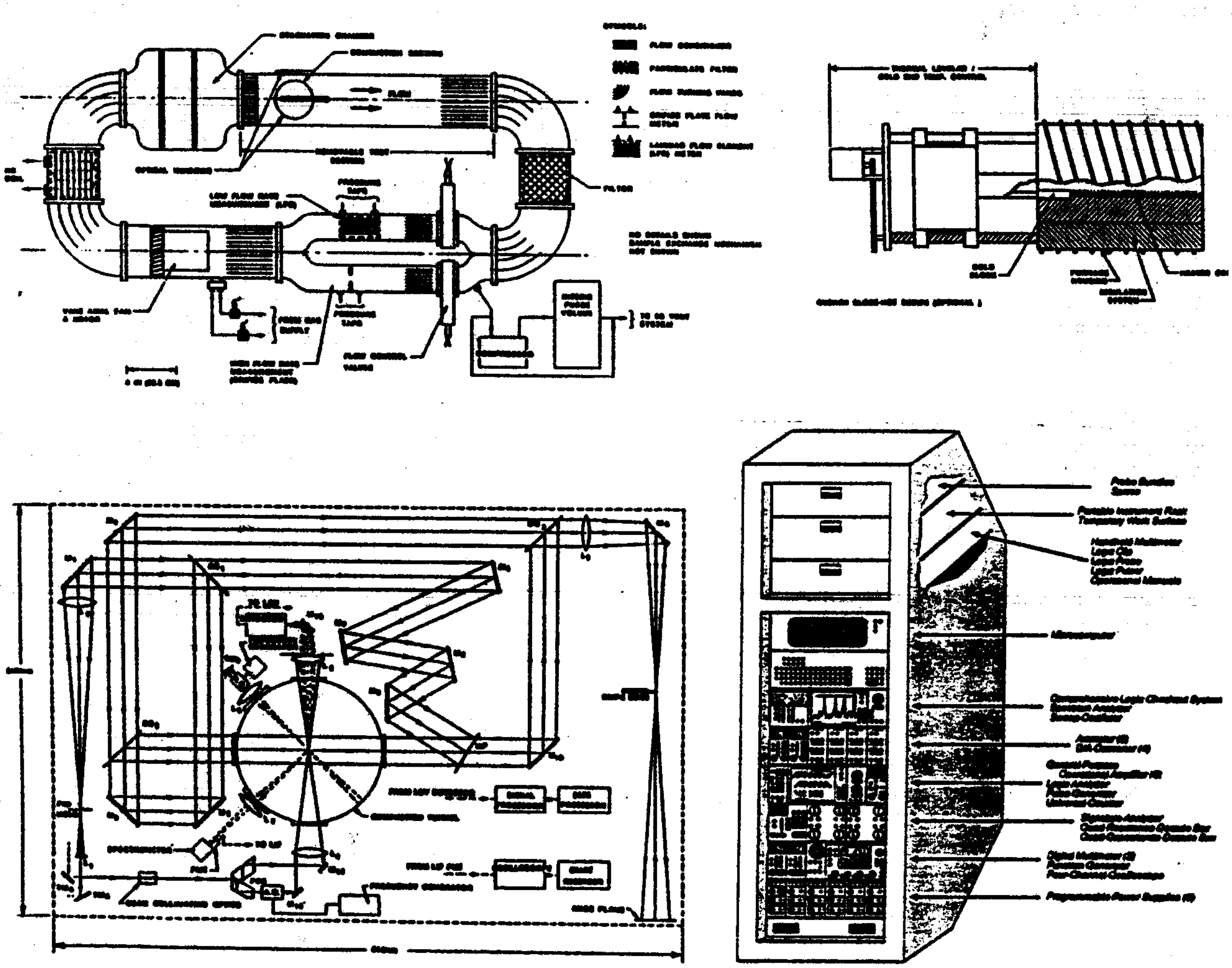
CR - 179535

EQUIPMENT CONCEPT DESIGN AND DEVELOPMENT PLANS FOR MICROGRAVITY SCIENCE AND APPLICATIONS RESEARCH ON SPACE STATION

COMBUSTION TUNNEL
LASER DIAGNOSTIC SYSTEM
ADVANCED MODULAR FURNACE
INTEGRATED ELECTRONICS LABORATORY



(NASA-CR-179535) EQUIPMENT CONCEPT DESIGN AND DEVELOPMENT PLANS FOR MICROGRAVITY SCIENCE AND APPLICATIONS RESEARCH ON SPACE STATION: COMBUSTION TUNNEL, LASER DIAGNOSTIC SYSTEM, ADVANCED MODULAR FURNACE, INTEGRATED G3/29
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WYLE LABORATORIES NASA / LEWIS RESEARCH CENTER

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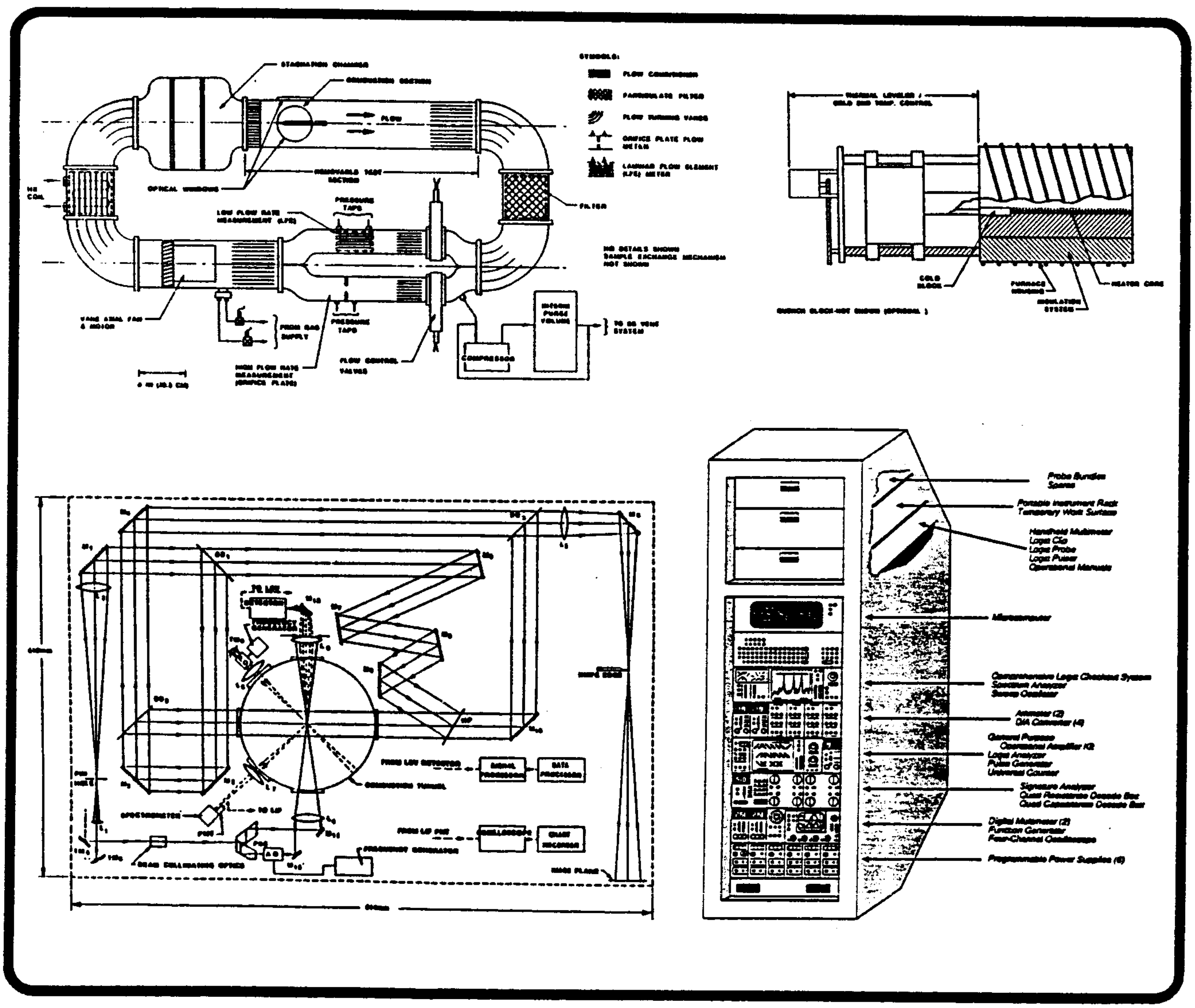

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TASK 2 - EQUIPMENT CONCEPT DESIGN AND DEVELOPMENT PLANS

WYLE LABORATORIES
September 1986

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INTRODUCTION

Contract No. NAS3-24654, "Space Station Microgravity Science Accommodation Requirements Study", was initiated by Wyle Laboratories in May 1985 under the direction of the NASA Lewis Research Center, Space Experiments Office. The NASA technical monitor for the effort was Mr. Richard J. Parker.

The study effort included two primary tasks:

- Task 1: Identification of the General Requirements for Performing Microgravity Science and Commercial Process Experiments on the Space Station.

- Task 2: Preparation of Conceptual Designs and Development Plans for Experiment Apparatus and Laboratory Support Equipment.

Task 1 was completed in December 1985 and the results reported under separate cover (ref. 1). Task 2 has been completed and the study results are reported herein.

The objective of Task 2 was to prepare selected equipment concept designs to a level-of-detail which would permit rough-order-of-magnitude (ROM) cost and development schedule estimation. An additional important aspect of each concept design was the identification of **technology development issues** associated with the respective apparatus. Provisions for the analytical and experimental resolution of these issues are therefore included in each apparatus development plan.

Four equipment items were selected for study as follows:

- Combustion Tunnel
- Laser Diagnostics System
- Advanced Modular Furnace
- Integrated Electronics Lab

Individual **Concept Design and Development Plans** for each selected apparatus are provided in Appendices A-D. These plans indicate completion of Phase A: Planning and Conceptual Design, and include ROM estimates for Phase B: Preliminary Design and Prototype Construction/Testing. An **Integrated Equipment Development Plan** is provided in Section 1.3. This top-level plan is keyed to the Space Station program schedule in order to illustrate the concurrent activities required to resolve technology development issues in the near-term and consequently ensure the availability of reliable and productive flight equipment for the Space Station era.

1.0 SUMMARY OF CONCEPTUAL DESIGNS AND DEVELOPMENT PLANS

A broad variety of candidate experiment apparatus and support equipment have been suggested to support microgravity science and applications research in a planned pressurized laboratory module on Space Station. The selection of appropriate candidates for development is a function performed by NASA based on a determination of need and an assessment of the potential return on the public investment. The high cost and long lead-time associated with the development of space flight systems restricts the range of equipment concepts which can be pursued. Since research productivity is the primary criteria for equipment selection, resources must be focused in relatively narrow areas in order to thoroughly and systematically resolve technology development issues and maximize individual system reliability. An adequate program of ground-based and sub-orbital testing supports this objective, thereby allowing later flight experiments to concentrate on scientific advance rather than incremental changes in engineering design.

1.1 Approach to Equipment Concept Design

During Task 1, top-level functional requirements were identified for seventeen items of experiment apparatus and twenty items of core support equipment. Under Task 2, two items of experiment apparatus - the **Combustion Tunnel** and **Advanced Modular Furnace,** and two items of support equipment - the **Laser Diagnostics System** and **Integrated Electronics Lab** were selected for concept design. Functional requirements for these equipment items were refined through further discussions with both NASA and potential users. Alternative approaches were investigated and preliminary assessments made of potential technical and cost impacts for each approach. The initial effort resulted in a narrowing of these alternatives and final selection of concepts to be pursued for each of the four equipment items.

The concept design process included the following activities:

- Assessment of Performance Requirements: The desired characteristics and capabilities of the apparatus were studied to determine design driving parameters and their relationship to Space Station design constraints.
- Review of Ground-based Equipment Analogues: Currently available sub-systems and components were identified and evaluated for apparatus/Space Station compatibility.
- Projection of Evolving Technologies: The prospect for advances in the state-of-the-art arising from current industrial R&D thrusts was studied to determine the availability of supporting technologies.

- Identification of Technology Development Issues: Shortfalls between available/projected technology and apparatus performance requirements were documented and provisions for resolution included in the respective development plans.

Concept designs were prepared to a level-of-detail which would permit estimation of rough-order-magnitude (ROM) costs and development schedules. Preliminary drawings were prepared for top-level systems, subsystem interfaces, and component interfaces where required to effectively illustrate the concept. Operational diagrams and reconfiguration scenarios were also prepared to supplement the system description.

Development plans are included for each concept. The plans provide an overall schedule for the major phases required to translate a research objective into a workable integrated system. The four major phases include:

Phase A: Planning and Concept Design* - During this phase user requirements are assembled, documented, and assessed for Space Station compatibility. Design options are evaluated and an approach is selected for concept development. ROM costs and development schedules are estimated.

Phase B: Preliminary Design and Prototype Construction/Testing - For concepts requiring technology development activity a breadboard unit is designed, fabricated, and tested. Development issues are investigated analytically during the design activity and resolved experimentally during the test activity through ground-based and sub-orbital experiments. Phase C/D development plans are finalized.

Phase C: Final Design - Based on results of the Phase B effort, final design drawings and detailed cost estimates for the flight unit are prepared.

Phase D: Fabrication and Testing - The flight unit is assembled and submitted to performance verification and flight qualification tests. Final documentation and safety reviews are completed and the equipment is maintained in a standby environment until space flight.

The effort reported herein represents completion of Phase A: Planning and Concept Design. Hence, the development plans presented in Appendices A-D concentrate on advancing the concepts through the next phase. Phase B subtasks include:

B-1: Breadboard Design

B-2: Analytical Resolution of Technology Development Issues

B-3: Hardware Procurement and Fabrication

B-4: Breadboard Assembly

* Phase A has been completed under this study effort for each of the four selected equipment items.

B-5: Software Development

B-6: Ground-Based Testing

B-7: Sub-Orbital Flight Testing

B-8: Experimental Resolution of Technology Development Issues

The Combustion Tunnel, Laser Diagnostics System, and Advanced Modular Furnace are each presented in the previously described context due to the significant technology development issues which require resolution through a Phase B effort. The Integrated Electronics Laboratory, however, represents existing demonstrated technology. As such, the development plan addresses a Phase C/D effort culminating in delivery of the flight unit prototype.

1.2 Concept Design Summaries

The sections which follow summarize the research objectives, performance requirements, and concept designs for the four selected equipment items. Detailed design and development plans are provided in Attachments A-D.

1.2.1 Combustion Tunnel

Experimental and research objectives for the Space Station-based combustion tunnel have been tabulated as follows based on discussions with NASA/LeRC personnel:

a. Fundamental studies of specific combustion research topics where low flow velocities are required.

b. Fire safety experimental research
   - Pre-EVA preparation at 10.2 psia and 30 percent O_2
   - Special space craft laboratory environments (e.g., 11-12 percent O_2 at 2 atmospheres, up to 80 percent O_2 at 1 atmosphere)
   - Provide data obtained from very low gravity (i.e., SS) conditions that may be used to substantiate and interpret the extensive 1.0 g data base.

The primary objective of the Space Station-based combustion tunnel is to provide a research apparatus for the study of combustion and flame spread of burning materials in the presence of low velocity convection under microgravity conditions. This primary objective has as its goal an increased understanding of the burning and flame spreading of space craft materials. The flow velocities in the combustion tunnel test section shall be quite low, i.e., less than those encountered in buoyant flows in the vicinity of flames at 1.0 g conditions on earth.

The desired operational parameters of the concept design combustion tunnel are summarized as follows:

Test Section Dimensions and Flow Characteristics:

- Test Section dimensions
  - Inside diameter of 20 cm (~8.0 in) or greater, or
  - Square cross section of 20 by 20 cm (~8 by 8 in) or greater.
  - Unobstructed streamwise path of 25-30 cm (~10-12 in).

- Desired Flow Characteristics
  - Uniform, low-speed flow across test specimen and optical paths.
  - Flow velocities in region of test specimen as low as 1-2 cm/sec (~ 2-4 ft/min) up to 60 cm/sec (120 ft/min) and special cases as high as 1.0 m/sec (200 ft/min).
  - Nonintrusive (optical) flow diagnostics.

Combustion Tunnel Environment:

- Static temperature, ~20-22°C (~68-72°F)
- Static pressures,
  - 70.3 kPa (10.2 psia)
  - 101.4 kPa (14.7 psia)
  - 202.8 kPa (29.4 psia)
  - Up to 304.2 kPa (44.1 psia)
- Background (flow) gas mixtures (typical),
  - N_2 with up to 30 percent O_2 at 70.3 kPa
  - N_2 with 11-12 percent O_2 at 202.8 kPa
  - N_2 with up to 80 percent O_2 at 101.4 kPa
  - Argon or helium with up to 80 percent O_2 at 101.4 kPa.

Fuels of Interest:

The research combustion tunnel should be able to accommodate a variety of solid and liquid fuels. The primary interest is that of solid fuels including thin samples of paper and plastics. Liquid fuels may ultimately be considered to include any that would be used on spacecraft; however, corrosive fuels are not under current consideration.

A review of currently perceived Space Station-imposed constraints on the accommodation and operation of SS-based experimental systems has indicated that the most severe limitations would be those relative to power consumption, the disposal of waste materials, especially the venting of waste gases, and all safety-related aspects. These constraints influenced Wyle to suggest a fully recirculating design concept. The fully recirculating system is basically a very low-speed flow facility designed to produce a relatively uniform, flat velocity profile flow field in a well-defined test section.

The full Concept Design and Development Plan for the Combustion Tunnel is provided in Appendix A.

1.2.2 Laser Diagnostics System

The concept design for the laser diagnostics system is a nonintrusive optical measurement system for the research combustion tunnel proposed for use on the Space Station. Although numerous combustion diagnostics techniques are available, most of the published flame structure data have been obtained by introducing various types of probes into the flow. Introduction of a probe into a flow field alters the static pressure distribution and flow patterns and can result in measurement errors, especially when probing very low-velocity flows in reduced scale experiments. In the laser diagnostics system no physical probe needs to be inserted into the flow. The concept design is completely nonintrusive in character, produces pointwise measurements, and would use data storage capability for later analysis in a ground-based laboratory.

The following capabilities of the laser diagnostics system were established based on discussions with NASA/LeRC personnel:

- Flow visualization
- Temperature profiles
- Velocity of particles and flames
- Species concentration

Based on these requirements, conceptual designs for the following two systems are presented:

System I: Includes holography, classical optical techniques, Laser Doppler Velocimetry (LDV) and Laser Induced Fluorescence (LIF)

System II: Includes holography, LDV and LIF.

Both systems would acquire essentially the same basic data, but System I would be more versatile and could provide certain parameters, e.g., flame propagation and temperature profiles, in real time. The classical optical system provides Schlieren, shadowgraph, and Mach-Zehnder (M-Z) interferometeric investigating systems which would provide real-time data on the Space Station. The Schlieren system provides the flame propagation information and the M-Z interferometry provides the temperature profile measurements. Admittedly, this system would be very complex and its feasibility and application for use in a size and configuration suitable for the SS microgravity environments needs to be investigated in a ground-based "breadboard" system.

In the System II concept design, the classical optical system is completely eliminated, reducing, of course, the system's ability for real-time measurement of flame propagation and temperature profiles. Note that both the classical optical system and holography can provide essentially the same basic data measurement. The advantage of proposing holography in both systems is in recognition of its ability to store information for later analysis in a ground-based laboratory and its established application to other microgravity experiments. (Holography was used as a major portion of the data acquisition for the fluid experiment system (FES) on the Space Shuttle Spacelab-3 mission.)

The concept designs described herein are possible in principle, but the technologies of most of the subsystems need to be developed in a "breadboard" system. Realizing that a single comprehensive system would be very complex, it is suggested that effort for reducing the complexity of the system may be carried out at the technology development stage. For instance, the use of fiber optics to simplify the system has been suggested. However, there are a number of limitations in the current technology of fiber optics which need to be studied. The possibility of using the Schlieren/Doppler technique for measurement of the velocity of particles and flames also needs further study. If the Schlieren/Doppler technique can be satisfactorily established, it would greatly simplify the system by completely eliminating the LDV system.

An added advantage of this laser diagnostics system is that it can be used or adapted to accommodate other combustion and fluids experiments planned on the SS with modifications. The only necessary conditions are a transparent medium with optical access to the medium through transparent windows. The system described herein will accommodate a combustion tunnel of approximately 254 mm (10 in.) outside diameter; however, any significantly larger diameter tunnel may necessitate the redesign of the optical system. Other microgravity experiments which have a transparent medium, such as solution crystal growth, can be easily accommodated in the system for refractive index measurements and other data acquisition parameters. Thus, it can be used as a generic system for laser diagnostics of microgravity experiments.

The various optical investigation techniques and their subsystems identified show the extensive parameters that could be measured using the laser diagnostics system.

Optical Investigation Techniques	Parameters of Interest
1. Classical Optical System	
• Mach-Zehnder Interferometry	Refractive index Temperature gradient Density
• Schlieren	Flame propagation Refractive index gradient Velocity of flames
• Shadowgraph	Rate of change of refractive index gradient
2. Holography	
• Holographic M-Z Interferometer • Holographic Schlieren • Holographic Shadowgraph	Flow visualization Temperature Particle size measurement
3. Laser Doppler Velocimetry	Velocity measurements of particles and flames
4. Laser Induced Fluorescence	Species concentration measurements.

Wyle suggests that these concept designs are possbile in principle, but their practicality needs to be established by developing a breadboard system for ground-based research. Such a ground-based system can be used for the technology development of the systems, and also would provide a facility for the analysis of data brought back from the Space Station.

The full Concept Design and Development Plan for the Laser Diagnostics System is provided in Appendix B.

1.2.3 Advanced Modular Furnace

The primary objective of the Advanced Modular Furnace (AMF) project is to develop a family of flight furnaces that have advanced operational capabilities and are designed in subsystem and system modules for reconfigurability. In the Space Station time frame, it will be necessary to have furnaces with the capabilities of processing samples from 2.0 cm to 10.0 cm in diameter at temperatures from 200°C to 2200°C.

These furnaces must be configured for isothermal, gradient, and directional solidification modes with the capability of tailoring the thermal profiles in the sample and producing cooling conditions from slow, controlled rates to sample quench.

The design approach is to define the complete furnace system in terms of modules so that each furnace can be configured for a given set of compatible requirements by selecting and integrating the proper combination of modules. This allows one to establish the basis for a family of furnaces without falling into the trap of attempting to develop only one furnace configuration that will satisfy a large number of users. The modular approach used in the AMF will be primarily at the subsystem level, i.e., modules to configure different operational types of furnaces. However, it is anticipated that this approach to modularity will eventually be expanded to the system level, i.e., reconfigurability from one type of experiment apparatus to another.

In addition to the primary objective of the AMF project as described, it is important that the AMF incorporate the latest furnace technology. NASA's present furnace systems are not only few in number but are based, in most cases, on outdated technology, since their development occurred during the pre-Space Shuttle era. It is important that new hardware take full advantage of past lessons learned and improvements in materials and electronics as well as aim beyond immediate needs to include requirements for the Space Station era. Important objectives of the AMF in the technology development area therefore include:

- Advancement of high temperature processing furnace technology to support the development of future materials processing apparatus.
- Development of rapid sample exchange concepts leading ultimately to autonomous, fully automatic materials processing systems.
- Development of subsystem modules demonstrating the ability to reconfigure furnaces to meet given sets of operational requirements.
- Demonstration of capability to process toxic samples in a manned environment.

Design Approach:

Continuous research in materials processing aboard the Space Station will require flexible, reconfigurable furnace systems that produce, for each sample material, a specifically required thermal environment. The operational requirements are achieved by appropriate design sensitivity in the materials selection, thermal modeling, and assembly and test of an engineering breadboard. To address the requirement for flexibility and reconfigurability, however, one must take a modular approach in the system engineering for each element of the various furnace systems required. Taking this approach, the AMF can be described through four major modular elements: 1) furnace assembly, 2) mechanical drive subsystem, 3) fluids subsystem, and 4) instrumentation and controls subsystem. The furnace assembly consists of the following:

- Furnace housing
- Insulation system
- Heater core
- Cold block
- Quench block
- Thermal leveler
- Cold end temperature control.

The mechanical drive subsystem is comprised of:

- Furnace drive
- Quench drive
- Sample insertion/retrieval
- Sample selection.

The fluids subsystem consists of:

- Furnace environment
- Sample processing environment
- Furnace/cold block coolant
- Quench block coolant.

The instrumentation and controls subsystem is comprised of the following:

- Experiment processing controller
- Housekeeping measurements
- Experiment measurements
- Data recording.

By satisfying the operational requirements for the Space Station through the design of compatible modules, one can expect to achieve the flexibility and reconfigurability necessary to support long-term research aboard the Station.

Operational Requirements:

Operational parameters for the Space Station-based Advanced Modular Furnace (AMF) have been established based on discussions with potential users. These parameters, in conjunction with design constraints due to placement of the facility on the Space Station, have generated the design concepts presented herein. These operational parameters for two configurations of the AMF are shown in Table 1 for comparison with the capabilities of the existing ADSF-II and the AADSF, which is under development, and the requirements for the next furnace development - the Multiple Experiment Processing Furnace (MEPF).

The values of the parameters for the two AMF configurations shown in Table 1 are not to be considered as the only values possible on the AMF. These values will change since the furnace configuration changes are a function of user requirements with limits on these values to be determined in the future.

The Advanced Modular Furnace is being conceptually designed to support a number of crystal growth and solidification experiments by reconfiguring the furnace through replacing modules. This approach, in concert with requirements for higher temperatures (1600^{o}C to 2200^{o}C), larger numbers of samples (10 to 100), and quench, will require technology development in several areas of the furnace assembly. These include (1) materials utilization, 2) furnace design, 3) mechanical drive system, and 4) sample insertion/retrieval system.

The full Concept Design and Development Plan for the Advanced Modular Furnace is provided in Appendix C.

1.2.4 Integrated Electronics Laboratory

The objective of the Integrated Electronics Laboratory (IEL) is to provide on-orbit electronic fault diagnosis, repair, and calibration support to both mission specialists and the Space Station flight crew. The ability to implement on-orbit corrective measures for disabled electronic systems was a universal requirement identified under Task 1 of this study effort. Due to the high costs associated with payload delivery to

TABLE 1. COMPARISON OF FURNACE OPERATIONAL PARAMETERS

	ADSF-II	AADSF	MEPF	AMF (Metals and Alloys)	AMF (Semiconductors)
Sample size	0.6 cm	2 cm by 20 cm	2 cm by 8 cm	2 cm by 12 cm	2.5 cm by 20 cm
Number of samples/flight	4.0	1.0	Multiple (rapid changeout)	Multiple (rapid changeout)	Multiple
Sample exchange on orbit	No	No	Yes	Yes (semiautomatic and automatic)	Yes (automatic)
Operating temperature	1600°C	1100°C	1600°C	1600°C	1200°C
Gradient	300°C/cm	900°C/cm	100°C-400°C/cm	450°C/cm in air 200°C/cm in gray cast iron	450°C/cm in air
Quench rate	None	None	300°C/min	$>$ 300°C/min (cast iron)	None
Transition to quench	—	—	1 sec	<1 sec (<0.1 g)	—
Accommodation environment	Unmanned	Unmanned	Manned	Manned or unmanned	Unmanned
Solidification traverse mode	Furnace	Sample	Unspecified	Furnace (primary) Sample (secondary)	Furnace (primary) Sample (secondary)
Solidification traverse rate	0.002 mm/min 8 mm/min	0.01 mm/min 1 mm/min	0.01 mm/min 10 mm/min	0 to 450 mm/min	0 to 450 mm/min
Sample temperature sensors	6/sample	—	6/sample	6/sample	6/sample
Thermal zones (heaters)	1	5	Unspecified	2 (1 main, 1 trim)	3 (1 main, 1 guard, 1 trim)
Furnace efficiency	?	?	Unspecified	>60% (gray cast iron)	>60%

orbit, it is perceived essential that electronic faults be rapidly isolated, diagnosed, and repaired in order to minimize payload down time and prevent mission aborts whenever possible.

Although the IEL requirement was originally derived through discussions with potential users of the microgravity science laboratory, it is clear that such a capability is required to support electronic systems maintenance throughout the Space Station and its associated elements. Approaches to meeting this requirement range from the provision of small handheld diagnostic instruments and tools, as used in past programs (e.g., Spacelab); to an automated test equipment (ATE) system with slave software; to an expert system configuration with troubleshooting software. During the concept design phase, Wyle assessed each of these approaches and developed three technology options representing increasing levels of technical sophistication. These options, identified as Concepts A, B and C, are each presented in the Design and Development Plan.

Formulation of Requirements:

The Mission Payload Complement defined by NASA (ref. 2) was utilized as a model for typical payload facilities and equipment. Electronic subsystems were reduced to representative circuit types and failure modes for each type were matched to appropriate diagnostic techniques. Functional needs expressed by users were incorporated along with any implied peripheral capability.

The payload complement model revealed 27 relevant equipment items containing 44 typical circuits having a total of 42 discrete failure modes. Fifteen diagnostic techniques, capable of detecting the full range of potential failure modes, were identified as follows:

- Continuity Check
- Current Trace
- Curve Trace
- Frequency Response Check
- Gain Check
- Interactive Rate Check
- Isolation Check
- Load Check
- Checkout
- Logic Timing Trace
- Logic Trace
- Polarity Check
- Power Check
- Software Analysis
- Waveform Analysis

Three diagnostic equipment complements were assembled to meet these requirements. Complement A includes advanced diagnostic equipment at a high level of integration, requiring only task-trainable troubleshooting skills. Complement B incorporates limited slave testing capability and Complement C represents only general-purpose equipment requiring diagnostic expertise.

Candidate Conceptual Designs:

Based on the A/B/C complements of diagnostic equipment, three candidate conceptual designs were formulated. These three concepts differ primarily in the choice of instruments and are similar in geometry and overall physical configuration. Each concept is summarized as follows:

Conceptual Design A: Expert System - The expert system contains software which is capable of learning to troubleshoot systems. A data base of all observed failure modes, diagnostic techniques, and maintenance requirements is used to build an interactive troubleshooting tree which can prompt the operator if current symptoms/conditions match a previous observation. If the system is not familiar with a particular problem, it will wait until the problem is fixed and then query the operator for sufficient detail to recognize the new situation in the future.

Conceptual Design B: ATE System - The ATE (automated test equipment) System is composed primarily of slave-test capable instrumentation. Repetitive tests can be programmed into the system to run unattended. Results are stored on the microcomputer permanent media and retrieved as desired. Typical intermittent failure modes require a number of iterations to isolate the faulty component.

Conceptual Design C: Manual System - The manual system consists of general-purpose instrumentation without special features or software. As such, special knowledge of troubleshooting or a comprehensive test procedures manual is required. At best, a stable, dedicated two-way communication link is necessary to allow interactive dialogue during troubleshooting operations.

System specifications indicating instruments, microprocessors, interfaces, and utility requirements were developed for each of the three candidate concepts. Accessories to allow removal of instruments for remote troubleshooting and electronic systems maintenance were also identified.

Since the IEL represents currently available technology, a preliminary design and prototype testing effort is not required. Development of the IEL represents a systems integration project culminating in the delivery of a flight prototype unit rather than a ground-based breadboard as discussed for the previous three equipment items.

The full Concept Design and Phase C/D Development Plan for the Integrated Electronics Lab is provided in Appendix D.

1.3 Integrated Equipment Development Plan

The development of reliable space flight-qualified systems to accommodate micro-gravity science and applications research has been a continuing obstacle to technical progress. Most previously used equipment (e.g., GPRF, SAAL, ADSF, EML) was developed during the SPAR (Space Processing Application Rocket) era and refurbished/modified to support STS-based experiments. The need to advance the state of technology has been clearly documented (ref. 3) and in cases where advanced systems were utilized (e.g., FES/VCGS on Spacelab III) significant flight results were obtained.

A productive Space Station based research program implies the need for a new generation of hardware. The lead-time for Space Station IOC is sufficiently great to allow the technology development phase necessary to support advanced systems design. However, in order to achieve this goal, ground-based breadboards must be designed and tested in the near-term, thereby allowing the final design and fabrication of reliable space flight systems during the early 1990's.

Development Schedule:

The equipment development plans included herein are fully responsive to the need for a technology development phase which includes provisions for analytical and experimental resolution of technical issues through a ground-based and sub-orbital test program. Figure 1 summarizes the tasks and subtasks required for an overall development effort from initial concept to flight qualified system. Figure 2 keys this effort to the Space Station development schedule and indicates the concurrent activities necessary to ensure availability of the four selected equipment items by IOC. Figure 3 provides a detailed breakout by subtask for the critical technology development phase (Phase B: Preliminary Design and Prototype Construction/Testing).

PHASE A: PLANNING AND CONCEPT DESIGN (COMPLETE)
A-1: USER REQUIREMENTS A-2: CONCEPT DESIGN
PHASE B: PRELIMINARY DESIGN AND PROTOTYPE CONSTRUCTION / TESTING
B-1: BREADBOARD DESIGN B-2: ANALYTICAL RESOLUTION OF TECHNOLOGY DEVELOPMENT ISSUES B-3: HARDWARE PROCUREMENT AND FABRICATION B-4: BREADBOARD ASSEMBLY B-5: SOFTWARE DEVELOPMENT B-6: GROUND-BASED TESTING B-7: SUB-ORBITAL TESTING B-8: EXPERIMENTAL RESOLUTION OF TECHNOLOGY DEVELOPMENT ISSUES
PHASE C: FINAL DESIGN
C-1: FLIGHT UNIT DESIGN C-2: CONFIGURATION MANAGEMENT C-3: VERIFICATION C-4: DESIGN REVIEW
PHASE D: FABRICATION AND TESTING
D-1: FABRICATION AND ASSEMBLY D-2: FINAL SOFTWARE PREPARATION D-3: VERIFICATION D-4: ACCEPTANCE REVIEW D-5: GROUND TESTING (LABORATORY MOCK-UP) D-6: LABORATORY MISSION

FIGURE 1: DEVELOPMENT SUBTASKS BY PHASE

During the planning and conceptual design phase, specific areas were identified that require significant technology advancements to enable or enhance the development of the hardware. Advancements such as nonintrusive combustion diagnostics and advanced materials and instrumentation for higher temperature furnaces will require significantly long development efforts. It is believed that some of these more critical technology needs should be addressed and development initiated early in the hardware development process. The development schedule in Figure 2 allows for a one-year period of initiation of these critical advanced technology development efforts.

The integrated development schedules represent a combination of the four individual equipment development plans provided in Appendices A through D.

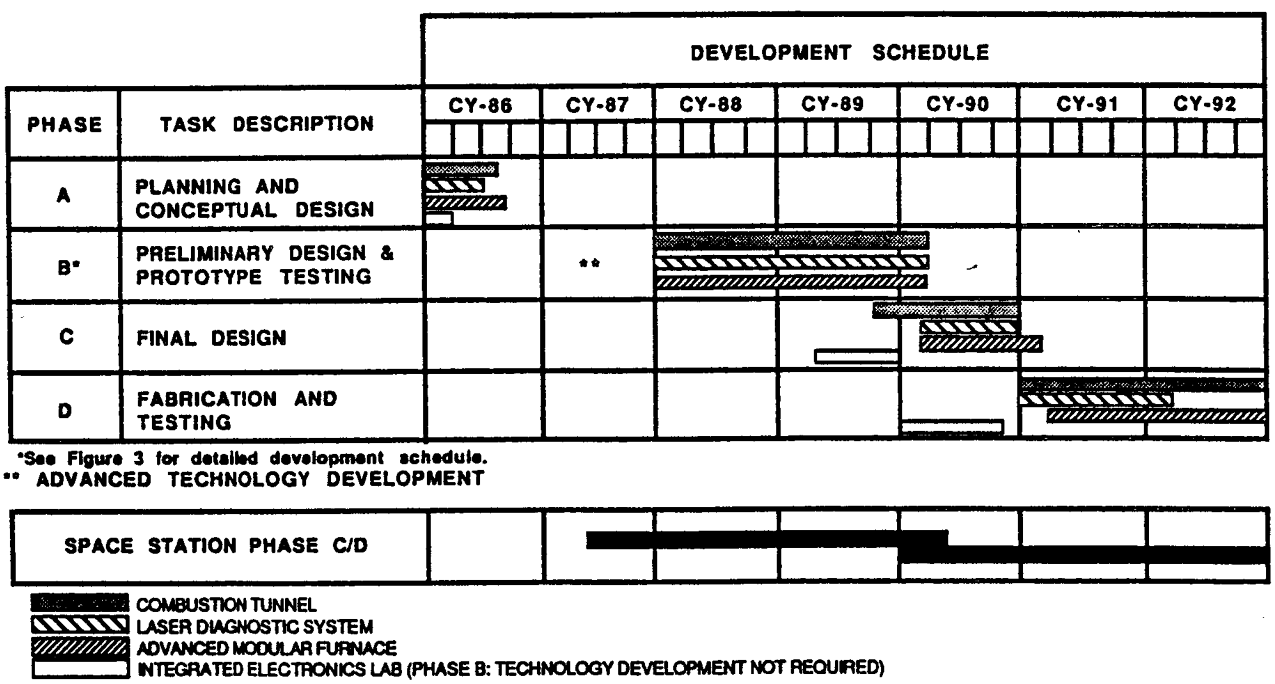

FIGURE 2: INTEGRATED TOP-LEVEL EQUIPMENT DEVELOPMENT PLAN

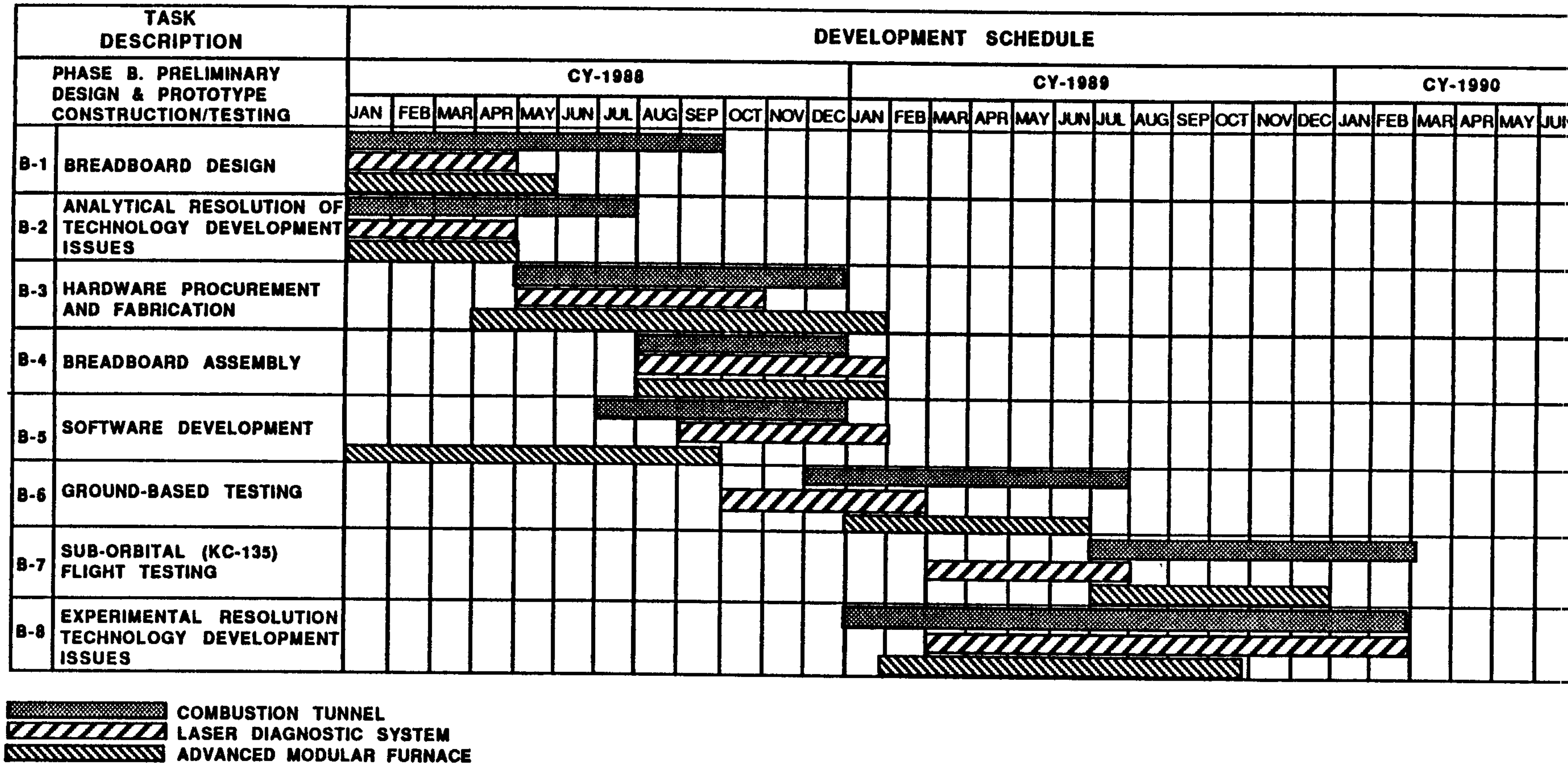

FIGURE 3: INTEGRATED EQUIPMENT DEVELOPMENT SCHEDULE FOR SYSTEMS REQUIRING TECHNOLOGY DEVELOPMENT PHASE

ROM Development Costs:

A rough-order-of-magnitude (ROM) development cost was estimated for the four selected equipment items. Since three of these items require breadboard design, fabrication, and testing, the ROM costs represent only this level of development. It must also be noted that the technology development phase will include engineering research and several decision points which can significantly impact the ROM costs. Discussion of breadboard design options and alternative approaches are presented in the individual concept design appendices. Figure 4 is provided as a summary of the ROM equipment development costs.

EQUIPMENT ITEM	DEVELOPMENT LEVEL	LABOR	MATERIALS	TOTAL* COST
COMBUSTION TUNNEL	BREADBOARD	5,900 m/hrs	<$80,000	$400,000.
LASER DIAGNOSTIC SYSTEM	BREADBOARD	5,000 m/hrs	$190,000.	$460,000.
ADVANCED MODULAR FURNACE	BREADBOARD	12,000 m/hrs	<$150,000.	<$795,000.
INTEGRATED ELECTRONICS LABORATORY • CONCEPT A • CONCEPT B • CONCEPT C	FLIGHT PROTOTYPE	 $660,000. $540,000. $365,000.	 $45,000. $40,000. $25,000.	 $705,000. $580,000. $390,000.

* Costs estimated in 1986 dollars. Labor component converted to equivalent man-years (1,860 hrs = 1 m-yr) and estimated at $100,000./m-yr.

FIGURE 4: SUMMARY OF ROM EQUIPMENT DEVELOPMENT COSTS

References

1. Accommodation Requirements for Microgravity Science and Applications Research on Space Station - Task 1 Interim Report, NASA CR 175038, Wyle Laboratories, December 1985.

2. Mission Integration and Requirements Analyses study, Wyle Laboratories, Contract No. NAS8-36410, 1986.

3. Top-Level Requirements for Microgravity Science and Applications Research on Space Station, NASA Contract No. NAS8-36117, Wyle Laboratories, March 1985.

CONCEPT DESIGN
OF A
RESEARCH COMBUSTION TUNNEL
FOR
SPACE STATION

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1.0 INTRODUCTION AND SUMMARY

1.1 Introduction

The concept design material presented herein was prepared by Wyle Laboratories as an extension to current efforts at the NASA/LeRC where ground-based combustion tunnel equipment is being developed for low gravity research in drop-tower and sub-orbital (aircraft) tests. This Wyle effort is devoted to providing a set of concept design ideas and identifying design issues for a Space Station (SS) based combustion tunnel.

Experimental and research objectives for the SS based combustion tunnel have been tabulated as follows based on discussions with NASA/LeRC personnel:

a. Fundamental studies of specific combustion research topics where low flow velocities are required.

b. Fire safety experimental research

- Pre-EVA preparation at 10.2 psia and 30% O_2
- Special space craft laboratory environments (e.g., 11-12% O_2 at 2 atmospheres, up to 80% O_2 at 1 atmosphere)
- Provide data obtained from very low gravity (i.e., SS) conditions that may be used to substantiate and interpret the extensive 1.0 g data base.

The primary objective of the Space Station (SS) based combustion tunnel, therefore, is to provide a research apparatus for the study of combustion and flame spread of burning materials in the presence of low velocity convection under microgravity conditions. This primary objective has as its goal an increased understanding of the burning and flame spreading of space craft materials. The flow velocities in the combustion tunnel test section shall be quite low, i.e., less than those encountered in buoyant flows in the vicinity of flames at 1.0 g conditions on earth.

1.2 Summary

A set of desired operational parameters for the Space Station based combustion tunnel was established through discussions with cognizant NASA/LeRC personnel (Refs. 1 and 2). These desired operational parameters, along with the design constraints associated with the location of such a facility on the Space Station (SS), have driven the design concept ideas discussed herein. Section 1.2.1 provides a summary of the combustion tunnel's operational parameters and Section 1.2.2 presents an overview of the complete system.

1.2.1 Combustion Tunnel Operational Parameters. The desired operational parameters of the concept design combustion tunnel are summarized in the following paragraphs.

Test Section Dimensions and Flow Characteristics:

- Test section dimensions
  - Inside diameter of 20 cm (~8.0 in) or greater, or
  - Square cross-section of 20 x 20 cm (~8 x 8 in) or greater
  - Unobstructed streamwise path of 25-30 cm (~10-12 in).
- Desired Flow Characteristics
  - Uniform, low-speed flow across test specimen and optical paths
  - Flow velocities in region of test specimen as low as 1-2 cm/sec (~2-4 ft/min) up to 60 cm/sec (120 ft/min) and special cases as high as 1.0 m/sec (200 ft/min).
  - Non-intrusive (optical) flow diagnostics.

Combustion Tunnel Environment:

- Static temperature, ~20-22°C (~68-72°F)
- Static pressures,
  - 70.3 k Pa (10.2 psia)
  - 101.4 k Pa (14.7 psia)
  - 202.8 k Pa (29.4 psia)
  - Up to 304.2 k Pa (44.1 psia)
- Background (flow) gas mixtures (typical),
  - N_2 with up to 30% O_2 at 70.3 k Pa
  - N_2 with 11-12% O_2 at 202.8 k Pa
  - N_2 with up to 80% O_2 at 101.4 k Pa
  - Argon or helium with up to 80% O_2 at 101.4 k Pa.

Fuels of Interest:

The research combustion tunnel should be able to accommodate a variety of solid and liquid fuels. The primary interest is that of solid fuels including thin samples of paper and plastics. Liquid fuels may ultimately be considered to include any that would be used on space craft; however, corrosive fuels are not under current consideration.

Flow and Flame Diagnostics:

Since it is the detailed characterization of the flow field and burning process (i.e., combustion and flame spreading) that is of interest, it is highly desirable that non-intrusive measurement techniques be used in the combustion tunnel test section. This is especially true in any region in close proximity to the fuel and flame. These requirements emphasize the need for optical diagnostics. The concept design for laser-based optical diagnostics is described in Reference 3. In general, the optical diagnostics of interest includes the following:

a. Flow visualization
b. Local velocities
c. Selected species concentration
d. Temperature profiles
e. Density profiles

1.2.2 <u>Combustion Tunnel System Overview</u>. This subsection presents a brief overview of some concept design ideas for a SS-based research combustion tunnel. Subsequent sections of this report provide more detail regarding the merits and/or limitations of the concept design material.

A review of currently preceived SS imposed constraints on the accommodation and operation of SS-based experimental systems has indicated that the most severe limitations would be those relative to power consumption, the disposal of waste materials, especially the venting of waste gases (e.g., see Ref. 5 and Appendix A), and all safety related aspects. These constraints influenced Wyle to suggest a fully recirculating design concept as shown schematically in Figure A-1. The associated laser diagnostics system (Ref. 3) is shown in a preliminary form as Figure A-2. The fully recirculating combustion tunnel system illustrated by Figure A-1 is basically a very low speed flow facility designed to produce a relatively uniform, flat velocity profile flow field in a well-defined test section. The system is composed of individual components and subsystems including the following:

a) Removable Test Section
b) Fuel Introduction/Removal Subsystem
c) Stagnation (Settling) Chamber and Flow Conditioners
d) Flow Rate Measurement and Control Subsystem
e) Fan/Motor Subsystem
f) Heat Rejection Coils
g) Interim Purge Storage Subsystem.

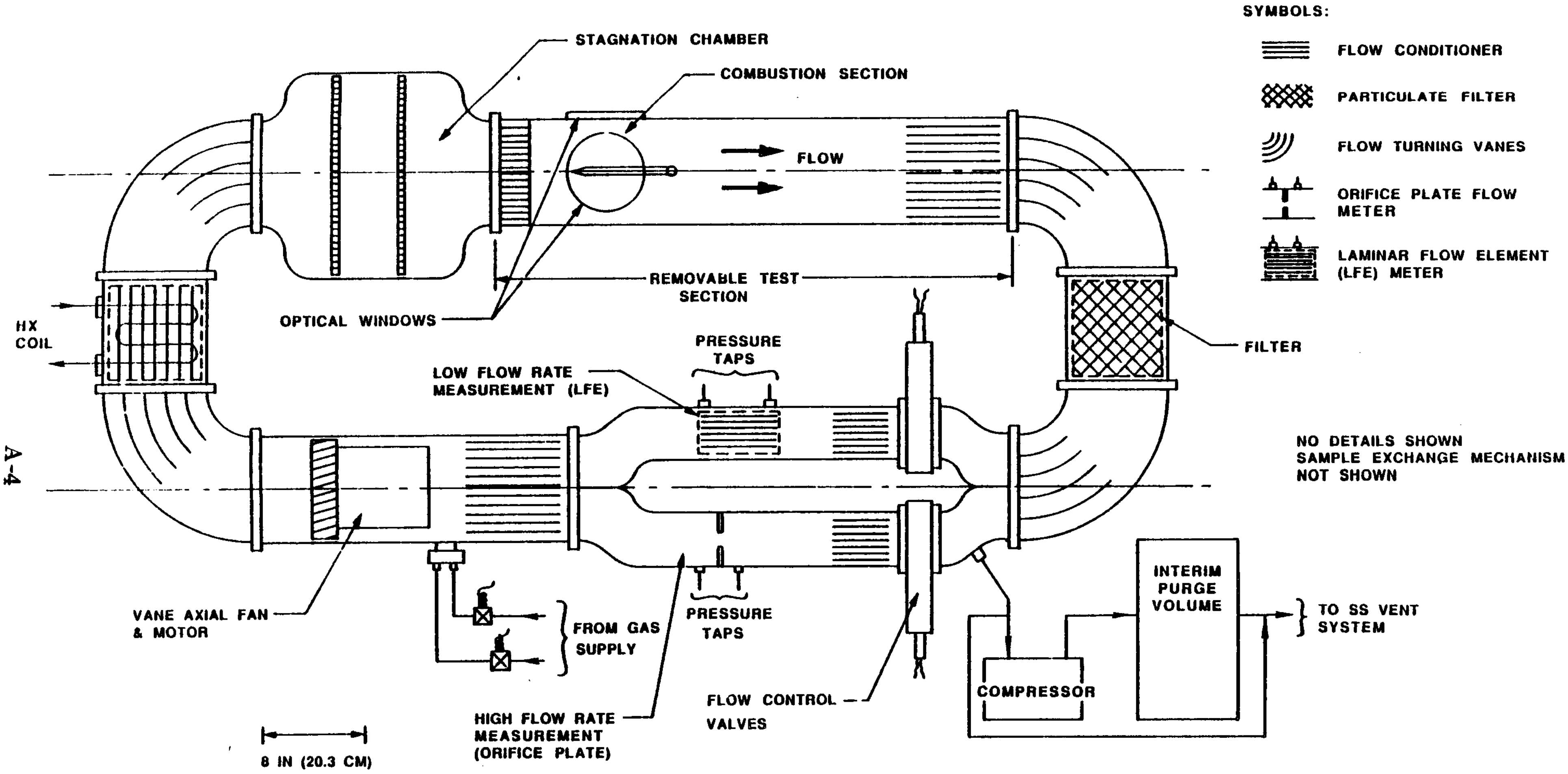

FIGURE A-1. RESEARCH COMBUSTION TUNNEL - OVERALL CONFIGURATION

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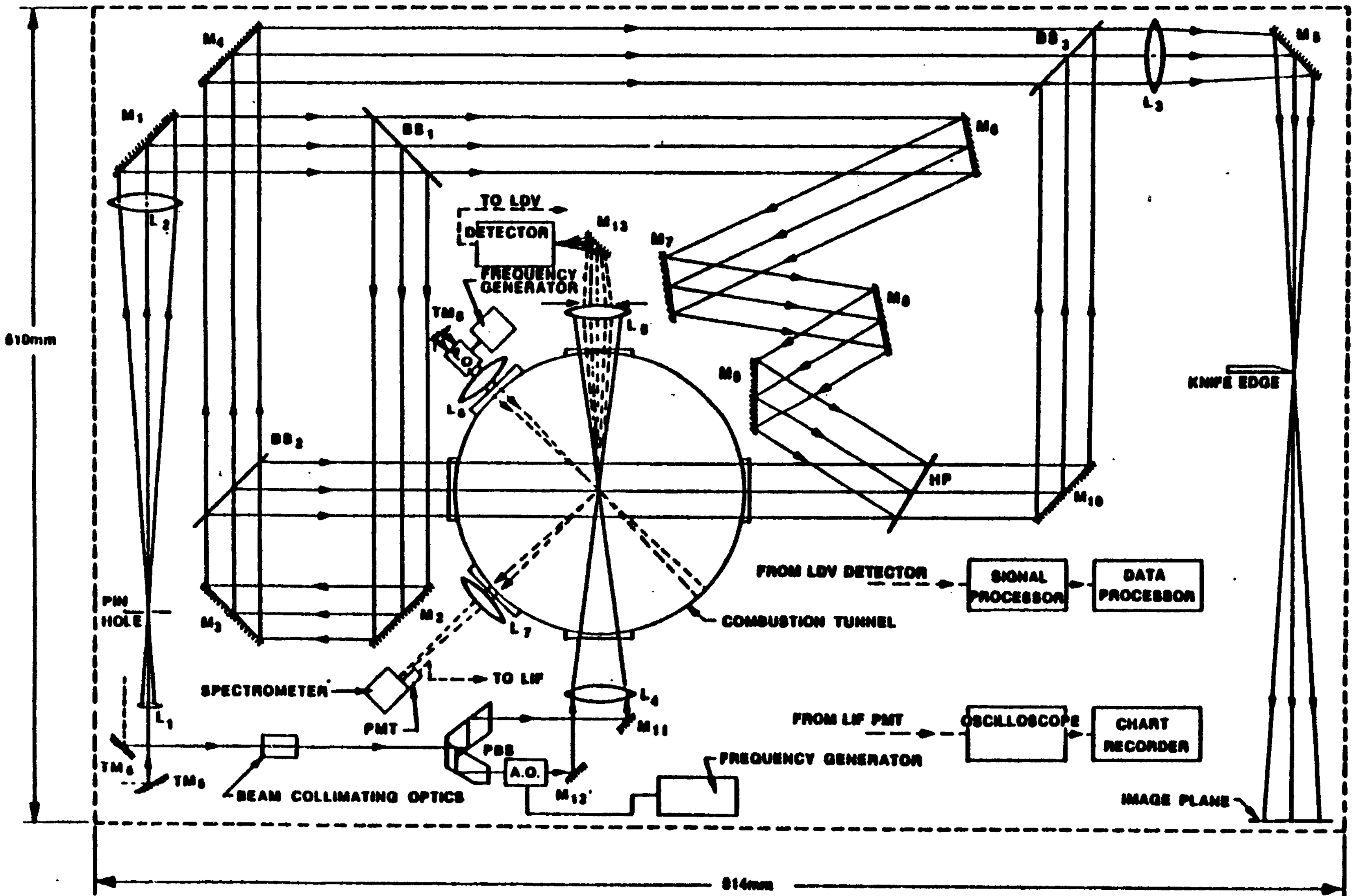

FIGURE A-2. SCHEMATIC OF THE LASER DIAGNOSTIC SYSTEM FOR THE COMBUSTION TUNNEL

Each of the above components and subsystems are discussed in Sections 2.0 and 3.0 of this attachment.

One of the major design goals was to provide unobstructed optical paths through the combustion tunnel test section and to provide the experiment with the ability to translate the ignited fuel sample as desired with respect to the optical path. Some methods for accomplishing this are presented in Section 2.3 (Fuel Introduction Methods), but the problem is not fully solved. Reference to Figures A-3 and A-4 should provide the reader with a better understanding of the complexity of the relationship between the fuel sample being consumed and the laser diagnostics system. The rate of which the flame spreads on a given fuel sample (Figure A-3) depends on the combustion tunnel test parameters and fuel material. Thus, a method is required to locate the optical path in a desired region or regions of the flame as the flame spreads. The problem is further complicated by noting that up to three (3) optical beams are necessary to fully characterize the combustion and flame spread process (see Reference 3 for details). Clearly, the ideal solution would be to direct all three optical paths through the same "point" within the test section and move the sample as desired past this point (see Concept A of Figure A-4). However, it may be physically impractical to calibrate and establish the required optical resolution with Concept A.

Concepts B and C of Figure A-4 indicate the use of three optical paths, but not simultaneously. From the standpoint of the design of the optical and mechanical systems, Concepts B and C may be accomplished. The severe disadvantage is that experiment run times would be significantly increased and/or multiple runs with identical, fresh samples would be required. Again, the reader is directed to Reference 3 for a more complete understanding for the requirement of three separate optical paths.

An additional and challenging problem is that of accommodating the wide range of desired flow velocities, pressures, and gas mixtures outlined in Section 1.2.1 with a single combustion tunnel system. The implications of these test parameters relevant to the system design are discussed in Sections 2.0 and 3.0. The range of desired test section flow velocities and tunnel flow rates are illustrated in Figures A-5 and A-6 for several test section pressures and diameters.

