrolled chemical reaction with water, yielding large amounts of heat and excessive oxygen. It has been demonstrated that a lithium peroxide system used with the proper catalyst can be controlled to give the proper O_2/CO_2 system balance without encountering the safety hazards of the superoxide system. A lithium peroxide system would be lighter weight, smaller, and more easily packaged and stored than the separate oxygen and CO_2 removal systems presented used. Such a system would be particularly advantageous for long, inactive docking periods.

7.1.4 Waste Management and Personal Hygiene

Present methods of waste management involve considerable effort and extensive handling. In addition, uncontained waste products have occasionally become free within cabin areas. Hygiene facilities, such as washing, have been limited to damp sponge or chemically treated napkins. It is suggested that the entire concepts of waste management and personal hygiene be developed for improved comfort and to be more appropriate for use in a vehicle that will be used repeatedly over a 10-year period.

7.1.5 Reusable ECS

The ECS/LSS will be subjected to repeated stresses from multiple launches over a 10-year period. To date, systems have been used for only single missions. To maintain system reliability, it will be necessary to improve present equipment operating capability or plan for replacement as necessary to overcome effects of repeated stresses.

7.1.6 Multimode Environmental Control System

Present space vehicle environmental control systems are not designed to provide support for aircraft-type modes of operation, such as go-around on landing and ferry flights. It is desirable to minimize vehicle turnaround time and to provide the desired flexibility to develop a single system to accommodate all modes of vehicle operation.

7.1.7 Elimination of Suit Loop

One specific requirement imposed on the vehicle environmental control system is to provide operation with a shirtsleeve environment. It has been suggested that this requirement will result in elimination of the suit loop. The advisability of removal of the suits must, however, be weighed against considerations of weight, power, and cost savings as well as thermal and reliability aspects. In addition, an alternate means of providing the same hazard protection to the personnel must be developed.

7.1.8 Equipment Temperature Control System Design

Equipment components, some of which generate energy that must be rejected, are maintained within required temperature limits by coupling to a coolant loop or, in some cases, only to the structural frame. Batteries are an example of components requiring precise control.

An analysis should be conducted to determine the components that require active cooling and those whose temperature can be controlled passively. This study should have an interface with the ECS design effort because the fluid involved and the coolant flow rates impact the ECS.

A thermal control system will be designed for rejection of applicable heat loads and duty cycles.

7.2 CREW SYSTEMS TECHNOLOGY

The pacing technological problems in crew systems (human factors) and related areas primarily concern questions of compatibility between the spacecraft and aircraft features of equipment and operations. Flight crew operational and equipment development for spacecraft have developed from those for aircraft; but for the Space Shuttle, an integration of spacecraft and aircraft flight crew considerations is necessary.

7.2.1 Vehicle Flying Qualities

Tradeoffs in vehicle and control system characteristics will necessitate compromise in handling qualities between orbital and atmospheric flight regimes. Pilot and rotational axes placement dictated by configuration and flying quality considerations for descent and landing pilotage will probably be incompatible with optimum placements of the pilot, rotational centers, and docking ports for orbital operations. Greatest impact is likely to fall upon docking pilotage, but rendezvous and other orbital maneuvers will also be affected. Likely increased cross-coupling effects between attitude control freedoms as compared with current spacecraft can impact orbital maneuver fuel consumption, time required, pilot skill requirements, maneuver precision, and hazard. Another likely problem is increased and more variable thrust misalignments in orbital maneuvers.

Early man-in-the-loop flight simulation constitutes the only effective means of identifying flying quality problems, suggesting solutions, and assuring that solutions in one flight regime do not critically degrade another. Simulation must provide evaluations and assurance of configuration and design features with respect to flying qualities at the earliest point of their consideration in order to provide a timely influence on the design process.

