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SPACECRAFT FIRE-SAFETY EXPERIMENTS FOR SPACE STATION TECHNOLOGY DEVELOPMENT MISSION

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(Wyle Report No. 68300-1)

April 1988

Contract No. NAS3-25067

Prepared for
National Aeronautics and Space Administration
Lewis Research Center
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FOREWORD

This report was prepared by Wyle Laboratories for the National Aeronautics and Space Administration (NASA), Lewis Research Center, under Contract Number NAS3-25067. The NASA technical manager for this effort was Mr. Robert Friedman, Microgravity Science and Technology Branch, NASA Lewis Research Center, Cleveland, Ohio.

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LIST OF SYMBOLS

(See Note 1)

AFB	Air Force Base
AIAA	American Institute of Aeronautics and Astronautics
CY	Calendar Year
DACS	Data Acquisition and Control System
ECLSS	Environmental Control/Life Support System
EDPE	Electronic Data Processing Equipment
EMI	Electromagnetic Interference
EVA	Extravehicular Activity
FES	Fluids Experiment System
g	Gravitational Acceleration
HX	Heat Exchanger
IOC	Initial Operating Capability
JANNAF	Joint Army-Navy-NASA-Air Force
JSC	(Lyndon B.) Johnson Space Center
LDV	Laser Doppler Velocimeter
LeRC	Lewis Research Center
LIF	Laser Induced Fluorescence
M-Z	Mach-Zehnder
MSFC	(George C.) Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NIR	Near-Infrared
PMMA	Polymethylmethacrylate
PVC	Polyvinyl Chloride
RFI	Radio Frequency Interference
SS	Space Station
STP	Standard Temperature and Pressure
STS	Space Transportation System
T/C	Thermocouple
TDM	Technology Development Mission
WMS	Waste Management System
WPAFB	Wright Patterson Air Force Base

NOTE 1: All other symbols in text have common engineering and scientific usage.

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SPACECRAFT FIRE-SAFETY EXPERIMENTS FOR SPACE STATION TECHNOLOGY DEVELOPMENT MISSION

SUMMARY

Definitions, overall descriptions, and preliminary apparatus and instrumentation requirements are presented for three spacecraft fire-safety experiments appropriate for inclusion in a growth-version of the Space Station. The experiments are as follows:

1. Combustion and Flame Spread of Typical Spacecraft Materials in a Low-Velocity Convective Flow in Low Gravity
2. Fire and Fire-Extinguishant Interactions with Various Fire Scenarios in Low Gravity
3. Smoldering and Deep-Seated Combustion in Low Gravity.

The experiments were selected from an assessment of recommendations for advanced technologies for prevention, detection, and control of fires in spacecraft. The experiments and their facilities are intended to constitute a portion of a Spacecraft Fire Safety Technology Development Mission (TDM). Basic requirements for the mission study are that the Space Station is essential for the accomplishment of the experimental objectives and that the technology being developed is appropriate for the growth version of the Space Station. The advantages of these three experiments are that, not only do they explore problems relevant to the Space Station operation and utilization, but also they constitute tests adaptable to two multiuse facilities installed in the Space Station laboratory module, the Combustion Tunnel Facility and the Combustion Facility. Three additional spacecraft fire-safety experiments, essential precursors to the TDM for near-term performance, are also described as follows:

1. Near-Term Testing of Materials for Combustion and Flame Spread
2. Near-Term Extinguishment of Fires in a Low-Gravity Test Bed
3. Post-Fire Recovery of Sensitive Electrical and Electronic Equipment.

For all the experiments, the study defines accommodations in terms of first-order space, mass, power, consumables, and crew-time estimates. The study also reviews the key problems to be addressed, namely experiment safety hazards, non-intrusive diagnostics development and waste-products disposal. A preliminary task and time schedule for design, development, and experiment fabrication is proposed.

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1.0 INTRODUCTION

With the advent of the NASA Space Station, efforts are once again intensifying in all areas of manned spaceflight safety. New materials and new structural-design concepts have been and continue to be developed and new fire-detection and suppression techniques continue to be assessed. While it is not suggested that the fire safety measures developed during the late 1960s and early 1970s are inappropriate, the number of new technologies in all relevant areas of research (materials, toxicology, medical health/physiology, fire detection/suppression, etc.) provide strong impetus to reassess many spacecraft fire safety design concepts.

The Space Station shall provide a clearly unique set of problems and opportunities. The primary advantage of the Space Station to the research and technology development community is the investigator's opportunity to conduct long-term activities in the low-gravity environment of Earth orbit. Further, the ability to perform these activities with some crew (i.e., payload specialist) involvement is clearly attractive to many potential Space Station users. As the interest in using the Space Station grows, the demand for lowering the cost of access will intensify. However, the demand for access must not diminish in any way the safety imperatives as regards the crew or the nation's capital investment in the Space Station. Thus, it is incumbent on the Space Station designers to continue the development of all safety-related technologies.

Spacecraft fire safety technical concerns were placed in focus at the Spacecraft Fire Safety Workshop sponsored by the NASA Lewis Research Center (Cleveland, Ohio) in August 1986 (Ref. 1). The technical concerns discussed at the Workshop were organized under the following interrelated headings:

- Ignition and Detection of Fires
- Extinguishment
- Toxicity and Human Effects
- Spacecraft Materials and Configurations
- Spacecraft Atmospheres.

A number of specific technology issues and related recommendations were identified at the Workshop for each of these topics. Summaries of the key issues relevant to areas of spacecraft fire safety have been discussed in a recent AIAA paper (Ref. 2). In this paper, the authors reviewed the historical findings of low-gravity combustion experiments and demonstrated the relationship of these findings to spacecraft fire safety. It should be noted that most low-gravity, combustion science experiments conducted to date have utilized earth-based drop towers, aircraft flying Keplerian or ballistic flight paths, and the NASA Skylab in a limited, though important, test (Experiment M479, Ref. 3). Some of the low-gravity combustion findings resulting from experimentation in these various facilities may be tabulated as follows (from Ref. 2):

1. Although the ignition energy required to initiate combustion of typical materials is generally unaffected by gravity, the total incident energy required for ignition may be reduced due to the absence of natural convection heat losses.
2. In the absence of forced-convection flows, the burning rate and flame spread of most solid materials are reduced in low gravity.
3. Low-gravity flames are generally cooler and sootier than comparable flames in normal gravity. Also, other flame "signature" aspects may be different (e.g., color, shape, fluctuations, etc.).
4. Low-gravity flame spread may be enhanced by the forced convection imposed by spacecraft ventilating systems.
5. The burning of some materials in low gravity may result in hot globules of the material scattering and drifting in all directions to adjacent surfaces. (Recent confirmation of this hazard was observed and reported by S. Olson and R. Sotos (Ref. 4) for the dispersion of particles from nylon Velcro).
6. Although low-gravity flames may be cooler than comparable normal-gravity flames, the radiation heat transfer to adjacent surfaces may be higher due to the concentration of high emissivity soot particles.

Several low-gravity combustion research projects are currently in progress and/or are awaiting resumption of the STS Space Shuttle flights for manifesting. Some of these projects that are related to spacecraft fire safety were described by R. Friedman in a presentation at the May 1987 JANNAF Safety and Environmental Protection Subcommittee Meeting (Ref. 5). It was noted that two ground-based projects are to be conducted in the NASA Lewis Research Center drop towers and Learjet airplane. One project is to investigate low-gravity combustion in the presence of low-speed forced flow. The second project is concerned with the analysis and experimental investigation of smoldering (i.e., nonflaming) combustion that may persist in some spacecraft materials such as foam cushions. In addition, three combustion science experiments have been described (Ref. 6) that are planned for eventual Space Shuttle flights. Although these experiments, covering solid-surface combustion, particle-cloud combustion, and droplet combustion, are directed towards fundamental combustion science, their application to the resolution of some fire safety technology issues is compelling.

The purpose of the study presented in this report is to define and develop specific experiments that address the key issues of fire safety for the Space Station (Ref. 7). Six experiments are included. Three of these have near-term significance as precursors for application to eventual Space Station-based missions. The other three constitute a Space Station Technology Development Mission in spacecraft fire safety. The concepts and designs for the TDM experiments include the provisions for multiuse facilities and estimates of accommodation requirements for the Space Station. The TDM experiments are intended for inclusion in a second-generation, or growth-version Space Station. The precursor experiments are intended for the initial Space Station or even the Shuttle.

This report describes the conceptual designs and requirements for the six selected experiments, grouping the near-term and the TDM experiments together, where relevant. The results of the definition studies are applied to derive first-order estimates of experiment accommodations and development plans for the Space Station. Also included is a preliminary assessment of technical limitations and problems to be addressed in the eventual experiment developments.

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2.0 RELEVANCE OF SELECTED LOW-GRAVITY EXPERIMENTS TO SPACECRAFT FIRE SAFETY

2.1 Relationship of Selected Experiments to Fire Safety Issues

A prioritized set of experiments has been identified that is deemed appropriate to the growth era of the Space Station (i.e., post IOC) and that appears to demand the use of the Space Station for experiment basing. These experiment classes are listed in Table 2-1. Three of these low-gravity experiments were selected for a Space Station TDM and are described and identified herein as follows:

1. Fire Safety Aspects Related to the Combustion and Flame Spread of Typical Thicknesses of Candidate Spacecraft Materials ("Combustion and Flame Spread")
2. Evaluation of the Safety and Effectiveness of Candidate Extinguishants in Low Gravity Fire Scenarios ("Fire/Fire Extinguishants Interaction")
3. Fire Safety Aspects Related to the Smoldering and/or Deep-Seated Combustion of Selected Spacecraft Materials ("Smoldering Combustion").

Some of the ground-based and near-term low-gravity precursor activities and experiments are described which may be necessary to support development of the Space Station-based TDM experiments. From an extensive list of potentially desirable near-term experiments (i.e., those low-gravity experiments that could be performed in the 1990 to 1995 timeframe to benefit the Space Station IOC), the following set of three were selected, and they are also described herein:

- Post-Fire Recovery of Electrical and Electronic Equipment in Low Gravity
- Extinguishment of Fires in Low Gravity
- Combustion and Flame Spread in Low Gravity.

2.1.1 Post-Fire Recovery of Electrical and Electronic Equipment in Low Gravity.

The interruption of spacecraft systems as a result of any fire scenario is unwanted and, in the case of many systems, may be critical to the safe continuation of the spacecraft mission and crew safety. Even a false alarm condition could potentially cause a critical system failure or interruption by, e.g., unwarranted release of extinguishant and/or shut-down or blockage of ventilation systems within the spacecraft (i.e., interruption of the ECLSS).

TABLE 2-1. SELECTED FIRE SAFETY RELATED EXPERIMENT CLASSES FOR SPACE STATION BASING

EXPERIMENT CLASS	FIRE SAFETY DISCIPLINE
1. Perform tests to obtain low-gravity, combustion and flame spread data relevant to solid materials and liquids.	Materials and Configurations
2. Perform tests to investigate smoldering combustion of selected materials in low gravity. This experiment class may include deep-seated combustion as well.	Materials and Configurations
3. Determine the chemical mechanisms of Halons and other candidate extinguishants acting in the presence of low-gravity flames.	Fire Extinguisment
4. Accumulate fire signature data from the above series of tests: - flame spectral lines - particle sizes/concentrations - flame temperature and density profiles - combustion product species	Materials and Configurations, Fire Detection
5. Test and evaluate the effectiveness of candidate extinguishants and/or inertants on smoldering and flaming combustion.	Fire Extinguishment
6. Perform research and verification tests of multiple signal (pattern recognition) fire detection systems in situ. This experiment class may also include any candidate fire detectors.	Fire Detection
7. Evaluate post-fire recovery of electrical and electronic components after application of extinguishants.	Fire Extinguishment

Post-fire restoration to operational status of sensitive electrical and electronic components and assemblies is of concern in any environment. The recovery to uninterrupted continuous operation of such equipment in space may be critical. Damage due to fire may terminate the operation of directly affected components and is not, therefore, the subject of this experiment. However, the recovery of all sensitive equipment that had been subjected to the application of an extinguishant in low gravity is of interest. The ways in which extinguishants and combustion by-products can adversely affect sensitive equipment includes at least the following:

a. Electrical shorting caused by condensed liquids and/or soot particles.

b. Coating of components by acids produced in the fire/fire extinguishant interaction.

There are immediate, near-term and long-term concerns relevant to the continued operation of sensitive equipment exposed to a fire scenario. The immediate failure of a component may be due to electrical shorting, arcing, cracking due to heat, obscuration of optical paths due to soot particles, etc. The near- and long-term concerns are more subtle, and eventual failure may be manifested in corrosion, breakdown of insulation coatings, etc.

Clearly, the fire safety-related aspects of these concerns apply to any critical or essential equipment, whether ground-based or spacecraft-based. However, the criticality increases in spacecraft equipment, and the thirty-year-plus lifetime of the Space Station provides additional concern, especially regarding long-term corrosion and other forms of degradation.

2.1.2 <u>Extinguishment of Fires in Low Gravity</u>. Some of the fire safety issues regarding the use of candidate fire extinguishants in spacecraft environments were discussed in some detail by Dr. J. deRis at the Spacecraft Fire Safety Workshop (Ref. 1). Dry powders and water-based foams were discounted (for general use) due to the clear problems related to cleaning the spacecraft internal environment after application of such extinguishants. Note, however, that in the current effort no extinguishant is being fully discounted. For example, the use of water-based foams may well be ideal for use in pre-EVA airlocks where the oxygen concentration may be 30 percent or higher.

Regarding Halon 1301 (Bromotrifluoromethane, CF_3Br), Dr. deRis identified several problems and uncertainties relevant to its use on spacecraft:

- The long-term effects of Halon 1301 to human exposure in its original "neat" state are not fully known.
- The products of combustion from fires being suppressed by the Halons can be highly toxic and are often corrosive.
- Adequate removal of Halon 1301 from the spacecraft atmosphere is not currently possible.
- The Halons are generally ineffective under high oxygen concentrations, such as in hyperbaric chambers, and are also relatively ineffective on some deep-seated and glowing combustion fire scenarios.

The use of CO_2 versus N_2 as an atmosphere inertant and fire suppressant was discussed. Although manned spacecraft have an ability to remove CO_2 from the environment, there are weight penalties in storing CO_2 on the spacecraft, and there may be long-term physiological effects associated with its use. The use of water sprays or high pressure water misting systems was also discussed at the Workshop. Water extinguishants minimize the formation of toxic compounds and can be extremely effective on smoldering and deep-seated combustion. In the application of nearly all candidate extinguishants, there are a variety of "modes" of use. These modes include flooding, manual operation of portable units, misting, directed sprays, etc.

From the above comments and other background material, it is clear that there is currently no consensus on what constitutes a fully appropriate extinguishant and/or extinguishment system for use on manned spacecraft. In the near-term, Halon 1301 flooding and hand-held extinguishers will probably continue to be used; however, it is suggested that water sprays and other extinguishants be considered as well. Toxicity studies, especially those of long-term effects of candidate extinguishants are important, although they can be accomplished, at least in part, on earth under normal-gravity conditions.

2.1.3 **Combustion and Flame Spread in Low Gravity.** A fundamental uncertainty in spacecraft fire safety lies in all aspects of the ignition and burning of solid (condensed phase) materials in low-gravity environments. Basically, without a thorough understanding of the ignition and flame spread resulting from the combustion of typical thicknesses of spacecraft materials in low gravity, it is difficult to conceive realistic fire scenarios and plan appropriate fire detection and suppression measures in the spacecraft.

Only limited low-gravity experimental combustion and flame spread investigations have been performed on candidate materials having thicknesses typical of spacecraft end-use applications. In an effort to address this deficiency, the Combustion and Flame Spread Experiments described herein are designed to address the following technology issues:

1) Scientific validation of flammability testing for materials screening under normal gravity for application to low gravity

2) Identification of combustion by-products obtained in low gravity for use in human physiology and toxicology studies

3) Determination of fire signature data for use in selecting and testing candidate fire detectors.

With regard to the first technology issue, i.e., screening of spacecraft materials for flammability, it is normally deemed conservative to accept materials that have passed a series of earth-based screening tests, including normal-gravity flammability tests (see Ref. 8) for application to low-gravity use. However, there is significant concern that slow convective flows may enhance the spread of diffusion flames even in a low-gravity environment (Ref. 9). In the practical case of the habitable areas of manned spacecraft, there is often a slow, forced convective flow for ventilation and the continuous regeneration of the atmosphere.

The second of the above technology issues, i.e., that concerning the by-products of combustion in low-gravity, is of interest to several fire-safety technical disciplines. Appropriate design of the Space Station's Environmental Control and Life Support Subsystem (ECLSS) requires knowledge of the aerosols and particulate material that must be removed for crew safety. The possibility that combustion in low-gravity environments may produce different toxic compounds and/or different amounts of toxic compounds than observed in normal-gravity combustion cannot be discounted. The short- and long-term effects on human physiology due to exposure to these compounds are also of interest. Also, the toxic compounds produced when various candidate extinguishants interact with flames in low-gravity may be of concern.

Fire detectors and fire detection systems should be selected based on a risk assessment of the potential fire hazards. The choice of the type(s) of fire detectors for use on the Space Station and other advanced spacecraft continues to be an important challenge. Since fire signature data from potential fire hazards are extremely useful in choosing fire detectors/systems, maximum advantage of any combustion and flame spread experiment should be made. The fire signature data under consideration here include at least the following:

- Flame Characteristics (size, shape, temperature, color, etc.)
- Spectral Content of Flame
- Smoke Particle Sizes and Concentrations
- Selected Species Production.

Finally, since there may be some effects on material flammability due to long-term aging, the combustion and flame spread experiment apparatus described herein could be used for accelerated aging evaluations.

2.1.4 Smoldering and Deep-Seated Combustion in Low Gravity. Smoldering is a mode of nonflaming combustion occurring in porous and permeable materials. It is characterized by exothermic thermal degradation of the combustible material followed by combustion (often complete) of the gaseous degradation products, with little emission of visible radiation. It has been observed that a smolder combustion wave propagates through a permeable fuel just as an open flame would, but at a greatly reduced velocity and maximum temperature, i.e., 700-1300K (800-1880°F) for smoldering versus up to 1800K (2780°F) or higher for flaming combustion (Ref. 10). In many respects, smoldering, or non-flaming combustion is similar to deep-seated combustion, and no distinction will be made between smoldering and deep-seated combustion in this report.

Since some spacecraft materials and fire scenarios make smoldering combustion possible, it appears compelling to pursue this technology issue. Smoldering combustion could occur in such diverse material applications as the following:

a) Permeable insulation in aircraft and spacecraft cabins
b) Cushions that are filled with porous or permeable foams, fiber, cloth, etc.
c) Waste bins containing any of the above or other porous materials.

Further, any of the larger spacecraft such as the Space Shuttle/Spacelab, Space Station, etc. will have low- to medium-velocity forced air circulation systems that could enhance smoldering combustion wave propagation and, thus, increase the potential fire safety hazard. In any event, it may be shortsighted to assume that such a hazard can be totally avoided by ground-based testing and materials screening procedures. In fact, it isn't clear at the present what would constitute an adequate ground-based screening test for materials that may smolder in low gravity.

The smolder combustion experiment described herein is intended to address the following scientific and fire safety technology issues:

1) Scientific validation of smolder combustion testing for materials screening under normal-gravity levels for application to low gravity
2) Identification of by-products from low-gravity smoldering combustion to compare their quantity and toxicity with those produced under normal-gravity levels
3) Determination of fire signatures to enhance the data base used for the selection and testing of candidate fire detectors and fire-signature generators
4) Evaluation of the effects of long-term aging on the propensity of a material to support smoldering combustion. (Some materials, such as cellulosics, are more easily ignited with age.)

2.2 Justification for the Space Station Basing of Selected Fire Safety Experiments

The safety of any spacecraft, especially manned spacecraft, must always be of the highest priority. However, the justification for any low-gravity combustion science-related and/or fire safety-related experiment demands consideration of cost versus information returned. The cost of performing such experiments in ground-based drop towers, aircraft flying Keplerian ballistic trajectories, and even sub-orbital ballistic rockets will be modest compared to Space Shuttle- or Space Station-based experimentation. Thus, Space Station basing of any experiment may be unwarranted if the technology involved can be satisfied adequately by other less costly and/or more timely means. Competing technologies will place a major burden on the use of the Space Station's accommodations in all respects (experiment berthing, crew time, power, consumables, etc.).

The approach taken herein relevant to the justification for Space Station-basing of the selected experiments is that current knowledge must demonstrate that the Space Station is essential for the accomplishment of the currently stated objectives. Basically, the need to conduct Space Station-based fire safety-related experiments stems from requirements for relatively long periods of low gravity (of the order of 30 seconds to several minutes), readily controllable environments and other test parameters, experiment sizes that are not highly restrictive, and modest crew interaction. Justification for conducting comparable near-term, low-gravity experiments relevant to fire safety is clearly established if the Space Station-based experiments are justified.

2.2.1 **Combustion and Flame Spread Experiment Justification.** To date, nearly all low-gravity investigations of solid (condensed phase) material ignition and flame spread have been conducted in facilities capable of producing only a few seconds of burning time. For example, typical drop tower facilities produce experimental times of only 1-5 seconds and aircraft parabolic flights produce only slightly longer periods of low gravity (~ 15-25 seconds). Thus, the materials investigated in such facilities are generally very thin so that the ignition and burning time is very short. Generally, ignition occurs in normal gravity with subsequent flame spread in low gravity, and steady-state burning conditions are seldom achieved.

For a thorough understanding of the ignition, combustion and extinction of solid fuels in low gravity, experiment run times of the order of many seconds to a minute or more are needed. Thus, in order to test typical thicknesses of candidate spacecraft materials in low gravity such that ignition, flame spread, extinction, etc. can all be studied thoroughly, experiment run times are required that can only be met by basing the experiment on the Space Shuttle, a free-flyer package, or, ultimately, on the Space Station or a Station-tended facility.

The evolution of a combustion and flame spread experiment, such as is being described herein, may be based on a limited number of Space Shuttle precursor tests. However, access to an experimental apparatus capable of providing the type of data desired may be very difficult, even on the Space Shuttle. In order to perform adequate investigations, the combustion and flame spread apparatus will require interaction by a crewmember. This interaction dictates basing the apparatus within a Spacelab module, further limiting payload accommodation. Thus, although Space Shuttle-based experimental investigations of combustion and flame spread on thermally thick solid fuels are feasible and desirable, the availability of flight opportunities and crewmember involvement is likely to be inadequate.

Because of the limitations associated with Space Shuttle-based experiments, the Combustion and Flame Spread Experiment described herein is deemed highly appropriate for Space Station-basing. Experiment time and crewmember access to the apparatus should permit highly useful determinations of the following data:

- Energy required to initiate ignition
- Ignition transient time and flame spreading rates
- Extinction limits
- Burning rates (mass loss rates)
- Flame characteristics (e.g., size, shape, color, temperature, etc.)
- Types and amounts of combustion intermediates and soot particles (particulate size distribution, particulate concentrations, species, etc.).

2.2.2 Fire/Fire Extinguishants Interaction Experiment Justification. Nearly all low-gravity investigations relevant to the interaction of fires with fire extinguishants and various inertants have been conducted in ground-based drop towers and in aircraft flying ballistic trajectories. Thus, investigations to date have been limited to very brief periods of microgravity, on the order of seconds. These periods do not allow enough time to ignite and establish combustion of the fuel and the subsequent studies of extinguishment. To study the effects of various extinguishants and their application to various combustion scenarios may take several seconds or minutes depending on the type of fuel and application. These potentially long run times can only be met by basing the experiment/facility on the Space Shuttle, a free-flyer or, ultimately, on the Space Station or a Space Station-tended facility.

2.2.3 Smoldering Combustion Experiment Justification. There is a continuing interest in performing near-term smoldering combustion research by use of multiple parabolic trajectories provided by, e.g., the NASA KC-135 aircraft, and there are plans for extending this effort to the Space Shuttle. Experiment process time, as well as the low-gravity condition, is critically important to smolder combustion experiments. Smolder propagation velocities are typically of the order of 5 to 50 cm/hr (2-20 in/hr) (Ref. 11). In low gravity, even in the presence of forced convection, propagation may be lower, implying negligible combustion-wave movement in the test facilities whose test time at low-gravity is only a few seconds. Presently planned aircraft parabolic flight testing is justified, however, on the basis of early availability and the anticipation that much useful information may be obtained by flying such an experiment through a series of parabolic trajectories and subsequently correlating the measurements (smolder velocity and temperature) with the recorded gravity vector. Aircraft basing of the smolder combustion experiment is further justified as an experimental precursor to an eventual Space Shuttle experiment to provide valuable information toward the final design and performance of the experiment.

An extensive concept definition study (Ref. 10) relative to the Spacelab-basing of smoldering experiments was prepared by M. Summerfield and his associates at the Princeton Combustion Research Laboratories. Recognizing the limitations of ground-based smoldering experiments, they designed a set of co-current and counter-current smolder experiments to be conducted on board Spacelab in a combustion chamber facility.

The smoldering experiments under planning for aircraft parabolic flights and the Space Shuttle/Spacelab are appropriate precursors to any Space Station-based studies of a similar nature. Space Station smoldering combustion experiments may be justified from the standpoint of fire safety, if the related technology issues are not adequately resolved by the planned precursor efforts.

3.0 CONCEPT DESIGNS OF SELECTED SPACECRAFT FIRE SAFETY EXPERIMENTS

An overall description of three spacecraft fire safety-related experiments is provided in this section. Taken together, these three low-gravity experiments constitute a proposed Space Station-based Technology Development Mission (TDM): Spacecraft Fire Safety. Although the emphasis herein has been placed on the Space Station-based experiments, the concepts and descriptions of the three near-term low-gravity fire-safety experiments are included within the discussions of the TDM experiments.

It should be noted that all of the experiments described herein (both near-term and Space Station-based) require the use of either of two generic experiment facilities, i.e., the Combustion Tunnel Facility and the Combustion Facility. These experiment facilities are discussed in context with the appropriate fire safety-related experiments.

