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ADVANCED SPACECRAFT FIRE SAFETY: PROPOSED PROJECTS AND PROGRAM PLAN

Wallace W. Youngblood and Dr. M. Vedha-Nayagam

WYLE LABORATORIES

Huntsville, Alabama

(Wyle Report No. 60300-1)

October, 1989

Prepared for
Lewis Research Center
Under Contract NAS3-25367

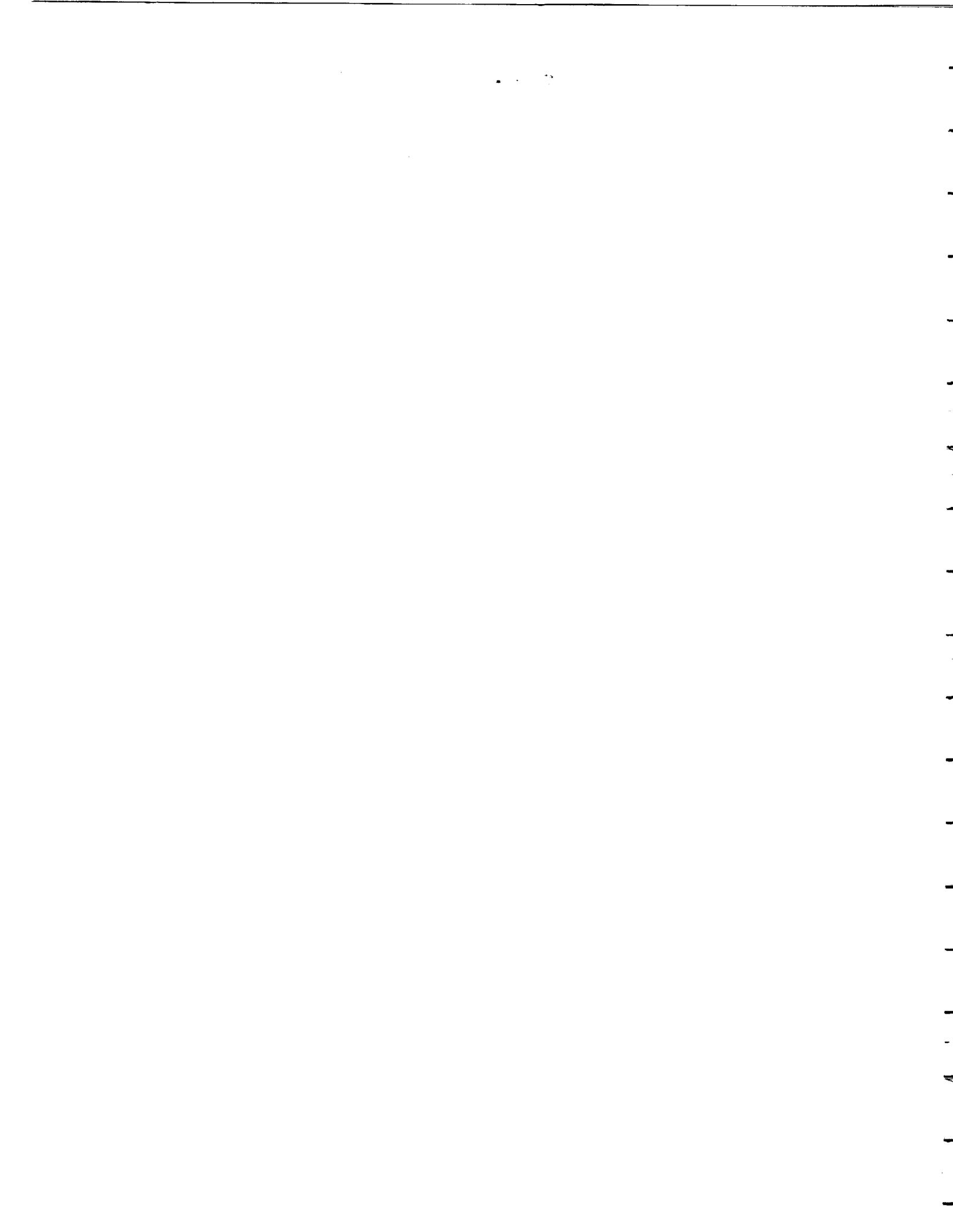
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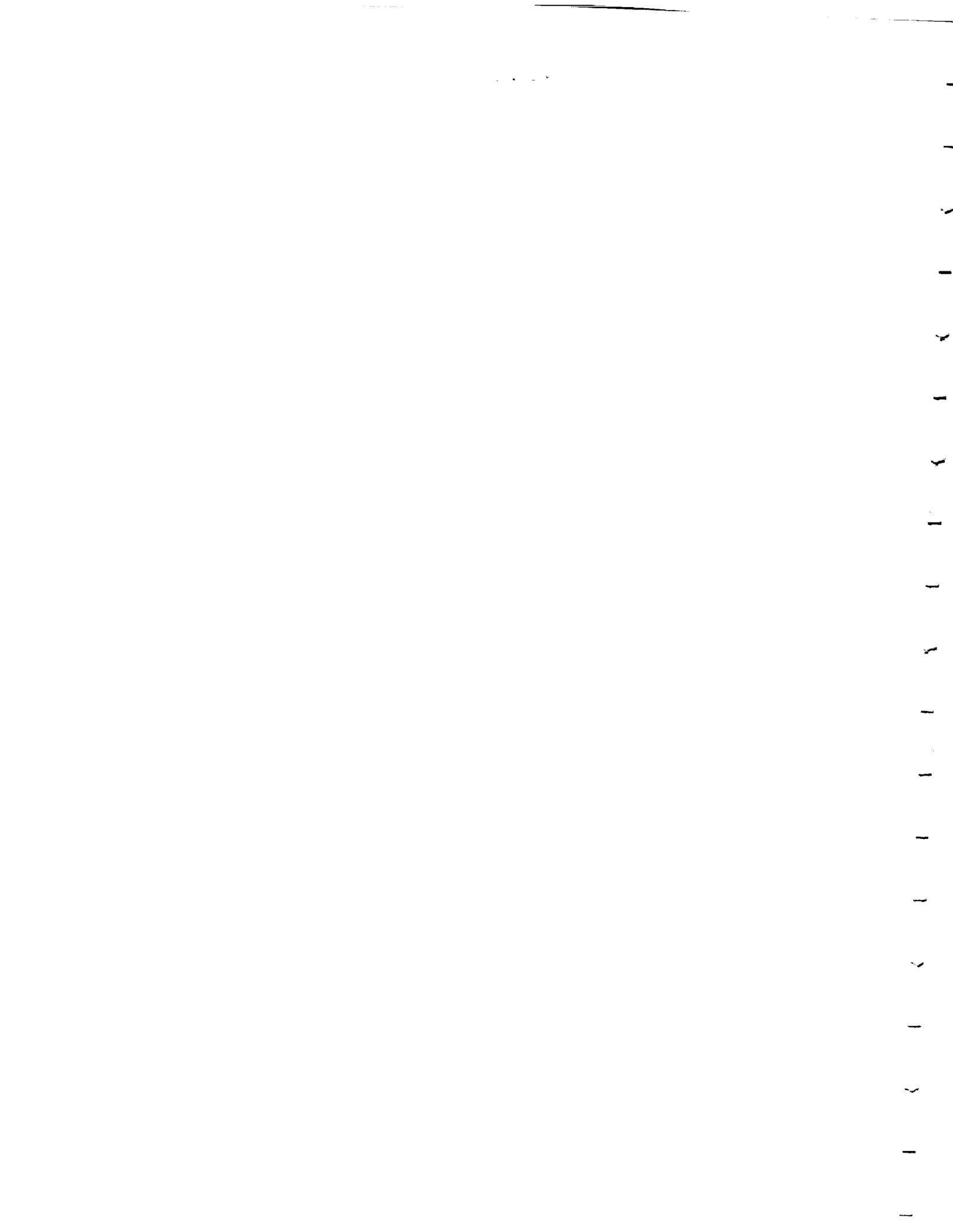
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FOREWORD