Rules of thumb derived from experience with aircraft and spacecraft have proven to be useful in conceptual and early preliminary design phases for each type of vehicle. However, a very high risk would be incurred in the use of such rules to the same extent on a combined spacecraft/aircraft vehicle as appropriate to a spacecraft or aircraft separately. Analytical simulations in which a transfer function mathematical model is subsituted for man-in-the-loop have been notoriously unsuccessful in the past, and satisfactory models are not likely to become available within the next 10 years.

Simulations for flying qualities will be required in rendezvous and docking, orbital maneuver, atmospheric descent, and approach and landing flight regimes and possibly in launch, ascent, and reentry regimes. The required performance characteristics for simulations in each regime must be determined through analysis, and the appropriate simulation technique must be identified to satisfy the requirements. Undoubtedly, several simulators will be required, since a single device to cover all flight regime requirements is not within the current or near-term state-of-the-art. In-flight simulators, in addition to conventional ground simulator facilities, must be considered for the approach and landing flight regime. The simulation of the cockpit display complement for both avionics and control parameters in all cases must be adequate to evaluate the effectiveness of transitions between automatic and manual flight control. Such simulators must be designed to accommodate later problem diagnosis exercises during flight test and early crew training before training simulators are available.

7.2.2 Visibility

Adequate visibility for vehicle flight control operations is essential even where manual control is a backup mode. The problem breaks down into two parts: first, to determine the required line-of-sight and field-of-view for each pilotage operation and to evaluate techniques to make the required field-of-view available to the pilot; and, second, to determine the visibility requirements and availability within the provided field-of-view.

Pacing line-of-sight and field-of-view availabilities are for approach and landing and for docking maneuvers. Although these requirements can be determined from analysis of the flight profile and vehicle dynamic response characteristics in each flight regime, conventional viewport visiblity to meet all visibility needs may be difficult to achieve. Indirect visibility must be explored as a complement or alternative to satisfy these requirements. Electro-optical, fiber optics, and conventional relay optics imaging systems must be evaluated for use in early flight operations for which required direct viewing cannot be readily provided. Each indirect viewing technique has drawbacks from a vision standpoint, and none can approach the optimum balance of direct viewing. However, for a limited range of conditions, such as low light level, an indirect system can be superior to a direct viewing system. Another approach to solving line-of-sight and field-of-view incompatibilities between different flight regimes is to provide separate work station locations for flight control operations in different flight regimes. For instance, a station for vehicle flight control during docking might be located near the docking capture point to provide visual information for the docking operation.

Although line-of-sight and field-of-view requirements can be adequately determined from analytic and mockup techniques in preliminary design stages, visibility requirements within the specified field of view cannot be determined by similar techniques within the current state-of-the-art. Only physical simulation can provide adequate evaluations, although direct man-in-the-loop simulations are not always required where photometric measurement can be adequately related to visibility. Visibility within the required field of view is determined by the characteristics of the viewing optics and image relay system, the susceptibility of the optics to interferences from ambient environmental variation, illumination and oscuration of objects of interest within the field of view, and internal cabin lighting. Sun shafting through or causing veiling scatter within viewport optics is a familiar problem in high-altitude and orbital operations, particularly docking. The techniques for docking must result in minimum window and approach angle constraints in order to provide for maximum Space Shuttle operational flexibility. Artificial scene lighting for dark side docking and other operations must be evaluated. The desirability of imaging sensor use, which is capable of penetrating the weather conditions and presenting a visual scene analog to the pilot, must be considered with regard to landing under category 3 visibility.

All visibility conditions can be easily synthesized and evaluated. However, this test work must be initiated with preliminary design start in order to receive required tradeoff weighting against analytically determined considerations. The incompatibility of visibility requirements between orbital and atmospheric operations dictate an earlier consideration than might be tolerable in an aircraft or spacecraft separately.