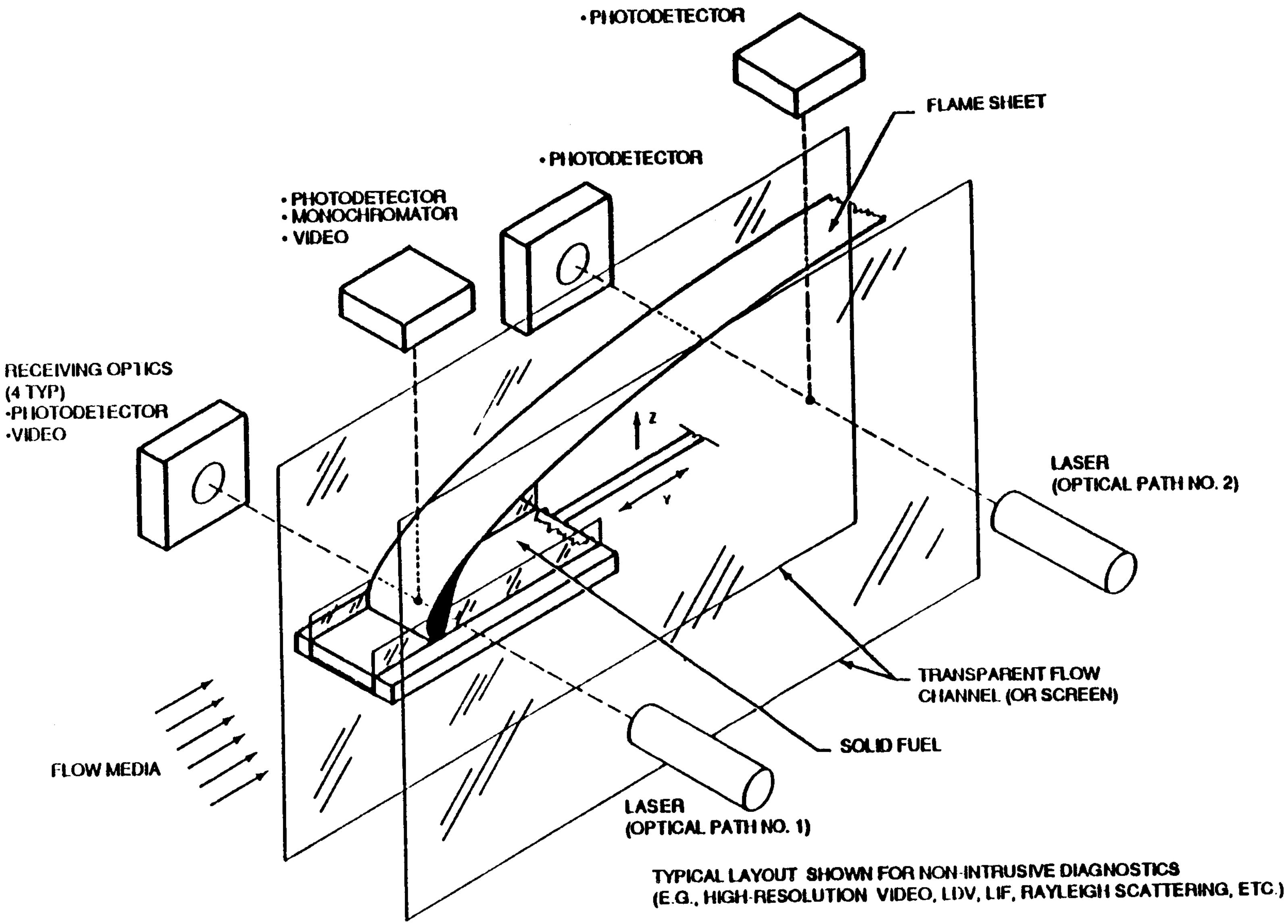
3.1 Combustion and Flame Spread of Typical Spacecraft Materials

3.1.1 Overall Description of the Experiment. The purpose of this experiment is to investigate the details of a number of combustion and flame spread parameters in a low-gravity, low-convective-velocity flow environment. In terms of spacecraft fire safety, the desired output from experiments of this type should include the following information and data:

- Flame shape, temperature and velocity field, color, spread rate, and extinction limits
- Mass loss rate of bulk fuel
- Production of toxic by-products
- Smoke (soot) particle size distribution and number density.

The ability to measure all of these parameters simultaneously during any specific run time is highly desirable, but quite difficult. The types of special instrumentation and diagnostic measurement equipment required for this experiment will be described.

Figures 3.1-1 and 3.1-2 are, respectively, representative of single- and double-sided combustion and flame spread taking place within the test section of a special combustion flow facility. The thermally-thick solid fuels of interest are shown mounted in such a flow facility capable of providing a uniform flow (a flat velocity



TYPICAL LAYOUT SHOWN FOR NON-INTRUSIVE DIAGNOSTICS
(E.G., HIGH-RESOLUTION VIDEO, LDV, LIF, RAYLEIGH SCATTERING, ETC.)

FIGURE 3.1-1. <u>IDEALIZED FLAME SPREAD EXPERIMENT IN COMBUSTION TUNNEL</u>

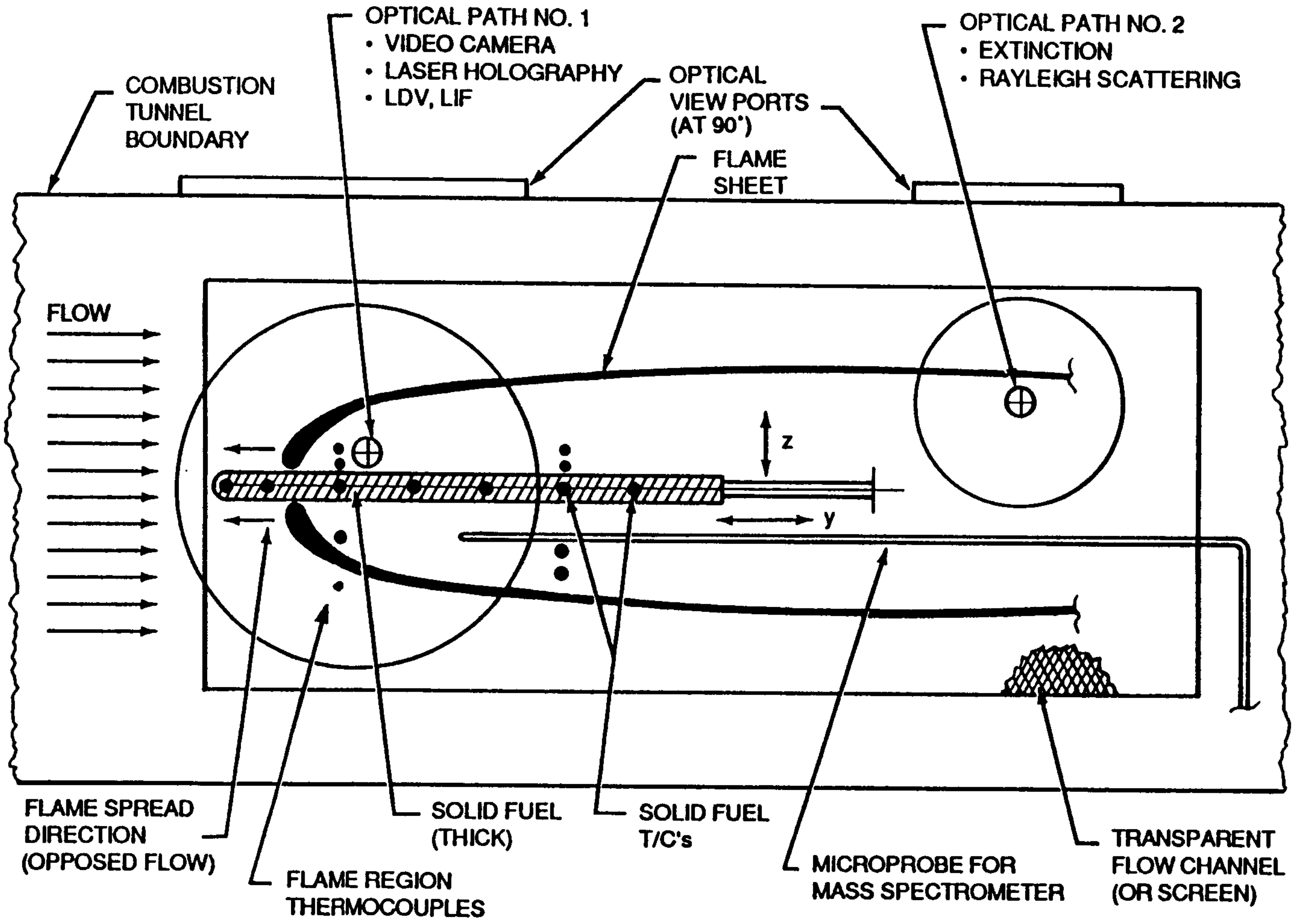


FIGURE 3.1-2. CONCEPT OF COMBUSTION AND FLAME SPREAD EXPERIMENT TEST SECTION

profile) at velocities from ~0.5 cm/sec (1.0 ft/min) up to ~15 cm/sec (30 ft/min). The flow media could include those with compositions and pressures such as the following:

- N_2 with up to 30% O_2 at 70.3 kPa (10.2 psia)
- N_2 with up to 80% O_2 at 101.4 kPa (14.7 psia)
- N_2 with 11-12% O_2 at 202.8kPa (29.4 psia)
- Other inertants with up to 80% O_2 at 101.4 kPa (14.7 psia)

Note that the percentage range of oxygen in the oxidizer gas flow may be from close to 80% to the extinction limit for a particular set of test parameters (estimated at no less than 7% for a pressure of two atmospheres). The actual percentages of oxygen allowable will be determined from safety-related calculations and ground-based tests.

Solid fuel candidates will initially include those for which there is a significant amount of ground-based flame spread data. These materials include cast polymethylmethacrylate (PMMA) and, possibly, some wire insulations (e.g., Teflon and Kapton). The preferred configuration of the PMMA is that of a rectangular plate, while the Teflon and Kapton may be tested in the form of a wire insulation. It should be noted that an additional test option is that of performing the flame spread experiments at selected bulk fuel temperatures. Although not shown herein, this variation could be accomplished by embedding resistance wires in the bulk fuel. A steady and stable fuel temperature is desired before initiation of the combustion process. For example, the desired bulk fuel temperature range for PMMA is from approximately ambient (20°C (68°F)) to 150°C (300°F).

For any given set of flow parameters (velocity, oxidizer gas mixture, and pressure), the solid fuel will be ignited, and the burning and flame spread will proceed in accordance with the established conditions. The most likely means of ignition will be a nichrome resistance heater element located either at the leading or trailing edges of the fuel (as desired).

Throughout the ignition and burning process, a number of measurements can be taken simultaneously. These measurements may consist of a combination of both non-intrusive diagnostics (laser-based optics, video camera, etc.) and intrusive sensors (thermocouples, mass spectrometer microprobe, etc.). As the state of the art progresses, some—if not all—of the intrusive sensors may be replaced with non-contact, optical diagnostics.

During the flame spread over the fuel specimen, the fuel would be held stationary with respect to the instrumentation probes and optical paths. However, after the flame spread is complete, it is suggested that the burning fuel be made to move in the y- and z-directions (i.e., longitudinal and lateral directions, respectively) in order to investigate a profile through the flame. The side view shown in Figure 3.1-2 indicates a minimum of two separate optical paths through the flame, each having also a 90 degree observation angle. The purpose and function of these optical paths will be described more fully in the section on special instrumentation and diagnostic measurement equipment. Also shown in Figure 3.1-2 are schematic locations of several thermocouples and the mass spectrometer microprobe. All of these sensors, as well as the optical paths, would be fixed relative to the flow channel, and only the fuel moves relative to the sensors and optical paths. The flame spread may have to be restricted to one side of the fuel, as shown in Figure 3.1-1, to limit the heat release to practical values.

The solid-fuel samples, sample exchange mechanism and all instrumentation are proposed to be a part of, or related to, a continuous flow facility referred to herein as the Combustion Tunnel Facility. This facility and its major components and peripheral apparatus are described in the next subsection. A completely different technique that could be used to simulate slow convective flow is to move the burning sample at a steady velocity in a quiescent medium. However, this technique is not addressed in this report, since such a procedure does not produce the same flow conditions as that where the flow field is moving over a stationary sample, and since there are a number of practical problems as well (e.g., limited path length, location of diagnostic sensors, etc.).

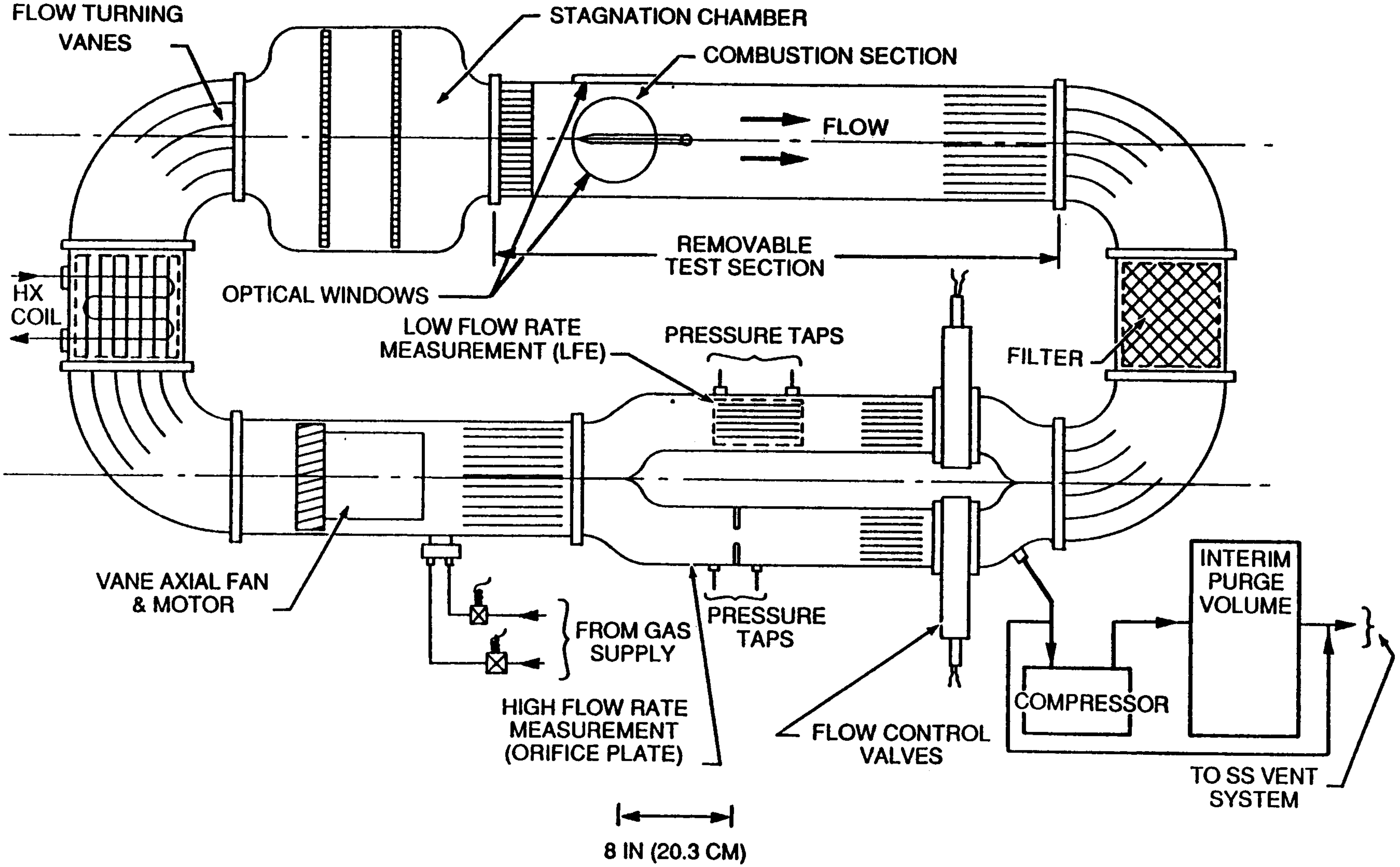
In terms of the desired measurements, the following fundamental techniques are suggested. A video camera recording, or alternatively a hologram recording, would be made through the large optical port. Also, the local velocity field would be measured by means of a laser Doppler velocimeter (LDV) via optical path number 1 along with laser induced fluorescence (LIF) measurements of some combustion by-products (at least the OH radical). Temperature measurements would be obtained at various locations in the flame by means of the thermocouples shown located adjacent to the solid fuel. Optical path number 2 could be used for Rayleigh scattering to monitor the soot particle size distribution and number density. Finally, the mass spectrometer microprobe would be used to monitor a broader range of combustion by-products. If the LDV measurements and the particle seeding that may be necessary are deemed too complex, velocity measurements may be obtained by analyzing the particle tracks on a laser sheet. Further, if the LIF measurements cannot be justified, they would be deleted in favor of the mass spectrometer probe. These simpler diagnostic techniques may be justified for the initial tests.

3.1.2 Basic Apparatus Required for the Experiment. The major apparatus item required for the Combustion and Flame Spread Experiment is a facility referred to herein as the Combustion Tunnel Facility, which was conceived and designed by W. W. Youngblood and described in Reference 12. It is suggested that such a facility could be used for a wide range of fire-safety technology investigations, as well as for its original intent of providing a low-gravity test bed for fundamental combustion and flame-spread studies. A schematic of the Combustion Tunnel is shown as Figure 3.1-3. The facility consists of the following major basic components:

a) Removable test section
b) Fuel sample introduction/retrieval subsystem
c) Flow recirculation components
  - Stagnation (settling) chamber
  - Fan/motor
  - Heat rejection coils
  - Gas makeup and flow filter subsystem
d) Flow rate measurement and control subsystem
e) Interim purge/storage subsystem.

In addition to the fundamental Combustion Tunnel facility, the following items make up the remainder of the basic apparatus:

f) Flow characterization subsystem
g) Flame diagnostic instrumentation
h) Data acquisition and control subsystem (DACS).



SAMPLE EXCHANGE MECHANISM
NOT SHOWN

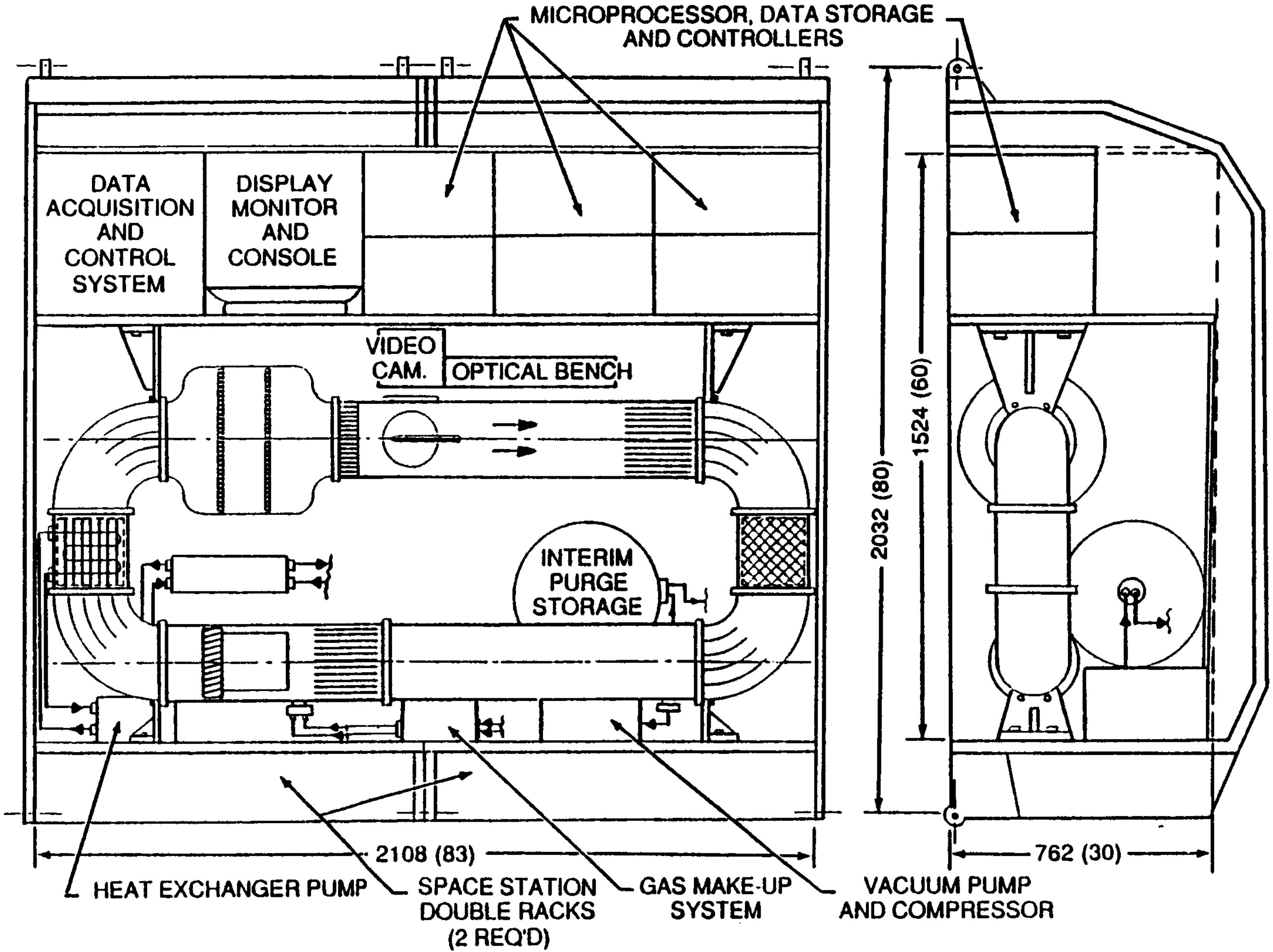
FIGURE 3.1-3. RESEARCH COMBUSTION TUNNEL - OVERALL CONFIGURATION

The complete Combustion Tunnel facility is shown in a proposed Space Station-based accommodation in Figure 3.1-4. Design concepts of the Combustion Tunnel components a) to e) are described briefly in the following paragraphs, and the additional subsystems f) and g) are described later. The details of the DACS, item h), are outside of the scope of this study.

Removable Test Section. Figure 3.1-5 represents the combustion and flame spread test section as adapted to 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.

The overall dimensions of the test section are open to further review. The scale used in Figure 3.1-5 suggests an overall length of 102 cm (40 in) for the test section from flange-to-flange. This is for a test section whose reference cross-sectional dimension is 20 cm (8 in), either circular or square, as shown. The very short flow-path distance from the upstream inlet/flow conditioner to the sample position is suggested to provide a 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. In addition, the test section cross-sectional dimension may have to be increased for use with the thermally-thick solid fuels. However, a dimension greater than 25 cm (10 in) is impractical since it may make the entire Combustion Tunnel facility too large for Space Station basing.

Fuel Sample Introduction/Retrieval Subsystem. A method must be provided for introducing the solid fuel samples into the test section of the Combustion Tunnel. The concept design in Reference 12 presented three different methods for introducing thermally-thin sheet fuels (paper, plastic, etc.) into the test section. Clearly, the introduction of the more rigid, thermally-thick solid fuels poses new problems. For example, the preferred configuration for cast polymethylmethacrylate (PMMA) is that



NOTES:
- ALL DIMEN.: mm (in.)
- SPACE STATION INTERFACES: →} ←}

FIGURE 3.1-4. SPACE STATION ACCOMMODATION OF THE COMBUSTION AND FLAME SPREAD EXPERIMENT - TYPICAL LAYOUT

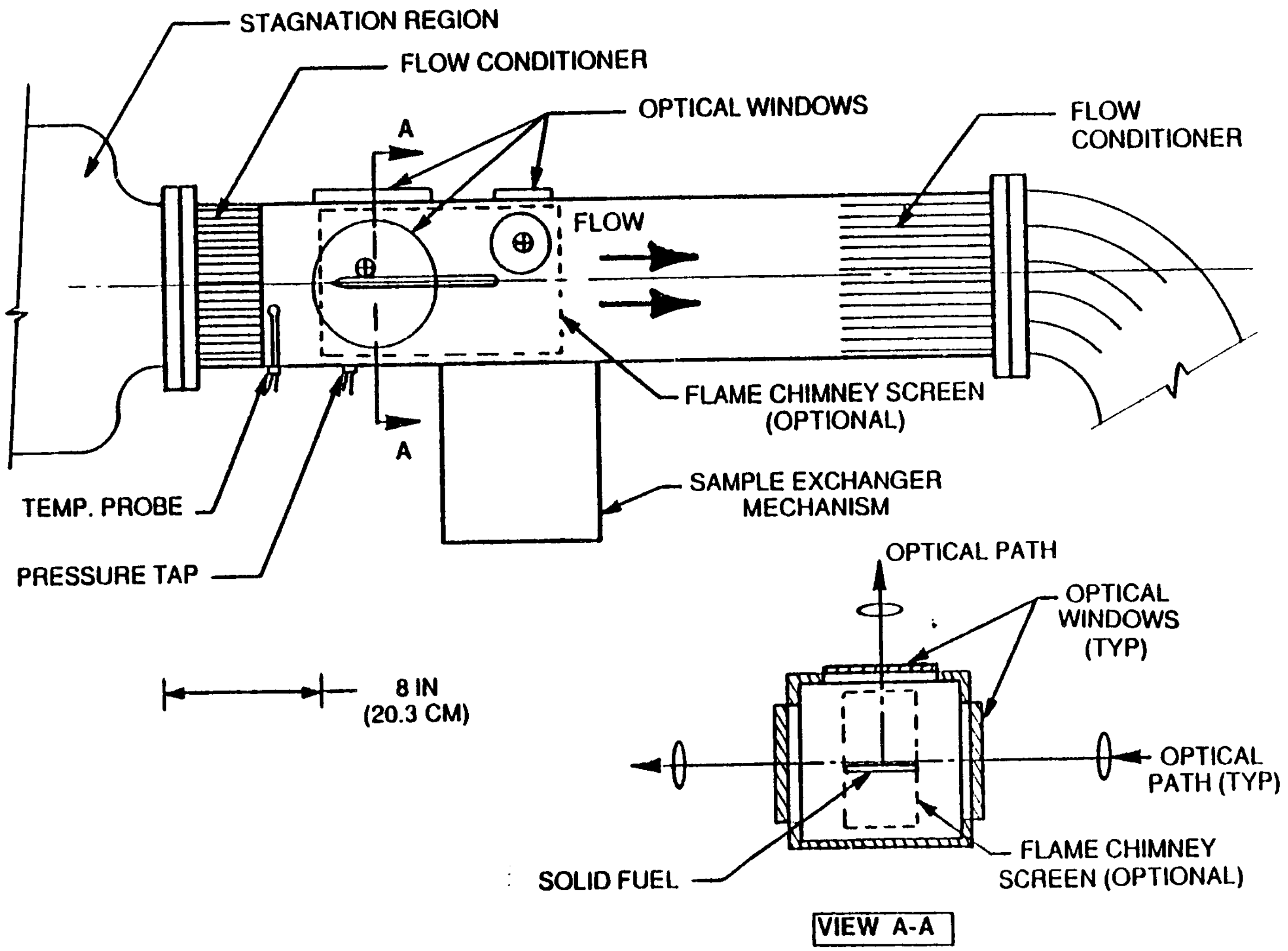


FIGURE 3.1-5. REMOVABLE TEST SECTION - COMBUSTION TUNNEL

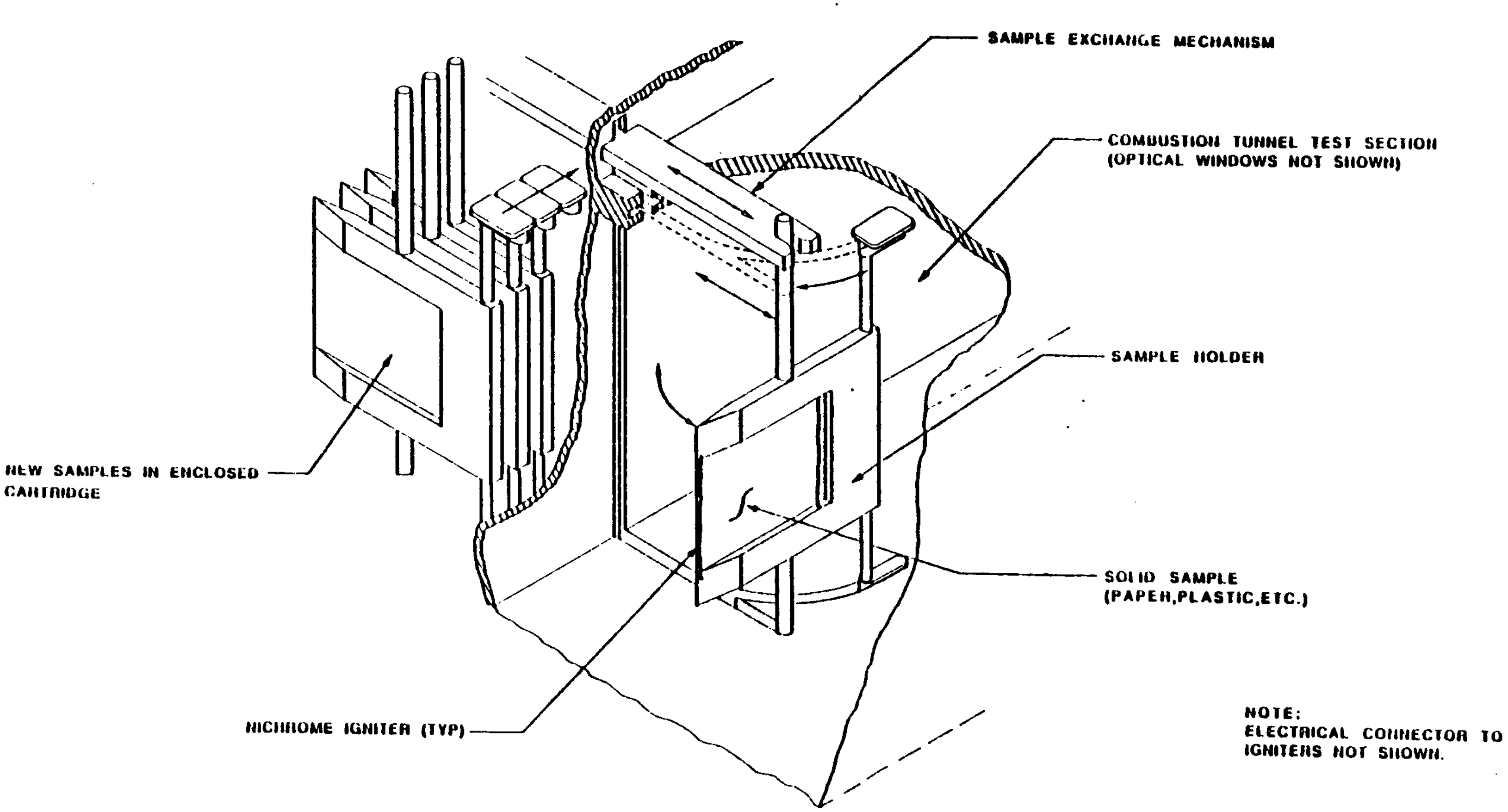
of a rectangular plate whose suggested dimensions are as follows:

- Opposed-flow flame spread:
  3 cm (1.2 in) wide, 1 cm (0.4 in) thick, 10 cm (3.9 in) long
- Concurrent-flow flame spread:
  5 cm (2.0 in) wide, 1 cm (0.4 in) thick, 15 cm (5.9 in) long.