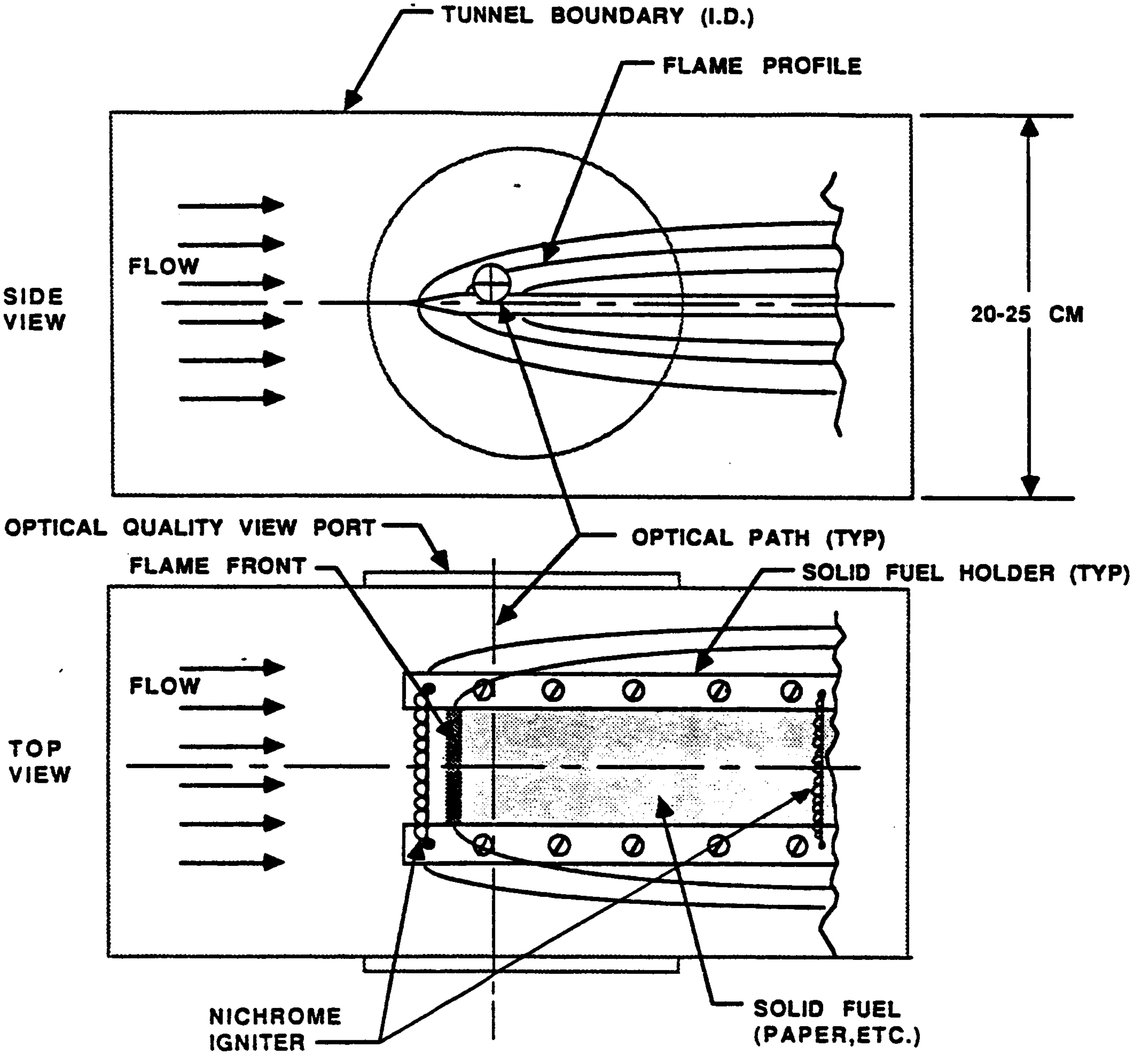

FIGURE A-3. TYPICAL COMBUSTION PROCESS IN THE FLOW TEST SECTION

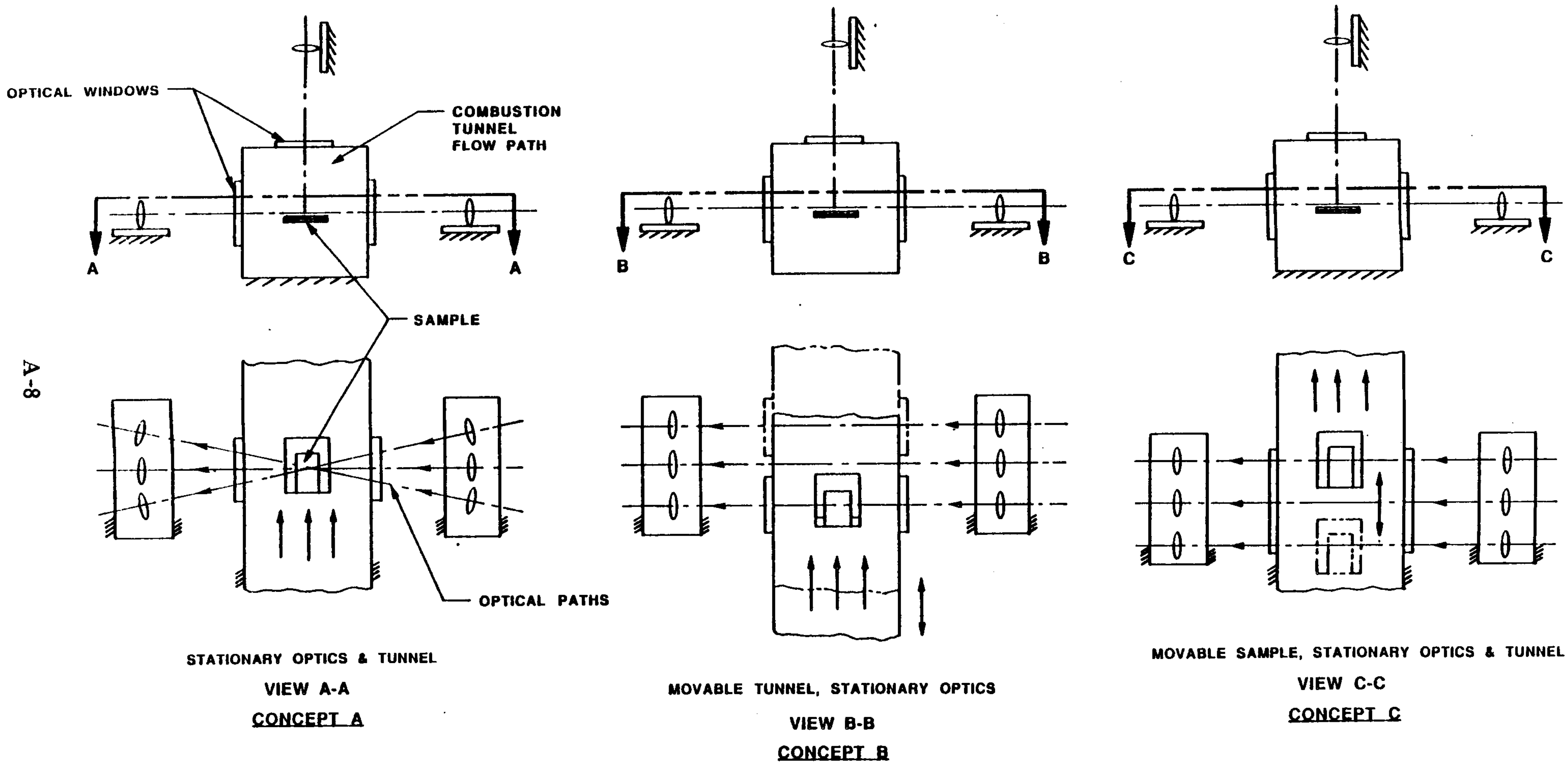

FIGURE A-4. BASIC LAYOUT CONCEPT - COMBUSTION TUNNEL AND OPTICS

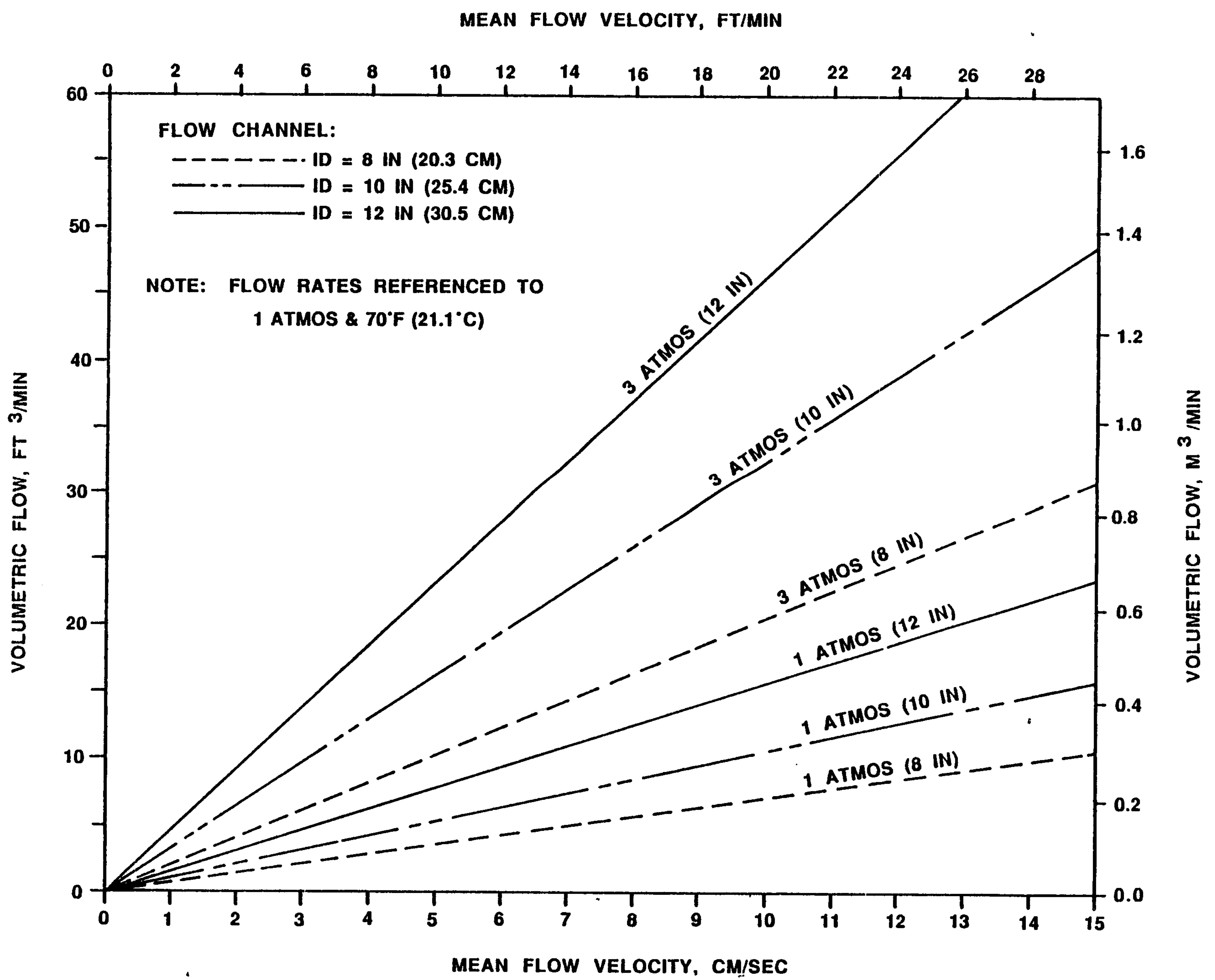

FIGURE A-5. COMBUSTION TUNNEL VOLUMETRIC FLOW RATES (LOW VELOCITY RANGE)

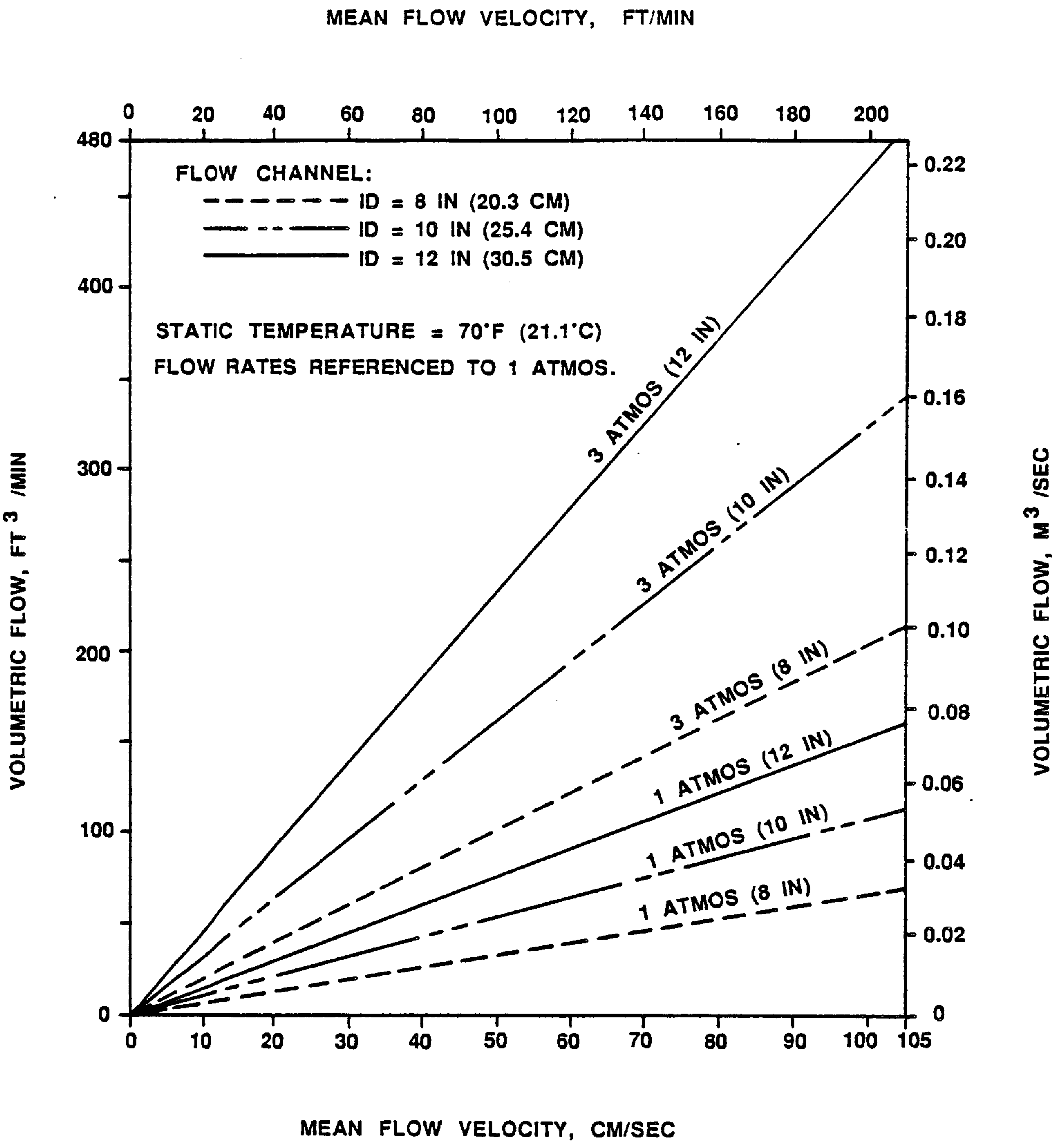

FIGURE A-6. COMBUSTION TUNNEL VOLUMETRIC FLOW RATES (HIGH VELOCITY RANGE)

Section 4.0 identifies some of the technology development requirements associated with a SS-based combustion tunnel system. Section 5.0 provides an outline of the overall development plan for the research combustion tunnel with emphasis placed on the Phase B (breadboard design, construction and testing) portion of the plan. Finally, Appendix A discusses allowable venting from the SS.

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2.0 EQUIPMENT CONCEPT DESIGN

The concept design ideas presented herein for a Space Station (SS) based combustion tunnel are based on the application of readily available technology from low speed, ground-based flow facilities. Moving the ground-based technology into the SS should require only minimal technical refinement. The following subsections describe a baseline concept design along with alternate approaches where appropriate. The equipment related concept design(s) are described under the following headings:

2.1 Equipment Design Constraints

Any concept design for Space Station (SS) based equipment will ultimately be impacted by a number of unique physical and operational constraints. The SS related constraints are not neglected herein, but emphasis has been placed on constraints related to the general design considerations of the combustion tunnel itself. Some of the more pertinent design considerations are presented below, followed by a summary of Space Station constraints identified to date.

2.1.1 General Design Considerations. The desired operational parameters of a SS based combustion tunnel were summarized in Section 1.2.1. These operational parameters provide the baseline goals which dictate a number of overall design considerations. These design considerations are listed below along with comments regarding resolution of a particular problem or identification of unresolved problems.

2.1.1.1 Test Section Size. The tunnel test section must be large enough in both cross sectional area and length to accommodate reasonably sized fuel samples without significant wall influence and yet small enough to use reasonably sized flow components (fan/motor subsystem, etc.)

The effect of flow conditions on the test section wall boundary layer and velocity profile is illustrated in Figures A-7 and A-8. It is clear that the lowest test section velocities of 1-2 cm/s (2-4 ft/min) result in significant boundary layer growth and

FLOW PARAMETERS:

D = TUNNEL TEST SECTION DIAMETER, 20.3 CM (8 IN)

X = DISTANCE FROM TUNNEL INLET, CM (IN)

$\bar{V}$ = BULK VELOCTIY, 1.0 CM/SEC (2.0 FT/MIN)

V = VELOCITY AT RADIAL DISTANCE, r, FROM CENTERLINE

r_w = TUNNEL RADIUS AT WALL, 10.2 CM (4 IN)

Re_D = REYNOLDS NUMBER BASED ON TUNNEL DIAMETER (8 IN), 331.7

FLOW MEDIA = AIR @ 2.5 atmos.,22.2°C (72°F)

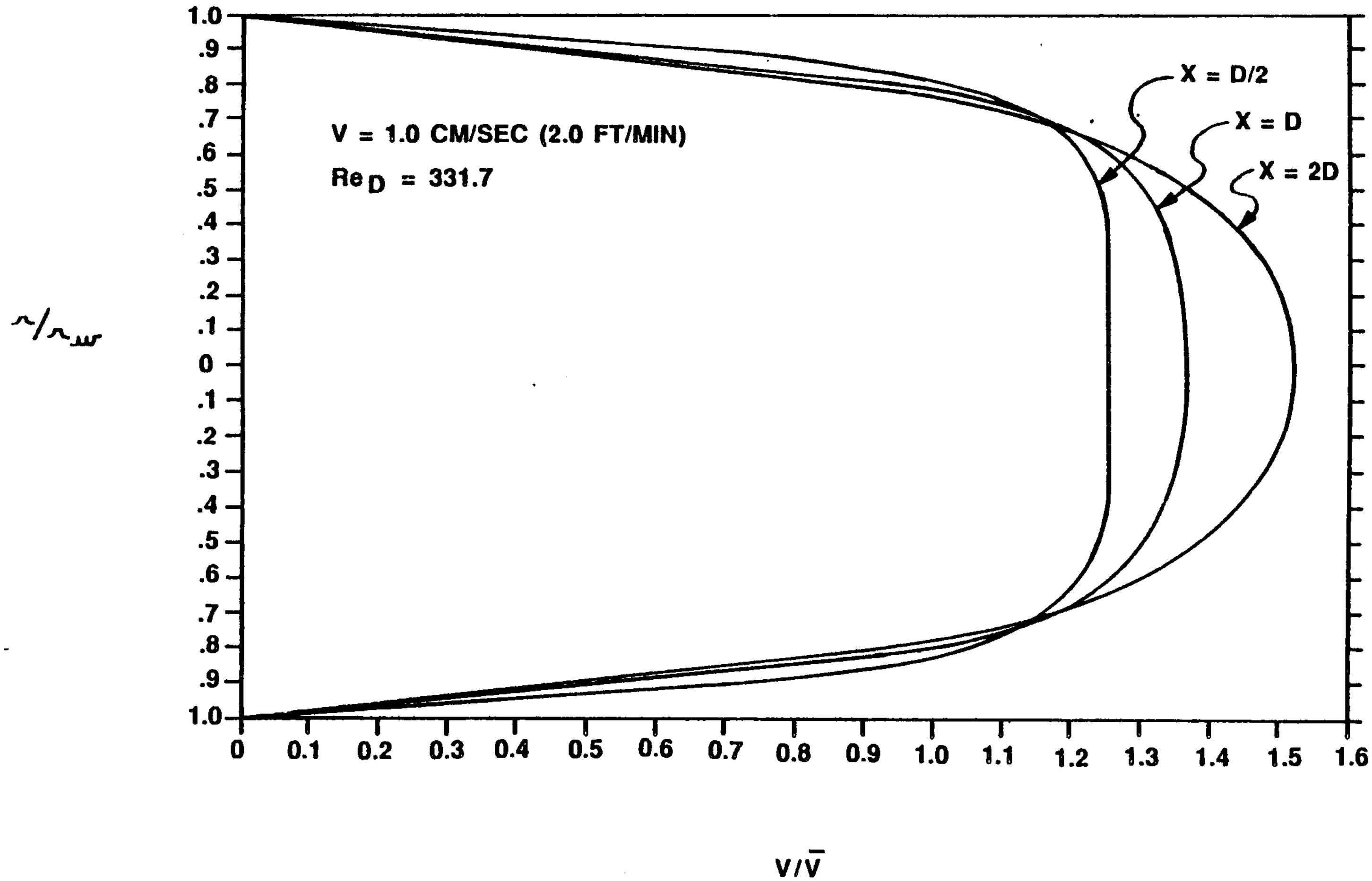


FIGURE A-7. TEST SECTION VELOCITY PROFILES - LOW VELOCITY CASE (1.0 CM/SEC)

FLOW PARAMETERS:

D = TUNNEL TEST SECTION DIAMETER, 30.5 CM (12 IN)

X = DISTANCE FROM TUNNEL INLET, CM (IN)

V = BULK VELOCITY, 50 CM/SEC (98.4 FT/MIN)

V = VELOCITY AT RADIAL DISTANCE, r , FROM CENTERLINE

r_w = TUNNEL RADIUS AT WALL, 15.2 CM (6 IN)

FLOW MEDIA = AIR @ 3.0 ATMOS., 2-2.2°C (72°F)

Re_D = REYNOLDS NUMBER BASED ON TUNNEL DIAMETER (12 IN), 2.9856×10^4

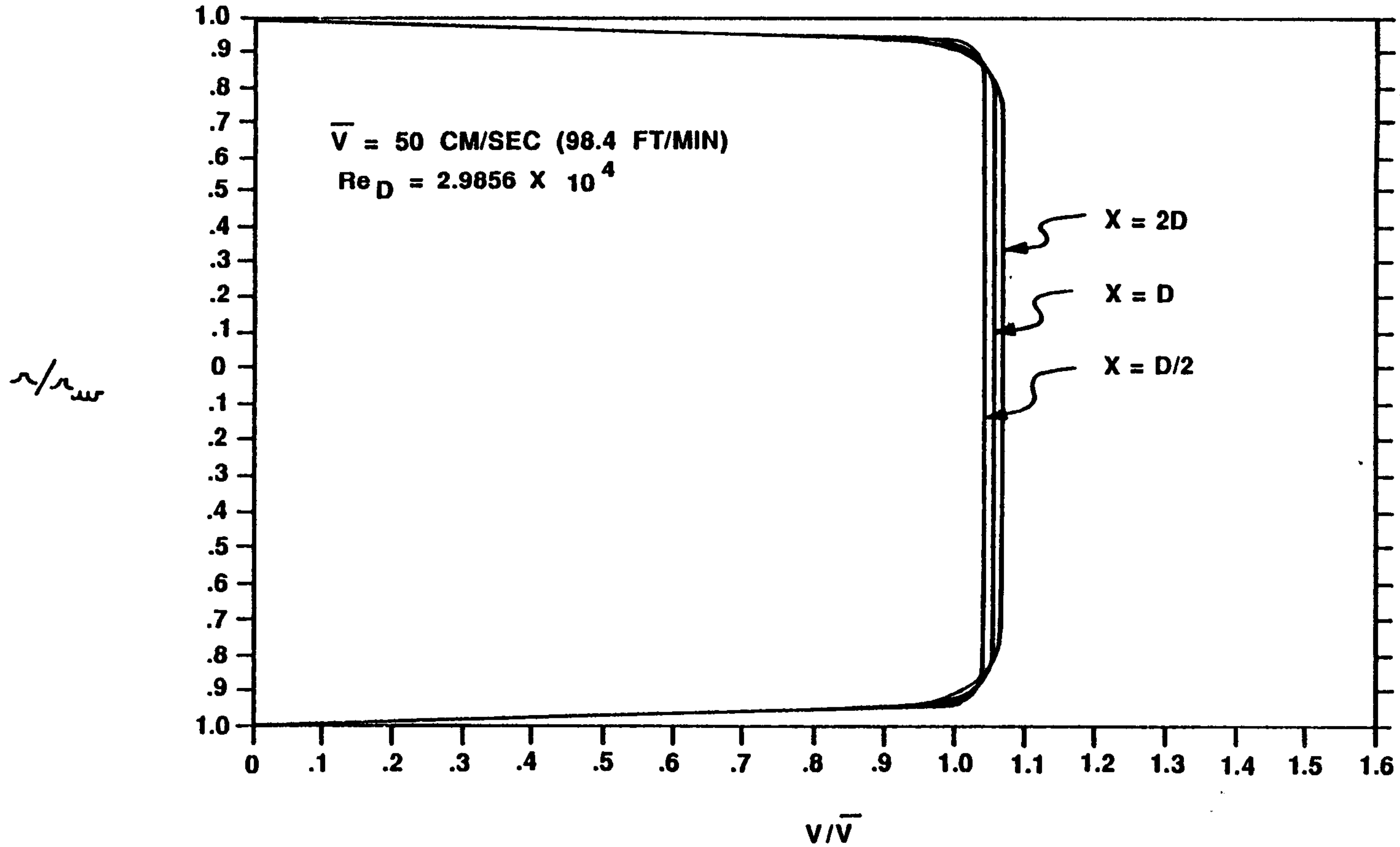


FIGURE A-8. TEST SECTION VELOCITY PROFILES - HIGH VELOCITY CASE (50 CM/SEC) velocity profile development. The velocity profiles shown in Figures A-7 and A-8 are based on 20.3 cm (8 in) and 30.5 cm (12 in) test section diameters and assume no disturbances to the flow. Most of the discussions herein are based on the assumption that the test section dimensions are at least 20.3 cm (8 in) in diameter (or, 20.3 cm (8 in) square) and at least two diameters in length from the inlet.

2.1.1.2 Provision of a Uniform Flow Field in the Test Section. One of the desired goals for the research combustion tunnel is that the flow field has a uniform, flat and well-characterized velocity profile in the test section.

Although the desired velocity range of the combustion tunnel flow media is high (i.e., from 1-2 cm/sec to at least 60 cm/sec (2-4 ft/min to 120 ft/min)), the flow path Reynolds number is quite low at the lower velocities and pressures and the velocity profile quickly approaches a parabolic shape a short distance from the inlet. Careful design of the test section inlet configuration and the apporpriate use of flow conditioners is required. The methodology used to initially establish the flow also requires special consideration. A more detailed discussion of the methodologies available for establishing the required uniform flow field and for measuring the flow velocities is provided in Section 2.2.2 and 2.2.3.

2.1.1.3 Automated Multiple Experimental Runs Between System Servicing. In order to limit the amount of SS crew time required and maximize the number of experimental runs per tunnel charge, it will be highly desirable to provide a means for automatically changing samples. An automated sample changer would permit a number of experimental runs to be made without opening or fully recharging the combustion tunnel.

Several concept designs are presented herein for the automatic or semi-automatic loading and unloading of fuel samples in the combustion tunnel test section. Most of these concepts are directly related to the solid (sheet) samples such as paper, PMMA, etc. No engineering detail is presented, but each concept design is discussed on its own merit in Section 2.3.

2.1.1.4 Provision of Unobstructed Optical Paths. The research combustion tunnel requires a non-intrusive diagnostic system to monitor the combustion process and/or flame spread in the tunnel test section. A laser optical system is indicated and the work of Reference 3 suggests that a minimum of two, and possibly three, optical paths through the test section is required. Also, the progression of the combustion process must be followed in some manner.

The complete resolution to this problem has not been identified. Several concept designs are suggested for the test section/optical system arrangement. The advantages and shortcomings of each concept is briefly described in Section 1.2.2.

2.1.1.5 Gas Mixtures Taken from Space Station Supply. In order to minimize safety and logistics problems, the gases used in the combustion tunnel should be taken from the SS supply. This should pose no major problem except in the case of very special gas mixtures or higher purity gases than would normally be stored on the SS.

2.1.1.6 Removable Test Section. The combustion tunnel test section must be readily accessible for cleaning at routine intervals and for loading and unloading test samples. Removable filters must be used, but these cannot eliminate the need for periodic cleaning of the system.

2.1.2 Space Station Imposed Design Constraints. The accommodation and operation of any experimental apparatus on the SS will have its design strongly influenced by constraints imposed by the SS. Some of the more pertinent SS constraints relevant to the combustion tunnel are addressed in this concept design effort. Additional SS imposed design constraints will simply be identified and left for later evaluation.

a. Safety Considerations.

Comment: Since combustible gases are to be introduced into the combustion tunnel at pressures up to 3 atmospheres, the control and venting of these gases pose the greatest safety related concerns. The removal and recompression of the spent gases to even higher pressures provide additional safety concerns. Such recompression of the spent gases may not be permitted on the SS.

b. Overall System Size and Mass.

Comment: Ultimately, a concept design for the combustion tunnel will be chosen for design and development for the SS. The overall combustion tunnel size and mass will have to be optimized beyond the concept designs shown herein. The physical space required by the combustion tunnel system is critical since each experimental apparatus must compete for the available SS space.

c. <u>Venting and Purging.</u>

Comment: Handling of the contaminated and/or purge gases from individual experiments aboard the SS shall be under the controlled management of a dedicated system or systems. A preliminary description of some of these SS integral systems is described in Reference 5. The external contamination constraints imposed on these systems have been divided into the following two classifications (Ref. 5):

- Molecular column densities
- Molecular deposition/contamination.

A brief explanation of these venting constraint classifications is provided in Appendix A herein and is based on information from Reference 5. The impact of these constraints on experiments such as the combustion tunnel is that direct venting to the space atmosphere is not permitted and the rate at which an experiment's waste gases may be delivered to the SS gaseous waste management system is limited by the aggregate of all sources.

The SS imposed constraints on venting (e.g., Appendix A) has forced the combustion tunnel concept design presented herein to be fully recirculating until the test gas is too contaminated or depleted in one or more constituents to be used further. Intermediate exhaust and purging of the combustion tunnel spent gases into a separate storage tank is possible, but would require a dedicated compressor. This scenario may ultimately be not acceptable.

d. <u>Space Station Crew Involvement.</u>

Comment: Ideally, an experimental apparatus such as the combustion tunnel would best be operated under close control of a payload specialist. However, the limited amount of SS crew time available for each experiment may force more automation than would normally be desired. Preliminary concepts are provided herein for automated tunnel operation and multiple sample exchange, but full automation of the system has not been addressed.

e. <u>Power and Heat Rejection Requirements.</u>

Comment: The research combustion tunnel is not a large power consuming apparatus and the heat rejection should also be modest. At the maximum flow rate (i.e., maximum test section velocity) and pressure condition, the major power consuming device will be the tunnel fan/motor subsystem. This subsystem may be held to 500 watts or less. The sample exchange and transversing subsystem should require no more than about 100 watts and the associated instrumentation and data system should be less than about 500 watts.

The power and heat rejection requirements of the laser optics system are not included herein (see Ref. 3).

f. <u>Noise and Vibration.</u>

Comment: The major noise and vibration generating subsystems associated with the combustion tunnel are likely to be the fan/motor subsystem and the intermediate purge subsystem compressor (if permitted). In general, a vaneaxial fan operates at a higher RPM than the centrifugal or centraxial fan. Thus, fan noise and vibration is a function of the fan type, bearings, etc.

Other noise and vibration sources from the combustion tunnel include the sample exchange and translation mechanism and solenoid valves. All of these items, especially the larger solenoid valves, will require close attention during design.

2.2 Flow System Components

As was shown in Figure A-1, the suggested overall configuration concept for the research combustion tunnel system consists of a large number of components and subsystems. Comments are provided in the following paragraphs on each of the more significant of these.

2.2.1 Removable Test Section. Figure A-9 illustrates a suggested concept for the test section portion of the combustion tunnel. The engineering design of the test section should provide for relatively quick removal for periodic cleaning of the test section and repair or maintenance of the sample exchange mechanism. Although no engineering detail is shown, the flanges at each end of the test section could be of the quick-removal, ring clamp type (e.g., Marmon).

As discussed in the combustion tunnel system overview section (Section 1.2.2), the physical configuration of the test section is critical to the attainment of a uniform, repeatable flow condition in the vicinity of the test specimen. The cross-sectional shape of the test section has not been firmly established, but the representation shown in Figure A-10 is suggested for consideration. The flattened walls provide a means for the optical windows to be essentially flush, thereby reducing flow disturbances from the wall. Also, the rounded corners of the test section are likewise intended to reduce flow disturbances. Although the square (or rectangular) test section may be somewhat heavier than a cylindrical test section, it is suggested that the square-shaped test section can produce a flow field that is less disturbed by the optical windows and other wall penetrations.

The overall dimensions of the test section have not been fully established. The scale used in Figure A-9 suggests an overall length of 102 cm (40 in) for the test section from flange-to-flange. This is for a test section whose cross-sectional dimension is 20.3 cm (8 in). The very short flow path distance from the upstream inlet/flow conditioner to the sample position is suggested for the purpose of providing the most

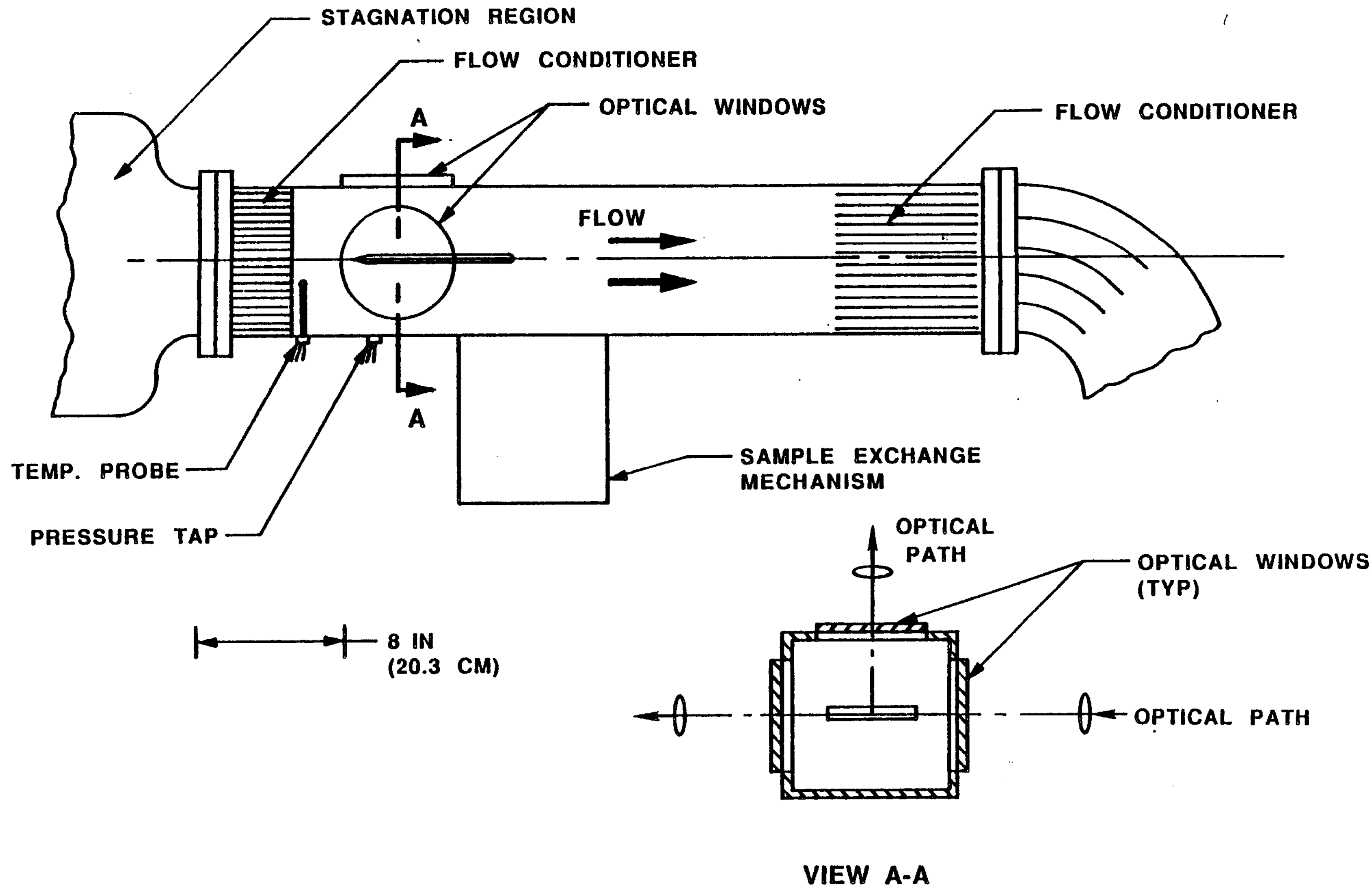


FIGURE A-9. REMOVABLE TEST SECTION - COMBUSTION TUNNEL

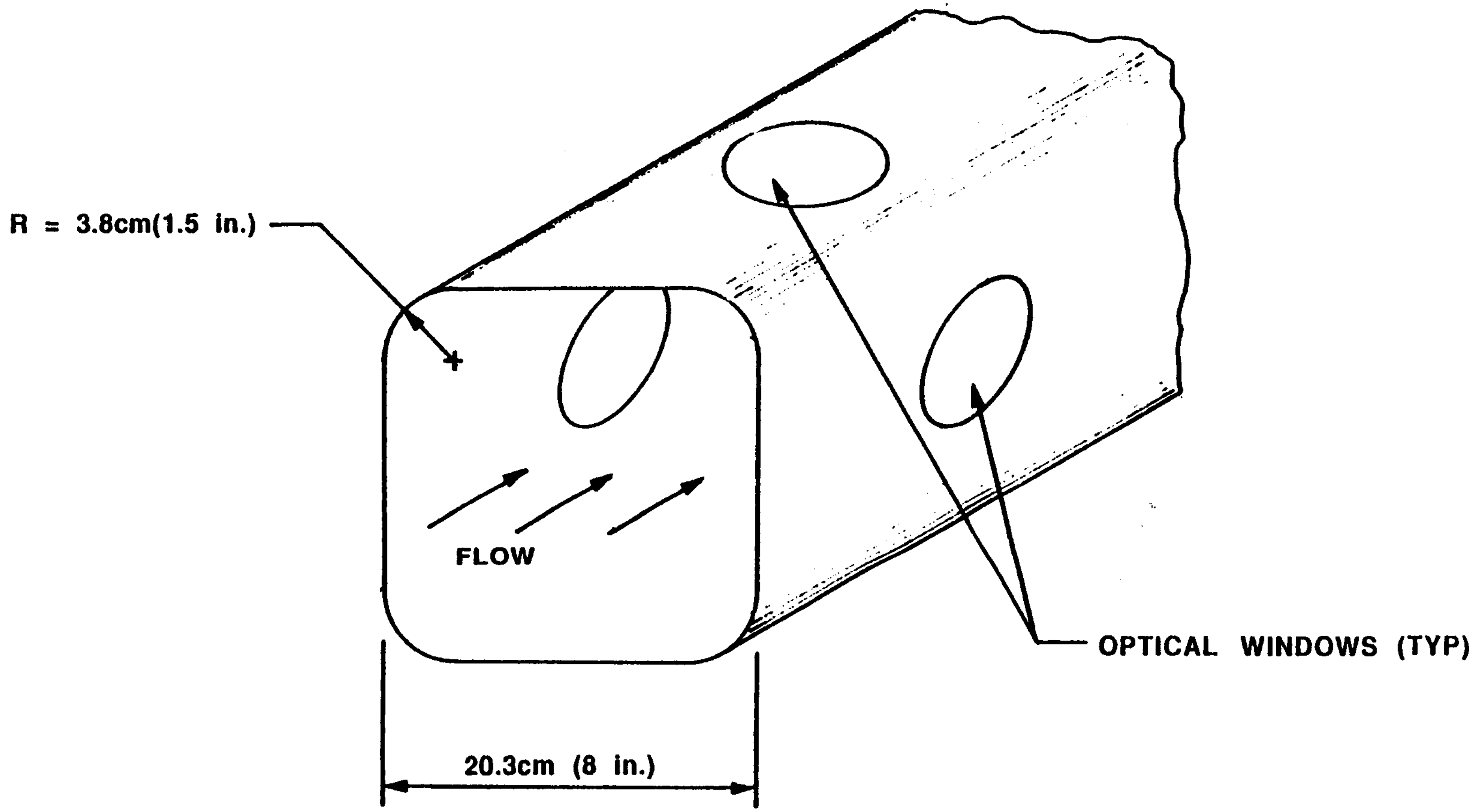


FIGURE A-10. TUNNEL TEST SECTION CROSS-SECTIONAL CONFIGURATION uniform and flat velocity profile and to provide open space downstream of the sample for the sample exchange mechanism. The final determination of the flow channel length downstream of the test specimen will depend on the ability of the downstream flow conditioner to prevent flow turning disturbances from propagating upstream.

A filter to remove particulate material from the combustion process is shown located in the flow turning section of Figure A-1. Ultimately, it may be possible to locate the filter just past the downstream flow conditioner (see Fig. A-9). Some space could be saved if the filter were designed to also serve as a flow conditioner. A selection of a specific filter has not been made in this study. Before such a recommendation can be made, it will be necessary to specify the minimum particle size that is required to be trapped, the amount of particulate material required to be retained before filter change out, and the maximum allowable pressure drop for the desired flow conditions. The pressure drop is especially important to a Space Station based combustion tunnel design since the fan power required is proportional to the total flow path resistance. It would be desirable to limit the pressure drop across the filter to 1.0 in H_2O (0.25 kPa) or less. This may be impractical under the conditions of the highest flow velocities at 3.0 atmospheres pressure.

The use of special filters such as those used in gas chromatography to scavenge selected species has been identified as an area for further investigation (see Section 4.0, Technology Development).

2.2.2 <u>Stagnation Chamber and Flow Conditioners</u>. Figures A-1 and A-9 both show the inclusion of a stagnation (settling) chamber upstream of the tunnel test section inlet and a number of flow conditioners and turning vanes located in several sections of the system. The purposes of these devices are well established and their design and application are described in many texts (e.g., Ref. 6).

The stagnation (i.e., settling) chamber indicated just upstream of the inlet to the combustion tunnel test section serves the purpose of reducing and smoothing the flow velocity just ahead of the inlet. The bulk velocity in the stagnation chamber is related to that in the test section by their respective cross-sectional areas. The practical design diameter of the stagnation chamber could, for example, be twice that of the tunnel test section, resulting in a stagnation chamber bulk velocity that is one-fourth that in the test section. The use of a finite diameter for the stagnation chamber will result in an inlet velocity profile that is not fully flat. Some improvement can be obtained by locating a honeycomb or mesh flow conditioner at the test section inlet (see Figures A-1 and A-9). However, the usefulness of a flow conditioner at the inlet must be compromised by the consideration of a reasonable pressure drop across the device. It is suggested that a maximum allowable pressure drop for the inlet flow conditioner be no more than 0.5 in H_2O (0.12 kPa). Note that a detailed design of the stagnation chamber and inlet flow conditioner and their effect on the inlet velocity profile is not possible in this concept design effort. The provision of an acceptably uniform (flat) velocity profile has been identified as a technology development area (Section 4.0).

The other flow conditioners and turning vanes indicated in Figure A-1 are of the more conventional type whose purpose is to remove swirl and distortion from local velocity profiles. Some of these flow conditioners are of industry accepted design and generally produce a very low pressure loss. Typical flow conditioners designs are illustrated by Figure A-11 (reproduced from Ref. 6). It should be clearly understood that these low pressure-loss conditioners provide essentially no flattening of the velocity profile across the flow path. For this reason, it should be noted that the selection of a flow conditioner for the inlet to the combustion tunnel test section (Figures A-1 and A-9) would be of a special design to remove inlet swirl and distortion and to also flatten the velocity profile.

The actual velocity profiles in the test section must be measured for different mass flow rates and gas mixtures. It is suggested that this tunnel calibration (flow characterization) be performed either by hot wire anemometry, or by the laser Doppler velocimeter (LDV) method. The LDV method is preferred for this application since it is to be developed for the flame diagnostics (Ref. 3).

2.2.3 Flow Rate Measurement and Flow Control. Reference to Figure A-1 indicates that the flow in the current concept design of the research combustion tunnel is generated by a fan/motor subsystem. A desired tunnel flow rate may be established by microprocessor control of both the fan motor speed and the use of a flow control valve (or valves). The importance of this flow rate control must not be minimized.

The input signal to the flow rate control microprocessor may be based on the total mass flow rate through the tunnel, or it may be based on a specific velocity such as

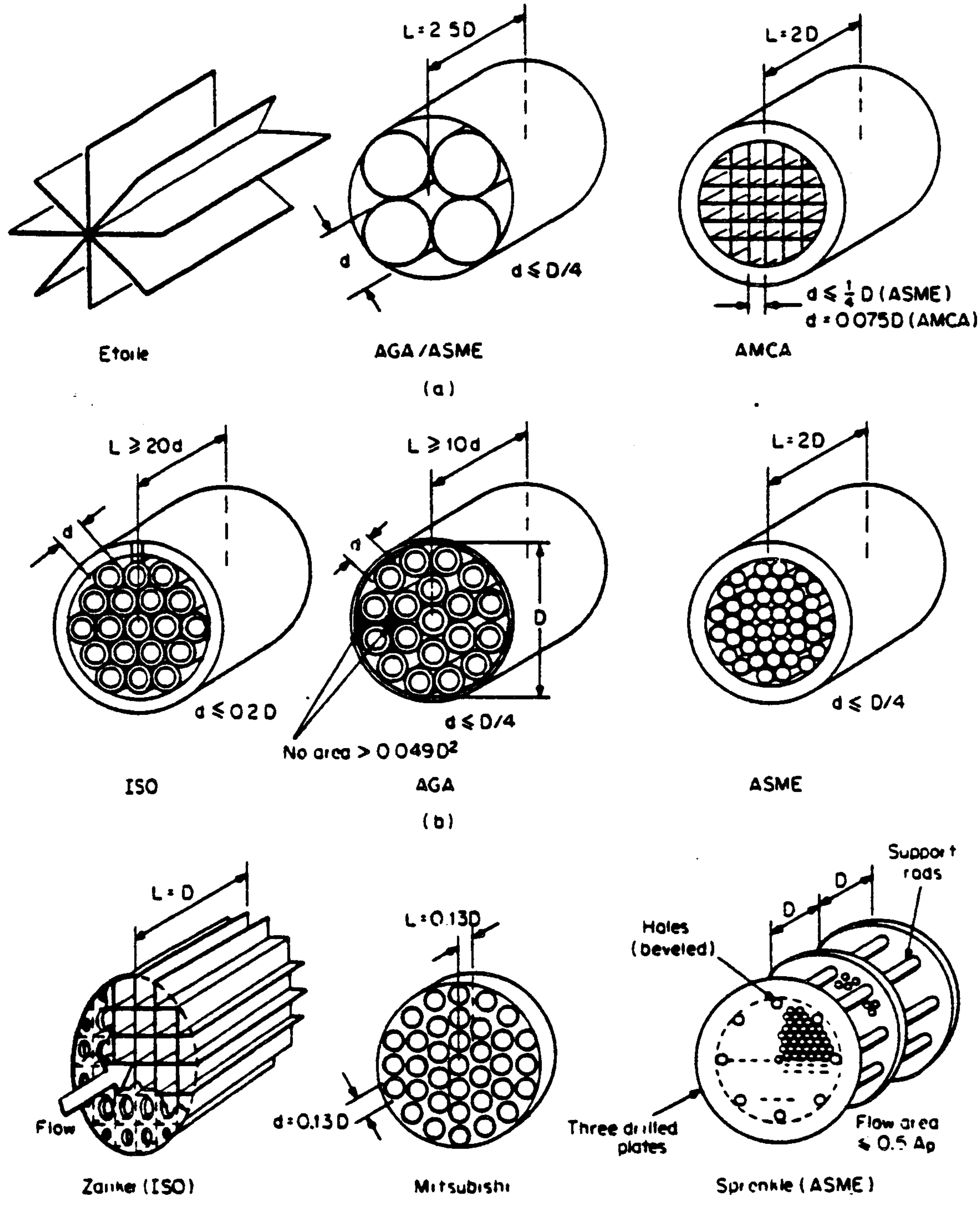


FIGURE A-11. FLOW CONDITIONERS. (a)SWIRL, (b)SWIRL AND MODERATE DISTORTION, (c)SWIRL AND DISTORTION (FROM REF. 5) the centerline velocity in the test section. It is suggested in this concept design that the in situ measurement of mass flow rate be used as the controlling input signal. As shown in Figure A-1, two secondary reference standard flow rate measurement techniques are suggested for inclusion in the combustion tunnel. The higher flow rate measurements could be made by use of a calibrated orifice plate system (i.e., for test section flow velocities up to 100 cm/sec (200 ft/min) or greater). The very lowest flow rate measurements may be made by use of a calibrated laminar flow element (LFE) system. The LFE is capable of making very precise flow rate measurements, but is generally a high pressure loss device. This is the reason for suggesting at least two separate flow rate measurement techniques.

2.2.4 Fan and Fan Motor. As discussed in the section on the system overview of the research combustion tunnel (Section 1.2.2), the system must be fully recirculating and fully closed during any specific experiment. Thus, a flow generation subsystem must be designed that will have the following attributes:

a) Fully controllable over a wide range of speeds
b) Minimal input power required
c) Safe and reliable in high precentage oxygen gas mixtures
d) Low noise and vibration characteristics.

The most appropriate fan/motor subsystem for this application appears to be of the vaneaxial type. The desired flow rates can be attained and they are of compact design. A disadvantage of the vaneaxial is that they generally operate at higher RPMs than, for example, centrifugal or centraxial blowers at the same flow rate.

The power input to the fan/motor subsystem is proportional to the total flow resistance (in terms of pressure drop) for any desired flow rate. It is suggested that the research combustion tunnel be configured to operate with a total flow resistance of 5 in of H_2O (1.24 kPa) or less at the highest mass flow rates.

It remains to determine the allowable noise and vibration characteristics of available fan/motor subsystems. Also, the reliability of the fan motor operating in a high percentage oxygen atmosphere must be investigated.

2.2.5 Heat Rejection. The heat rejection requirements of the research combustion tunnel flow system will largely be due to the heat dissipated by the fan/motor subsystem and the sample exchange and translation motors. Most of this heat may be assumed to be dissipated in the combustion tunnel flow media and must, therefore, be removed upstream of the tunnel test section and stagnation chamber. Preliminary estimates of this heat rejection requirement total approximately 700-800 watts. This amount of heat should be easily removable by means of an air-to-liquid heat exchanger shown in Figure A-1.

2.2.6 Interim Purge Subsystem. One of the more significant design constraints imposed on the research combustion tunnel is that related to the venting of waste gases from the Space Station (SS) (see Section 2.1.2 and Appendix A). Thus, if permitted, an interim purge storage subsystem would be highly desirable. As shown in Figure A-1, this would consist of a compressor and storage cylinder placed in the lines between the combustion tunnel and the SS vent system. The size of the compressor and storage cylinder would be determined by the number of combustion tunnel charges required to be accommodated between discharges to the SS waste gas handling system.

It is noted that the recompression of gases, especially combustible gases, may not be permitted.

2.3 Fuel Introduction Methods

A method (or methods) must be provided for introducing fuels into the research combustion tunnel. The fuels considered herein include solid sheet materials (e.g., paper, plastic, etc.) and various liquid fuels. Introduction of such fuels into a SS based combustion tunnel requires the design of mechanisms that can insert fresh fuel samples essentially automatically. Further, the sample holder and fuel exchange (i.e., supply) mechanisms must provide minimal flow disturbance.

The following paragraphs provide a description of some concept designs for fuel insertion and removal for both solid and liquid fuels.

2.3.1 Solid Fuel Introduction. The following paragraphs describe three separate design concepts for the introduction of solid fuels into the research combustion tunnel and the removal of the spent fuel. The three concept designs suggested include the following:

a) Concept 1 - Cartridge Type Loader
b) Concept 2 - Reel-to-Reel Sample Holder
c) Concept 3 - Rotating Wheel Type Sample Holder.

Note that in all of the figures used to illustrate the various concepts, the dimensions shown are approximate and no engineering details are demonstrated. Also, note that the combustion tunnel test section is variously shown as cylindrical or as a square or rectangular shape. The preferred test section configuration was discussed in Section 2.2.1 (Removable Test Section).

Concept 1 - Cartridge Type Loader:

Figure A-12 shows a wedge-shaped sample holder for the cartridge type loader. The sample material is secured in the holder and may be ignited from either end. It will be desirable to make the sample holder as thin as possible to reduce flow disturbances.

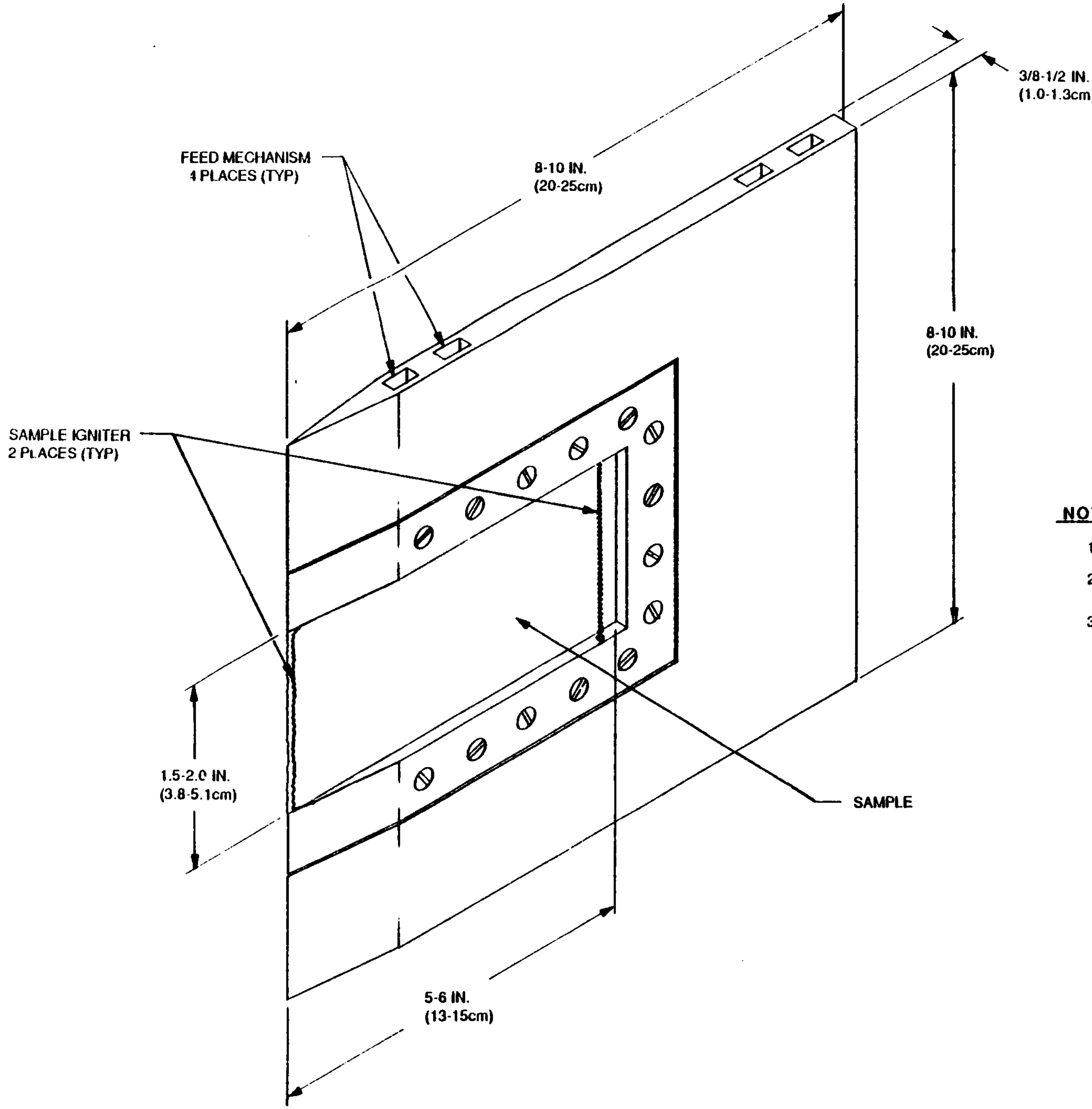
Figure A-13 indicates one variation of a cartridge type sample loading mechanism. In this design, fresh fuel samples are brought in from one side of the combustion tunnel through a narrow slot. They are caused to turn into the flow path where they are ignited when conditions are ready. The spent sample is caused to be removed from the tunnel through the same slot.

Figure A-14 indicates a second variation of a cartridge type sample loader. In this case the fresh samples are brought into the tunnel from one side (i.e., from the sample supply cartridge) and the spent samples are removed to the opposite side of the tunnel. This design has the clear disadvantage that the relatively large openings into the combustion tunnel from the cartridges are likely to cause undesirable flow disturbances.

Note also that in both variations (Figures A-13 and A-14) of the cartridge type loader, no design provision is shown for causing the fuel to translate appropriately in relation to the optical windows. A separate mechanism is required to cause this additional motion.

Concept 2 - Reel-to-Reel Sample Holder:

Figures A-15 and A-16 illustrate a concept for the use of an essentially continuous strip of fuel to be introduced into the combustion tunnel from a supply reel and disposed of by a spent fuel reel on the opposite side. This concept illustrates several desirable features, including an axial translation mechanism and minimal flow disturbances from



NOTES

1. ALL DIMENSIONS APPROXIMATE
2. SAMPLE MATERIAL IS SHEET PAPER,PMMA,ETC.
3. NOT TO SCALE

FIGURE A-12. CONCEPT 1 - SAMPLE HOLDER FOR CARTRIDGE TYPE LOADER

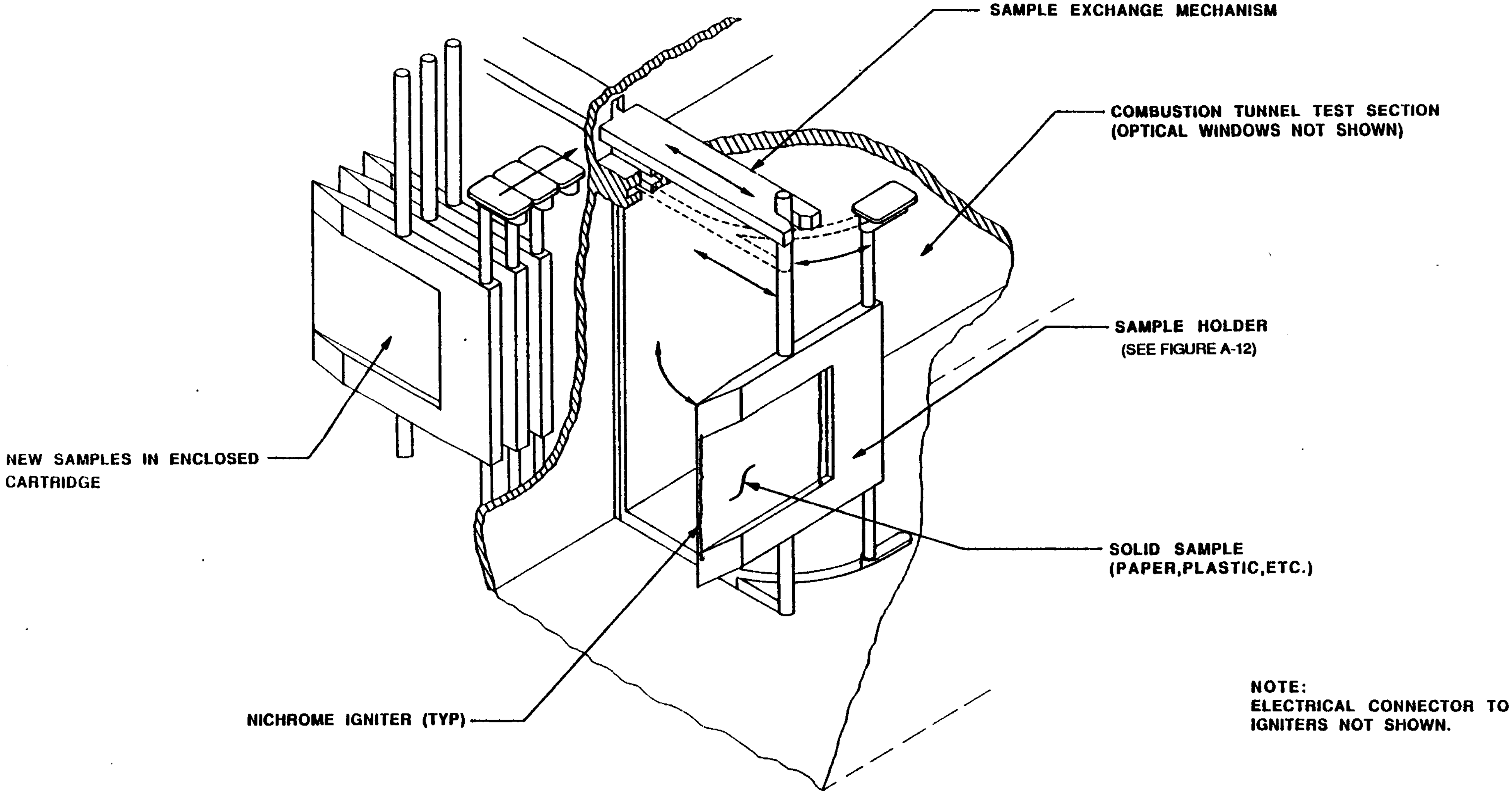


FIGURE A-13. CONCEPT 1 - CARTRIDGE TYPE SAMPLE LOADING - PICTORIAL

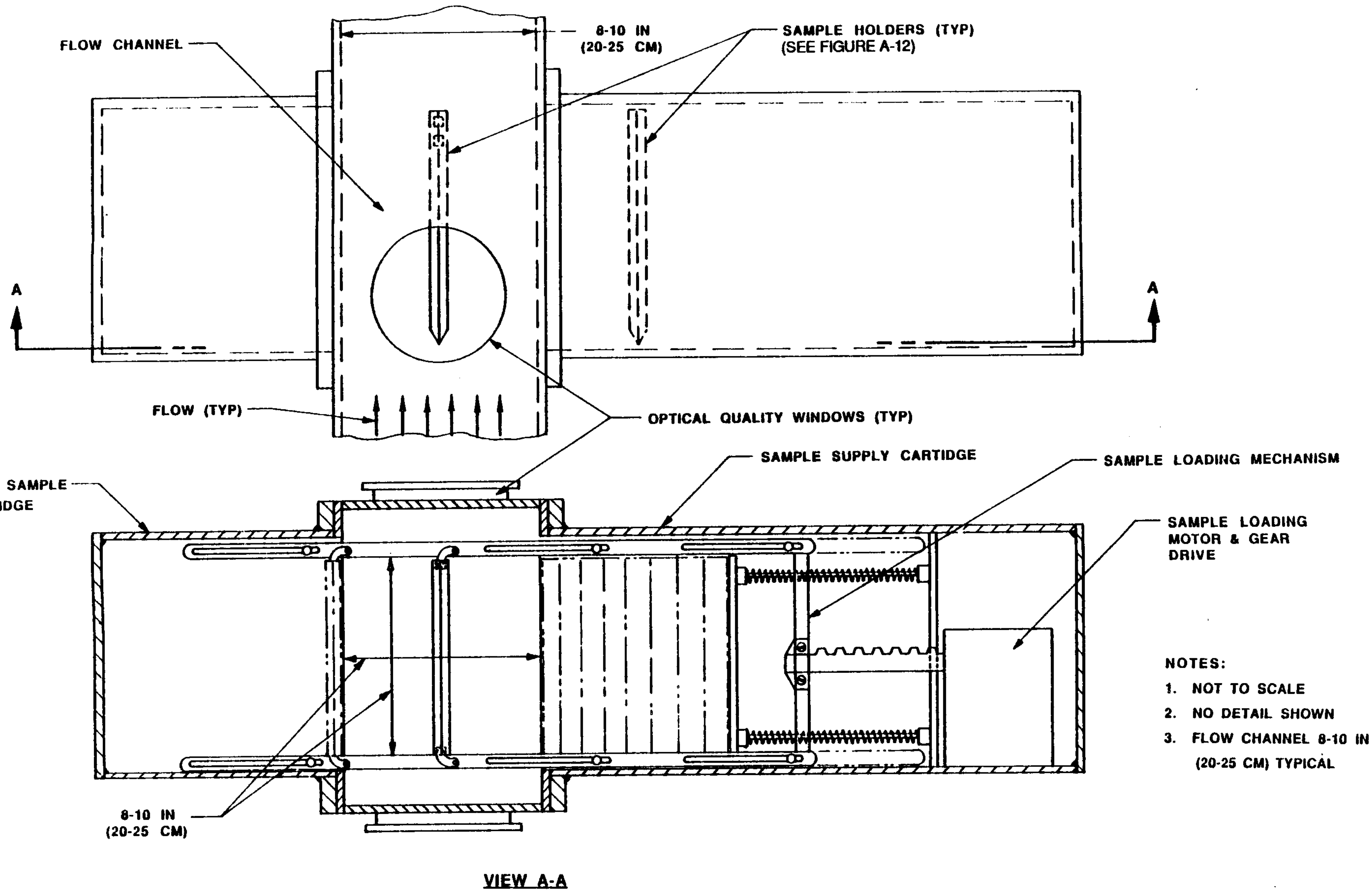


FIGURE A-14. CONCEPT 1 - CARTRIDGE TYPE SAMPLE LOADING MECHANISM

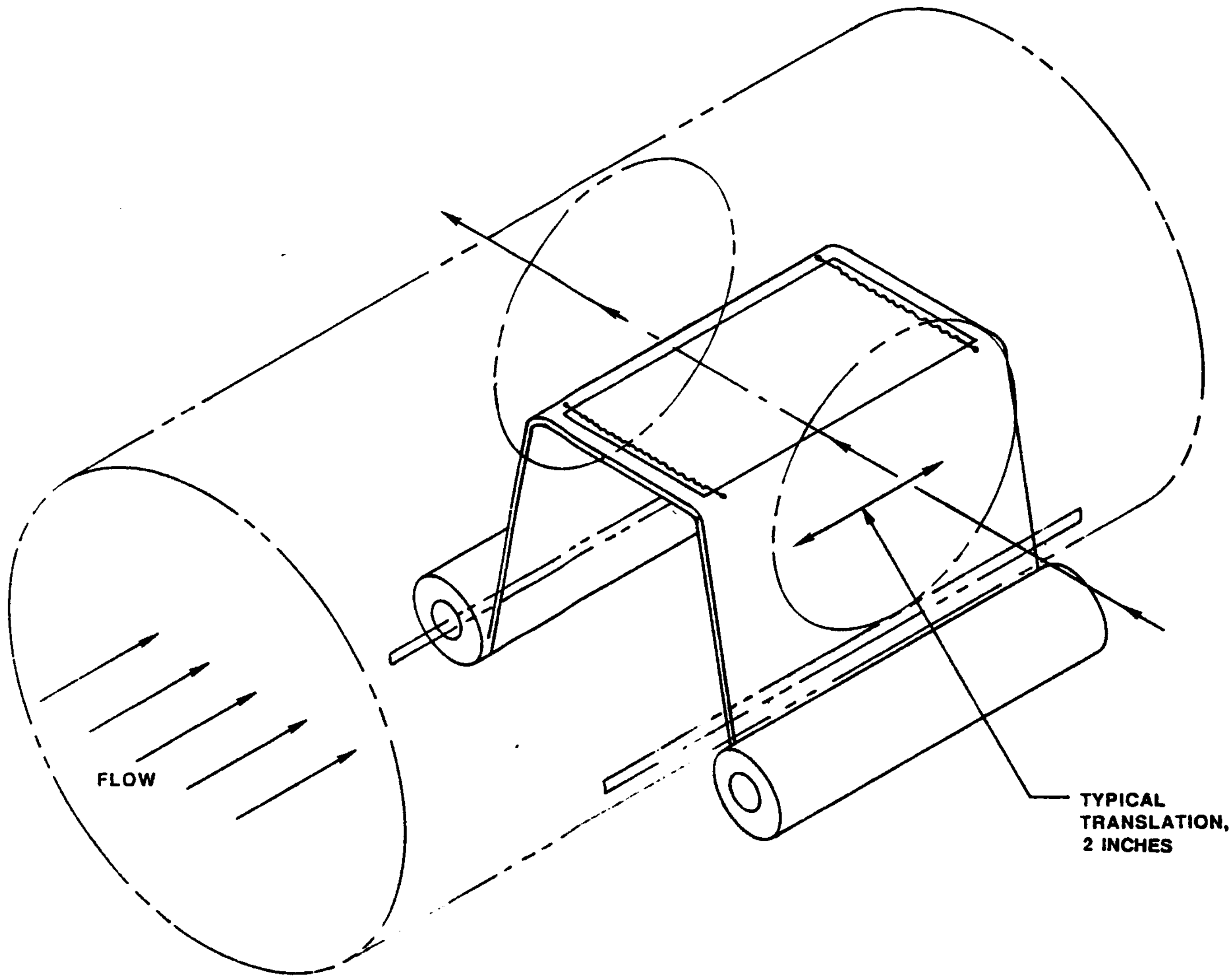


FIGURE A-15. CONCEPT 2 - REEL-TO-REEL SAMPLE HOLDER, PICTORIAL VIEW

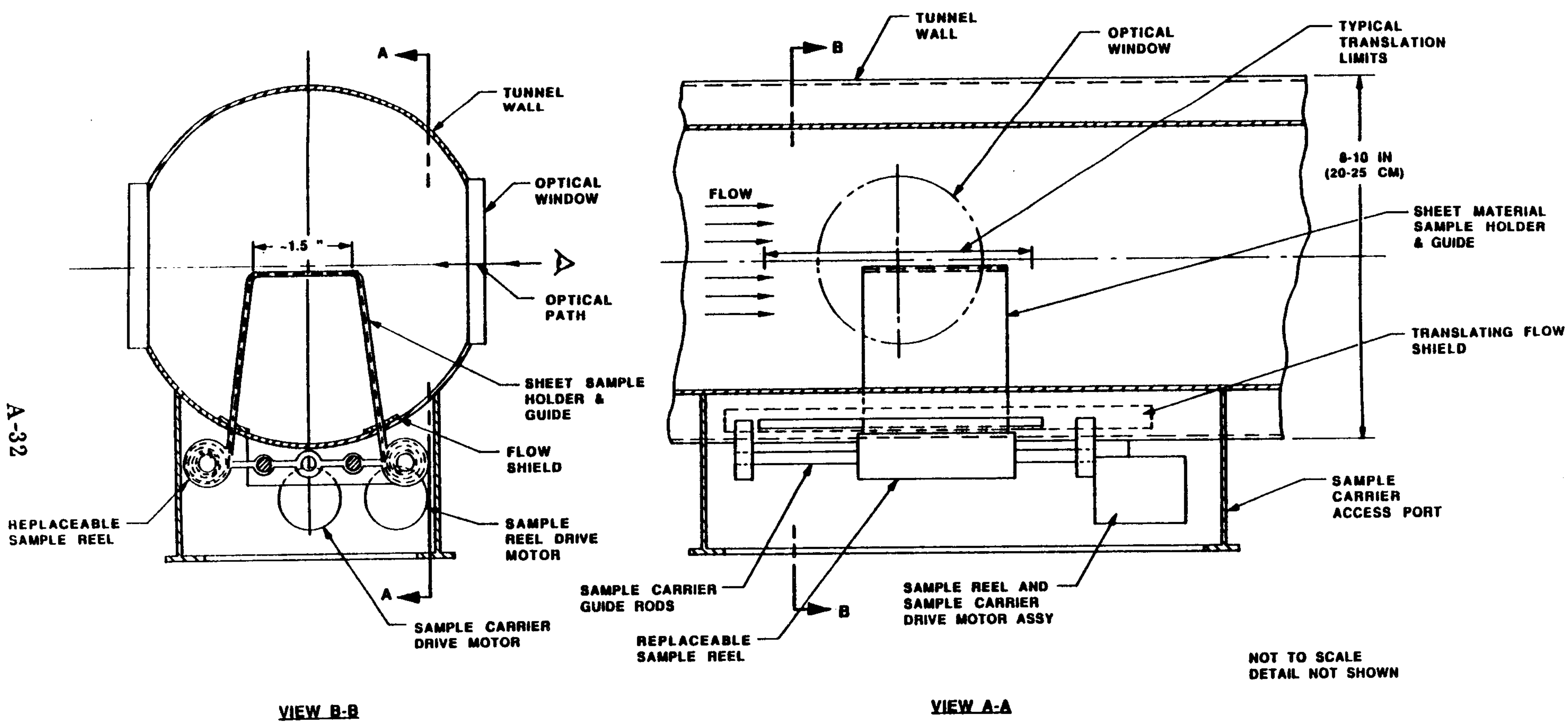


FIGURE A-16. CONCEPT 2 - REEL-TO-REEL SAMPLE HOLDER, CROSS-SECTIONAL VIEW the tunnel wall penetrations. A clear design problem with this concept is that of causing the sample strip material to be rigid enough to not bind or tear when attempting to reel a new sample into place after a combustion process. A tentative solution to this problem would be to provide a noncombustible, flexible edging along the sides of the combustible sample. This flexible edging would be constructed of a material that would not be harmed during the burning process and would remain to pull the fresh sample into place.