7.2.3 Crew Safety and Escape

Ejection envelope constraints imposed by consideration of aircraft escape techniques in certain flight regimes impose a constraint on flight crew work station and seating design not present in current Apollo spacecraft. Early evaluation of this constraint on the work stations in orbital flight regimes must be accomplished to prevent a degradation from earlier spacecraft in work station effectiveness. This suggests a need for more complete and sophisticated mockup evaluations during conceptual and preliminary design than might otherwise be required.

Escape from orbit will require use of techniques completely foreign to aircraft technology and only in the study stage for spacecraft technology. However, because backup reentry and descent capabilities will undoubtedly be considered, provisions for crew access to these capabilities must receive the earliest consideration in orbital life cell design. Escape from orbit as considered here does not only include backup reentry bodies but, also, nonnominal reentry and descent with the Space Shuttle in an abort from orbit.

7.2.4 Crew Organization

Because pilotage, communication, navigation, and flight engineering functions have been divided among three or four flight crewmen in aircraft operations and because a two-man flight crew complement is a requirement for the Space Shuttle, an early evaluation of alternative function allocations must be conducted. Workload analyses for each flight regime should be conducted as a function of the degree of automation in order to identify requirements for reallocation of functions. In a recent aircraft design (Navy S-3A), these functions are allocated between only two crewmen. As this aircraft engages in complex flight plans, its crew function allocation may be an appropriate point-of-departure for allocating Space Shuttle crew functions during atmospheric flight.

7.2.5 Cockpit Display Instrument Concept

The combination of both spacecraft and aircraft flight information display requirements precludes the traditional dedication of a unique instrument to each displayed parameter. Some degree of integrated display will be required, and the techniques for integrated display calls for use of new display combinations, techniques, and formats. New requirements for display will also result from the onboard checkout system. Early simulation will determine the most effective format for information transfer and thus establish the format requirements for the display instruments and computer outputs. The effect of combination and integration of avionics with navigation and control information can be demonstrated and evaluated. Most importantly, forced display for alerting while under automatic flight control and information display for transitioning between automatic and manual flight control modes can be developed to establish equipment design requirements. Heads-up and heads-down visual image combination with integrated display symbology formats can be evaluated as an approach and landing aid. Such an integrated display simulator, used in conjunction with a simulator for establishing visibility within the field of view for pilotage, can be used to evaluate instrument lighting and readability under all flight conditions of cabin illumination.

Section 8

TECHNOLOGY DEVELOPMENT

The technology requirements for the Space Shuttle have been identified in the preceding sections, in which a brief description of each of these technology elements was given. For some of the elements, more detailed descriptions are given. Schedule and cost estimates are provided in the following pages.