Figure 3.1-6, from Reference 12, illustrates one practical concept of automatic fuel-sample insertion and retrieval for thick specimens, 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 removed from the tunnel through the same slot. This design has the advantage of requiring minimal scarring of the test section since insertion and retrieval takes place through one side of the wall only. The major disadvantages of this design are as follows: 1) the process of insertion and retrieval would interfere with any fixed sensors (e.g., thermocouples) located in the flow path; and 2) provision of a mechanism to permit the streamwise (longitudinal) and lateral movement of the fuel sample would be difficult. Alternative methods of sample insertion and retrieval are being investigated. There may be some advantage to having each fuel sample instrumented with its own thermocouples and sample holder (sting).

Design of the solid fuel insertion and retrieval subsystem is clearly challenging. The larger, longer-burning, thick fuel samples may preclude automatic or even semi-automatic change-out of fuel samples. The need for development of such mechanisms depends on the ultimate requirements in terms of number and types of fuel samples to be combusted and the trade-off of payload specialist time versus experiment automation.

Flow Recirculation Components. One of the most demanding and restrictive constraints relevant to the Space Station-or Space Shuttle/Spacelab-basing of a combustion facility of any size is that of venting, or discharging, of the spent gases after a combustion process. In spacecraft-based experiments, neither venting nor compressing of the spent gases is permitted without severe restriction. The Combustion Tunnel facility described herein is conceptually designed to be of the fully recirculating type with only minimal venting and gas makeup allowed. The Reference 12 study



NOTE:
ELECTRICAL CONNECTOR TO IGNITERS NOT SHOWN.

FIGURE 3.1-6. CONCEPT FOR CARTRIDGE TYPE SAMPLE LOADING - PICTORIAL considered flow-through designs and rejected them due to the Space Station design constraints on venting to the Space environment or, alternatively, on the basis of the excessive power required for real-time waste gas recompression and storage.

As shown in Figures 3.1-3 and 3.1-4, the major components of the flow recirculation system include the following:

- Stagnation (settling) chamber
- Heat rejection coils
- Fan/motor subassembly
- Filter subsystem
- Gas make-up subsystem.

Each of these components is common to nearly all recirculating flow facilities, and is described in some detail in Reference 12. However, some additional comments are deemed appropriate here relative to the heat rejection coils, gas makeup subsystem, and filter subsystem.

The heat rejection requirements of the Combustion Tunnel facility will be due largely to a combination of the heat released in the combustion process and the heat dissipated by the fan/motor subsystem. Most of the fan/motor heat may be assumed to be absorbed by the tunnel flow media and must, therefore, be removed upstream of the tunnel test section. Preliminary estimates of the combustion process heat releases are approximately 1.0-1.5 kW (3400-5100 Btu/hr). This amount of heat rejection will require use of an air-to-liquid heat/exchanger (see Figure 3.1-4). Detailed design may indicate the need to locate the major heat exchanger coils just downstream of the test section.

During any combustion and flame spread experiment performed in the Combustion Tunnel facility, the flow medium will be continuously changing. The percentage of oxygen will be decreasing and particulate matter (soot and smoke) and the by-products of combustion will be increasing. The oxygen content of the flow medium can be continuously monitored by, preferably, a dedicated oxygen analyzer or by a mass spectrometer. As the oxygen content is depleted, it may be made up by various methods. Reference 12 described several methods of regulating the composition of the initial or makeup gas flow in the combustion tunnel. Of these, one of the most accurate methods is through the use of a calibrated volume. The central element of this method consists of a precisely machined calibration chamber whose volume has been accurately determined. The calibration chamber is supplied by each gas (e.g., oxygen) in turn, through a series of pressure regulators, solenoid valves and critical flow orifices. The pressures and temperatures in the calibration chamber and the Combustion Tunnel are continuously monitored, which permits precisely calibrated masses of each gas to be introduced into the Combustion Tunnel under microprocessor control. This procedure would be repeated for each additional gas component required to obtain the desired mixure. An advantage of this method is that precise quantities of makeup gases may be added to the mixture during and between experimental runs.

It is recommended that the Combustion Tunnel flow medium be filtered during and between experimental runs. As a minimum, filters should be used to remove the largest soot and smoke particles. The next priority may be to remove the water vapor and other condensibles formed as combustion by-products. It is possible that the removal of the condensible materials (by cooling coils and/or desiccants) may allow sufficient makeup of oxygen to extend the combustion and flame spread experiment run times to satisfactory values.

A further refinement of the flow filter subsystem would be the addition of various process absorbants and rare earth catalysts to aid in the removal of the other major combustion by-products (e.g., CO, CO_2, and certain hydrocarbons). For example, cannisters containing LiOH are used to remove CO_2 while noble metal catalysts are used in oxidation reactions to convert CO to CO_2. Many of the hydrocarbon products may be converted and removed from the flow medium in a similar oxidation reaction process. Unless converted and otherwise removed, the accumulation of these fuel vapors that have not been combusted could pose an explosive hazard within the Combustion Tunnel. The use of such elaborate gas purification and conversion systems for Combustion Tunnel operation and interim purging is identified as a technology development item (see Section 5.0).

Flow Rate Measurement and Control System. The schematic of Figure 3.1-3 indicates two parallel flow-rate measurement techniques. Higher flow rates can be measured through a calibrated orifice-plate system. Very low flow rates can be measured through a calibrated laminar flow element (LFE) system. The LFE is capable of making very precise flow-rate measurements at the cost of a high pressure loss.

Flow-rate measurements would furnish input signals to a microprocessor and the flow characterization subsystem. The subsystem would then control the fan motor speed for precise settings of the total gaseous mass flow and, consequently, the test section velocity.

Interim Purge/Storage Subsystem. An interim purge/storage subsystem shall be required for temporary and safe storage of spent gases from the Combustion Tunnel facility. The gases would be evacuated from the Combustion Tunnel facility and compressed slowly (i.e., at low power) into a pressure vessel. The purposes of the interim purge/storage subsystem are as follows:

a) Temporarily store spent gases prior to delivery to the Space Station vent system
b) Temporarily store the spent gases prior to subsequent clean-up and reuse
c) Provide access to the Combustion Tunnel for cleaning, routine maintenance, etc.

As shown in Figure 3.1-3, this subsystem would consist of a compressor and storage cylinder placed in the lines between the Combustion Tunnel and the Space Station vent system. The size of the compressor and storage cylinder would be determined by the amount of Combustion Tunnel gas charge required to be accommodated between discharges to the Space Station waste gas handling system and the time allowed for the compression process (i.e., dependent on the desired timeline for each experiment).

3.1.3 <u>Near-Term Combustion and Flame Spread Experiment Requirements.</u> Section 3.1.2 described the basic components required for a Space Station-based Combustion Tunnel to be used in fundamental and fire safety-related flame spread experiments. Clearly, there must be a prerequisite of low-gravity combustion and flame spread experiments, new and on-going, to be conducted in the 1990-1995 time frame.

It is recognized that several combustion and flame spread experiments are planned (and some recently completed) for ground-based and Space Shuttle operation. Some of these have already been cited in the INTRODUCTION.

In addition to the on-going near-term experimentation, an aggressive comprehensive program is necessary to study flame spread systematically in a low-gravity, low-velocity convective flow environment as a precursor to the Space Station-based experimentation. Such a comprehensive program would include the following major steps:

Step 1. Design, construct and operate a ground-based, laboratory breadboard model of a Combustion Tunnel facility.

Step 2. Based on the knowledge gained from Step 1., design and construct a Combustion Tunnel apparatus to be operated on an aircraft such as the NASA KC-135A.

Step 3. Develop a Spacelab-based Combustion Tunnel experiment package based on the experience of Step 2. and identify the unresolved fire safety-related technology issues.

A ground-based, laboratory breadboard model of the Combustion Tunnel facility is shown in Figure 3.1-7. As shown, this model is not optimized in terms of size or packaging; rather, the model is intended to be used to conduct a series of low-velocity, convective-flow flame spread studies under normal-gravity conditions. Facility design questions regarding flow control and measurement, diagnostic instrumentation, particulate filters, oxygen depletion and makeup, sample exchange, etc. can best be investigated with such a model.

Note that the Combustion Tunnel laboratory breadboard illustrated in Figure 3.1-7 may be modified as required to be installed on a suborbital aircraft such as the NASA KC-135A. The size of the KC-135A aircraft would easily accommodate the large laboratory Combustion Tunnel model, for multiple parametric testing.

In general, the Combustion Tunnel described here for near-term combustion and flame spread experiments would be essentially identical—except for final size optimization and packaging—to that of the Space Station-based facility. However, the near-term experiment apparatus need not be as fully automated, and, therefore, no sample exchange mechanism is indicated.

Figure 3.1-8 shows another version of the Combustion Tunnel test section for near-term testing. The intent of this configuration is to permit removal of the test section during, e.g., KC-135A aircraft flights. Several test sections could be readied and exchanged during a single flight. An alternative would be to clean and reload a single test section with new fuel specimens during a flight. Note also the movable video camera shown adjacent to the test section. This mounting suggests manual operation of the camera during a flame spread process.

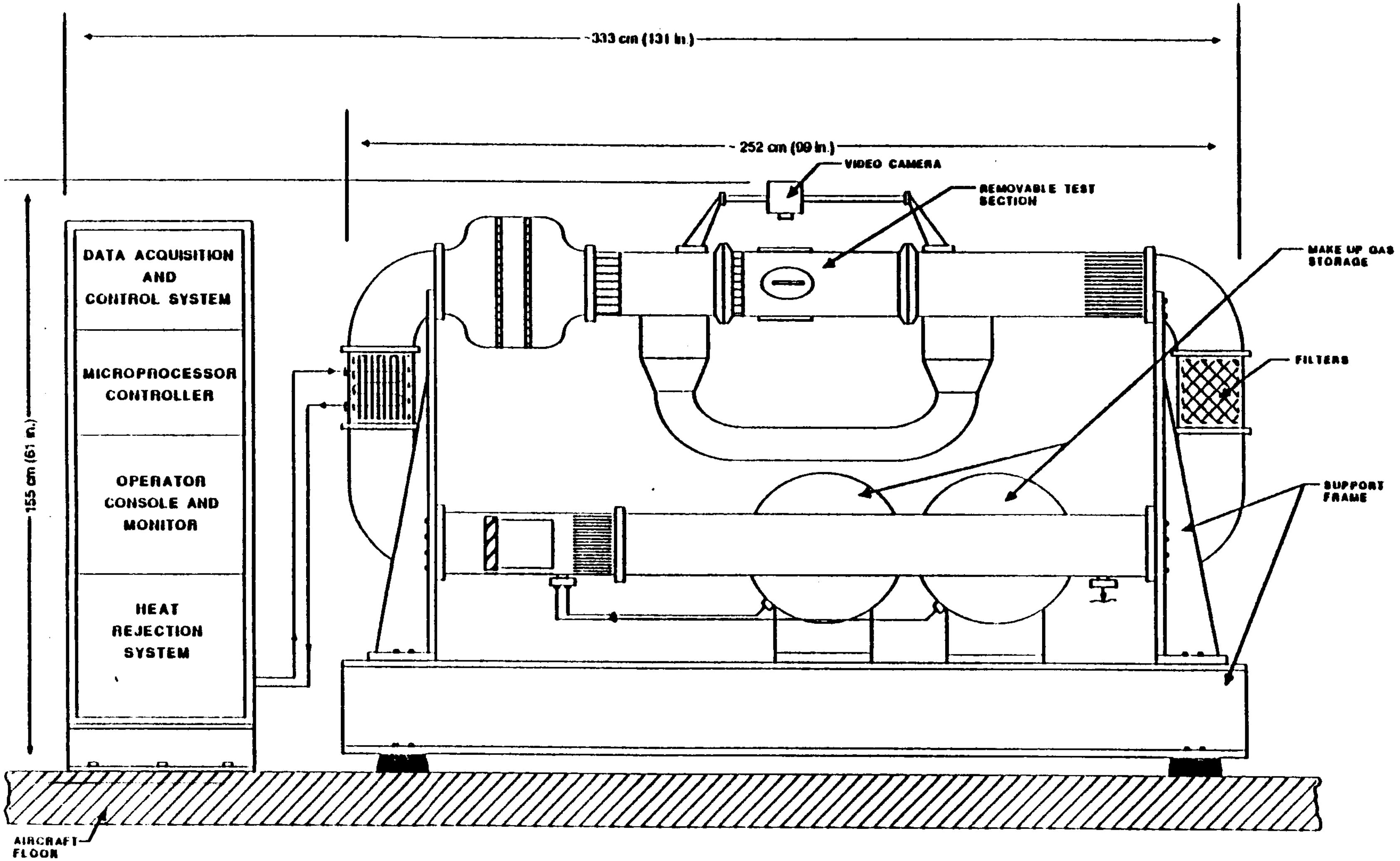


FIGURE 3.1-7. GROUND- AND AIRPLANE-BASED ACCOMMODATIONS FOR THE COMBUSTION AND FLAME SPREAD EXPERIMENT

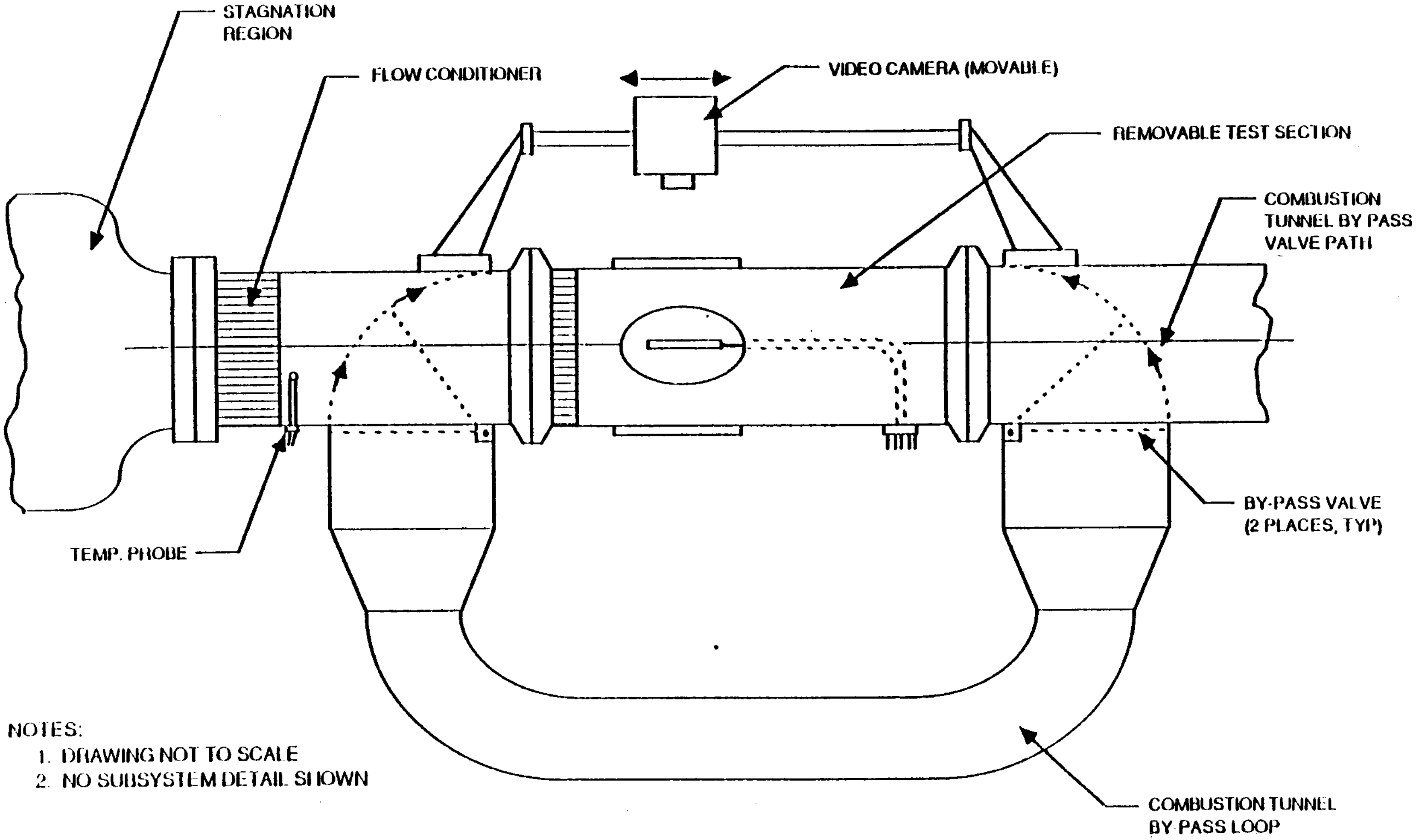


FIGURE 3.1-8. <u>COMBUSTION TUNNEL TEST SECTION WITH BYPASS LOOP</u>

3.1.4 Special Instrumentation and Diagnostic Measurement Equipment for the Experiments. **Desired Measurements.** Some of the experimental information and data desired from the combustion and flame spread experiments was identified in earlier sections of this report. Again, the information and data sought include, but is not limited to, the following:

a) Energy required to initiate ignition
b) Mass loss rates
c) Ignition transient, flame spread and extinction limits
d) Flame characteristics (size, shape, color, temperature and velocity field, etc.)
e) By-products of combustion.

The basic requirements will be discussed, and some examples of intrusive and non-intrusive sensors and diagnostic measurement equipment will be presented. The reader is referred to two state-of-the-art papers that may be applicable in several repects to these combustion and flame spread experiments. K.C. Smyth, et al. (Ref. 13), describe a detailed experimental characterization of a diffusion flame (methane/air) using both optical (non-intrusive) and mass spectrometric (intrusive) diagnostics. The optical methods included the following: 1) laser Doppler velocimetry (LDV) for velocity profiles; 2) laser-induced fluorescence (LIF) for measuring relative concentrations of OH and the monitoring of the production of C_2 by fluorescence; and 3) laser-induced scattering (Rayleigh). R.J. Santoro, et al. (Ref. 14), describe a laser extinction/scattering technique for particle size measurement.

The reader is also referred to a study prepared by T. Georgekutty of Wyle Laboratories and documented in NASA CR-179535 (Ref. 12). The study by Georgekutty describes a concept design for a laser-based diagnostics system for a Space Station combustion tunnel facility. Georgekutty's design suggests that the current state-of-the-art be improved upon by insisting that the diagnostics system be completely non-intrusive in character (i.e., completely optical). Two levels of complexity were described, each level having its own merits,

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 far more complete and could provide certain parameters, e.g., flame propagation and temperature profiles, in real time. The classical optical system includes Schlieren, shadowgraph and Mach-Zehnder (M-Z) interferometric investigation capabilities 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 Space Station microgravity environments would need 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 capability 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 (Ref. 15).

The level of sophistication of the System I diagnostic techniques introduced above may be considered to be entirely too complex for the combustion and flame spread experiments described herein. The System II diagnostics system (i.e., holography, LDV and LIF) is less complex and may be more feasible. However, taken alone the System II diagnostic system may not produce all of the information and data required. Thus, it is recommended at this time that the simpler, more well-established, diagnostic techniques be used that include both non-intrusive (i.e., video camera or laser holography) and intrusive (i.e., thermocouples, mass spectrometer probes, etc.) measurement techniques.

Measurement of Ignition energy. The energy required to initiate ignition on a solid fuel in low-velocity, low-gravity environmental conditions may be of interest. Although the exact amount of ignition energy is not important to flame spread and extinction limit experiments as long as the energy is large enough to initiate combustion, knowledge of the minimum ignition energy and its dependence on different ignition modes may be important from a fire safety point of view. The Combustion and Flame Spread Experiment suggested here will provide an opportunity to study low-gravity ignitability of a material.

Mass Loss Rate Determination. Mass loss rate is of interest since each solid fuel material will exhibit its own production rate of combustion by-products. Laboratory methods for measuring burning mass loss rates have included those of the determination of the wedge angle formed across the thickness of the sample by the steadily spreading flame (Ref. 16) and the depletion of oxygen in the exhaust products (Ref. 17). Another method of determining burning mass loss rate may be that in which the solid fuel specimen mass is correlated directly with the frequency response of the sting support. This technology isn't new, but it may not have been applied to combustion experimentation. Finally, the fuel sample may be weighed (after removal from the test section) to obtain a global burning rate.

The heat release could be excessive if the experiment run times are more than a few seconds and if the fuel samples are large. For this reason, flame spread may have to be limited to only one side of the fuel sample as shown in Figure 3.1-1.

Ignition Transient and Flame Spread. Both the ignition transient and flame spread are of considerable interest in fire safety. Observations may be made by means of a video camera or by the use of laser holography. In terms of the levels of complexity, a video camera would be relatively straightforward and would allow real-time monitoring of the combustion process. Both the flame front and pyrolysis front can be readily photographed since laminar flames are most likely. The use of fine thermocouples mounted on the fuel surface will also yield significant information, since the thermocouple output will provide a continuous trace of temperature as the flame progresses. The use of a classical Schlieren optical system to provide real-time monitoring of the flame propagation represents a much higher level of complexity and may not be warranted.

The study of T. Georgekutty (Ref. 12) recommends the consideration of a holographic recording system. The subsequent reconstruction of the holographic recorded data would provide flow visualization and other information to aid in defining temperature and density profiles.

Determination of Flame Characteristics. The initial chemical steps in the flame leading to the formation of larger molecules (and eventually to soot-particle inception) are of great interest to the combustion community. However, to date it has been determined that optical techniques alone are inadequate. Further, once the measurements are moved into the soot particle formation region, nearly all optical measurements are masked by the soot particles, except for extinction and scattering determinations.

With the current state-of-the-art of diffusion flame diagnostics, it isn't clear that fully non-intrusive optical systems can provide the needed information. Thus, the following discussion of measurements to characterize the flame will incorporate both optical (non-intrusive) and conventional (intrusive) sensors.

The determination of various flame parameter profiles (e.g., temperature and density) by non-intrusive means would require either a classical optical system (Mach-Zehnder Interferometry) for real-time observations, or a holographic recording system for later data analysis. These methods were described in some detail by T. Georgekutty (Ref. 12).

A more direct, although intrusive, method is to use extremely fine-wire thermocouples located at selected postions above the solid fuel. This technique was used successfully by K.C. Smyth, et al. (Ref. 13) in a study of methane/air diffusion flames. Uncoated Pt/Pt-10% Rh thermocouple (T/C) wire of 125 μm diameter was stated as being used. The T/C wire supports were located just outside of the high-temperature flame zone.

A relatively common method for making velocity measurements in fluid streams is that of laser Doppler velocimetry (LDV). Again, the optical system required to make LDV measurements was described by T. Georgekutty in Reference 12, and such measurements were taken by K. C. Smyth, et al. (Ref. 13) in a methane/air diffusion flame. Both the vertical and horizontal velocity components were obtained by means of a LDV system using a conventional argon ion laser (~1 W). Since the air and methane were relatively pure and clean, the flow was seeded by nominal 1μm (4×10^{-5} in) diameter aluminum oxide particles. The LDV technique measures velocity point-by-point, and, therefore, the use of LDV for determining the velocity profiles in a spreading flame may be extremely difficult. Basically, one must know the position of the velocity point relative to the flame. A simpler method might make use of the observation of particle tracks and a laser sheet to provide a more complete flame-field picture.