This report was prepared by Wyle Laboratories for the National Aeronautics and Space Administration (NASA), Lewis Research Center, under Contract Number NAS3-25367. 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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The authors wish to acknowledge the many contributions to this effort made by Wyle Laboratories' Consultants, Mr. J. Howard Kimzey (Houston, Texas) and Dr. Harold L. Kaplan (San Antonio, Texas). The authors wish also to recognize the guidance and advice provided by the NASA technical manager throughout this effort, Mr. Robert Friedman, Microgravity Science and Technology Branch, NASA Lewis Research Center, Cleveland, Ohio.

Finally the authors wish to thank the many organizations and individuals who responded to the Spacecraft Fire Safety Survey conducted by Wyle. Among these respondees, special recognition is given to Mr. Matthew B. Cole, Safety Division, NASA Johnson Space Center (Houston, Texas) and Mr. Charles D. Ray, Environmental Control and Life Support Branch, NASA Marshall Space Flight Center (Huntsville, Alabama) for their many contributions of advice, information, and technical recommendations.

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LIST OF ACRONYMS AND SYMBOLS

(See Note 1)

AR	Applied Research
ARC	Ames Research Center
ARS	Atmosphere Revitalization System
ATA	Atmospheres Absolute
AV	Avionics
BR	Basic Research
CDR	Critical Design Review
CY	Calendar Year
ECLSS	Environmental Control/Life Support System
ESA	European Space Agency
EVA	Extra-Vehicular Activity
FAA	Federal Aviation Administration
FDS	Fire Detection/Suppression
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes and Effects Criticality Analysis
g	Gravitational Acceleration
GC/MS	Gas Chromatograph/Mass Spectrometer
GSFC	Goddard Space Flight Center
GT	Ground (-Based) Testing
HAL	Hyperbaric Airlock
HMF	Health Maintenance Facility
HEPA	High Efficiency Particulate Aerosol (Filter)
Hx	Heat Exchanger
IFO	Infrared Fiber Optics
IMS	Ion Mobility Spectrometer
IR	Infrared
JEM	Japanese Experiment Module
JPL	Jet Propulsion Laboratory
JSC	(Lyndon B.) Johnson Space Center
KSC	(John F.) Kennedy Space Center
LaRC	Langley Research Center
LDV	Laser Doppler Velocimeter
LeRC	Lewis Research Center
LIF	Laser Induced Fluorescence
MSFC	(George C.) Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (Japan)
NBS	National Bureau of Standards (Currently, NIST)
NFPA	National Fire Protection Agency
NIST	National Institute for Standards and Technology (Formerly, NBS)
NRL	(U.S. Navy) Naval Research Laboratory
NSTS	National Space Transportation System
PCB	Printed Circuit Board
PDR	Preliminary Design Review
PMMS	Process Materials Management System
RBP	Reactive Bed Plasma
SC	Source Code

LIST OF ACRONYMS AND SYMBOLS (Continued)
(See Note 1)

SMAC	Spacecraft Maximum Allowable Concentration
SRM & QA	Safety, Reliability, Maintainability, and Quality Assurance
SRU	Smoke Removal Unit
SS	Space Station (Freedom)
SSP	Space Station Program
STS	Space Transportation System
TC	Thermocouple
TD	Technology Development
UV	Ultra Violet
VESDA	Very Early Smoke Detection Apparatus
WBS	Work Breakdown Structure
WSTF	(NASA/JSC) White Sands Test Facility
μ -g	Microgravity

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

**ADVANCED SPACECRAFT FIRE SAFETY:
PROPOSED PROJECTS AND PROGRAM PLAN
EXECUTIVE SUMMARY**

A detailed review was performed to identify new or currently unresolved spacecraft fire-safety issues and the efforts deemed necessary to be initiated or expanded for their resolution. The major thrust of the review was devoted to advanced manned spacecraft, such as Space Station Freedom, where the spacecraft's size, complexity, mission, and on-orbit duration may pose new and/or more exacerbating fire safety-related threats. An important source of information and identification of fire safety-related issues and concerns was from a formal survey conducted by the authors. The survey resulted in approximately 155 total recommendations accumulated from 36 individual respondees or organizations representing fire-safety workers from industry, academia, NASA and other government agencies. These 155 recommendations have been combined and correlated with the independent reviews performed by the authors and synthesized into some 58 clearly defined technical issues and recommendations.

A recommended program plan is presented for those spacecraft fire safety-issues or concerns deemed to have the highest priority for initiation and/or resolution over the next five years. To accomplish this, the authors combined a large portion of the 58 tabulated issues into approximately 30 research and engineering projects. These projects were prioritized with respect to their perceived urgency (for, e.g., Space Station Freedom design and issue resolution), their long-term importance to the safety of all advanced, manned spacecraft, status of enabling technology, cost and effort, and other factors. Some 14 of the highest priority of these projects are described in detail herein, along with their proposed schedules and work breakdown structures (WBSs). These projects are grouped within the following thematic areas:

- o Advanced Fire Detection Techniques and Hardware
- o Fire Extinguishment and Atmosphere Cleanup
- o Risk and Hazard Assessment
- o Toxicology, Human Response and Atmosphere Control
- o Ground-Based Testing and Standard Test Methods

Clearly, the projects identified and described herein are at various stages of development. Some of the projects are already underway, some are recommended for immediate initiation for resolution within the next two to five years, and others are

admittedly of a much longer-term nature due to their dependence on emerging technologies and/or their need for substantial testing in a low-gravity environment. The highest-priority projects are as follows:

Near-Term Projects: (Present through Calendar Year (CY) 1992)

- o Evaluation of New Fire Risk Analysis Tools
- o Test Procedures for Electrical Wire Insulation Flammability
- o Evaluation of Contaminants and Continuous Monitoring for Toxicity
- o Development of Centralized Fire Detectors/Monitors
- o Research on Numerical Modeling of Spacecraft Fire Scenarios
- o Review and Revision of Current Spacecraft Material Flammability Tests
- o Evaluation of Ventilation Flow Models for Spacecraft

Intermediate-Term Projects: (CY 1990 through 1993/1994)

- o Development of Expert Systems for Fire Detection/Suppression
- o Evaluation of Fire Extinguishants for Hyperbaric Atmospheres
- o Development of High-Capacity Environmental Cleanup Unit
- o Development of Techniques for Early Detection of Incipient Fire Conditions
- o Development of Smoke Detectors Using Microsensor Techniques

Long-Term Projects: (through 1995 and beyond)

- o Research on Candidate Fire Extinguishants for Low Gravity
- o Research on Low-Gravity Fire Characteristics

In addition, brief discussions of another 12 lower-priority projects and nine unranked suggestions present further information on important issues in spacecraft fire safety.