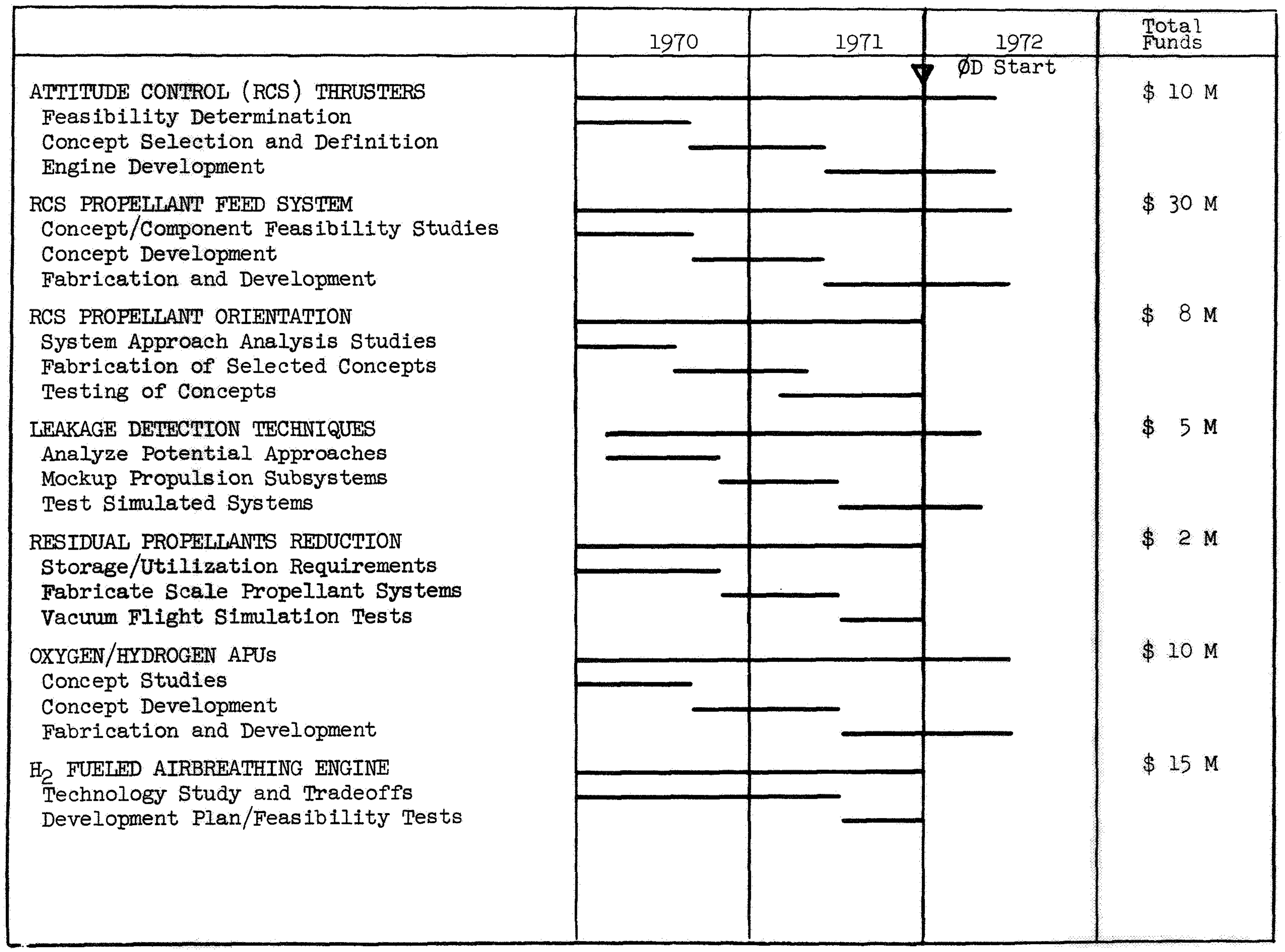
It is important to note that none of the programs presented in this volume require technological breakthroughs. This means that all of the technology efforts associated with the development of the Space Shuttle can be accomplished with the application of existing and demonstrated methods and techniques or, as in some cases, by an extension of today's state-of-the-art to that envisioned for 1972.

The schedules reflected in the following development summaries cover only development to the point of proving the concept feasible. The hardware development, which follows, is considered to be a cost of the Development and Operations Phase.