Concept 3 - Rotating Wheel Type Sample Holder:

Figures A-17 and A-18 illustrate a rotating wheel concept which contains from 4 to 6 fuel samples mounted as shown. The operation of this concept depends on a mechanism (not illustrated) which would cause the wheel to rotate after each experimental run, bringing a fresh fuel sample into the flow stream. This rotating wheel concept is relatively simple to construct in the configuration shown. However, the concept has the severe disadvantage of holding only 4-6 samples. Again, no sample translation mechanism is shown that would move the sample streamwise relative to the optical diagnostics subsystem.

2.3.2 Liquid Fuel Introduction. The introduction and ignition of liquid fuels and the observation of their burning is also of interest for the SS combustion tunnel (Ref. 1). However, the techniques and methodology for creating the appropriate conditions for liquid fuels ignition and burning remain to be developed (Ref. 4). In this concept design study only the most rudimentary concepts are presented relative to the use of liquid fuels. Pool or surface (sheet) liquids and liquid droplets are addressed briefly in the following paragraphs.

Liquid Pool (Sheet) Concept:

Figure A-19 shows one design concept for creating a liquid pool which may be ignited at either the upstream or downstream flow location. The concept depends upon the wicking action of a porous substrate to provide a fully wetted surface. The mass and material properties of the wick material should be chosen such that it is not consumed or otherwise harmed as a result of the burning of the liquid surface.

Note that it is probably appropriate to seal the peripheral edges of the wick substrate such that burning takes place only on its large area surfaces (i.e., in the plane of the optical path).

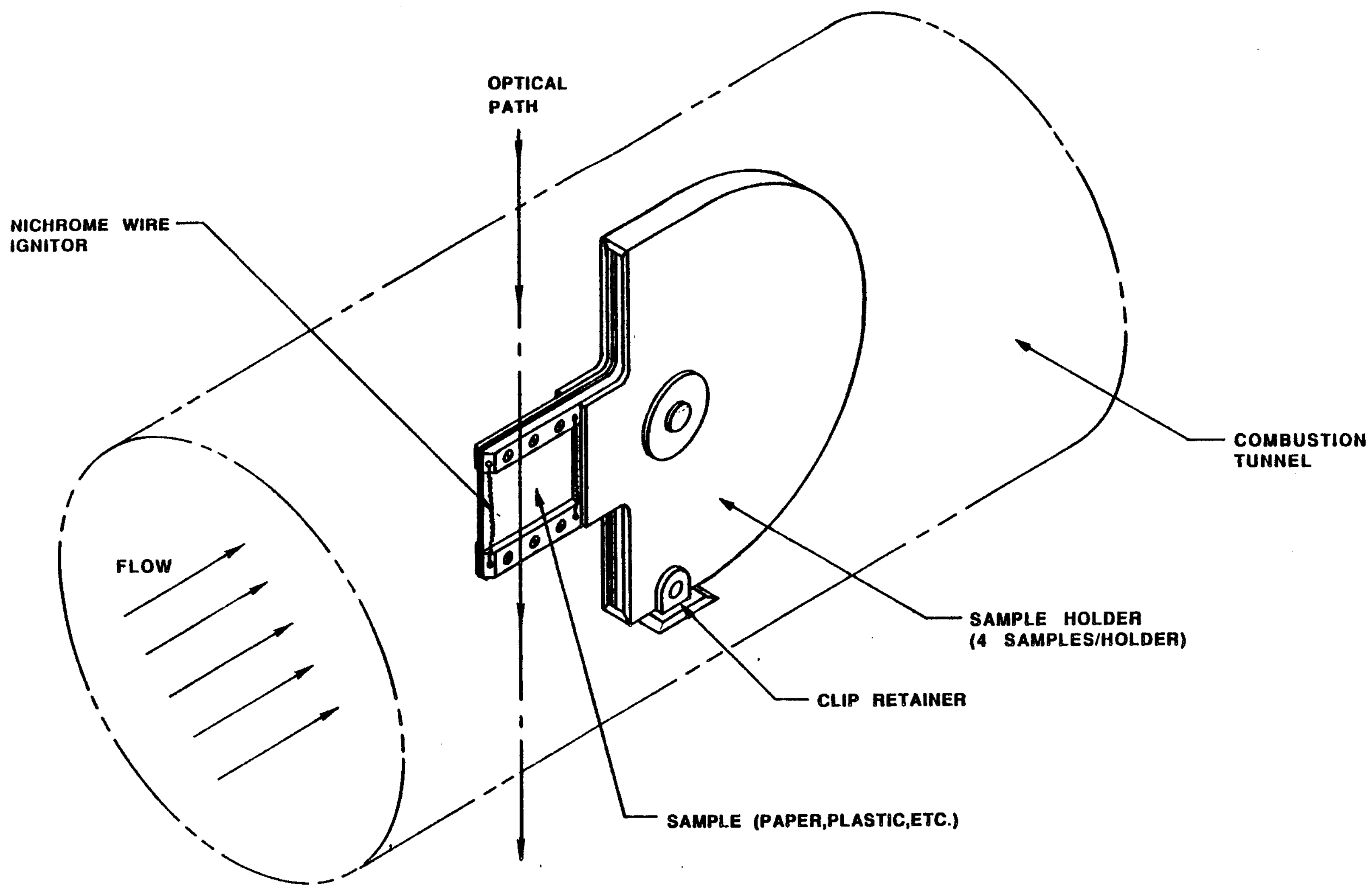


FIGURE A-17. CONCEPT 3 - ROTATING WHEEL TYPE SAMPLE HOLDER, PICTORIAL

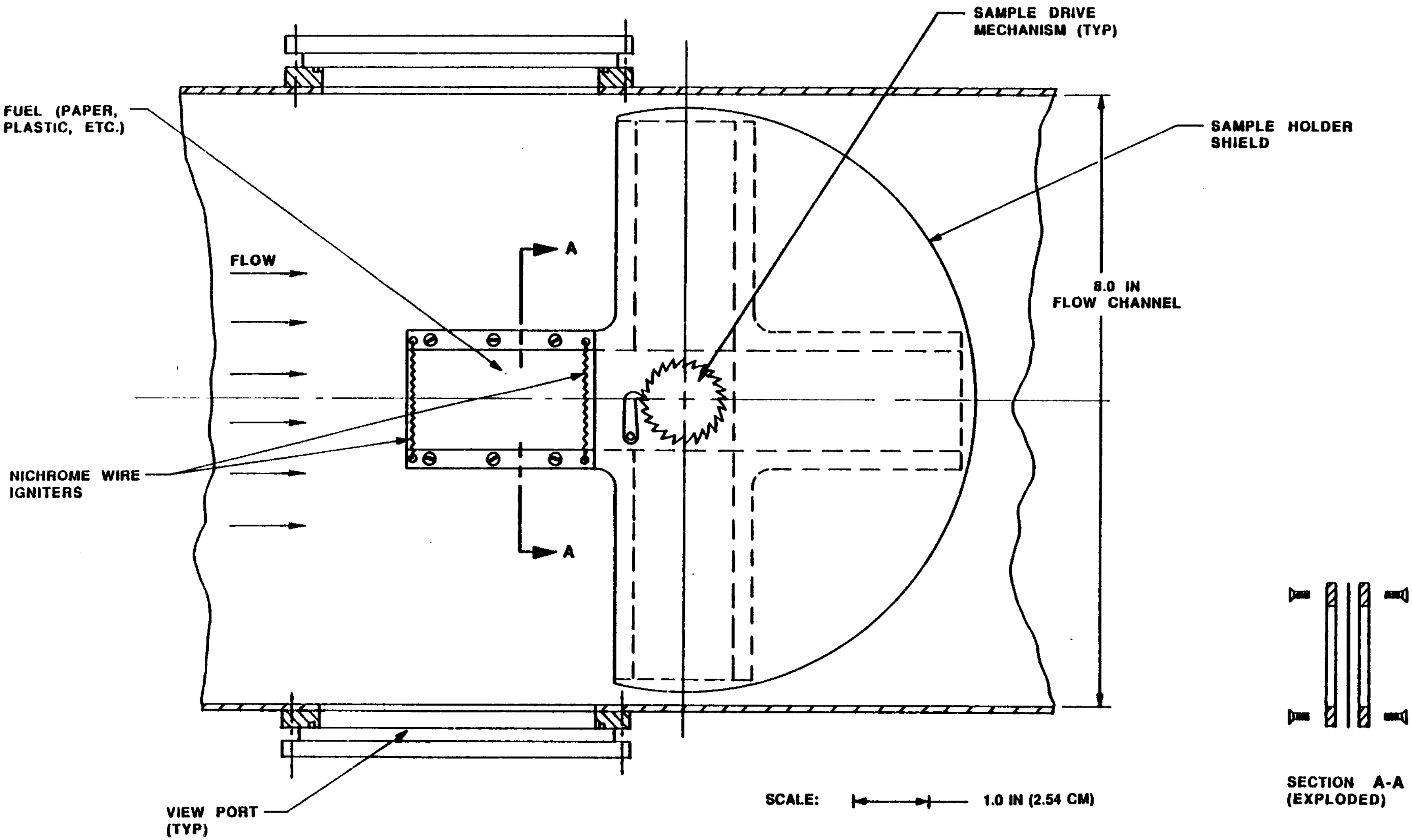


FIGURE A-18. CONCEPT 3 - ROTATING WHEEL TYPE SAMPLE HOLDER

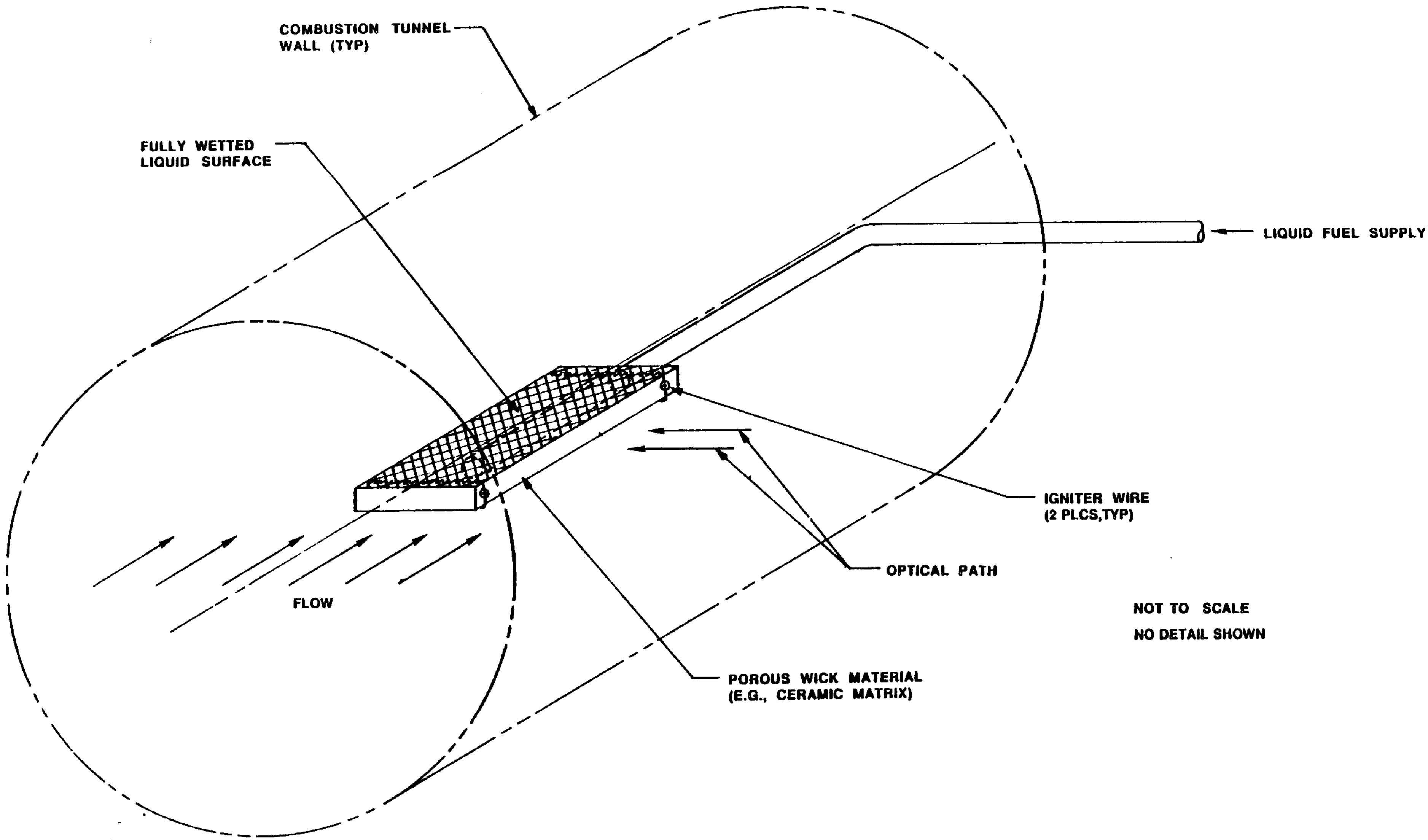


FIGURE A-19. LIQUID FUEL INTRODUCTION - CONCEPT FOR LIQUID POOL (SHEET)

Precise control of the amount of liquid fuel to be pumped to the wick must be attained. Combustion of the liquid fuel on the wick surface could be essentially continuous for the desired run times.

Liquid Droplet Concept:

Figure A-20 shows an elementary concept for the introduction of liquid droplets into the SS combustion tunnel. Unlike the liquid pool concept where the liquid location may be stationary, the liquid droplets may be allowed to move with the tunnel flow across the optical path. An alternative might be that the liquid droplets would be caused to attach themselves to stationary wires or posts located at any of the points shown in Figure A-20.

In either case, whether the droplet is to move with the tunnel flow or be held stationary, the methodology for igniting the droplet remains to be established. The use of some type of spark igniter (see Figure A-20, Detail A) may be the most appropriate. Any other method is likely to excessively disturb the local flowfield or the shape of the droplet (e.g., the use of a micro-torch or heated wire igniter).

2.4 Instrumentation and Data Acquisition

The instrumentation required for the research combustion tunnel shall include pressure and temperature transducers, linear position indicators (LVDTs), mass flow meters, oxygen analyzers, and the laser diagnostics system (Ref. 3). Specific instruments for the SS-based combustion tunnel have not been selected.

Very little attention has been given herein to the data acquisition requirements for either a ground-based or SS-based combustion tunnel. It is apparent that the data handling requirements of the laser diagnostics system (Ref. 3) will be significant.

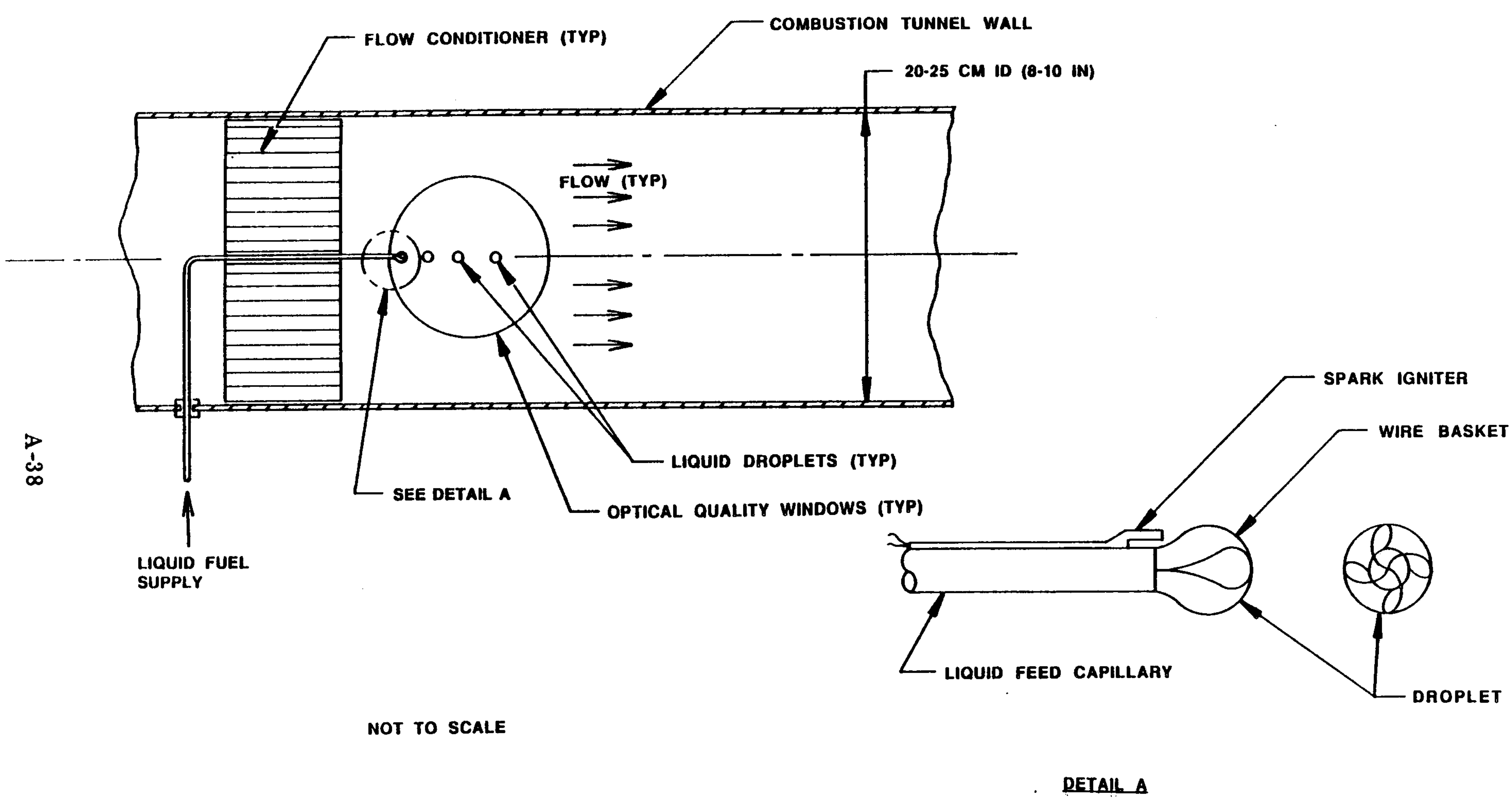


FIGURE A-20. LIQUID FUEL INTRODUCTION - CONCEPT FOR DROPLETS

3.0 OPERATIONAL CONCEPTS

In addition to the combustion tunnel equipment design concepts discussed in Section 2.0, some consideration has been given to these aspects related to the operation of the facility in both a ground-based and Space Station (SS) configuration. The operational concepts discussed in this section have incorporated the most demanding SS constraints where possible. Thus, this section addresses the following system operation topics:

Section 3.1 Establishment of Required Gas Mixtures
Section 3.2 System Venting, Cleaning and Test Re-Initiation
Section 3.3 Safety

3.1 Establishment of Desired Gas Mixtures

The introduction of the appropriate mixture of gases into the SS-based combustion tunnel may be accomplished in a number of ways. Included among these are the following methods:

1) Partial Pressures
2) Premixed, Pressurized Gas Samples
3) Critical Flow Orifii
4) Calibrated Volume.

The selection of any of these gas mixture establishment methods - or a combination of these methods - depends on whether the gas mixture is being initially established before the first experimental run, or the oxygen (O_2) component or some other gas is being replenished after a run or series of runs. In addition, one scenario for increasing the number of experimental runs between complete purging of the system suggests that initial runs be performed at the lowest pressure condition with subsequent runs being performed at increasing increments of pressure. This may be accomplished under microprocessor control by either the partial pressures method or the calibrated volume method. In any scenario, the introduction of additional gases (e.g., O_2, N_2, etc.) into the tunnel requires an accurate determination of the O_2 content of the mixture.

3.1.1 Partial Pressures Method. Initial filling of the combustion chamber by the method of partial pressures is straight forward and the resulting gas mixture will be as accurate as the measurement of the tunnel static pressure and corrections for any temperature variations. Regarding the operational safety during filling, it will be most appropriate to introduce the inert gas(es) first, followed by oxygen and any other combustible gases. This method can be performed automatically under microprocessor control, with combustion tunnel static pressure and temperature as the measured inputs. The gas mixture should be able to be established to at least an accuracy of 1.0 percent of the desired mole fraction.

Filling the combustion tunnel initially by the method of partial pressures permits the use of the SS gas storage/delivery systems except for very special gases or gases whose purity must be greater than that provided by the central storage.

3.1.2 **Premixed, Pressurized Gas Samples.** Clearly, the use of premixed, pressurized gas samples prepared on earth under laboratory conditions can provide the highest accuracy of the gas mixture. The use of such premixed gas samples may be completely justified for some experimental runs where either the gas mixture is unique or the required mixture accuracy cannot be obtained by any other method.

Limitations relevant to the use of premixed samples include the increased handling required, more complex transport and storage, and lack of versatility. The lack of versatility is manifested by the observation that the premixed sample must be used as prepared and does not permit make-up of a particular gas component, except through separate means such as the method of partial pressures or the calibrated volume method.

3.1.3 **Critical Flow Orifice Method.** The use of precisely calibrated critical flow orifii is common to more than one method of establishing gas mixtures. However, in the simplest case a number of appropriately sized critical flow orifii may be used to permit reasonably accurate microprocessor control of the initial filling of the combustion tunnel, as well as the introduction of makeup gases if that is desired.

A simple example of the critical flow orifice method is illustrated by Figure A-21, where oxygen and nitrogen are admitted simultaneously into the combustion tunnel under microprocessor control.

The total mass of each gas (e.g., oxygen and nitrogen) required to be introduced into the combustion tunnel may be determined approximately from a predetermination of the tunnel volume, the desired volume fraction of the gas, and the combustion tunnel static pressure and temperature. Equation (1) may be used for this determination.

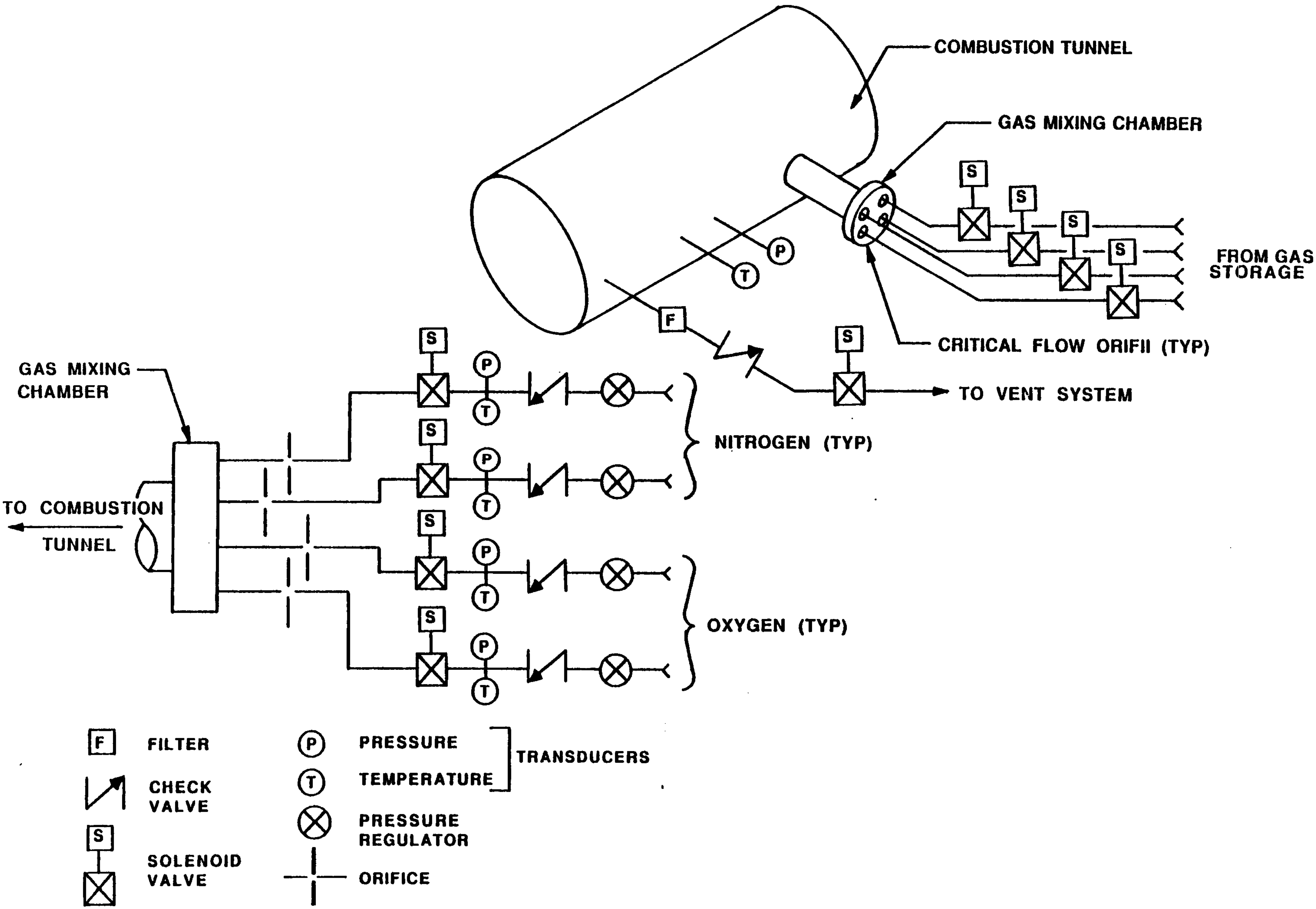


FIGURE A-21. ESTABLISHMENT OF GAS MIXTURE - CRITICAL FLOW ORIFICE METHOD

$$m(g) = F(g)\, V_{CT}\, \rho_g\, \frac{P_{CT}\, T_{std}}{P_{std}\, T_{CT}} \qquad (1)$$

where:

$m(g)$	=	Mass of gas component required, lbm (kg)
$F(g)$	=	Mass fraction of gas component
V_{CT}	=	Free volume of combustion tunnel, ft^3 (m^3)
ρ_g	=	Density of gas component at standard conditions, lbm/ft^3 (kg/m^3)
P_{CT}, T_{CT}	=	Static pressure and temperature in combustion tunnel
P_{std}, T_{std}	=	Pressure and temperature at standard conditions.

Using Equation (1), the mass of N_2 and O_2 required may be calculated for the following conditions:

$F(N_2) =$ 0.70
$F(O_2) =$ 0.30
$V_{CT} =$ 6.0 ft^3 (0.170 m^3)
$P_{CT} =$ 45 psia (0.31 MPa)
$T_{CT} =$ 530^oR (294^o K)

Thus, the required masses of nitrogen and oxygen may be calculated as 1.003 lbm and 0.468 lbm, respectively. These values are based on nitrogen and oxygen densities of 0.078 lbm/ft^3 and 0.085 lbm/ft^3, respectively, at standard conditions (1.0 atmosphere pressure at 530^oF (294.4^oK)).

Sizing of the critical flow orifii requires the selection of both a fill time and a supply pressure. For this example, assume that the stagnation pressure upstream of each orifice is 100 psia. Regarding the selection of a fill time, a long fill time implies a small orifice size, while a very large orifice reduces control over the mass of gases admitted.

For this example, assume that the fill time for simultaneous admission of N_2 and O_2 is 30 seconds. Then the mean flow rate of each gas may be calculated as

$$\dot{m}_{N2} = \frac{1.003 \text{ lbm}}{30 \text{ sec}} = 0.0334 \text{ lbm/sec } (0.0152 \text{ kg/sec})$$

$$\dot{m}_{O2} = \frac{0.468 \text{ lbm}}{30 \text{ sec}} = 0.0156 \text{ lbm/sec } (0.00708 \text{ kg/sec})$$

The critical flow orifice cross-sectional areas may now be computed from Equation (2),

$$A^* = \frac{\dot{m}(g)\sqrt{T_o}}{P_o} \left(\frac{kg_o}{R(g)} \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \right)^{-1/2} \qquad (2)$$

where: A^* = Critical flow area for which the gas flow Mach number is unity, in^2 (cm^2)
$\dot{m}(g)$ = Mass flow rate of gas, lbm/sec (kg/sec)
T_o = Stagnation temperature of gas upstream of critical flow orifice, ^oR (^oK)
P_o = Stagnation pressure of gas upstream of critical flow orifice, psia (MPa)
k = Ratio of gas specific heats
R(g) = Gas constant, in British units, ft - lbf/(lbm^{o}R)
g_o = Constant defined in British units as 32.174 lbm - ft/(lbf-sec).

Now, using Equation (2), A* for nitrogen and oxygen may be calculated for the assumed stagnation conditions of 100 psia (0.689 MPa) and 530^{o}R (294^{o}K). The results of these example calculations are as follows:

$$A^*_{N2} = 0.0147 \text{ in}^2 \ (0.095 \text{ cm}^2)$$
$$A^*_{O2} = 0.00642 \text{ in}^2 \ (0.0414 \text{ cm}^2).$$

The preceding calculations indicate that a critical flow orifice diameter of 3.4 to 3.6 mm (0.134 to 0.142 in) for nitrogen and 2.25 to 2.35 mm (0.089 to 0.093 in) would permit the filling of a 6.0 ft^3 combustion tunnel volume in approximately 30 seconds for the stated conditions. These calculations are very approximate and are provided only as an example.

Fine adjustment of the mixture may be obtained by use of additional, smaller orifii for each gas component. The precision in obtaining a desired gas mixture by this method depends on the accuracy of the calibrated orifii and the pressure and temperature transducers. In addition, this method depends upon precise measurement of the time during which each gas component is flowing through the critical orifii.

3.1.4 **Calibrated Volume Method.** A highly accurate method of introducing the appropriate quantity of gases into the combustion tunnel is that which utilizes a calibrated volume. The central element of this method (shown schematically in Figure A-22) consists of a precisely machined calibration chamber whose volume has been accurately determined. The calibration chamber is supplied by each gas in turn, through a series of pressure regulators, solenoid valves and critical flow orifii. The pressures and temperatures in the calibration chamber and the combustion tunnel are continuously monitored and permit precisely calibrated masses of each gas to be introduced into the combustion tunnel under microprocessor control.

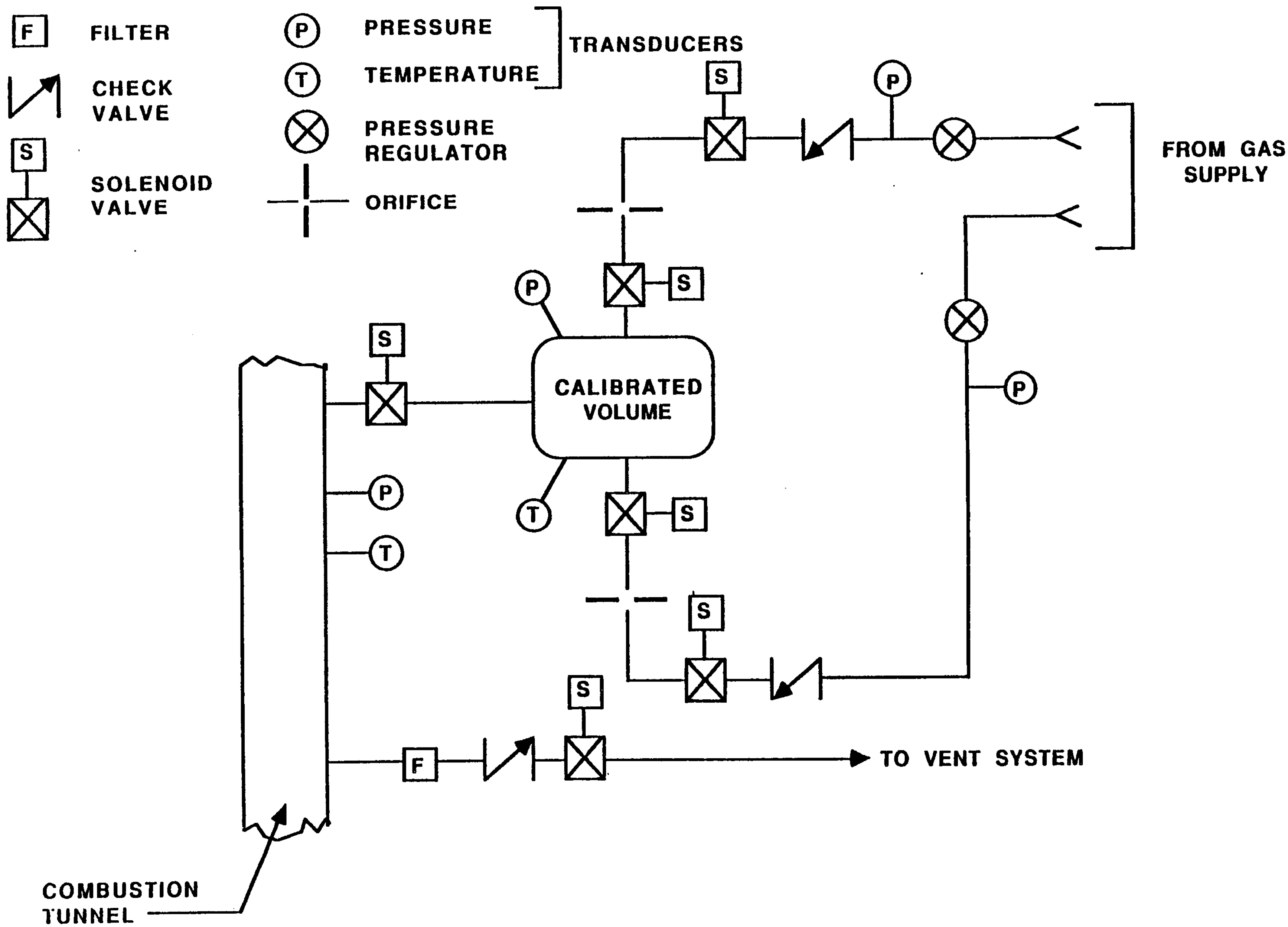


FIGURE A-22. CALIBRATED VOLUME METHOD OF GAS ADDITION

The steps required for utilizing the calibrated volume method have been summarized as follows. Assume that the combustion tunnel has been prepared for an experimental run and is fully secured. Under microprocessor control, both the combustion tunnel and the calibration volume are evacuated to the vacuum pressure level permitted by the Space Station vent system. After a predetermined period of venting below a desired pressure level in the combustion tunnel, the vent system is closed along with the solenoid valve that isolates the calibration volume from the tunnel. An appropriate gas is then introduced into the calibration volume until a predetermined set of pressure and temperature values are obtained. This mass of gas is then introduced into the combustion tunnel and the process is repeated until the desired mass of that gaseous component has been introduced. This procedure is repeated for each additional gas component required to obtain the desired mixture.

Note that the calibrated volume method described here depends on the use of software containing algorithms of gas-law relationships for each gas to be introduced.

The accuracy of the method depends on the predetermination of the calibration chamber volume and the precision of the pressure and temperature transducers. The method does not depend on flowmeters and/or timing of flow through critical orifii. An advantage of this method is that precise quantities of make-up gases (e.g., oxygen) may be added to the mixture between experimental runs.

3.2 System Venting, Cleaning and Test Re-Initiation

Some preliminary comments relevant to the venting of waste and/or purge gases to the Space Station (SS) gaseous waste management system were provided in Section 2.1.2 and Appendix A. It may be assumed that direct venting to space from any SS-based experiment or process will not be permitted. An interim purge storage subsystem (see Section 2.2.6) would permit some relief to the venting problem if such equipment were permitted. From an operational consideration, the number of experimental runs possible over any time period will be severely restricted if some relief to venting isn't provided.

Periodically, the combustion tunnel will require a thorough cleaning and maintenance inspection. Each experimental run involving combustion will, of course, contribute a finite amount of contamination, including particulate material. The engineering design of the SS-based combustion tunnel must address the type, size and location of filters to be used routinely. It is suggested that the system design be such that periodic cleaning of the removable test section (Section 2.2.1) be all that is necessary over a relatively large number of experimental runs. Periodic cleaning of the optical windows is most critical.

Details regarding the allowable cleaning procedures and disposal of waste materials on the SS have not been fully established.

3.3 Safety

The safety related aspects of a Space Station (SS)-based research combustion tunnel have not been addressed herein in any detail. Unless an interim purge storage subsystem (Section 2.2.6) is included, pressures within the combustion tunnel will be regulated to approximately 3.0 atmospheres, or less. Of course, the gaseous and liquid supply lines to the tunnel will of necessity be at pressures higher than that of the tunnel. A review of the safety related aspects relevant to the preliminary design of a Spacelab combustion facility (Ref. 7) suggests similar safety measures for the Space Station. In addition to suitable check valves, pressure relief valves, and interlocks on certain valves, the SS-based combustion tunnel facility may require a dedicated fire suppression subsystem and an emergency vent system.

4.0 TECHNOLOGY DEVELOPMENT RECOMMENDATIONS

The complete engineering design of both the research combustion tunnel and its laser diagnostics system shall provide a number of technical challenges. However, the design of the basic portions of the combustion tunnel should follow relatively well-established practices for the design of any low-flow velocity laboratory apparatus of the low-speed wind tunnel type. Optimization of a ground-based breadboard tunnel for the Space Station application will provide an additional challenge.

During this concept design effort, a number of technical design issues were identified which appear to be especially difficult and are generally outside of common engineering design practice. Some of these design issues are briefly described below with the intent of alerting the reader to the technical concern.

4.1 Temporal Location of Combustion Process Relative to Laser Diagnostics Optical Paths

This technical design issue was identified and discussed in some detail in Section 1.2.2, herein. The problem may be restated in the following manner. How can one provide three (or even two) separate optical paths passing through the tunnel test section, such that the full laser diagnostics described in Reference 3 may be accomplished during each experimental run? Use of a single optical window (Figure A-4, Concept A) would result in serious laser reflections and loss of resolution. Provision of separate optical windows has the drawback of causing flow disturbances in the test section.

An associated problem is that of providing a means for moving (translating) the burning sample and its flame in a prescribed manner relative to the optical paths and being able to control this movement temporally.

4.2 Calibration and Measurement of Test Section Velocity Profile on Orbit

Prior to the initiation of any combustion and/or flame spreading process in the combustion tunnel, it is necessary to establish precisely the required test section velocity field. This is a relatively straight forward process in a ground-based laboratory and the test section velocity profile may be characterized by hot-wire anemometry or by an LDV system (see Ref. 3). However, this is a time consuming process and would not be practical in the Space Station-based application. It is suggested that some tunnel calibration and flow field characterization must be performed in the Space Station environment and correlated with earth-based results.

4.3 Introduction of Particle Seeding for LDV Application

The use of the laser Doppler velocimetry (LDV) methodology for non-intrusive flow velocity determination requires that the flow field be seeded appropriately. An appropriate method for introducing particles into the combustion tunnel must be developed for both a ground-based breadboard facility and the Space Station-based system. It is understood that some special techniques may require development for low-gravity seeding.

4.4 Introduction of Liquid Fuel into Combustion Tunnel

The introduction of liquid fuels into a low gravity environment flow facility poses a unique challenge since, for example, gravity can't be used to hold the liquid fuel in a pool form for combustion. Some possible solutions to this problem were described in Section 2.3.2, herein. However, this area of concern demands additional attention.

4.5 Other Technology Development Issues

In addition to the design issues described above, there are several other areas of technology development that were only briefly addressed in Sections 1-3 herein. The design and provision of velocity-profile flatteners in the tunnel test section is of prime importance. Ordinary flow conditioners (e.g., flow straighteners) will not provide an adequately flat velocity profile without significant pressure loss. Thus, the design of the entrance of the flow media to the test section must be carefully researched.

A second issue is that regarding the filter system used to remove particulate material from the flow during combustion processes. Care must be taken to select filter materials and configurations to minimize the pressure loss across the filter while scavenging an acceptable percentage of the particulates. Filters used to selectively scavenge specific particulates will be investigated (e.g., such as those used in gas chromatography).

Alternate techniques for spent gas disposal or recycling must be investigated further. For Space Station (SS) accommodation, the disposal and/or recycling of experiment spent gases can be a significant problem. If the spent gases are adequately cleaned they may be recompressed and stored for other uses. However, the acceptability of recompressing spent gases on the SS has not been resolved.

5.0 DEVELOPMENT PLAN - RESEARCH COMBUSTION TUNNEL

Sections 1 to 3 herein have presented a fundamental concept design review of a research combustion tunnel that would ultimately be accommodated on the Space Station (SS). Section 4 provided a brief summary of some of the technology development issues which have been identified to date.

This section outlines a preliminary development plan for the research combustion tunnel leading to SS accommodation at IOC (Initial Operational Capability).

5.1 Overall Development Plan (Phases A-D)

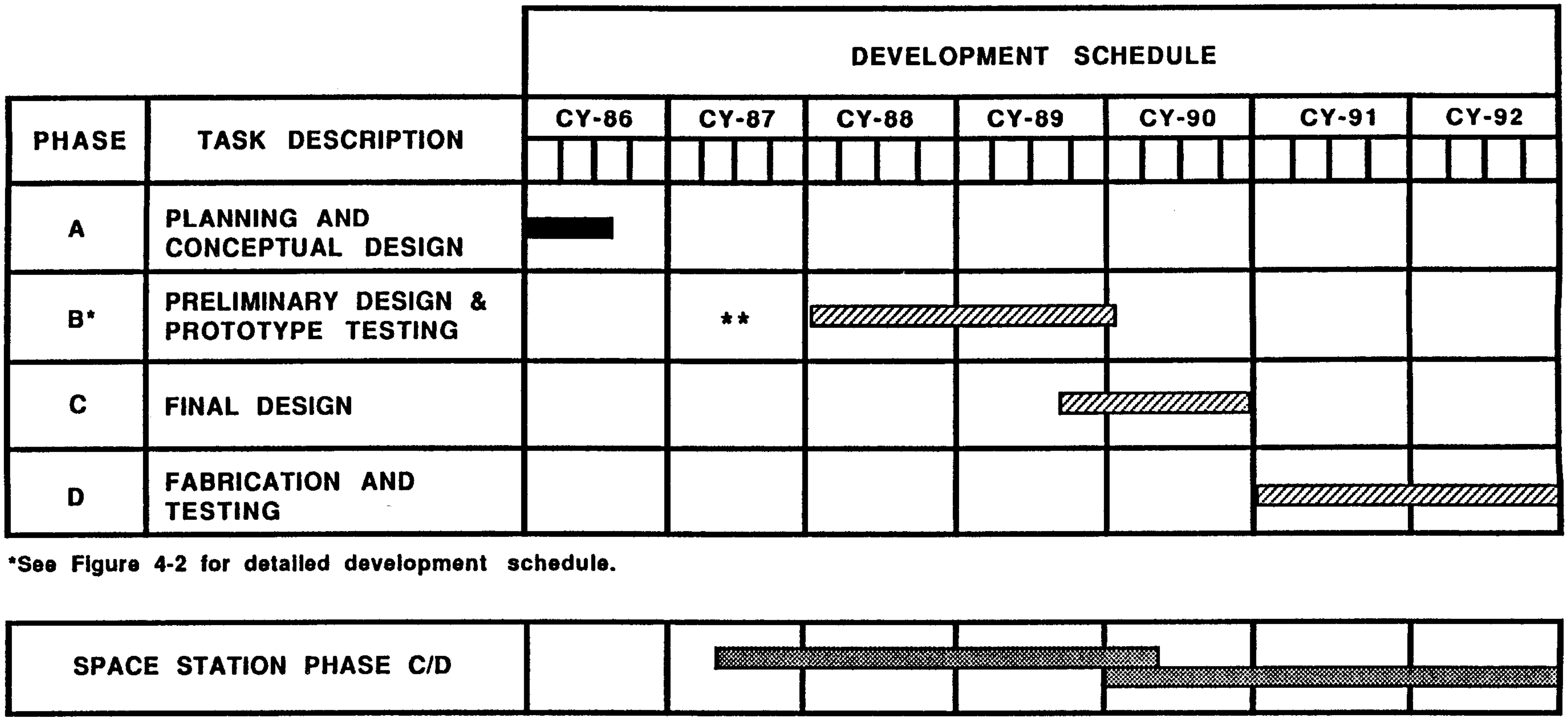
Figure A-23 indicates a suggested schedule for the overall development of the combustion tunnel through phases that basically parallel the development of the Space Station (SS). Phase A denotes a concept design effort and included a definition of operational parameters and design constraints. The Phase A concept design is essentially complete as reported herein.

Phase B of the development plan is defined as the design, construction and testing (ground-based and sub-orbital flights) of a breadboard configuration (Section 5.2). Phases C and D would then consist of design, construction, flight qualification, and integration into the SS. No details are provided herein on the efforts necessary for Phases C and D, except for the general listing of subtasks given in Figure 1 (page 17).

5.2 Preliminary Design and Testing (Phase B)

Figure A-24 outlines the basic subtasks proposed for the design, construction and testing of a breadboard version of the research combustion tunnel. This Phase B effort would use the research combustion tunnel concept design described in this report as the basis for a detailed engineering design and fabrication of a ground-based breadboard facility. Figure A-24 shows a preliminary estimate of the calendar time and manhours for each major subtask under Phase B.

A preliminary listing of the major components that must be either fabricated or purchased is outlined in Table A-1. Again, these items are relevant to a ground-based



*See Figure 4-2 for detailed development schedule.

**ADVANCED TECHNOLOGY DEVELOPMENT INITIATION (SEE PAGE 18).

FIGURE A-23. TOP-LEVEL COMBUSTION TUNNEL DEVELOPMENT PLAN

	TASK DESCRIPTION	ROUGH-ORDER-OF-MAGNITUDE MAN-HOUR REQUIREMENTS																														TOTAL BY TASK
	PHASE B. PRELIMINARY DESIGN & PROTOTYPE CONSTRUCTION/TESTING	CY-1988												CY-1989												CY-1990						
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	
B-1	BREADBOARD DESIGN	150	150	225	225	225	225	225	225	225																						1875
B-2	ANALYTICAL RESOLUTION OF TECHNOLOGY DEVELOPMENT ISSUES	75	75	45	45	45	45	45																								375
B-3	HARDWARE PROCUREMENT AND FABRICATION					45	45	90	90	90	120	120	120																			720
B-4	BREADBOARD ASSEMBLY								45	45	45	45	45																			225
B-5	SOFTWARE DEVELOPMENT							30	30	45	45	45	45	30																		270
B-6	GROUND-BASED TESTING													195	195	195	150	150	150	150	90											1275
B-7	SUB-ORBITAL FLIGHT TESTING																				60	60	90	90	60	60	90	90				600
B-8	EXPERIMENTAL RESOLUTION TECHNOLOGY DEVELOPMENT ISSUES													30	30	30	60	60	60	60	30	30	30	30	30	30	30	30				570
	TOTAL BY MONTH	225	225	270	270	315	315	390	390	405	210	210	210	255	225	225	210	210	210	210	180	90	120	120	90	90	120	120				5910

FIGURE A-24 COMBUSTION TUNNEL BREADBOARD DEVELOPMENT PLAN

TABLE A-1. COMBUSTION TUNNEL COMPONENTS-BREADBOARD CONFIGURATION

	Fabricate	Purchase
1. Removable Test Section		
o Shell and flanges	X	
o Optical windows and flanges		X
o Velocity profile flattener	X	
o Other flow conditioners		X
o Flow media filters		X
2. Sample Holder/Sample Exchanger		
o Sample holders and exchange hardware	X	
o Sample exchange motor drive system		X
o Limit switches, positioners		X
3. Stagnation Chamber/Remainder of Flow Channel	X	
4. System Sensors		X
o Pressure and temperature sensors		
o Velocity sensor (e.g., hot-wire)		
o Mass flow meters		
o Oxygen analyzer		
5. Fan/Motor System		X
6. Heat Removal System	X	X
7. System Controller/Computer Interface		X
8. Data Acquisition System		X

test apparatus (Subtask B-6 of Figure A-24) with potentially some low-gravity aircraft flight testing (e.g., NASA KC-135 flights) as noted by Subtask B-7 of Figure A-24. These schedule and manhour estimates do not include any STS or SS mission activities.

Subtasks B-2 and B-8 (Figure A-24) are included in recognition of the technology development issues that must be addressed. These technology development issues (some of which are outlined in Section 5 herein) are expected to require both analytical and experimental resolution. Subtask B-2 would be used to investigate information currently available that would aid in the preliminary breadboard facility design and resolve some of the technology issues requiring no further experimentation. Subtask B-8 is a continuation of Subtask B-2, but suggests a requirement for testing using the breadboard combustion tunnel to investigate the resolution of technology issues not fully satisfied by Subtask B-2.

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APPENDIX A

ALLOWABLE GAS VENTING FROM THE SPACE STATION

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APPENDIX A

ALLOWABLE GAS VENTING FROM THE SPACE STATION

Studies are currently underway (e.g., Ref. 5) to establish the handling of all waste materials (solids, liquids and gases) produced on the Space Station. The studies presented in Reference 5 are devoted to the Manufacturing and Technology Laboratory (MTL), but tend to illustrate the overall constraints on such important waste handling topics such as gaseous venting.

In summary, the external contamination constraints on venting were divided into two classes:

a) Molecular column density
b) Molecular deposition constraints

Current requirements or guidelines for these constraints are summarized in Table A-2.

Table A-2. Space Station External Contamination Requirements (Ref. 5)

PARAMETER	REQUIREMENT
Column Densities	10^{11} Molecules/cm^2 max for $H_2O + CO_2$ 10^{13} Molecules/cm^2 for $O_2 + N_2$ 10^{10} Molecules/cm^2 for other sources
Deposition of Generated Matter as a Result of Direct Atmospheric Scattering	Deposits of contaminants originating from the MTL shall not significantly degrade the performance of the items on which these deposits occur. In the region of optical instruments, deposits shall not exceed 100 angstroms/yr for surfaces at 298°K and 40 angstroms/yr for surfaces at 4°K.

Note that the column density is defined (Ref. 5) as the number of molecules residing in an infinite column of 1.0 cm^2 cross section and may be calculated from the

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approximate relation,

$$C = \frac{M}{V_a \, 2 \, \pi R_1}$$

where:

C	=	Column density (molecules/cm^2)
M	=	Venting rate (molecules/sec)
V_a	=	Sonic velocity of gas at stagnation temperature (T_o), cm/sec
R_1	=	Distance to point of interest from vent source, cm.

The allowable venting quantities for a period of 90 days is provided in Table A-3.

Table A-3. <u>MTL Venting Allowables (Ref. 5)</u>

CHEMICAL SPECIES		ALLOWABLE VENTED MASS PER 90 DAY CYCLE BASED ON COLUMN DENSITY REQUIREMENTS FOR THE ENTIRE SPACE STATION CLUSTER
H_2O		35 KG
CO_2		86 KG
O_2		6221 KG
N_2	Others	5447 KG
H_2	Others	0.3 KG
He	Others	0.6 KG
Ar	Others	6.2 KG

The above relationship for column density, C, has been plotted in Figure A-25.

Note that the 90 day allowable masses for venting in Table A-3 have assumed that the venting is at a constant rate over the full 90-day period. Any short duration venting <u>must not</u> exceed the column densities or deposition guidelines shown in Table A-2

Example:

Figure A-25 indicates that a venting rate of only approximately 5 x 10^{-2} g-moles/sec may exceed the allowable column densities of N_2 or O_2 (i.e., 10^{13} molecules/cm^2).

This is a mass flow rate for N_2 of

$$\dot{m}_{N2} = 5 \times 10^{-2} \text{g-moles/sec} \times \frac{28 \text{ g}}{\text{g-mole}} = 1.4 \text{ g/sec}$$

$$\dot{m}_{N_2} = 0.18 \text{ lbm/min}$$

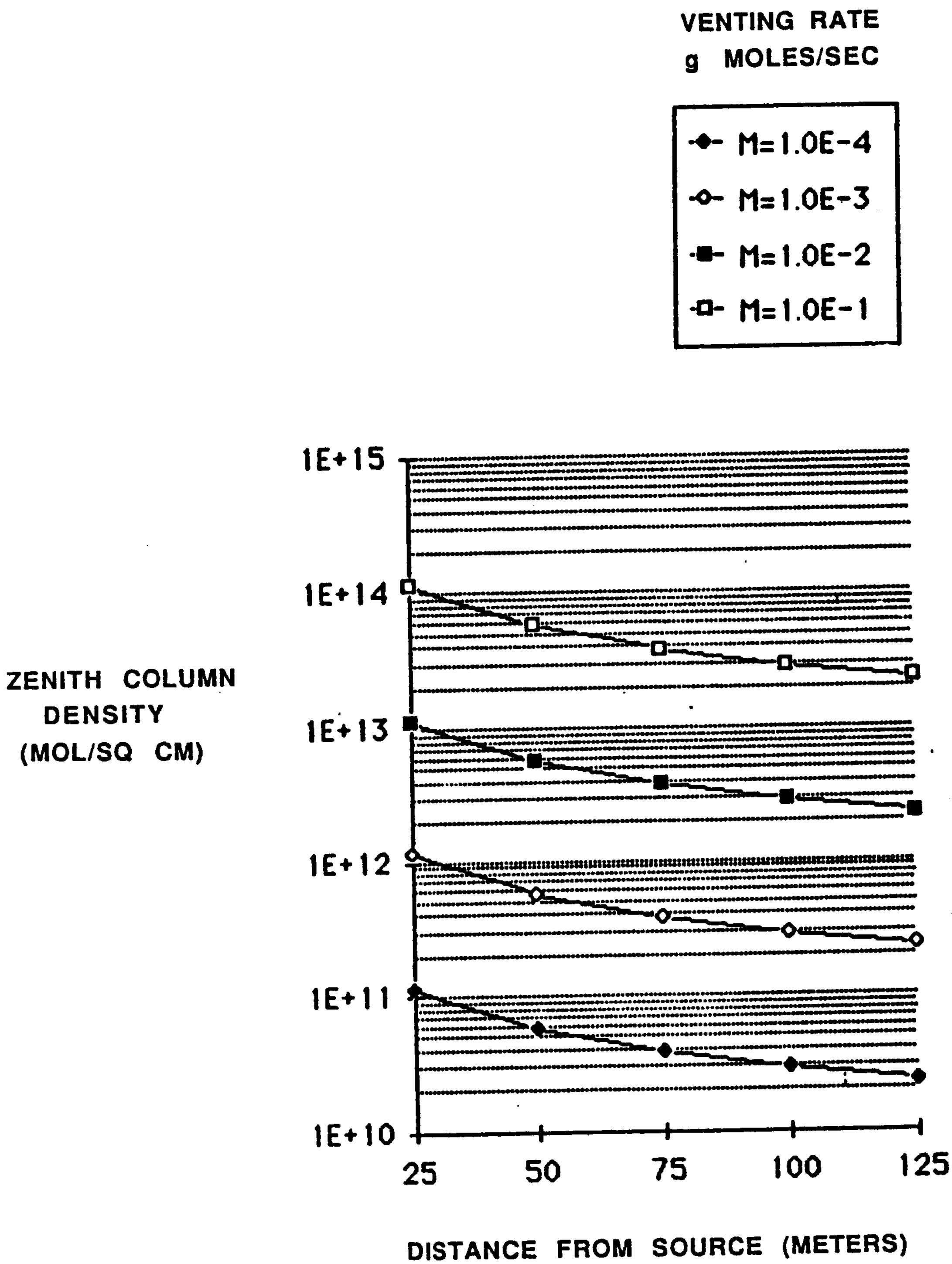

FIGURE A-25. ZENITH VIEW COLUMN DENSITY VERSUS DISTANCE FROM SOURCE FOR VARIOUS RATES (FROM REF. 5)

This may be shown to be much below the spent gas flow rates for even the moderate condition of a combustion run of 30 cm/sec velocity at 2 atmospheres pressure. Flowing N_2 with 30% O_2 by volume, the desired flow rate is approximately 7.15 lbm/min.