Techniques for optical determination of species profiles are somewhat limited. K.C. Smyth, et al. (Ref. 13) used laser-induced fluorescence (LIF) to obtain profiles of OH and C_2. Since the stated purpose of the work by Smyth et al. was to improve the understanding of the soot formation processes, specifically the early chemical steps which lead to the formation of larger molecules and eventually to particle inception (soot formation), the LIF measurements of OH and C_2 were not considered adequate. Thus, a direct-sampling mass spectrometer was used to monitor a number of the intermediate species including methane, toluene, hydrogen, nitrogen, carbon dioxide, water vapor, etc. A quartz microprobe was used to draw samples from the diffusion flame. The microprobe was stated to have an outside diameter of ~6 mm (0.24 in) with a tapered tip orifice inside diameter of ~140 μm (0.0055 in). It was stated that this probe would clog with soot if it was moved beyond the soot inception line above the burner tip.

The determination of species profiles through a spreading flame is compelling, but the current state-of-the-art suggests that such determinations are difficult at best. Thus, it is recommended that near-term efforts be devoted to measurement and analysis of the combustion by-products well downstream of the soot inception region.

By-Products of Combustion. Of significant interest to spacecraft fire safety are the combustion by-products that may be observed at some distance away from the flame source. By-product measurements include the smoke and soot particle size distribution, particle concentration, density, and quantity and type of toxic gaseous compounds.

R.J. Santoro, et al. (Ref. 14) presented the detailed results of a study to measure soot particles in ethene/air and ethane/air diffusion flames. A laser extinction/scattering technique was used to obtain the spatial distributions of particle volume fraction, mean particle size, and particle number concentration. This is not a new technology, but coupled with the types of diagnostics reported by K.C. Smyth, et al. (Ref. 13) a relatively complete characterization of a diffusion flame may be obtained.

3.2 Interaction of Extinguishants with Fires in Low Gravity

3.2.1 Overall Description of the Experiment. The purpose of this experiment is to investigate a variety of fire/fire extinguishant interaction parameters in a low-gravity environment. In addition, there is an interest in evaluating the immediate and longer-term effects on sensitive electronic components (e.g., printed circuit boards, switchgear, optical readers, etc.) that may result from the local exposure to extinguishants and combustion products. Even temporary interruption of such components could be critical to the Space Station mission. This investigation is discussed further in Section 3.2.3.

The apparatus identified to meet this objective, the Space Station-based Combustion Facility, has been conceptually designed as a versatile, general-purpose, reusable research facility, which will enable the experimenter to make optimum use of the extended low-gravity, shirt-sleeve environment of the Space Station. The Combustion Facility is intended to permit the experimenter to:

1. Use suitably contained liquid, gaseous or solid fuels (i.e., insulation, coatings, wire/cable covers, etc.)
2. Specify and establish the composition and pressure level of the atmosphere in the Combustion Facility
3. Study the effects of various extinguishing agents (i.e., Halons, CO_2, H_2O, foams, etc.) on the fuels
4. Study the effects on extinguishment by varying the geometry and means of application of extinguishing agents (i.e., continuous stream, spray, mist, variable flow rate)
5. Characterize the experiment with common types of instrumentation as well as selected specialized equipment
6. Study the combustion and extinguishment process visually by direct observation and by video camera coverage to obtain time histories of pertinent experimental parameters.

Figure 3.2-1 is a conceptual design of the Combustion Facility configured within a standard Space Station double and single rack. The facility will utilize standard Space Station mechanical and electrical interfaces.

Typical Combustion Facility operations would include the insertion and subsequent positioning of the liquid, gaseous or solid fuel within the chamber. The positioning could be accomplished by use of a robot arm within the chamber. The robot arm would be controlled by the Data Acquisition and Control Subsystem (DACS), exterior to the chamber, on the commands of the mission specialists. Once the desired geometry of the fuel has been attained, the access door is closed, and a microcomputer based within the DACS is used to establish the various experimental parameters specified:

- Extinguishants
  - Halon 1301
  - Water
  - CO_2
  - Foam
  - Etc.
- Desired Geometric Application of Extinguishants
  - Stream
  - Spray
  - Mist
  - Flow Rate and Particle Size
- Composition and Pressure Level of the Atmosphere Within the Chamber
  - Inlet Gases/Composition
    - N_2
    - O_2
    - Argon
    - Etc.
  - Working Pressure Up to 101.4 kPa (14.7 psia)
- Chamber Flow Rate/Velocity.

For any given set of parameters specified, the fuel will be ignited, and the introduction of extinguishants will proceed in accordance with the specified conditions. It may be noted that the above list of parameters implies a large number of possible fire/fire extinguishants interaction scenarios. However, a practical number of experiments may be chosen from the most likely extinguishants, nozzles, and solid fuels. Some suggested scenarios are illustrated by Figure 3.2-2 through 3.2-7. These

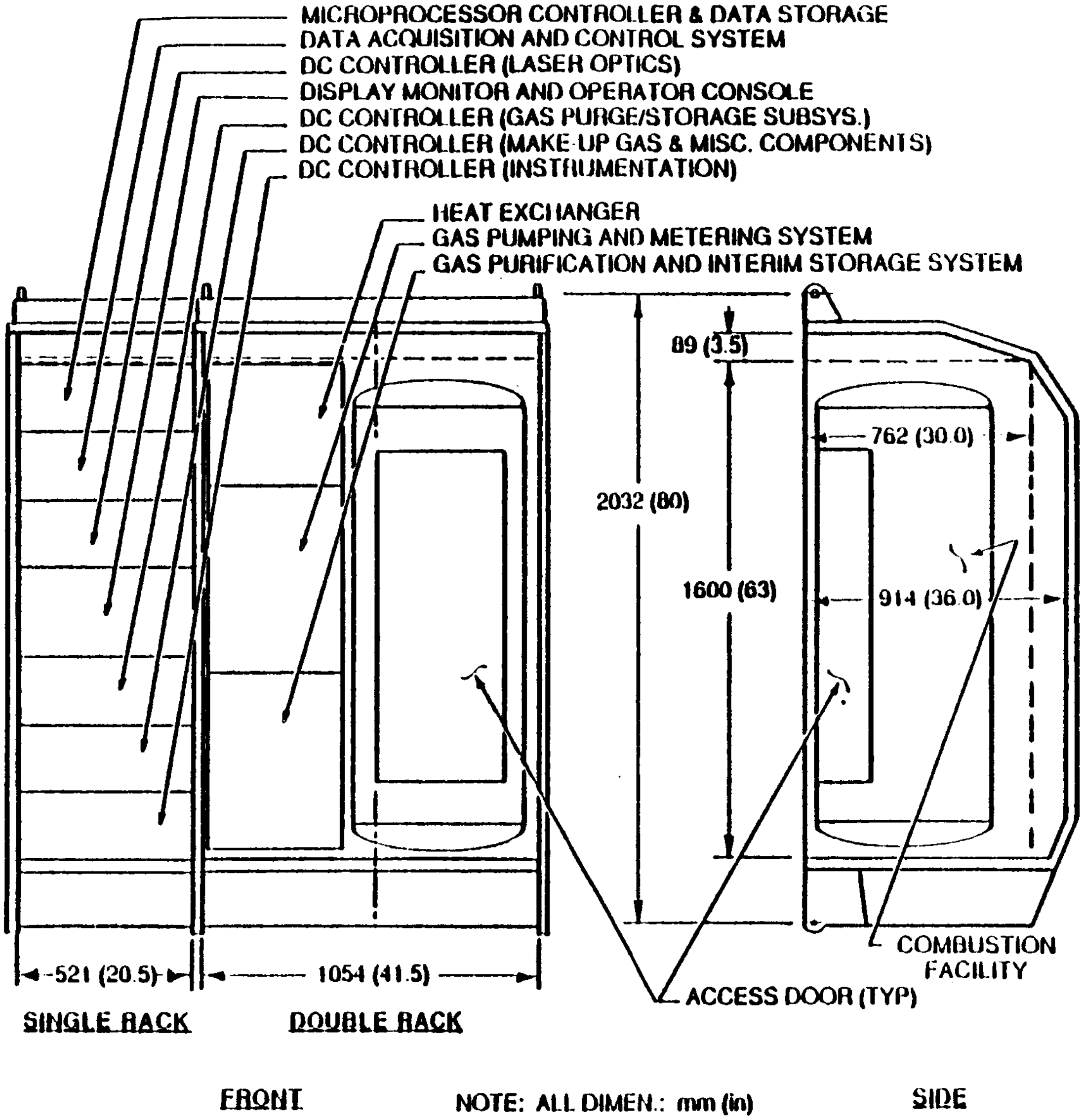


FIGURE 3.2-1. SPACE STATION ACCOMMODATION OF FIRE/FIRE EXTINGUISHANTS INTERACTION EXPERIMENT - TYPICAL LAYOUT

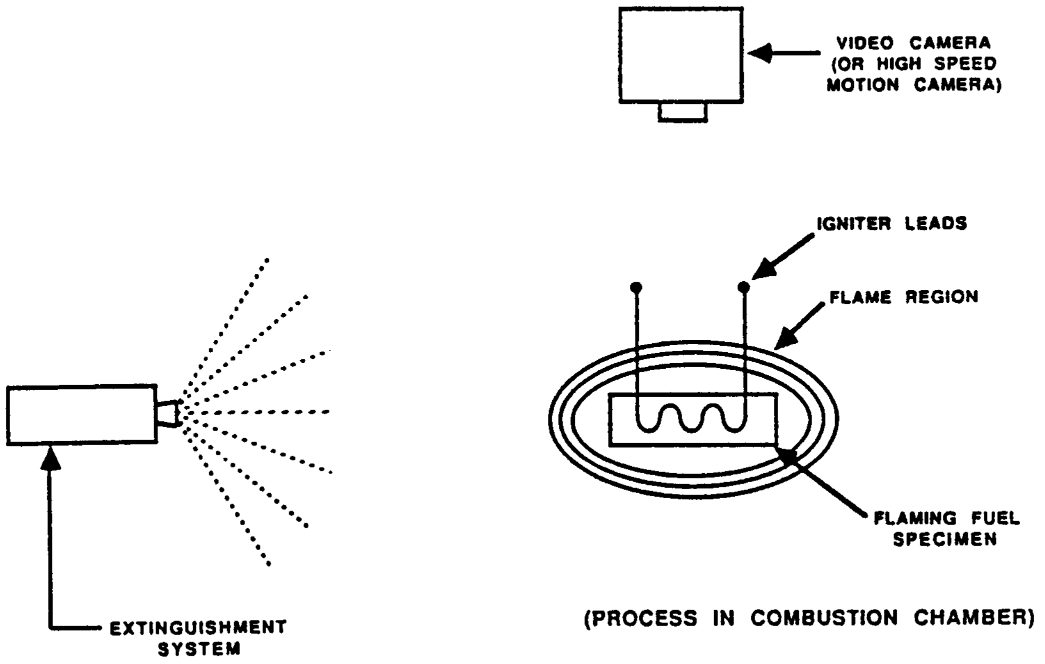


FIGURE 3.2-2. EXTINGUISHMENT OF SURFACE BURNING FUEL: QUIESCENT ATMOSPHERE, DIRECTED APPLICATION OF EXTINGUISHANT

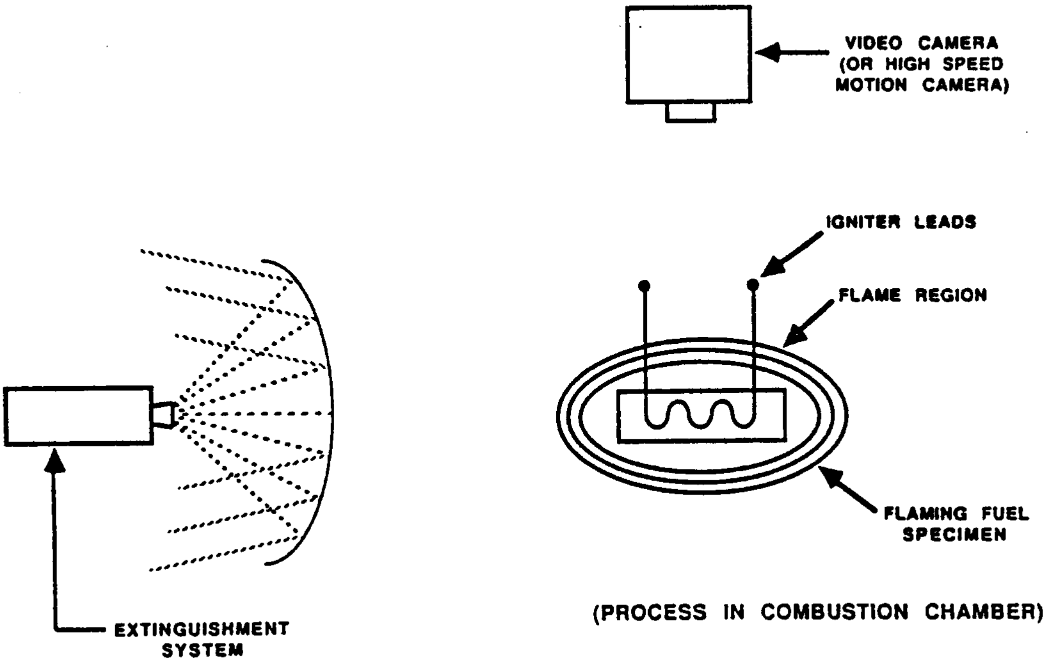


FIGURE 3.2-3. EXTINGUISHANT OF SURFACE BURNING FUEL: QUIESCENT ATMOSPHERE, BAFFLED (DIFFUSED) EXTINGUISHANT APPLICATION

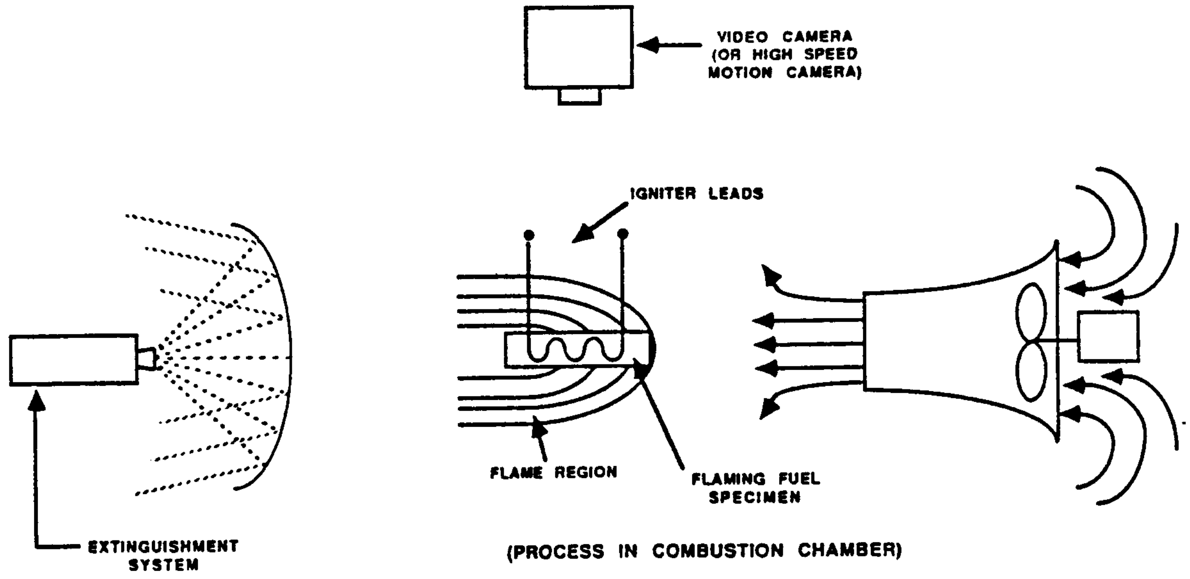


FIGURE 3.2-4. EXTINGUISHMENT OF SURFACE BURNING FUEL: LOW VELOCITY FLOW, BAFFLED (DIFFUSED) EXTINGUISHANT APPLICATION

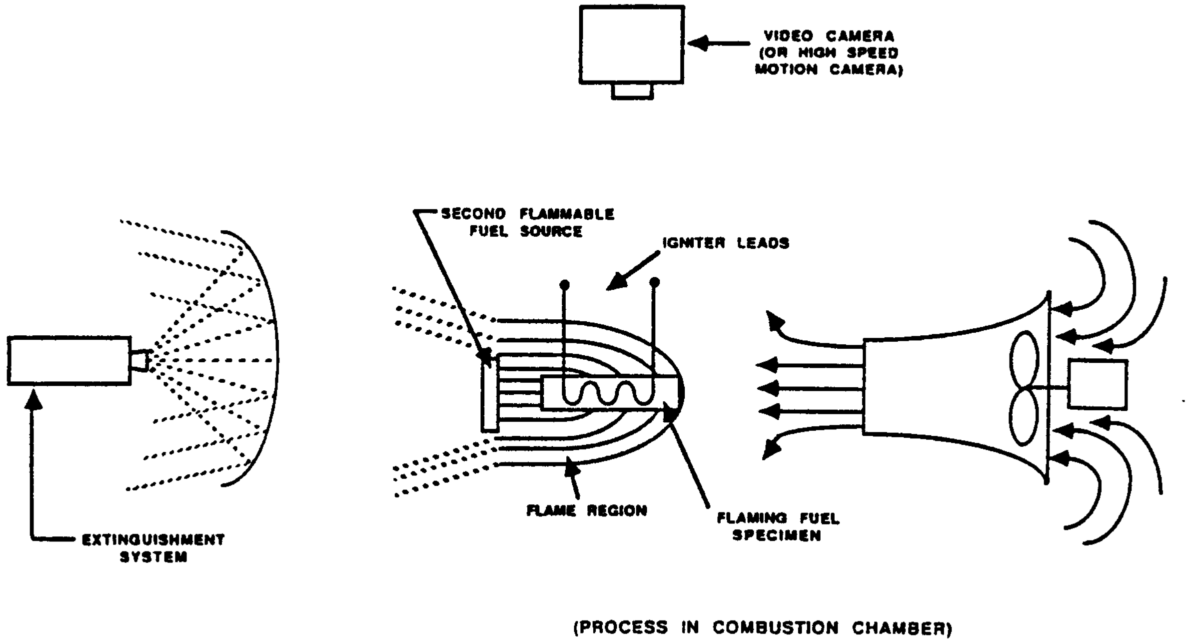


FIGURE 3.2-5. EXTINGUISHMENT OF SURFACE BURNING FUEL: LOW VELOCITY FLOW, BAFFLED (DIFFUSED) EXTINGUISHANT APPLICATION, POTENTIAL IGNITION OF SECOND FUEL SOURCE

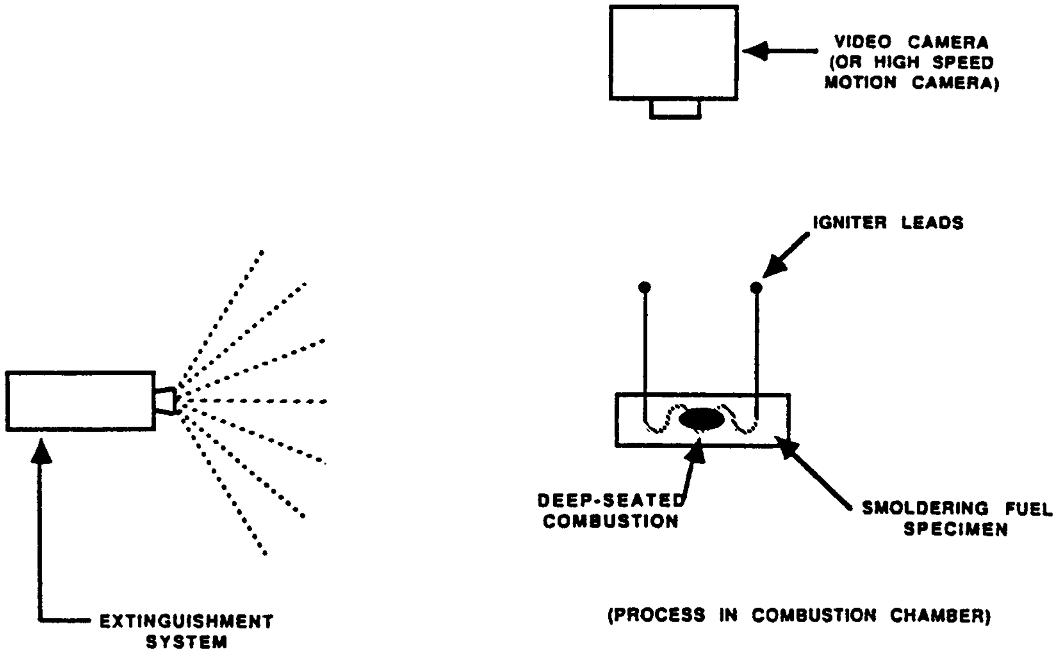


FIGURE 3.2-6. EXTINGUISHMENT OF DEEP-SEATED COMBUSTION: QUIESCENT ATMOSPHERE, DIRECTED APPLICATION OF EXTINGUISHANT

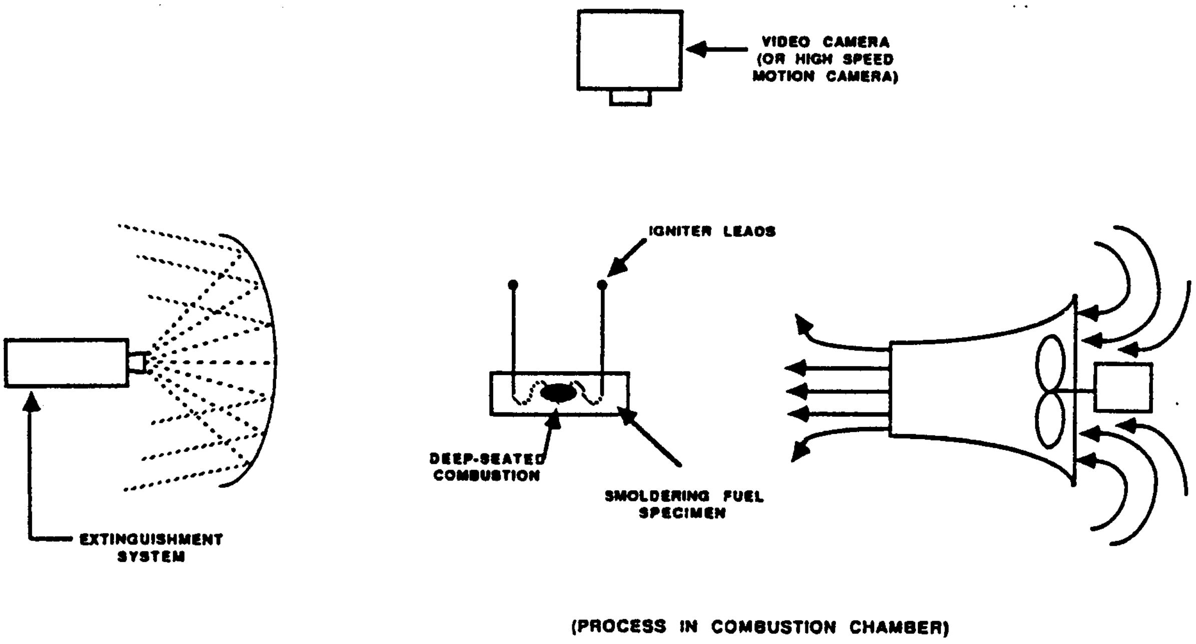


FIGURE 3.2-7. EXTINGUISHMENT OF DEEP-SEATED COMBUSTION: LOW VELOCITY FLOW, BAFFLED (DIFFUSED) EXTINGUISHANT APPLICATION

limited scenarios are tabulated as follows:

	Extinguishment Scenario	Illustration
o	Surface burning fuel - quiescent atmosphere - direct application	Figure 3.2-2
o	Surface burning fuel - quiescent atmosphere - baffled application	Figure 3.2-3
o	Surface burning fuel - low velocity flow - baffled application	Figure 3.2-4
o	Surface burning fuel - low velocity flow - baffled application - potential second fuel source	Figure 3.2-5
o	Deep-seated combustion - quiescent atmosphere - direct application	Figure 3.2-6
o	Deep-seated combustion - low velocity flow - baffled application.	Figure 3.2-7

Throughout the ignition, burning and subsequent extinguishment, a number of measurements will be taken simultaneously. These measurements are proposed to consist of a combination of both non-intrusive diagnostics (laser-based optics, video cameras, etc.) and intrusive sensors. As the state of the art progresses, some - if not all - of the intrusive sensors may be replaced with non-contact, optical diagnostics.

Once the fire has been extinguished, measurements and characterization of the atmosphere will continue, thus providing the necessary data for post-fire clean-up measurements. Post-fire clean-up will then begin. The chamber will be evacuated, purged with an inert gas, sprayed with a cleanser, purged with inert gas, and readied for another investigation.

The following fundamental observations may be made regarding the desired measurements. A video camera, or alternatively a holograph, recording of the ignition/extinguishant process will be obtained through any of the large optical quality ports on the chamber. The chamber internal temperature, pressure and oxygen concentration will be monitored with thermocouples, pressure transducers, and an oxygen analyzer, respectively. Laser-induced fluorescence (LIF) could be used to measure relative concentrations of OH and monitor the production of C_2 by fluorescence. Laser-induced scattering (Rayleigh) could be used to monitor the particle sizes and number densities after extinguishment. However, the use of LIF and Rayleigh scattering may require considerable development prior to incorporation into this experiment.

3.2.2 Basic Apparatus Required for the Experiment. As mentioned previously, the primary facility for the Fire/Fire Extinguishants Interaction Experiment, the Combustion Facility, is a chamber modeled after the "Zero-Gravity Combustion Facility" conceptually designed for Spacelab by R.L. DeWitt (Ref. 18).

As shown in Figures 3.2-1 and 3.2-8, the Combustion Facility will consist of the following major systems:

1) Combustion Chamber
2) Extinguishants System
    - Spray Nozzles
    - Pumping System
    - Gas Purge/Storage
3) Fuel Handling Equipment
    - Ignition Attachment
4) Data Acquisition and Control System (DACS)
5) Heat Exchanger
6) Fan/Motor Assembly
7) Combustion/Extinguishants Measurement Systems
    - Video Recording/Holography Video
    - LDV
    - LIF
    - Rayleigh Scattering
    - Oxygen Analyzer.

A brief description of the above mentioned systems is provided in the sections that follow.