Finally, recommendations are presented relevant to the overall program management and oversight deemed necessary to ensure successful and efficient initiation and completion, or resolution, of the proposed projects. It is recommended that responsibility for the technical management of the projects should be retained by the appropriate spacecraft project officer and NASA field center engineering directorates and laboratories. However, the safety-related issue coordination and oversight activities should be formalized through direct involvement of NASA's Safety, Reliability, Maintainability, and Quality Assurance (SRM & QA) offices at all levels. Specifically, these recommendations may be summarized as follows:

- 1) Oversight responsibility for spacecraft fire safety should be maintained by NASA Headquarters, preferably by Code Q (SRM & QA office).

- 2) Each NASA field center involved in some aspect of manned spacecraft should establish a "Spacecraft Fire Safety Committee."
- 3) At least one representative from each field center's SRM & QA Office should be a member of that center's Spacecraft Fire-Safety Committee.
- 4) The exchange of information and concerns relevant to fire-safety related issues between each field center's Spacecraft Fire-Safety Committee should be the responsibility of the Committee's chairman.

A narrative review of fire-protection guidelines and experience for the historic and current NASA manned-space missions is included as an appendix to the report, contributed by J. Howard Kimzey, a consultant.

1.0 INTRODUCTION

The possibility of a fire event in a spacecraft is real; it has happened in the past and it is highly probable to happen in the future. In the recent Space Station Freedom Toxic and Reactive Materials Handling Workshop (Huntsville, Alabama, November 1988), Skylab Astronaut Dr. Bill Pogue stressed the need to have reliable, false-alarm free fire detectors and the means to quickly and precisely locate the fire source in manned spacecraft. The following notes, written by the Soviet Cosmonaut V. Lebedev during his stay aboard the Salyut 7 Space Station, vividly illustrates the threat of fire:

"In the case of fire (and it is very possible up here) we have to turn off all the electrical equipment, including the ventilation system, put on our protective suits with respirators, and use fire extinguishers."
(September 7, 1982)

Eighteen days later:

"We felt (sic) the smell of burning lacquer or insulation. We turned off all the fans and closed all the hatches to the supply ship. If smoke continues it won't enter the resupply ship. We took fire extinguishers and began to fly across the station, sniffing for smoke Something probably got inside of the fan, and it overheated." (September 25, 1982)

Luckily for the Soviet Cosmonauts, the fire source was spotted quickly and the damage contained. However, this may not be possible all the time. Large, permanently orbiting, complex space structures, such as the Space Station Freedom, and other advanced spacecraft with long-duration missions pose new fire-safety problems that were not anticipated until this time. NASA's effort to commercialize space and derive maximum utilization from the space-borne facilities brings a renewed need to have a coordinated and balanced program in spacecraft fire safety.

Current spacecraft fire-safety procedures rely primarily on materials screening so that the amount of flammable material that is present inside a spacecraft is a minimum. Since there have been no major fire-safety related occurrences in the Space Shuttle and the Spacelab, fire-hardened spacecraft with limited fire fighting capability have proven to be adequate. However, in view of advanced spacecraft designs, the judgement that the present technology and knowledge is adequate may be extremely short sighted. Also, even the relatively minor instances of wire insulation smoldering and/or electrical shorting that have been reported after STS-6 and STS-28 flights serve as reminders of the potential for a fire event.

The objective of this study was to understand the shortcomings of the present fire-safety technology, identify projects that will lead to improved fire safety in future spacecraft, and prepare a program plan that will provide NASA with recommendations for a coordinated, balanced development program in fire safety.

Section 2.0 describes the methodology to identify, classify, and prioritize the topics and critical issues in spacecraft fire safety, to provide a coordinated set of projects for research and applications in this field. In Sections 3.0 to 7.0, descriptions and schedules for the 14 highest-priority projects are presented, grouped in the categories of fire detection, extinguishment, risk assessment, toxicology, and testing. Section 8.0 contains a detailed program management and oversight plan. It is illustrated by organization responsibilities for NASA Headquarters and field centers. This offers a clear example of the plan, but in no way does it constitute an endorsement or criticism of NASA policies in safety management. Section 9.0 provides some concluding remarks relevant to the study.

Appendix A presents a list of the respondees to Wyle's formal survey of fire-safety experts. The cooperation of these individuals is greatly appreciated. Appendix B describes the details of the prioritization procedure used by Wyle to rank recommended fire-safety projects. Finally, Appendix C presents a historical and critical review of spacecraft fire protection from the perspective of a retired NASA fire safety and materials specialist, Mr. J. Howard Kimzey.

2.0 PROJECT IDENTIFICATION AND PROGRAM PLAN

This section describes the process through which topics that lead to improved fire safety of advanced spacecraft were identified, and it provides an overview of the priority projects constituting the program plan.

2.1 Information Sources For Fire-Safety Projects

Spacecraft fire safety is inherently a multi-disciplinary effort involving diverse areas, such as microgravity combustion science, fire detection/suppression technology, toxicology and human response, risk and hazard analysis, and detailed planning and management. A comprehensive assessment of the current status of spacecraft fire safety must include input from all of these groups. The Wyle team, consisting of Wyle personnel and two consultants (J.H. Kimzey and Dr. H. Kaplan), collected the relevant information by means of literature reviews, interviews and discussions, and a formal survey of selected experts in fire-safety and low-gravity combustion research.

An exhaustive review of the published literature in the area of spacecraft fire safety was conducted. Wyle's internal data base was augmented using computerized literature searches conducted at Redstone Scientific and Information Center (RSIC) and the NASA-sponsored NERAC Inc. (Tolland, Conn.). Attendance at several fire-safety related workshops/conferences and review of published proceedings provided further information regarding current activities that may impact spacecraft fire safety. For example, the International Microgravity Combustion Workshop held at the NASA Lewis Research Center January 25-26, 1989, and the Space Station Freedom Toxic and Reactive Materials Handling Workshop sponsored by the NASA/Marshall Spaceflight Center November 29 - December 1, 1988, provided information on current problems and research activities in the fire-safety area.

During the course of this study, Wyle team members were in routine contact with a number of researchers working in the area of spacecraft fire safety. In particular, regular contact with fire safety personnel at Boeing Aerospace Company, NASA Johnson Space Center (JSC), Marshall Spaceflight Center (MSFC), Lewis Research Center (LeRC), and JSC's White Sands Test Facility (WSTF) kept the Wyle team abreast with Space Station Freedom fire-safety plans. Telephone interviews and written communications with these and other researchers provided valuable insights, information, and additional contacts to expand Wyle's comprehension of the fire-safety issues.

As a part of the projects identification effort, a formal survey was conducted among a selected group of fire-safety experts. The respondents are acknowledged and identified in Appendix A. Written responses to the survey were collected and documented. When needed, follow-up discussions were conducted in person or over the telephone with the respondent. To enhance the effort, Wyle team members visited NASA/JSC, MSFC, JSC's WSTF, Factory Mutual Research Corporation, Southwest Research Institute, and the National Institute for Standards and Technology.

The outcome of this effort was a list of issues that covered the overall study objective, namely improving the fire safety of advanced spacecraft. As one would expect, the list covers a variety of projects ranging from radiant ignition of condensed fuels to crew training in fire-fighting, with each respondent emphasizing the critical need in his/her area of expertise. A complete list of the suggestions, identified as 58 topics, broadly classified under 11 categories of interest is given in Table 2-1. The source code (SC) numbers given in Table 2-1 correspond to the respondents (Appendix A) who have suggested the particular issue. Table 2-1 is at the end of Section 2.0.