CONCEPT DESIGN
OF A
LASER DIAGNOSTICS SYSTEM
FOR
COMBUSTION TUNNEL

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CONCEPT DESIGN OF A LASER DIAGNOSTICS SYSTEM FOR COMBUSTION TUNNEL

INTRODUCTION

The concept design of a laser diagnostics system prepared by Wyle Laboratories and described herein is a non-intrusive optical measurement system for a research combustion tunnel proposed for use on the Space Station (SS). Although numerous combustion diagnostics techniques are available, most of the published flame structure data have been obtained by introducing various types of probes into the flow. Introduction of a probe into a flow field alters the static pressure distribution and flow patterns and can result in measurement errors, especially when probing very low-velocity flows in reduced scale experiments. In a laser diagnostics system no physical probe needs to be inserted into the flow. The concept design described herein is completely non-intrusive in character, produces point-wise measurements, and would use data storage capability for later analysis in a ground-based laboratory.

The following capabilities of the laser diagnostics system were established based on discussions with NASA/LeRC personnel:

- Flow visualization
- Temperature profiles
- Velocity of particles and flames
- Species concentration.

Based on these requirements, two conceptual designs are suggested, each design having a different level of complexity:

System I: Includes holography, classical optical techniques, Laser Doppler Velocimetry (LDV) and Laser Induced Fluorescence (LIF)

System II: Includes holography, LDV and LIF.

Both systems would acquire essentially the same basic data, but System I would be more versatile and could provide certain parameters, e.g., flame propagation and temperature profiles, in real time. The classical optical system provides Schlieren, shadowgraph and Mach-Zehnder (M-Z) interferometeric investigating systems which would provide real-time data on the SS. The Schlieren system provides the flame propagation information and the M-Z interferometry provides the temperature profile measurements. Admittedly, this system would be very complex and its feasibility and application for use in a size and configuration suitable for the SS microgravity environments needs to be investigated in a ground-based "breadboard" system.

In the System II concept design, the classical optical system is completely eliminated reducing, of course, the system's ability for real-time measurement of flame propagation and temperature profiles. Note that both the classical optical system and holography can provide essentially the same basic data measurement. The advantage of proposing holography in both systems is in recognition of its ability to store information for later analysis in a ground-based laboratory and its established application to other microgravity experiments. Holography was used as a major portion of the data acquisition for the fluid experiment system (FES) on the Space Shuttle Spacelab-3 mission.

The concept design systems described herein are possible in principle, but the technologies of most of the subsystems need to be developed in a "breadboard" system. The hardware items required for the establishment of the breadboard system are specified herein, providing preliminary estimates of the physical dimensions, weight, electric power requirements, cooling systems and an estimate of the cost of development of the system.

Again, realizing that the complete system would be very complex, it is suggested that effort for reducing the complexity of the system may be carried out at the technology development stage. The use of fiber optics to simplify the system has been suggested. However, there are a number of limitations in the current technology of fiber optics which need to be studied. The possibility of using the Schlieren/Doppler technique for measurement of the velocity of particles and flames also needs further study. If the Schlieren/Doppler technique can be satisfactorily established, it would greatly simplify the system by completely eliminating the LDV system.

An added advantage of the laser diagnostics systems described herein is that they can be used or adapted to accommodate other combustion and fluids experiments planned on the SS with small modifications. The only necessary conditions are a transparent medium with optical access to the medium through transparent windows. The satisfactory application of the holographic system on the Spacelab-3 mission greatly enhances this concept.

Wyle suggests that these concept designs are possible in principle, but their practicality needs to be established by developing a breadboard system for ground-based research. Such a ground-based system can be used for the technology development of the systems, and also would provide a facility for the analysis of data brought back from the SS.

1.0 OBJECTIVE

The objective of the concept designs discussed herein is the provision of a non-intrusive laser diagnostics system for the acquisition of data taken from combustion tunnel experiments in microgravity. An additional objective is that of identifying the areas which require technology development activities.

A comprehensive optical system is presented which incorporates the classical optical system/holography, laser Doppler velocimetry and laser induced fluorescence systems. The successful development of this complete system poses some challenges, but is possible in principle. The system technologies need to be developed in a ground-based "breadboard" system prior to the development of the Space Station (SS) flight hardware.

The various optical investigation techniques and their subsystems identified show the extensive parameters that could be measured using the laser diagnostics system.

Optical Investigation Techniques	Parameters of Interest
1. Classical Optical System	
• Mach-Zehnder Interferometry	Refractive index Temperature gradient Density
• Schlieren	Flame propagation Refractive index gradient Velocity of flames
• Shadowgraph	Rate of change of refractive index gradient
2. Holography	Flow visualization Temperature profile Particle size measurement
3. Laser Doppler Velocimetry	Velocity measurements of particles and flames
4. Laser Induced Fluorescence	Species concentration measurements.

The holographic system helps to record permanently the wavefront emanating from the object during the experiment, on a special photographic high-resolution film. These photographic records, called holograms, can be brought back to earth, processed and analysed in a ground-based laboratory. The holographic reconstruction can be used in holographic Schlieren, holographic shadowgraph and holographic M-Z interferometric systems for analysis of temperature profiles and flow visualization.

The classical optical system described is optional and can be incorporated into the complete system. This system may also be used for the Schlieren, shadowgraph and interferometric analyses of flames in real-time; however, its inclusion makes the system more complex, and its practicality needs to be investigated.

All these techniques, though applicable in principle, need to be developed in a ground-based breadboard system leading to SS application. The technology development issues include analysis of data for various investigating techniques, development of the SS hardware, and the simplification of the system itself. A complete data base needs to be established for each system for various materials of flame at different operating conditions.

2.0 CONCEPT DESIGNS

The comprehensive laser diagnostics system (referred to herein as System I) shown in Figure B-1 incorporates the various investigation techniques, i.e., classical optical systems, holography, laser Doppler velocimetry, and laser induced fluorescence. These systems have different applications in the non-intrusive measurement of various parameters in combustion of flames. The system uses a large number of fixed optical components and electro-optical systems which include beam collimating and condensing lenses, mirrors, beam splitters, hologram recording materials, detectors, lasers and acousto-optic beam deflectors, etc. All these components are to be specially designed and fabricated for SS application.

In this comprehensive system, the holography and classical optical systems require a vibration-free environment since in both systems the information resides in the interference pattern at the image plane. It is therefore important that the relative positions of the optical components remain stable to within a small fraction of the wavelength of light over the period of the holographic plate exposure. Thus, during the recording of the hologram, any movement that can translate the fringes must be avoided. This means movement of the object being recorded, optical components and laser systems, and even the air through which the light beam must pass during recording. A movement of less than one-tenth fringe width will not offset the hologram, but movement of more than one quarter fringe width will seriously offset the image brightness of the hologram.

During exposure, temperature changes in any part of the system must be eliminated. If the optical path varies during the exposure due to temperature changes, the effect is the same as though the optical elements had moved. Hence, wherever possible all the heat generating sources must be properly insulated and shielded to reduce the effect of temperature on the optical systems.

Vibration problems can be solved by providing vibration isolation for the work surface and by devising sufficiently rigid holders for the optical elements. All the optical components are firmly mounted on the top of an optical table whose size is approximately 914 mm by 610 mm by 50 mm (3 ft by 2 ft by 0.2 ft), which is rigid, stiff and internally damped. By locating the laser sources on the side of the table

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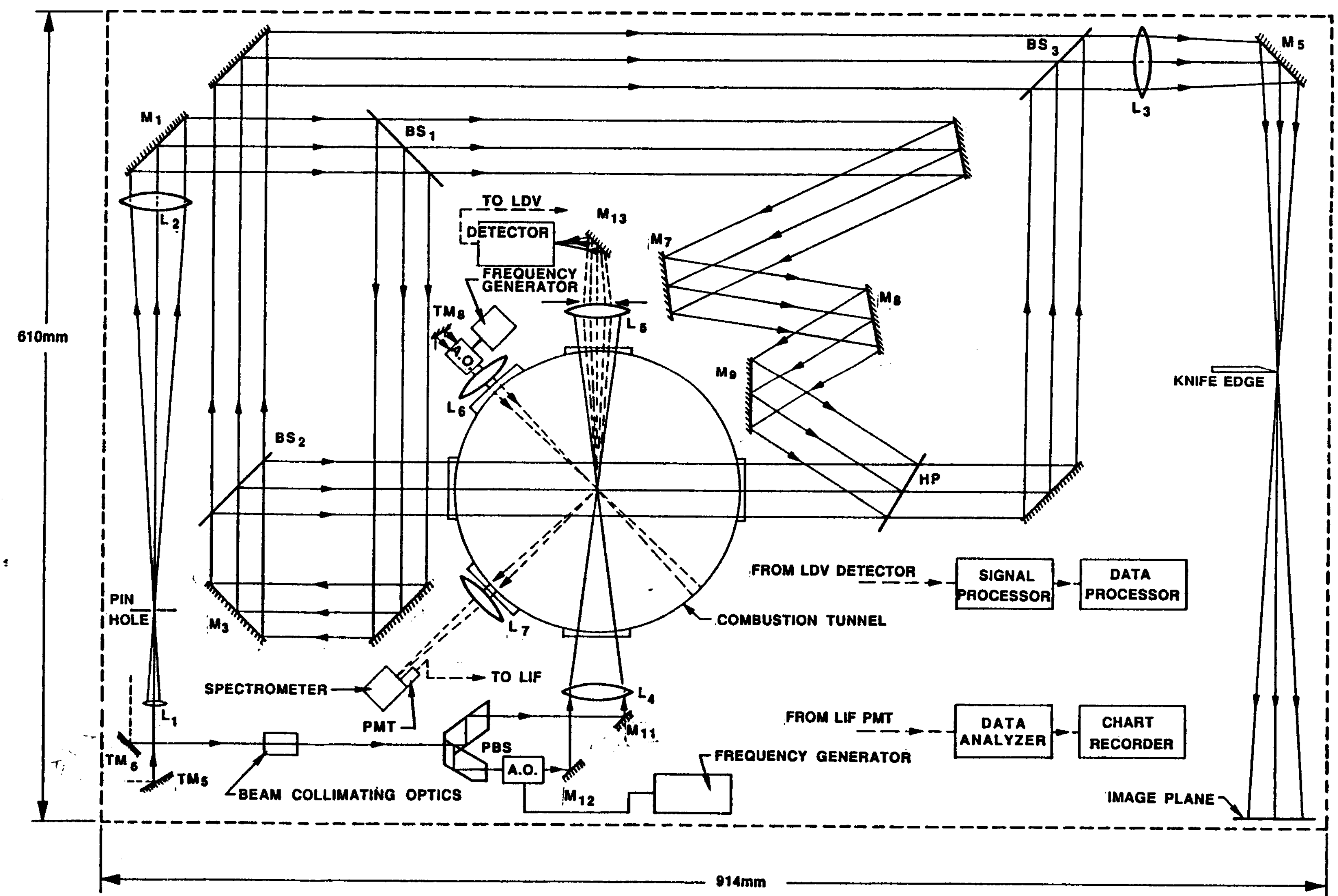

FIGURE B-1. SCHEMATIC OF THE LASER DIAGNOSTIC SYSTEM FOR THE COMBUSTION TUNNEL SYSTEM I opposite the optical system (Figure B-2), a substantial amount of space will be conserved. The physical dimensions of the laser diagnostics system would increase approximately twofold if the lasers were also accommodated on the same side of the table as the optics. The lasers are cooled to prevent any unacceptable thermal gradients on the optical table.

The system described herein can accommodate a combustion tunnel of approximately 254 mm (10 in.) diameter, and any significantly larger diameter tunnel may necessitate the redesign of the optical system. Other microgravity experiments which have a transparent medium, such as the solution crystal growth, can be easily accommodated in the system for refractive index measurements and other data acquisition parameters. Thus, it can be used as a generic system for laser diagnostics of microgravity experiments.

This comprehensive system, if provided with three sets of optical windows (i.e., three separate optical paths) on the combustion tunnel, could be used for the measurement of any three of the desired experimental parameters at any given time. This includes the use of laser induced fluorescence, laser Doppler velocimetry and holography or any one of the subsystems of classical optical systems. Thus, during the entire operation of the experiments, different classical systems may be used separately, although not simultaneously, for various data acquisition. Holography can be used to record the complete information and later reconstructed for holographic Schlieren, holographic shadowgraph and holographic Mach-Zehnder interferometry.

Both the holographic and classical systems provide the same type of data, but each has different applications. The holographic system can be used for both the flow visualization and the determination of the temperature profiles of the flame. Moreover, the holographic system provides a means for storing the information for later analysis either on the Space Station or in a ground-based laboratory. The hologram, upon reconstruction, may be used in holographic Schlieren, holographic shadowgraph and holographic M-Z interferometric systems. Such optical techniques can be employed on the same hologram repeatedly and sequentially, since the reconstruction of the hologram actually reproduces the wavefront originally emergent from the test region.

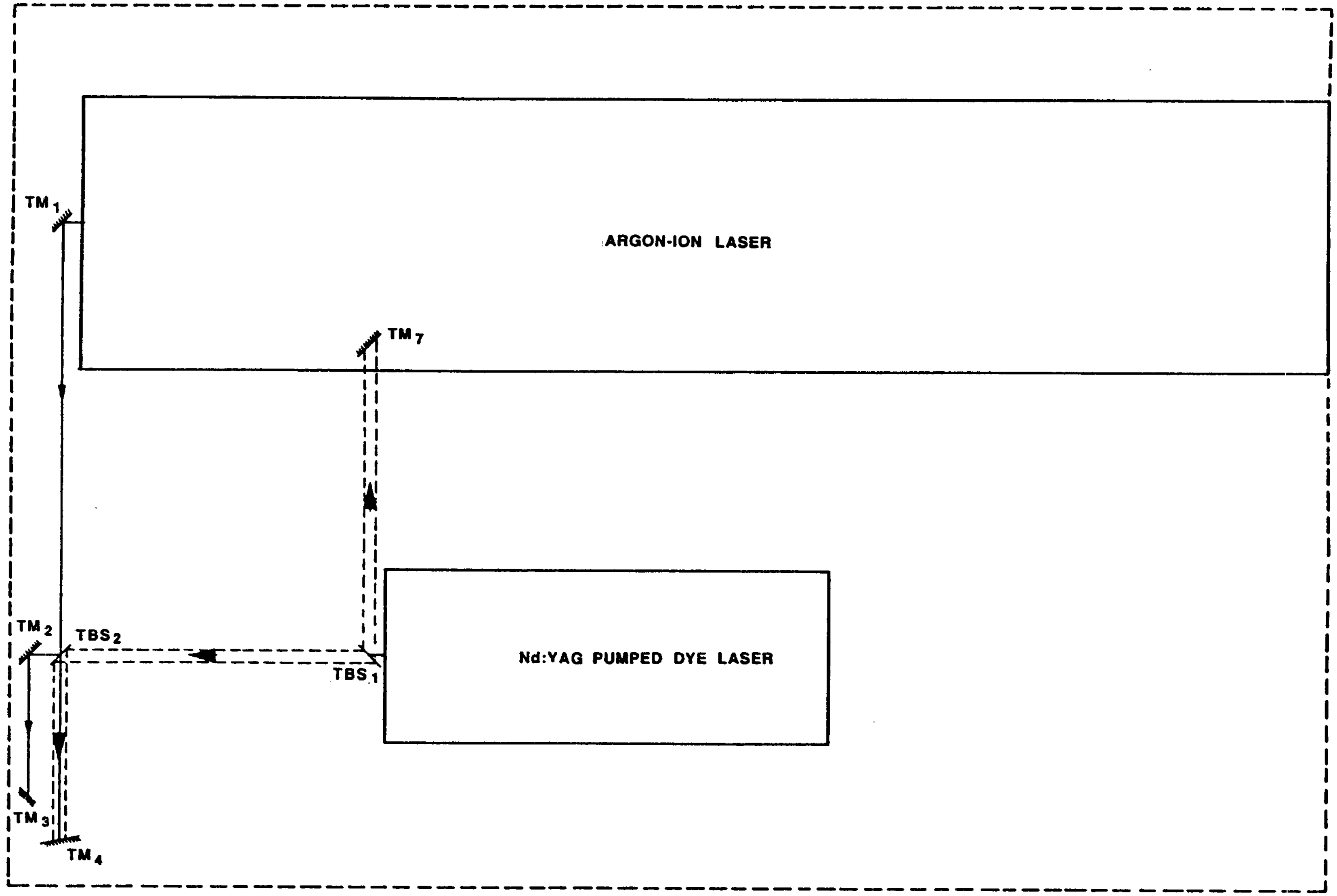

FIGURE B-2. LASERS AND TURNING OPTICS MOUNTED UNDERNEATH THE TABLE

Classical optical systems may also be used for the Schlieren, shadowgraph and M-Z interferometric analyses. Although the alignment of the Mach-Zehnder interferometric system on the Space Station may be difficult, it is possible to achieve if the alignment procedures are performed systematically.

Even though both systems (holography and classical optical systems) provide the same type of measurements, each system has different applications:

1. Temperature profiles and flame propagation may be obtained in real time by classical optical techniques.
2. Holography provides a permanent record of the whole combustion process so that the data may be analyzed in detail at a later time.

If the real-time analysis of flame propagation and temperature profiles are not required on the Space Station, the diagnostics system described herein as System I can be modified by completely eliminating the classical optical system (System II) as illustrated by Figure B-3. This eliminates a number of fixed optical components and results in a greatly simplified system.

A summary of the System II capabilities is outlined below.

System II Capabilities (see Figure B-3)

1.	Holography	Flow Visualization Temperature profile Particle size measurement
2.	Laser Doppler Velocimetry	Velocity measurements of particles and flames
3.	Laser Induced Fluorescence	Species concentration measurement

Holograms taken on the Space Station may either be brought back to earth, processed and analyzed in a ground-based laboratory or they can be processed on the Space Station itself. The development of the holograms and their reconstruction on the Space Station would require more space for developing, storing the processing chemicals, a complete optical reconstruction system, and the involvement of more crew time.

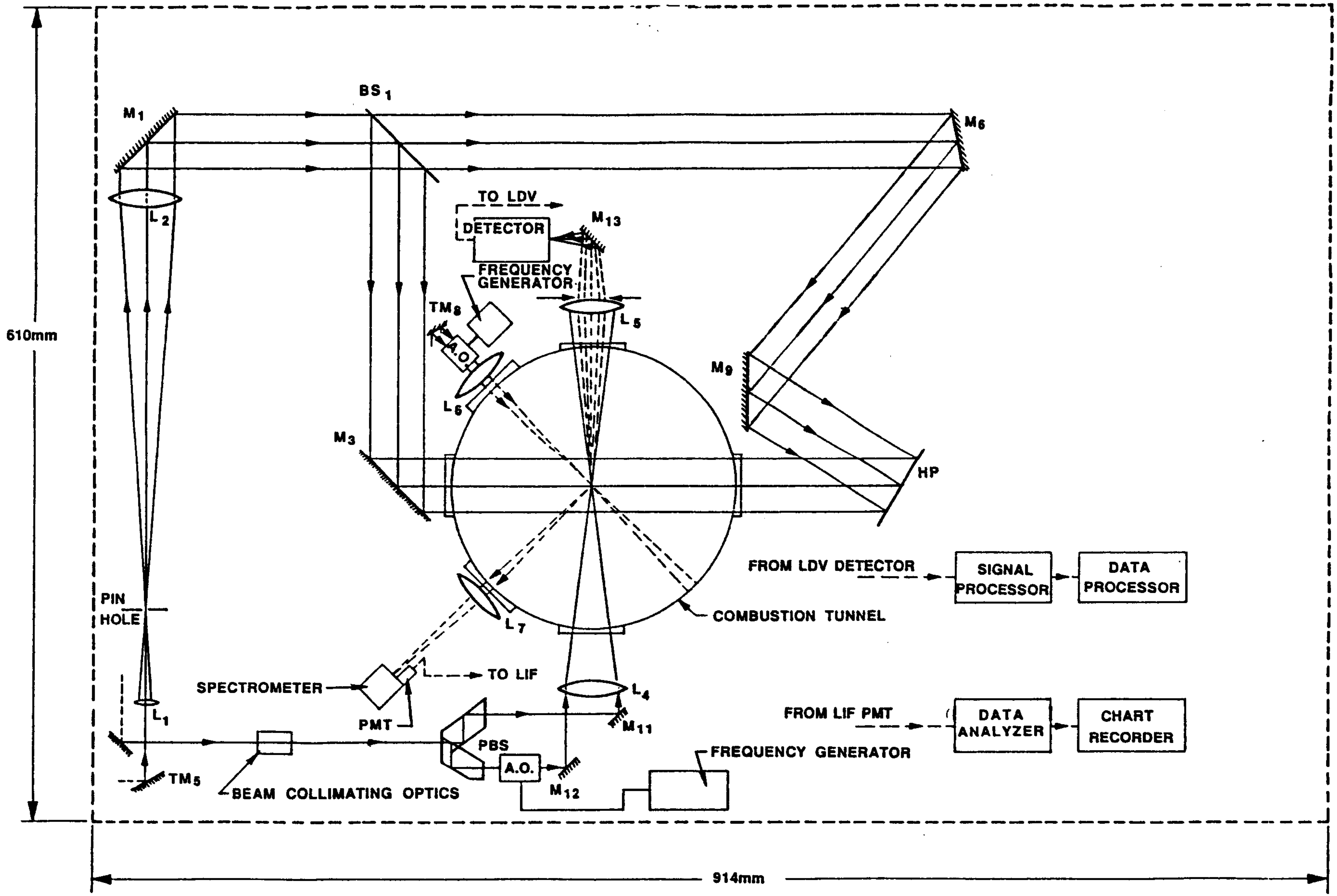

FIGURE B-3. SCHEMATIC OF THE LASER DIAGNOSTIC SYSTEM FOR THE COMBUSTION TUNNEL SYSTEM II

Laser Doppler velocimetry is a non-contact optical technique for the investigation of the velocity of the particles and flames. It probes the flow with focused laser beams and can sense the velocity without disturbing the flow. The only necessary conditions are a transparent medium with a suitable concentration of particles (or seeding) and optical access to the flow through transparent optical windows. This technique has been used extensively for making measurements in flames under laboratory and industrial conditions, in gases, liquid fuel, and solid particle flames. Velocities as low as few micrometers per second to several hundred meters per second can be measured by this technique.

The Laser Induced Fluorescence (LIF) is a precision investigating technique for the measurement of species concentration in flames. The method consists of illuminating the flame with a dye laser tuned to an absorption line of the species of interest. The species is excited and fluoresces. The fluorescence is observed at 90 degrees to the laser beam, and is measured using suitable detectors. This measurement indicates the species concentration of the particles in the flame.

In this concept design study no effort was made to identify in any detail the data processing systems required for all of the optical investigation techniques. It is likely that some of the systems may be procured off-the-shelf and modified for the Space Station applications.

Wyle fully understands the complexity of the laser diagnostic systems described herein, but if all of the combustion and flame spread parameters are to be measured as desired the system will be complex. One alternative is to divide the experiments into three separate optical systems, one for each category of investigations. This would, of course, introduce a number of other problems, including an increased demand on the physical accommodations, more involvement of the crews time, and more experimental runs at the same conditons.

Again, the laser diagnostics system described herein are possible, but the technology needs to be developed for applications relevant to the Space Station. This includes the technology development for the data analysis of various systems, systems hardware, and the systems to reduce the complexity of the system.

2.1 Flowchart Description of the concept Design

In Figure B-4, a system flowchart of the overall conceptual design is provided. The complete system can be considered as being composed of three functional system categories. Many of the components of one optics system will also be common to the other optics systems. The functional systems included in the design are:

- Wavefront generation optical system
- Various investigating systems
- Data analysis system.

2.1.1 **Wavefront Generation System** (Figure B-5)

The argon ion laser beam after reflection from the turning mirror TM_1 is taped* to the table top through an access hole by a beam steering unit. This beam steering unit (referred to here as 1) consists of two turning mirrors TM_4 and TM_5 with provision for precision height and angular adjustments. The laser beam incident on the beam expander is spatially filtered and collimated by the collimator lens L_2 and is reflected by mirror M_1 to a beam splitter BS_1. The collimated beam is then taped from BS_1 for the classical and holographic optical systems.

The pulsed laser beam originating from the Dye laser is partially reflected by TBS_2 to TM_4 and is also taped to the table top by the first beam steering unit (1). This beam traverses exactly the same path as that of the argon ion laser and is collimated by the lens L_2 to the beam splitter BS_1 (Figure B-1). This collimated beam is used for the pulsed laser holography.

The continuous wave (CW) argon ion laser after partial reflection from TBS_2 is reflected to TM_2 and on to the table top by a second beam steering unit (2) consisting of turning mirrors TM_3 and TM_6. This beam is then incident on a collimator unit (e.g., TSI model 9108) which is used to control the beam divergence for a given optical system. This control is necessary to assure that the beam crossing point and the waist of the focused laser beam are at the same place. Proper crossing and focusing assures that the fringes are parallel and enhance the overall signal to noise ratio of the entire measurement system. This collimated beam is then used for the laser Doppler velocimetry.

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*Taped means to allow the laser beam to pass through an access hole in the table.

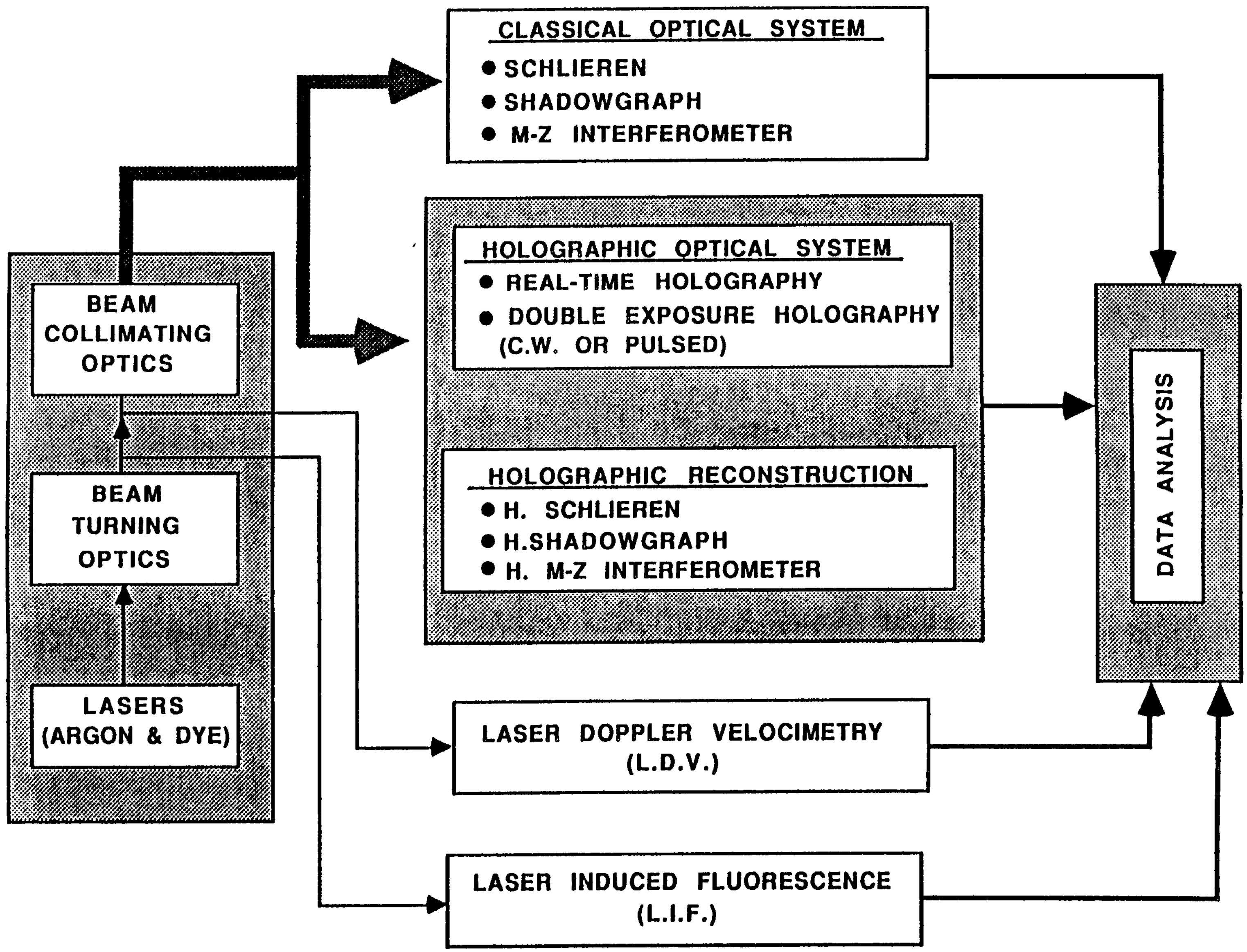

FIGURE B-4. FLOWCHART OF SYSTEM DESIGN

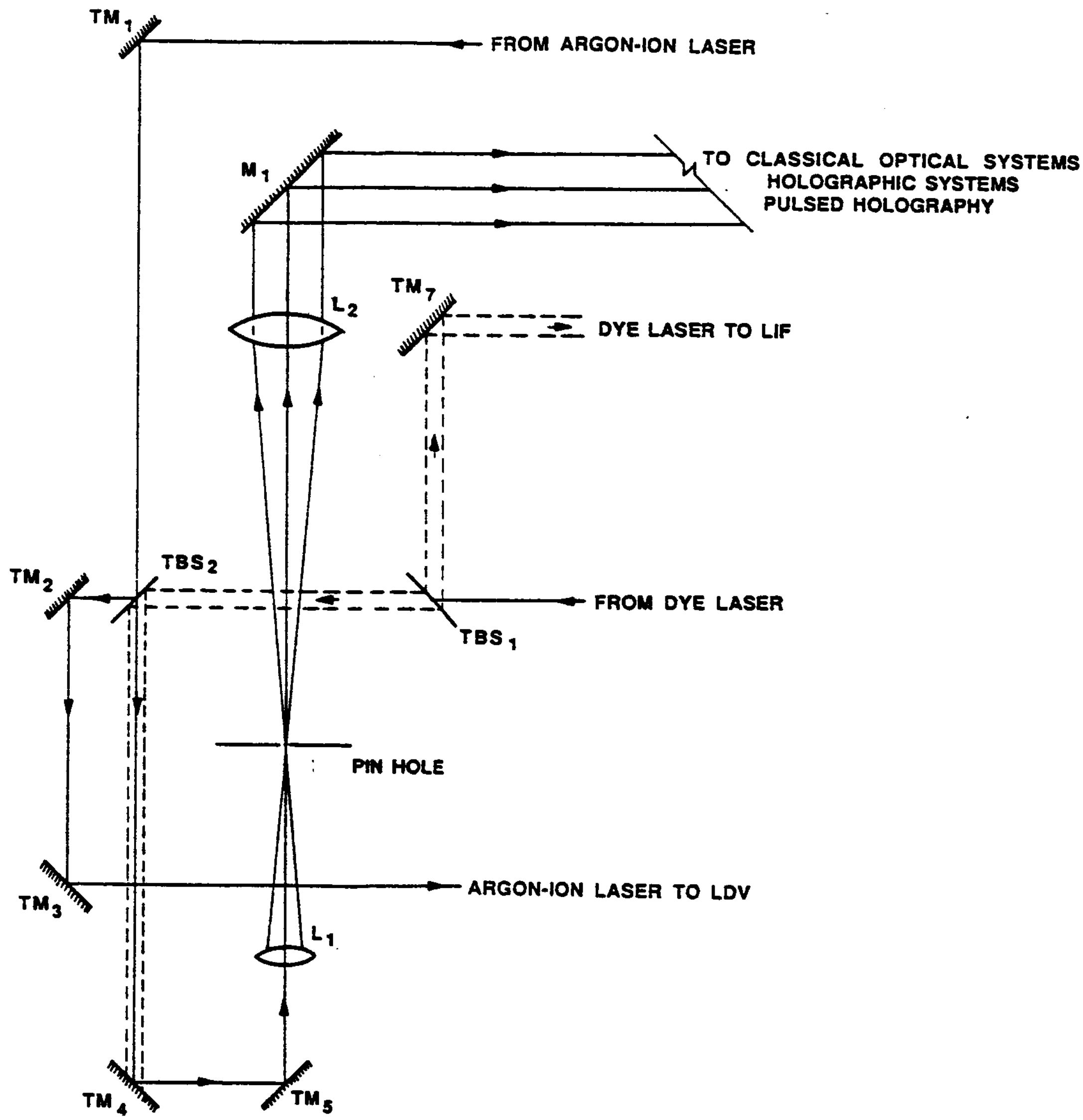

FIGURE B-5. WAVEFRONT GENERATION SYSTEM

The dye laser beam reflected from TBS_1 is taped to the table top by a third beam steering unit (3) consisting of turning mirrors TM_7 and TM_8 (Figure B-1). This beam is used for the laser induced fluorescence. This set of optics so described and included in the left most rectangle, constitutes the first functional optics system, the wavefront generation optical system.

The beam paths generated for the various systems are as follows:

Beam Paths	Investigation Techniques
1. From argon ion laser to the turning mirror TM_1, and on to the beam steering unit (1) consisting of turning mirrors TM_4 and TM_5.	• Classical optical systems • Holographic optical systems
2. From Dye laser to TBS_2, and on to the beam steering unit (1).	• Pulsed laser holography
3. From Dye laser to TBS_1 and on to the beam steering unit (2) consisting of turning mirrors TM_7 and TM_8.	• Laser induced fluorescence
4. From argon ion laser to TM_1 - TBS_2 - TM_2 and on to the beam steering unit (3) consisting of turning mirrors TM_3 and TM_6.	• Laser Doppler velocimetry

2.1.2 Investigation Techniques

The second of the categories include the following optical investigation techniques:

- Classical optical systems
- Holographic optical systems
- Laser induced fluorescence
- Laser Doppler velocimetry.

Real-time data analysis may be performed by using some of the investigation techniques mentioned above and in addition, the holographic system has the ability of storing the information for later analysis. All four sets of experiments can be performed sequentially in any order provided three sets of optical windows are mounted on the chamber or the chamber be rotated through 90 degrees during the entire experiment. Classical and holographic optical systems use one set of windows and the other two systems use one set of windows for each of the entire data observations. If three set of windows are used and the chamber remains stationary, then the flammability material, if opaque, may have to be rotated through 90 degrees for passage of the laser beam.

2.1.3 Data Analysis

The last of the three system categories is that of the general data analysis system. This system includes the camera and video recording systems for the classical and holographic optical systems, signal and data processors for the laser Doppler velocimetry system, and detector, data analyzer and chart recorders for the laser induced fluorescence system. All of this equipment can be procured off-the-shelf from various manufacturers for system integration, at least for ground-based system development.

3.0 MEASUREMENT

3.1 Classical Optical System

The classical optical systems described herein measure the index of refraction or spatial derivatives of the index of a medium and from this the temperature field is inferred. Although all the methods depend on variation of the index of refraction in a medium and the resulting effects on a light beam passing through the test region, quite different quantities are measured in each one. Shadowgraph systems are used to indicate the variation of the second derivative of the index of refraction. With a Schlieren system the first derivative of the index of refraction is determined. Interferometers permit direct measurement of differences in optical path length essentially giving the index of the refraction field directly.

3.1.1 Classical Schlieren

Schlieren photography refers to the recording of gradients in refractive index. In combustion studies, gases are of principle interest, and in these cases the refractive index is generally directly proportional to the density. Thus, Schlieren observations are sensitive to gradients in temperature, pressure and or composition. In general, Schlieren observations are used in qualitative investigations and the ease of obtaining Schlieren photographs makes it a popular tool for the study of flames (Refs. 1-3).

A schematic of the single pass, parallel light Schlieren is shown in Figure B-6. The most important parts of this system consist of a perfectly parallel beam, a Schlieren lens L_3, a marking aperture and a photographic recording device. The marking aperture can be either a knife edge, a slit, stop or a grid so that a normal image of the flame would be produced. In the absence of any flame, the parallel light passes through the combustion tunnel without being deflected and the presence of a flame changes the local density gradients and deflect the light rays. The knife edge deprives the image of all light in zones corresponding to downward deflection, while allowing unimpeded passage to rays deflecting upward.

For our observation, the angle of deflection θ is the relevant quantity. The Schlieren image, i.e., the focus of regions where a maximum change in intensity occurs, is then calculable for combustion phenomena by deducing the angle of deflection θ. Thus,

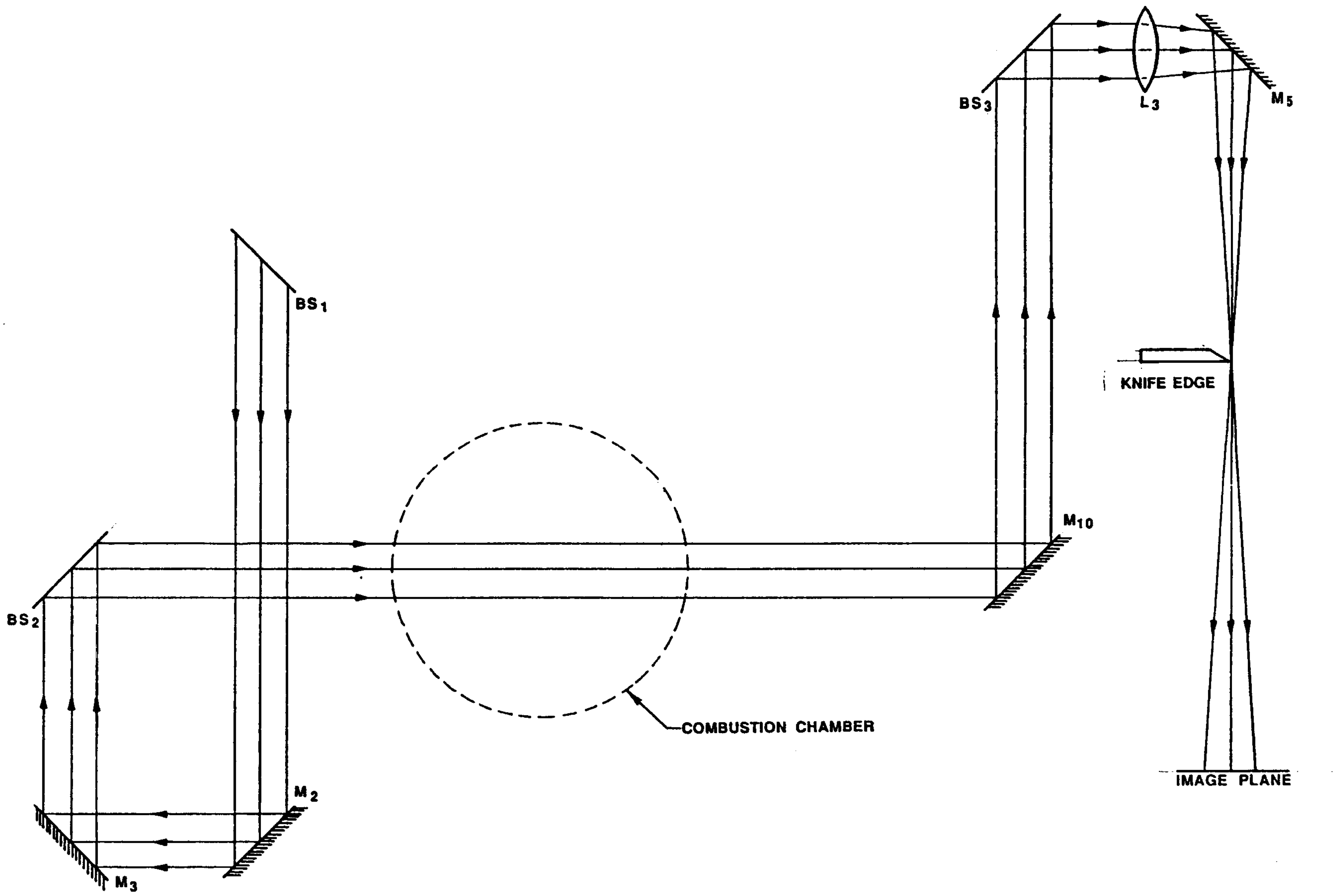

FIGURE B-6. CLASSICAL SCHLIEREN SYSTEM

basically a Schlieren system is designed to measure this small angle (typically of the order of 1 μrad) as a function of position in the X-Y plane normal to the light beam.

Schwar and Weinberg (Ref. 4) demonstrated that velocity measurements can be obtained by combining the Doppler principle with Schlieren method. They tested this method experimentally in several forms on a wide variety of experimental objects. These included moving gratings (radially ruled, 5,600 lines rotated at speeds up to about 600 rpm, mean track diameter of about 10 cm), ultrasonic beams generated by a quartz crystal transducer, flames (burner stabilized and made to move across the test space by a mechanical device) and dispersions of particles. In the case of the flame, interference was achieved between the beam deflected through a small angle by the flame front and the undeflected beam. The fringes were monitored by a photomultiplier and displayed on an oscilloscope. The range of velocities covered by these illustrations extended from a few centimeters per second to the speed of sound. The accuracy of the measurement was generally limited only by that of determining the geometry of the optical system, in particular the width of the Schlieren aperture in relation to its displacement from the optical axis.

Velocity of Flames Based on the Doppler Principle

When the direction of a light beam is deflected through an angle θ, by an encounter with a flame moving at a velocity U at right angles to the incident beam direction, the frequency of the light is altered from ν_1 to ν_2 where

$$\nu_2 = \nu_1 \left[1 + \frac{(U \sin\theta)}{c}\right]$$

and where c is the velocity of light. It is possible to measure the beat frequency $(\nu_2 - \nu_1) = \nu_b$ when the Doppler shifted beam is made to interfere with a reference wave of an unperturbed part of the same laser beam.

Then the beat frequency

$$\nu_b = \nu_1 U (\sin \theta)/c$$

$$= U \frac{\sin\theta}{\lambda}$$

$$\nu_b \simeq U \frac{\theta}{\lambda}$$

Thus the change in frequency can be used to measure the velocity of combustion flames.

3.1.2 Shadowgraph

Shadowgraph systems are used to indicate the variation of the second derivative (normal to the beam) of the index of refraction and are often employed in studying shock and flame phenomena (Refs. 1 and 3) where very large temperature and density gradients are present. The essential feature of shadowgraphy, in distinction from Schlieren methods, is that the image plane is not optically conjugate with the test region and the linear displacement of the perturbed light beam is measured rather than the angular deflection.

A schematic of the shadowgraph system is shown in Figure B-7 in which a parallel light beam enters the combustion tunnel. Assuming that variation exists only in one direction (say y) at the exit of the tunnel, the beam is usually not parallel having been deflected by an angle θ which is a function of y. This linear displacement of the light beam is measured and is then related to the refractive index (density) relation.

This parallel beam system offers several advantages. Its sensitivity is greater, and since there is no magnification, illumination at the image plane is independent of the flame distance from the image plane. The diameter of the collimated beam being as large as the test space is the major concern of the system. In applications to the study of flames, however, this difficulty does not usually arise.

The standard shadowgraph is rarely used for quantitative measurements. If large gradients of density or temperature are present as in a shock wave or a flame, shadowgraph pictures can be very useful.

3.1.3 Mach-Zehnder Interferometer

Interferometers are often used in quantitative studies for the measurement of temperature or density (Ref. 5). Unlike the Schlieren and shadowgraph systems, interferometry does not depend upon the deflection of a light beam to determine density (refractive index) but permits direct measurement of differences in optical

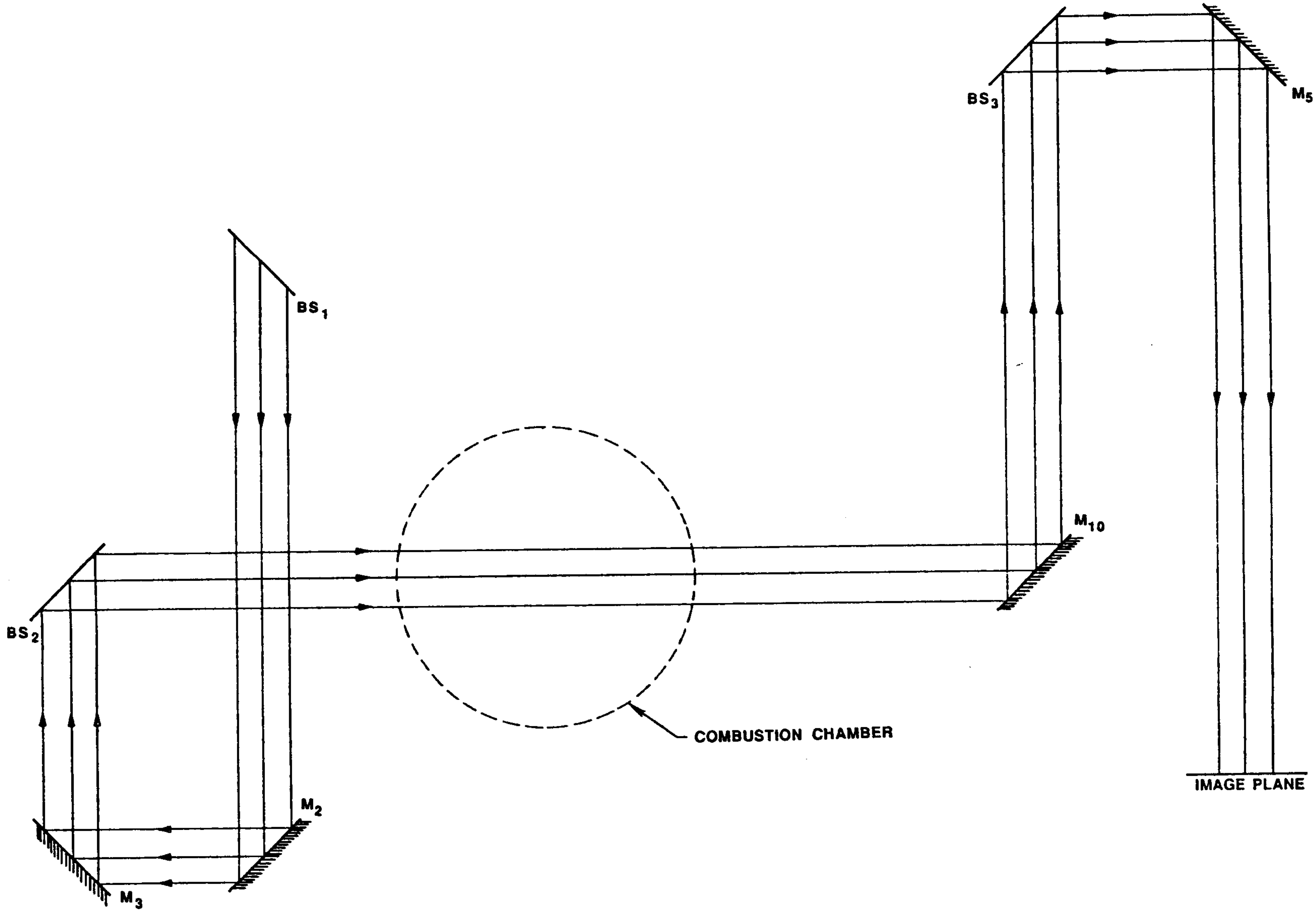

FIGURE B-7. CLASSICAL SHADOWGRAPH SYSTEM path length essentially giving the index of the refraction field directly. This index of refraction can be easily related to density and in turn, through the gas laws, to temperature.

The Mach-Zehnder interferometer is often employed in heat transfer and combustion studies. One of the main advantages of the M-Z system over other interferometers is the large displacement of the reference beam from the test beam. In this way the reference beam can pass through a uniform field. In addition, since the test beam passes through the disturbed region only once, the image is sharp and optical paths can be clearly defined. Although the M-Z interferometer may be difficult to use in a Space Station environment, it is highly desirable that its use be developed. Dimensional stability can possibly be achieved by the use of very rigid mounts for the optical components and mounting the whole system on a rigid optical table.

Figure B-8 is a schematic diagram of a M-Z interferometer. The collimated beam is divided into two separate beams by beam splitter BS_2, the reference beam and the test beam. They traverse paths that take them to beam splitter BS_3 where they combine to produce the interference fringes.

The M-Z interferometer is generally operated in two positions:

1. infinite fringe setting
2. reference fringe setting.

In the infinite fringe setting, the rays uniting at BS_3 are coincident. With no disturbance, the screen will appear either uniformly bright or dark depending upon the difference between the two paths (O, λ, 2λ, etc. for bright, and $\lambda/2$, $3\ \lambda/2$, etc. for dark). When a disturbance is introduced, the screen will show a succession of dark and bright bands of contours where the distrubance occurs. Each of these contours is a locus of constant path difference. While the infinite fringe interferogram gives a realistic picture of the disturbance, the reference fringe setting is normally used for quantitative analysis.

In the reference fringe setting, one or two of the plates are rotated a very small angle from parallel. The two light paths are no longer coincident but intersect. A path

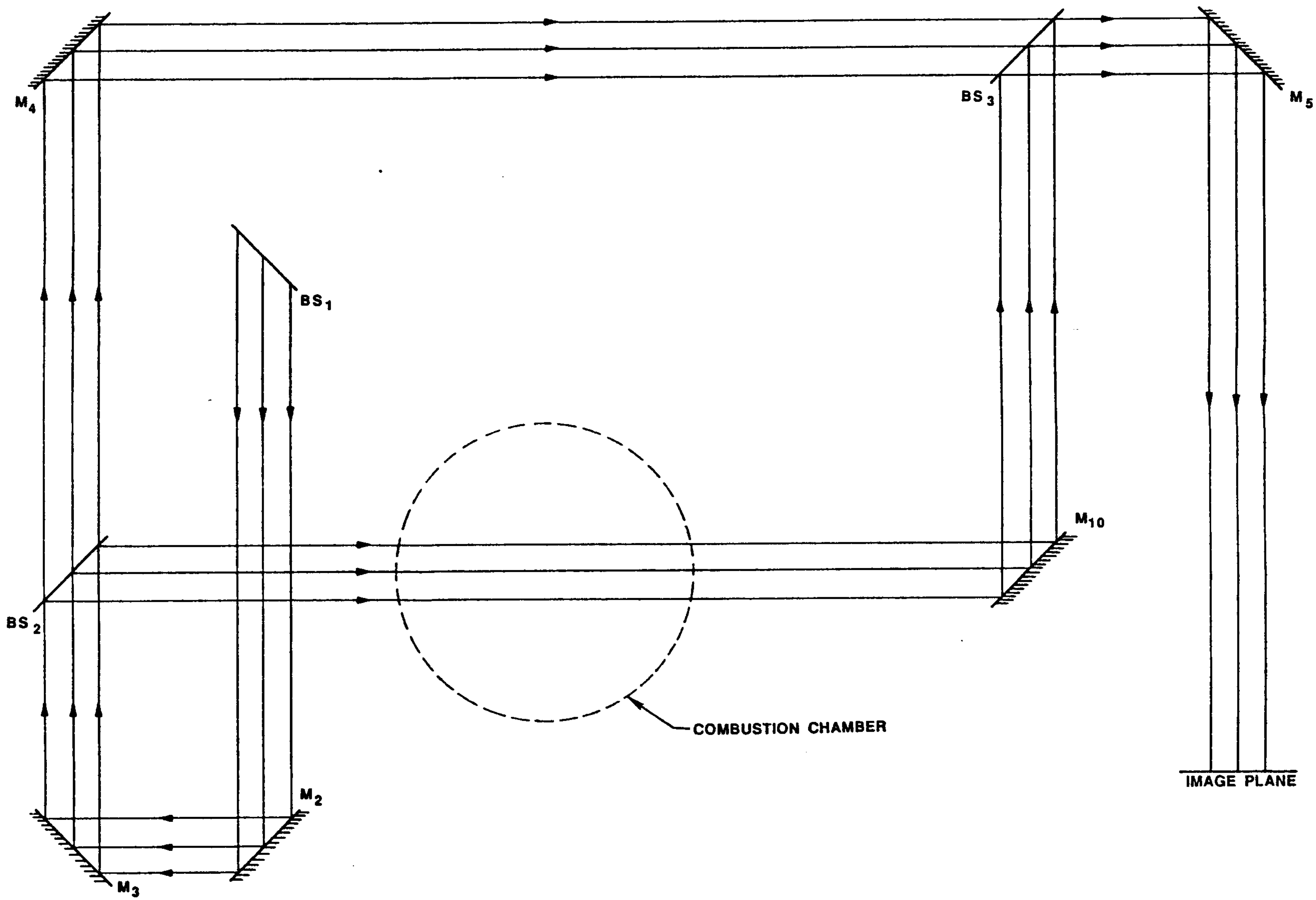

FIGURE B-8. CLASSICAL MACH-ZEHNDER INTERFEROMETRY difference is created, resulting in a series of parallel evenly spaced bright and dark bands, in the absence of disturbance. These are called reference fringes and can be adjusted to any desired spacing and location. When a disturbance is introduced, the shift of one undisturbed fringe width constitutes a path difference of the reference fringes (in the undisturbed field). By projecting the fringe pattern on the image plane, the fringe shift at various positions in the beam can be obtained. This fringe shift is related to the index of refraction and may be used to evaluate the densities and temperature of the flame.

3.2 Holography

Holography is essentially a method of recording both the amplitude and phase information of an object and later reconstructing that information with the aid of a reference beam. This technique has the following application in combustion studies (Refs. 6-11):

1. Flow visualization
2. Storing information for later analysis by:
   - Holographic Schlieren
   - Holographic shadowgraph
   - Holographic M-Z interferometer.

3.2.1 Flow Visualization

A schematic of the holographic recording system is shown in Figure B-9. The collimated beam transmitted and reflected at BS_1 form the reference and object beams for the holography. The object beam after reflections from BS_1, M_2, M_3 and BS_2 pass through the combustion tunnel and to an incidence on the hologram holder, HH. The reference beam passes through BS_1 and after reflections from M_6, M_7, M_8 and M_9 strike the hologram plate at an angle to the object beam. The path lengths of the object and reference beams are equally matched from BS_1 to the hologram holder HH. For best results, the object to reference beam ratio should be within the range of 1:4 to 1:10. This can be adjusted by the use of neutral density filters in the object and reference beam paths.

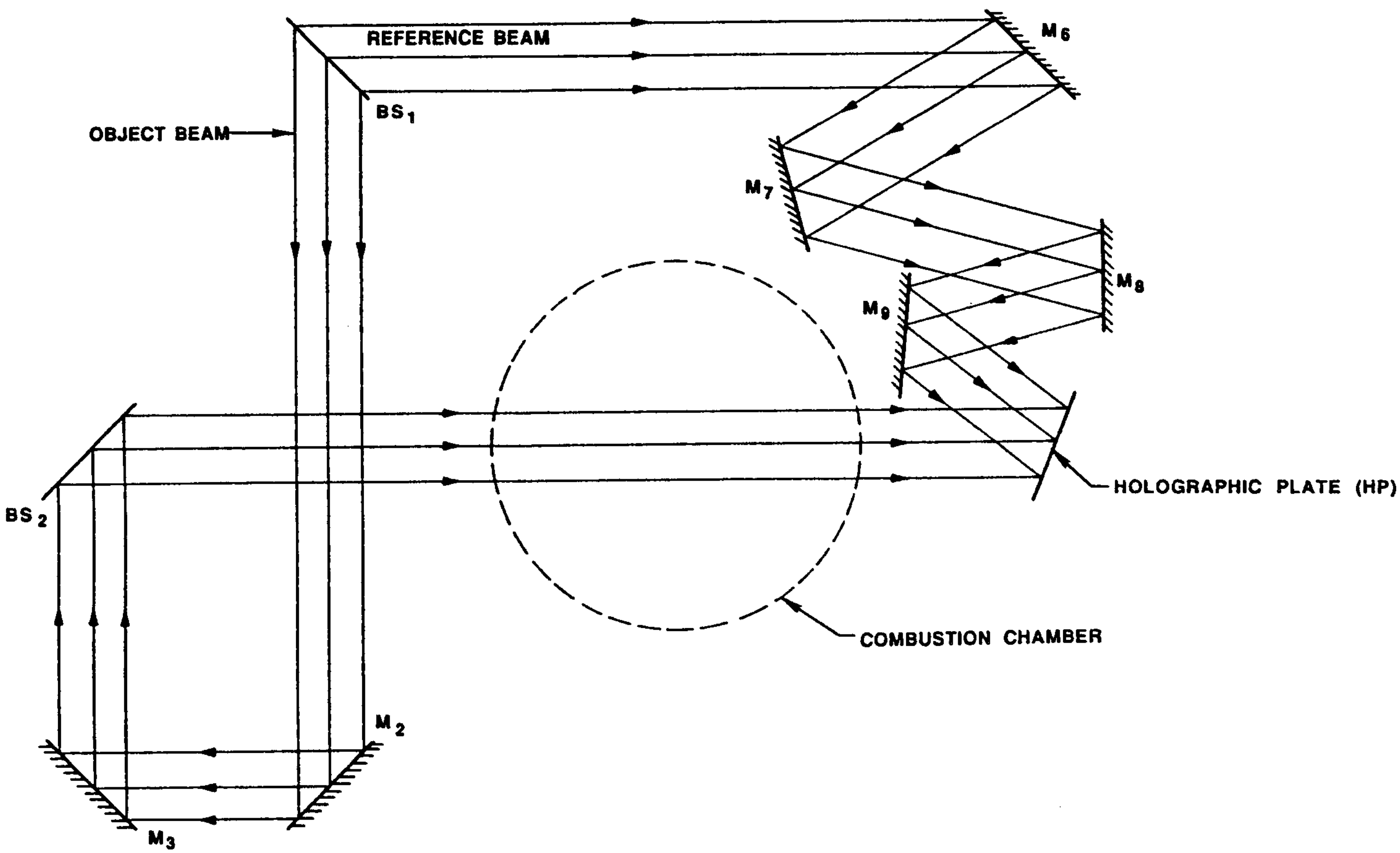

FIGURE B-9. SCHEMATIC OF THE HOLOGRAPHC RECORDING SYSTEM (CONTINUOUS AND PULSED)

Double Exposure Holography

The light beam changes its phase when, for example, it passes through a combustion tunnel flame, since the refractive index varies with temperature and density. Thus, a hologram can record these phase variations directly, although the phase variation is not normally visible, and cannot be photographed unless the phase variation is first turned into an intensity variation in some kind of interferometer. This can be performed by recording a second hologram of the phase distribution on the same plate as the first (double exposure hologram). The wavefronts reconstructed by each hologram will each carry the appropriate phase variation, and the two wavefronts will be in a condition to interfere, giving a visible pattern (flow visualization) which represents the difference in the phase variation.

If a turbulent flame is being diagnosed, then we can actually map out the contours of the refractive index of this flame with double pulsed holography. The exposure time will be of the order of a few nanoseconds or picoseconds with a few nanoseconds delay between the exposures. Exposure time of the order of nanoseconds will help to arrest the motion of any optical components or the flames.

High resolution photographic films or plates, with fine silver-halide dispersed in gelatin, are often used to produce holograms. Several appropriate holographic plates and films are readily available, and the selection may be made depending on the power of the laser and its wavelength in use.

Holograms taken during the experiment may be processed either on earth or on the Space Station. If it is ultimately determined that a holographic system should be developed for use with the combustion tunnel, it may be necessary to process and analyse the data in a ground-based facility. This would, of course, be done to provide the most extensive and detailed analysis of the data and would minimize the involvement of Space Station specialists on orbit.

It is also possible to process the recorded holograms on the SS, but there are a number of serious disadvantages to this process. For example, the following functions would have to be provided:

1. Use of physical space and equipment for developing the holographic film.
2. Storage and disposal of photographic chemicals.
3. A hologram reconstruction facility would have to be provided. The holographic recording equipment may be used as a reconstruction facility, but this would restrict the use of the laser diagnostics system for other experiments.
4. More demands would be placed on the time and skill levels of the SS crew.

Recent studies show the successful use of photopolymers as hologram recording materials for real time analysis. Honeywell, Inc. has developed an instant hologram recording device[1] using photopolymers as the recording material with 10 seconds developing time. The application of photopolymers for the combustion flame studies may be investigated further at the technology development stage.

Another important feature of the holographic system is its ability to store the information for later analysis by the following techniques. These techniques will yield the same information as that of the classical optical systems.

1. Holographic Schlieren
2. Holographic Shadowgraph
3. Holographic M-Z Interferometer.

3.2.2 Holographic Schlieren

A schematic of the holographic Schlieren is shown in Figure B-10. A hologram of the combustion flame taken using the setup given in Figure B-9 is processed and replaced back into the hologram plate holder for reconstruction. The reference beam with maximum intensity is allowed to fall on the hologram. The hologram reconstructs a wavefront identical to the wavefront which passes through the flame at the time of recording. This reconstructed wavefront is in a static state. Deflection in the beam path is directed by mirror M_5 into the appropriate imaging system.