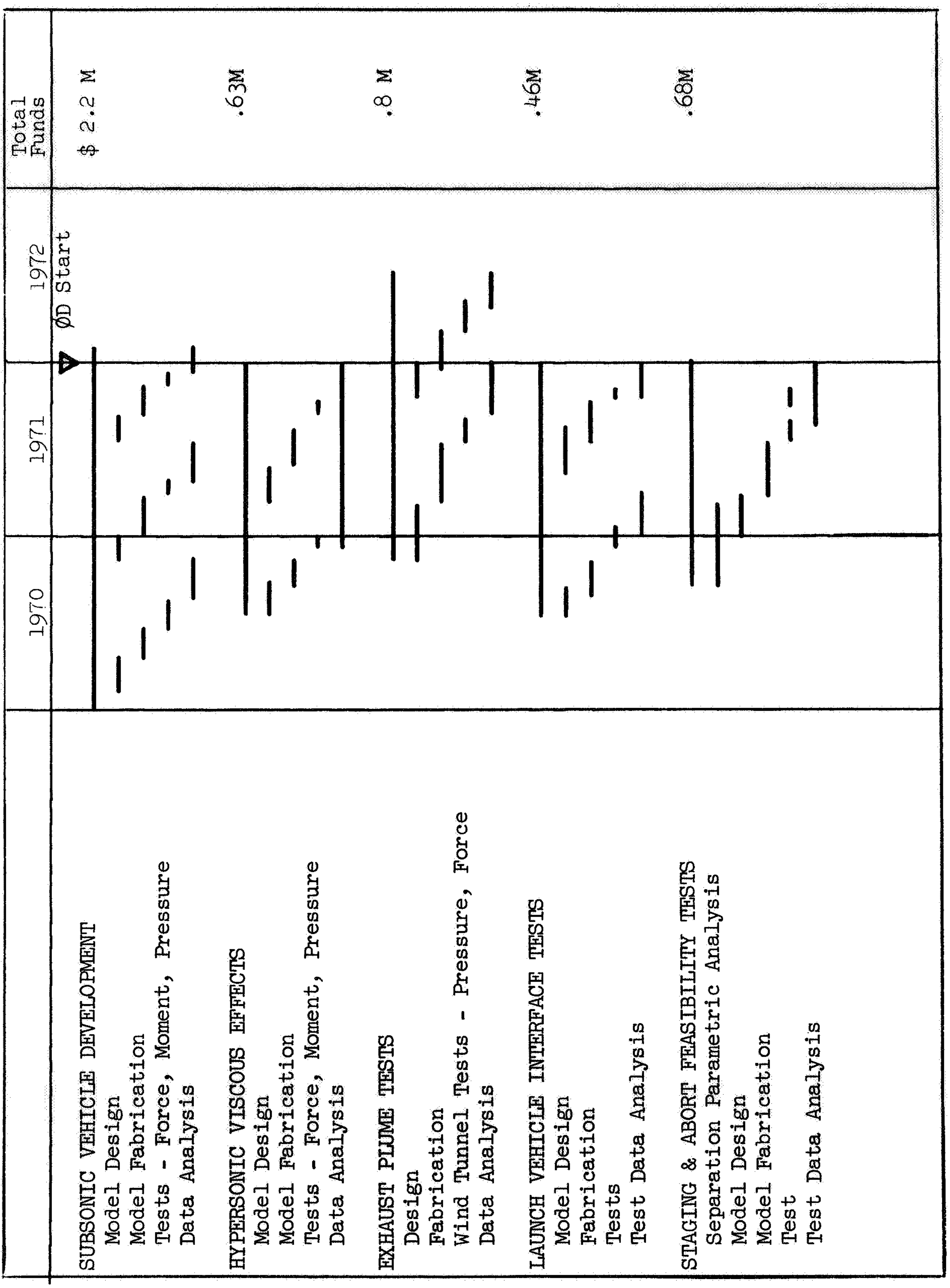
Costs estimated for development in most cases are for all identified key developments in their technology areas. Notable exceptions are aerodynamics and aerothermodynamics. These recommended programs are only those considered pacing to the program.

Programs are summarized in the succeeding pages by their technology areas. Spans are shown by major tasks and for the overall development item. Costs are reflected for the individual programs.