2.2 Prioritization Of Fire-Safety Projects

While all the suggestions in Table 2-1 have merit, they differ in relative importance with respect to their relevance to spacecraft needs, feasibility, and cost, among other factors. To develop a coordinated plan from the suggestions, prioritized projects must be defined (Figure 2-1). The 58 topics shown in Table 2-1 were first grouped together according to their work discipline. The four major work disciplines used for the purpose of the prioritization process are 1) Basic Research and Microgravity Testing (BR), 2) Applied Research and Engineering (AR), 3) Technology Development (TD), and 4) Ground-Based Testing (GT). This grouping brings diverse projects under organized headings and makes prioritization feasible within each group. The details of the prioritization scheme used in this study are given in Appendix B. In the process of work discipline prioritization, 41 of the original topics were selected; and then, with some combining of topics, a work breakdown structure comprising 30 prioritized projects was devised (Figure 2-2).

The time constraint imposed by Space Station Freedom's development schedule, and the cost/benefit consideration are two obvious factors that influence the prioritization scheme. For example, the microsensor technology, when available, will have a major

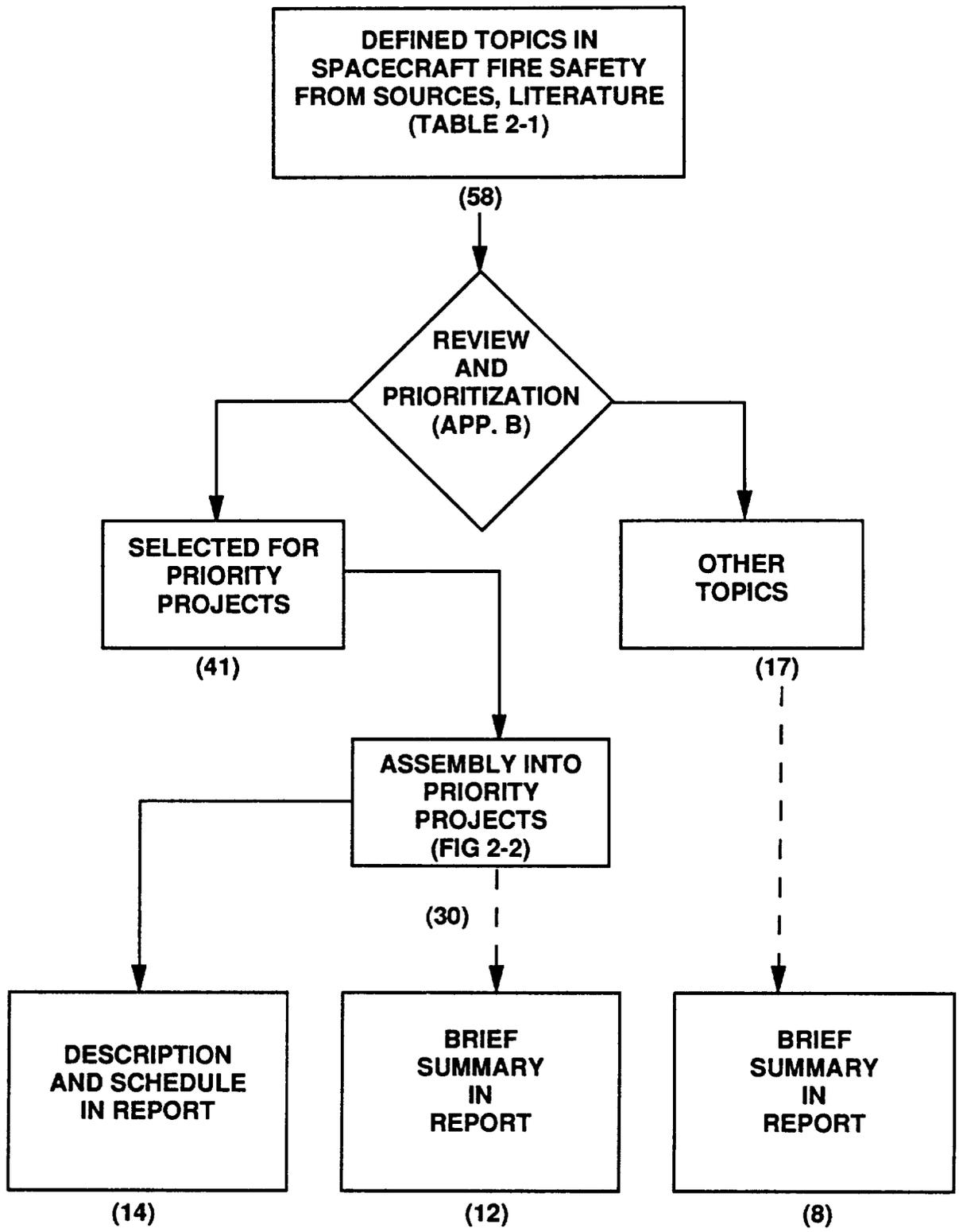


FIGURE 2-1. FLOWCHART OF SPACECRAFT FIRE SAFETY PROJECT SELECTION

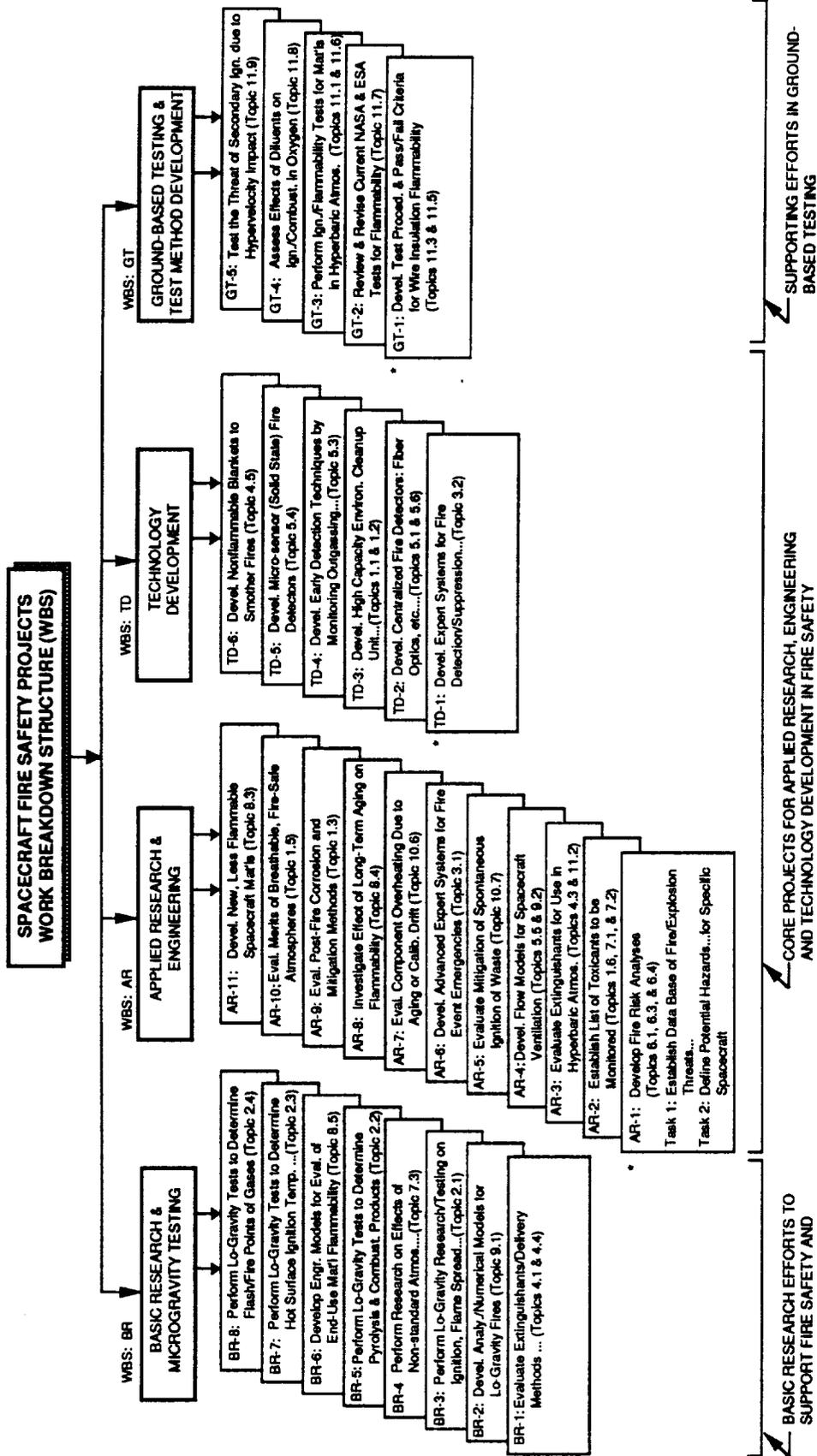


FIGURE 2-2. HIGHEST PRIORITY FIRE SAFETY PROJECTS' WORK BREAKDOWN STRUCTURE BY WORK DISCIPLINE

impact on fire detection techniques. However, the maturation period for this technology is still several years away. Therefore, based on the Freedom's time schedule, this project must be given a lower priority than other projects such as expert systems development. Similar comments apply to the idea of developing less flammable, new spacecraft materials.

There are other factors that play a subtle role in the prioritization process. These depend on the baseline philosophy for the spacecraft design and operation and the overall fire-safety strategy. Depending on the fire-safety strategy, emphasis must be placed on prevention, control, or recovery. A general fire-safety strategy for advanced spacecraft was previously proposed (Reference 1), and it was adopted for the present study as well (see Figure B-1, Appendix B). This strategy involves a balanced approach in which prevention, detection/suppression, and recovery aspects are all treated equally important. It is worthwhile to note here that, historically, NASA has placed the most emphasis on prevention. With the advent of the Space Station Freedom and other advanced, manned spacecraft, a balanced fire-safety strategy has become a necessity.