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[1]These recording devices may be obtained from Newport Corporation, Fountain Valley, CA, 1983-84 Catalog (2nd Edit.).

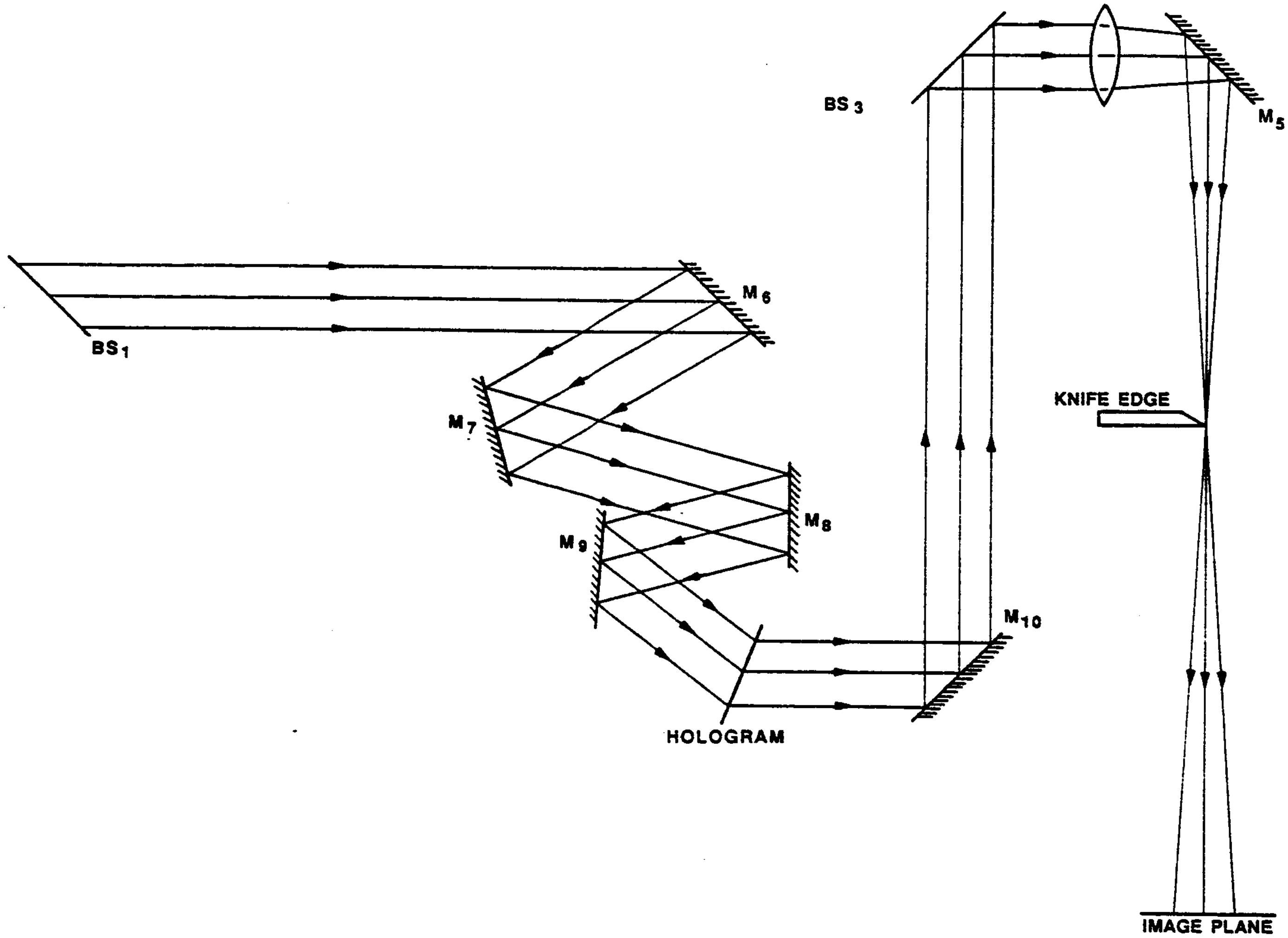

FIGURE B-10. HOLOGRAPHIC SCHLIEREN

3.2.3 Holographic Shadowgraph

A schematic of the holographic shadowgraph is shown in Figure B-11. This system uses the same reconstruction beam as does the holographic Schlieren. The wavefront reconstructed by the hologram is directed by the mirror M_5 through the optical axis of the common imaging system, and a shadow image in the light beam is formed on the screen.

3.2.4 Holographic M-Z Interferometer

A schematic of the holographic M-Z interferometer is shown in Figure B-12. The reference beam reconstructs the wavefront identical to the wavefront which passes through the combustion tunnel at the time of recording, forming the object beam arm of the interferometer. The reflected beam from BS_1 after reflections from M_2, M_3 and M_4 form the other arm of the interferometer. These beams recombine at BS_3 and form a unique high performance system. The measurement taken from this interferometer is related to the index of refraction and may be used to evaluate the densities and temperature of the flame.

3.3 Laser Doppler Velocimetry (LDV)

Laser Doppler velocimetry has been used extensively for making measurements in flames under laboratory and industrial conditions, in gases, liquid fuel, and solid partical flames (Refs 12-15). Measurements have been made in both laminar and turbulent diffusion flames and industrial burner flames, etc. Velocities as low as a few micrometers per second to several hundred meters per second can be measured by this technique. Studies also have been reported about the extensive use of LDV with special application to various combustion flames.

The question of selecting between forward and back scattering systems is generally dictated by the degree of access to the combustion system. If clear access to the combustion chamber is possible, a forward scattering system may be selected. A schematic of the forward scattering LDV system is shown in Figure B-13. The arrangement shown here is the most common technique in LDV and has the advantages of easy alignment and flexibility.

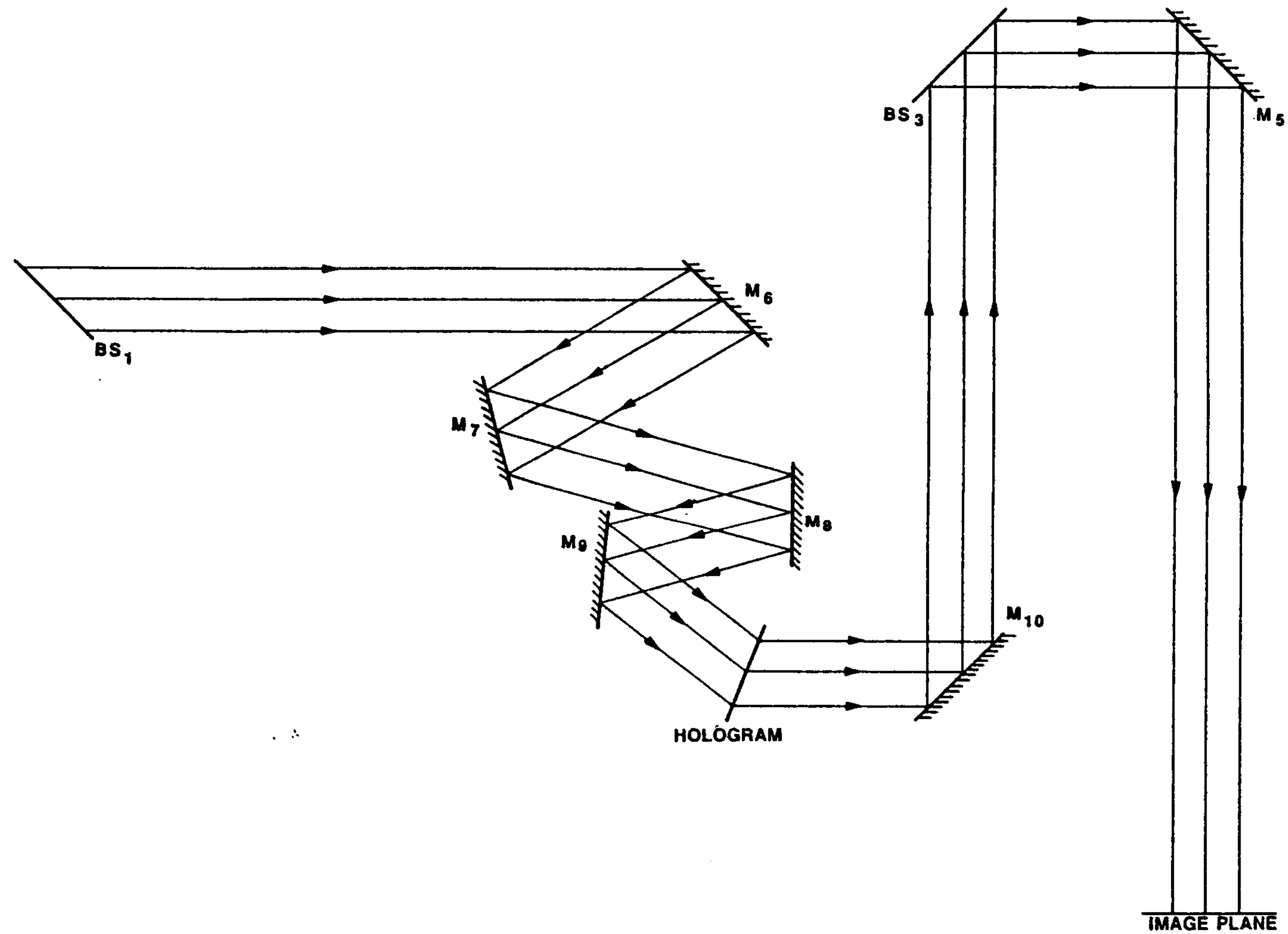

FIGURE B-11. HOLOGRAPHIC SHADOWGRAPH

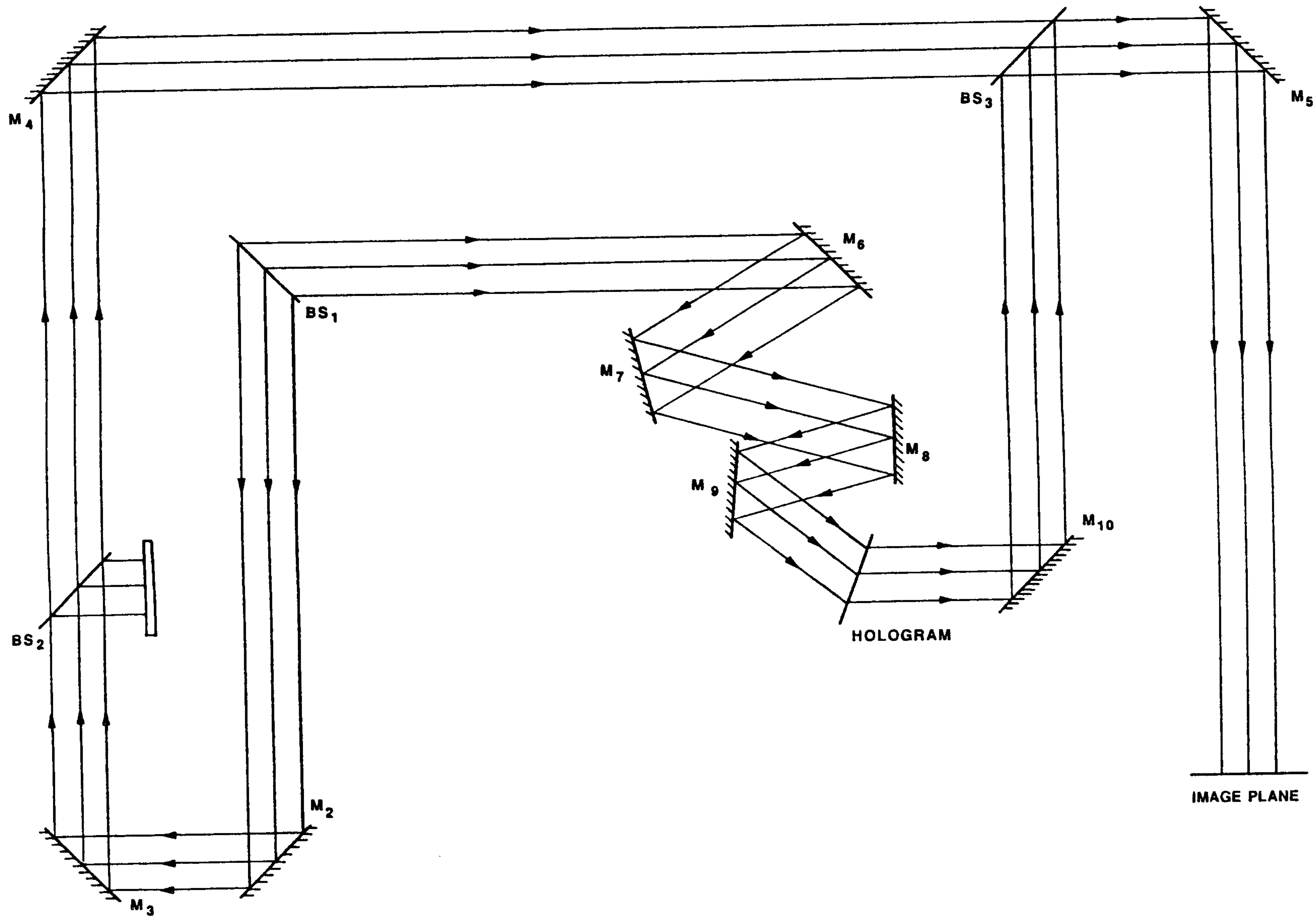

FIGURE B-12. HOLOGRAPHIC M-Z INTERFEROMETER

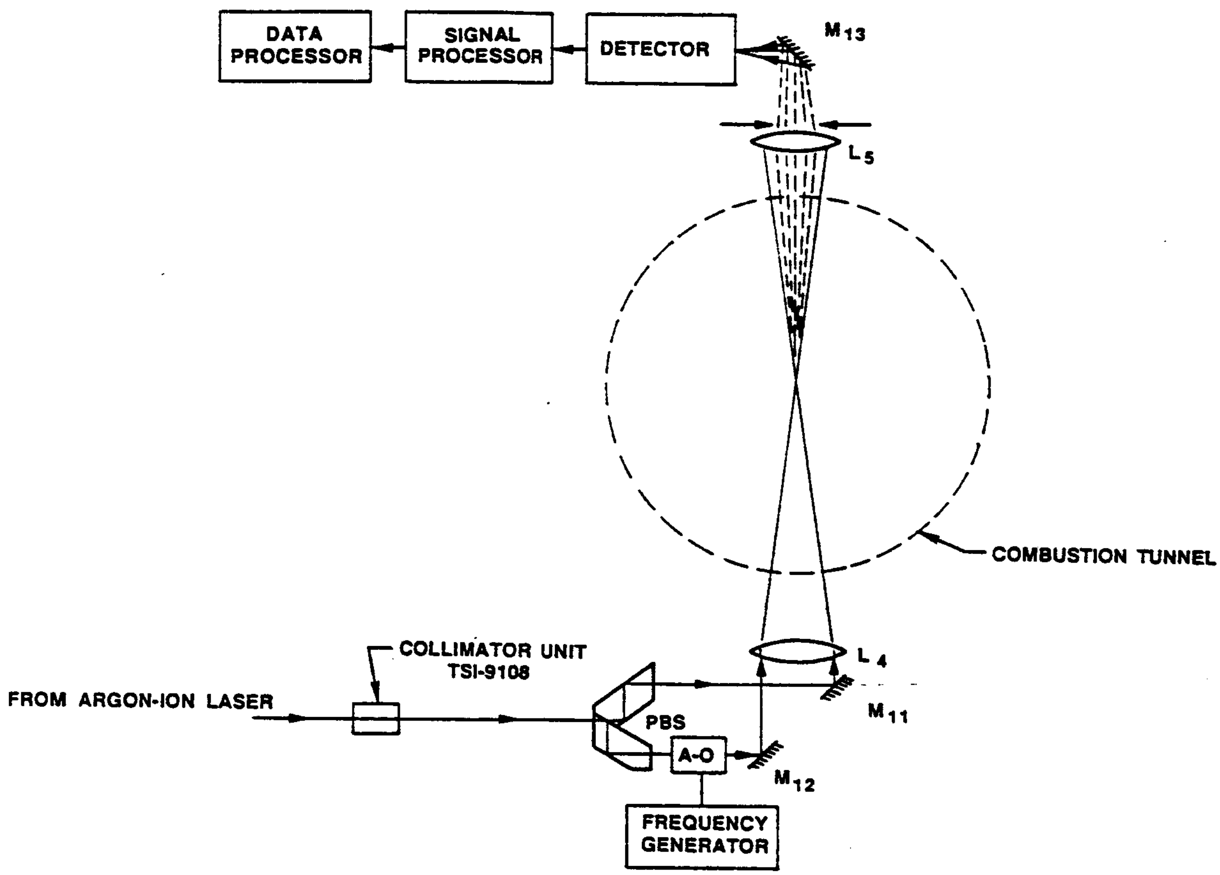

FIGURE B-13. LASER DOPPLER VELOCIMETER

The system consists of the following components:

- High powered argon ion laser
- Collimating optics
- Prism beam splitter
- Acousto-optic cell
- Beam focusing optics
- Beam receiving optics
- Photodetector
- Signal processor
- Data processor.

It has been reported in the literature that laser powers as low as 0.2 mW would be sufficient to make measurements in forward scatter; however, use of laser powers less than 100 mW has led to significant difficulties in making measurements in combustion systems. An argon ion laser of 1-watt power output in all lines would be sufficient for both LDV and other interferometric and holographic systems. This laser beam is incident on a collimator unit (e.g., TSI model 9108) which is used to control the beam divergence. This control is necessary to assure that the beam crossing point and the waist of the focused laser beams are at the same place. Proper crossing and focusing assures that the fringes are parallel and enhance the overall signal-to-noise ratio of the entire measurement system.

The prism beam splitter has a prism which splits the incoming laser beam into two parallel beams. The two beams are of equal intensity with equal optical path lengths for each beam. The acousto-optic (A-O) frequency shifter gives a linear shift of the frequency versus velocity calibrations of a laser Doppler velocimeter (see Section 3.6 for a discussion of the A-O cell). This permits measurements through zero velocity, allowing the LDV to make accurate measurements where the flow direction reverses. An adjustable mirror M_{12} permits the angular offset introduced by the Braggcells to be corrected and insure that beam intersection after the transmitting lens L_4 occurs at the beam waists. The beam focusing and receiving optics are of 150 mm and 50 mm focal lengths respectively with antireflection coating on both sides. The photo detector is an RCA type 4526 photo multiplier tube with quantum efficiency of 22 percent at 500 nm. The TSI model number 1990 C signal processor processes the photodetector signal to give a binary digital output or an analog voltage proportional to the velocity of the particle causing the Doppler burst. Digital data interfaces connect the signal processors with common computers for data analysis.

A knowledge of the details of the application is necessary before one can choose the correct signal processor. For example, TSI model 1990 C signal processor is applicable to a wide variety of flows, but requires a good signal-to-noise ratio from the photodetector. This signal processor also finds applications in wind tunnels, water channels, exhaust gas research, heat exchanger studies, etc.

In LDV, the data may be improved by adding appropriate seed particles to the flow. Strehlow (Ref. 16) has used a fluidized bed and settling tube technique to seed the gas flow. However, this system is not a viable system under low gravity conditions since it relies on gravity to develop a seeded gas flow. For low gravity conditions, Strehlow suggested a modified system in which the tube is rotated at such a velocity that the fluidized bed at the terminus of the tube experiences essentially a gravitational force equivalent to that on earth.

The combustion tunnel is fitted with three sets of optical glass windows for viewing the combustion flames, with one set of windows earmarked solely for LDV. Depending upon the design of the combustion tunnel, it may or may not become necessary to fold the optical system without any basic design change. The LDV measurement can be performed simultaneously in a single run along with other experiments.

3.4 Laser Induced Fluorescence (LIF)

Laser induced fluorescence is a powerful technique for the accurate measurement of combustion flame radical species (Ref. 17-21). In this technique, a laser is tuned so that its frequency matches that of an absorption line of some atom or molecule of interest. The absorption of the laser photons by this species produces an electronically excited state which then radiates. This radiation (fluorescent emission) is detected using a filter (monochromator) followed by a photomultiplier.

The experimental configuration for the LIF studies is shown in Figure B-14. The laser beam is focused into the flame through the Schlieren windows of the combustion

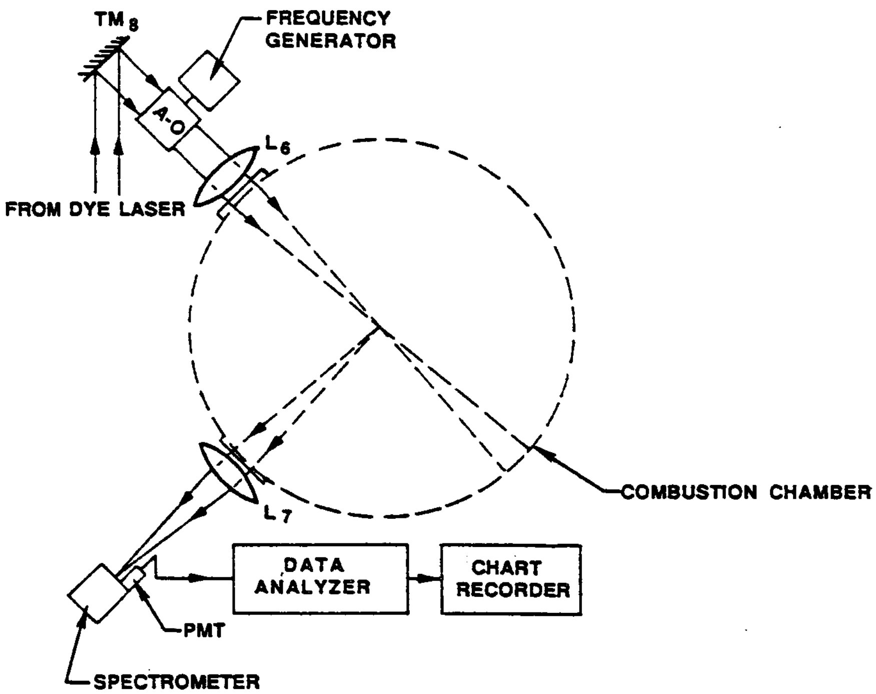

FIGURE B-14. LASER INDUCED FLOURESCENCE

tunnel. The fluorescence emitted at a right angle to the beam direction is focused through a filter into a photoelectric detector, oscilloscope and the chart recorder. The detector and the filter may be chosen so that fluorescence from any excited level can be detected.

If a particular species is of interest, a single frequency laser may be used if its frequency happens to coincide with that of the absorption line of the species, but a tunable laser is more versatile. It permits the performance of experiments on different species. Both continuous wave (CW) and pulsed lasers can be used for the LIF measurements. Continuous wave lasers have the advantage of more stable output amplitude while pulsed lasers have higher peak powers, and thus higher instantaneous signal levels and is possible to use for a variety of non-linear processes including frequency doubling and shifting methods. A Nd:YAG laser-pumped, tunable dye laser is an ideal choice for the LIF measurements. The Nd:YAG laser operating at 10.64 μm is frequency doubled to 532 nm. This green laser beam is used as the pump source for the tunable dye laser. Suitable laser dyes are used for the selection of various frequencies required for the excitation of the various species of interest.

The average spectral energy density required for the operation is nearly 2-4 mJ/cm^2. The spectra physics Nd:YAG DCR-II and DCR-II pumped dye laser shown in Table B-1 provides an output of 100 mJ/cm^2 at 360 nm which can be used for most of the LIF measurements. The coherent CR-599 can also be used as a continuous wave laser in the wavelength range 360-950 nm.

The experiment setup for the measurement of the OH^-species concentration in the combustion flame is as shown in Figure B-14. The OH^-molecule has been the most commonly studied combustion species using LIF because it is an intermediate species in the chemistry of nearly every flame and the availability of convenient UV lasers to excite it. For many of the other species which are of interest, further research needs to be performed in order to establish a firm spectroscopic data base for the quantitative analysis of LIF data.

The dye laser, after reflections from beam turning optics, TBS_1, TM_7 and TM_8, is focused to the center of the combustion tunnel by the focusing lens L_6. The combustion tunnel, designed by Wyle, can be used for the study of combustion and

TABLE B-1. LASER MATRIX

TYPE OF LASER	MFGR.	WAVE-LENGTH μm	CW / PULSED	MAX. POWER	PHYSICAL DIMENSIONS			COOLING	ELECT. POWER	COMMENTS
					LASER HEAD cm	POWER SUPPLY cm	TOTAL WT. IN kg			
He-Nc	1 SPECTRA PHYSICS	0.6328µm 3.39 1.15	CW	50 mW	172x 20x18	40.6x39x 15.2	30+17	AIR	110 OR 220 VAC 50/60HZ 350 VA	
	2 SPECTRA PHYSICS	0.6328µm 3.39 1.15	CW	25 mW	98x10x 10	29x20x10	8+8	AIR	110 OR 220 VAC 50/60HZ 350 VA	
ARGON -ION	SPECTRA PHYSICS	458-515 (ALL LINES)	CW	65 mW	31x21.3 x14	28.7x21 x13.5	5 +6.4	AIR	110 VAC 47 TO 63 HZ 17 AMP SINGLE PHASE	
	OMNI-CHROME	SINGLE LINE 0.488 0.515		20mW						
	UNIPHASE			20mW						
	SPECTRA PHYSICS MODEL# 2025-03	MULTILINE	CW	3 WATTS		81.6x54.3 x37.2	68+75	WATER 2-5 gal/min 15-75 psi	3 PHASE 208 VAC 61 AMP /PHASE 22 KVA	
	COHERENT	MULTILINE	CW	1 WATT	86.6x18.6 x16.5	44.7x36.5 x21.5	34+34	WATER 2-25 gal/min 20-60 psi	3 PHASE 190-260 VAC 50/60 HZ 35 AMP	RECOMMENDED BECAUSE OF IT'S SMALL PHYSICAL DIMENSIONS

TABLE B-1. LASER MATRIX (CONCLUDED)

TYPE OF LASER	MFGR.	WAVE-LENGTH μm	CW / PULSED	MAX. POWER	PHYSICAL DIMENSIONS: LASER HEAD cm	PHYSICAL DIMENSIONS: POWER SUPPLY cm	PHYSICAL DIMENSIONS: TOTAL WT. IN kg	COOLING	ELECT. POWER	COMMENTS
Nd-YAG DCR - II	SPECTRA PHYSICS	1.064 0.532 0.355 0.266	PULSED	275 mJ 135 mJ 60 mJ 30 mJ	102x23 x23	59x55x50	25+68		190-250 VAC 50/60HZ 10 A	
DCR - II PUMPED DYE LASER	SPECTRA PHYSICS	.360-.950	PULSED	100 mJ	79.7x56 x24				208 VAC SINGLE PHASE	
ARGON	COHER-ENT INNOVA 70-4	MULTILINE	CW	4 WATTS	103x18.6 x16.5	44.7x36.5 x21.5	43+34	WATER 2-5 gal/min 20-60 psi	3 PHASE 190-260 VAC 50/60HZ 40 AMP	
DYE LASER CR-599	CR-599	.360-.950	CW	200 mW SINGLE LINE	66x34.3 x19.2	55.3x50.2 x19.7				
NITRO-GEN LASER VSL-337	LASER SCIENCE VSL-337	.337	PULSED	100 μJ	25x11.8 x5.3	12 VOLT BATTERY PACK	2 kg		12 VOLT BATTERY	
VSL-337 PUMPED DYE LASER VSL			PULSED		31.1x11.8 x5.3 (INCLUDING THE PUMPING LASER)	12 VOLT BATTERY PACK	3 kg		12 VOLT BATTERY	

flame spread of burning materials in the presence of low velocity convection under microgravity conditions. The UV laser light for the fluorescence excitation of the OH molecule is provided by the dye laser. Fluorescence radiation from the OH molecules that are present is gathered at right angles to the laser beam by the beam collecting lens L_7 onto the detector. The detector consists of a monochromator and a photomultiplier tube, where the monochromator is used as a broad band-pass filter. The output terminals of the photomultiplier is displayed on an oscilloscope, where the results are based on the fluorescence signal which indicates the OH species concentration.

As the material's burning progresses, the flame position changes and it becomes important to refocus the laser accordingly. The flame can be brought back to the laser focusing position either by mechanical means or by refocusing the laser to the center of the displaced flame by means of acousto-optic (A-O) beam deflectors. A-O beam deflectors are precision beam deflecting devices that operate by varying the frequency of the sound wave. A sound wave is passed through a liquid or solid medium and the acoustic pressure waves interact with the laser light travelling orthogonal to the sound wave. The pressure variations form a diffraction grating that varies in refractive index with the local pressure and thus diffracts the light beam as it exits the cell. In Bragg diffraction devices, diffraction takes place only in one principal order. This diffracted beam, deflected in proportion to the frequency of the sound wave, is focused by the focusing lens. The scanning area is limited by the frequency range of the deflector and the physical size of the tunnel window.

4.0 GROUND-BASED SYSTEM FOR CONCEPT DEVELOPMENT

The laser diagnostics systems described in Section 3 are considered to be possible in principle, but the technology has to be developed in a ground-based "breadboard" system. A breadboard system may be used for the evaluation of various data acquisition and analysis options, hardware development, and may also be used as a ground-based laboratory for the analysis of the data ultimately obtained from the Space Station.

The various optical components required for the laser diagnositics system for a ground-based breadboard system are given in Table B-2. This preliminary listing will provide an idea of the electrical power requirements, system weight, physical dimensions and approximate cost, etc., in establishing a ground-based breadboard system. A brief description of all the major components is provided in the following subsections.

4.1 Optical Table

The basic function of an optical table is to provide the stable base required for optical and laser system development. For applications involving optical interferometry and holography a great deal of stability is required. Thus the optical table must provide a firm, reliable, vibration-free surface isolated from external disturbances. Since optical tables are heavy, thick and require pneumatic vibration isolation systems, special thin optical tables (51 mm (2 in.) thick) are recommended for this design. In comparison with optical tables, they are exceptionally rigid, stiff and internally damped. They are useful in applications requiring smaller sizes and should not be used in cases requiring large components.

The thin optical table described herein has the overall dimensions of 914 mm by 610 mm by 51mm (3 ft by 2 ft by 0.2 ft) mounted on 510 mm (1.7 ft) high mounting poles and will provide the space required to mount a maximum of 254 mm (10 in.) diameter combustion tunnel and its associated optical diagnostics systems on the table top. The lasers and other turning optics are mounted underneath the table (Figure B-2) to provide more working space on the table.

TABLE B-2. COMPONENTS OF A GROUND-BASED BREADBOARD SYSTEM

COMPONENTS	REQUIRMENT / SPECIFICATION	SUGGESTED MANUFACTURER	APPROXIMATE WEIGHT IN KG.	POWER NEEDS	COST	COMMENTS
OPTICAL TABLE	914x610x50mm (BREAD BOARD) FLATNESS ± 0.2mm (INTERNALLY DAMPED)	MELLES GRIOT	46 kg	NIL	$1,500	
ARGON-ION LASER	INNOVA 70-2 WATT SIZE: OPTICAL HEAD: 1029x186x165mm POWER SUPPLY: 447x365x222mm	COHERENT	43 kg 34 kg	3 PHASE WITH GRD. 190-260 VAC 50 OR 60 HZ 40 AMP / PHASE	$13,200	
Nd:YAG PUMPED DYE LASER	DCR-11 Nd:YAG LASER 838x229x267mm POWER SUPPLY (495x591x558mm) PDL-2 PULSED DYE LASER (312x221x100mm)	SPECTRA PHYSICS	25kg 68kg	SINGLE-PHASE 208 V	$65,600	

TABLE B-2. COMPONENTS OF A GROUND-BASED BREADBOARD SYSTEM (CONTINUED)

COMPONENTS	REQUIRMENT / SPECIFICATION	SUGGESTED MANUFACTURER	APPROXIMATE WEIGHT IN KG.	POWER NEEDS	COST	COMMENTS
BEAM TURNING OPTICS MIRRORS WITH MOUNTS TM_1 THRU TM_8 M_1 THRU M_{13}	HIGHLY REFLECTING MIRRORS TO DIRECT UNEXPANDED LASER BEAM. FLATNESS: / 20 COATING: ALUMINUM REFLECTIVITY: >90%	1. MELLES GRIOT 2.NEWPORT RESEARCH CORPORATION	ALL MIRRORS 20 kg	NIL	$15,000	
BEAM SPLITTING DEVICE WITH MOUNTS TBS_1 , TBS_2 , BS_1 ,BS_2 ,BS_3 , & PBS	BEAM RATIO T : R / 50 : 50 DIAMETER : 50 mm FLATNESS : / 20	1. MELLES GRIOT 2. N R C	5 kg	NIL	$5,000	

TABLE B-2. COMPONENTS OF A GROUND-BASED BREADBOARD SYSTEM (CONTINUED)

COMPONENTS	REQUIRMENT / SPECIFICATION	SUGGESTED MANUFACTURER	APPROXIMATE WEIGHT IN KG.	POWER NEEDS	COST	COMMENTS
BEAM COLLIMATING OPTICS WITH MOUNTS (INCLUDES L_1, L_2, & PINHOLE)			7 kg	NIL	$5,000	
PINHOLE	PINHOLE DIAMETER : :11 μ m	1. MELLES GRIOT 2. N R C				
L_1 (MICROSCOPE OBJECTIVE)	MAGNIFICATION : 20x f : 9 mm					
LENSES	DIAMETER : 50 mm					
L_2	f_2 : 350 mm					
L_3	f_3 : 337 mm					
L_4	f_4 : 150 mm					
L_5	f_5 : 50 mm					
L_6	f_6 : 110 mm					
L_7	f_7 : 50 mm					
	(ALL OPTICS ARE ANTIREFLECTION COATED)					

TABLE B-2. COMPONENTS OF A GROUND-BASED BREADBOARD SYSTEM (CONCLUDED)

COMPONENTS	REQUIRMENT / SPECIFICATION	SUGGESTED MANUFACTURER	APPROXIMATE WEIGHT IN KG.	POWER NEEDS	COST	COMMENTS
SHUTTER	ELECTRONICALLY CONTROLLED EXPOSURE TIME : NANO SECONDS		8 kg	110 VAC 50-60 HZ 60 W	$3,000	
HOLOGRAPHIC PLATE HOLDER	TO HOLD HOLOGRAPHIC PLATES SIZE : 50 x 50 mm	1. N R C 2. JODON	1 kg	NIL	$1250	
HOLOGRAPHIC FILM	DATA RECORDING MEDIA	KODAK OR AGFA	1 kg	NIL	$1000	
PHOTO - DETECTOR SIGNAL PROCESSOR DATA ANALYZER	FOR LDV REF. TSI SPECIFICATIONS	TSI			$5,500 $19,000 $12,000	 (OPTIONAL)
SPECTROMETER DETECTOR DATA ANALYZER	FOR LIF				$7500 $26,000 $18,500	

4.2 Lasers

Classical optics, holography and laser Doppler velocimetry require a stable medium power gas laser operating in the visible region, whereas, laser induced fluorescence studies require a tunable dye laser having wavelength extending from ultraviolet to infrared regions. The following two lasers are identified for the ground-based research.

1. Argon Ion Laser, Innova 70-2 from Coherent
2. Nd: YAG Laser DCR-2 and Nd: YAG Pumped Pulsed Dye Laser PDL-2 from Spectra Physics.

4.3 Beam Turning Optics

The suggested beam turning optics are all high reflection aluminum coated mirrors of the following specifications:

Beam turning mirrors (TM_1-TM_8) diameter:	25.4 mm (1 in)
System mirrors (M_1-M_{13}) diameter:	50.8 mm (2 in)
Surface accuracy:	$\lambda/20$
Surface coating:	Aluminum

Aluminum is the most widely used metal coating for high reflections (above 90%) throughout the near ultraviolet, visible and near infrared regions of the spectrum which is of interest. These mirrors are mounted on precision translation and rotational stages for accurate positioning of the beam.

4.4 Beam Steering Units

The beam steering instruments are premier devices for adjusting the elevation and azimuth angle of laser beams. They feature independent coarse and fine control over the entrance angle. The lower mirror is pivoted to the desired angle using a pin that protrudes horizontally from the mirror support. The upper mirror holder can be pivoted over a 360-degree range with a hand sized knob or over a 15-degree range with a vernier micrometer which reads out directly in units of 20 arc-sec. Another micrometer controls the elevation exit angle over a range from +7 degrees to -20 degrees. The elevation of the mirrors can be controlled individually using a rack and pinion drive mechanism.

4.5 Beam Splitting Optics

These are all high quality polished optical blanks partially coated with aluminum for the desired transmittance and reflectance ratio.

Beam turning beam splitters (TBS_1, TBS_2) diameter:	25.4 mm (1 in)
System beam splitters (BS_1, BS_2, BS_3) diameter:	50.8 (2 in)
Transmittance/Reflectance:	50/50)
Surface accuracy:	$\lambda/20$
Coating:	Aluminum

These beam splitters are broadband anti-reflection (AR) coated on one side and the other side is left uncoated. AR coatings are commonly used to increase the efficiency of transmitting optics and to reduce the intensity of unwanted surface reflections. These beamsplitters are mounted on precision translation and rotational stages for accurate positioning of the beam.

4.6 Electronic Shutter System

The electronic shutter system is essential for the controlled exposure of the holographic film for double exposure and pulsed holography. The system (e.g., NRC model No. 880) consists of a photosensor, an electronic shutter and a controller console and has four operational modes: Laser power meter, laser energy meter, times shutter controller and automatic shutter controller.

4.7 Holographic Plate Holder

The holographic plate holder (e.g., NRC model No. 520) is designed to hold a wide range of film plates from 25.4 mm (1 in.) square to 102 mm by 127 mm (4 in. by 5 in.) plates. For precise micropositioning of the film plate, this holder is mounted on the model 525A 2-axis micropositioning base with a total translation range of 500 μm in both the X and Y axis.

4.8 Holographic Plates

Holography requires high resolution recording materials with spatial resolutions on the order of several thousand lines per millimeter (2000 to 3000 lines/mm). Even though several hologram recording materials are available in the market, silver halide emulsion is most commonly being used for hologram recording applications because of its high resolution, moderate exposure, wide spectral sensitivity, etc. This high resolution decreases the photographic speed, but with a high-powered laser source, this reduction in speed can easily be overcome.

4.9 Other Optical Diagnostics Equipment

For a detailed discussion of the laser Doppler velocimetry and laser induced fluorescence systems, refer to the measurement section (Sections 3.3 and 3.4).

5.0 TECHNOLOGY DEVELOPMENT REQUIRED

The various laser diagnostics system as described conceptually in Section 3.1 can provide valuable measurements of many parameters of interest relevant to combustion flames. These experimental systems are possible in principle, but the techniques of data acquisition and analysis needs to be developed for the precise measurement of these parameters. Moreover, these techniques are to be applied under microgravity conditions. Thus, it is important to establish a ground-based breadboard laser diagnostics system to develop the experiments and the system hardware for the Space Station research. This ground-based system could later be used for the analysis of data collected from the Space Station experiments.

Areas identified for further technology development activities include the following:

1. Doppler/Schlieren technique for the measurement of the velocity of particles and flames.
2. Use of fiber optics to simplify the system.
3. Holography: real-time analysis and temperature profile measurement.
4. M-Z interferometer: temperature profile measurement.
5. Laser Doppler Velocimetry: low velocity particle measurements, particle seeding, etc.
6. Laser Induced Fluorescense: species concentration measurements of various combustion flames.
7. Use of laser for the ignition of the fuel materials.

Each of the technology development areas is discussed further in the following paragraphs.

Schwar and Weinberg (Ref. 4) demonstrated that velocity measurements may be obtained by combining the Doppler principle with the Schlieren method. They tested this method experimentally in several forms, on a wide variety of experimental objects. These included moving gratings (radially ruled, 5600 lines rotated at speeds up to about 600 rpm, mean track diameter of about 10 cm), ultrasonic beams generated by a quartz crystal transducer, and flames (burner stabilized and made to move across the test space by a mechanical device). The range of velocities covered by these experiments extended from a few centimeters per second to the speed of sound.

Wyle has found no recent references to indicate that this subject has been developed further. Since the suggested laser diagnostics system contains a classical optical system with Schlieren, this problem would be studied with minimal additional capital investment. The advantage of this technique is that if the technique can be satisfactorily demonstrated for the combustion diagnostics in a breadboard system, the LDV system may be eliminated completely.

The use of fiber optics to simplify and enhance such a complex system is very compelling. However, there are a number of limitations in the current technology of fiber optics which need to be studied. In a M-Z interferometric system, where the beam collimation is of paramount importance, fiber optics is not normally used since the fragile nature of the fiber is likely to change the collimation of the beam. In addition, some of the following difficulties arise when using fiber optics in holography:

1. Changes in the polarization state occur in the fiber which may lead to a reduction in fringe visibility[2].
2. The power that can be satisfactorily transmitted by the fiber is limited.
3. Thermally induced phase shifts in the fibers blur the fringes during exposures.

These difficulties may be resolved as the fiber optics technology continues to develop. If the applicability of fiber optics in this system can be established, it would certainly simplify the system.

Interferometry and holography does not measure temperature directly, but provides the refractive index distributions. It is possible to deduce the temperature profiles from the refractive index distributions; however, a considerable effort is needed in the data acquisition and analysis of a complete data base.

Laser Doppler velocimetry may be used for the measurement of the velocity of particles and flame. In principle, it is possible to measure the velocity as small as micrometers per sec, but practically is it very difficult to achieve. Further effort is needed to establish the smallest velocity that could be measured and the seeding mechanism.

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[2] Single mode polarization-preserving fibers are available for NIR wavelengths. Special fibers for the visible region needs to be developed. The use of polarization-preserving fibers requires proper alignment, together with good linear polarization of the source.

Laser induced fluorescence is a very precise investigating technique for the measurement of species concentration in flames. There are well established procedures for the measurement of OH species concentration in combustion flames in ground-based laboratories. For many of the other species which are of interest, further research needs to be performed in order to establish a firm spectroscopic data base for the quantitative analysis of LIF data. These experiments need to be performed on the flames produced by the various materials and gases that would be investigated on the Space Station.

An entirely non-diagnostics application of lasers is the possibility of using focused laser beams to ignite the fuel materials in the chamber. As a method of achieving point ignition, the technique appears to offer a number of considerable advantages: The energy release occurs in an exceedingly short time (of the order of nanoseconds), over a very small volume, and is not associated with the proximity of electrode surfaces. It may be investigated further for use in the combustion tunnel and for other applications.

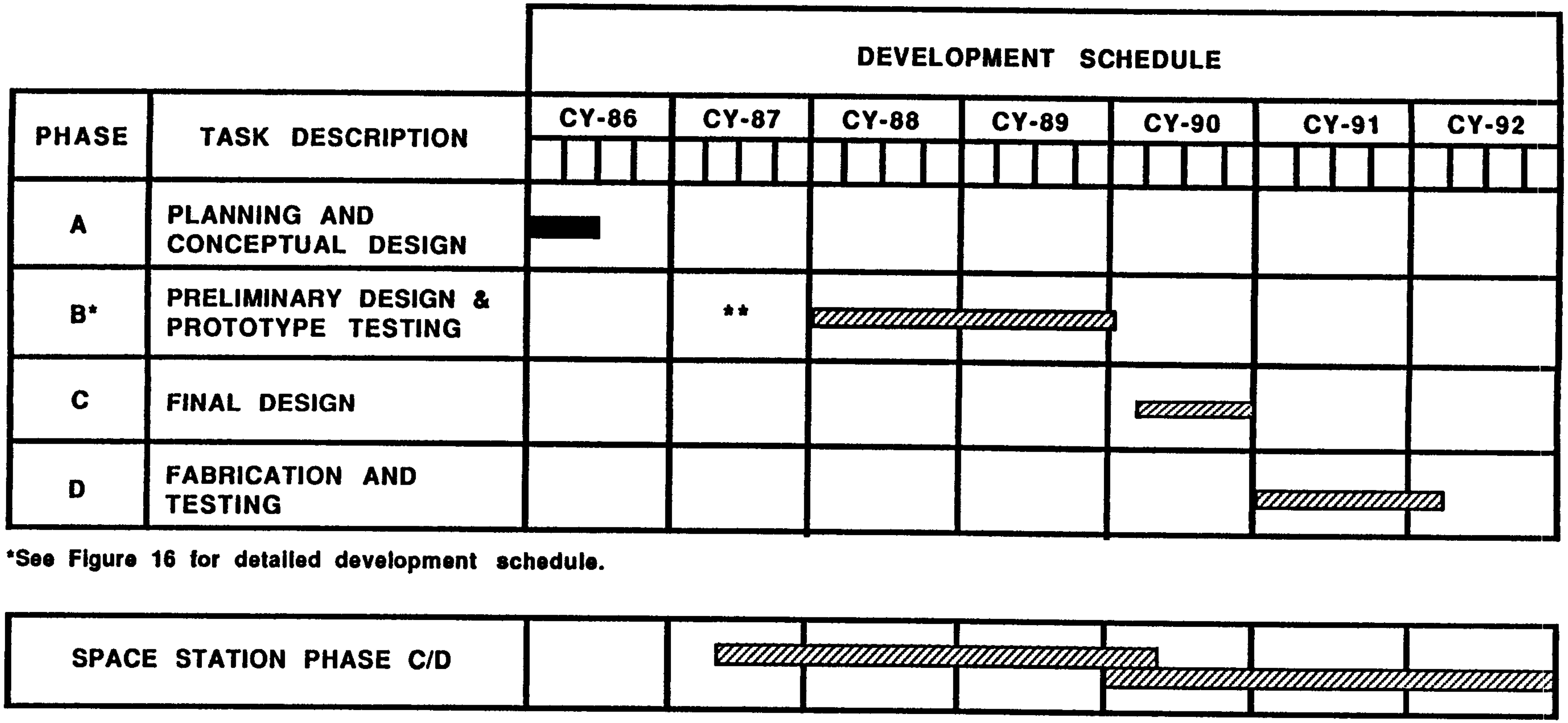
Each of the technology development areas previously discussed represent potential topics which will require further investigation, concurrent with the ground-based breadboard development task (Phase B). Cost estimates for these discrete technology development activities were not made.

6.0 GROUND-BASED SYSTEM DEVELOPMENT PLAN

The ground-based breadboard system development plan is broadly classified into four phases, A through D, and is projected as shown in Figure B-15. The concept design of the laser diagnostics system (Phase A) has been completed. Phases B includes the development of a breadboard system for the technology development and ground-based research. A brief discussion on the technology development activities is described in Section 5.

A detailed approach of Phase B given in Figure B-16 provides an estimate of the manhour requirements in developing the breadboard system and Table B-3 gives an estimate of the off-the-shelf equipment items required for the system development. The system may also be developed in two phases as mentioned in Table B-3. It is suggested that the complete system be flight tested in a low gravity environment by using KC-135 low gravity simulation aircraft. It may be mentioned here that the use of M-Z interferometry and holography in a low gravity environment has already been established (Ref. 22) and may not require any rigorous testing.

The final design (Phase C) would incorporate the results of the technology development activities and Phase D would be the development of the flight hardware for the Space Station. An estimate of two years would be required for the completion of these two phases.



*See Figure 16 for detailed development schedule.

** ADVANCED TECHNOLOGY DEVELOPMENT

FIGURE B-15. TOP-LEVEL LASER DIAGNOSTIC SYSTEM DEVELOPMENT PLAN

	TASK DESCRIPTION	ROUGH-ORDER-OF-MAGNITUDE MAN-HOUR REQUIREMENTS																														TOTAL BY TASK
	PHASE B. PRELIMINARY DESIGN & PROTOTYPE CONSTRUCTION/TESTING	CY-1988												CY-1989												CY-1990						
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	
B-1	BREADBOARD DESIGN	80	80	80	80																											320
B-2	ANALYTICAL RESOLUTION OF TECHNOLOGY DEVELOPMENT ISSUES	80	80	80	80																											320
B-3	HARDWARE PROCUREMENT AND FABRICATION					60	60	160	160	160	160																					760
B-4	BREADBOARD ASSEMBLY								60	60	60	60	60	60																		360
B-5	SOFTWARE DEVELOPMENT									100	100	100	100	100	100																	600
B-6	GROUND-BASED TESTING											100	100	100	160	160																620
B-7	SUB-ORBITAL FLIGHT TESTING																40	40	40	60	60	60	60	60	60							480
B-8	EXPERIMENTAL RESOLUTION TECHNOLOGY DEVELOPMENT ISSUES																160	160	160	100	100	100	100	100	100	160	160	160				1560
	TOTAL BY MONTH	160	160	160	160	60	60	160	220	320	320	260	260	260	260	160	200	200	200	160	160	160	160	160	160	160	160	160				5020

FIGURE B-16. LASER DIAGNOSTIC SYSTEM BREADBOARD DEVELOPMENT PLAN

TABLE B-3.
AN APPROXIMATE COST ESTIMATE OF A GROUND-BASED SYSTEM

1.	Lasers (Argon-ion, Nd: YAG and Nd: YAG pumped dye laser)	$ 78,800
2.	Data Analyzer System for LIF	52,000
3.	Data Analyzer for LDV	24,500
4.	Optics	31,700
		$187,000

This system may also be developed in two phases:

Phase I: Development of interferometry, holography and LDV.

Estimated off-the-shelf equipment cost:

Argon-ion Laser	$ 13,200
LDV	24,500
Optics	31,700
	$ 69,400

Phase II: Addition of LIF System.

Estimated cost:

Dye Lasers	$ 65,600
LIF	52,000
	$117,600

7.0 CONCLUSIONS

The concept design of a laser diagnostics system for the measurement of various parameters relevant to combustion flames in microgravity has been outlined in this report. The design consists of two separate systems (I and II): System I is the most complex of the two systems and includes the use of an interferometric system. As described herein, System I would be a very versatile system where all the desired measurements could be carried out in real-time. A reduction in the complexity of the system without loss of measurement flexibility may be carried out during the technology development stage.

In System II, the interferometric system is completely eliminated as compared to System I. Because of this, the real-time measurement of the temperature profiles and flame propagation may be difficult to achieve. Otherwise, both Systems I and II have the same characteristics. In comparison to System I, System II is much less complex and would not be difficult to accommodate in the Space Station.

The various components required for the establishment of a ground-based breadboard system were identified. This provided a preliminary estimate of the electric power requirements, weight, physical dimensions and costs required for the establishment of such a system. Some areas are identified which require extensive technology development in a ground-based breadboard system.

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CONCEPTUAL DESIGN
OF AN
ADVANCED MODULAR FURNACE

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OF AN ADVANCED MODULAR FURNACE

1.0 INTRODUCTION AND SUMMARY

One of the more promising areas concerning the utilization of the low gravity environment for research and potential commercialization deals with the study of the solidification process for various metals and alloys and the potential production in space of electronic materials. This area is presently being pursued onboard the Space Shuttle. However, the Space Station will provide a more appropriate environment for the continuation of such research and the eventual commercialization of material production. In order to pursue this work on the Space Station, new furnaces must be developed with capabilities that exceed our present furnaces.

The Electronic Materials Science Discipline Working Group for Microgravity Science and Applications identified the need for a modular furnace allowing rapid and easy reconfiguration for several different types of directional solidification experiments. An early definition of furnace requirements along with some operational parameters were presented in an earlier report by Wyle to LeRC (see ref. 1). The rapid turnaround time generated by this type of furnace is representative of the "GAS-can" approach that should be used by experiment designers wishing to utilize the Space Station.

Wyle has developed a conceptual design of an Advanced Modular Furnace (AMF). The intent of this report is to provide a set of concept ideas and identify design issues for a Space Station-based AMF. The AMF will allow reconfiguration for the following types of solidification experiments:

- Float Zone Solidification
- High Temperature Isothermal Solidification
- Crystal Growth (nonmetallic)
- Directional Solidification (metallic)

Technological developments required for the AMF are discussed in section 6.0, and an Engineering Development Plan for the AMF is presented in section 7.0.

2.0 OBJECTIVES

The primary objective of the Advanced Modular Furnace (AMF) concept is to provide a family of flight furnaces that have advanced operational capabilities and are designed in subsystem and system modules for easy reconfigurability. In the Space Station time frame, it will be necessary to have furnaces with the capabilities of processing samples from 2.0 cm to 10.0 cm in diameter at temperatures from 200°C to 2200°C (ref. 1 and 2). These furnaces must be configured for isothermal, gradient, and directional solidification modes with the capability of tailoring the thermal profiles in the sample and producing cooling conditions from slow, controlled rates to sample quench.

The design approach is to define the complete furnace system in terms of modules so that each furnace can be configured for a given set of compatible requirements by selecting and integrating the proper combination of modules. This allows one to establish the basis for a family of furnaces without the complexity and difficulty of attempting to develop only one furnace configuration that will satisfy a large number of users. The modular approach used in the AMF will be primarily at the subsystem level, i.e., modules to configure different operational types of furnaces. However, it is anticipated that this approach to modularity will eventually be expanded to the system level, i.e., reconfigurability from one type of experiment apparatus to another.

In addition to the primary objective of the AMF concept as described, it is important that the AMF support certain furnace technology development objectives. NASA's present furnace systems are not only few in number but are based, in most cases, on outdated technology since their development base is the pre-Space Shuttle era. It is important that new hardware take full advantage of past lessons learned, improvements in materials and electronics, and aim beyond immediate needs to include requirements for the Space Station era. Supporting objectives of the AMF in the technology development area therefore include

- Advancement of high temperature processing furnace technology to support the development of future materials processing apparatus.
- Development of rapid sample exchange concepts leading ultimately to autonomous, fully automatic materials processing systems.
- Development of subsystem modules demonstrating the ability to easily reconfigure furnaces to meet given sets of operational requirements.

- Demonstration of capability to process toxic samples in a manned environment. The need for this capability is discussed further in section 6.0.

3.0 METHODOLOGY

Continuous research in materials processing aboard the Space Station will require flexible, reconfigurable furnace systems that produce, for each sample material, a specifically required thermal environment. The operational requirements are achieved by appropriate design sensitivity in the materials selection, thermal modeling, and assembly and test of an engineering breadboard. However, to address the requirement for flexibility and reconfigurability, one must take a modular approach in the system engineering for each element of the various furnace systems required. Taking this approach, the AMF can be described through four major modular elements: 1) furnace assembly, 2) mechanical drive subsystem, 3) fluids subsystem, and 4) experiment control and data acquisition (ECDA) subsystem. The concept for these major modules is shown in Figure C-1. The furnace assembly, shown in Figure C-2, consists of the following:

- Furnace housing and cooling
- Insulation module
- Heater core module
- Cold block module
- Quench block module
- Thermal leveler
- Cold end temperature control module

The mechanical drive subsystem, shown in Figure C-3, is comprised of the following:

- Furnace drive
- Quench drive
- Sample insertion/retrieval
- Sample selection

The fluids subsystem, shown in Figure C-4, consists of the following:

- Coolant circulation system
- Coolant storage system

- Furnace environment
- Sample processing environment

The experiment control and data acquisition subsystem, shown in Figures C-5a and b, is comprised of the following:

- Thermal control system
- Mechanical drive control system
- Fluids control system
- Data acquisition

By satisfying the operational requirements for the Space Station through the design of compatible modules, one can expect to achieve the flexibility and reconfigurability necessary to support long-term research aboard the Station. The mix-and-match modularity of the AMF is shown in Figure C-6.

4.0 REQUIREMENTS ANALYSIS

Operational parameters for the Space Station-based Advanced Modular Furnace (AMF) have been established previously for various furnace configurations (ref. 1). These parameters, in conjunction with design constraints due to placement of this facility on the Space Station, have generated the design concepts presented herein. These operational parameters for two configurations of the AMF are shown in Table C-1 for comparison with the capabilities of the existing ADSF-II and the AADSF, which is under development, and the requirements for a current furnace under development--the Multiple Experiment Processing Furnace (MEPF).

The values of the parameters for the two AMF configurations shown in Table C-1 are not to be considered as the only values possible on the AMF. Other furnace configurations will be possible as a function of user requirements to be determined as the AMF progresses through development to fully utilize the modularity of the system.