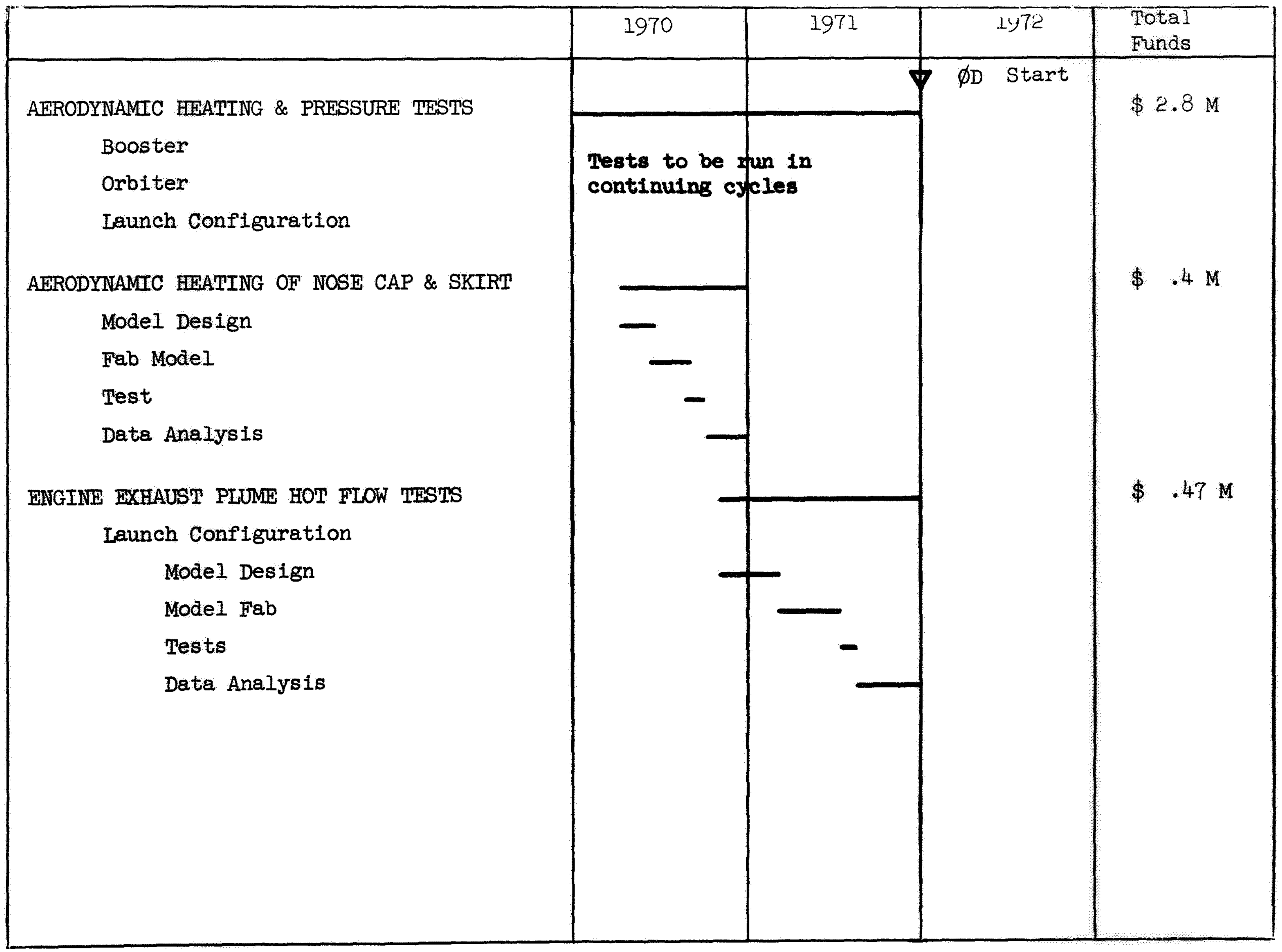
PROPULSION SYSTEM TECHNOLOGY DEVELOPMENT