Thus, a further selection of projects yielded 14 projects worthy of more detailed definition, in terms of background and objectives, work effort, and schedule. The description of priority spacecraft fire-safety projects constitutes the major portion of this report. For descriptive purposes, the priority projects are regrouped into five fire-safety thematic areas, covered in separate sections of this report, as follows:

- Section 3.0 Fire Detection
- Section 4.0 Fire Extinguishment and Atmosphere Cleanup
- Section 5.0 Risk and Hazard Assessment
- Section 6.0 Toxicology and Human Response
- Section 7.0 Ground-Based Testing and Flammability Test Methods.

Table 2-2 lists the 14 highest-priority projects, with reference to the report thematic area and the identifying number for the work breakdown structure (WBS) of Figure 2-2. In addition to the full descriptions of the highest-priority projects, this report includes a brief discussion of another 12 lower-priority projects and further comments on eight or nine unranked topics selected from Table 2-1.

**TABLE 2-2. ORGANIZATION OF HIGHEST-PRIORITY
FIRE-SAFETY PROJECT DESCRIPTIONS**

REPORT SUBSECTION	FIGURE 2-2 WORK DISCIPLINE NUMBER	PROJECT TITLE
3.3	TD-1	Development of Expert System for Fire Detection/Suppression
3.4	TD-2	Development of Centralized Fire Detectors/Monitors With Distributed Sensors
3.5	TD-4	Development of Techniques for Early Detection of Incipient Fire Conditions
3.6	TD-5	Development of Smoke Detectors Using Microsensor Techniques
3.7	BR-3	Research on Low-Gravity Fires
4.3	AR-3	Evaluation of Fire Extinguishants for Hyperbaric Atmospheres
4.4	TD-3	Development of High-Capacity Environmental Cleanup Unit
4.5	BR-1	Research on Candidate Fire Extinguishants for Low Gravity
5.3	AR-1	Evaluation of New Fire Risk Analysis Tools
5.4	BR-2	Research on Numerical Modeling of Spacecraft Fire Scenarios
5.5	AR-4	Evaluation of Ventilation Flow Models for Spacecraft
6.3	AR-2	Evaluation of Contaminants and Continuous Monitoring for Toxicity
7.3	GT-1	Test Procedures for Electrical Wire Insulation Flammability
7.4	GT-2	Review and Revision of Current Spacecraft Material Flammability Tests

2.3 Overall Program Plan

An advanced spacecraft fire-safety program, in principle, must be a continually evolving process where the 'state-of-art' technology is constantly assimilated as it becomes available and research goals are upgraded as new understanding of micro-gravity fire behavior is gained. Still, an overall, structured program schedule is necessary for effective planning and management of these efforts. The Space Station Freedom's project schedule provides a convenient time-line reference frame (Figure 2-3) for an advanced spacecraft fire-safety program plan. The limiting dates, for reference, as of the writing of this report, are the Freedom Preliminary Design Review (PDR) in April 1990 and the Critical Design Review (CDR) in the spring of