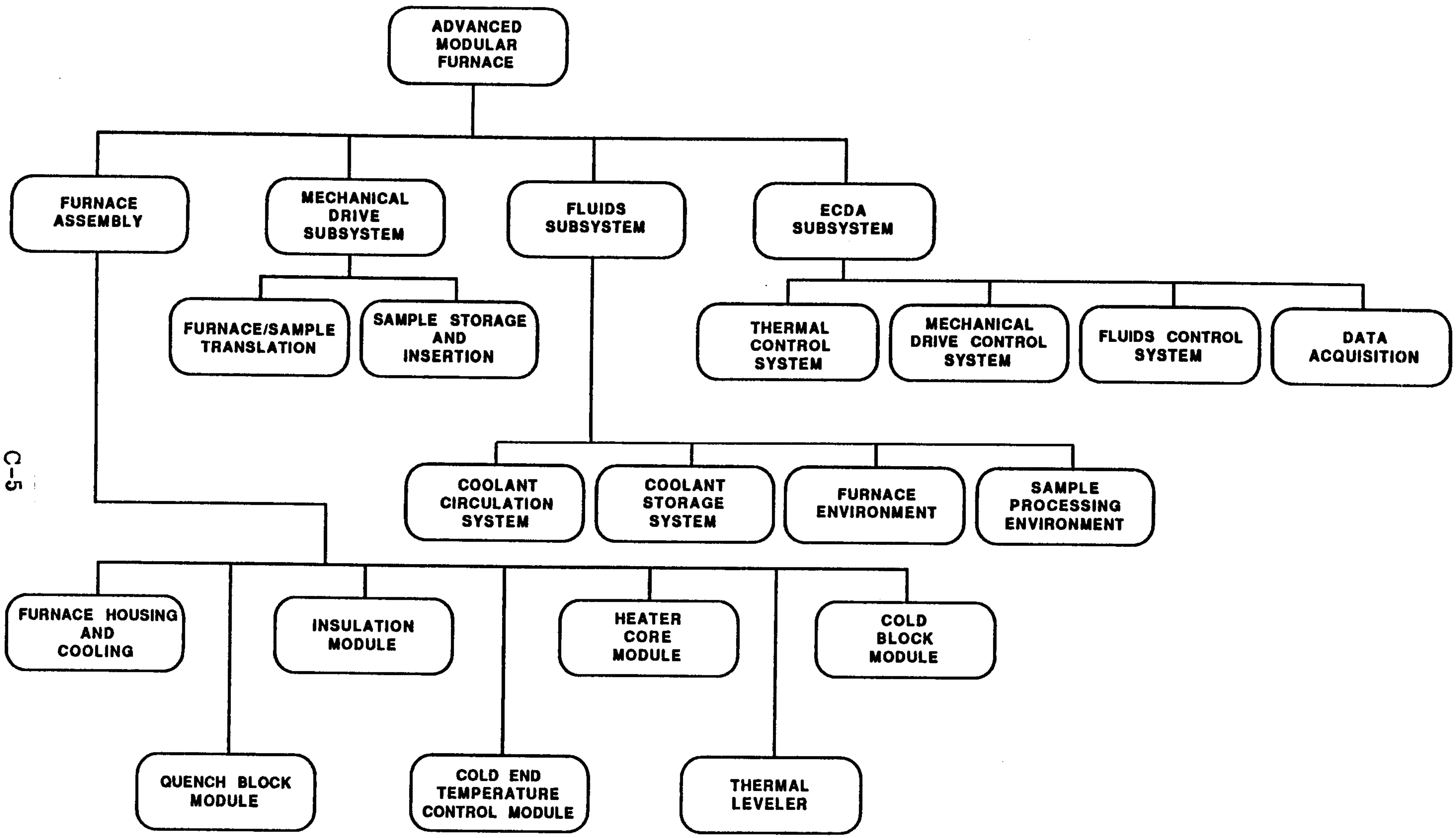


FIGURE C-1. ADVANCED MODULAR FURNACE (AMF) MAJOR SUBSYSTEMS

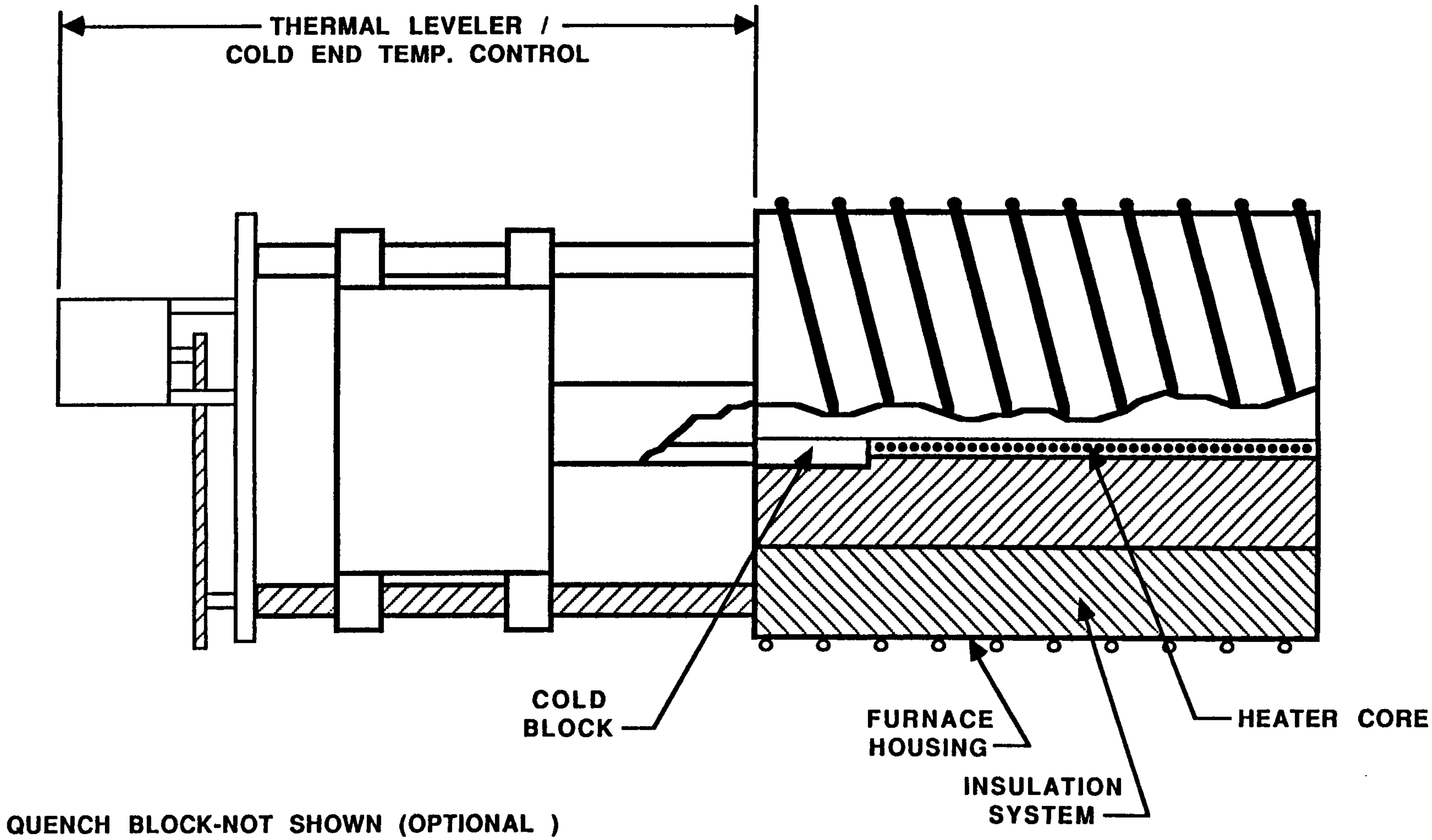


FIGURE C-2. AMF ASSEMBLY

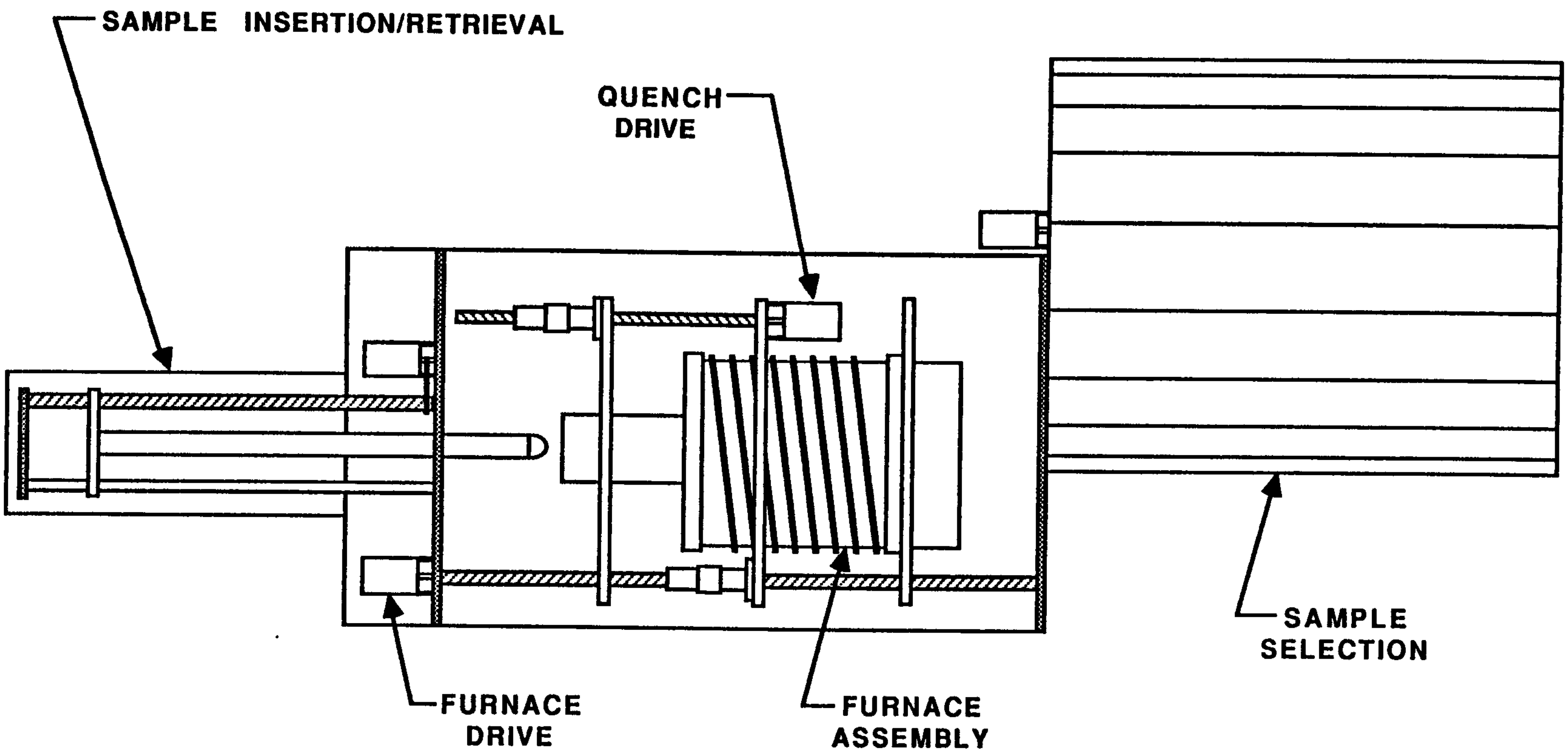


FIGURE C-3. AMF MECHANICAL DRIVE SUBSYSTEM

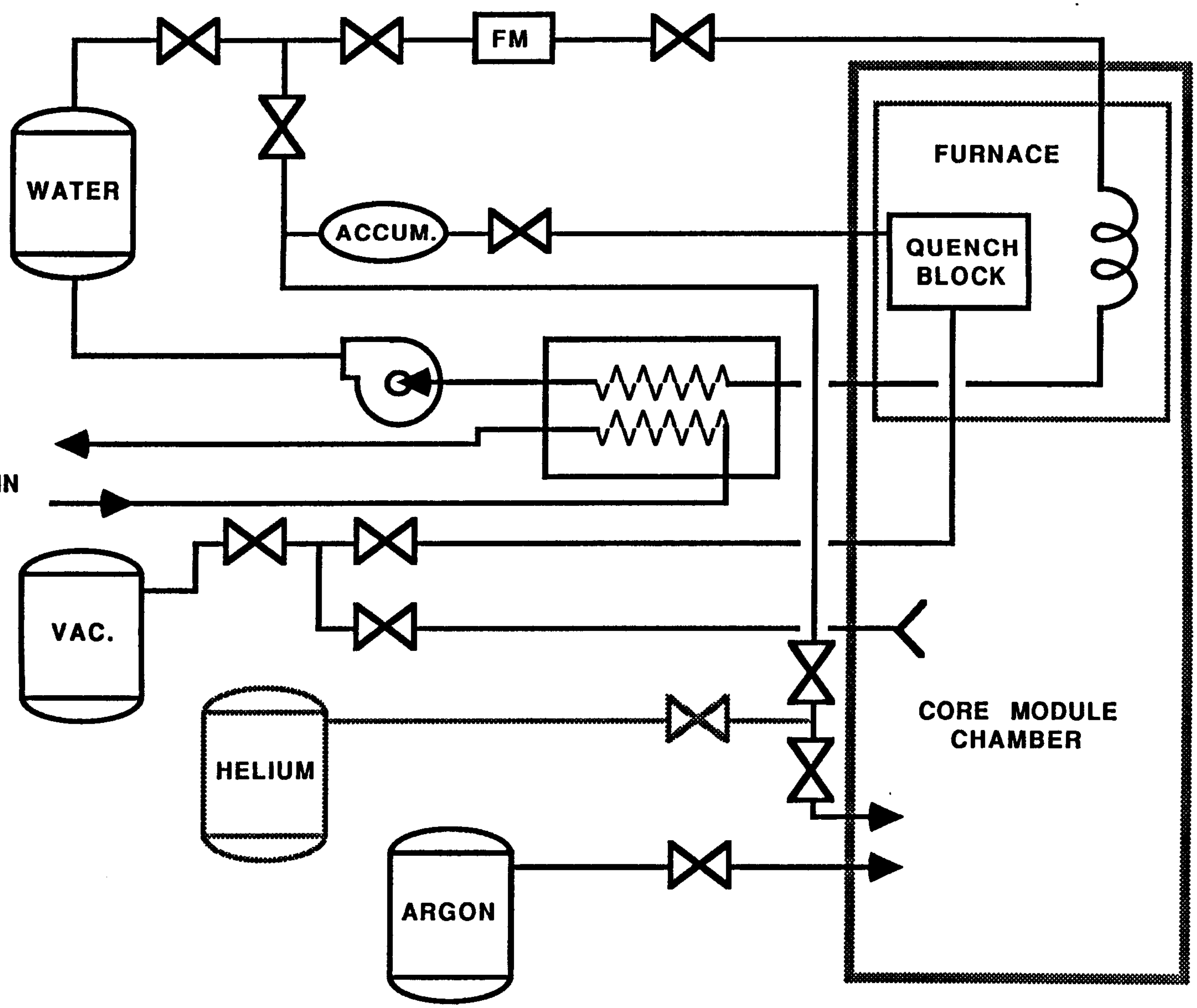


FIGURE C-4. AMF EXPERIMENT CONTROL & DATA ACQUISITION SUBSYSTEM-FLUIDS CONTROL

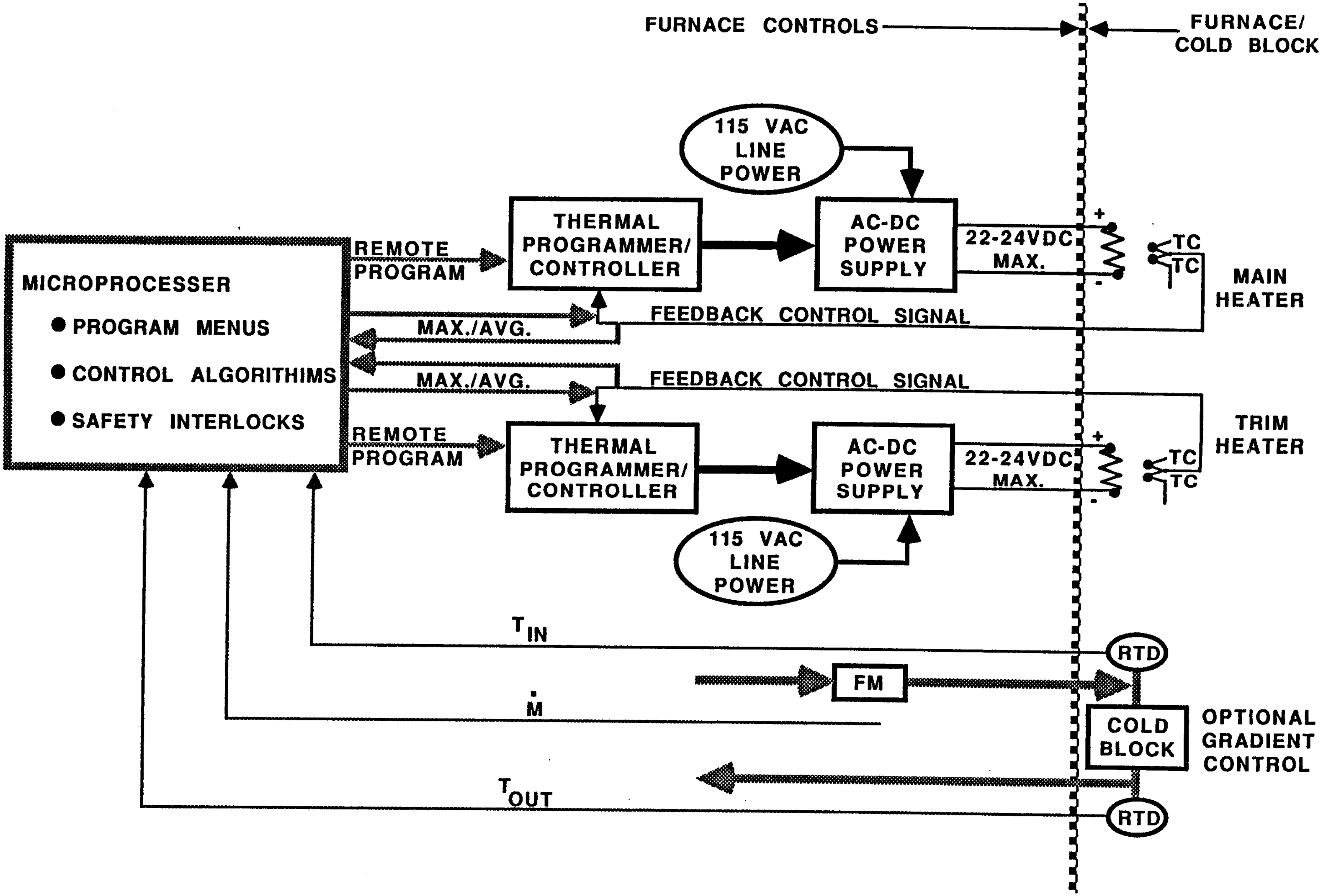


FIGURE C-5a. AMF EXPERIMENT CONTROL & DATA ACQUISITION SUBSYSTEM-THERMAL CONTROL

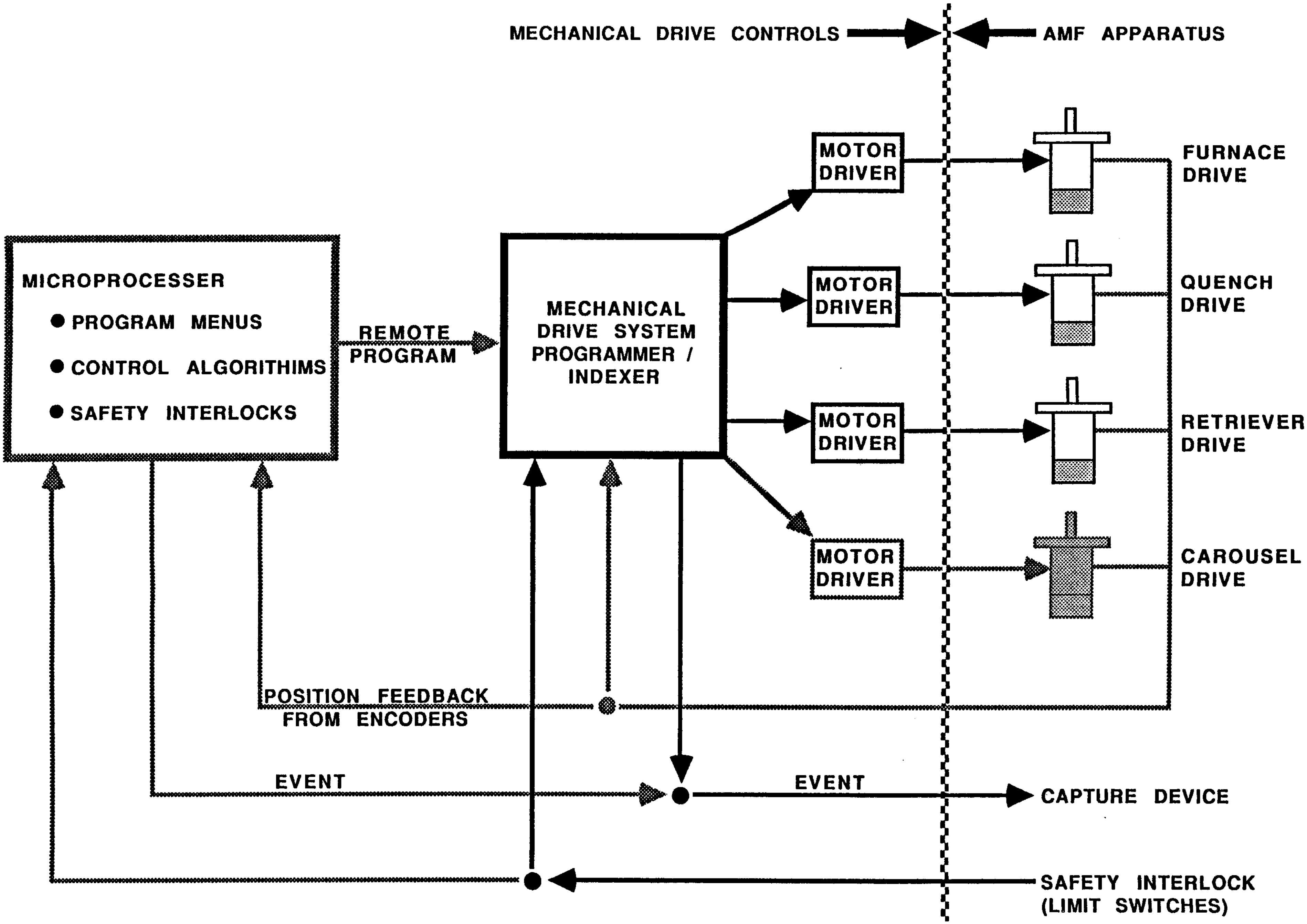


FIGURE C-5b. AMF EXPERIMENT CONTROL & DATA ACQUISITION SUBSYSTEM-MECHANICAL DRIVE CONTROL

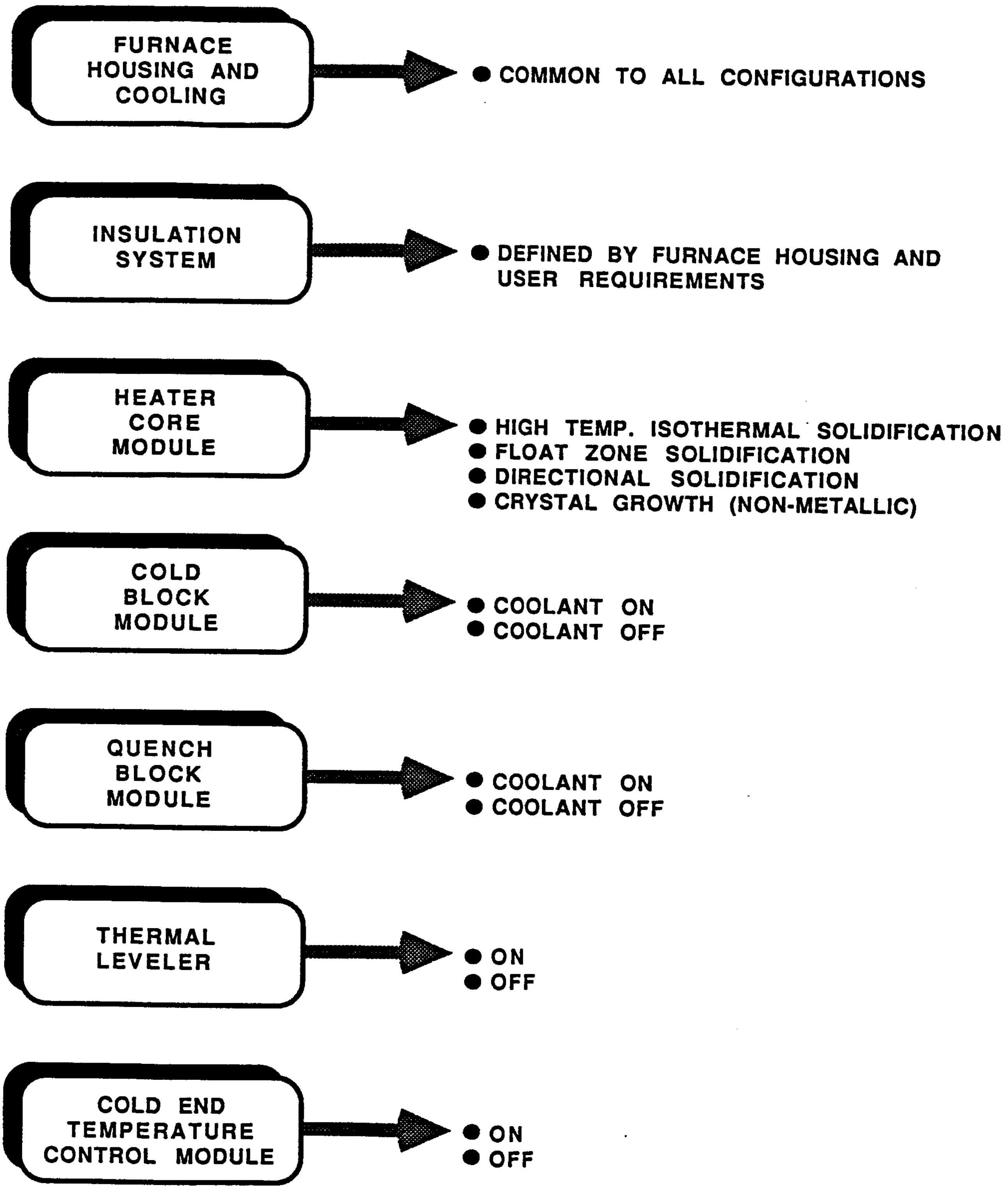


FIGURE C-6. AMF MODULARITY

TABLE C-1. COMPARISON OF FURNACE OPERATIONAL PARAMETERS

	ADSF-II	AADSF	MEPF	AMF (Metals and Alloys)	AMF (Semiconductors)
Sample size	0.6 cm	2 cm by 20 cm	2 cm by 8 cm	2 cm by 12 cm	2.5 cm by 20 cm
Number of samples/flight	4.0	1.0	Multiple (rapid changeout)	Multiple (rapid changeout)	Multiple
Sample exchange on orbit	No	No	Yes	Yes (semiautomatic and automatic)	Yes (automatic)
Operating temperature	$1600^{\circ}C$	$1100^{\circ}C$	$1600^{\circ}C$	$1600^{\circ}C$	$1200^{\circ}C$
Gradient	$300^{\circ}C/cm$	$900^{\circ}C/cm$	$100^{\circ}C-400^{\circ}C/cm$	$450^{\circ}C/cm$ in air $200^{\circ}C/cm$ in gray cast iron	$450^{\circ}C/cm$ in air
Quench rate	None	None	$300^{\circ}C/min$	$>300^{\circ}C/min$ (cast iron)	None
Transition to quench	—	—	1 sec	<1 sec (<0.1 g)	—
Accommodation environment	Unmanned	Unmanned	Manned	Manned or unmanned	Unmanned
Solidification traverse mode	Furnace	Sample	Unspecified	Furnace (primary) Sample (secondary)	Furnace (primary) Sample (secondary)
Solidification traverse rate	0.002 mm/min 8 mm/min	0.01 mm/min 1 mm/min	0.01 mm/min 10 mm/min	0 to 450 mm/min	0 to 450 mm/min
Sample temperature sensors	6/sample	—	6/sample	6/sample	6/sample
Thermal zones (heaters)	1	5	Unspecified	2 (1 main, 1 trim)	3 (1 main, 1 guard, 1 trim)
Furnace efficiency	?	?	Unspecified	60% (gray cast iron)	>60%

5.0 CONCEPTUAL DESIGN

The Advanced Modular Furnace (AMF), in keeping with the "GAS-can" concept of quick turnaround, will be designed to consist of four major modular elements. These are the following:

- Furnace assembly
- Mechanical drive subsystem
- Fluids subsystem
- Equipment control and data acquisition subsystem

The furnace will be designed so that each of these four elements can be easily reconfigured for a specific application. In the following sections, each of these elements will be discussed individually.

5.1 Furnace Assembly

To maintain the desired modularity of the AMF, the furnace assembly will consist of the following elements:

- Furnace housing and cooling assembly
- Insulation module
- Heater core module
- Cold block module
- Quench block module
- Cold end temperature control module
- Thermal leveler

Except for the furnace housing and cooling assembly, which will be common to all furnace configurations, each of these elements will be designed for quick changeout and/or replacement, as briefly described in the following sections.

5.1.1 Furnace Housing and Cooling

This will consist of a water-cooled outer shell with common power, thermocouple, and coolant connections which will ease furnace reconfiguration. Specific dimensions have not yet been determined.

5.1.2 Insulation Module

The insulation design will accommodate a heater module up to 7.6 cm in diameter and with operating temperatures up to 1600^{o}C inside the module. The end plates and outside shell of the insulation will be water cooled.

5.1.3 Heater Core Module

This assembly consists of the heater element(s), adiabatic zone, cold-end heat extraction/control, and support structure necessary to provide the required thermal profile in the sample. Configurations will include isothermal, gradient, directional solidification, quench, and gradient control, i.e., position and level. This module will be easily removable and may be provided by the user along with his specimen.

The AMF will have four basic configurations. These are the following:

- High temperature isothermal solidification
- Float zone solidification
- Directional solidification
- Crystal growth (nonmetallic)

Based on current practice, heating elements will probably consist of platinum/rhodium or tungsten/rhenium resistance heating wires wound around a ceramic core into which the sample cartridge is placed. Depending upon the configuration, a heater element might require up to four separate windings placed sequentially. Each of these would require separate controllers, and each should have at least two thermocouples for control feedback.

Development of these modules will require extensive thermal analysis. This will include selection of materials for sample, crucible, heater module, insulation, and design of all these, including the cold block module so that an accurate thermal profile in the sample can be determined. By varying these materials and designs in the thermal analysis, the most efficient furnace assembly for each of the four basic configurations can be achieved.

5.1.4 Cold Block Module

This assembly consists of a water-cooled copper chill block which acts as a heat sink and is located on the trailing end of the heater core module to effect directional solidification. The design of this module, if used, is to be determined by individual user requirements.

5.1.5 Quench Block Module

This assembly consists of a water or gas spray which actually quenches the sample during solidification. It, if used, would be located behind the cold block module on the trailing edge of the heater core module. The actual design of this module, as well as specification of the quench medium, is again to be determined by individual user requirements.

5.1.6 Thermal Leveler and Cold End Temperature Control Module

The cold end temperature control module is similar to the cold block module; however, it will also have a built-in heater so that the thermal gradient in a directionally solidifying sample can be altered without changing the melt temperature. This module, when used with the thermal leveler, will also allow for precise placement of the melt interface in a sample as well as control of the interface shape. Its design, if used, could also be altered somewhat based on individual user requirements.

5.2 Mechanical Drive Subsystem

As shown in Figure C-3, the AMF will actually have two mechanical furnace drives, one for slow translation of the furnace to effect directional solidification and a second for rapid translation of the furnace to effect high speed translation in the quench mode. The most distinguishing feature of this concept is the technique employed for achieving both slow and rapid translation using independent drive systems.

Both drives will use computer-controlled microstep motors. The advantage of using a microstep motor for the drives is the capability to preprogram acceleration, velocity, and position profiles for each furnace configuration as a function of time. In effect, this capability enables the drive motor to function both as a translator and as a brake although each drive will also have an independent braking system.

The quench drive is anchored between the middle drive plate (which in turn is driven by the furnace drive system) and the base furnace support plate. The middle drive plate is connected to the furnace through the quench drive head screw. This arrangement eliminates any need to adjust the quench drive to compensate for normal furnace translation while simultaneusly providing a capability to rapidly accelerate the furnace relative to the main furnace drive.

In addition to the two furnace drives, there will be separate drive systems for sample insertion/retrieval and rotation of the sample storage carousel. These also will be driven by computer-controlled microstep motors. Capture of samples by the retriever will be activated by a lock mechanism at the end of the retriever, which will allow the sample to be pulled into the furnace for processing and subsequently placed back into the sample storage carousel.

5.3 Fluids Subsystem

This system consists of all lines, tubing, valves, pumps, reservoirs, and heat exchangers used to remove heat from the cold end of the sample. In addition, vent lines for steam generated in the quench mode will be provided. Flow switches will be located throughout the system to initiate power shutdown if coolant flow should stop for some reason. Connections will be common so that each heater module installed can be quickly equipped with cooling capabilities.

In addition, both the furnace and sample processing environment will be controlled and monitored by this system. The furnace environment will consist of either air, or inert gas, or vacuum, while the sample processing environment could consist of the above gases or a number of others, depending upon user requirements.

5.4 Experiment Control and Data Acquisition (ECDA)

The ECDA will be a digital system easily reconfigurable with both software changes and plug-in board replacement or addition. It will be a personal computer-compatible system and contain sufficient storage for all housekeeping data as well as up to six thermocouples in the sample. It will not only control the normal experiment functions (thermal, mechanical drive, and fluids control) but will also provide for Peltier pulsing in the sample if individual users require it.

6.0 TECHNOLOGY DEVELOPMENT

The Advanced Modular Furnace is being conceptually designed to support a number of crystal growth and solidification experiments by reconfiguring the furnace through replacing modules. This approach, in concert with requirements for a wide range of temperatures ($200^{o}C$ to $2200^{o}C$), larger numbers of samples (10 to 100), and quench, will require technology development in several areas. These include (1) materials utilization, 2) furnace design, 3) mechanical drive system, and 4) sample insertion/ retrieval system.

6.1 Materials Utilization

The types of requirements being defined by the discipline working groups for future space experimentation call for operational temperatures and cooling rates that present problems for the types of materials presently used in furnace development and sample encapsulation. This suggests that materials for items such as heater windings, heater cores, insulation systems, and sample crucibles must be selected to withstand the hostile environment of higher temperatures and more rapid cooling rates. Not only will the material for the wire and core for the traditional wound resistance heating element need to be upgraded, it may also be prudent to evaluate solid heater elements such as machined graphite.

Quench rates of several hundred degrees centigrade per minute and greater will cause additional material problems with the present sample crucibles. Many of the presently used materials, such as graphite, will not take this thermal shock and will shatter. This is not a problem in normal gravity; however, different materials will be required for sample containment in microgravity. Also, many samples will need to be instrumented for temperature measurements. Therefore, smaller thermocouples, compatible with the sample melt, will be required.

6.2 Furnace Design

Based on available technology, most current directional solidification furnaces are somewhat outdated. Hence, there are a number of elements that should be pursued as part of a technology development program culminating in concept verification through test. Some of these elements are discussed further in the next few paragraphs.

The most complex furnace available today offers three separate heaters (main, trim, and cold block heater). Allowing for multizone heaters while maintaining the high level of modularity desired poses a challenge to engineers and scientists who wish to accurately control melt temperature profiles and thermal gradients in the sample. This can also be accomplished through better adiabatic barrier design to achieve more ideal adiabatic conditions.

Most of the current directional solidification furnaces do not utilize any type of cold end thermal control. This feature, if developed, allows very precise solidification front positioning and gradient control as well as control of interface shape.

Other areas of furnace design that require further technological development include design of insulation assemblies for maximum thermal efficiency, cold block design to effect closed-loop gradient control, quench block design to achieve effective sample quenching, development of magnetic damping and Peltier pulsing techniques, and development of high-temperature (greater than or equal to 1600°C) heat pipes.

6.3 Mechanical Drive

The drive system necessary for directional solidification should have a large operational range and impart no unwanted effects on the growing material. Many systems to date employ linear motors driving through gear trains. These systems require motor and/or gear assembly changes in order to provide the desired operational range. Development work utilizing digitally controlled motors should be undertaken to verify their range of usefulness in directionally solidified materials.

6.4 Sample Insertion/Retrieval

The need exists to operate furnaces in modes ranging from semiautomatic (i.e., one sample at a time manually positioned and automatically processed) to fully automatic (i.e., samples automatically positioned, processed, and retrieved). An automatic sample insertion/retrieval system should be developed such that one basic design allows both the semiautomatic and fully automatic modes to be employed without redesign.

6.5 Provisions for Toxic Samples

It will sometimes be desirable to process toxic samples in the AMF (directionally solidified Ni-C eutectic alloys, for example). Design of the AMF must take this into account, and the technology must be developed to allow processing of these samples in a low-g environment. This development could range from venting the furnace cannister outside the spacecraft to design of sealed sample cartridges.

7.0 AMF DEVELOPMENT PLAN

The objective of this section is to provide a preliminary development plan for the AMF. Included in this is a timeline for AMF development which will provide for a completed flight-qualified furnace at about the expected date for Space Station completion.

The scope of this project consists of four major phases as follows:

A — Planning and Conceptual Design

B — Preliminary Design and Prototype Construction/Testing

C — Final Design

D — Fabrication and Testing

Each of these phases is divided into tasks as shown in Figure C-7.

7.1 Phase A, Planning and Conceptual Design

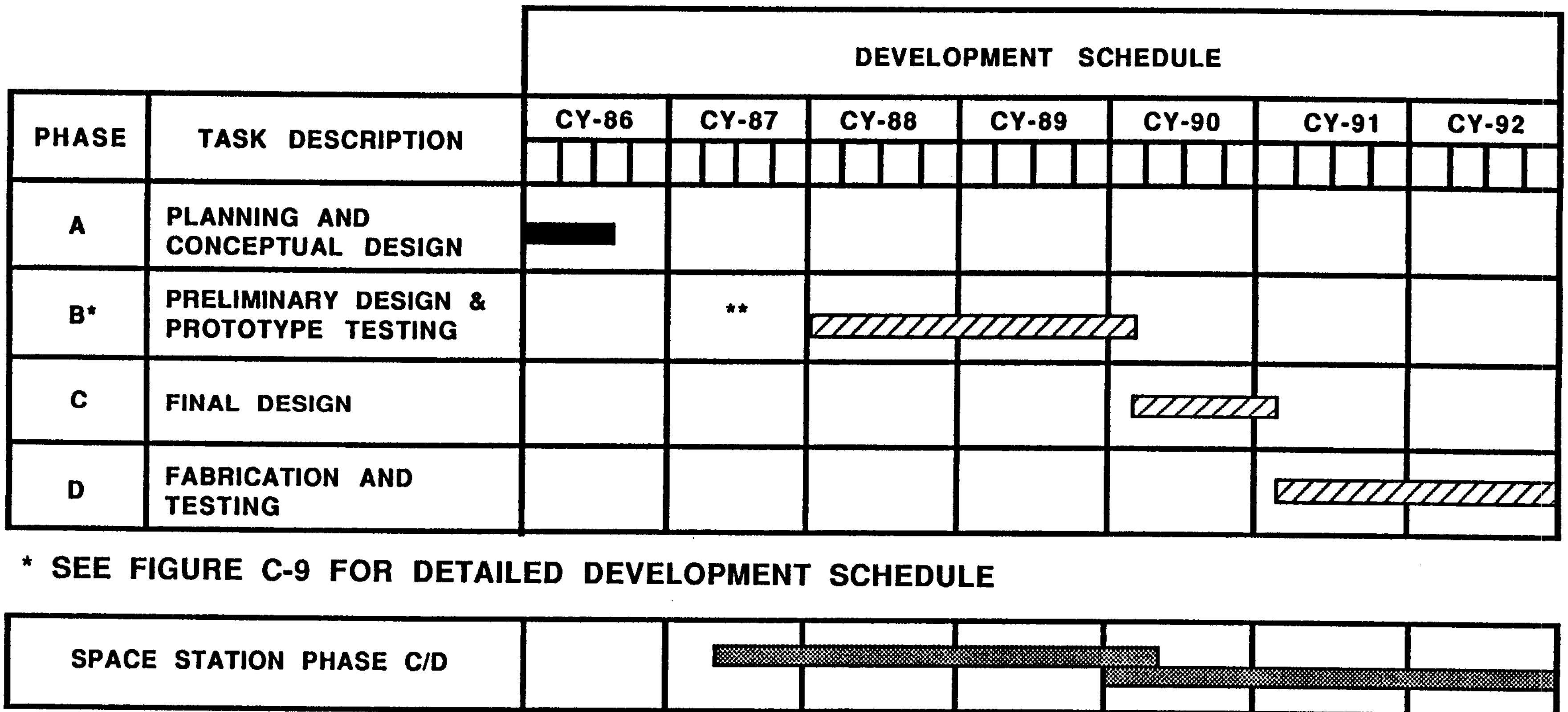
Phase A consists of two separate but interactive tasks associated with the general planning for the AMF. The first of these is to define user requirements for microgravity science and applications research on board the Space Station. This was completed under NASA LeRC contract No. NAS3-24654, "Accommodation Requirements for Microgravity Science and Applications Research on Space Station," in December 1985. The second of these tasks, the preparation of conceptual designs for various flight hardware, is included in this document, also prepared under NASA LeRC contract No. NAS3-24654. A top-level time schedule for development of the AMF concept, indicating that phase A is complete at this time, is shown in Figure C-8.

7.2 Phase B, Preliminary Design and Prototype Construction/Testing

Phase B consists of eight individual tasks associated with the preliminary design and development of the AMF. A detailed breakdown and schedule for individual tasks are

PHASE A: PLANNING AND CONCEPT DESIGN (COMPLETE)
A-1: USER REQUIREMENTS A-2: CONCEPT DESIGN
PHASE B: PRELIMINARY DESIGN AND PROTOTYPE CONSTRUCTION / TESTING
B-1: BREADBOARD DESIGN B-2: ANALYTICAL RESOLUTION OF TECHNOLOGY DEVELOPMENT ISSUES B-3: HARDWARE PROCUREMENT AND FABRICATION B-4: BREADBOARD ASSEMBLY B-5: SOFTWARE DEVELOPMENT B-6: GROUND-BASED TESTING B-7: SUB-ORBITAL (KC-135) TESTING B-8: EXPERIMENTAL RESOLUTION OF TECHNOLOGY DEVELOPMENT ISSUES
PHASE C: FINAL DESIGN
C-1: FLIGHT UNIT DESIGN C-2: CONFIGURATION MANAGEMENT C-3: VERIFICATION C-4: DESIGN REVIEW
PHASE D: FABRICATION AND TESTING
D-1: FABRICATION AND ASSEMBLY D-2: FINAL SOFTWARE PREPARATION D-3: VERIFICATION D-4: ACCCEPTANCE REVIEW D-5: GROUND TESTING (MTL MOCK-UP) D-6: MTL MISSION

FIGURE C-7. AMF DEVELOPMENT PHASE BREAKDOWN



** ADVANCED TECHNOLOGY DEVELOPMENT PERIOD

FIGURE C-8. TOP-LEVEL ADVANCED MODULAR FURNACE DEVELOPMENT PLAN

shown in Figure C-9. An estimation of time-phased labor distribution is also shown and labor requirements are presented for each month of the period of performance. These eight tasks lead to and include the design, fabrication, and KC-135 flight testing of a prototype (breadboard) AMF. The KC-135 was chosen for low-g flight tests because of its accessibility, low relative cost, and size. A full-scale AMF could easily be tested during KC-135 flight. Not only would this allow for AMF testing but also training of personnel who use the AMF, all in a low-g environment.

Tasks B-1 and B-2 include the design of a breadboard unit and analytical resolution of technology development issues that may arise during the design stage. This approach will identify and solve many design problems before they reach the machine shop. Tasks B-3 and B-4 involve the procurement of hardware, fabrication, and assembly of the breadboard unit. Task B-5 is the development of all software used to control the AMF. This will include thermal control, mechanical drive control, fluids control, and data acquisition. Tasks B-6 and B-7 involve testing of the AMF breadboard unit, both on ground and in KC-135 suborbital flights. Finally, task B-8 is the experimental resolution of technology development issues that may arise during the ground and KC-135 flight testing of the AMF.

7.3 Phases C/D, Final Design and Fabrication and Testing

Phase C consists of four distinct tasks associated with the final design of a flight-qualified AMF. These tasks include the actual design of a flight unit (based on results of prototype ground and KC-135 flight tests), configuration management during these phases to allow for rapid identification and resolution of both management and technical issues, verification of final flight unit design, and a final design review.

Phase D consists of six tasks associated with the fabrication, assembly, verification, and testing of the flight-qualified AMF. The first two tasks include the fabrication and assembly of the flight unit and final software preparation for the flight unit. After final verification and acceptance review (tasks D-3 and D-4), the final two tasks in phase D include ground testing in the Manufacturing and Technology Laboratory (MTL) test bed and, finally, an orbital MTL mission. The cost of phases C/D implementation has yet to be determined because of the unknown extent of necessary redesign and labor costs that may accrue at that time.

TASK DESCRIPTION		ROUGH-ORDER-OF-MAGNITUDE MAN-HOUR REQUIREMENTS																														TOTAL BY TASK
PHASE B. PRELIMINARY DESIGN & PROTOTYPE CONSTRUCTION/TESTING		CY-1988												CY-1989												CY-1990						
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	
B-1	BREADBOARD DESIGN	300	300	600	600	300	300																									2400
B-2	ANALYTICAL RESOLUTION OF TECHNOLOGY DEVELOPMENT ISSUES	200	200	100	100	100																										700
B-3	HARDWARE PROCUREMENT AND FABRICATION				200	200	200	200	400	400	400	200	200	200																		2600
B-4	BREADBOARD ASSEMBLY								200	200	200	200	200	200																		1200
B-5	SOFTWARE DEVELOPMENT	100	100	100	200	200	200	100	100	100																						1200
B-6	GROUND-BASED TESTING														200	200	200	200	200	200												1200
B-7	SUB-ORBITAL (KC-135) FLIGHT TESTING																				200	200	200	200	200	200						1200
B-8	EXPERIMENTAL RESOLUTION TECHNOLOGY DEVELOPMENT ISSUES														100	100	100	200	200	200	200	200										1500
TOTAL BY MONTH		600	600	800	1100	800	700	300	700	700	600	400	400	400	300	300	300	400	400	400	400	400	200	200	200	200						12000

FIGURE C-9. ADVANCED MODULAR FURNACE BREADBOARD DEVELOPMENT PLAN

8.0 REFERENCES

1. "Accommodation Requirements for Microgravity Science and Applications Research on Space Station." NASA CR 175038, Wyle Laboratories, December 1985.

2. MMPF Study Data Release, MMPF Study Contract No. NAS8-36122, June 30, 1986.

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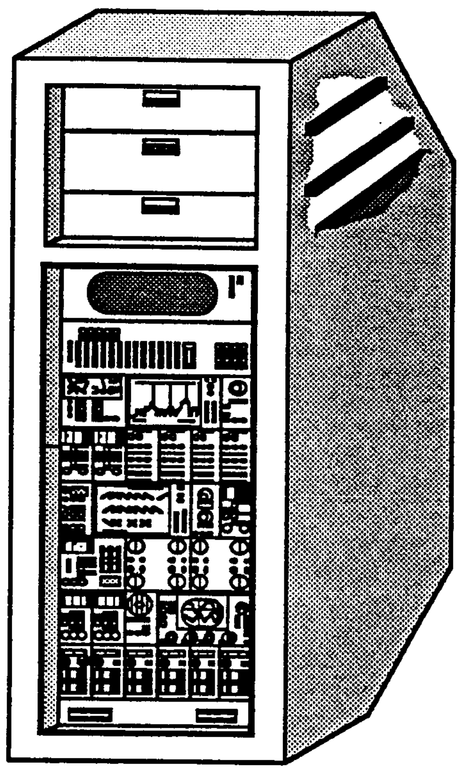
CONCEPT DESIGN
of an
INTEGRATED ELECTRONICS LABORATORY
for
SPACE STATION

September 1986



WYLE LABORATORIES

Task 2
Contract No. NAS3-24654
NASA/Lewis Research Center

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INTRODUCTION

The Integrated Electronics Laboratory (IEL) concept represents a potential item of payload support equipment which could be used to isolate, identify, and correct electrical and electronic failures occuring in a payload complement located on the Space Station. The IEL system concept provides for both diagnosis and repair of payload electrical malfunctions during the on-orbit period of the mission. The system objective is to minimize equipment downtime on-orbit and avoid mission aborts which could result from equipment electrical failure. In meeting this objective, the IEL concept serves to enhance research productivity by ensuring continuous operation of the laboratory.

Functional requirements for the IEL were identified through numerous discussions with potential laboratory users and experienced payload specialists. These requiremnents were documented in the Task 1 report (NASA CR-175038). The need for electrical diagnostic and repair techniques on-orbit was a common concern among all investigators contacted during the Task 1 effort.

1.0 METHODOLOGY

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Continuous basic and applied research aboard the Space Station will require flexible, reconfigurable facilities which cannot be produced with dedicated-apparatus design philosophies. Such a Strawman Approach addresses worst-case requirements without considering a cross-section, leading to systems that operate well at performance extremes but exhibit suboptimal performance in median cases. The converse Functional Approach surrounds a requirements cross-section to yield systems which are optimal for the average case and incrementally less responsive toward the extremes. These approaches are contrasted in Figure 1.

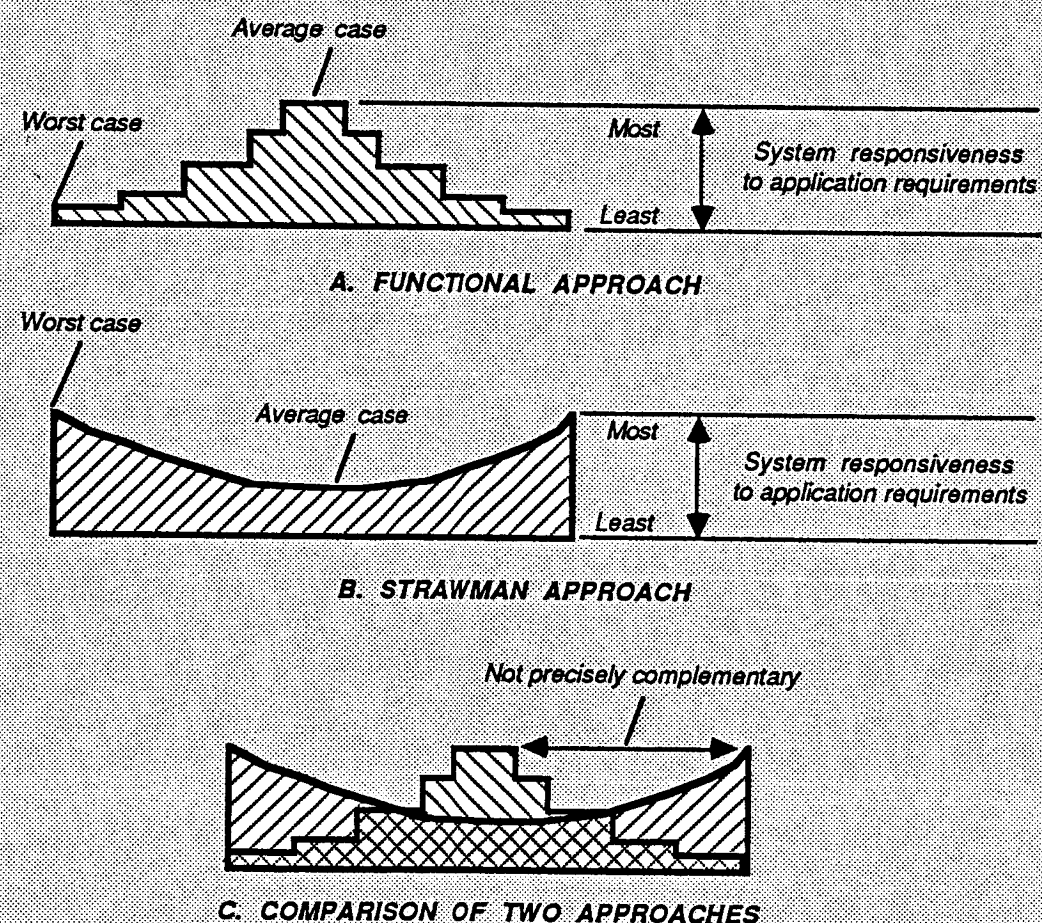

FIGURE D-1 *COMPARISON OF FUNCTIONAL AND STRAWMAN APPROACHES TO FACILITY DESIGN*

While the two approaches are not precisely complementary, they can be combined into a more comprehensive requirements set by forcing the functional requirements toward artificial extremes beyond the expected performance range. This Combined Approach is diagrammed in Figure 2. Where requirements must be tailored to fit station and program constraints, artifical requirements may be removed as shown below. Additional trimming may be accomplished, if necessary, by reducing the overall "fit" between system and application in small increments. The resultant system is considerably more responsive to application requirements over the desired performance range without loss of flexibility.

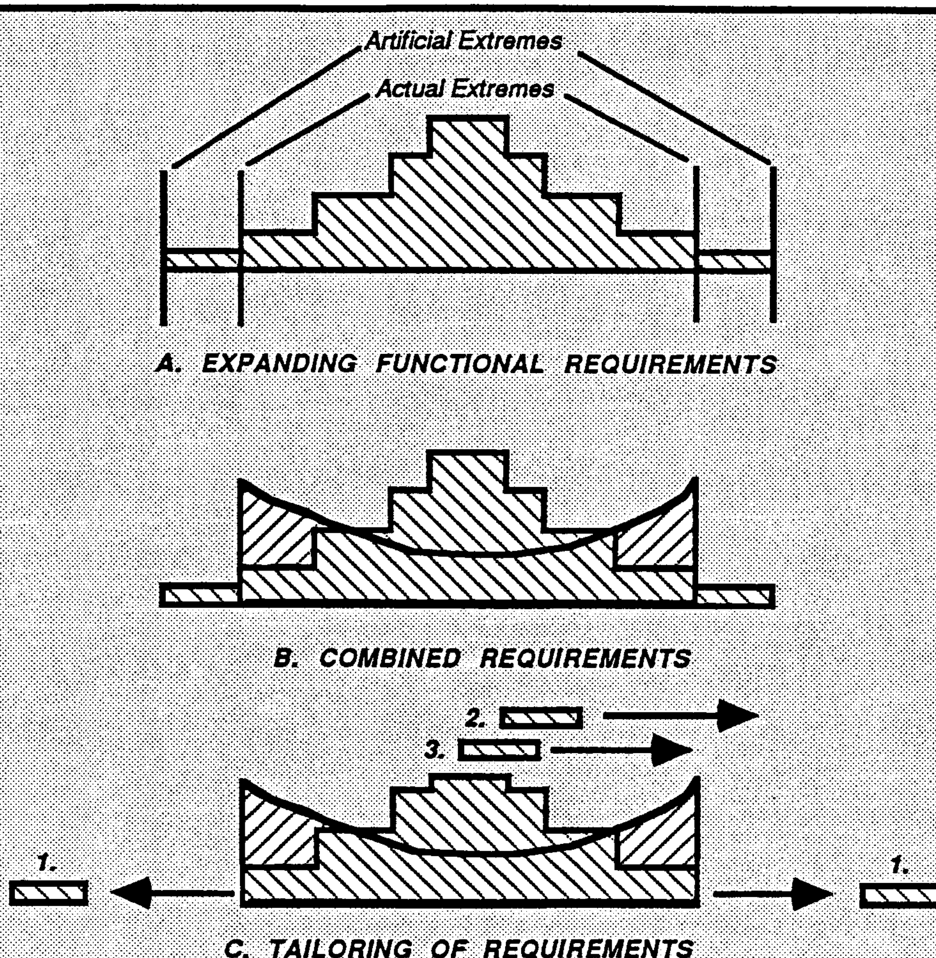

FIGURE D-2 *COMBINED APPROACH TO FACILITY DESIGN*

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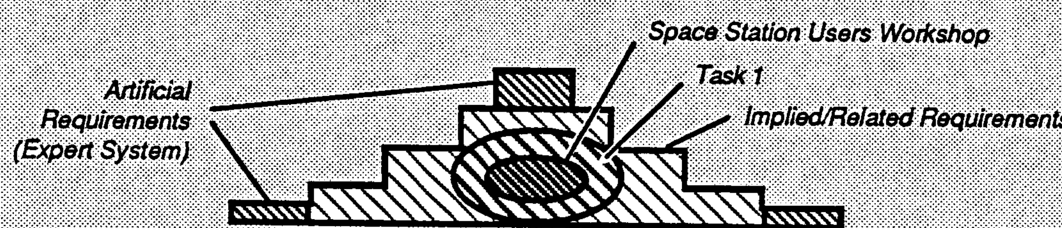
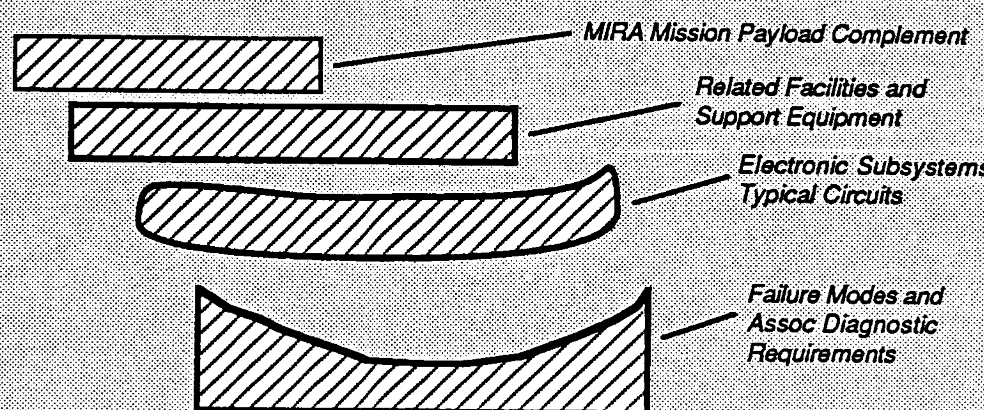
1.1 Formulation of Requirements

The Mission Payload Complement defined under the Mission Integration Requirements Analysis (MIRA) Study September 1985 Space Station Customer Accomodation Plan [1] is the basis of strawman requirements. Facilities and support equipment identified therein were distilled down to electronic subsystems. Functional requirements were seeded with data from the December 1984 Space Station Users Workshop [6] and from the Interim Report for Task 1 [57] of the current contract.



A. FUNCTIONAL REQUIREMENTS BUILDUP



B. STRAWMAN REQUIREMENTS BUILDUP

FIGURE D-3 *FORMULATION OF FUNCTIONAL AND STRAWMAN REQUIREMENTS*

1.2 Requirements Analysis

MIRA experiment facilities and equipment were reduced through electronic subsystems into typical circuits, estimated to converge on IOC requirements. Failure modes for these circuits were matched to appropriate diagnostic techniques from which three complements of suitable diagnostic instrumentation were specified. Functional needs expressed by the user community were incorporated along with any implied peripheral capability. Figure 4 illustrates the requirements analysis process.

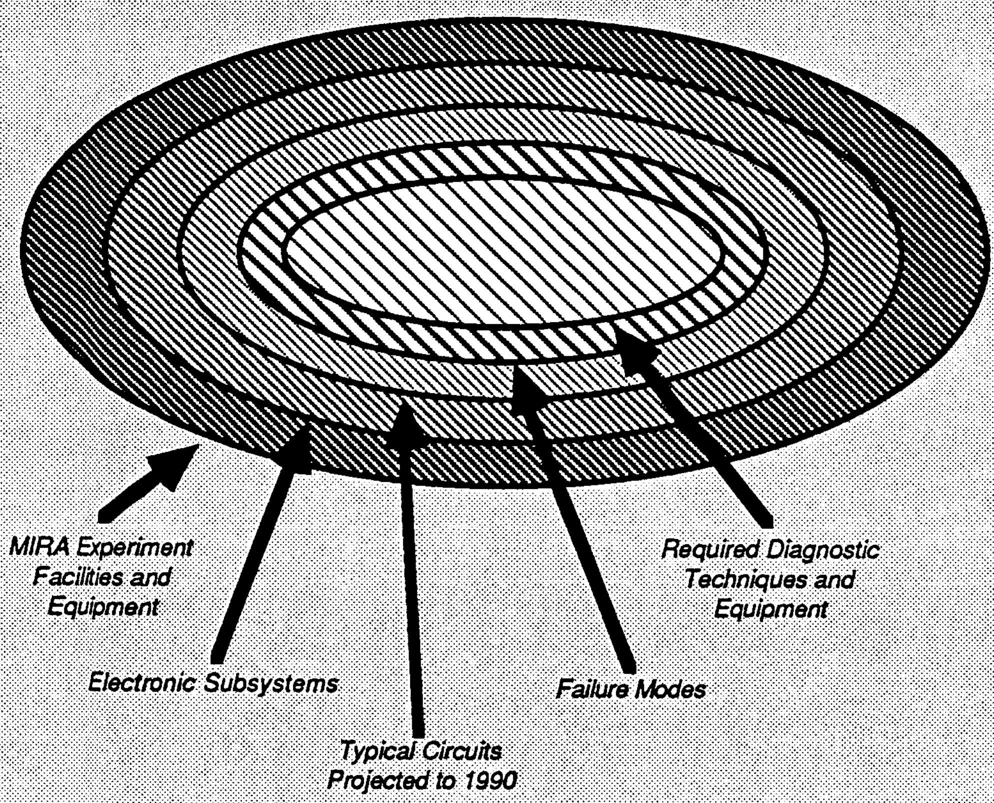


FIGURE D-4 ***REQUIREMENTS ANALYSIS***

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1.3 Concept Analysis and Evaluation

Each complement of diagnostic equipment was structured into a candidate laboratory configuration. Macintosh MacProject ® was used to develop an integral engineering development plan, development schedule, and baseline cost estimate. The candidate laboratory configurations and analysis results were compared in a decision matrix The engineering analysis and design process is diagrammed by Figure 5. A comprehensive design flow is given in Figure 6.

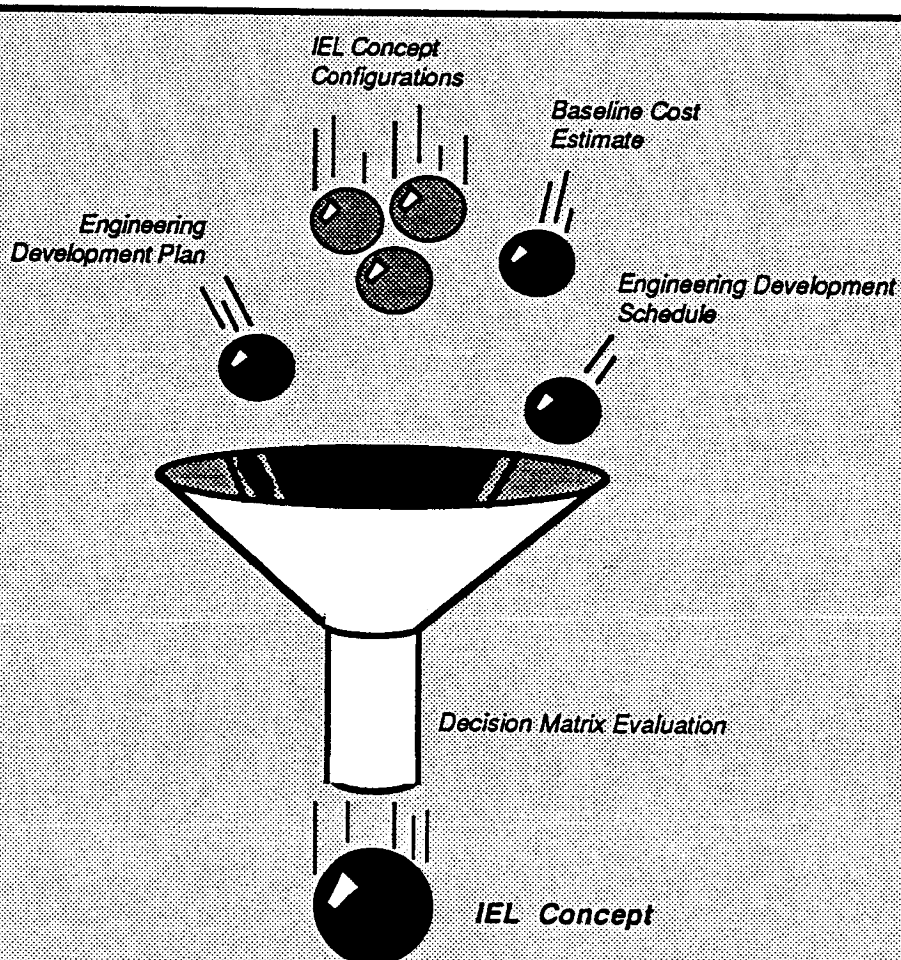

FIGURE D-5 ***CONCEPTUAL DESIGN ANALYSIS***

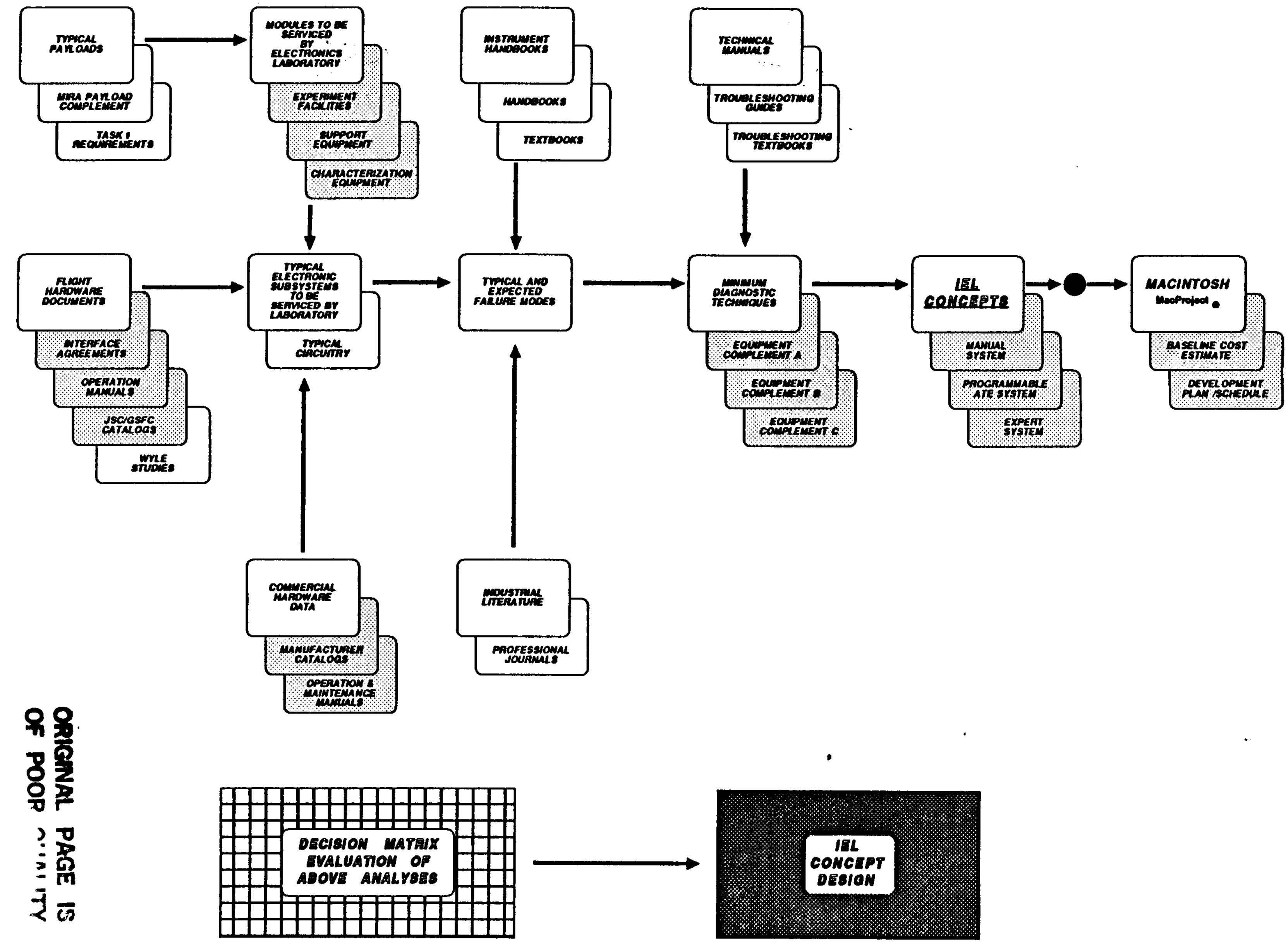

FIGURE D-6 *COMPREHENSIVE CONCEPTUAL DESIGN FLOW*

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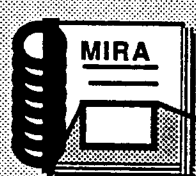
2.0 REQUIREMENTS ANALYSIS

2.1 Strawman Mission

The Mission Payload Complement defined under the MIRA September 1985 Customer Accommodation Plan (1) forms the requirements strawman for this analysis. The eight experiments identified in this strawman (Figure 7) are assumed to represent a typical Space Station MMPF complement at a given time. It is understood that the MMPF is intended to be highly reconfigurable, and that the payload complement at a given time cannot be anticipated at this time. The complement of experiment facilities and characterization equipment may vary considerably from this assumed complement. However, it is believed that the set of electronic subsystems and the circuits they contain are a fair representation of the expected MMPF complements.