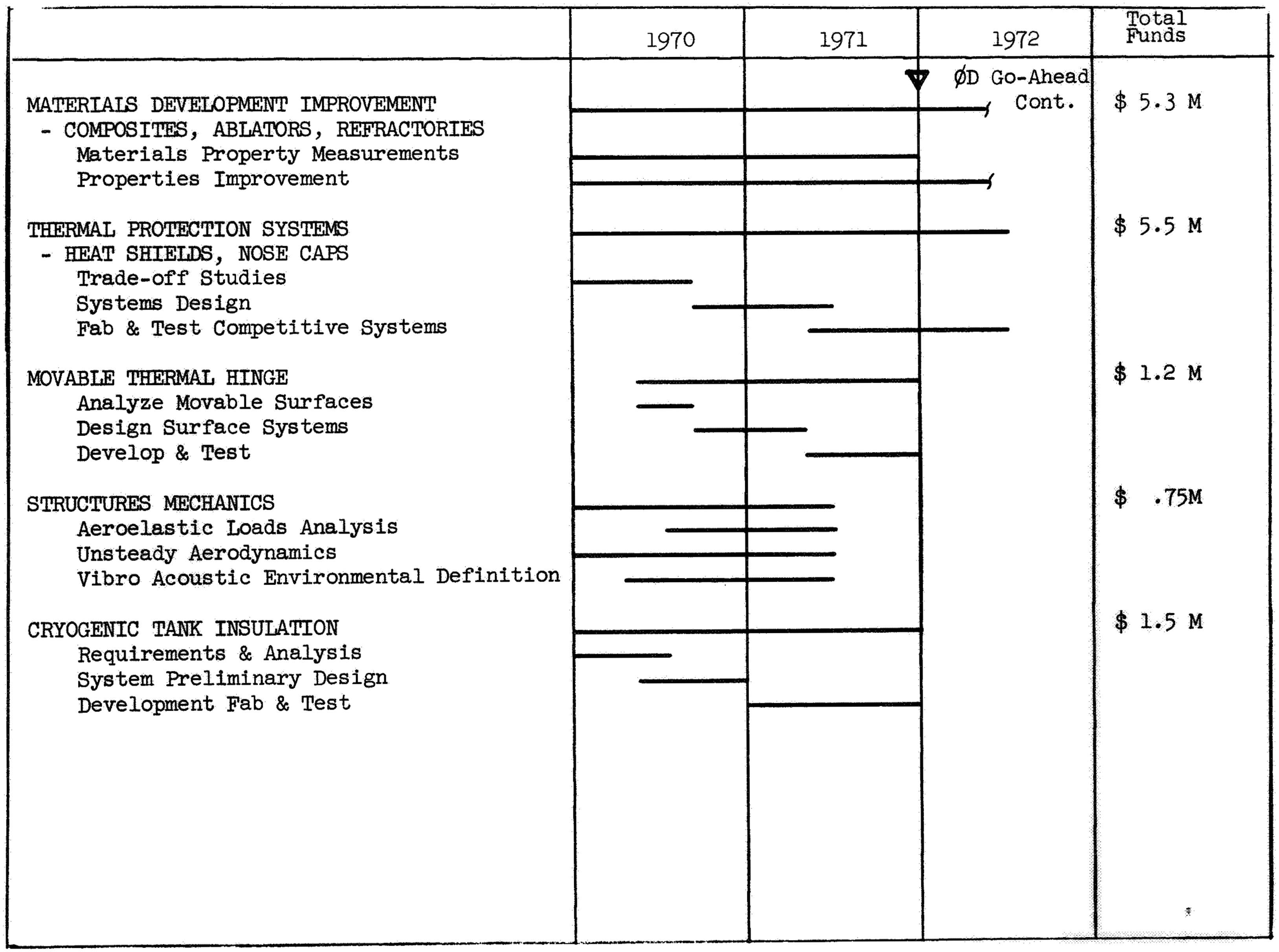
AERODYNAMICS TECHNOLOGY DEVELOPMENT



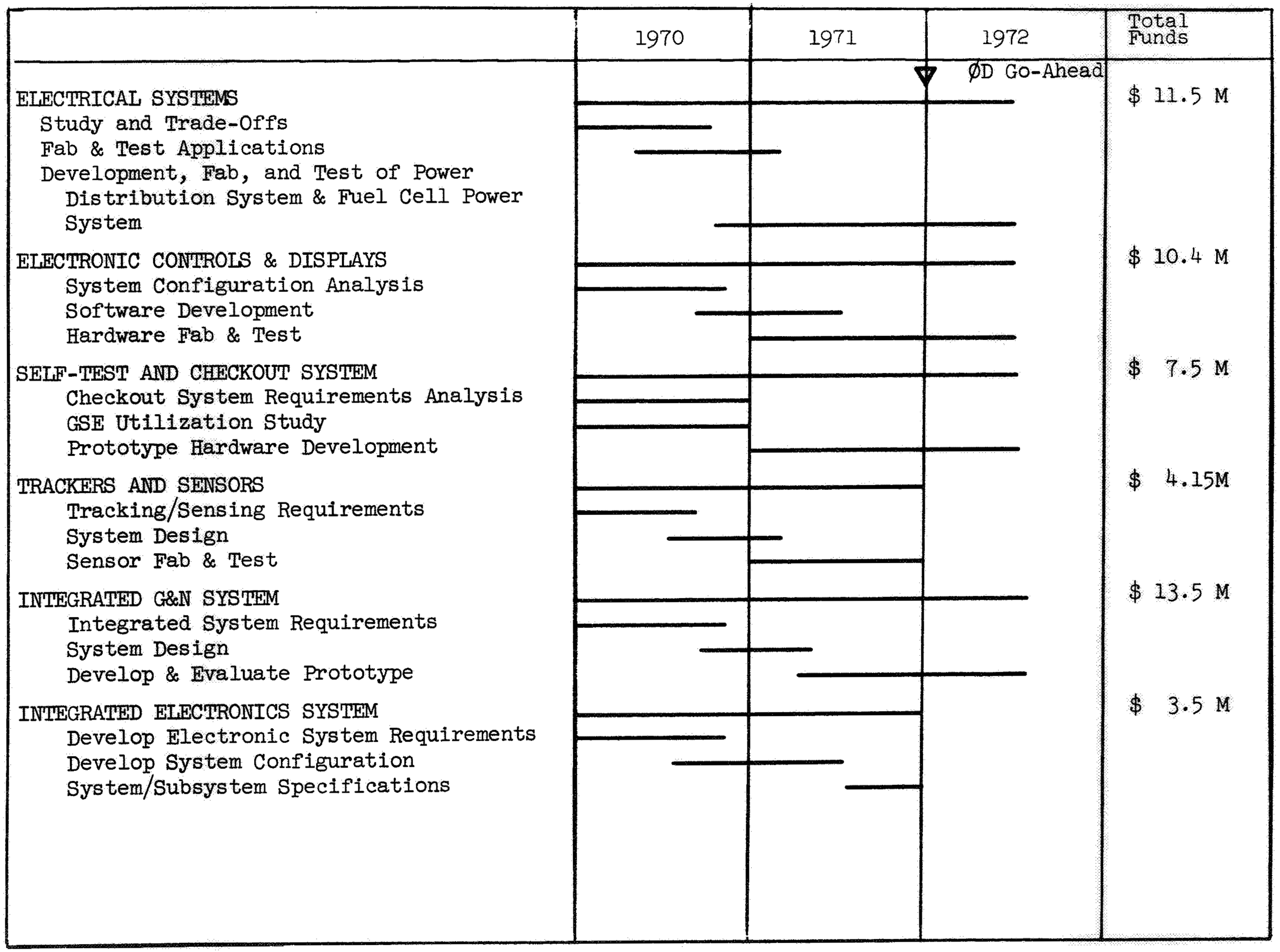
AEROTHERMODYNAMICS TECHNOLOGY DEVELOPMENT



STRUCTURES TECHNOLOGY DEVELOPMENT



AVIONICS TECHNOLOGY DEVELOPMENT



BIOASTRONAUTICS TECHNOLOGY DEVELOPMENT