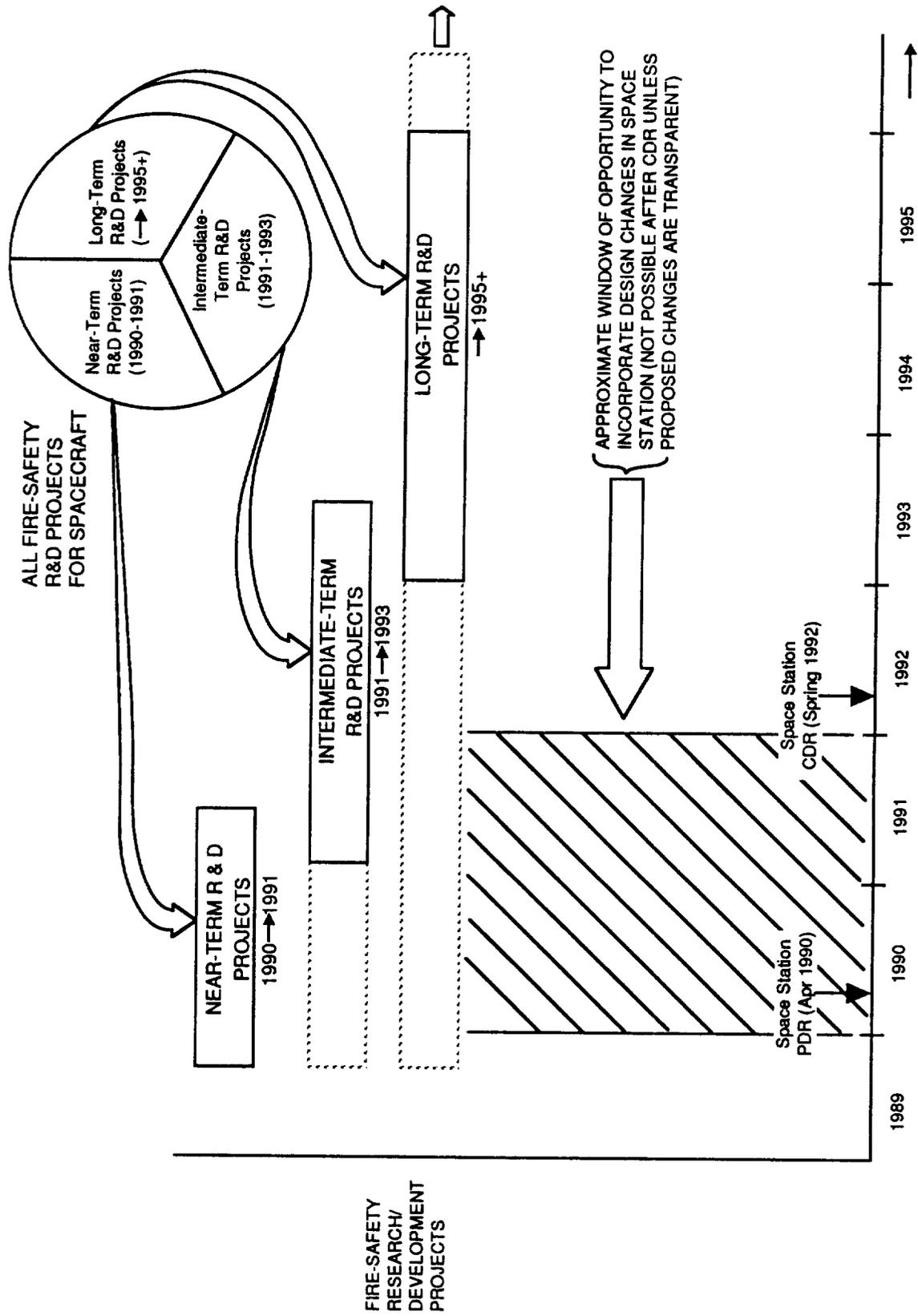


FIGURE 2-3. TIME-LINE FOR SPACECRAFT FIRE SAFETY PROJECTS (BY CALENDAR YEAR)

1992. Thus, a list of the projects would group those whose schedule may conform to the near-term timeline (through 1992), namely:

- AR-1 Evaluation of New Fire Risk Analysis Tools
- GT-1 Test Procedures for Electrical Wire Insulation Flammability
- AR-2 Evaluation of Contaminants and Continuous Monitoring for Toxicity
- TD-2 Development of Centralized Fire Detectors/Monitors With Distributed Sensors
- BR-2 Research on Numerical Modeling of Spacecraft Fire Scenarios
- GT-2 Review and Revision of Current Spacecraft Material Flammability Tests
- AR-4 Evaluation of Ventilation Flow Models for Spacecraft.

The intermediate-term (1990 through 1993-1994) projects are:

- TD-1 Development of Expert Systems for Fire Detection/Suppression
- AR-3 Evaluation of Fire Extinguishants for Hyperbaric Atmospheres
- TD-3 Development of High-Capacity Environmental Cleanup Unit
- TD-4 Development of Techniques for Early Detection of Incipient Fire Conditions
- TD-5 Development of Smoke Detectors Using Microsensor Techniques.

The long-term (through 1995 and beyond) projects are:

- BR-1 Research on Candidate Fire Extinguishants for Low Gravity
- BR-3 Research on Low-Gravity Fire Characteristics.

Clearly, some of these projects have already been started and are currently in progress. For example, some numerical flow modeling work has already been initiated by NASA, the European Space Agency (ESA), and the Japanese National Space Development Agency (NASDA). The White Sands Test Facility has expanded its flammability testing in hypo- and hyperbaric environments; and at NASA/LeRC, preliminary work is underway to evaluate flame signatures and other fire-related parameters during low-gravity solid fuel combustion in drop-tower experiments.

It is recommended that the other near-term projects identified above be started immediately. The intermediate-term projects that need results from the near-term projects must be initiated at the appropriate time. The long-term projects are essentially basic science and research projects. The results of these projects improve our fundamental understanding of materials combustion in microgravity and feed information into other fire-safety projects.

**TABLE 2-1. RESEARCH AND TECHNOLOGY DEVELOPMENT TOPICS:
SPACECRAFT FIRE SAFETY**

(SC is Source Code, see Appendix A)

1.0 Atmosphere Control, Monitoring, and Post-Fire Cleanup

- 1.1 Develop a High Capacity Environmental Cleanup Auxiliary Unit (SC: 8.0, 17.0, 18.0, 25.0, 29.0, 32.0, 43.0)
- 1.2 Develop a Combined Vacuum Cleaner/Fire Suppressant Device (SC: 29.0)
- 1.3 Evaluate Methods for Mitigating the Effects of Post-Fire Corrosion (SC: 9.0)
- 1.4 Evaluate the Merits of Inerting Atmospheres for Use in Powered Equipment Racks, Cable Runs, etc. (SC: 9.0, 43.0)
- 1.5 Evaluate the Merits of Breathable, "Fire-Safe" Atmospheres in Advanced Spacecraft (SC: 2.0, 33.0)
- 1.6 Select Those Gases Which Should Be Continuously Monitored for Spacecraft Atmosphere Impurities, Toxic Compounds and Irritants (SC: 2.0, 17.0, 43.0)
- 1.7 Outline Detailed Procedures for Optimum Post-Fire Cleanup on Orbit (SC: 17.0, 18.0, 20.0, and 44.0)
- 1.8 Evaluate the Merits of Providing a "Safe Haven" for Spacecraft Crew (SC: 2.0, 43.0)

2.0 Low-Gravity Ignition, Flame Spread, and Flame Characteristics

- 2.1 Perform Low-Gravity Tests to Evaluate the Ignition, Flame Spread, Flame Characteristics, etc., of Selected Materials (SC: 2.0, 3.0, 18.0, 21.0, 23.0, 35.0, 39.0, 43.0)
- 2.2 Perform Low-Gravity Investigations Relevant to the Pyrolysis and Combustion Products of Selected Materials (SC: 7.0, 14.0, 23.0, 28.0, 43.0)
- 2.3 Determine the Hot Surface Ignition Temperatures of Selected Flammable/Combustible Fluids in Low Gravity (SC: 5.0, 9.0)
- 2.4 Perform Tests to Determine the Effects of Low Gravity on the Flash Points and Fire Points of Selected Flammable Fluids (SC: 19.0, 39.0)

3.0 Expert Systems (Hardware/Software)

- 3.1 Develop Advanced Expert Systems (Artificial Intelligence) for Handling Spacecraft Emergencies (Such as a Fire Event) (SC: 7.0, 14.0, 21.0)
- 3.2 Develop Expert Systems for Fire Detection/Alarm/Suppression Systems (SC: 2.0, 14.0, 21.0, 42.0, 43.0)

4.0 Fire Extinguishants and Suppression Techniques

- 4.1 Evaluate Effectiveness of Candidate Fire Extinguishants (Including Portable Units) in Various Low-Gravity Fire Scenarios (SC: 3.0, 7.0, 17.0, 18.0, 22.0, 27.0, 28.0, 32.0)
- 4.2 Develop an Appropriate Replacement for the Commonly Used Halon Fire Extinguishants (SC: 5.0, 14.0, 32.0, 41.0)
- 4.3 Evaluate the Need for the Use of Special Fire Extinguishants and/or Fire Suppression Techniques in Spacecraft Hyperbaric and Hypobaric Atmospheres (SC: 7.0, 17.0)
- 4.4 Consider the Specific Use of Water Sprays (Mists) as Candidate Fire Extinguishants (SC: 9.0)
- 4.5 Develop a Nonflammable Blanket to Smother Crew Accessible Fires (SC: 9.0)

TABLE 2-1. RESEARCH AND TECHNOLOGY DEVELOPMENT TOPICS (Continued)