MIRA MISSION PAYLOAD COMPLEMENT

1. Continuous Flow Electrophoresis
2. Protein Crystal Growth
3. Droplet Burning
4. Directional Solidification
5. Isothermal Solidification
6. Vapor Phase Crystal Growth
7. Monodisperse Latex Spheres
8. Acoustic Containerless Processing

FIGURE D-7 *MIRA MISSION PAYLOAD COMPLEMENT*

2.2 Facilities and Support Equipment

The MIRA Mission Payload Complement requires 55 unique equipment items, including 8 experiment facilities, 28 support equipment units, and 22 characterization equipment units. Twenty-two items contain no significant electronics, while 6 cannot be adequately described. Twenty-seven facility/equipment items in the complement rely on major electronic subsystems for which definitive specifications are available. This process of elimination is diagrammed in Figure 8. The distribution of these 27 relevant equipment items across the Payload Complement is illustrated in Figure 9.

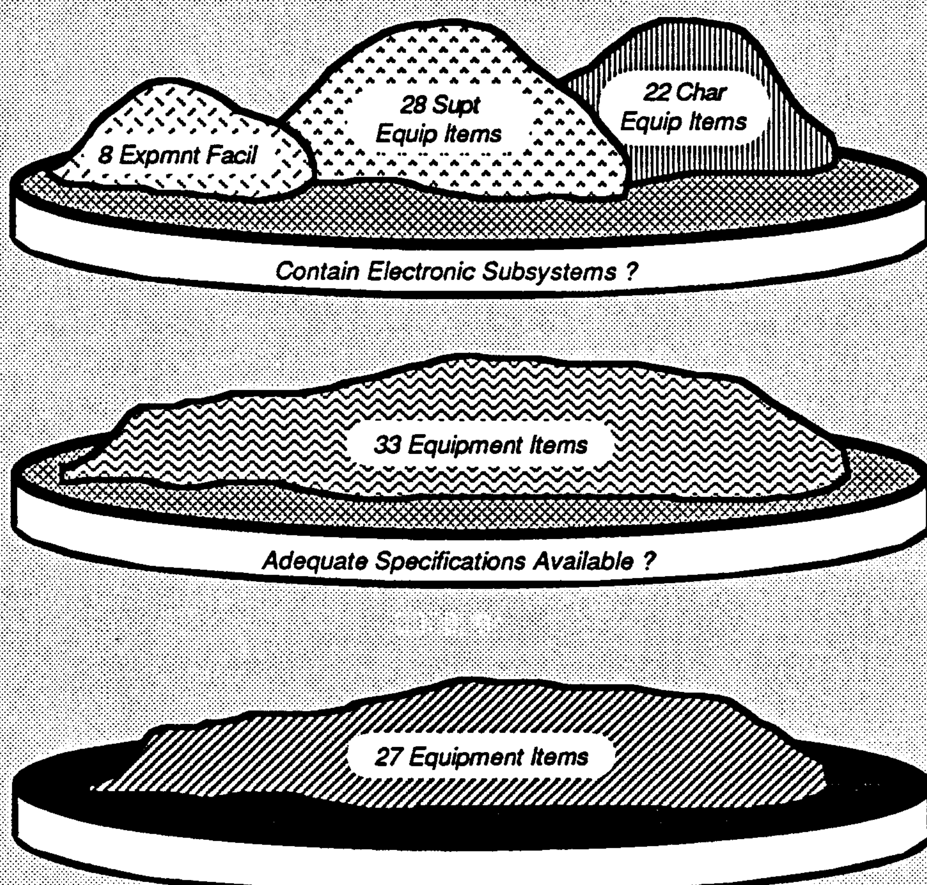


FIGURE D-8 ***FILTERING OF STRAWMAN REQUIREMENTS***

MIRA PAYLOADS \ RELEVANT EQUIPMENT ITEMS	Acous Cont Exp System (ACES)	3-Axis Recording Accelerometer	Automated Cutting/Polishing Unit	Cutting/Forming Facility	Data Recording Unit	Differential Scanning Calorimeter	Digital Multimeter	Digital Recording Oscilloscope	ADSF	Electrical Conductivity Probe	CFES	Fourier Infrared Spectrometer	Gas Chromatograph	HP Liquid Chromatograph	GPRF	Monodisperse Latex Reactor	Mass Measurement System	Mass Spectrometer	Master Computer	Optical Refractometer	SEM	Sputtering Deposition Unit	Ultracentrifuge	UV/VIS/NIR Spectrometer	VCGS (FES)	Video Facilities	X-Ray Topography Unit
Continuous Flow Electrophoresis		●			●		●	●			●			●					●				●			●	
Protein Crystal Growth					●	●											●		●							●	
Droplet Burning		●			●		●	●					●					●	●							●	
Directional Solidification			●	●	●				●	●		●					●		●							●	●
Isothermal Solidification		●	●	●	●		●	●							●				●							●	
Vapor Phase Crystal Growth		●	●	●	●					●		●					●		●						●	●	
Monodisperse Latex Spheres																●			●								
Acoustic Containerless Processing	●	●	●		●	●	●	●									●		●	●	●	●		●		●	

FIGURE D-9 *RELEVANT PAYLOAD EQUIPMENT VS. MIRA PAYLOAD COMPLEMENT*

2.3 Electronic Subsystems

Typical electronic subsystems requiring service by the Integrated Electronics Laboratory were identified from the twenty-seven relevant payload equipment items. Where possible, flight configurations were analyzed [2,3,7,8,9,16,19,20,21,22,23,42], the balance of data drawn from commercial hardware specifications [27,31,33,35,36,37,39,40,41,42,44]. Figure 10 illustrates this analysis process. Figure 11 cross-references 111 identified electronic subsystems to the relevant payload equipment.

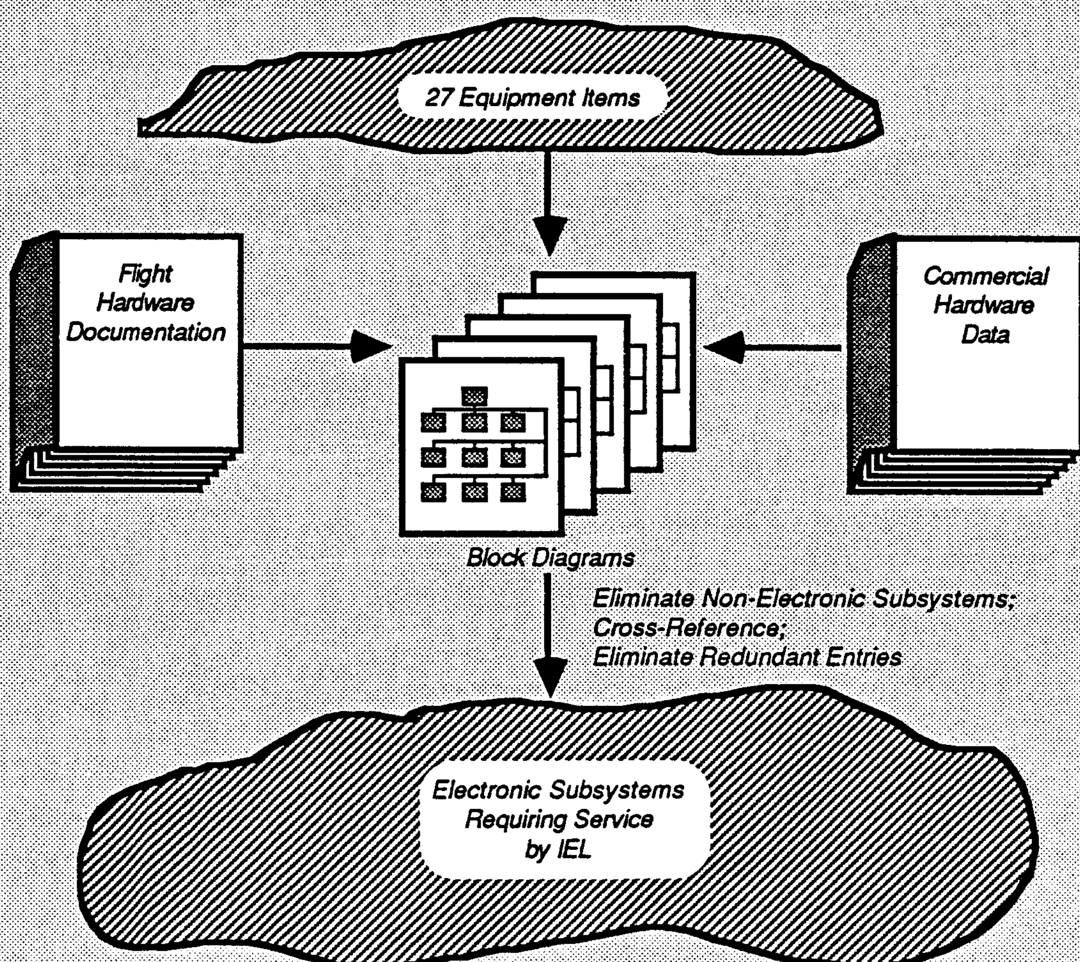


FIGURE D-10 *IDENTIFICATION OF ELECTRONIC SUBSYSTEMS*

RELEVANT PAYLOAD EQUIPMENT / ELECTRONIC SUBSYSTEMS	Accelerom Signal Amplifier	Accelerom Signal Preamp	Amplifier Attenuator	Analog-Digital Converter	Astigmatism Control Coil	Audio Amplifier	Audio Preamplifier	Audio Switch/Mix Unit	Auto-Range Selector	Beam Align Control Coil	Beam Center Control Coil	Bulk Filters	CCTV Circuit	CDMS Interface	Chopper Driver	Control Software	Cooling Loop	CRT Display	Current Cont Rectifier	Data Recording Unit	Deflection Control Grid	Delta Volume Sensor	Delta V Sensor Amplifier	Delta V Sensor Preamp	Demultiplexer	Detector Bridge
Acous Cont Exp System (ACES)				●		●	●						●	●		●									●	
3-Axis Rec Accelerometer	●	●		●																					●	
Auto Cut/Polish Unit																										
Cut/Form Facility																										
Data Recording Unit				●										●		●		●							●	
Diff Scan Calorimeter				●																						
Digital Multimeter			●	●					●			●		●		●									●	
Digital Rec Oscope			●	●								●		●		●		●								
ADSF														●		●	●								●	
Elec Conductivity Probe				●																						
CFES				●										●		●	●								●	
Fourier Infrared Spectrom			●									●			●	●									●	●
Gas Chromatograph			●						●			●		●		●	●								●	●
HP Liquid Chromatograph			●						●			●		●		●									●	
GPRF														●		●	●								●	

FIGURE D-11A ***ELECTRONIC SUBSYSTEMS VS. RELEVANT PAYLOAD EQUIPMENT, PART 1***

RELEVANT PAYLOAD EQUIPMENT \ ELECTRONIC SUBSYSTEMS	Digital Display	Digital Switching Supply	Digital-Analog Converter	Electron Detector Amp	Electron Detector Preamp	Fast Data Recorder	Field Generator	Flow Controller	Fourier Transform Circuit	f-Weighted Signal Filters	Heater Controller	High Rate Multiplexer	High Voltage Power Supply	High Voltage Regulator	HVPS Filters	HVPS Impulse Protection	I/O Expander	Instrumentation Amplifier	Integrator	Intercom Central	Interface Panel	Lighting Circuit	Limit Switch	Linearity/dB Filters	Low Voltage Power Supply	Mass Memory Unit
Acous Cont Exp System (ACES)		●	●																		●					
3-Axis Rec Accelerometer			●							●																
Auto Cut/Polish Unit																					●		●			
Cut/Form Facility																					●		●			
Data Recording Unit	●		●														●				●					
Diff Scan Calorimeter			●																		●					
Digital Multimeter	●		●							●								●	●		●			●		
Digital Rec Oscope			●							●							●	●	●		●			●		
ADSF			●					●					●	●	●	●					●				●	
Elec Conductivity Probe	●																	●			●					
CFES			●				●	●													●					
Fourier Infrared Spectrom			●						●									●	●		●					
Gas Chromatograph	●		●	●	●			●		●								●	●		●					
HP Liquid Chromatograph	●		●								●							●	●		●					
GPRF			●					●			●										●				●	

FIGURE D-11B *ELECTRONIC SUBSYSTEMS VS. RELEVANT PAYLOAD EQUIPMENT, PART 2*

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RELEVANT PAYLOAD EQUIPMENT \ ELECTRONIC SUBSYSTEMS	Master Clock	Microprocessor	MS Electronics	Multiplexer	Narrow Band Amplifier	Omega Position Encoder	Oscilloscope Trigger	Overload Protection	Overvoltage Protection	Parallel Data Bus	PCM Decoder	PCM Encoder	Peak Detector	Phase Detector	Position Detector	Power Amplifier	Power Distribution Bus	Pressure Transducer	Press Transducer Amp	Press Transducer Preamp	Probe	Probe Amplifier	Probe Preamplifier	Programmable Controller	KU-Band Signal Processor	S-Band Signal Processor
Acous Cont Exp System (ACES)		●		●				●	●																	
3-Axis Rec Accelerometer		●		●									●													
Auto Cut/Polish Unit								●	●						●											
Cut/Form Facility								●	●						●											
Data Recording Unit	●	●		●				●		●	●	●				●										
Diff Scan Calorimeter								●																●		
Digital Multimeter		●		●	●		●	●	●	●			●				●									
Digital Rec Oscope		●		●	●		●	●	●	●			●	●			●									
ADSF		●		●				●	●						●		●							●		
Elec Conductivity Probe								●	●												●	●	●			
CFES		●		●				●	●								●									
Fourier Infrared Spectrom		●		●	●			●	●					●												
Gas Chromatograph		●		●	●			●	●					●			●									
HP Liquid Chromatograph		●		●	●			●	●					●	●		●									
GPRF		●		●				●	●						●		●	●	●	●						

FIGURE D-11C *ELECTRONIC SUBSYSTEMS VS. RELEVANT PAYLOAD EQUIPMENT, PART 3*

C-3

RELEVANT PAYLOAD EQUIPMENT \ ELECTRONIC SUBSYSTEMS	Random Access Memory	Read Only Memory	Recorder	Reference Oscillator	Reference Voltage Source	Resistance Network	RMS Detector	Sampling Control	Sensor Amplifier	Sensor Preamplifier	Solvent Delivery System	Spectrometer	Stepping Motor	Stepping Motor Controller	Strain Gage Sensors	Sweep Oscillator	Synchronization Clock	Synchronous DC Motor	Temp Comp Bridge	Thermocouple Amplifier	Thermocouple Preamplifier	Transformer	Trigger Unit	Variable Speed Controller	Video Camera System	Video Recorder
Acous Cont Exp System (ACES)									●	●						●	●			●	●				●	●
3-Axis Rec Accelerometer				●			●		●	●					●		●									
Auto Cut/Polish Unit																		●						●		
Cut/Form Facility													●	●				●						●		
Data Recording Unit	●	●						●	●	●							●									
Diff Scan Calorimeter	●							●												●	●					
Digital Multimeter		●		●		●	●	●									●						●			
Digital Rec Oscope	●	●	●	●			●	●								●	●						●			
ADSF									●	●			●	●			●			●	●					
Elec Conductivity Probe					●														●							
CFES									●	●							●									
Fourier Infrared Spectrom			●					●									●		●							
Gas Chromatograph	●	●	●				●	●									●		●							
HP Liquid Chromatograph	●	●	●	●			●	●			●						●		●							
GPRF																	●			●	●					

FIGURE D-11D ***ELECTRONIC SUBSYSTEMS VS. RELEVANT PAYLOAD EQUIPMENT, PART 4***

RELEVANT PAYLOAD EQUIPMENT \ ELECTRONIC SUBSYSTEMS	Video Switching Network	Voltage Controlled Rectifier	Voltage Rectifier	Voltage Regulator	X-Ray Detector Amplifier	X-Ray Detector Preamplifier	Zero Adjust Circuit
Acous Cont Exp System (ACES)				●			
3-Axis Rec Accelerometer				●			●
Auto Cut/Polish Unit			●	●			
Cut/Form Facility			●	●			
Data Recording Unit				●			
Diff Scan Calorimeter				●			
Digital Multimeter				●			
Digital Rec Oscope							
ADSF			●				
Elec Conductivity Probe			●				●
CFES							
Fourier Infrared Spectrom			●	●			●
Gas Chromatograph			●	●			●
HP Liquid Chromatograph			●	●			●
GPRF				●			

FIGURE D-11E ***ELECTRONIC SUBSYSTEMS VS. RELEVANT PAYLOAD EQUIPMENT, PART 5***

RELEVANT PAYLOAD EQUIPMENT \ ELECTRONIC SUBSYSTEMS	Accelerom Signal Amplifier	Accelerom Signal Preamp	Amplifier Attenuator	Analog-Digital Converter	Astigmatism Control Coil	Audio Amplifier	Audio Preamplifier	Audio Switch/Mix Unit	Auto-Range Selector	Beam Align Control Coil	Beam Center Control Coil	Bulk Filters	CCTV Circuit	CDMS Interface	Chopper Driver	Control Software	Cooling Loop	CRT Display	Current Cont Rectifier	Data Recording Unit	Deflection Control Grid	Delta Volume Sensor	Delta V Sensor Amplifier	Delta V Sensor Preamp	Demultiplexer	Detector Bridge
Monodisp Latex Reactor				●										●		●	●					●	●	●	●	
Mass Meas System				●																						
Mass Spectrometer			●	●					●			●		●		●									●	
Master Computer								●								●		●		●					●	
Optical Refractometer																										
SEM			●		●					●	●	●									●					
Sputt Deposition Unit																			●							
Ultracentrifuge				●										●												
UV/VIS/NIR Spectrom															●										●	●
VCGS (FES)				●										●			●		●						●	
Video Facilities									●			●	●	●												
X-Ray Topography Unit																	●									

FIGURE D-11F *ELECTRONIC SUBSYSTEMS VS. RELEVANT PAYLOAD EQUIPMENT, PART 6*

RELEVANT PAYLOAD EQUIPMENT \ ELECTRONIC SUBSYSTEMS	Digital Display	Digital Switching Supply	Digital-Analog Converter	Electron Detector Amp	Electron Detector Preamp	Fast Data Recorder	Field Generator	Flow Controller	Fourier Transform Circuit	f-Weighted Signal Filters	Heater Controller	High Rate Multiplexer	High Voltage Power Supply	High Voltage Regulator	HVPS Filters	HVPS Impulse Protection	I/O Expander	Instrumentation Amplifier	Integrator	Intercom Central	Interface Panel	Lighting Circuit	Limit Switch	Linearity/dB Filters	Low Voltage Power Supply	Mass Memory Unit
Monodisp Latex Reactor			●					●													●					
Mass Meas System	●																				●					
Mass Spectrometer	●		●	●	●				●	●								●	●		●					
Master Computer						●						●					●			●	●					●
Optical Refractometer																					●	●				
SEM				●	●													●			●					
Sputt Deposition Unit							●							●	●						●					
Ultracentrifuge	●											●									●					
UV/VIS/NIR Spectrom			●						●												●					
VCGS (FES)			●					●										●			●					
Video Facilities																		●			●					
X-Ray Topography Unit								●					●	●	●	●					●		●			

FIGURE D-11G ***ELECTRONIC SUBSYSTEMS VS. RELEVANT PAYLOAD EQUIPMENT, PART 7***

RELEVANT PAYLOAD EQUIPMENT / ELECTRONIC SUBSYSTEMS	Master Clock	Microprocessor	MS Electronics	Multiplexer	Narrow Band Amplifier	Omega Position Encoder	Oscilloscope Trigger	Overload Protection	Overvoltage Protection	Parallel Data Bus	PCM Decoder	PCM Encoder	Peak Detector	Phase Detector	Position Detector	Power Amplifier	Power Distribution Bus	Pressure Transducer	Press Transducer Amp	Press Transducer Preamp	Probe	Probe Amplifier	Probe Preamplifier	Programmable Controller	KU-Band Signal Processor	S-Band Signal Processor
Monodisp Latex Reactor		●		●				●	●								●									
Mass Meas System								●	●																	
Mass Spectrometer		●	●	●	●			●	●				●	●	●		●									
Master Computer	●			●				●	●	●	●	●				●	●								●	●
Optical Refractometer								●																		
SEM						●		●	●						●	●	●									
Sputt Deposition Unit								●	●							●										
Ultracentrifuge				●				●	●		●	●			●	●	●							●		
UV/VIS/NIR Spectrom		●		●	●			●	●					●												
VCGS (FES)		●		●				●	●								●							●		
Video Facilities								●	●							●	●									
X-Ray Topography Unit								●	●							●	●									

FIGURE D-11H ***ELECTRONIC SUBSYSTEMS VS. RELEVANT PAYLOAD EQUIPMENT, PART 8***

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RELEVANT PAYLOAD EQUIPMENT \ ELECTRONIC SUBSYSTEMS	Random Access Memory	Read Only Memory	Recorder	Reference Oscillator	Reference Voltage Source	Resistance Network	RMS Detector	Sampling Control	Sensor Amplifier	Sensor Preamplifier	Solvent Delivery System	Spectrometer	Stepping Motor	Stepping Motor Controller	Strain Gage Sensors	Sweep Oscillator	Synchronization Clock	Synchronous DC Motor	Temp Comp Bridge	Thermocouple Amplifier	Thermocouple Preamplifier	Transformer	Trigger Unit	Variable Speed Controller	Video Camera System	Video Recorder
Monodisp Latex Reactor																	●			●	●					
Mass Meas System				●																						
Mass Spectrometer	●	●	●	●			●	●									●		●	●	●					
Master Computer	●	●																								
Optical Refractometer																						●				
SEM				●				●	●	●			●	●				●								
Sputt Deposition Unit																										
Ultracentrifuge									●	●																
UV/VIS/NIR Spectrom			●					●									●		●							
VCGS (FES)									●	●		●					●									
Video Facilities				●				●																	●	●
X-Ray Topography Unit													●	●				●								

FIGURE D-111 *ELECTRONIC SUBSYSTEMS VS. RELEVANT PAYLOAD EQUIPMENT, PART 9*

RELEVANT PAYLOAD EQUIPMENT \ ELECTRONIC SUBSYSTEMS	Video Switching Network	Voltage Controlled Rectifier	Voltage Rectifier	Voltage Regulator	X-Ray Detector Amplifier	X-Ray Detector Preamplifier	Zero Adjust Circuit
Monodisp Latex Reactor			●	●			
Mass Meas System			●				●
Mass Spectrometer			●	●			●
Master Computer	●		●				
Optical Refractometer							
SEM			●	●	●	●	
Sputt Deposition Unit		●					
Ultracentrifuge				●			
UV/VIS/NIR Spectrom			●	●			●
VCGS (FES)			●	●			
Video Facilities	●		●				
X-Ray Topography Unit				●			

FIGURE D-11J *ELECTRONIC SUBSYSTEMS VS. RELEVANT PAYLOAD EQUIPMENT, PART 10*

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2.4 Representative Typical Circuitry

The identified electronic subsystems are best analyzed as a condensed list of 44 more general typical circuits which are equivalent for failure analysis. The distillation process is illustrated in Figure 12. These circuits, presenting the full range of fault diagnosis and maintenance requirements, are cross-referenced to relevant payload equipment in Figure 13. These generalized circuits are drawn from instrumentation and circuitry handbooks [35,41,43,45,46,48,50,51,52,53,55,56].

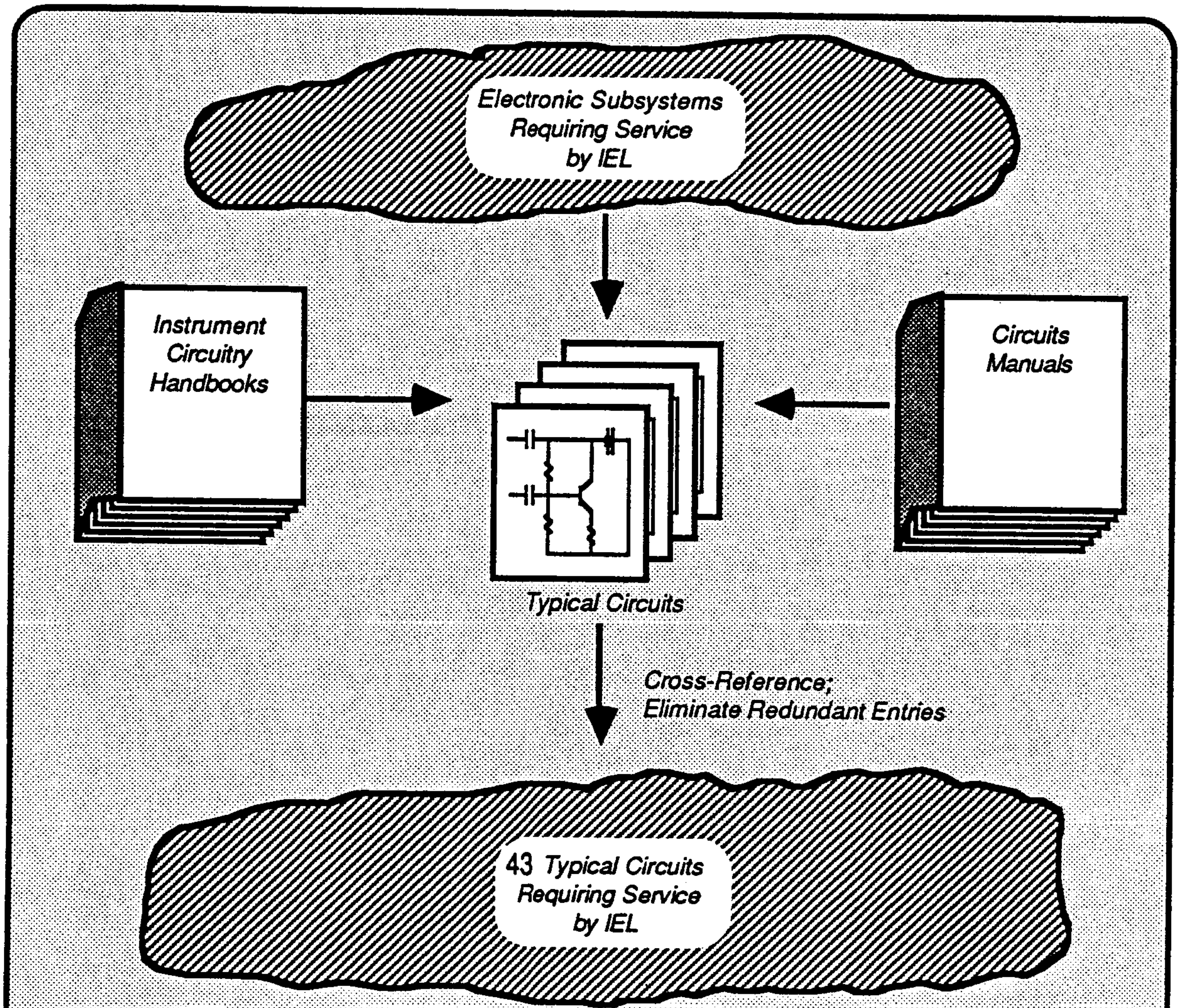

FIGURE D-12 *CONDENSATION OF ELECTRONIC SUBSYSTEMS INTO TYPICAL CIRCUITS*

RELEVANT PAYLOAD EQUIPMENT \ TYPICAL CIRCUITS	Analog-Digital Converter	Audio Amplifier	Audio Preamplifier	Auto-Range Selector	Chopper Driver	CRT Display	Current Cont Rectifier	Demultiplexer	Detector Bridge	Digital Display	Digital Switching Supply	Digital-Analog Converter	Fast Data Recorder	f-Weighted Signal Filters	General Instrumentation Amp	General Integrator Circuit	Generalized Trigger Circuit	High Rate Multiplexer	High Voltage Power Supply	Low Voltage Power Supply	Microprocessor	Microproc Controller	Multiplexer	Narrow Band Amplifier	Omega Position Encoder	Parallel Data Bus
Acous Cont Exp System (ACES)	●	●	●					●				●			●						●		●			
3-Axis Rec Accelerometer	●							●				●		●	●						●		●			
Auto Cut/Polish Unit																										
Cut/Form Facility																										
Data Recording Unit	●					●		●		●		●			●		●				●		●			●
Diff Scan Calorimeter	●											●					●					●				
Digital Multimeter	●			●				●	●	●		●		●	●	●	●				●		●	●		●
Digital Rec Oscope	●					●						●		●	●	●	●				●		●	●		●
ADSF								●			●	●			●				●	●	●	●	●			
Elec Conductivity Probe	●									●					●											
CFES	●							●				●			●						●	●	●			
Fourier Infrared Spectrom					●			●	●			●			●	●	●				●		●	●		
Gas Chromatograph				●				●	●	●		●			●	●	●				●	●	●	●		
HP Liquid Chromatograph				●				●		●		●			●	●	●				●	●	●	●		
GPRF								●				●			●					●	●	●	●			

FIGURE D-13A ***TYPICAL CIRCUITS VS. RELEVANT PAYLOAD EQUIPMENT, PART 1***

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RELEVANT PAYLOAD EQUIPMENT \ TYPICAL CIRCUITS	PCM Decoder	PCM Encoder	Phase Detector	Power Amplifier	Press Transducer Amp	Random Access Memory	Recorder	Reference Oscillator	Stepping Motor Controller	Sweep Oscillator	Synchronization Clock	Temp Comp Bridge	Thermocouple Amplifier	Thermocouple Preamplifier	Video Camera	Voltage Regulator	Zero Adjust Circuit
Acous Cont Exp System (ACES)										●	●		●	●	●	●	
3-Axis Rec Accelerometer								●			●					●	●
Auto Cut/Polish Unit																●	
Cut/Form Facility									●							●	
Data Recording Unit	●	●		●		●					●					●	
Diff Scan Calorimeter						●							●	●		●	
Digital Multimeter						●		●			●					●	
Digital Rec Oscope			●			●	●	●		●	●						
ADSF									●		●		●	●			
Elec Conductivity Probe												●					●
CFES											●						
Fourier Infrared Spectrom			●				●				●	●				●	●
Gas Chromatograph			●			●	●				●	●				●	●
HP Liquid Chromatograph			●			●	●	●			●	●				●	●
GPRF											●					●	

FIGURE D-13B *TYPICAL CIRCUITS VS. RELEVANT PAYLOAD EQUIPMENT, PART 2*

RELEVANT PAYLOAD EQUIPMENT / TYPICAL CIRCUITS	Analog-Digital Converter	Audio Amplifier	Audio Preamplifier	Auto-Range Selector	Chopper Driver	CRT Display	Current Cont Rectifier	Demultiplexer	Detector Bridge	Digital Display	Digital Switching Supply	Digital-Analog Converter	Fast Data Recorder	f-Weighted Signal Filters	General Instrumentation Amp	General Integrator Circuit	Generalized Trigger Circuit	High Rate Multiplexer	High Voltage Power Supply	Low Voltage Power Supply	Microprocessor	Microproc Controller	Multiplexer	Narrow Band Amplifier	Omega Position Encoder	Parallel Data Bus
Monodisp Latex Reactor	●							●				●			●						●	●	●			
Mass Meas System	●									●																
Mass Spectrometer	●			●				●		●		●		●	●	●	●	●			●		●	●		
Master Computer						●		●				●	●		●								●			●
Optical Refractometer																										
SEM															●	●	●								●	
Sputt Deposition Unit							●												●							
Ultracentrifuge	●									●					●			●				●	●			
UV/VIS/NIR Spectrom					●			●	●			●					●				●		●	●		
VCGS (FES)	●						●	●				●			●						●	●	●			
Video Facilities				●											●		●									
X-Ray Topography Unit																			●			●				

FIGURE D-13C ***TYPICAL CIRCUITS VS. RELEVANT PAYLOAD EQUIPMENT, PART 3***

RELEVANT PAYLOAD EQUIPMENT / TYPICAL CIRCUITS	PCM Decoder	PCM Encoder	Phase Detector	Power Amplifier	Press Transducer Amp	Random Access Memory	Recorder	Reference Oscillator	Stepping Motor Controller	Sweep Oscillator	Synchronization Clock	Temp Comp Bridge	Thermocouple Amplifier	Thermocouple Preamplifier	Video Camera	Voltage Regulator	Zero Adjust Circuit
Monodisp Latex Reactor											●					●	
Mass Meas System								●									●
Mass Spectrometer			●			●	●	●			●	●				●	●
Master Computer	●	●		●		●					●						
Optical Refractometer																	
SEM				●				●								●	
Sputt Deposition Unit				●													
Ultracentrifuge	●	●		●												●	
UV/VIS/NIR Spectrom			●								●					●	●
VCGS (FES)							●									●	
Video Facilities				●				●							●		
X-Ray Topography Unit				●												●	

FIGURE D-13D *TYPICAL CIRCUITS VS. RELEVANT PAYLOAD EQUIPMENT, PART 4*

2.5 Failure Analysis of Typical Circuitry

Failure modes for the 43 identified typical circuits were researched from circuit and instrumentation handbooks and textbooks [33,40,41,46,48,52,56]. A total of 41 discrete failure modes were identified by the process diagrammed in Figure 14. Figure 15 cross-references faliure modes to typical circuits.

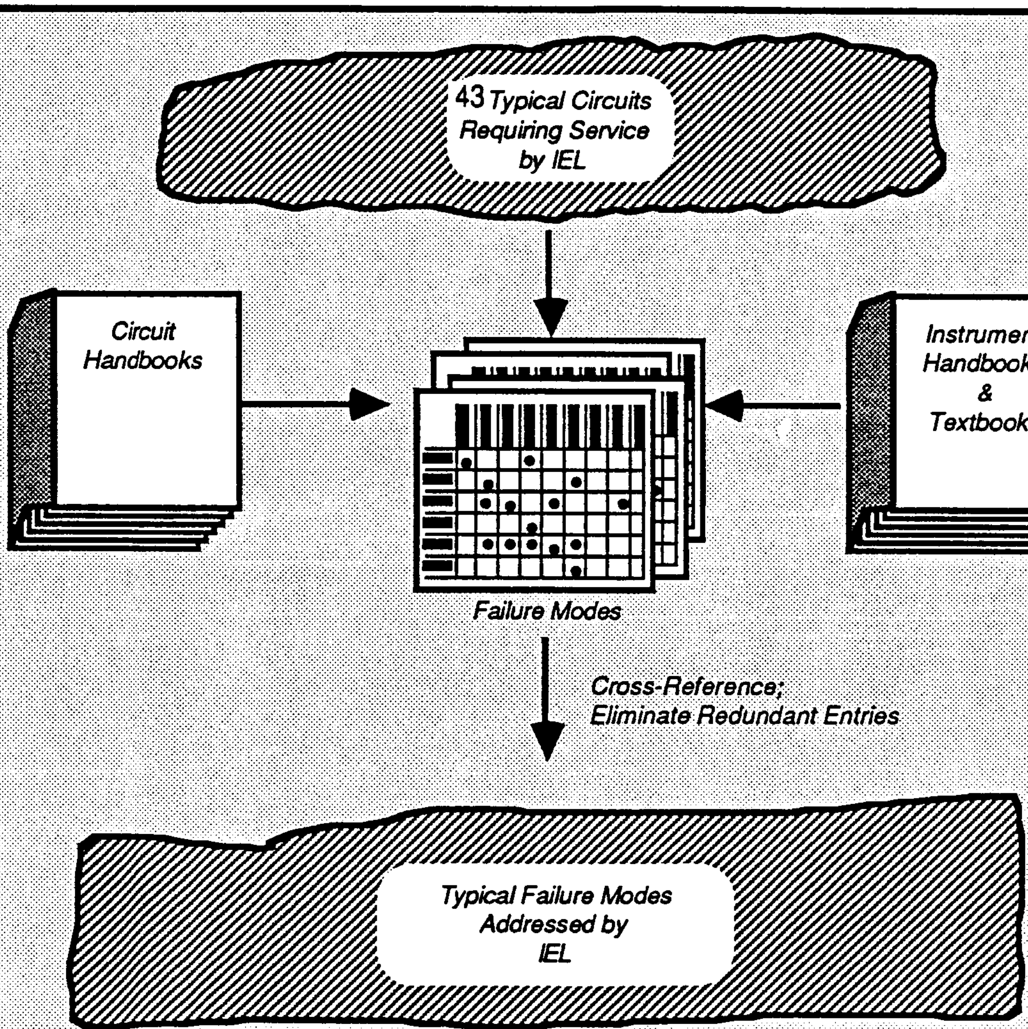

FIGURE D-14 ***FAILURE ANALYSIS OF TYPICAL CIRCUITS***

FAILURE MODES \ TYPICAL CIRCUITS	Analog-Digital Converter	Audio Amplifier	Audio Preamplifier	Auto-Range Selector	Chopper Driver	CRT Display	Current Cont Rectifier	Demultiplexer	Detector Bridge	Digital Display	Digital Switching Supply	Digital-Analog Converter	Fast Data Recorder	f-Weighted Signal Filters	General Instrumentation Amp	General Integrator Circuit	Generalized Trigger Circuit	High Rate Multiplexer	High Voltage Power Supply	Low Voltage Power Supply	Microprocessor	Microproc Controller	Multiplexer	Narrow Band Amplifier	Omega Position Encoder	Parallel Data Bus
Alpha-Induced Soft Error	●							●				●	●					●			●	●	●			
Bias Variation	●	●	●	●	●	●		●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		
Component Seal Leak	●	●	●	●	●	●		●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		
Contact Degradation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Corrosion	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Cross-Talk																										●
Crowbarred Interrupts	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		
Cutoff	●	●	●	●	●	●		●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		
Decoupling Ckt Breakdown		●	●					●			●			●	●	●			●	●				●		
Decoupling Ckt Short		●	●							●	●			●	●	●			●	●				●		
Electromigration	●	●	●	●	●	●		●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		
Excessive Load Impedance					●				●	●					●	●	●		●	●						
Excessive Noise Margin	●			●				●		●		●											●	●		●
Fatigue	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Gate-to-Gate Faults	●	●	●	●	●	●		●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		

FIGURE D-15A *TYPICAL CIRCUITS VS. FAILURE MODES, PART 1*

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FAILURE MODES \ TYPICAL CIRCUITS	PCM Decoder	PCM Encoder	Phase Detector	Power Amplifier	Press Transducer Amp	Random Access Memory	Recorder	Reference Oscillator	Stepping Motor Controller	Sweep Oscillator	Synchronization Clock	Temp Comp Bridge	Thermocouple Amplifier	Thermocouple Preamplifier	Video Camera	Voltage Regulator	Zero Adjust Circuit
Alpha-Induced Soft Error	●	●				●	●		●								
Bias Variation	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	
Component Seal Leak	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	
Contact Degradation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Corrosion	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	
Cross-Talk																	
Crowbarred Interrupts	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	
Cutoff	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	
Decoupling Ckt Breakdown			●	●	●								●	●			
Decoupling Ckt Short			●	●	●								●	●			
Electromigration	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	
Excessive Load Impedance				●												●	
Excessive Noise Margin			●							●							
Fatigue	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Gate-to-Gate Faults	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	

FIGURE D-15B ***TYPICAL CIRCUITS VS. FAILURE MODES, PART 2***

FAILURE MODES \ TYPICAL CIRCUITS	Analog-Digital Converter	Audio Amplifier	Audio Preamplifier	Auto-Range Selector	Chopper Driver	CRT Display	Current Cont Rectifier	Demultiplexer	Detector Bridge	Digital Display	Digital Switching Supply	Digital-Analog Converter	Fast Data Recorder	f-Weighted Signal Filters	General Instrumentation Amp	General Integrator Circuit	Generalized Trigger Circuit	High Rate Multiplexer	High Voltage Power Supply	Low Voltage Power Supply	Microprocessor	Microproc Controller	Multiplexer	Narrow Band Amplifier	Omega Position Encoder	Parallel Data Bus
General Logic Glitch	●							●		●	●	●	●					●			●	●	●			●
Ground Fault	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Harmonic Distortion	●	●	●								●			●	●	●			●	●				●		
High Gain		●	●									●			●	●	●		●	●				●		
High Logic Level	●							●		●	●	●	●					●			●	●	●			
High Transfer Impedance																										●
Hysteresis		●	●								●			●	●	●			●	●				●		
Incorrect Baud Rate								●										●			●	●	●			
Intermodulation Distortion		●	●								●			●	●	●			●	●				●		
Load Tolerance Exceeded					●				●	●					●	●	●		●	●						
Loaded Stack																					●	●				
Logic Wrapback																										
Low Gain		●	●								●			●	●	●			●	●				●		
Low Logic Level	●							●		●	●	●	●					●			●	●	●			
Non-Harmonic Distortion		●	●								●			●	●	●			●	●				●		

FIGURE D-15C ***TYPICAL CIRCUITS VS. FAILURE MODES, PART 3***

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FAILURE MODES \ TYPICAL CIRCUITS	PCM Decoder	PCM Encoder	Phase Detector	Power Amplifier	Press Transducer Amp	Random Access Memory	Recorder	Reference Oscillator	Stepping Motor Controller	Sweep Oscillator	Synchronization Clock	Temp Comp Bridge	Thermocouple Amplifier	Thermocouple Preamplifier	Video Camera	Voltage Regulator	Zero Adjust Circuit
General Logic Glitch	●	●	●			●	●				●						
Ground Fault	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Harmonic Distortion			●	●									●	●			
High Gain			●	●	●								●	●			
High Logic Level						●	●								●		
High Transfer Impedance															●		
Hysteresis			●	●	●								●	●			
Incorrect Baud Rate																	
Intermodulation Distortion			●	●	●								●	●			
Load Tolerance Exceeded				●												●	
Loaded Stack						●											
Logic Wrapback						●											
Low Gain			●	●	●								●	●			
Low Logic Level						●	●										
Non-Harmonic Distortion			●	●	●								●	●			

FIGURE D-15D *TYPICAL CIRCUITS VS. FAILURE MODES, PART 4*

FAILURE MODES \ TYPICAL CIRCUITS	Analog-Digital Converter	Audio Amplifier	Audio Preamplifier	Auto-Range Selector	Chopper Driver	CRT Display	Current Cont Rectifier	Demultiplexer	Detector Bridge	Digital Display	Digital Switching Supply	Digital-Analog Converter	Fast Data Recorder	f-Weighted Signal Filters	General Instrumentation Amp	General Integrator Circuit	Generalized Trigger Circuit	High Rate Multiplexer	High Voltage Power Supply	Low Voltage Power Supply	Microprocessor	Microproc Controller	Multiplexer	Narrow Band Amplifier	Omega Position Encoder	Parallel Data Bus
Open Circuit	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Q-Injection	●	●	●	●	●	●		●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●
Feedback Breakdown		●	●	●	●						●			●	●	●								●		
Polarity Reversed		●	●								●			●	●	●			●	●				●		
Shifted Freq Response		●	●								●			●	●	●			●	●				●		
Short Circuit	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Surface Charge (Static)	●					●		●													●	●				●
Saturation	●	●	●	●	●			●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		
Third Overtone Oscillation																										
Upstream Power Glitch	●						●			●	●	●	●					●			●	●	●			
Winding Break	MOTORS (NOT REF ABOVE SINCE TYP CKT NOT REQUIRED)																									

FIGURE D-15E *TYPICAL CIRCUITS VS. FAILURE MODES, PART 5*

FAILURE MODES \ TYPICAL CIRCUITS	PCM Decoder	PCM Encoder	Phase Detector	Power Amplifier	Press Transducer Amp	Random Access Memory	Recorder	Reference Oscillator	Stepping Motor Controller	Sweep Oscillator	Synchronization Clock	Temp Comp Bridge	Thermocouple Amplifier	Thermocouple Preamplifier	Video Camera	Voltage Regulator	Zero Adjust Circuit
Open Circuit	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Q-Injection	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	
Feedback Breakdown				●	●			●	●							●	
Polarity Reversed	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●
Shifted Freq Response			●	●	●								●	●	●	●	
Short Circuit	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Surface Charge (Static)						●					●						
Saturation	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	
Third Overtone Oscillation											●						
Upstream Power Glitch						●	●								●		
Winding Break																	

FIGURE D-15F *TYPICAL CIRCUITS VS. FAILURE MODES, PART 6*

2.6 Required Diagnostic Techniques

Diagnostic techniques required to detect and characterize the expected failure modes were identified through troubleshooting texts and handbooks [40,46,48], as diagrammed in Figure 16. Figure 17 cross-references diagnostic techniques to failure modes.

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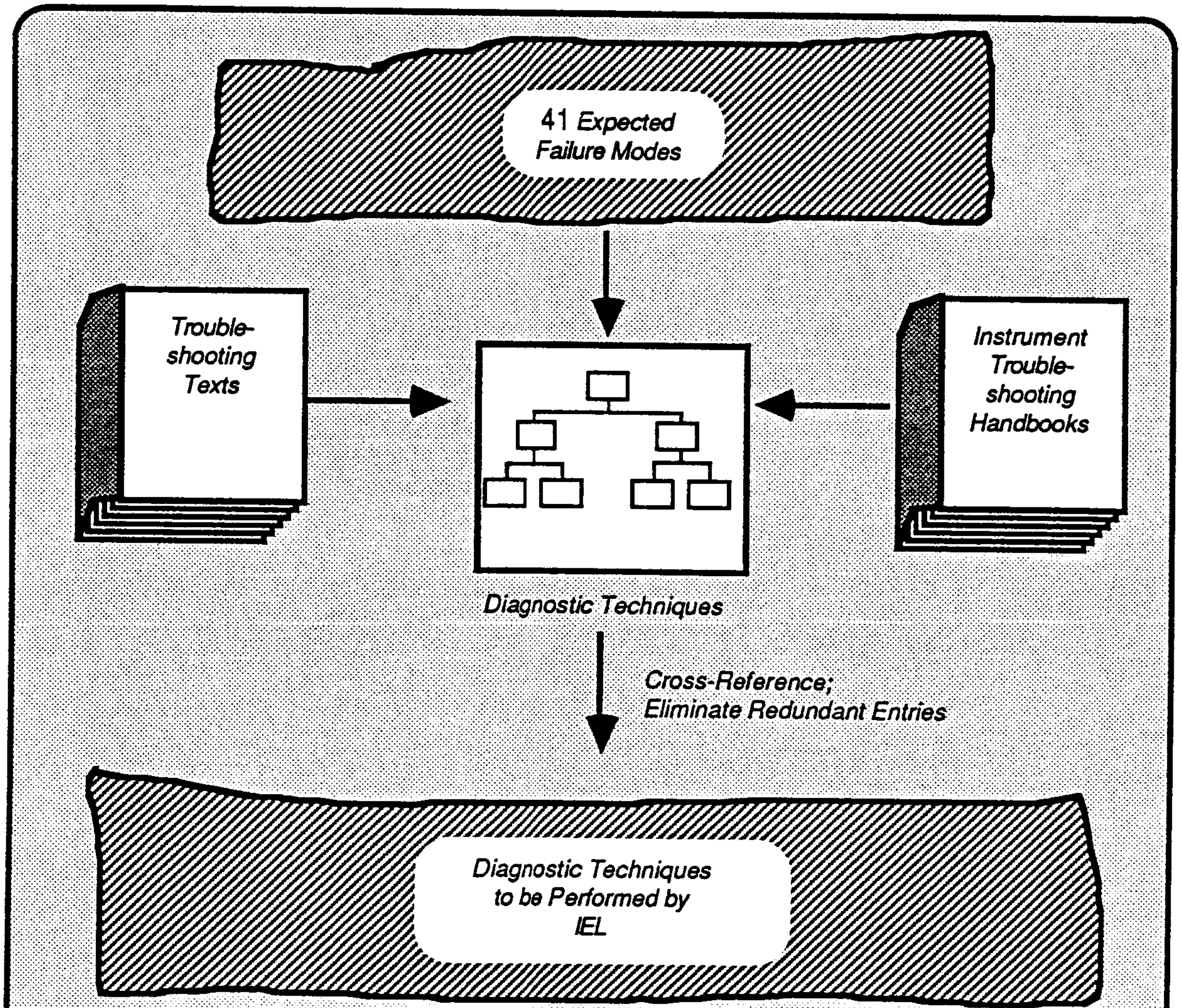

FIGURE D-16 ***DERIVATION OF REQUIRED DIAGNOSTIC TECHNIQUES***

DIAGNOSTIC TECHNIQUES \ FAILURE MODES	Alpha-Induced Soft Error	Bias Variation	Component Seal Leak	Contact Degradation	Corrosion	Cross-Talk	Crowbarred Interrupts	Cutoff	Decoupling Ckt Breakdown	Decoupling Ckt Short	Electromigration	Excessive Load Impedance	Excessive Noise Margin	Fatigue	Gate-to-Gate Faults	General Logic Glitch	Ground Fault	Harmonic Distortion	High Gain	High Logic Level	High Transfer Impedance	Hysteresis	Incorrect Baud Rate	Intermodulation Distortion	Load Tolerance Exceeded	Loaded Stack
Continuity Check		●	●	●				●	●		●			●	●	●	●			●			●			
Current Trace		●		●	●		●	●		●		●		●		●	●			●						
Curve Trace		●						●					●					●	●		●	●		●	●	
Freq Response Check		●		●	●				●	●			●	●				●	●		●	●		●	●	
Gain Check				●	●				●	●			●	●				●	●		●	●		●	●	
Interactive Rate Check						●	●									●							●			
Isolation Check		●		●	●	●	●	●	●	●	●	●		●	●	●	●		●	●	●				●	
Load Check		●		●					●	●	●	●		●	●		●				●	●			●	
Logic Checkout	●		●		●		●				●				●	●				●			●			●
Logic Timing Trace							●									●				●						
Logic Trace						●	●								●	●				●						
Polarity Check		●		●				●	●	●		●	●	●			●		●	●	●				●	
Power Check		●													●	●	●		●	●		●				
Software Analysis						●	●								●	●							●			●
Waveform Analysis													●					●	●		●	●		●	●	

FIGURE D-17A *DIAGNOSTIC TECHNIQUES VS. FAILURE MODES, PART 1*

DIAGNOSTIC TECHNIQUES \ FAILURE MODES	Logic Wrapback	Low Gain	Low Logic Level	Non-Harmonic Distortion	Open Circuit	Q-Injection	Feedback Breakdown	Polarity Reversed	Shifted Freq Response	Short Circuit	Surface Charge (Static)	Saturation	Third Overtone Oscillation	Upstream Power Glitch	Winding Break
Continuity Check					●		●	●		●		●			●
Current Trace					●	●	●			●		●			●
Curve Trace			●	●		●	●		●			●	●		
Freq Response Check		●	●	●			●		●						
Gain Check		●	●	●			●		●				●		
Interactive Rate Check													●		
Isolation Check			●		●	●	●	●		●	●	●			●
Load Check		●			●	●	●			●					●
Logic Checkout	●										●		●		
Logic Timing Trace													●		
Logic Trace			●								●			●	
Polarity Check			●		●		●	●		●					●
Power Check			●		●		●	●		●		●			●
Software Analysis											●		●		
Waveform Analysis			●	●			●		●				●		

FIGURE D-17B *DIAGNOSTIC TECHNIQUES VS. FAILURE MODES, PART 2*

2.7 Required Diagnostic Equipment

Three diagnostic equipment complements were identified, each adequate to effect the diagnostic techniques derived in Section 2.6. Complement A includes advanced diagnostic equipment at a high level of integration, requring only task-trainable troubleshooting skills. Complement B incorporates limited slave testing capability, while Complement C contains only general-purpose equipment requiring some diagnostic expertise. Figure 18 describes the process of defining these complements. A cross-reference relating diagnostic techniques to the identified diagnostic equipment appears in Figure 19.

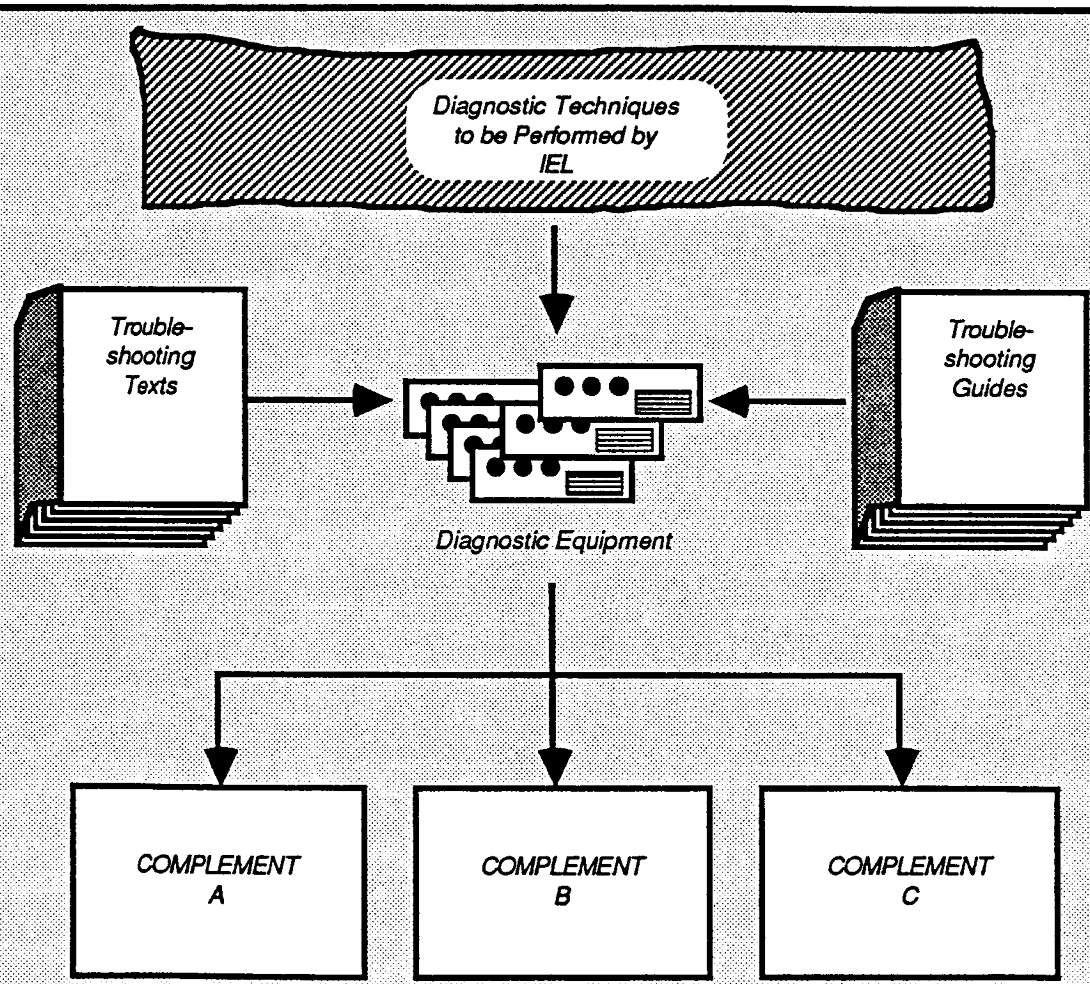

FIGURE D-18 ***DERIVATION OF DIAGNOSTIC EQUIPMENT REQUIREMENTS***

DIAGNOSTIC TECHNIQUES \ DIAGNOSTIC EQUIPMENT	Ammeter	Logic Checkout System	D/A Converter	Decade Capacitor	Decade Resistor	Digital Multimeter	Function Generator	Op-Amp Board	Handheld Multimeter	Logic Analyzer	Logic Clip	Logic Probe	Logic Pulser	Oscilloscope	Probe Bundles	Programmable Supplies	Pulse Generator	Signature Analyzer	Spectrum Analyzer	Sweep Oscillator	Universal Counter	Microcomputer	ATE Software	Expert System Software		
Continuity Check						●			●						●							●		●		
Current Trace	●								●						●							●		●		
Curve Trace			●				●	●						●	●		●		●	●	●	●		●		
Freq Response Check			●	●	●		●	●						●	●		●		●	●	●	●		●		
Gain Check			●	●	●	●	●	●	●					●	●	●	●		●	●	●	●		●		
Interactive Rate Check		●								●					●							●		●		
Isolation Check	●				●	●			●						●	●						●		●		
Load Check	●				●	●			●						●							●		●		
Logic Checkout		●								●	●	●			●		●	●				●		●		
Logic Timing Trace		●	●							●	●	●			●		●	●				●		●		
Logic Trace		●	●							●	●	●	●		●		●	●				●		●		
Polarity Check						●									●							●		●		
Power Check	●					●			●						●							●		●		
Software Analysis		●	●							●					●							●		●		
Waveform Analysis				●		●			●						●	●			●	●	●	●		●		

FIGURE D-19A ***DIAGNOSTIC TECHNIQUES VS. DIAGNOSTIC EQUIPMENT COMPLEMENT A***

DIAGNOSTIC TECHNIQUES \ DIAGNOSTIC EQUIPMENT	Ammeter	Logic Checkout System	D/A Converter	Decade Capacitor	Decade Resistor	Digital Multimeter	Function Generator	Op-Amp Board	Handheld Multimeter	Logic Analyzer	Logic Clip	Logic Probe	Logic Pulser	Oscilloscope	Probe Bundles	Programmable Supplies	Pulse Generator	Signature Analyzer	Spectrum Analyzer	Sweep Oscillator	Universal Counter	Microcomputer	ATE Software	Expert System Software		
Continuity Check						●			●						●							●	●			
Current Trace	●								●						●							●	●			
Curve Trace			●				●	●						●	●		●				●	●	●			
Freq Response Check			●	●	●		●	●						●	●		●				●	●	●			
Gain Check			●	●	●	●	●	●	●					●	●	●	●				●	●	●			
Interactive Rate Check										●					●							●	●			
Isolation Check	●				●	●			●						●	●						●	●			
Load Check	●				●	●			●						●							●	●			
Logic Checkout										●	●	●	●		●		●	●				●	●			
Logic Timing Trace			●							●	●	●	●		●		●	●				●	●			
Logic Trace			●							●	●		●		●		●	●				●	●			
Polarity Check						●									●							●	●			
Power Check	●					●			●						●							●	●			
Software Analysis			●							●					●							●	●			
Waveform Analysis				●		●	●		●					●	●	●					●	●	●			

FIGURE D-19B ***DIAGNOSTIC TECHNIQUES VS. DIAGNOSTIC EQUIPMENT COMPLEMENT B***

DIAGNOSTIC TECHNIQUES / DIAGNOSTIC EQUIPMENT	Ammeter	Logic Checkout System	D/A Converter	Decade Capacitor	Decade Resistor	Digital Multimeter	Function Generator	Op-Amp Board	Handheld Multimeter	Logic Analyzer	Logic Clip	Logic Probe	Logic Pulser	Oscilloscope	Probe Bundles	Programmable Supplies	Pulse Generator	Signature Analyzer	Spectrum Analyzer	Sweep Oscillator	Universal Counter	Microcomputer	ATE Software	Expert System Software		
Continuity Check						●			●						●											
Current Trace					●	●			●						●											
Curve Trace							●							●	●											
Freq Response Check				●	●		●							●	●											
Gain Check				●	●	●	●		●					●	●	●										
Interactive Rate Check														●	●											
Isolation Check					●	●			●						●	●										
Load Check					●	●			●						●											
Logic Checkout											●	●	●		●											
Logic Timing Trace											●	●	●		●											
Logic Trace						●					●	●	●		●											
Polarity Check						●									●											
Power Check				●		●			●						●											
Software Analysis															●											
Waveform Analysis				●	●	●	●		●					●	●	●										

FIGURE D-19C *DIAGNOSTIC TECHNIQUES VS. DIAGNOSTIC EQUIPMENT COMPLEMENT C*

2.8 Summary of Diagnostic Equipment Requirements

A summary of the three diagnostic equipment complements developed from MIRA payload equipment is given in Figure 20. The three complements are cross-referenced to MIRA payloads in Figure 21 (Complement A), Figure 22 (Complement B), and Figure 23 (Complement C).