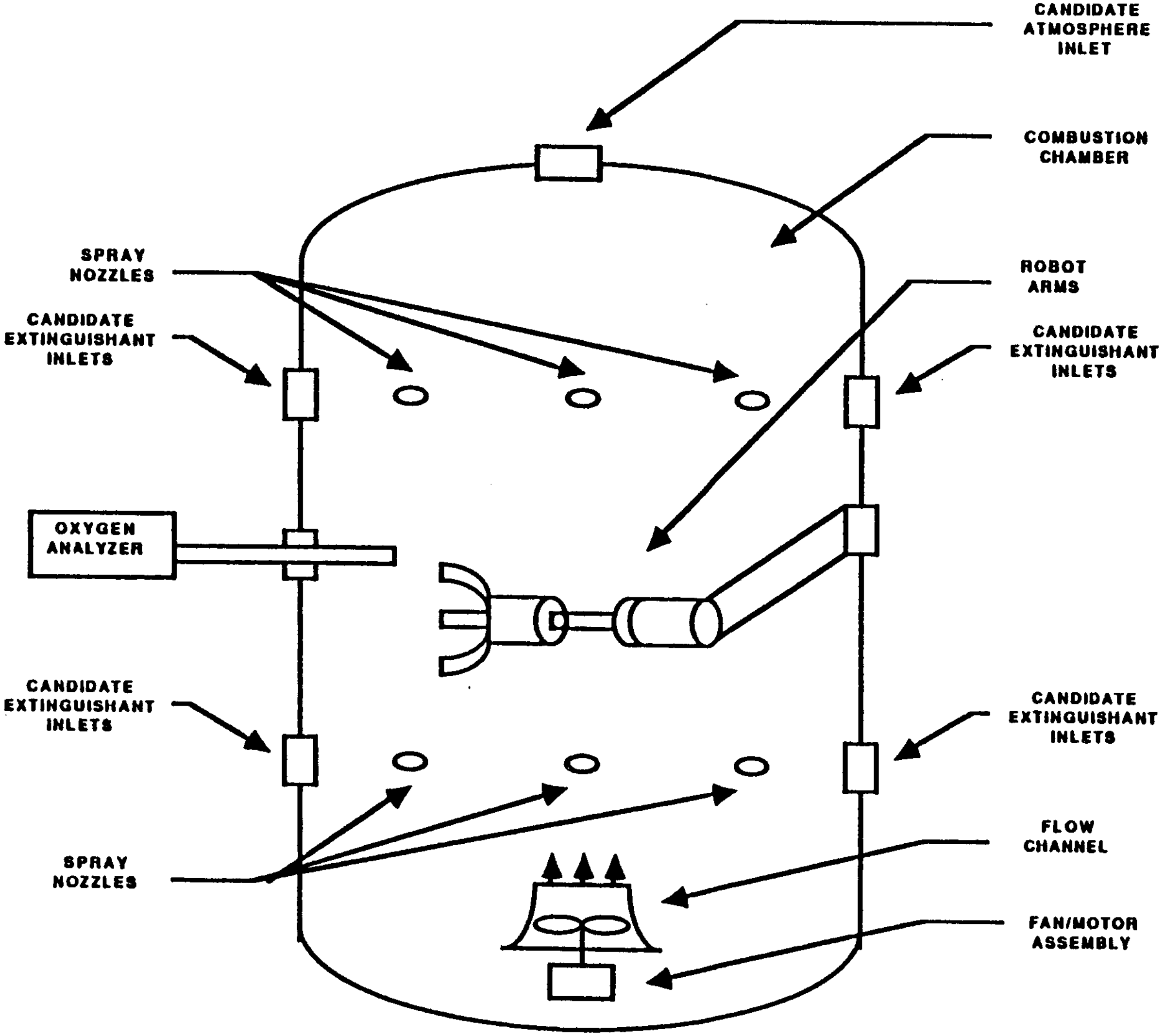


FIGURE 3.2-8. COMBUSTION FACILITY INTERNAL CHAMBER EQUIPMENT

The Combustion Chamber. The combustion chamber, as shown in Figure 3.2-8, will be a stainless steel cylinder approximately 0.62 meters (25 in.) in outside diameter by 1.2 m (47 in.) long with elliptical head ends. The overall height of the chamber will be approximately 1.5 m (59 in.), which is the maximum height available for experimental hardware in the rack. The internal volume of the chamber (exclusive of the elliptical heads) is approximately 0.4 m^3 (14 ft^3), although up to twice this volume would be more desirable, if it could be accommodated, to increase the facility's working volume and versatility.

A minimum of four ports is suggested to be located on the sides of the cylindrical combustion chamber. These ports would have cover plates of optical-quality transparent material. Three ports could be aligned on one side of the chamber, with their vertical axes parallel to the vertical axis of the chamber. The upper and lower ports could be used for video camera coverage of combustion experiments taking place within the chamber. The middle port could be used, e.g., for a laser beam directed in the vicinity of an experiment located within the chamber. A fourth port would be located directly across the chamber from the middle port. This port would allow a photodetector to be mounted outside the chamber to observe the experiment being irradiated by the laser beam. Additional optical ports and/or mirrors may be incorporated into the design.

The Combustion Facility will have an access door approximately 0.51 m (20 in.) wide and 1.02 m (40 in.) in height on the "front" of the combustion chamber. The access door would incorporate the three optical quality ports located on the front of the chamber. The door must be easily removable to allow access to the chamber interior and easily resealable to isolate the chamber and equipment during in-flight testing. Seals must be easily refurbished or replaceable during servicing or in-flight maintenance.

Extinguishants and Purge System. The Combustion Facility extinguishment and gas handling system is comprised of the following:

1) Spray Nozzles
2) Pumping System
3) Gas Purge/Storage.

Spray nozzles would be located around the interior of the chamber (Figure 3.2-8) and be controlled by the DACS. These nozzles shall be designed to may permit investigation of the effects on extinguishment by varying the geometry and mode of application of the extinguishing agent (i.e., the nozzles would be capable of producing a stream, spray, or mist). The nozzles could also possess the capacity to gimbal, thus altering the geometry of the agent application on the fire. The nozzles should be capable of spraying a variety of extinguishing agents such as Halon 1301 (CF_3 Br), liquid water (H_2O), etc. The same nozzles could be used for safety extinguishment and for post-fire atmospheric clean-up. Extinguishment techniques through atmospheric control, such as nitrogen pressurization and vacuum-depressurization, may also be investigated in the chamber by deactivating the nozzles.

The pumping system would be located exterior to the chamber and would be controlled by the DACS. The pumping system can provide the designated extinguishing agents to the spray nozzles at the specified rate and also provide the designated atmosphere in the chamber. The specific requirements for the pumping system are to be determined.

An interim purge/storage system shall be required to safely store spent gases and residual extinguishants from the Combustion Facility. The gases would be evacuated from the combustion chamber and slowly compressed (i.e., at low power) into a pressure vessel. The purposes of the purge/storage system are as follows:

1) Temporarily store spent gases prior to delivery to the Space Station Waste Management System (WMS)
2) Temporarily store the spent gases prior to subsequent clean-up and reuse.

The system would consist of a compressor and spherical storage container placed in the lines between the Combustion Facility chamber and the Space Station WMS. The size of the compressor and storage sphere would be determined by the amount of chamber gas charge required to be accommodated between discharges to the Space Station WMS and the time allowed for the compression process (i.e., dependent on the specific experimental time-line).

The Fuel Handling Equipment. Different types of fuels can be accommodated in the facility. The fuels may range from suitably contained liquids and gaseous or solid fuels (i.e., coatings and insulations used on electronic instruments, components, etc.). Thus, the configuration of the fuels may range from small sheets or cylinders to much larger and/or more complex shapes. To accommodate this wide range of fuels, the Combustion Facility may be equipped with a Robot Arm (Figure 3.2-8) to hold the fuel at the specified orientation within the chamber. The Robot Arm would be controlled by the DACS, and the fuel would be held in the specified orientation required relative to the nozzles and/or the fan/motor assembly. The movement of the arm should allow complete access to any position or location within the chamber. The method of ignition used will be assumed to depend on the type and configuration of fuel. For example, the Robot Arm could itself be equipped with a special ignition attachment. This attachment would consist of a small nichrome wire which, when heated, would ignite the fuel. However, it should be noted that only in the cases of liquid and gaseous fuels will this special attachment be used. In many cases the experimenter may wish to design his own unique ignition system, locating it on or within the fuel itself. The ignition system will be controlled by the DACS.

The Experiment Data Acquisition and Control System (DACS). The DACS will consist of a microprocessor-based, on-board computer-controlled system. The computer system will control and monitor the following systems and functions for the experiment:

1) Gas Purge/Storage System
2) Extinguishment System
3) Atmospheric Control
4) Robot Arm
5) Spray Nozzle Geometry and Flow Rate
6) Data Acquisition.

The DACS will be a digital system, easily reconfigurable with both software changes and plug-in board replacements or additions. Further, the DACS can be a personal computer-compatible system, which will control, monitor, display and store the normal experimental/chamber functions.

Facility Heat Exchanger. The heat rejection requirements for the Combustion Facility result primarily from the heat released in the combustion process, the heat dissipated by the fan/motor assembly, and the DACS. Since the routine operation of the facility will not include any external recirculation of the combustion chamber atmosphere during an experimental run, nearly all of the heat generated will be absorbed by the combustion chamber and its atmosphere. By restricting the amount of heat released during any experimental run, an experiment time-line may be established that would most likely permit passive heat rejection to the laboratory module.

If higher heat release experiments are anticipated, an active cooling coil may be incorporated directly inside the combustion chamber itself. Also, heat dissipated by the low-power compressor and vacuum pump (i.e., for the interim gas purge/storage system) and the DACS can most likely be accommodated by the Space Station active convection loop.

Facility Fan/Motor Assembly. A flow generation system, when required, must be designed that will have the following attributes:

1) Full control by the DACS over a wide range of speeds
2) Minimal input power
3) Safe and reliable operation in high percentage oxygen gas mixtures and extinguishant agents
4) Low noise and vibration.

The most appropriate fan/motor assembly for this application appears to be of the vane axial type. The vane axial fan/motor system can produce a wide range of flow rates and is of compact design. The power input to the fan/motor assembly is proportional to the total flow resistance (in terms of pressure drop) for any desired flow rate. However, the resistance produced within the chamber by the chamber's internal equipment (i.e. nozzles, inlet valves, etc.) is estimated to be minimal.

3.2.3 Near-Term Fire/Fire Extinguishants Interaction Experiment Requirements.

Section 3.2.1 described a number of Space Station-based fire/fire extinguishants interaction experiments that would require use of a "Combustion Facility." This facility is an updated version of a similar combustion facility proposed for Spacelab (see Ref. 18). It is recommended that the experiments and apparatus described in the preceding sections be developed through extensive ground-based laboratory testing and then prepared for selected testing on the NASA KC-135 aircraft. Although the periods of low gravity are limited (i.e., 15-25 seconds), the experiment can be operated in such a manner that the fuel would be ignited and burning just prior to a low-gravity portion of the flight. Extinguishment would than be initiated a few seconds into the low-gravity period. Based on the results of these ground-based and sub-orbital flight experiments, tests and experimental apparatus may be planned and designed for potential accommodation on the Spacelab and, ultimately, on the Space Station.

The fire safety-related importance of these measurements stems from a fundamental lack of understanding of how effective various fire extinguishants and/or extinguishment systems are in low-gravity fire situations. Thus, rigorous testing and data gathering in an earth-based laboratory is recommended prior to any extensive low-gravity experimentation.

3.2.4 Post-Fire Recovery of Sensitive Electronic Components Experiment Requirements. A separate, but related, experiment is that whereby sensitive electrical and electronic components are exposed to post-fire by-products of combustion for the purpose of investigating their effect on the operation or integrity of the component. The post-fire recovery or uninterrupted operation of such equipment as microprocessors, optical readers, switchgear, etc. in space could be critical to the mission of the spacecraft. The concern of this experiment is not the direct failure of components due to excessive heat or burning and scorching; rather, the concern is that of the immediate and longer-term effects of the by-products of combustion, with and without use of extinguishants, produced by a fire or combustion process adjacent to the sensitive components.

There are a number of ways in which sensitive equipment may be adversely affected by exposure to extinguishants and/or the by-products of a fire/fire extinguishant interaction:

a. Components (printed circuit boards, resistors, switches, etc.) may be shorted by condensates and/or soot particles

b. Optical sensors or readers may be obscured

c. Electrical coatings and exposed metals (e.g., connectors, switches, etc.) may degrade and/or corrode.

These concerns have been the subject of a number of ground-based investigations for several years. Some of these investigations are summarized in Table 3.2-1. Although the studies cited in Table 3.2-1 were devoted largely to the fire protection of sensitive and critical ground-based electronic data processing equipment (EDPE), the results are somewhat applicable to similar concerns for spacecraft. The most severe corrosion of electronic components was observed in one series of tests (Ref. 19) where the components were in the presence of burning PVC electrical wire insulation. References 19 and 20 also determined the amounts (in parts per million, ppm) of hydrogen flouride (HF) and hydrogen bromide (HBr) produced during fire/fire extinguishant tests where Halon 1301 was used to extinguish fires for a variety of controlled fuels (wood, excelsior, shredded paper, punched cards, etc.). In general, these limited, ground-based tests indicated minimal to nil immediate adverse affects on electronic components in the presence of the combustion by-products when the fire was extinguished with Halon 1301.

The justification for the performance of similar "post-fire recovery" tests in low gravity has not been fully established. It is clear that there is a need to evaluate the immediate and longer-term affects of combustion by-products on sensitive spacecraft components, but the influence of low gravity is difficult to quantify. However, there are at least two low-gravity effects which may make such investigations compelling. These two low-gravity fire/fire extinguishant interaction effects are the following:

1. Low-gravity combustion in quiescent or very low velocity flows tends to result in lower flame temperatures and <u>may</u> produce sootier and more highly toxic and corrosive combustion by-products.
2. Condensates (water combined with soot and other combustion by-products) may tend to "coat" and reside on a component's surface more in low gravity than in normal gravity.

If either of these effects is determined to be realistic, then a series of post-fire recovery tests on sensitive electronic components may be justified. However, it is suggested that extensive ground-based screening tests be performed to identify those fuels and extinguishants that produce the severest post-fire component degradation. Assuming that low-gravity post-fire recovery tests can be justified, it is proposed that such tests be performed in the Combustion Facility described in Section 3.2.2.

TABLE 3.2-1. SOME SELECTED STUDIES OF EXTINGUISHANTS APPLIED OVER ELECTRONIC GEAR

TYPE OF APPLICATION/STUDY	EXTINGUISHANTS STUDIED	RESULTS OF APPLICATION/STUDY	STUDY REFERENCE
1. Repeated application of Halon 1301 to a desk-top type of computer during false alarms. (Battelle Columbus Laboratories).	Halon 1301	No disruption of operation or hardware damage noted. (Details proprietary).	Personal communication from J.J. Reuther, Battelle Columbus Laboratories, 1987.
2. Analysis of controversy between Halon 1301 and water sprinkler systems for essential Electronic Data Processing Equipment (EDPE) located in computer rooms. (Air Force Institute of Technology WPAFB).	Halon 1301, water (Flooding Systems)	Based on a literature survey and numerous inquiries, the study concluded that water sprinkler systems were superior to Halon 1301 for fire protection of Air Force EDPE. (No experimental tests performed).	Ref. 21. Doerr, R.L. and Gross, T.H., Air Force Institute of Technology (WPAFB), 1980.
3. Experimental investigation of the immediate and long-term effects of exposure of sensitive EDPE in a computer room to a series of fire extinguishment scenarios (Air Force Engineering Services Center, Tyndall AFB).	Halon 1301, water (Flooding Systems)	Based on a series of tests using Halon 1301 to extinguish various fire scenarios in an EDPE (computer) room, the study concluded that Halon 1301 was superior to the use of water sprinklers. The single application of water resulted in severe failure of the EDPE system.	Ref. 20. Reichelt, E.F., et al., Air Force Engineering Services Center, Tyndall AFB, 1982.
4. Experimental investigation of the ability of Halon 1301 to extinguish various configurations and quantities of fuels (wood, excelsior, shredded paper, PVC insulated wire, punched cards, etc.) under controlled conditons. (Safety First Products Company).	Halon 1301 (Flooding System)	A series of 24 tests were conducted with varying configurations and quantities of the noted fuels. It was concluded that class A surface fires could be readily extinguished with Halon 1301 concentrations as low as 3.6 percent (at 20°C). Certain deep-seated fires required Halon 1301 concentrations as high as 20 percent. Limited exposure of electronic components to Halon 1301 fire extinguishments indicated no change in contact resistance and no corrosion. However, smoke from PVC wire cable did result in severe corrosion of electronic components.	Ref. 19. Cholin, R., Safety First Products Company, 1972.

Further, it is suggested that these tests be considered to be conducted in the Spacelab as a near-term precursor to Space Station-basing. It is highly unlikely that the short periods of low gravity obtainable during aircraft parabolic flights would be in any way useful to these post-fire recovery experiments.

Figure 3.2-9 illustrates one method for exposing a number of sensitive components during a combustion process. A candidate fuel (e.g., wiring insulation, urethanes, paper, etc.) is ignited in an oxidizing atmosphere, combined with a low-velocity flow inside the Combustion Facility chamber. The combustion by-products pass through a heat exchanger and then flow over a rack of various sensitive components (see Figure 3.2-10). The velocity in the vicinity of the components would, ideally, be adjusted close to that typical of spacecraft avionics enclosures or experiment "racks." Figure 3.2-9 shows a number of measurement stations in the flow path of the combustion by-products recirculating to the combustion chamber. Although not shown in the figures, an access door would permit the chamber to be loaded and unloaded. Also, electrical feed-throughs may be provided so that selected components could be activated and monitored for immediate effects resulting from the exposure of the component to the combustion by-products.

The experimental information from each combustion process can be enhanced in a number of ways. As shown in Figure 3.2-9, one or more video cameras can record the ignition and combustion of the candidate fuel. A Rayleigh light extinction/scattering station could be included to monitor particle sizes and number densities. A filter station could be provided to both remove the larger soot particles and to permit their later analysis. Finally, a mass spectrometer probe could be provided to monitor selected species of the combustion by-products.

After the combustion process (or processes) is complete, the exposed electronic components and other sensitive materials would be removed, inspected and tested immediately (if appropriate). The components would then be stored in appropriate containers to observe longer-term degradation effects. The evaluation tests can range from simple visual inspections to very precise electrical tests. Table 3.2-2 summarizes some of the evaluations that may be used.

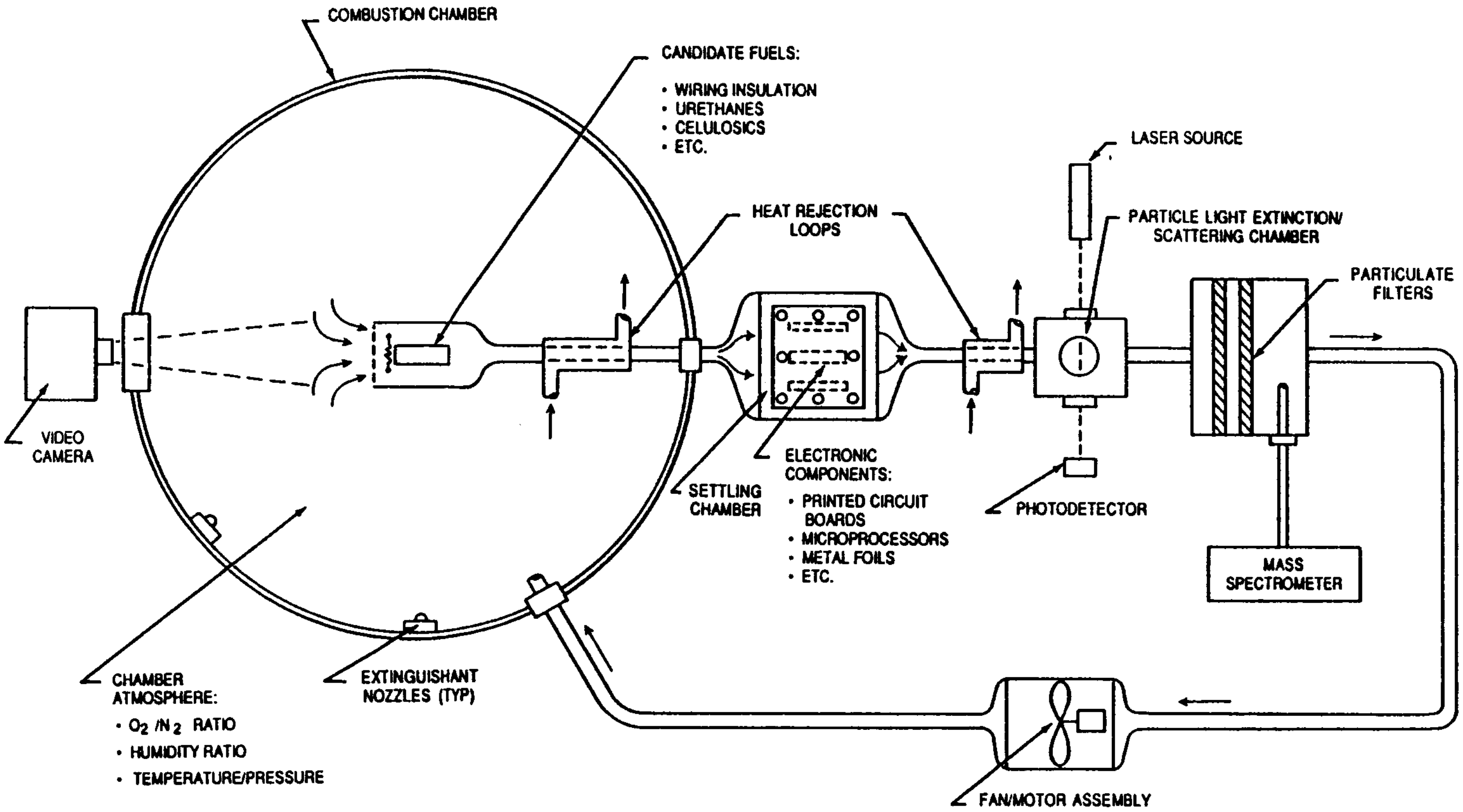


FIGURE 3.2-9. CONCEPT OF POST-FIRE RECOVERY OF SENSITIVE ELECTRONIC COMPONENTS EXPERIMENT

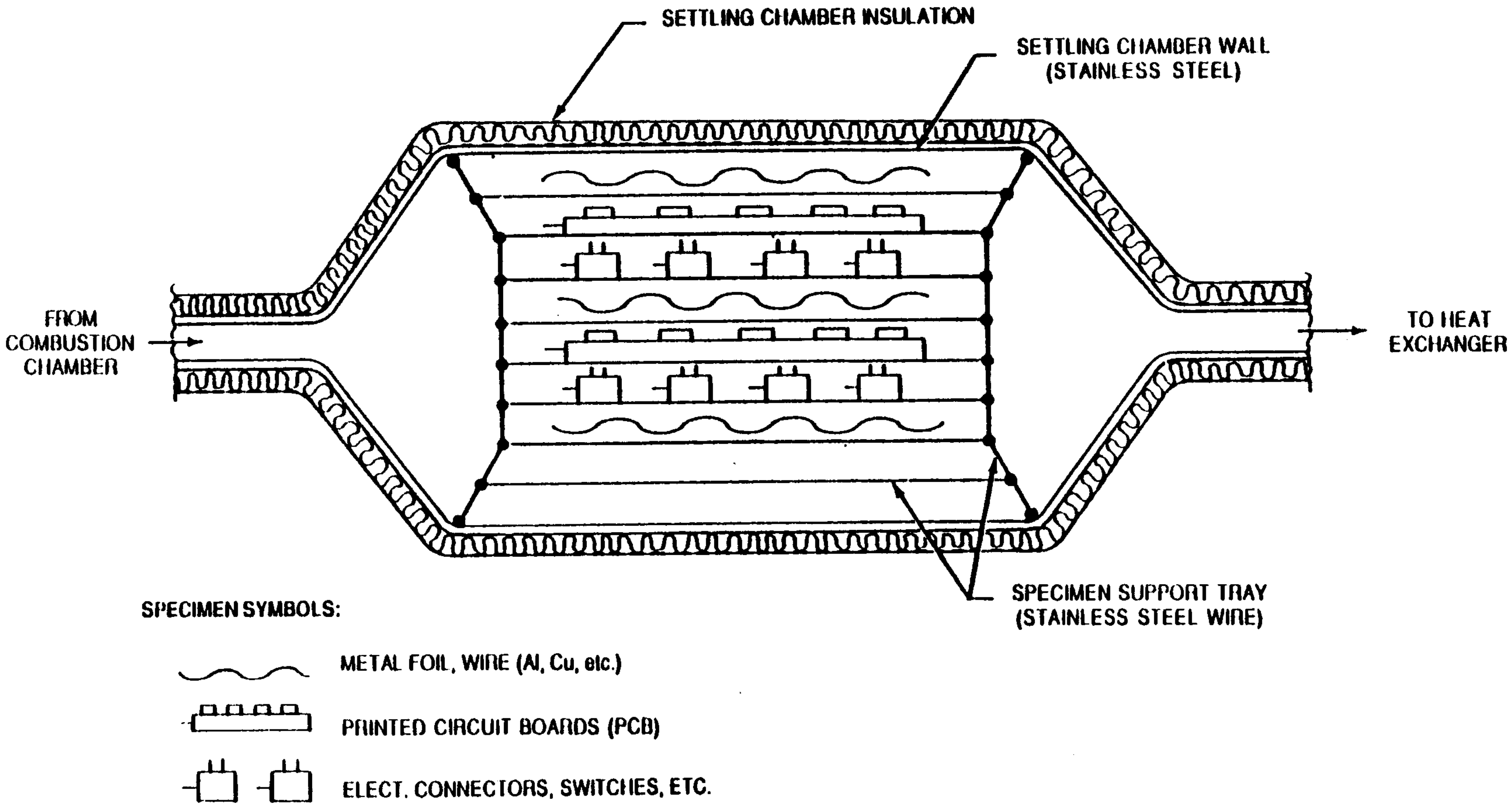


FIGURE 3.2-10. EXPOSURE (SETTLING) CHAMBER FOR SENSITIVE COMPONENTS

TABLE 3.2-2. EVALUATION PARAMETERS FOR POST-FIRE RECOVERY OF SENSITIVE ELECTRONIC COMPONENTS EXPERIMENT

CLASSES OF COMPONENTS	EVALUATION
All Specimens:	1. Visual residue 2. Corrosion, surface staining, change in color
Printed Circuit Boards and Other Electronic Components:	1. Corrosion, pitting 2. Electrical shorts, loss of continuity 3. Change in resistance, voltage or signal levels 4. Change in contact resistance of connector
Metal Foils and Wires:	1. Corrosion, pitting 2. Change in electrical resistance (of wires)
Non-Metallic Coatings and Insulations:	1. Change in dielectric strength 2. Change in material hardness 3. Cracking, splitting, crazing

3.2.5 Special Instrumentation and Diagnostic Measurement Equipment for the Experiments. Two major types of data and other experimental information are required from each Fire/Fire Extinguishants Interaction Experiment:

1) Rate of extinguishment in relation to the following specified parameters:
    - Quantity and type of extinguishant
    - Application of extinguishant (spray, mist, etc.)
    - Chamber atmosphere/composition
    - Chamber flow rate
    - Fuel geometry and fuel type
2) Combustion extinguishant by-products to determine toxicity.

The rate of extinguishment of a fire may be determined from a video recording system positioned on one of the optical quality ports along the chamber door (see Figure 3.2-11). This would provide a record of the ignition of the fuel, the application of the extinguishant to the burning fuel, and the extinguishment process. A holographic video system may be substituted in place of the video recording system due the ability of the holographic system to store information for later analysis in a ground-based laboratory and its established application to other microgravity experiments. A holographic video system (see Ref. 15) was used as a major component of the Spacelab-3 Fluids Experiment System (FES).