5.0 Fire Detectors and Fire Detection Systems

- 5.1 Evaluate Use of a Centralized Smoke Detection Monitor that Would Receive Multiple Air Samplings from Remote Points (SC: 7.0, 29.0, 43.0)
- 5.2 Incorporate the Technique of "Cross-Zoning" to Enhance Fire Detection While Reducing False Alarms (SC: 9.0, 17.0)
- 5.3 Investigate Early Detection of an Overheated Component by Monitoring the Increased Outgassing of Selected Gases (or Use of Micro-Encapsulated Gas "Tags") (SC: 2.0, 11.0, 21.0, 37.0, 43.0)
- 5.4 Accelerate the Development of Micro-Sensor (Including Solid State) Fire Detectors (SC: 14.0, 21.0, 37.0)
- 5.5 Evaluate the Effectiveness of Temperature Sensors for Use as Fire Detectors in Low-Gravity Fires (SC: 23.0)
- 5.6 Continue the Development of Optical Detection (Including IR Fiber Optics) of Flames and Overheat Conditions (SC: 17.0, 29.0, 32.0, 42.0, 43.0)

6.0 Fire Risk/Hazard Assessment

- 6.1 Review Crew Activity and Use of Materials on Past Space Flight Missions to Assess Potential Fire Hazards (SC: 7.0, 11.0, 17.0)
- 6.2 Prepare a Detailed Spacecraft Fire Safety/Fire Event Handbook (SC: 5.0)
- 6.3 Develop a Detailed Fire Risk Assessment Methodology for Advanced Spacecraft (SC: 1.0)
- 6.4 Assess the Fire and Explosion Risk Associated With Spacecraft Impact by Meteoroids and Space Debris (SC: 17.0, 32.0)

7.0 Human Effects and Toxicity

- 7.1 Perform Toxicity Analyses of the Offgassed Products from Overheated Components (SC: 7.0, 11.0)
- 7.2 Establish a Policy Position Relevant to the Toxicological Hazards Associated with the Pyrolysis Products of Spacecraft Materials (SC: 8.0, 41.0, 42.0, 43.0)
- 7.3 Expand Research Relevant to the Effects on Human Physiology Due to Long-Term Exposure to Non-Standard Atmospheres (SC: 20.0, 41.0)

8.0 Materials and Material Configurations

- 8.1 Review the Criterion for the Selection and Utilization of "Fire-Safe" Fluids (SC: 5.0, 9.0, 32.0, 44.0)
- 8.2 Investigate Crew Use of Materials, Especially Nonmetallics (SC: 7.0)
- 8.3 Expand Efforts for the Development of New or Modified Spacecraft Materials (SC: 15.0, 21.0, 32.0, 41.0, 42.0)
- 8.4 Investigate the Effects of Long-Term Aging on the Degradation (Including Flammability) of Spacecraft Materials (SC: 41.0)
- 8.5 Develop Engineering Models to Aid in the Evaluation of the Effects of End-Use Configurations on Material Flammability (SC: 15.0, 32.0, 41.0, 43.0)
- 8.6 Update and Distribute an Approved Materials List for Those Materials Which Meet the NASA Test Requirements for Flammability (SC: 17.0)
- 8.7 Prepare Data Base Relevant To The Long-Term Compatibility of Storage/Handling Materials With Chemically Reactive Gases, Liquids, and Solids (SC: 17.0, 32.0, 44.0)

TABLE 2-1. RESEARCH AND TECHNOLOGY DEVELOPMENT TOPICS (Concluded)

9.0 Modeling of Fire Scenarios

- 9.1 Prepare Analytical and Numerical Models to Aid in the Study of Microgravity Fire Safety Concerns (SC: 9.0, 14.0, and 43.0)
- 9.2 Develop Numerical Flow Models of Spacecraft Ventilation Systems In Order to Estimate Local Convection (SC: 14.0, 23.0, 29.0, 42.0, and 43.0)

10.0 Other Fire-Safety Related Issues

- 10.1 Investigate Methods for Mitigating the Potential Fire Hazards Associated With Dust and Other Debris That May Accumulate on Filters, Heat Exchangers, Etc. (SC: 7.0)
- 10.2 Establish Stringent Safety Protocols for the Storage, Use, and Disposal of Chemically Reactive Materials (SC: 9.0, 17.0)
- 10.3 Establish an Industry-Government "Fire-Safety Working Group" (SC: 4.0)
- 10.4 Establish an Intensive Fire-Safety Training Program for Spacecraft Crews (SC: 41.0)
- 10.5 Develop Guidelines for the Design of "Fire-Safe" Appliances -- Such as a Clothes Dryer -- for Use on Spacecraft (SC: 17.0)
- 10.6 Evaluate the Potential for Overheating of Electrical Components as a Result of Aging and/or Drift in Calibration (SC: 17.0)
- 10.7 Evaluate Methods for Mitigating the Potential Hazard of Spontaneous Ignition of Stored Waste Material (SC: 17.0)
- 10.8 Evaluate the Potential Fire Hazards Associated With the Storage of Supplies for Long-Duration Mission Spacecraft (SC: 17.0)

11.0 Testing and Test Standards (Ground-Based)

- 11.1 Perform Expanded Ignitability and Flammability Tests on Materials for Use in Hyperbaric Atmospheres (SC: 15.0, 19.0, 42.0)
- 11.2 Perform Tests to Evaluate Candidate Extinguishants for Use in Hyperbaric and Hypobaric Atmospheres (SC: 7.0)
- 11.3 Establish a Test Procedure and "Pass/Fail" Criterion Relative to Wire Insulation "Arc Tracking" (SC: 19.0, 32.0)
- 11.4 Develop New or Revised Screening Tests for Materials to Be Used in High-Pressure Oxygen Systems (SC: 19.0, 32.0)
- 11.5 Perform Accelerated Aging Testing of Electrical Insulation for Use in Long-Duration Mission Spacecraft (SC: 17.0)
- 11.6 Perform Detailed Testing to Determine the Relative Reactivity of Air Versus Selected Oxygen-Inert Gas Mixtures at Increasing Levels of Pressure (SC: 17.0, 32.0)
- 11.7 Perform a Critical Review of Current NASA (and ESA) Test Methods for the Screening of Flammable Materials: Revise Current Test Methods as New Data is Received (SC: 32.0)
- 11.8 Perform Tests To Assess the Effects of Various Diluents on the Suppression of Ignition and Combustion of Aerospace Materials Used in Oxygen Systems (SC: 32.0)
- 11.9 Perform Expanded Tests to Ascertain the Effects of Hypervelocity Impact of Particles on Various System Configurations (SC: 17.0, 32.0)

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3.0 PROJECT DESCRIPTIONS: FIRE-DETECTION TECHNIQUES AND HARDWARE

Sections 3.0 to 7.0 provide individual project summaries and proposed program plans for the highest priority fire-safety projects. Each project summary includes a proposed work breakdown structure (WBS) composed of specific tasks and subtasks. The background material included for each project is based upon available reference material and recent consultations with cognizant fire-safety experts.

3.1 Background

Most conventional fire detection/fire alarm systems depend upon responses from one or more of the following types of detectors: 1) ionization and optical detectors (physical properties of smoke aerosols), 2) thermal detectors (temperature level or rate-of-rise in temperature), and 3) radiation detectors (electromagnetic radiation emitted by a fire or overheat condition). The appropriate selection of any fire detector depends largely on its end-use application, availability, reliability, and cost. The various types of fire detectors that have been developed and used over the years in ground-based applications have been described in numerous reports and in the open literature (see References 2-4). A paper describing a generalized response theory for fire detectors was published by J.S. Newman (Reference 5).