COMPLEMENT A ONLY

Comprehensive Logic Checkout System
Spectrum Analyzer
Sweep Oscillator
Expert System Software

COMPLEMENTS A & B

Ammeter
D/A Converter
General Purpose Op-Amp Boards
Logic Analyzer
Pulse Generator
Signature Analyzer
Universal Counter
Microcomputer

COMPLEMENT B ONLY

ATE Software

COMPLEMENTS A, B, & C

Decade Capacitor
Decade Resistor
Digital Multimeter
Function Generator
Handheld Multimeter
Logic Clip
Logic Probe
Logic Pulser
Oscilloscope
Programmable Supplies
Probe Bundles

FIGURE D-20 ***SUMMARY OF DIAGNOSTIC EQUIPMENT REQUIREMENTS***

MIRA PAYLOADS / DIAGNOSTIC EQUIPMENT	Ammeter	Logic Checkout System	D/A Converter	Decade Capacitor	Decade Resistor	Digital Multimeter	Function Generator	Op-Amp Board	Handheld Multimeter	Logic Analyzer	Logic Clip	Logic Probe	Logic Pulser	Oscilloscope	Probe Bundles	Programmable Supplies	Pulse Generator	Signature Analyzer	Spectrum Analyzer	Sweep Oscillator	Universal Counter	Microcomputer	ATE Software	Expert System Software
Continuous Flow Electrophoresis	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●
Protein Crystal Growth	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●
Droplet Burning	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●
Directional Solidification	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●
Isothermal Solidification	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●
Vapor Phase Crystal Growth	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●
Monodisperse Latex Spheres	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●
Acoustic Containerless	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●

FIGURE D-21 ***MIRA PAYLOADS VS. DIAGNOSTIC EQUIPMENT COMPLEMENT A***

MIRA PAYLOADS \ DIAGNOSTIC EQUIPMENT	Ammeter	Logic Checkout System	D/A Converter	Decade Capacitor	Decade Resistor	Digital Multimeter	Function Generator	Op-Amp Board	Handheld Multimeter	Logic Analyzer	Logic Clip	Logic Probe	Logic Pulser	Oscilloscope	Probe Bundles	Programmable Supplies	Pulse Generator	Signature Analyzer	Spectrum Analyzer	Sweep Oscillator	Universal Counter	Microcomputer	ATE Software	Expert System Software
Continuous Flow Electrophoresis	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	●	
Protein Crystal Growth	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	●	
Droplet Burning	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	●	
Directional Solidification	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	●	
Isothermal Solidification	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	●	
Vapor Phase Crystal Growth	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	●	
Monodisperse Latex Spheres	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	●	
Acoustic Containerless	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●	●	

FIGURE D-22 ***MIRA PAYLOADS VS. DIAGNOSTIC EQUIPMENT COMPLEMENT B***

MIRA PAYLOADS / DIAGNOSTIC EQUIPMENT	Ammeter	Logic Checkout System	D/A Converter	Decade Capacitor	Decade Resistor	Digital Multimeter	Function Generator	Op-Amp Board	Handheld Multimeter	Logic Analyzer	Logic Clip	Logic Probe	Logic Pulser	Oscilloscope	Probe Bundles	Programmable Supplies	Pulse Generator	Signature Analyzer	Spectrum Analyzer	Sweep Oscillator	Universal Counter	Microcomputer	ATE Software	Expert System Software
Continuous Flow Electrophoresis				●	●	●	●		●		●	●	●	●	●	●								
Protein Crystal Growth				●	●	●	●		●		●	●	●	●	●	●								
Droplet Burning				●	●	●	●		●		●	●	●	●	●	●								
Directional Solidification				●	●	●	●		●		●	●	●	●	●	●								
Isothermal Solidification				●	●	●	●		●		●	●	●	●	●	●								
Vapor Phase Crystal Growth				●	●	●	●		●		●	●	●	●	●	●								
Monodisperse Latex Spheres				●	●	●	●		●		●	●	●	●	●	●								
Acoustic Containerless				●	●	●	●		●		●	●	●	●	●	●								

FIGURE D-23 ***MIRA PAYLOADS VS. DIAGNOSTIC EQUIPMENT COMPLEMENT C***

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3.0 CANDIDATE CONCEPTUAL DESIGNS

Based on the A/B/C complements of diagnostic equipment developed in Section 2.0, three candidate conceptual designs were formulated. These three concepts differ primarily in the choice of instruments and are similar in geometry and overall configuration. Figure 24 highlights the differences between concepts.

CONCEPTUAL DESIGN A: EXPERT SYSTEM

Highly-Specialized Instrumenataion
Microcomputer with Expert System Troubleshooting Software
Requires Task-Trainable Operator

CONCEPTUAL DESIGN B: Automated Test Equipment (ATE) SYSTEM

Standard Instrumentation
Microcomputer with Slave (ATE) Software
Requires Technician - Level Operator

CONCEPTUAL DESIGN C: MANUAL TEST EQUIPMENT SYSTEM

Most Generic Instrumentation
No Microcomputer or Software
Requires Commlink/Manual/Special Training

FIGURE D-24 ***CANDIDATE CONCEPTUAL DESIGN FEATURES***

3.1 Conceptual Design A: Expert System

Candidate Conceptual Design A, identified as the Expert System Configuration, contains software which is capable of learning to troubleshoot systems. A database of all observed failure modes, diagnostic techniques, and maintenance requirements is used to build an interactive troubleshooting tree which can prompt the operator if current symptoms/conditions match a previous observation. If the system is not familiar with a particular problem, it will wait until the problem is fixed and then query the operator for sufficient detail to recognize the new situation in the future. An example dialogue is given in Figure 25. A drawing of the Expert System concept is found in Figure 26.

```
Symptom?
  - Readings inconsistent with observed values
Recheck observed values, call out OK/NOK?
 - OK
Sensor type?
  - Thermocouple
Check thermocouple against known temperature,
     call out OK/NOK?
 - OK
Payload?
 - ADSF
Thermocouple function?
  - Furnace status
Remove thermocouple preamplifier board from slot
    6, unit 3, ADSF rack, call out DONE?
 - Done
Power up following instruments: oscilloscope,
     function generator, digital multimeter, call out
    DONE?
 - Done
Connect oscilloscope channel 1 to T/C preamp as
     follows, call out DONE:
```

FIGURE D-25 *EXPERT SYSTEM USER DIALOGUE*

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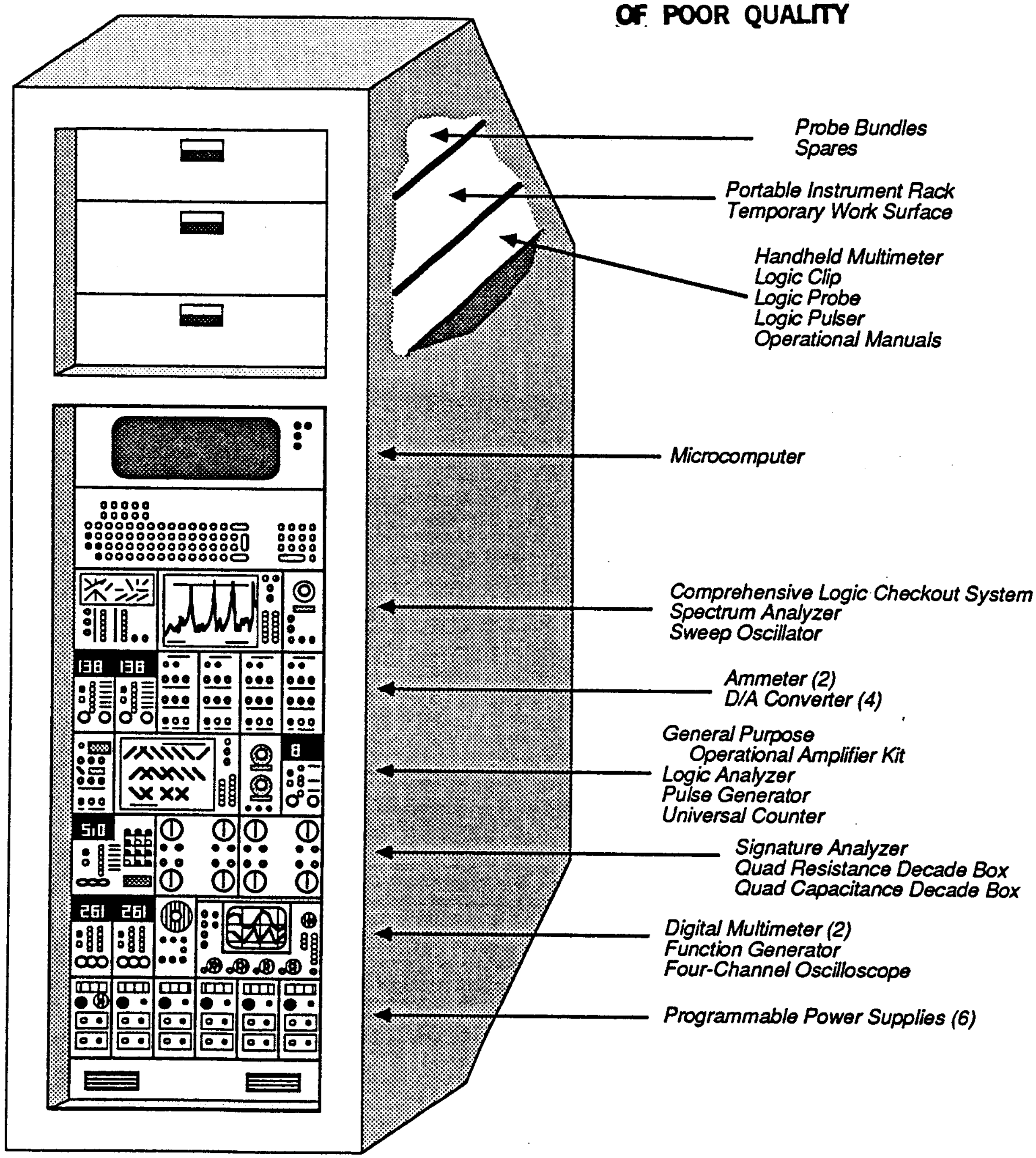

FIGURE D-26 *EXPERT SYSTEM CONFIGURATION*

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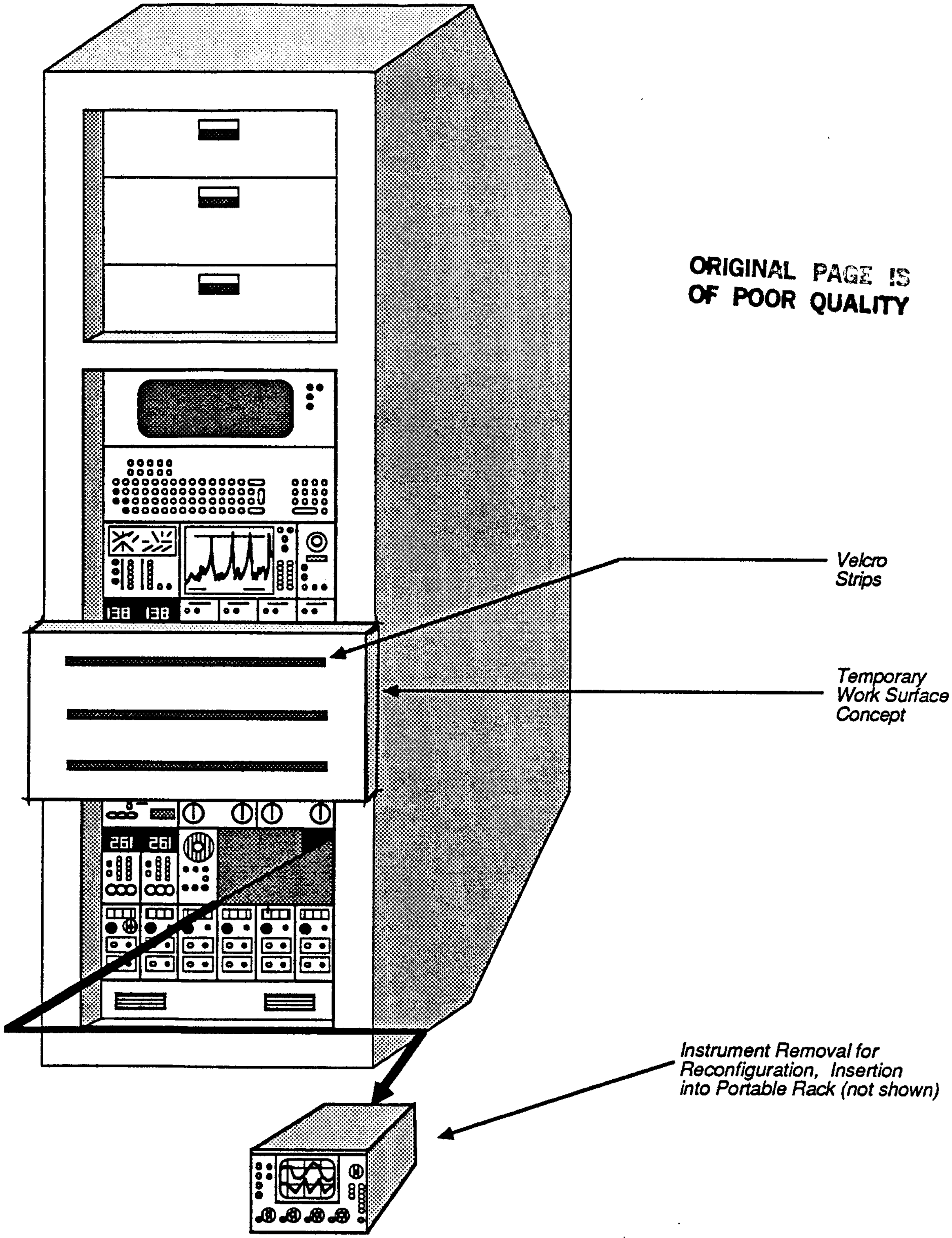

FIGURE D-26A *DETAILS OF EXPERT SYSTEM CONFIGURATION*

EXPERT SYSTEM SPECIFICATIONS

Instrumentation:

Comprehensive Logic Checkout System: Logic verification involves the stimulation of input pins on a chip under test with a known set of input vectors to produce and capture a set of output vectors. Comparing desired with actual outputs identifies faults in the chip. In addition, parametric evaluation of logic to precisely characterize timing and level parameters is essential in narrowing down potential failure modes. Considerable time is spent setting up discrete instruments to debug a chip, typically with logic analyzer, logic pulser, and various peripheral components. A single-package instrument is needed which can clamp over a DIP (Dual Inline Package) and run the necessary input/output/function timing and level tests.

Spectrum Analyzer: Complex frequency domain analysis such as out-of-band noise evaluation, cross modulation detection, and non-linear frequency response and distortion often exceed the capabilities of the oscilloscope. The solution is a Spectrum Analyzer, which provides a gradicule output of system waveforms, filtered and frequency-swept over the range of interest.

Sweep Oscillator: The swept oscillator is basically a frequency-swept function generator, used in applications where inputs have to be varied to stimulate suspect circuit response. These are most commonly used in detecting attenuation null points, testing circuit or device frequency response, and troubleshooting analog-to-digital conversion problems.

Ammeter(s): Some high-current applications may exceed the dynamic response of the standard digital multimeter, and a general purpose ammeter (wide-range) will satisfy these needs. Two should be included for complex network analysis in conjunction with the Spectrum Analyzer and Programmable Power Supplies.

Digital-to-Analog Converter(s): Needed to complement A/D functions and to convert digital control system signatures into oscilloscope/operational amplifier format. Four should be supplied in this configuration.

General-Purpose Operational Amplifier Boards: The hybrid nature of most small control systems implies actuator testing using simple analog control circuitry. A small-scale general purpose OP-AMP board should be available, reconfigurable for the full range of analog computing functions, perhaps to include as many as six separate control outputs. Such a boardset would be easily stored inand integral storage locker, and would most likely be constructed by the integration contractor. Computer interfacing for slave testing would require enough reciprocal A/D channels to service each control input and output.

Logic Analyzer: Regardless of the complexity of the digital system, the sequential nature of state-driven operation requires exquisite timing. The major portion of digital troubleshooting is diagnosing timing faults of one sort or another (timing-oriented or state-oriented), forcing a degree of complexity and effort beyond benefit on convential analog instrumentation. Since time will be limited, a logic analyzer is essential for state and timing analysis (complementing and extending the capability of the signature analyzer).

Programmable Power Supplies: Wide-range variable power supplies are essential to functional testing and can also be used to locate power supply problems by functional substitution. Programmable power supplies are handled and specified somewhat differently, providing standard power supply outputs along with ramp, step, and impulse functions which are needed for intermittent fault detection and slave cycling.

Pulse Generator: Used for parametric analysis, such as clocking simple logic circuits, simulating precisely-timed logic bursts or discrete analog inputs. Essentially in the same function category as sweep oscillators and function generators, except that it provides bursts (pulses) as opposed to CW (Continuous Wave) or SWO (Square Wave Oscillator) outputs. Used for in-line analysis, almost impossible to use more than one at a time and interpret results.

Signature Analyzer: High-density intelligent logic systems are roughly as difficult to service as a mainframe computer system, a problem often enhanced by the "homebrew" nature of many such units. The signature analyzer detects and displays the unique digital signatures (word patterns) in the bit-stream at any data node, permitting the "end-to-end" in-circuit analysis typically employed in troubleshooting analog systems. Tracing similar patterns with primitive analog equipment requires 20 to 30 times the effort and is prone to error. One unit is sufficient for fundamental digital system testing.

Universal Counter: Counts frequencies, impulses, etc. Essential for attentuation of test equipment and quick-look elimination during in-circuit testing. Low fidelity required, should expect to use two off and on over the entire troubleshooting process.

Decade Resistors, Capacitors: Rarely does one escape from a complex analog troubleshooting session without establishing a test circuit to perturb input and/or output signals in the interest of evaluating circuit response. The applications of simple resistance/capacitance sources are virtually unlimited. The complexity of these test networks typically requires four each R&C decade boxes.

Digital Multimeter(s): DMMs at high integration offer full range of AC/DC voltage measurements, current and resistance measurements, and extended precision ATE operations. Other applications include signal and level tracing, power measurements, and system loading for measurements made under load. Most common applications are level tracing and resistance measurements, typically requiring two discrete units to stabilize induced circuit loading.

Function Generator: An excellent full-capability function generator produces signals of desired frequency, amplitude, and waveform which are used to simulate input signals over the entire range of analog/digital circuitry. Since the generator is typically inserted in the suspect circuit at one point upstream of the fault, one unit is sufficient for all analyses.

Handheld Multimeter(s): Required for quick-look elimination and troubleshooting of analog circuits and power supply problems. Two should be supplied to provide for black box testing of filters, attentuators, and power supply units.

Logic Clip(s): Instantaneous display of 2 to 16-pin states, clips directly over DIP. Analogous to a multi-channel logic probe for use on IC's. Two are needed for protocol problem troubleshooting.

Logic Probe(s): Handheld version of the pulse generator, usually sending clock and reset pulses as a single-line in-circuit signal. Essential for elimination to select suspect components for functional analyses.

Multichannel Oscilloscope: Required for virtually all signal analysis, including both analog and digital circuit analysis. Most common applications to analog systems are filtering and attentuation system troubleshooting; digital usage as a timing analysis system is supplanted by the logic analyzer in a limited range of situations. Very few applications require less than 4 channels, though more than four typically create an attentuation adjustment problem for the user.

Computing Resources:

Microcomputer System: Expert system software will require a 16-bit microcomputer with approximately 5 Megabytes (MB) of random access memory (RAM), 1 MB of removable mass storage capability, and 40 MB of fixed mass storage capability.

Software: Expert System for fault diagnosis and troubleshooting capable of learning and recognizing system faults and informing user of viable troubleshooting/repair techniques. System should have provisions for learning payload electronics system configurations as well as recognizing basic electronic system types w/o payload relationship. Operating system and language open.

Interface Requirements:

Instruments and microcomputer should interface through a standard bus similar to IEEE-488-1978. Compatibility with CDMS protocols is essential.

Power Requirements:

115 VAC +/- 4% at 5 amps. Should not exceed 1 kiloWatt.

Cooling:

Avionics Cooling Loop of Spacelab is adequate. System should be designed to take maximum advantage of this loop.

Physical:

Should not exceed 100 kg over roughly 1 cubic meter. Instruments should be configured in removable format to allow changeout of eye-level panels for convenience in troubleshooting. Overall system must conform to Space Station rack structure.

Safety Interlocks:

Standard safety procedures for instrument power supplies should be adequate. System should have power interlocks to limit number of instruments simultaneously powered on; limited the number of powered slots would be most effective method.

EMI Shielding:

The system will require shielding at top, bottom, and sides to prevent EMI in adjacent racks. Forward and rear EMI will not be significant. Internal shielding is not required.

Additional Accessories:

Portable instrument rack carrying up to 6 single-wide instruments, to be stowed until needed. Temporary work surface needed, possibly clamping to front of rack or to handrails; stowed until needed. Probe bundles for each instrument.

3.2 Conceptual Design B: ATE System

Candidate Conceptual Design B, denoted as the ATE System, is composed primarily of slave-test capable instrumentation. Repetitive tests can be programmed into the system to run unattended. Results are stored on the microcomputer permanent media and retrieved as desired. Typical intermittent failure modes require a number of iterations to isolate the faulty component. An example of a typical test is given in Figure 27. A drawing of the ATE System is given at Figure 28.

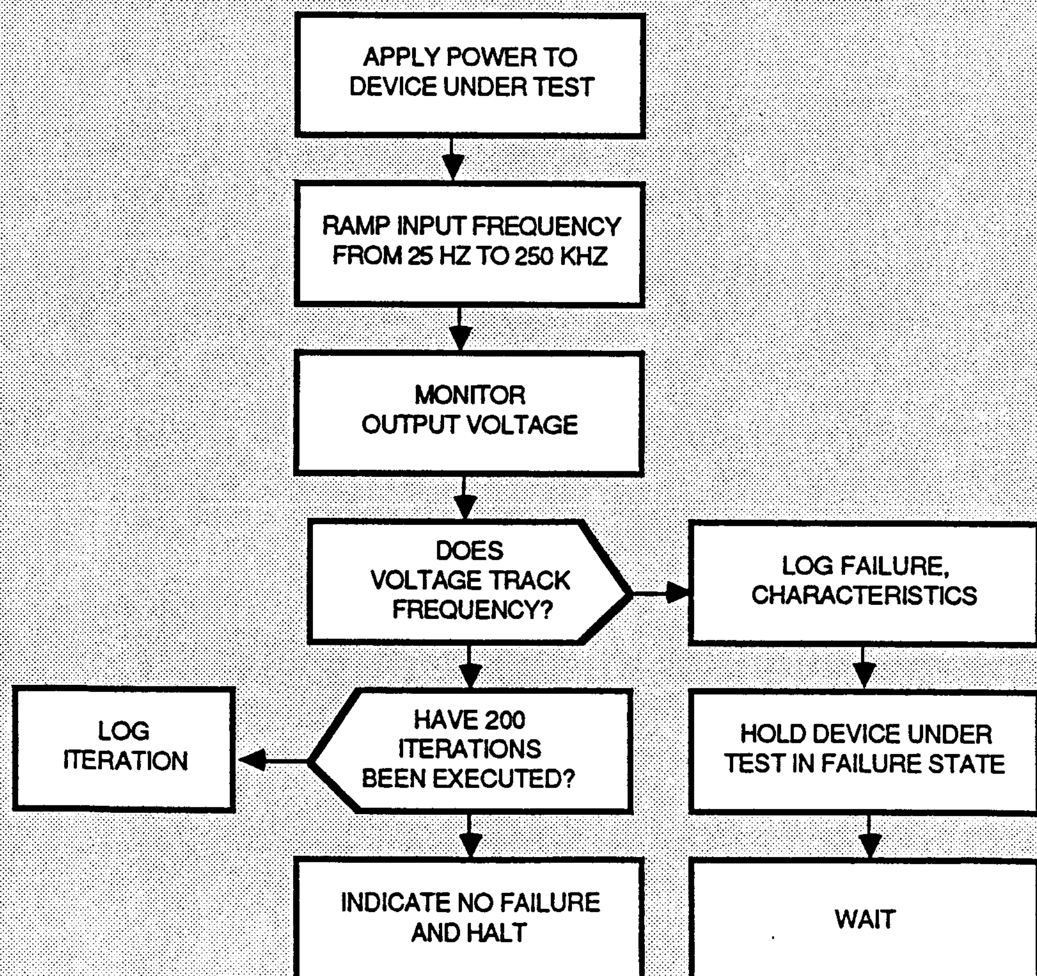

FIGURE D-27 ***TYPICAL ATE TEST***

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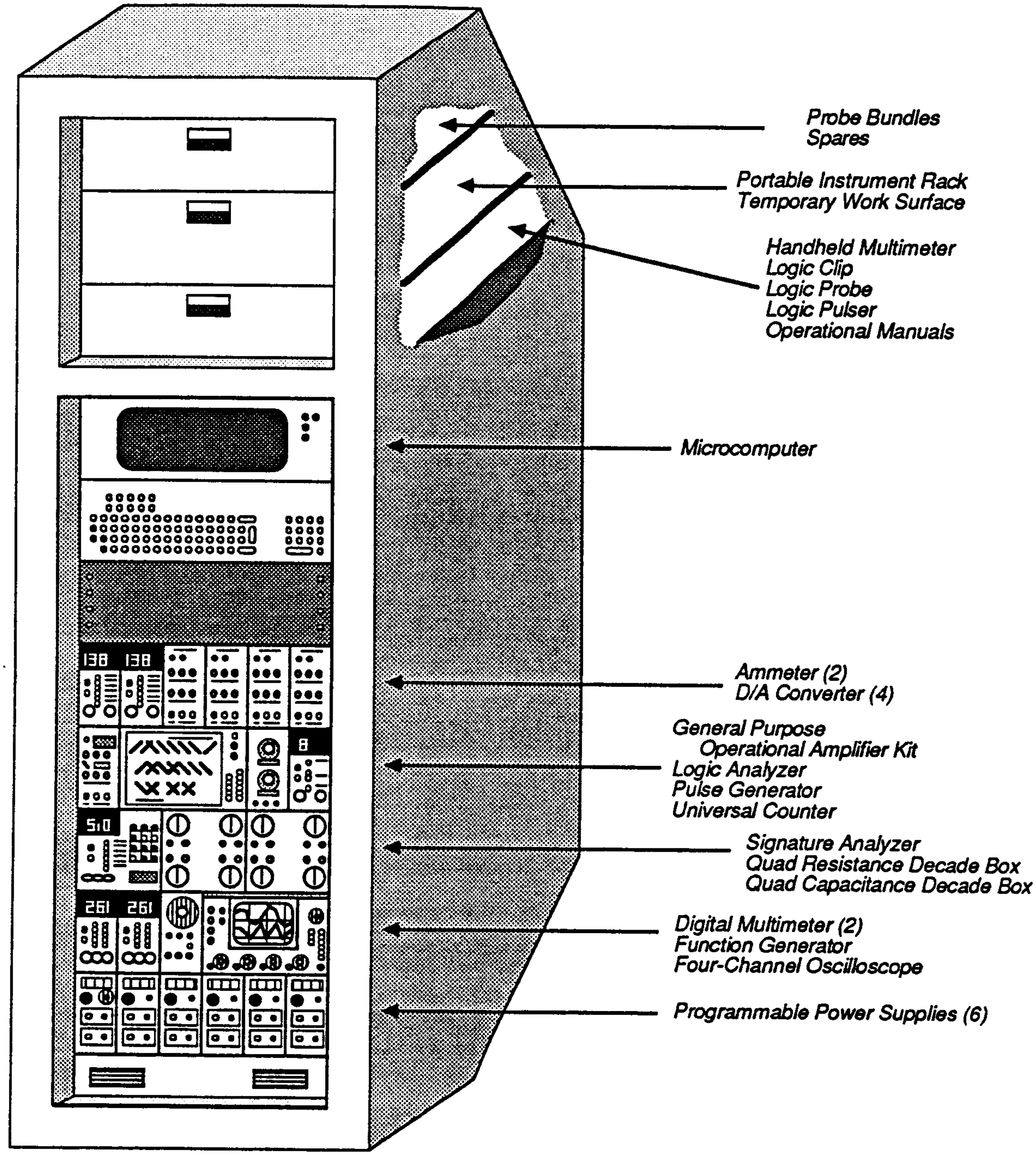

FIGURE D-28 *ATE SYSTEM CONFIGURATION*

ATE SYSTEM SPECIFICATIONS

Instrumentation:

Ammeter(s): Some high-current applications may exceed the dynamic response of the standard digital multimeter, and a general purpose ammeter (wide-range) will satisfy these needs. Two should be included for complex network analysis.

Digital-to-Analog Converter(s): Needed to complement A/D functions and to convert digital control system signatures into oscilloscope/operational amplifier format. Four should be supplied in this configuration.

General-Purpose Operational Amplifier Boards: The hybrid nature of most small control systems implies actuator testing using simple analog control circuitry. A small-scale general purpose OP-AMP board should be available, reconfigurable for the full range of analog computing functions, perhaps to include as many as six separate control outputs. Such a boardset would be easily stored inand integral storage locker, and would most likely be constructed by the integration contractor. Computer interfacing for slave testing would require enough reciprocal A/D channels to service each control input and output.

Logic Analyzer: Regardless of the complexity of the digital system, the sequential nature of state-driven operation requires exquisite timing. The major portion of digital troubleshooting is diagnosing timing faults of one sort or another (timing-oriented or state-oriented), forcing a degree of complexity and effort beyond benefit on convential analog instrumentation.

Programmable Power Supplies: Wide-range variable power supplies are essential to functional testing and can also be used to locate power supply problems by functional substitution. Programmable power supplies are handled and specified somewhat differently, providing standard power supply outputs along with ramp, step, and impulse functions which are needed for intermittent fault detection and slave cycling.

Pulse Generator: Used for parametric analysis, such as clocking simple logic circuits, simulating precisely-timed logic bursts, or emulating discrete analog inputs.

Signature Analyzer: High-density intelligent logic systems are roughly as difficult to service as a mainframe computer system, a problem often enhanced by the "homebrew" nature of many such units. The signature analyzer detects and displays the unique digital signatures (word patterns) in the bit-stream at any data node, permitting the "end-to-end" in-circuit analysis typically employed in troubleshooting analog systems. Tracing similar patterns with primitive analog equipment requires 20 to 30 times the effort and is prone to error. One unit is sufficient for fundamental digital system testing.

Universal Counter: Counts frequencies, impulses, etc. Essential for attentuation of test equipment and quick-look elimination during in-circuit testing. Low fidelity required, should expect to use two off and on over the entire troubleshooting process.

Decade Resistors, Capacitors: Rarely does one escape from a complex analog troubleshooting session without establishing a test circuit to perturb input and/or output signals in the interest of evaluating circuit response. The applications of simple resistance/capacitance sources are virtually unlimited. The complexity of these test networks typically requires four each R&C decade boxes.

Digital Multimeter(s): DMMs at high integration offer full range of AC/DC voltage measurements, current and resistance measurements, and extended precision ATE operations. Other applications include signal and level tracing, power measurements, and system loading for measurements made under load. Most common applications are level tracing and resistance measurements, typically requiring two discrete units to stabilize induced circuit loading.

Function Generator: An excellent full-capability function generator produces signals of desired frequency, amplitude, and waveform which are used to simulate input signals over the entire range of analog/digital circuitry. Since the generator is typically inserted in the suspect circuit at one point upstream of the fault, one unit is sufficient for all analyses.

Handheld Multimeter(s): Required for quick-look elimination and troubleshooting of analog circuits and power supply problems. Two should be supplied to provide for black box testing of filters, attentuators, and power supply units.

Logic Clip(s): Instantaneous display of 2 to 16-pin states, clips directly over DIP. Analogous to a multi-channel logic probe for use on IC's. Two are needed for protocol problem troubleshooting.

Logic Probe(s): Handheld version of the pulse generator, usually sending clock and reset pulses as a single-line in-circuit signal. Essential for elimination to select suspect components for functional analyses.

Multichannel Oscilloscope: Required for virtually all signal analysis, including both analog and digital circuit analysis. Most common applications to analog systems are filtering and attentuation system troubleshooting; digital usage as a timing analysis system is supplanted by the logic analyzer in a limited range of situations. Very few applications require less than 4 channels, though more than four typically create an attentuation adjustment problem for the user.

Computing Resources:

Microcomputer System: ATE system software will require an 8-bit microcomputer with approximately 512 kilobytes (KB) of random access memory (RAM), 512 KB of removable mass storage capability, and 10 Megabytes of fixed mass storage capability.

Software: ATE System for automated slave testing would consists of some number of fixed routines for each instrument, with an additional capability to configure new test routines based on instrument control primitives. Software should be menu-driven and must be implemented in machine language to meet timing requirements. Operating system open.

Interface Requirements:

Instruments and microcomputer should interface through a standard bus similar to IEEE-488-1978. Compatibility with CDMS protocols is essential.

Power Requirements:

115 VAC +/- 4% at 5 amps. Should not exceed 1 kiloWatt.

Cooling:

Avionics Cooling Loop of Spacelab is adequate. System should be designed to take maximum advantage of this loop.

Physical:

Should not exceed 100 kg over roughly 1 cubic meter. Instruments should be configured in removable format to allow changeout of eye-level panels for convenience in troubleshooting. Overall system must conform to Space Station rack structure.

Safety Interlocks:

Standard safety procedures for instrument power supplies should be adequate. System should have power interlocks to limit number of instruments simultaneously powered on; limited the number of powered slots would be most effective method.

EMI Shielding:

The system will require shielding at top, bottom, and sides to prevent EMI in adjacent racks. Forward and rear EMI will not be significant. Internal shielding is not required.

Additional Accessories:

Portable instrument rack carrying up to 6 single-wide instruments, to be stowed until needed. Temporary work surface needed, possibly clamping to front of rack or to handrails; stowed until needed. Probe bundles for each instrument.

3.3 Conceptual Design C: Manual System

Candidate Conceptual Design C, the Manual System, consists of general-purpose instrumentation without special features or software. As such, special knowledge of troubleshooting or a comprehensive test procedures manual is required. At best, a stable, dedicated two way communication link is necessary to allow interactive dialogue during troubleshooting operations. Figure 29 diagrams this issue. A drawing of the Manual System configuration is given at Figure 30.

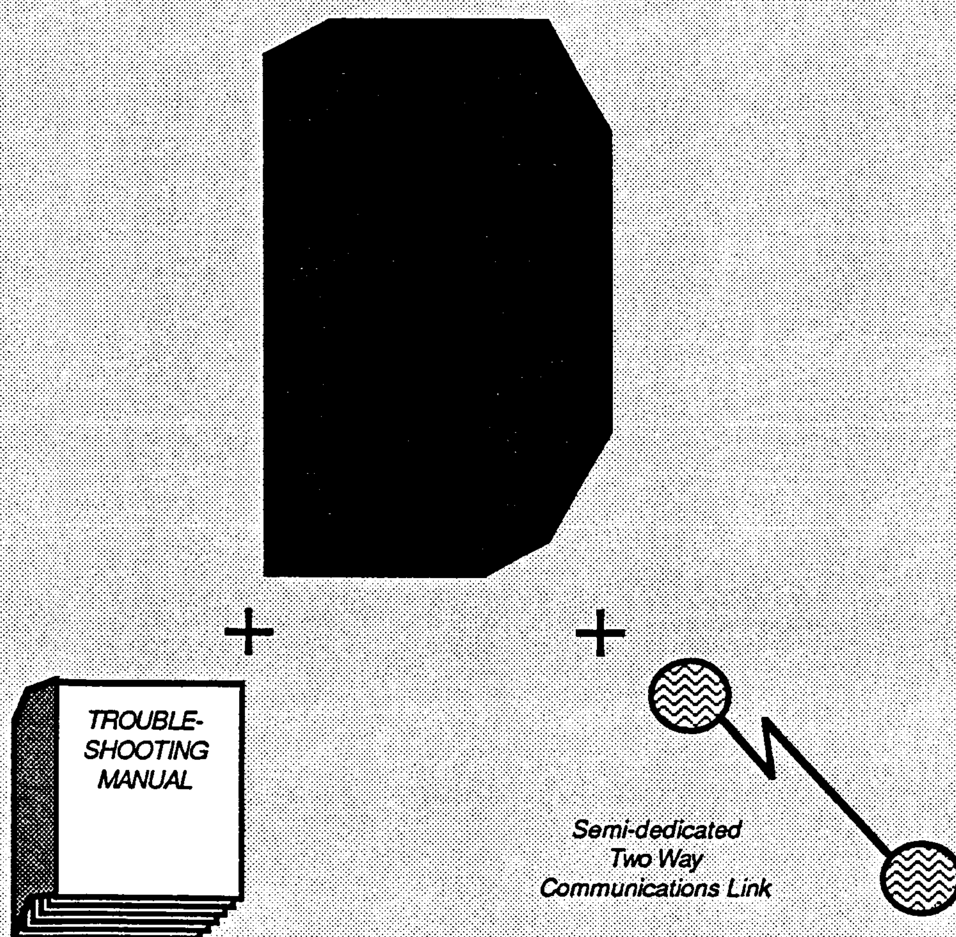

FIGURE D-29 ***USAGE OF MANUAL CONFIGURATION***

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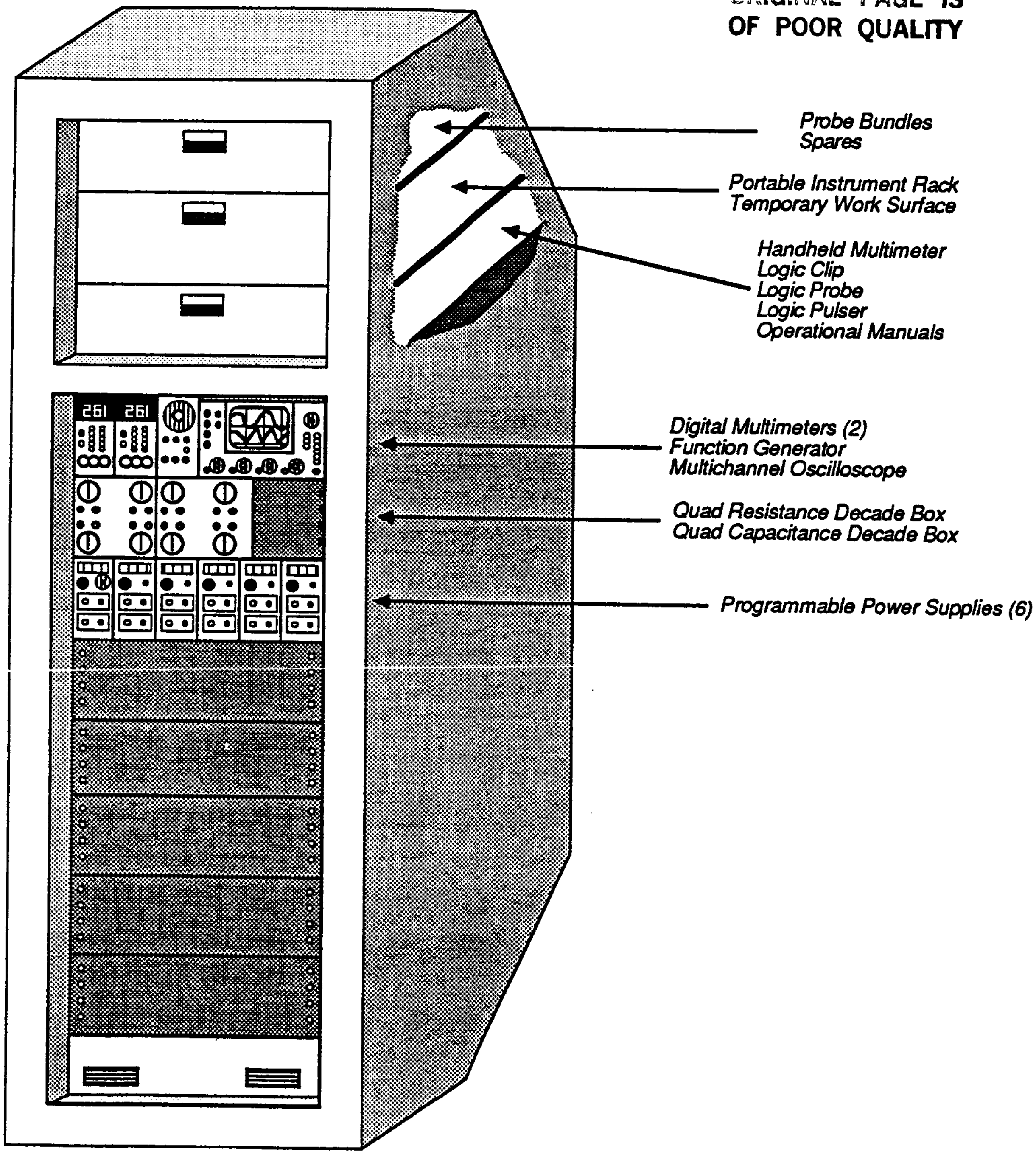


FIGURE D-30 *MANUAL CONFIGURATION*

MANUAL SYSTEM SPECIFICATIONS

Instrumentation:

Programmable Power Supplies: Wide-range variable power supplies are essential to functional testing and can also be used to locate power supply problems by functional substitution. Programmable power supplies are handled and specified somewhat differently, providing standard power supply outputs along with ramp, step, and impulse functions which are needed for intermittent fault detection and slave cycling.

Decade Resistors, Capacitors: Rarely does one escape from a complex analog troubleshooting session without establishing a test circuit to perturb input and/or output signals in the interest of evaluating circuit response. The applications of simple resistance/capacitance sources are virtually unlimited. The complexity of these test networks typically requires four each R&C decade boxes.

Digital Multimeter(s): DMMs at high integration offer full range of AC/DC voltage measurements, current and resistance measurements, and extended precision ATE operations. Other applications include signal and level tracing, power measurements, and system loading for measurements made under load. Most common applications are level tracing and resistance measurements, typically requiring two discrete units to stabilize induced circuit loading.

Function Generator: An excellent full-capability function generator produces signals of desired frequency, amplitude, and waveform which are used to simulate input signals over the entire range of analog/digital circuitry. Since the generator is typically inserted in the suspect circuit at one point upstream of the fault, one unit is sufficient for all analyses.

Handheld Multimeter(s): Required for quick-look elimination and troubleshooting of analog circuits and power supply problems. Two should be supplied to provide for black box testing of filters, attentuators, and power supply units.

Logic Clip(s): Instantaneous display of 2 to 16-pin states, clips directly over DIP. Analogous to a multi-channel logic probe for use on IC's. Two are needed for protocol problem troubleshooting.

Logic Probe(s): Handheld version of the pulse generator, usually sending clock and reset pulses as a single-line in-circuit signal. Essential for elimination to select suspect components for functional analyses.

Multichannel Oscilloscope: Required for virtually all signal analysis, including both analog and digital circuit analysis. Most common applications to analog systems are filtering and attentuation system troubleshooting; digital usage as a timing analysis system is supplanted by the logic analyzer in a limited range of situations. Very few applications require less than 4 channels, though more than four typically create an attentuation adjustment problem for the user.

Interface Requirements:

Instruments and microcomputer should interface through a standard bus similar to IEEE-488-1978. Compatibility with CDMS protocols is essential.

Power Requirements:

115 VAC +/- 4% at 5 amps. Should not exceed 1 kiloWatt.

Cooling:

Avionics Cooling Loop of Spacelab is adequate. System should be designed to take maximum advantage of this loop.

Physical:

Should not exceed 100 kg over roughly 1 cubic meter. Instruments should be configured in removable format to allow changeout of eye-level panels for convenience in troubleshooting. Overall system must conform to Space Station rack structure.

Safety Interlocks:

Standard safety procedures for instrument power supplies should be adequate. System should have power interlocks to limit number of instruments simultaneously powered on; limited the number of powered slots would be most effective method.

EMI Shielding:

The system will require shielding at top, bottom, and sides to prevent EMI in adjacent racks. Forward and rear EMI will not be significant. Internal shielding is not required.

Additional Accessories:

Portable instrument rack carrying up to 6 single-wide instruments, to be stowed until needed. Temporary work surface needed, possibly clamping to front of rack or to handrails; stowed until needed. Probe bundles for each instrument.

4.0 ENGINEERING DEVELOPMENT PLAN

Development plans for each of the three concept configurations were generated using the Macintosh applications tool MacProject. While the computations were performed under MacProject, the resultant schedule and milestone charts were converted to accomodate the format of this document. The charts given in this section were derived from a task network developed under MacProject and were generated by the applications software upon completion of this task network. All costs given in Section 5.0 were baselined against these development plans by the applications software.

		DEVELOPMENT SCHEDULE						
PHASE	TASK DESCRIPTION	CY-86	CY-87	CY-88	CY-89	CY-90	CY-91	CY-92
A	PLANNING AND CONCEPTUAL DESIGN							
B	PRELIMINARY DESIGN & PROTOTYPE TESTING	NO TECHNOLOGY DEVELOPMENT PHASE REQUIRED						
C*	FINAL DESIGN CONCEPT A- CONCEPT B- CONCEPT C-							
D*	FABRICATION AND TESTING							

SPACE STATION PHASE C/D							

*See pp. D-66 through D-68 for detailed development scheaule.

FIGURE D-31 TOP-LEVEL INTEGRATED ELECTRONICS LABORATORY DEVELOPMENT PLAN

FIGURE D-31A ENGINEERING DEVELOPMENT PLAN - CONCEPT A - EXPERT SYSTEM

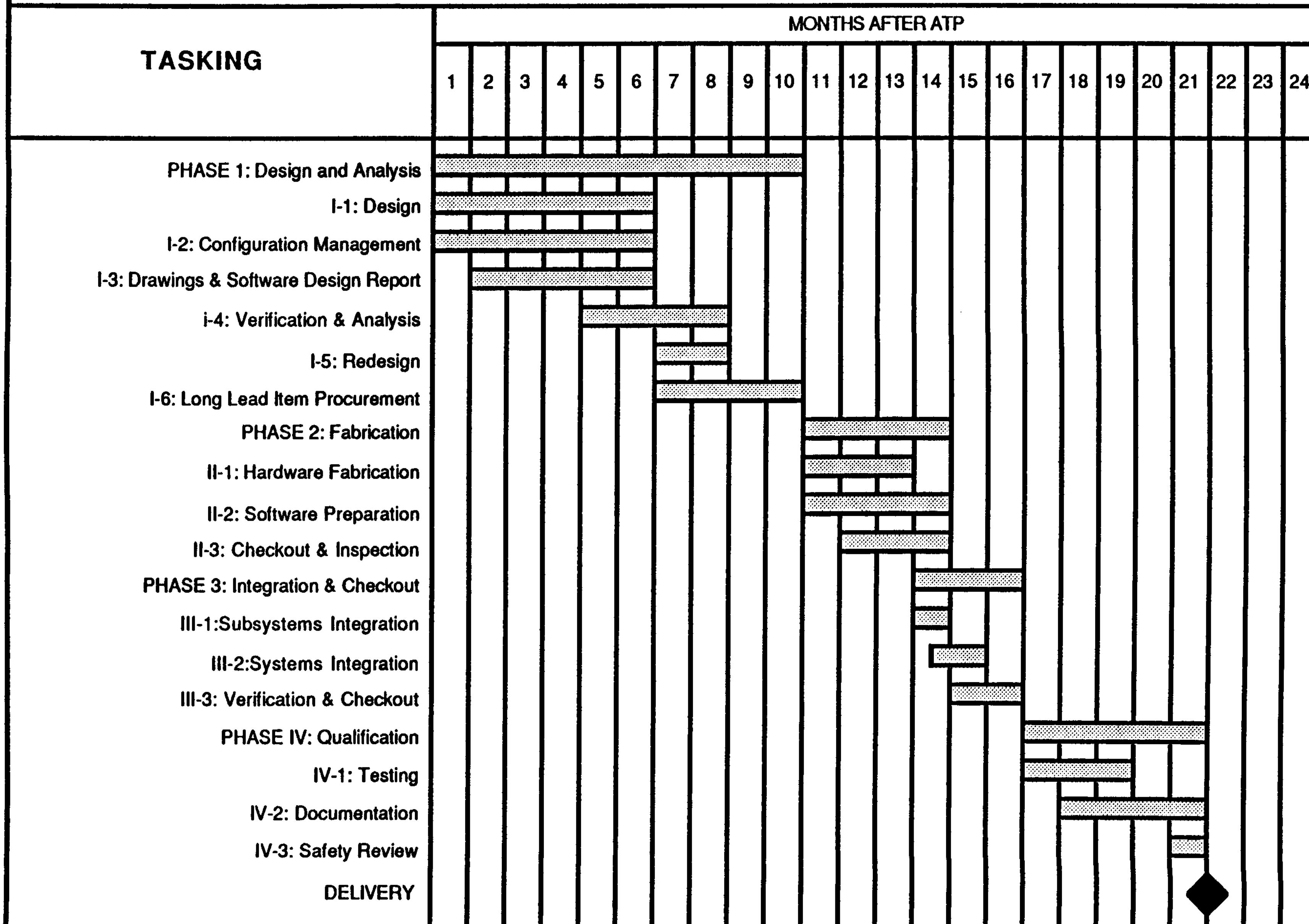


FIGURE D-31B ENGINEERING DEVELOPMENT PLAN - CONCEPT B - ATE SYSTEM

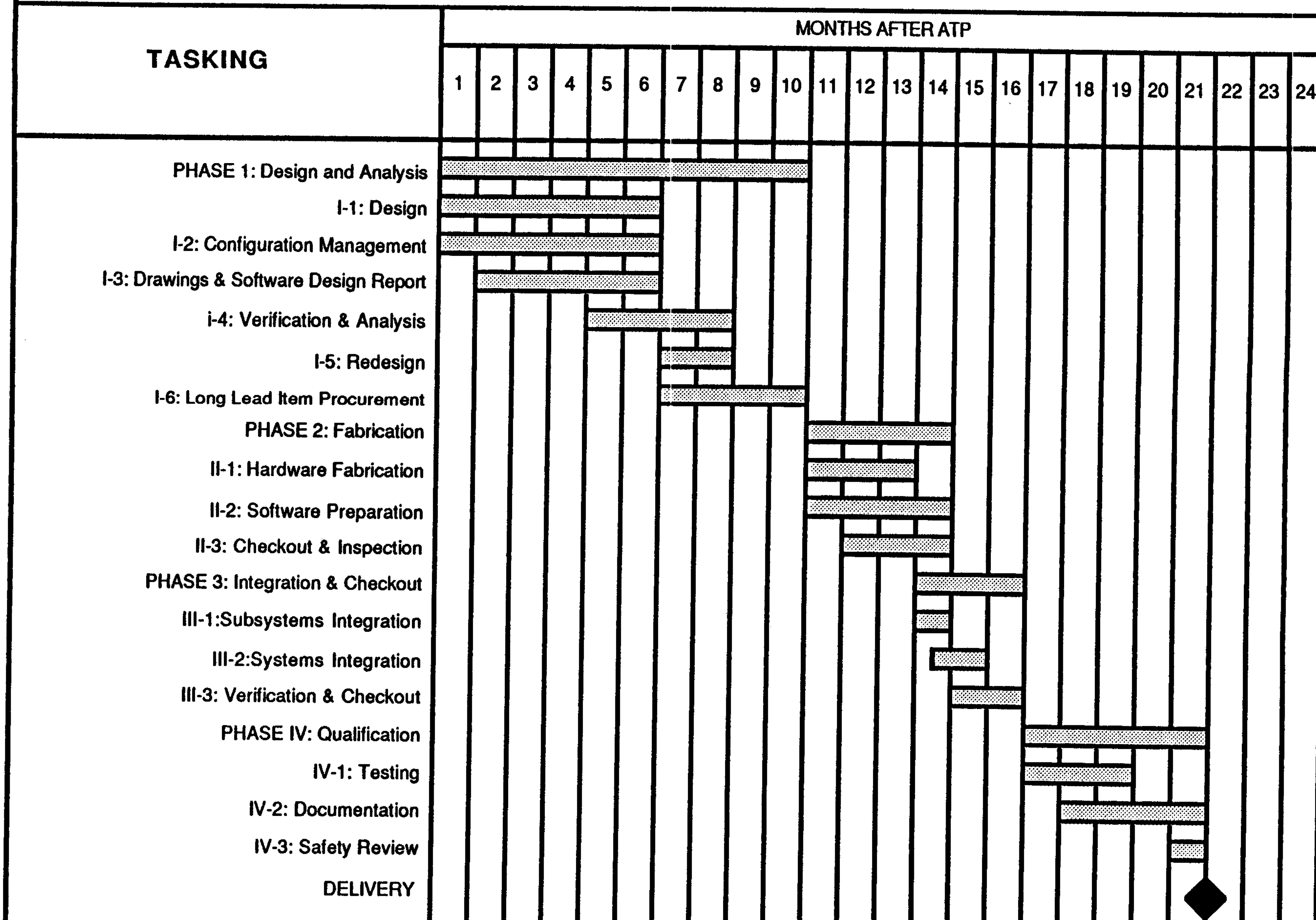
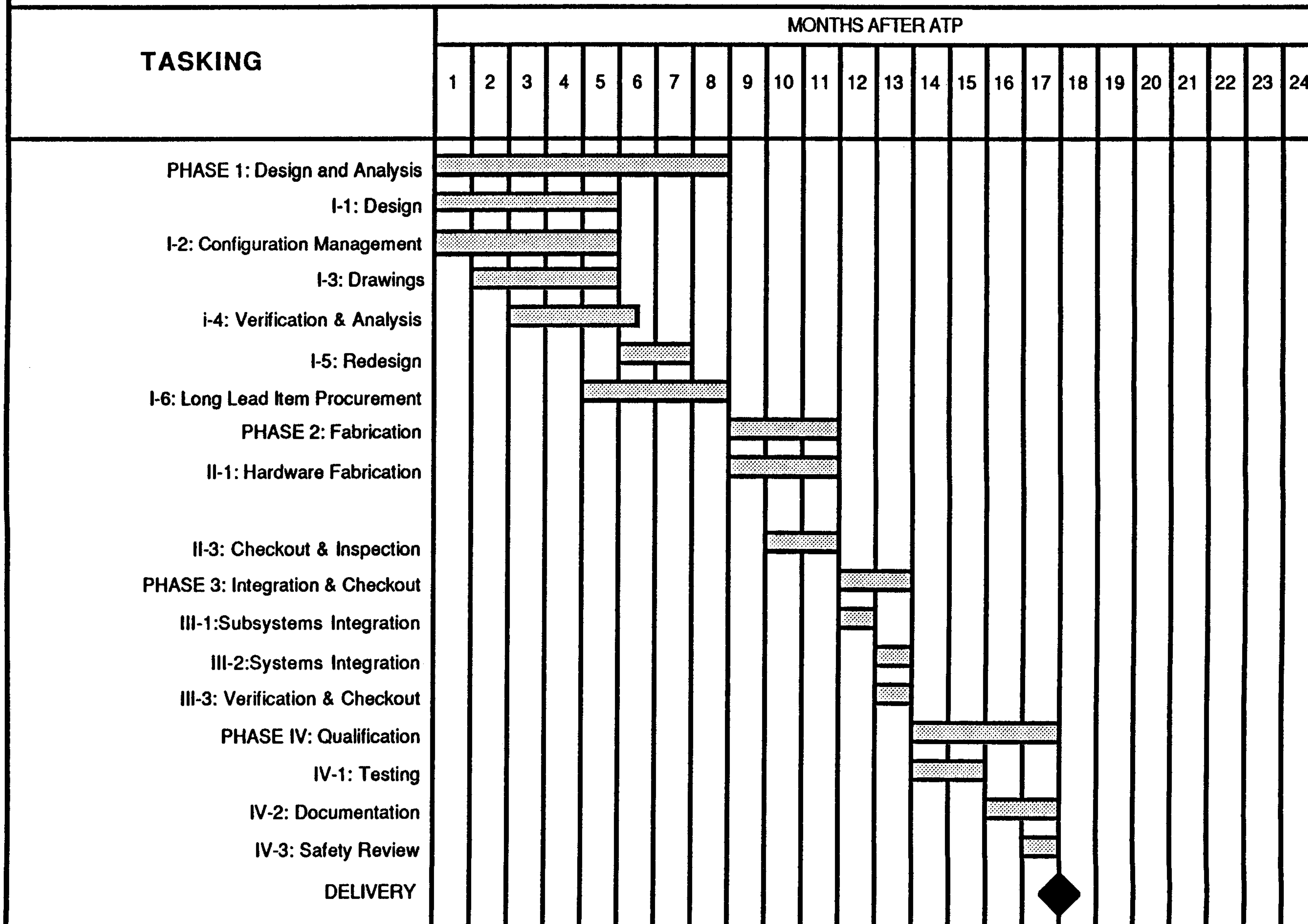


FIGURE D-31C ENGINEERING DEVELOPMENT PLAN - CONCEPT C - MANUAL SYSTEM



5.0 BASELINE COST ESTIMATES

Baseline Cost Estimates for each of the three concept configurations were generated using the development plans formulated under Section 4.0, and through the use of the Macintosh MacProject applications software package. Resource requirements are grouped at the topmost level due to the conceptual nature of the estimate, to include raw materials, engineering, support personnel, and purchased parts. Since the Integrated Electronics Laboratory represents existing hardware technology, there is no requirement for significant technology development or breadboard fabrication. As a result, the cost estimate has been prepared to reflect 1986 dollars required for design, fabrication, testing, and delivery of a prototype flight unit.

* PHASE	* TASK	Engineering Labor	Other Labor	Raw Materials	Purchased Parts	TOTAL
1	1	$15,000.00	$26,000.00	$2000.00	-0-	$43,000.00
1	2	50,000.00	7,800.00	100.00	-0-	57,900.00
1	3	30,000.00	26,000.00	500.00	-0-	56,500.00
1	4	25,000.00	39,000.00	100.00	-0-	64,100.00
1	5	12,500.00	2,600.00	100.00	-0-	15,200.00
1	6	50,000.00	7,800.00	100.00	40,000.00	97,900.00
2	1	20,000.00	15,600.00	2,000.00	1000.00	38,600.00
2	2	65,000.00	10,400.00	-0-	200.00	75,600.00
2	3	50,000.00	5,200.00	200.00	-0-	55,400.00
3	1	7,500.00	7,800.00	100.00	200.00	15,600.00
3	2	10,000.00	7,800.00	100.00	100.00	18,000.00
3	3	30,000.00	2,600.00	200.00	-0-	32,800.00
4	1	75,000.00	7,800.00	200.00	-0-	83,000.00
4	2	10,000.00	33,800.00	500.00	-0-	44,300.00
4	3	5,000.00	2,600.00	100.00	-0-	7,700.00
TOTAL		$455,000.00	$202,800.00	$6,300.00	$41,500.00	$705,600.00

*See Figure D-31A for phase and task descriptions.

FIGURE D-32A

BASELINE COST ESTIMATE FOR CONCEPTUAL DESIGN A: EXPERT SYSTEM CONFIGURATION

PHASE*	TASK*	Engineering Labor	Other Labor	Raw Materials	Purchased Parts	TOTAL
1	1	15,000.00	26,000.00	$2000.00	-0-	43,000.00
1	2	50,000.00	7,800.00	100.00	-0-	57,900.00
1	3	30,000.00	26,000.00	500.00	-0-	56,500.00
1	4	25,000.00	28,600.00	100.00	-0-	53,700.00
1	5	10,000.00	2,600.00	100.00	-0-	12,700.00
1	6	5,000.00	7,800.00	100.00	32,000.00	44,900.00
2	1	20,000.00	11,700.00	1,800.00	1000.00	34,500.00
2	2	45,000.00	10,400.00	-0-	200.00	55,600.00
2	3	40,000.00	5,200.00	200.00	-0-	45,400.00
3	1	7,500.00	6,500.00	100.00	200.00	14,300.00
3	2	10,000.00	7,800.00	100.00	100.00	18,000.00
3	3	25,000.00	2,600.00	200.00	-0-	27,800.00
4	1	55,000.00	7,800.00	200.00	-0-	63,000.00
4	2	10,000.00	33,800.00	500.00	-0-	44,300.00
4	3	5,000.00	2,600.00	100.00	-0-	7,700.00
TOTAL		352,500.00	187,200.00	6,100.00	33,500.00	579,300.00

*See Figure D-31B for phase and task descriptions.

FIGURE D-32B

BASELINE COST ESTIMATE FOR CONCEPTUAL DESIGN B: ATE SYSTEM CONFIGURATION

* PHASE	* TASK	Engineering Labor	Other Labor	Raw Materials	Purchased Parts	TOTAL
1	1	31,500.00	22,360.00	$2000.00	-0-	$55,860.00
1	2	37,500.00	7,800.00	100.00	-0-	45,400.00
1	3	25,000.00	20,800.00	500.00	-0-	46,300.00
1	4	17,500.00	26,000.00	100.00	-0-	43,600.00
1	5	12,500.00	2,600.00	100.00	-0-	15,200.00
1	6	5,000.00	2,600.00	100.00	17,000.00	24,700.00
2	1	20,000.00	13,000.00	1,100.00	1000.00	35,100.00
2	2					
2	3	25,200.00	5,200.00	200.00	-0-	30,600.00
3	1	5,000.00	5,200.00	100.00	100.00	10,400.00
3	2	5,000.00	2,600.00	100.00	100.00	7,800.00
3	3	1,500.00	2,000.00	200.00	-0-	3,700.00
4	1	25,000.00	6,500.00	200.00	-0-	31,700.00
4	2	10,000.00	20,800.00	500.00	-0-	31,300.00
4	3	5,000.00	2,600.00	100.00	-0-	7,700.00
TOTAL		$225,700.00	$140,060.00	$5,400.00	$18,200.00	389,360.00

*See Figure D-31C for phase and task descriptions.

FIGURE D-32C

BASELINE COST ESTIMATE FOR CONCEPTUAL DESIGN C: MANUAL SYSTEM CONFIGURATION

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Space Experiments Office
Lewis Research Center

16. Abstract

Scientific research conducted in the microgravity environment of space represents a unique opportunity to explore fluid processes and materials processing in the virtual abscence of gravity induced forces. In accordance with this opportunity, NASA has initiated the preliminary design of a permanently manned Space Station that will support technological advances in process science and stimulate the development of new and improved materials having applications across the commercial spectrum.

Previous studies have been performed to define from the researcher's perspective, the requirements for laboratory equipment to accommodate microgravity experiments on the Space Station. Functional requirements for the identified experimental apparatus and support equipment were determined. From these hardware requirements, several items were selected for concept designs and subsequent formulation of development plans.

This report documents the concept designs and development plans for two items of experiment apparatus - the Combustion Tunnel and the Advanced Modular Furnace, and two items of support equipment - the Laser Diagnostic System and the Integrated Electronics Laboratory. For each concept design, key technology developments were identified that are required to enable or enhance the development of the respective hardware.

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Materials Processing in Space
Space Station
Space Commercialization

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