Determination of the by-products of the combustion and extinguishment process poses a much more difficult obstacle. Figure 3.2-11 illustrates a suggested diagnostic technique for obtaining several fire safety-related measurements in the vicinity of the fire/fire extinguishants interaction region. The scavenged gases leaving the combustion chamber would pass through a laser-based extinction/scattering chamber where the soot and smoke particles may be monitored by size and number density distribution according to size. This diagnostic technique would be similar to that reported by R.J. Santoro, et al. (Ref. 14). The soot and smoke particle laden gases would then pass into a filter chamber where the largest particles can be trapped for subsequent analysis. In addition, this system of filters or condensate plates could be cooled to remove a large fraction of the water vapor and other condensible gases from the combustion by-product flow stream. This system of filters would be removed after every combustion process for a particular material and extinguishant. The removed particles and condensate could be analyzed on the Space Station and/or stored for later analysis in a ground-based laboratory.

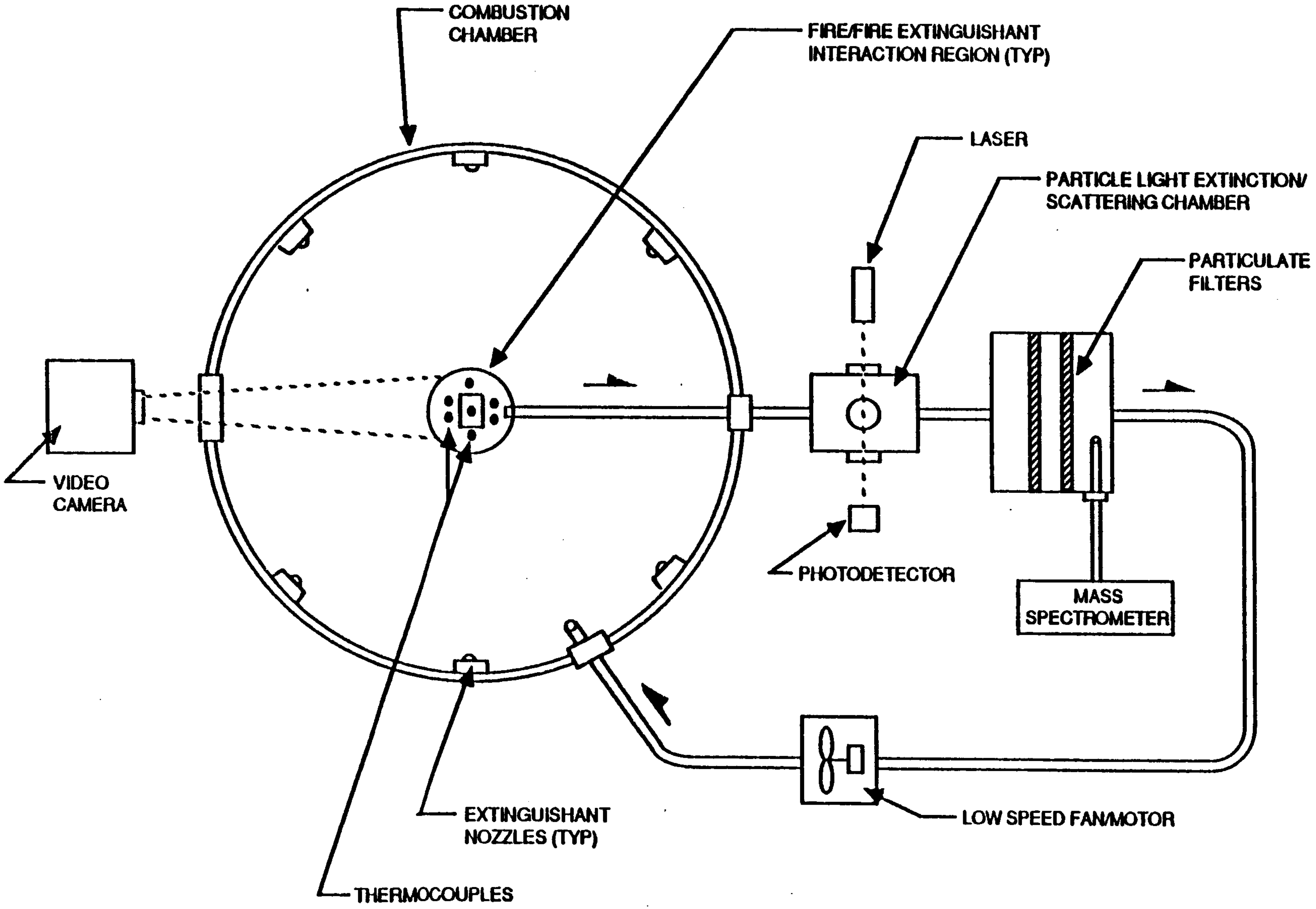


FIGURE 3.2.-11. INSTRUMENTATION AND DIAGNOSTIC MEASUREMENTS FOR THE FIRE/FIRE EXTINGUISHANTS INTERACTION EXPERIMENT

A quartz microprobe would be inserted into the flow downstream from the filter chamber. This probe would feed a small mass spectrometer tuned for selected species. The common major species of O_2, N_2, H_2, CO_2, and H_2O may be readily measured. The mass spectrometer can scan for other, selected species. This use of a quadrupole or magnetic-sector mass spectrometer would require some development for Space Station-basing. The ground-based use of such an instrument in the study of methane/air diffusion flames has been described by K.C. Smyth, et al. (Ref. 13).

Finally, a number of small thermocouples are recommended to be mounted in the near vicinity of the fuel sample. Thermocouples could also be embedded in the bulk fuel sample to monitor its temperature throughout the process.

3.3 Smoldering and/or Deep-Seated Combustion in Low Gravity

3.3.1 **Overall Description of the Experiment.** The purpose of this experiment is to investigate a number of smoldering and/or deep-seated combustion parameters in detail in a low-gravity environment. In terms of spacecraft fire safety, the desired output from such experiments should include the following information and data as a minimum:

- Smolder-wave propagation rate
- Maximum smolder-wave temperature
- Forced convection velocity below which the smolder combustion may not be sustained
- Identification of selected toxic by-products
- Smoke (soot) particle size distribution and number density
- Minimum forced convection velocity for transition to flaming combustion.

The ability to measure most of the above smolder-combustion process quantities is reasonably straightforward, even in a Space Station-based test facility. The exception is that relative to obtaining a complete description of the combustion by-products. These include the gaseous and liquid phases (especially the toxic by-products) and the particulate (soot and smoke) materials. A means for determining selected values of these quantities is described. However, it is noted that these measurements require a substantial amount of development.

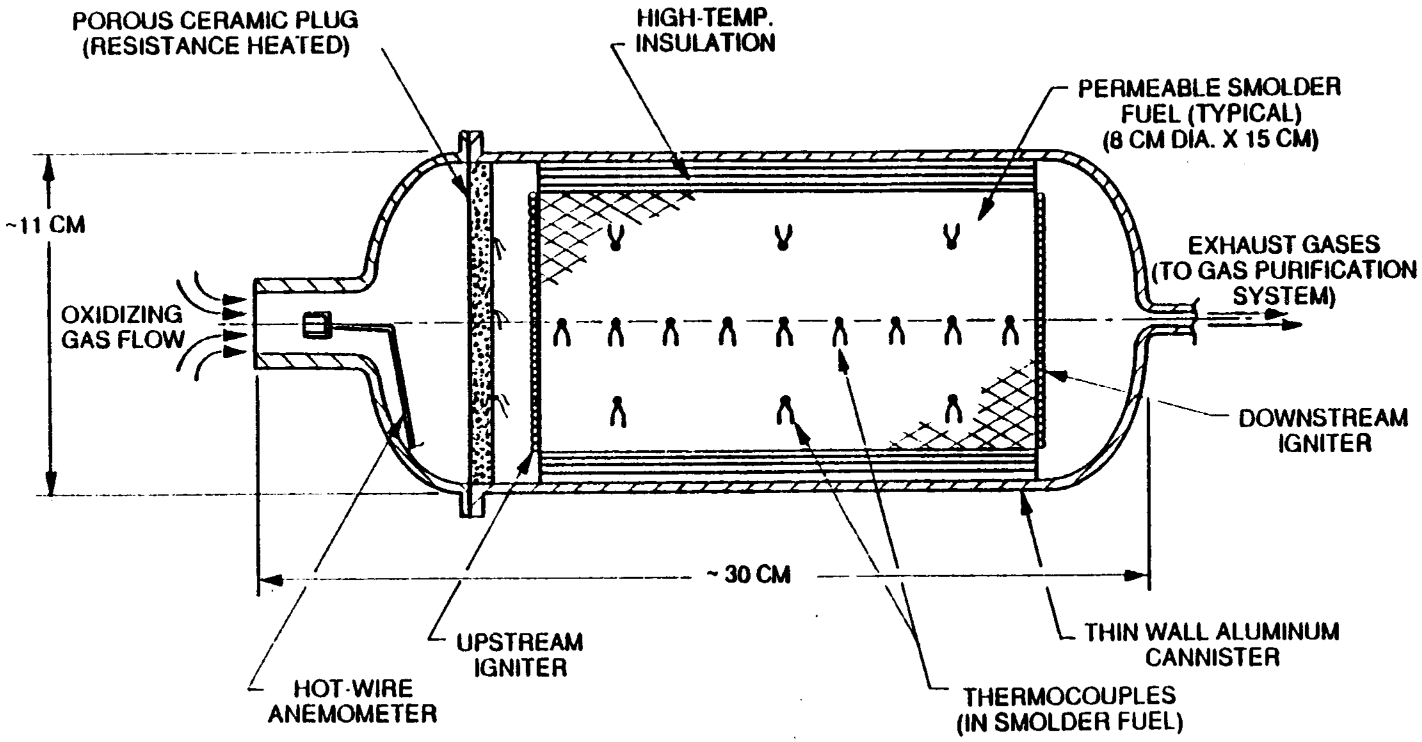
Figure 3.3-1, based on a conceptual design of M. Summerfield, et al. (Ref. 10), provides an illustration of a forced-convection smolder-combustion cannister in which candidate smolder materials would be contained for experimental processing. A number of these cannisters (up to eight) would be mounted in an enclosure (referred to herein as the Combustion Facility) as shown schematically in Figure 3.3-2. It is proposed to conduct the smolder-combustion process under forced convection conditions ranging from an oxidizer gas inlet flowrate that will just sustain smolder wave propagation to some limiting upper value yet to be established (~0.5 cm/s (0.2 in/s) or higher). The forced-convection smolder-combustion processes are planned to be performed with ignition initiated largely at the upstream end of the smolder material. Some smolder-combustion processes may be performed with ignition initiated at the downstream end of the smolder material, if smoldering can be sustained.

It is not planned at this time to attempt any smolder-combustion tests in the absence of forced convection. It is highly unlikely that smoldering can be sustained in the absence of both gravity and forced convection.

3.3.2 **Smolder Materials of Interest and Their Properties.** A short list of the general categories of candidate smolder materials is shown in Table 3.3-1, derived from Reference 10, where these materials are described in more detail.

TABLE 3.3-1. CANDIDATE SMOLDER MATERIALS

	Material Class	Configuration
1)	Cellulosics	Various (cylindrical elements, shredded and fluffed paper, sawdust, porous fiberboard, etc.)
2)	Polyurethanes	Flexible or Rigid Foams (permeable)
3)	Phenol Formaldehydes	Rigid or Granulated Foams
4)	Polystyrenes or Polyethylenes	(May be unacceptable due to thermoplastic (i.e., melting) action rather than forming a char)
5)	Urea Formaldehyde	Rigid Foams (may produce highly toxic fumes).



NOT TO SCALE

FIGURE 3.3-1. CONCEPT OF SMOLDERING AND/OR DEEP-SEATED COMBUSTION TEST SECTION

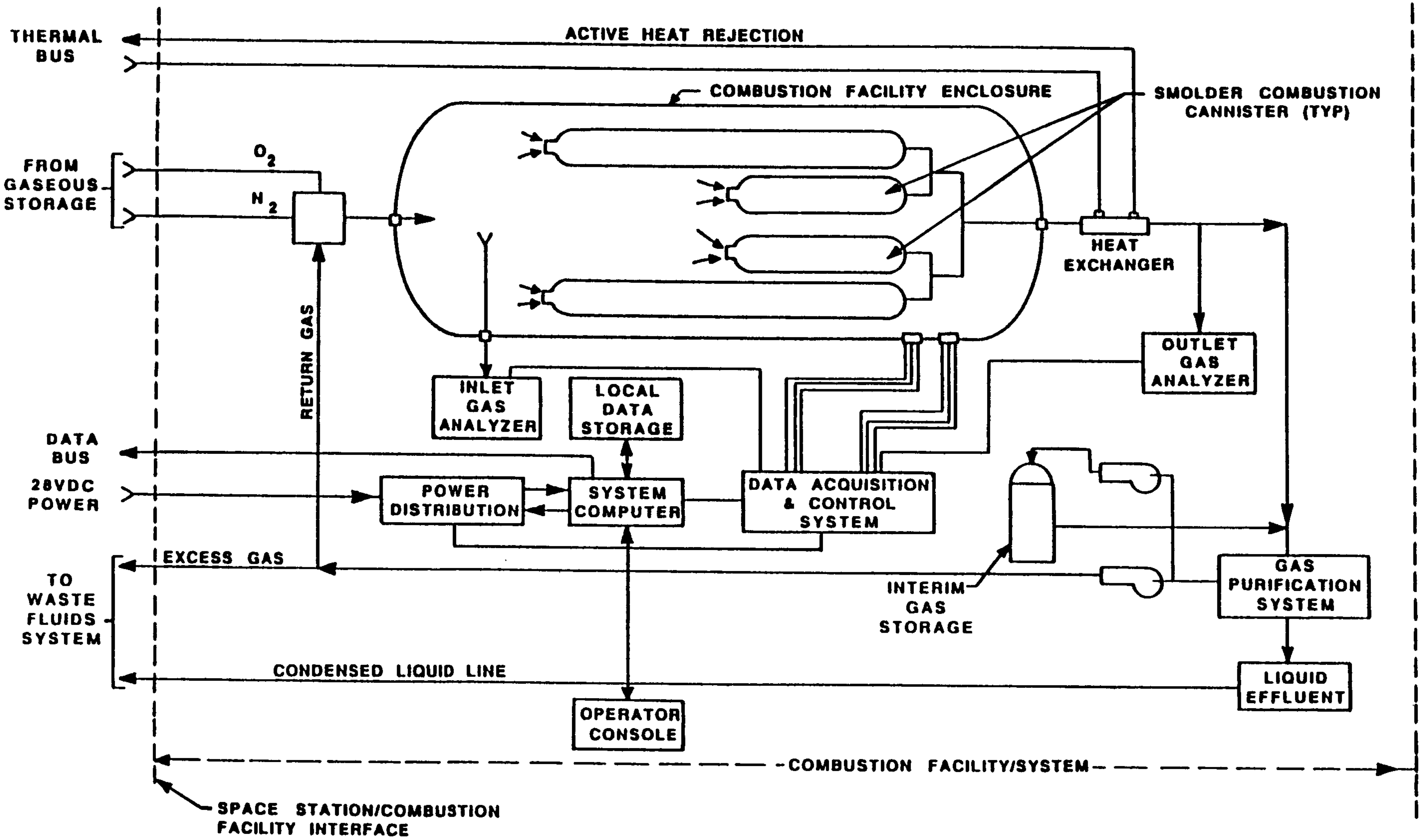


FIGURE 3.3-2. SCHEMATIC OF SMOLDER COMBUSTION EXPERIMENT IN COMBUSTION FACILITY

The fundamental physical properties of interest related to the smolder materials include those listed below:

- Permeability
- Chemical Composition
- Porosity
- Structure (flexible, open cell vs. granular)
- Shape and Size
- Confinement (i.e., packaging).

In addition to the above physical and mechanical material properties of interest, several thermophysical properties for each candidate material must be considered. These include specific heat, thermal conductivity, heat of combustion, minimum ignition energy, minimum ignition temperature, and stoichiometric flame temperature.

All of the above physical and thermophysical properties affect the smolder process to some degree. In addition, there are a number of test parameters that must be selected and/or monitored. These include the following:

- O_2/N_2 ratio of the oxidizing gas
- Gravitational level, or simulated g-level if used
- Forced convection flow rate
- Pressure level in test container
- Temperature of oxidizing gas
- Combustion configuration (co-current or counter-current).

Here co-current or counter-current combustion is defined as char proceeding in the direction of, or opposite to, the imposed forced velocity, respectively.

3.3.3 **Proposed Test Parameters.** As described in the preceding paragraphs, the smolder process for any of the candidate smolder materials is affected by the test parameters chosen as well as by the physical, thermophysical and mechanical properties of the material. M. Summerfield, et al. (Ref. 10) performed an analysis relevant to the range of test parameters of interest for Spacelab-based experimentation (i.e., g-level, O_2/N_2 ratio of the oxidizing gas, flow rate of oxidizing gas, pressure and temperature levels, etc.), which provided the test parameters for the experiment proposed herein, with the following exception. The concept design of Reference 10 provided a means for varying the gravitational level (g-level) by rotating the smolder-material cannisters about a central axis in the Combustion Facility. This level of detail is beyond the scope of the current effort.

The suggested oxidizer ratios range from O_2/N_2 = 20%/80% to 40%/60%, with these values being the preferred test parameters. Inertants other than nitrogen may be tested (e.g., argon, helium, etc.) with, possibly, a re-evaluation of the oxidizer ratios.

The velocities of the oxidizing gas flow imposed at the face of the smolder material should range from values less than 0.1 cm/s (0.04 in/s) to 0.5 cm/s (0.2 in/s) or higher. If the inlet oxidizer gas flow is taken directly from the atmosphere of the Combustion Facility, then the pressure will be limited to the allowable pressure of the Combustion Facility (i.e., approximately one atmosphere or 101.4 kPa). Higher pressures, if required, may be accommodated by routing the oxidizer gas flow directly to the combustion cannister via a pressure line.

Some control over the temperature of the incoming oxidizer gas flow may be desirable. It is generally impractical to heat the entire atmosphere in the Combustion Facility to attain the desired effect. However, a resistance heater located in the inlet of the smolder cannister (see Figure 3.3-1) can probably provide all of the temperature control necessary.

3.3.4 Basic Apparatus Required for the Experiment. The fundamental apparatus required for the Smolder-Combustion Experiment is a generic facility referred to herein as the Combustion Facility, which is the same facility concept as proposed for the Fire/Fire Extinguishants Interaction Experiment, described in Section 3.2.

A schematic of the use of the Combustion Facility, along with its supporting subsystems, was presented as Figure 3.3-2. This schematic indicates that the complete combustion facility experimental apparatus is comprised of the following major components and subsystems when used for the Smoldering-Combustion Experiment:

a) Combustion Facility chamber (enclosure)
b) Smolder-combustion cannisters
c) Oxidizer gas introduction and makeup subsystem

d) Interim purge/storage system
e) Heat rejection subsystem
f) Instrumentation and combustion diagnostic equipment
g) Data acquisition and control subsystem (DACS).

A brief description of items b), c), and e) follow. The Combustion Facility, items a) and d), would be identical to the facility described for the Fire/Fire Extinguishants Interaction Experiment in the preceding section. Details of the instrumentation, item f), are presented later. The details of the DACS, item g), are outside of the scope of this study.

Smolder-Combustion Cannister. The smolder material is proposed to be contained in cannisters such as that shown in Figure 3.3-1. Only one smolder process would be conducted at a time so that the inlet flow rate, outlet flow rate, and outlet gas composition can be adequately measured. The cannisters can be modified to accommodate different lengths and quantities of smolder material. One end of the cannister would be removable for loading and removal of the smolder sample, insulation, igniter, etc. In the design of Reference 10, the cannisters were to be constructed from thin-walled aluminum, and the porous material would be held within a heat loss barrier (e.g., foamed glass).

It is planned that each cannister could be assembled essentially as shown in the configuration of Figure 3.3-1 in an earth-based laboratory, complete with temperature sensors, hot-wire anemometer, smolder material and igniter, etc. The cannisters would then be packed and transported to the Space Station by means of the Space Shuttle. After the combustion process for each group of cannisters is completed, the cannisters would be stored for subsequent transport back to earth for further analysis of the combustion residue.

Oxidizer Gas Introduction and Makeup Subsystem. Figure 3.3-2 shows schematically the means for introduction of any required oxidizer gas from the Space Station supply. The actual operation of the facility would include a vacuum purge prior to introduction of the appropriate gases. After the appropriate pressure and mixture of gases has been obtained, the gas flow would be established with the "gas purification system" shown.

Although the gas flowrate through a smolder cannister would be very low (e.g., a volumetric flow of approximately 1.5 l/min (0.05 ft^3/min) at a velocity of 0.5 cm/s (0.2 in/s)), some makeup may be required to keep the oxidizer gas ratio within some acceptable limits. The oxygen content of the flow media may be continuously monitored by a mass spectrometer or, preferably, by a dedicated oxygen analyzer. Several companies manufacture oxygen monitors that can be suitably modified for use in the Space Station. It is suggested that as the oxygen content is depleted, it may be restored by the calibrated volume method described in Section 3.1.2.

It is recommended that the Combustion Facility flow medium passing through the smolder cannisters be filtered during and between experimental runs. As a minimum, filters should be used to remove the largest soot and smoke particles. The next priority may be to remove the water vapor and other condensibles formed as combustion by-products. It is possible that an adequate removal of the condensible materials (by cooling coils and/or desiccants) may permit adequate run times for the smolder-combustion experiments, especially if the oxygen depletion can be restored during the experiment.

Heat Rejection Subsystem. The amount of heat released during the smolder combustion process has not been determined for all possible test conditions. M. Summerfield, et al. (Ref. 10) addressed this problem for the Spacelab-based accommodation of the Combustion Facility. For a specific polyurethane foam, they assumed a smolder heat release of approximately 1050 J/g. Thus, for an assumed consumption of 30g of material in a cannister, the total heat release per cannister would be approximately 31.5 kJ (30 Btu). Even if this amount of heat were released in 5 minutes (a very short smolder process), the heat release rate (i.e., 6 Btu/min or 105 watts) may be readily accommodated with either an air-to-air or a liquid-to-air heat exchanger.

The interim purge/storage subsystem (vacuum pump and compressor) may be the single largest heat dissipating component in the Combustion Facility apparatus. This heat dissipation can be held to an acceptable value if the interim purge/storage time is extended. It is suggested that a reasonable power usage for this subsystem would be 300 watts, or approximately 17 Btu/min of heat rejection. This amount of heat rejection may be readily accommodated by an active cooling loop.

3.3.5 Special Instrumentation and Diagnostic Measurement Equipment for the Experiments. Desired Measurements. Smoldering-combustion processes do not readily permit any type of non-intrusive diagnostic investigation since there is essentially no visual flame to be monitored. An exception might be that where a laser-based optical system is used to measure the very low velocity of the inlet flow (e.g., by means of laser Doppler velocimetry (LDV)) and/or to analyze the soot and smoke particles leaving the smolder cannister (e.g., by extinction/Rayleigh scattering techniques).

The desired measurements may be listed as follows:

1. Temperature at discrete points along the smolder material centerline
2. Temperature at a smaller number of discrete points off the smolder material centerline
3. Temperature and flow rate of the oxidizer gas entering the smolder combustion cannister
4. Pressure in the smolder cannister (upstream of smolder material) and in the Combustion Facility outside of smolder cannister
5. Oxygen concentration at both the inlet and outlet of the smolder cannister
6. Ignition flux and smolder material temperature at initiation of combustion
7. Combustion by-products leaving the smolder cannister (both the gaseous by-products and the solid particles, e.g., soot and smoke)
8. Species concentration of combustion by-products.

Since the emphasis in these Space Station-based smolder experiments is fire safety, attention will be focused on the following determinations: 1) Environmental conditions of temperature and pressure in the smolder material and flow system; 2) Inlet velocity required to maintain smolder wave propagation; 3) Energy required to initiate combustion; and 4) Fire signature determinations (i.e., soot and smoke particle density and size distribution, selected combustion by-products). The instrumentation and diagnostic measurement equipment required are discussed in the following paragraphs.

Temperature and Pressure Measurements. Reference to the list of desired measurements presented above suggests that a number of temperature and pressure measurements are required during a smolder combustion process. The exact number of thermocouples to be embedded in the smolder material (Figure 3.3-1) must be heat fluxes required to initiate combustion. It was noted that the incident heat flux is a sensitive parameter, i.e., if the flux exceeds the ignition threshold for a specific material (e.g., polyurethane foam) the material may melt (tar) rather than char as desired.

M. Summerfield, et al. proposed a simple parallel-grid Nichrome wire igniter element at the upstream (or downstream) face of the smolder material (Figure 3.3-1). Further, it was suggested that the required heat flux for initiation of combustion be determined by ground-based experimentation for each candidate material.

Species Concentration of Smolder Combustion By-Products. Clearly, it is highly desirable to obtain measurements of the concentrations of combustion by-products leaving the smolder cannister. This determination is difficult because the combustion by-products are composed of a number of gases, particulate material and condensed droplets. The fire safety technology issues demand that these measurement problems be resolved. Thus, although the current state-of-the-art does not allow a complete determination of the combustion products, it is recommended that effort be made to obtain as much data as is reasonable.

The concept for monitoring the combustion by-products, as illustrated in Figure 3.3-3, involve the following procedure. The scavenged gases leaving the smolder cannister would pass through a laser-based extinction/scattering chamber where the soot and smoke particles may be monitored by size and number density distribution according to size. The soot and smoke particle-laden gases would then pass into a filter chamber where the largest particles may be trapped for subsequent analysis. In addition, this system of filters and/or condenser plates could be cooled to remove a large fraction of the water vapor and other condensible gases from the combustion by-product flow stream. This system of filters would be removed after every smolder combustion process for a particular material. The removed particles and condensate could be analyzed on the Space Station and/or stored for later analysis in a ground-based laboratory.

Finally, a quartz microprobe would be inserted in the flow downstream from the filter chamber. This probe would feed a small mass spectrometer tuned for selected species. The common gas species of O_2, N_2, H_2, CO_2, and H_2O may be readily measured. The

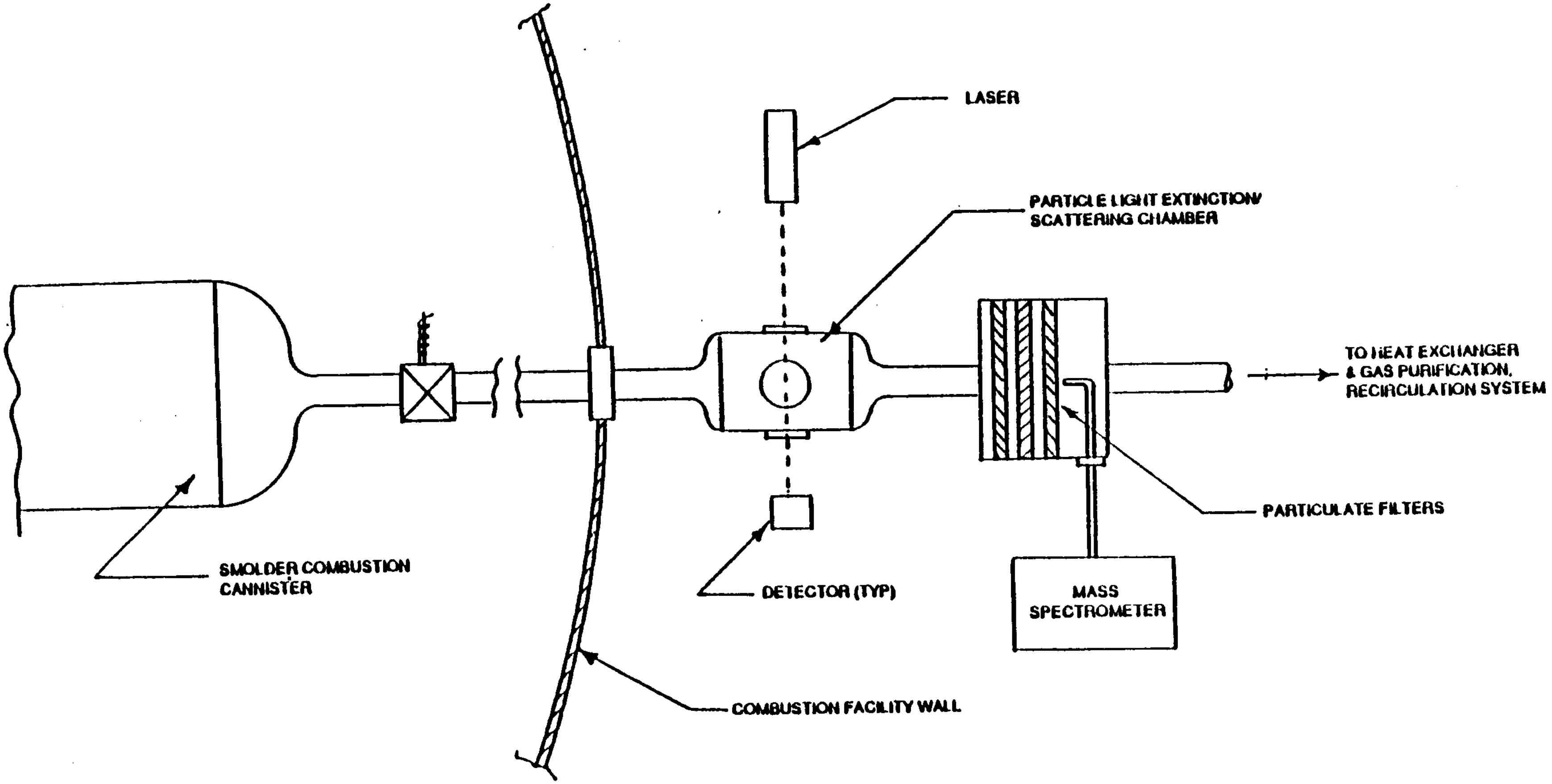


FIGURE 3.3-3. INSTRUMENTATION AND DIAGNOSTIC MEASUREMENTS FOR THE SMOLDERING AND/OR DEEP-SEATED COMBUSTION EXPERIMENT

mass spectrometer can scan for other, selected species. This use of either a quadrupole or a magnetic sector mass spectrometer would require some development for Space Station-basing.

4.0 EXPERIMENT ACCOMMODATION REQUIREMENTS

This section provides an overview of the accommodation requirements for Space Station-basing of the three fire safety-related experiments described conceptually in Section 3.0. Earlier manifesting of the experiments on the Space Shuttle/Spacelab would require similar accommodations, but such accommodations are not explicitly addressed. In either case, it is assumed that the experimental facilities would be accommodated within a pressurized laboratory module.

In the following subsections, the fundamental accommodation requirements are described and include the following: 1) spatial and mass estimates, 2) power and heat rejection, 3) consumables and waste disposal, 4) crew requirements and operational timelines, and 5) safety issues. The requirements discussed focus largely on the two major, generic test facilities, i.e., the Combustion Tunnel Facility and the Combustion Facility.

4.1 Spatial and Mass Estimates

4.1.1 First-Order Spatial Estimates. It is reasonable to limit the size of the Combustion Tunnel such that it may be accommodated within two Space Station double racks (Figure 3.1-3). For the purpose of this concept design effort, it is assumed that the usable working volume in two double racks is 2100 x 1600 x 760 mm (83 x 63 x 30 in). Approximately three-fourths of the working space available within the two double racks would be devoted to the Combustion Tunnel and its subsystems. The remaining working volume would be available to the DC controllers, data acquisition and control system (DACS), microprocessor (computer) control and data storage, and the display monitor and operator console.

For the generic Combustion Facility used for the Fire/Fire Extinguishants Interaction Experiment and the Smoldering Combustion Experiment, a double and a single rack are necessary. The combustion chamber alone would have a volume in excess of a single Space Station rack when its flanges, support brackets, etc. are considered. The usable volume in a combination double rack and single rack is approximately 1580 x 1600 x 760 mm (62 x 63 x 30 in).

The Space Station-based spatial requirements of the two generic test facilities may be summarized as follows:

1) Combustion Tunnel Facility: Two Standard Double Racks
2) Combustion Facility: A Standard Double Rack and Single Rack Combination.

Clearly, these spatial requirements have not been optimized. However, practical scaling considerations indicate that the spatial requirements of each facility are unlikely to be reduced more than a single rack.

4.1.2 **First Order Mass Estimates.** Mass-budget estimates for the three Space Station-based experiments described conceptually in Section 3.0 were obtained by summing the masses of each major component and subsystem. Obviously, the major masses are those components and subsystems of the two proposed generic test facilities, i.e., the Combustion Tunnel Facility and the Combustion Facility. These first-order mass estimates are summarized in Table 4-1 for the three experiments described in Section 3.0. As expected, the larger, more elaborate Combustion and Flame Spread Experiment in the Combustion Tunnel Facility is shown to have the highest mass (443 kg (976 lbm)).

4.2 Input Power and Heat Rejection Estimates

First-order input power estimates (Table 4-2) indicate relatively modest requirements for the three fire-safety related experiments. The total input power is a maximum demand, probably an overestimate since the individual demands do not all occur simultaneously. The single largest power consuming component for either of the two generic experiment facilities is noted to be the laser power suppy. At this stage of the experiment concept designs, the requirement for laser-based, non-intrusive optical diagnostics is the least established. Also, the input power summary of Table 4-2 does not include the short duration igniter power requirements. A single estimate is shown for the input power for both Combustion Facility experiments, although the Smoldering Combustion Experiment would require slightly less power since no use of the robot arm is needed.

A typical power profile for the Combustion and Flame Spread Experiment (Figure 4-1) using the Combustion Tunnel Facility, shows that near-maximum power demand occurs

TABLE 4-1. ESTIMATE OF EXPERIMENT FACILITY MASSES FOR SPACE STATION ACCOMMODATION

ITEM NO.	COMPONENT	COMBUSTION TUNNEL FACILITY MASS	COMBUSTION FACILITY MASS	
		Combustion & Flame Spread Experiment	Fire Extinguishants Interaction Experiment	Smoldering Combustion Experiment
		kg (lbm)	kg (lbm)	kg (lbm)
1.	Combustion Tunnel (Basic Components)	204 (450)	–	–
2.	Combustion Chamber (Basic Components)	–	114 (250)	114 (250)
3.	Interim Gas Purge Sphere	36 (80)	45 (100)	45 (100)
4.	Vacuum Pump/Compressor	14 (30)	14 (30)	14 (30)
5.	Gas Make-Up System	9 (20)	9 (20)	9 (20)
6.	Heat Exchangers/Pumps	4 (10)	4 (10)	4 (10)
7.	Automatic Sample Change Mechanism	9 (20)	–	–
8.	Robot Arm (Positioning Device)	–	9 (20)	–
9.	Smolder Combustion Cannisters (8 total)	–	–	6 (14)
10.	Candidate Extinguisher Nozzles	–	4 (10)	–
11.	Laser Diagnostics Equipment	14 (30)	9 (20)	9 (20)
12.	Data Acquisition and Control System (DACS)	23 (50)	11 (25)	11 (25)
13.	Video Camera(s)	3 (6)	3 (6)	–
14.	Display Monitor and Console	14 (30)	14 (30)	14 (30)
15.	Microprocessor Controller and Data Storage	9 (20)	9 (20)	9 (20)
16.	Subsystem Controllers (all)	45 (100)	36 (80)	36 (80)
17.	Miscellaneous Instrumentation	14 (30)	9 (20)	9 (20)
18.	Support Structure	45 (100)	32 (70)	32 (70)
	TOTAL MASSES	443 (976)	322 (711)	312 (689)

TABLE 4-2. ESTIMATE OF EXPERIMENT FACILITY INPUT POWER FOR SPACE STATION ACCOMMODATION

ITEM NO.	COMPONENT/SUBSYSTEM	COMBUSTION TUNNEL FACILITY POWER, kW	COMBUSTION FACILITY POWER, kW
1.	Combustion Tunnel Fan/Motor	0.5	-
2.	Combustion Chamber Fan/Motor	-	0.2
3.	DACS, Controllers, etc.	0.4	0.6
4.	Laser Power Supply	2.0	1.0
5.	Sample Exchange Mechanism	0.1	-
6.	Robot Arm (Fuel Positioning Device)	-	0.2
7.	Other Instrumentation, Valves, etc.	0.4	0.2
8.	Vacuum Pump & Compressor	0.2	0.2
	Total Input Power	3.6	2.4

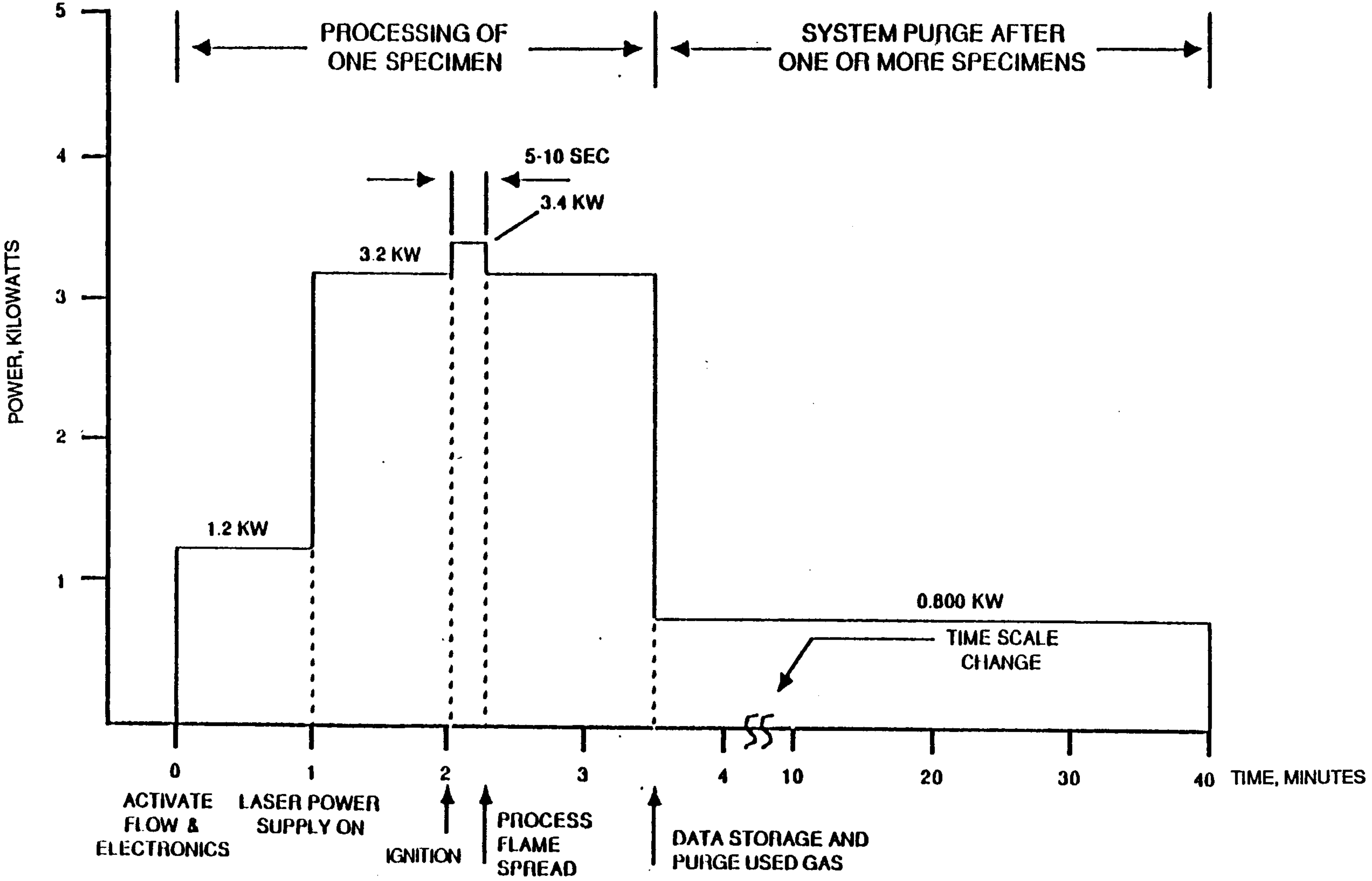


FIGURE 4-1. POWER PROFILE FOR THE COMBUSTION TUNNEL FACILITY

only during the 5 to 10 seconds of ignition. Power profiles for the other two experiments would have smaller peak power requirements.

Heat rejection requirements for each experiment includes all of the power dissipation from the input power quantities listed in Table 4-2. In addition, heat rejection capability must be provided for the heat released during each experiment's combustion process. Although these values have not been precisely established, it is proposed to scale each fuel to limit the heat release rate to no more than 1.0 - 1.5 kW (57 - 85 Btu/min) over a 0.5 to 1.5-min period for the Combustion and Flame Spread Experiment and the Fire/Fire Extinguishants Interaction Experiment. The heat release rate for the Smolder Combustion Experiment is estimated to be only approximately 0.10-0.15 kW (5.7-8.5 Btu/min) over a 50 to 60 min period.

4.3 Consumables and Waste Disposal

4.3.1 **Space Station-Supplied Consumables.** The major consumables required from the Space Station supply include gaseous oxygen and nitrogen for use in recharging the atmosphere within the two generic test facilities (i.e., the Combustion Tunnel Facility and the Combustion Facility). Smaller quantities of other commonly used gases, such as helium and argon, may also be required as alternative inertants and/or for use in purging the facilities. Also, some cleaning solvents may be required to flush the combustion regions of the test facilities on a periodic basis.

A precise estimate of the quantities of Space Station-supplied gases required for each of the experiments described in Section 3.0 cannot be established until more definitive test matrices and process run times are established. However, a first-order estimate may be made by assuming a number of experimental runs for each experiment per 90 day logistics period and further assuming the number of experimental runs per recharge of the respective test facility free volume. For each test facility, the recharge environment is assumed to be as follows:

Pressure:	101.4 kPa (14.7 psia)
Temperature:	22^{o}C (72^{o}F)
Oxygen:	21.0 percent by volume
Nitrogen:	79.0 percent by volume.

The gaseous consumables summarized in Table 4-3 for each experiment appear relatively modest. During each discharge of the facility, the free volume would be evacuated and partially purged with an inert gas (e.g., nitrogen). If one assumes that an additional 50 percent of the total gas mass is required for purge, the total mass of gases (oxygen and nitrogen) for each experiment is as follows:

Facility/Experiment	Total Consumable Gases (O_2 & N_2)
Combustion Tunnel Facility:	
o Combustion and Flame Spread	10.5 kg (23.2 lbm)
Combustion Facility:	
o Fire/Fire Extinguishants Interaction	25.0 kg (55.2 lbm)
o Smoldering Combustion	12.2 kg (26.9 lbm)

4.3.2 **Waste Disposal.** Disposal of the waste materials from the experiments is not expected to be demanding in terms of volume and weight. However, the waste materials are expected to be toxic and, in some cases, corrosive. The waste materials to be rejected will include filters used in the test facilities to remove the larger particulates, the spent combustion gases (and some condensates), and cleaning materials (solvents and cleaning pads) used to clean the facilities. No estimates have been made of the amount of condensates that may need to be disposed. However, the spent gases to be discharged will be assumed approximately equivalent to the amounts of gases required for recharging the free volume of the test facilities plus 20 percent for the combustion gases. A summary of the waste disposal requirements are given in Table 4-4 for an assumed 90 day logistics period.

4.4 Crew Requirements and Operational Time-Lines

The manhours required for operation of the Space Station-based fire safety-related experiments must be minimized due to the limited crew time available. It is highly unlikely that a payload specialist can be fully dedicated to these experiments, since the crewmembers' time will be distributed among several experiments and other activities. This implies a need to automate the operation of any fire safety-related experiment to the greatest extent possible. However, at this stage of the concept designs described herein, it is not possible to establish the degree to which each

TABLE 4-3. ESTIMATE OF SPACE STATION-SUPPLIED CONSUMABLE GASES

(90 DAY LOGISTICS PERIOD ASSUMED)

CALCULATION STEP	EXPERIMENT SPECIFIC PARAMETER		
	COMBUSTION TUNNEL FACILITY	**COMBUSTION FACILITY**	
	Combustion & Flame Spread Experiment	**Fire Extinguishants Interaction Experiment**	**Smoldering Combustion Experiment**
1. Total Number of Process Runs (90 Days)	100	50	96
2. Number of Process Runs per Complete Discharge/Recharge of Free Volume	4	2	8
3. Free Volume of Facility Combustion Region	0.25 m^3 (8.8 ft^3)	0.58 m^3(20.5 ft^3)	0.58 m^3(20.5 ft^3)
4. Total Number of Complete Discharges/Recharges of Free Volume	25	25	12
5. Gaseous Oxygen Required @ STP (Note 1)	1.3 m^3 (46 ft^3) 1.6 kg (3.5 lbm)	3.0 m^3(106 ft^3) 3.9 kg (8.6 lbm)	1.5 m^3(53 ft^3) 1.9 kg (4.2 lbm)
6. Gaseous Nitrogen Required @ STP	4.9 m^3(173 ft^3) 5.4 kg (12.0 lbm)	11.4 m^3(403 ft^3) 12.8 kg (28.2 lbm)	5.5 m^3(194 ft^3) 6.2 kg (13.7 lbm)
7. Mass of Purge Gas (Note 2)	3.5 kg (7.7 lbm)	8.3 kg (18.4 lbm)	4.1 kg (9.0 lbm)
8. Total Mass of Consumable Gases (5. + 6. + 7.)	10.5 kg (23.2 lbm)	25.0 kg (55.2 lbm)	12.2 kg (26.9 lbm)

NOTE 1: STP - Standard temperature and pressure conditions.

NOTE 2: Mass of purge gas required assumed to be 50 percent of total recharge gases (O_2 & N_2).

TABLE 4-4. ESTIMATES OF SPACE STATION WASTE DISPOSAL MASS REQUIREMENTS

(90 DAY LOGISTICS PERIOD ASSUMED)

	TEST FACILITY		
	COMBUSTION TUNNEL FACILITY	COMBUSTION FACILITY	
WASTE MATERIAL	Combustion & Flame Spread Experiment	Fire Extinguishants Interaction Experiment	Smoldering Combustion Experiment
	kg (lbm)	kg (lbm)	kg (lbm)
1. Spent Gases (Note 1)	12.6 (27.8)	30.0 (66.2)	14.6 (32.3)
2. Particulate Filters	5.7 (12.6)	5.7 (12.6)	5.7 (12.6)
3. Cleaning Solvents	2.3 (5.0)	2.3 (5.0)	2.3 (5.0)
4. Condensates	To Be Determined	To Be Determined	To Be Determined
Total Masses	20.6 (45.4)	38.0 (83.8)	22.6 (49.9)

NOTE 1: Spent gases includes all gases required to purge and recharge the facility free volume, plus an assumed twenty percent (by mass) released by combustion processes.

experiment may be automated. This is especially true with regard to the loading and unloading of fuel specimens within either the Combustion Tunnel Facility or the Combustion Facility.

In order to provide a preliminary estimate of crew manhours for each of the three Space Station-based experiments described herein, it was assumed that the loading and unloading of fuel specimens would be performed manually and that only the operation of the test apparatus would be automated under microprocessor control. Further, the number of experimental runs (i.e., number of fuel specimens) to be accomplished during each 90-day logistics period was estimated, as shown in Table 4-3. From these assumptions and the assignment of nominal manhours for logistics, apparatus assembly/disassembly, specimen loading/unloading, process run operation/monitoring, and apparatus cleanup, Table 4-5 was prepared as a summary of all crew manhours required for each of the three Space Station-based experiments. The mean crew manhours required is, therefore, estimated as approximately 150 hours per 90-day mission. This translates to 12.5 hours of crew time per week, probably not an unreasonable amount of time.

A typical time-line for crew operations is illustrated by Figure 4-2. The Smoldering Combustion Experiment was chosen for this illustration, since it is representative of the mean crew time required and contains the major operational elementals of all three Space Station-based experiments.

Again, the crew manhour and operational time-line requirements illustrated by Table 4-5 and Figure 4.2, respectively, are very approximate estimates at this stage of the experiment definition and development effort. Much more definitive test matrices and experiment designs (including degree of automation) are required before these estimates may be refined.

4.5 Safety Issues

There are a number of safety issues associated with the integration and operation of any of the Space Station-based fire safety-related experiments described herein. These issues may be conveniently separated into two groups; 1) those fundamental flight hazards associated with all flight hardware, and 2) those special safety issues relevant to these specific experiments.

TABLE 4-5. ESTIMATE OF CREW MANHOUR REQUIREMENTS FOR THE SPACE STATION BASED EXPERIMENTS

(90 DAY MISSION PERIOD ASSUMED)

WASTE MATERIAL	EXPERIMENT		
	Combustion & Flame Spread Experiment	**Fire Extinguishants Interaction Experiment**	**Smoldering Combustion Experiment**
	(Est. Manhours)	(Est. Manhours)	(Est. Manhours)
1. Logistics (Storage & Retrieval of Equipment)	8.0	8.0	8.0
2. Apparatus Assembly	16.0	16.0	16.0
3. Loading of Test Specimens & Operation Monitoring	48.0	60.0	72.0
4. Removal of Test Samples & Apparatus Cleanup	56.0	80.0	48.0
5. Disassembly and Storage of Apparatus	4.0	4.0	4.0
Total Manhours	132.0	168.0	148.0

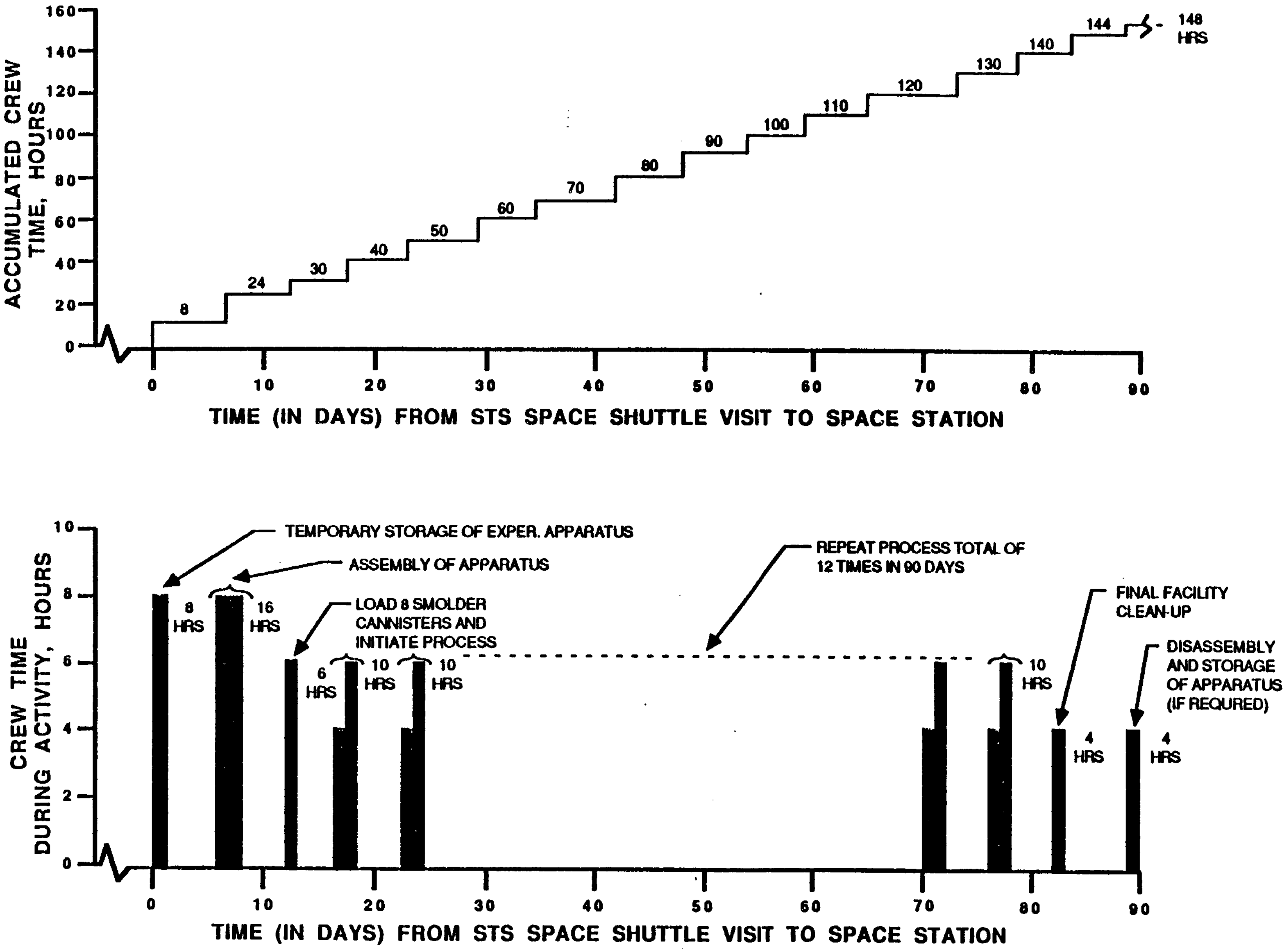


FIGURE 4-2. <u>OPERATIONAL TIME-LINE REQUIRED FOR THE SMOLDERING COMBUSTION EXPERIMENT (90 DAY LOGISTICS PERIOD)</u>

4.5.1 **Fundamental Flight Experiment Hazard Requirements.** Each experiment apparatus must be designed, constructed, and tested for compliance with all applicable STS Space Shuttle and Space Station hazard requirements. A complete list of these requirements documents will be prepared and reviewed for compliance. An example of such a list of documents for the Space Shuttle safety guidelines is presented as Table 4-6. Typical specific concerns of these guidelines include the following items:

1) Breakage of glass lenses
2) EMI/RFI
3) Offgassing
4) Stress corrosion
5) Sealed containers
6) Structural failures
7) Touch temperatures
8) Injury hazards due to sharp corners, etc.
9) Flammable materials
10) Electric shock
11) Fire-ignition sources.

TABLE 4-6

SOME SELECTED NASA STS SPACE SHUTTLE SAFETY GUIDELINES

o NHB 1700.7A	Safety Policy and Requirements
o KHB 1700.7	STS Payload Ground Safety Handbook
o JSC-13830A	Implementation Procedure for STS Payloads System Safety Requirements
o JSC-11123	Space Transportation System Payload Safety Guidelines Handbook
o NHB 8060.1B	Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environments that Support Combustion
o MSFC-SPEC-522	Design Criteria for Controlling Stress Corrosion Cracking
o JSC 08962	Compilation of VCM Data of Nonmetallic Materials

4.5.2 **Special Safety Issues.** Each of the Space Station-based fire safety experiments is expected to pose special safety and hazard issues since some toxic and corrosive substances will be produced as by-products of the process of combustion and extinguishment. Also, the combustion process will normally take place at, or slightly above, the laboratory module atmospheric pressure. Finally, hazardous gases (e.g., oxygen) will be transported to the experiment apparatus for purposes of atmosphere make-up and recharging.

All of these special safety and hazard issues will be addressed in detail during the experiment design phase. Some techniques and procedures that may be used to minimize the hazards are the following:

1) All fuel samples will be conservatively tested in ground-based facilities to ensure that no explosive materials are used.

2) The quantity of fuel placed in the experiment apparatus will be carefully restricted to minimize heat release and over-pressure during the combustion process.

3) Introduction of oxygen into the experiment apparatus will be initiated only after an appropriate amount of the inert gas (e.g., nitrogen) has been admitted. This should minimize the time that a flammable mixture is contained within the experiment apparatus prior to initiation of the combustion process.

4) Redundant oxygen sensors and pressure gauges will be used to monitor the gaseous mixture within the experiment apparatus.

5) Provision for emergency venting (to space vacuum) and/or nitrogen flooding will be provided in the event of a hazardous occurrence.

6) Dedicated fire detectors and fire extinguishers shall be located within the experiment apparatus enclosure (i.e., within the Space Station experiment racks).

5.0 EXPERIMENT-RELATED TECHNICAL LIMITATIONS

During the preparation of the spacecraft fire safety-related experiment concepts described in Section 3.0, a number of experiment-related technical limitations was identified. These technical limitations include topics that are currently at, or somewhat beyond, the current state-of-the-art as well as topics that simply pose challenging design problems. Nearly all of the identified technical limitations relate directly, or indirectly to the need to automate the Space Station-based experiments to the greatest degree possible.

The following paragraphs provide a brief discussion of the experiment-related technical limitations identified herein. These technical limitations include the following:

1) Non-Intrusive Combustion and Flowfield Diagnostics
2) Determination of Selected By-Products of Combustion
3) Disposal or Recycling of Combustion By-Products.

5.1 Non-Intrusive Combustion and Flowfield Diagnostics

The use of completely non-intrusive (e.g., laser-based optical) combustion and flowfield diagnostic techniques is compelling, but difficult at present. The use of various combinations of intrusive (i.e., probe) and laser-based optical diagnostic systems are described throughout Section 3.0. Since the Space Station-based experiments are some 8-10 years in the future (1996-1998), it may be anticipated that non-intrusive diagnostic measurements will be far more applicable than at the present time.

The various laser diagnostic systems described conceptually throughout Section 3.0 can provide valuable measurements of many parameters of interest relevant to combustion science and fire-safety experiments. These diagnostic systems are possible in principle, but the techniques of data acquisition and analysis need to be developed further for the precise measurement of these parameters. Although these techniques are to be applied under microgravity conditions, it is important to establish a ground-based breadboard laser diagnostics system to develop the experiments and the system hardware for Space Station research. The ground-based system can be used later for the analysis of data collected from the Space Station experiments.

Areas identified for further technology development activities include the following:

1) Holography: real-time analysis and temperature profile measurement
2) Use of fiber optics to simplify the system
3) Laser Doppler Velocimetry: low-velocity particle measurements, particle seeding, etc.
4) Laser Induced Fluorescence: species concentration measurements of various combustion flames
5) Use of laser for ignition of fuel materials.

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

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

5.1.2 **Use of Fiber Optics.** The use of fiber optics to simplify and enhance diagnostics systems is very compelling. However, there are a number of limitations in the current technology of fiber optics which need to be studied. Some of the following difficulties arise when using fiber optics in holography:

1) Changes in the polarization state occur, which may lead to a reduction in fringe visibility (see Note 1).
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 the diagnostic system can be established, fiber-optics transmission would greatly simplify the system.

Note 1: Single mode polarization-preserving fibers are available for NIR wavelengths. Special fibers for the visible region need to be developed. The use of polarization-preserving fibers requires proper alignment, together with good linear polarization of the source.

C-2

5.1.3 **Laser Doppler Velocimetry.** Laser Doppler Velocimetry may be used for the measurement of particle and flame velocities. In principle, it is possible to measure velocities as low as micrometers per second, but in practice, this precision is very difficult to achieve. Further effort is needed to establish the lowest velocity that can be measured and the seeding mechanism required.

5.1.4 **Laser Induced Fluorescence.** Laser Induced Fluorescence (LIF) is a very precise investigation technique for the measurement of species concentrations in flames. There are well established procedures for the measurement of OH species concentrations in ground-based laboratory studies of diffusion flames. For many of the other species of interest, further experimental research needs to be performed in order to establish a firm spectroscopic data base for the quantitative analysis of LIF data. This experimental research needs to be performed relative to flames produced by the various fuels and atmospheres that would be investigated on the Space Station.

5.1.5 **Laser Ignition of Fuel Materials.** An entirely non-diagnostics application of lasers is in the possible use of focused laser beams to ignite the fuel materials in the combustion 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 without the proximity of electrode surfaces.

5.2 Determination of Selected By-Products of Combustion

In any of the spacecraft fire safety-related experiments described herein, it is highly desirable to be able to measure the quantity of selected species of the by-products of the experimental combustion process. Although the measurement of the combustion intermediates is important for a complete understanding of the combustion process, such measurements may be currently beyond the state-of-the-art. For spacecraft fire safety purposes, it is desirable to monitor selected species, especially those compounds which may be highly toxic. Also, the measurement of the combustion process smoke particle-size distribution and concentration by size is important in assessing the process signature. It is suggested that these measurements be accomplished by a combination of laser optics (extinction/scattering determinations of particle sizes and number density by size), mass spectrometer, and particulate filters. These techniques have been used extensively in ground-based laboratories, but such a system for automated use on the Space Station clearly requires development.

5.3 Disposal or Recycling of Combustion By-Products

Disposal and/or recycling of the spent gases and other by-products of combustion (condensates, soot and smoke particles, etc.) from the Space Station experimental facilities may pose a significant technical challenge. Periodically, the gaseous environment within the Combustion Tunnel Facility and the Combustion Facility must be purged and reconstituted with the appropriate environment for subsequent tests. Even if a number of devices (e.g., smoke particle filters, condensate cold traps, etc.) are used within the experimental facility during a process run (experiment), the remaining gases will likely include some combustibles and toxic compounds. Thus, even with this real-time cleanup, disposal and/or recycling of the spent gases may require special attention.

Catalytic converters may be used to complete the combustion process and, for example, convert CO to CO_2. However, some combustible gases will remain, along with some toxic and corrosive compounds. A determination is required as to the quantity of such waste material that may be generated by the experiments. This type of determination is required before these waste materials may be delivered to the Space Station Waste Management System (WMS) for disposal. The fundamental question to be resolved is as follows: To what extent do the spent gases and other by-products of combustion require filtering and other modification prior to delivery to the WMS?

A related question is whether an interim purge/storage container is required. If so, a low-power compressor will be needed to evacuate and compress the spent gases from the experiment facilities. In any event, the questions regarding the use of particulate filters, condensate cold traps, catalytic converters, etc. must be resolved.

6.0 EXPERIMENT DEVELOPMENT PLANS

Sections 3.0 through 5.0 of this report have presented discussions of the concept designs, spacecraft accommodation requirements, and some of the technical problems identified to date for three specific Space Station-based, fire safety-related experiments and their experimental facilities. Also, three related near-term, precursor experiments were introduced that could be undertaken and accomplished during the 1990-1995 calendar year period.

This section provides a preliminary plan and schedule outlining the development of the identified Space Station-based experiments to the point of flight readiness for an early 1996 CY manifest. The plan also allows for the development of the related precursor experiments, whether they be executed in ground-based facilities, on sub-orbital ballistic flights, or on the Space Shuttle/Spacelab. The development plans and schedules presented are generic in that they may apply to any or all of the experiments described in Section 3.0, proposed as part of a Technology Development Mission in spacecraft fire safety.

6.1 Overall Development Schedule (Phases A-D)

Figure 6-1 illustrates a suggested schedule for the overall development of the hardware, software, and flight qualification of a generic experiment in phases that basically parallel the development of the Space Station. For scheduling purposes, it is assumed that the first available Space Station flight opportunity would occur no earlier than calendar year (CY) 1996. Thus, the schedule represented by Figure 6-1 is based on development activities through the end of CY 1995.

Phase A (Planning and Concept Design) is indicated as complete in Figure 6-1 for the experiments introduced in Section 3.0. However, only preliminary planning has been performed and no detailed test matrices have been prepared at this time. Phase B of the development plan is defined as the effort required to perform detailed planning and prototype design, construction and testing. Most of the ground-based and sub-orbital flight precursor activities would be performed during the Phase B effort. In accordance with normal NASA practice, Phases C and D would consist of the design, construction, flight qualification, and integration of the experiment and experiment facility (i.e., the Combustion Tunnel and/or Combustion Facility) into the Space Station.

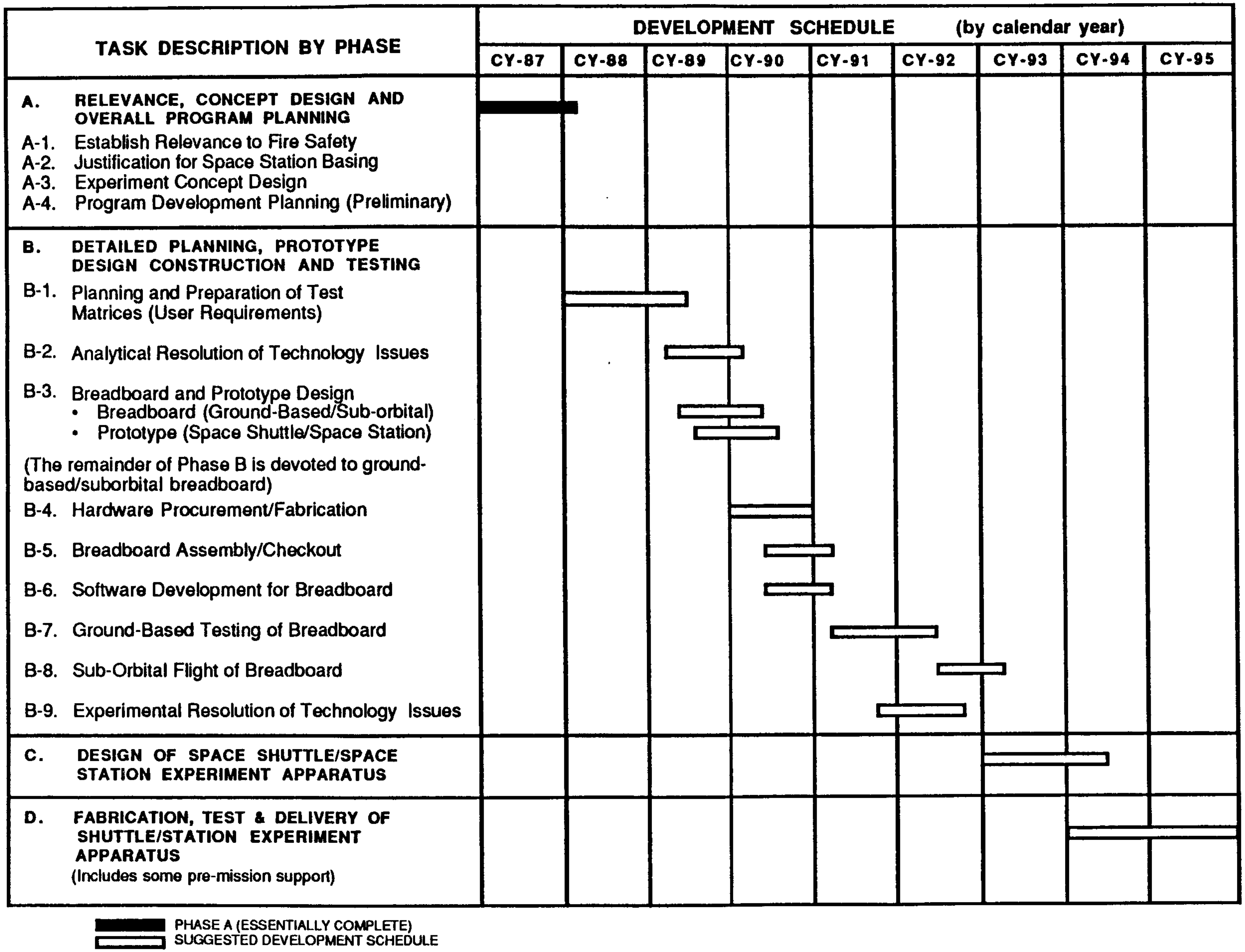


FIGURE 6-1. PRELIMINARY DEVELOPMENT SCHEDULE FOR THE SPACECRAFT FIRE SAFETY TECHNOLOGY DEVELOPMENT MISSION

6.2 Planning and Prototype Design, Construction and Testing (Phase B)

The major tasks to be performed during the Phase B development effort are defined in the first column of Figure 6-1.

Task B-1 would be devoted to the detailed planning and development of user requirements and test matrices for the use of each experiment facility. This task would include a resolution of the need for sub-orbital flight testing (e.g., based on the KC-135 aircraft) in addition to, or in lieu of, Space Shuttle/Spacelab-based testing. Task B-2 would be devoted to the analytical resolution of technology development issues (among which are those described in Section 5.0 of this report). The choice of appropriate diagnostic instrumentation would also be a part of the Task B-2 effort.

Hardware design is identified as Task B-3. It is recommended that the bulk of this effort be devoted to an experimental breadboard (i.e., prototype) that could be ultimately used in sub-orbital flight testing after ground-based checkout. It should be recalled that the full objectives of any of the Spacecraft Fire Safety-related TDM experiments are not likely to be fully met in the relatively short periods of low gravity (e.g., 15-25 seconds) obtainable in sub-orbital aircraft flights. However, such flights would be valuable in apparatus development. Note that Figure 6-1 indicates that two design efforts should be conducted during Task B-3. The first design is that of the breadboard already mentioned, while the second design should be a preliminary design of an appropriate experimental apparatus for the Space Shuttle/Spacelab. The nature of the second prototype design depends on a resolution of whether Space Shuttle/Spacelab-basing of the experiment is appropriate, or feasible. There is no way to make this judgment at this time. If the experiment cannot be manifested for operation in Spacelab prior to a Space Station flight opportunity, then this second prototype design should be treated as a preliminary design of the Space Station-based experiment apparatus.

Tasks B-4 through B-7 are devoted to the fabrication, assembly and checkout, software development, and ground-based testing of the experiment breadboard. The importance of this activity cannot be over-emphasized. Among other determinations, this ground-based checkout and testing could provide an opportunity to evaluate the ability of each experimental apparatus to satisfy the following requirements for typical fuel samples, oxidizer gas mixtures (O_2/N_2 ratios), flow rates, and other important test parameters for the proposed experiments:

Combustion and Flame Spread:

1) Provide a steady and adequately uniform velocity profile approaching the fuel sample
2) Maintain an adequately constant oxidizer gas mixture over the desired run time (i.e., 1-3+ minutes)
3) Provide adequate heat removal (via active heat exchanger) of the heat released by combustion and the fan/motor
4) Ensure appropriate operation of an automated or semi-automated fuel sample exchanger
5) Evaluate the various diagnostic instrumentation to monitor the ignition, flame spread and extinction processes.

Fire/Fire Extinguishant Interactions:

1) Evaluate the analytical computations for scaling of fuel sizes, fuel ignition energy, extinguishant nozzle configuration, size, etc., and extinguishant flow rates
2) Provide preliminary experimental determination of combustion heat release and fuel-burning times allowable prior to the initiation of extinguishant injection
3) Provide experimental determination of Combustion Facility pressure-and temperature-rise values.

Smoldering Combustion:

1) Maintain an adequately constant oxidizer gas mixture and flow throughout the desired run time (i.e., 5-10+ minutes)
2) Provide a means for experimentally determining the minimum energy required to initiate smoldering
3) Provide a means for evaluating the adequacy of diagnostic instrumentation
4) Provide an opportunity to evaluate various smolder cannister designs and sizes.

Task B-8 is devoted to the potential sub-orbital flight testing of the breadboard experiment apparatus. The need for such testing would be addressed during Task B-1 and re-evaluated at any time. It is recommended that such flight testing be considered for at least the following reasons:

1) Even limited sub-orbital flight testing would provide an opportunity to evaluate the complex apparatus in low gravity.

2) Some near-term, fire safety-related data and information may be obtained from the operation of such experiments.

Finally, Task B-9 is included in the schedule for the purpose of resolving any technology development issues remaining open from Task B-2. This task is shown in Figure 6-1 as overlapping the ground-based testing of the breadboard (Task B-7) and the potential sub-orbital flights (Task B-8). The intent of this scheduling is to provide an experimental apparatus (i.e., the breadboard) that could be used for the resolution of the open technology issues. However, the actual schedule of Task B-9 may be adjusted as needed when experimental equipment is available.

6.3 Detailed Design, Fabrication, Test, and Delivery of the Space Station-Based Experiment Apparatus (Phases C/D)

Table 6-1 is an expansion of the Figure 6-1 description for the major tasks required to design, fabricate, assemble, test, flight qualify, and otherwise prepare the experiment apparatus (including Combustion Tunnel and/or Combustion Facility) as a manned spacecraft flight item. The listing of tasks for both Phase C (Design of Flight Item) and Phase D (Fabrication and Test of Flight Item) illustrate the basic formal work breakdown structure (WBS) headings required. A detailed description of each of these tasks is not possible at this time, except in very general terms.

It should be noted that the Phase C/D effort has been compressed into calendar years 1993-1995. This was scheduled in this manner to provide the maximum amount of calendar time for the precursor activities required during the Phase B effort. However, if required, the Phase C/D effort can be initiated earlier by compressing the Phase B activity to an earlier completion date (e.g., end of CY 1991). This revision of the schedule may become desirable if manifesting becomes available for a Space Shuttle/Spacelab accommodation prior to any Space Station flight opportunity.

TABLE 6-1. PHASE C/D TASKS FOR FIRE-SAFETY SPACE STATION TECHNOLOGY DEVELOPMENT MISSION

PHASE C:	**DESIGN OF SPACE SHUTTLE/SPACE STATION EXPERIMENT APPARATUS**
C-1:	Special Studies
C-2:	Engineering Design
C-3:	Preparation of Engineering Drawings
C-4:	Configuration Management
C-5:	Preliminary Software Development
C-6:	Safety and Safety Compliance
C-7:	Quality Assurance
C-8:	Design Reviews
C-9:	Verification
C-10:	Alert System Reporting
PHASE D:	**FABRICATION, TEST AND DELIVERY (INCLUDING PRE-MISSION SUPPORT)**
D-1:	Special Studies
D-2:	Manufacture and Assembly
D-3:	Final Software Development
D-4:	Verification
D-5:	Acceptance Reviews and Technical Documentation
D-6:	Hardware Delivery
D-7:	Spare Parts Determination
D-8:	Quality Assurance
D-9:	Pre-Mission Support
D-10:	Alert System Reporting
D-11:	Safety and Safety Compliance
D-12:	Configuration Management

7.0 CONCLUDING REMARKS AND RECOMMENDATIONS

The three concept designs presented in this report for Space Station-based, fire-safety-related experiments were selected for the purpose of addressing key issues of enhancing safety yet encouraging access to spacecraft, especially the long-duration-mission NASA Space Station. The experiments and facilities described are intended to constitute a portion of a Spacecraft Fire Safety Technology Development Mission (TDM). Basic requirements for the mission study are that the Space Station is essential for the accomplishment of the experimental objectives and that the technology being developed is appropriate for the growth version of the Space Station.

The Space Station-based experiments described in this report, along with their precursor analyses and experiments, were selected from a lengthy list of candidate experiments derived from a survey of important issues in spacecraft fire safety. Again, the three experiments selected from those meeting the Space Station-applicability criteria are as follows:

1. Combustion and Flame Spread of Typical Spacecraft Materials in a Low-Velocity Convective Flow in Low Gravity
2. Fire and Fire-Extinguishant Interactions with Various Fire Scenarios in Low Gravity
3. Smoldering and Deep-Seated Combustion in Low Gravity

The advantages of these three experiments for the growth-version Space Station are that, not only do they explore problems relevant to the Space Station operation and utilization, but also they constitute tests adaptable to multiuse facilities installed in the Space Station laboratory module. Thus, the TDM study will include the development of modularized versions of the two highly versatile experiment facilities described herein, namely the Combustion Tunnel Facility and the Combustion Facility.

It is recognized that the proposed experiment concepts may be eight or more years away from operational realization. The experiments, however, represent the culmination of significant programs in preparation for the Space Station TDM. These programs cover, first, the derivation of models, analyses, and verification data in fields relevant to the proposed experiments, such as in microgravity combustion, extinguishment, and material assessment. Second, the programs include the conduct of precursor experiments in fire-safety-related technology and hardware development, using the available short-term, low-gravity ground facilities. Finally, based upon results of the precursor analyses and experiments, the programs result in the development of the detailed Space Station accommodations, instrumentation, test procedures, and test schedule priorities. Ideally, finalized development of the experiments and their precursors can yield hardware for inclusion of tests in the Shuttle or the Spacelab.

Three general recommendations to be derived from this study of experiment concepts for spacecraft fire safety in the Space Station can summarize the challenge for the future as follows:

1. The definition and implementation of ground-based research applicable to the fire-safety concerns raised in this report
2. The continued follow-on design and development of the proposed experiments and their precursors for low-gravity ground and space evaluation
3. The design and development of multipurpose experiment facilities for the growth Space Station, to include the two suggested combustion facilities.

8.0 REFERENCES

1. Spacecraft Fire Safety. NASA CP-2476, September 1987.

2. Friedman, R.; and Sacksteder, K.R.: Science and Technology Issues in Spacecraft Fire Safety. AIAA Paper 87-0467, January 1987.

3. Kimzey, J.H.: Skylab Experiment M479 Zero Gravity Flammability. Proceedings of the Third Space Processing Symposium - Skylab Results, Vol. I, NASA TM X-70252, June 1974, pp. 115-130.

4. Olson, S.L.; and Sotos, R.G.: Combustion of Velcro in Low Gravity. NASA TM-88970, March 1987.

5. Friedman, R.: Fire Safety Concerns in Space Operations. NASA TM-89868, May 1987.

6. Sacksteder, K.R.: Microgravity Combustion Science and Applications Program at the NASA Lewis Research Center. Space Operations: Problems, Issues, and Programs Related to Man in Space, D.S. Eggleston, ed. CPIA-PUB-415, Chemical Propulsion Information Agency, 1985, pp. 265-286.

7. Youngblood, W.W.; and Seiser, K.M.: Experiments to Ensure Space Station Fire Safety — A Challenge. AIAA Paper 88-0540, January 1988.

8. Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environments that Support Combustion. NASA TM-84066, 1981 (NASA NHB-8060.1B).

9. Foutch, D.W.; and T'ien, J.S.: Extinction of a Stagnation Point Diffusion Flame at Reduced Gravity. AIAA Journal, Vol. 25, 1987, pp. 972-976.

10. Summerfield, M.; Messina, N.A.; and Ingram, L.S.: Definition of Smoldering Experiments for Spacelab. NASA CR-159528, January 1979.

11. Ohlemiller, T.J.: Smoldering Combustion. NBSIR 85-3294, February 1986.

12. Uhran, M.L., et al.: Equipment Concept Design and Development Plans for Microgravity Science and Application Research on Space Station. NASA CR-179535, September 1986.

13. Smyth, K.C., et al.: Soot Inception in a Methane/Air Diffusion Flame as Characterized by Detailed Species Profiles. Combustion and Flame, Vol. 62, 1985, pp. 157-180.

14. Santoro, R.J.; Semerjian, A.G.; and Dobbins, R.A.: Soot Particle Measurements in Diffusion Flames. Combustion and Flame, Vol. 51, 1983, pp. 203-218.

15. Owen, R.B.; and Kroes, R.L.: Holography on the Spacelab 3 Mission. Opt. News, Vol. 11, No. 7, July 1985, pp. 12-16.

16. Sibulkin, M.; and Little, M.W.: Propagation and Extinction of Downward Burning Fires. Combustion and Flame, Vol. 31, 1978, pp. 197-208.

17. Huggett, C.: Estimation of Rate of Heat Release by Means of Oxygen Consumption Measurements. Fire and Materials, Vol. 4, 1980, pp. 61-65.

18. Dewitt, R.L.: Preliminary Concept, Specifications, and Requirements for a Zero-Gravity Combustion Facility. NASA TM-78910, June 1978.

19. Cholin, R.: How Deep is Deep? Use of Halon 1301 on Deep-Seated Fires. Fire Journal, March 1972, pp. 19-23.

20. Reichelt, E.F.: Report of Test Results: Halon 1301 vs. Water Sprinkler Fire Protection for Essential Electronics Equipment. Air Force Engineering Services Center, Report No. ESL-TR-82-28, July 1982.

21. Doerr, R.L.; and Gross, T.H.: A Comparative Analysis of Fire Protection Systems for Essential Electronic Data Processing Equipment. Air Force Institute of Technology, Report No. AFIT-LSSR-31-80, June 1980.

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16. Abstract

Three concept designs of low-gravity, fire-safety related experiments are presented, as selected for the purpose of addressing key issues of enhancing safety and yet encouraging access to long-duration, manned spacecraft such as the NASA Space Station. The selected low-gravity experiments are the following: (1) An investigation of the flame-spread rate and combustion-product evolution of the burning of typical thicknesses of spacecraft materials in very low-speed flows; (2) an evaluation of the interaction of fires and candidate extinguishants in various fire scenarios; and (3) an investigation of the persistence and propagation of smoldering and deep-seated combustion. Each experiment is expected to provide fundamental combustion-science data, as well as the fire-safety applications, and each requires the unique long-duration, low-gravity environment of the Space Station. Two generic test facilities, i.e., the Combustion Tunnel Facility and the Combustion Facility, are proposed for Space Station accommodation to support the selected experiments. In addition, three near-term, fire-safety related experiments are described along with other related precursor activities.

17. Key Words (Suggested by Author(s))
Combustion; Fire detection; Fire Suppression Microgravity Applications; Space Station; Spacecraft Fire Safety; Smoldering; Space Laboratory

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