In the special case of fire detector selection for manned spacecraft, cost has not been the driving factor as much as concerns regarding reliability, response time, sensitivity, size, and weight. However, even the aerospace community has been forced to select and rely upon well-developed detectors from ground-based technology. Friedman and Sacksteder (Reference 1) provided a brief summary of the fire detectors used to date in NASA's manned spacecraft program. They itemized several fire detector concepts, including some that have been rejected early in the NASA space program (e.g., a mass-spectrometer smoke gas detector). The present use of ionization smoke detectors in the STS Space Shuttle and Spacelab (see Appendix C) is a marginally adequate approach, but it does not apply current knowledge of low-gravity fire characteristics.

It isn't clear why other fire detection techniques or appropriate combinations of detectors have not been developed and adapted for spacecraft use. One reason given is that the full-time presence of crew in the STS Space Shuttle provides a human level of fire detection. Although at this writing the design requirements of the Space

Station Freedom (SS Freedom) are not complete, Mr. Harlan Burke of Boeing Aerospace Corporation (Source Code No. 3.0, Appendix A) has stated that the following types of fire detection sensors are under consideration for use in each powered equipment rack (Figure 3-1):

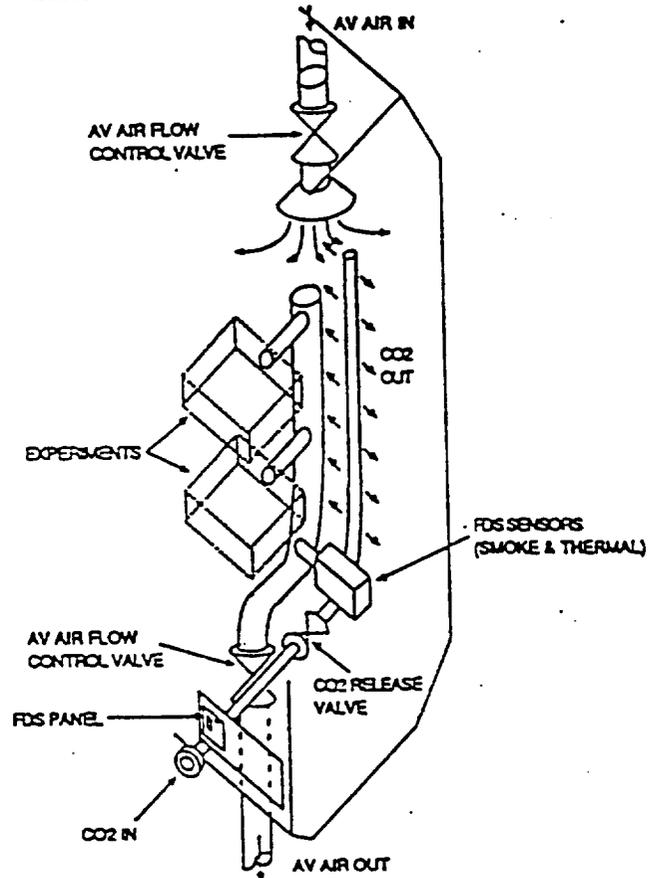
1. The primary fire detector may be an ionization or optical smoke detector. One smoke detector of this type would be located in each powered equipment rack's avionics air return duct.
2. A thermal (temperature rate-of-rise) sensor may also be located in each powered equipment rack's avionics air return duct.

In addition, there was discussion regarding the location of "smoke sensors" in each avionics air return duct manifold (external to the powered equipment racks). Note that there are smoke sensors currently located in the avionics air return ducts of the STS Space Shuttle and Spacelab. Mr. Burke also indicated that some type of flame detector (UV or IR) may be adopted for the open regions of the SS Freedom modules.

Several Wyle sources contributed information reflecting the concerns of the fire-safety community as a whole. These concerns are summarized below:

1. What are the characteristics of fires in microgravity in terms of
 - o Combustion rates
 - o Flame propagation (spread) rates
 - o Potential for flash-over
 - o Emission spectrum, etc.?
2. In low gravity, how much forced convection is required to render a smoke detector effective?
3. Given the uncertainties regarding air flow patterns in the SSF modules, what are the limitations inherent to the use of temperature sensors for detecting combustion (and overheat)?
4. Are there fuels and fire scenarios that may maintain such a low level of photon emission during combustion that they would not provide sufficiently early detection by a flame sensor to salvage the cabin atmosphere?
5. How does the time frame for ignition, flame spread, and combustion of spacecraft materials differ in microgravity from that in normal gravity?
6. What about smoldering combustion under low gravity conditions? Is this a possibility and what are the implications as regards detection of smoldering?

RACK FIRE DETECTION/SUPPRESSION CONCEPT



AV = AVIONICS

FDS = FIRE DETECTION AND
SUPPRESSION SYSTEM

FIGURE 3-1. CONCEPT FOR FIRE DETECTION SENSORS IN A SPACECRAFT RACK

Clearly, fire detection systems for use on advanced, manned spacecraft such as SS Freedom will be a significant portion of the spacecraft's safety system. In the case of SS Freedom, the increased size and complexity of the spacecraft, the increased experimentation activity, the much longer duration of the missions, and the lengthy periods of time when the spacecraft systems will be active in the absence of crew members all contribute to the importance of fire detection (and suppression systems). Such fire detection systems for advanced spacecraft must not only be highly reliable, but they must also be highly responsive. Equating increased sensitivity with an increased tendency for false alarms is not a valid assumption if the detector sensor and its monitoring system is well-understood and is appropriately designed and configured for its end-use application. This, then, demands the enhanced use of expert system technology and the appropriate selection of multiple detectors of various sensor types.

3.2 Proposed Fire-Detection Related Projects

Several topics have been identified during the course of this effort that are directly and specifically related to fire detectors and fire-detection related systems. These projects have been tabulated in Table 2-1 under the heading "Fire Detectors and Fire Detector Systems." In addition, several other topics have been identified that are either indirectly related to fire detection or that will ultimately be necessary to provide the desired low-gravity data base on ignition, flame spread, and flame characteristics that may affect decisions relative to fire detection sensor types, number, location, etc.

The final selection of projects based on the prioritization of topics has provided five highest-priority projects to be included in this thematic area of fire detection, listed below in the order of descending priority and identified by the discipline number shown in Figure 2-2:

<u>Priority Discipline No.</u>	<u>Project Title</u>
TD-1	Development of Expert Systems for Fire Detection/ Alarm/Suppression Systems
TD-2	Development of Centralized Fire Detector Monitors with Distributed Sensors

<u>Priority Discipline No.</u>	<u>Project Title</u>
TD-4	Development of Techniques for Early Detection of Incipient Fire Conditions by Monitoring Outgassing
TD-5	Development of Smoke Gas (Fire) Detectors Using Micro Sensor Technology
BR-3	Research on Low-Gravity Ignition, Flame Spread, Flame Characteristics, etc. for Selected Materials

Figure 3-2 illustrates a proposed schedule for the highest-priority fire detector projects. The proposed schedule is admittedly optimistic, but could be met with proper emphasis.

The schedule includes additional lower-priority projects (BR-5, BR-7, and BR-8), starting after calendar year (CY) 1992. To date, only limited low-gravity combustion and flame spread data have been obtained (see Reference 6). Additional data will be obtained in the interim from drop tower tests, aircraft flights, etc., but the extensive test data desired will not be available until large numbers of tests are performed on the STS Space Shuttle/Spacelab and SS Freedom.

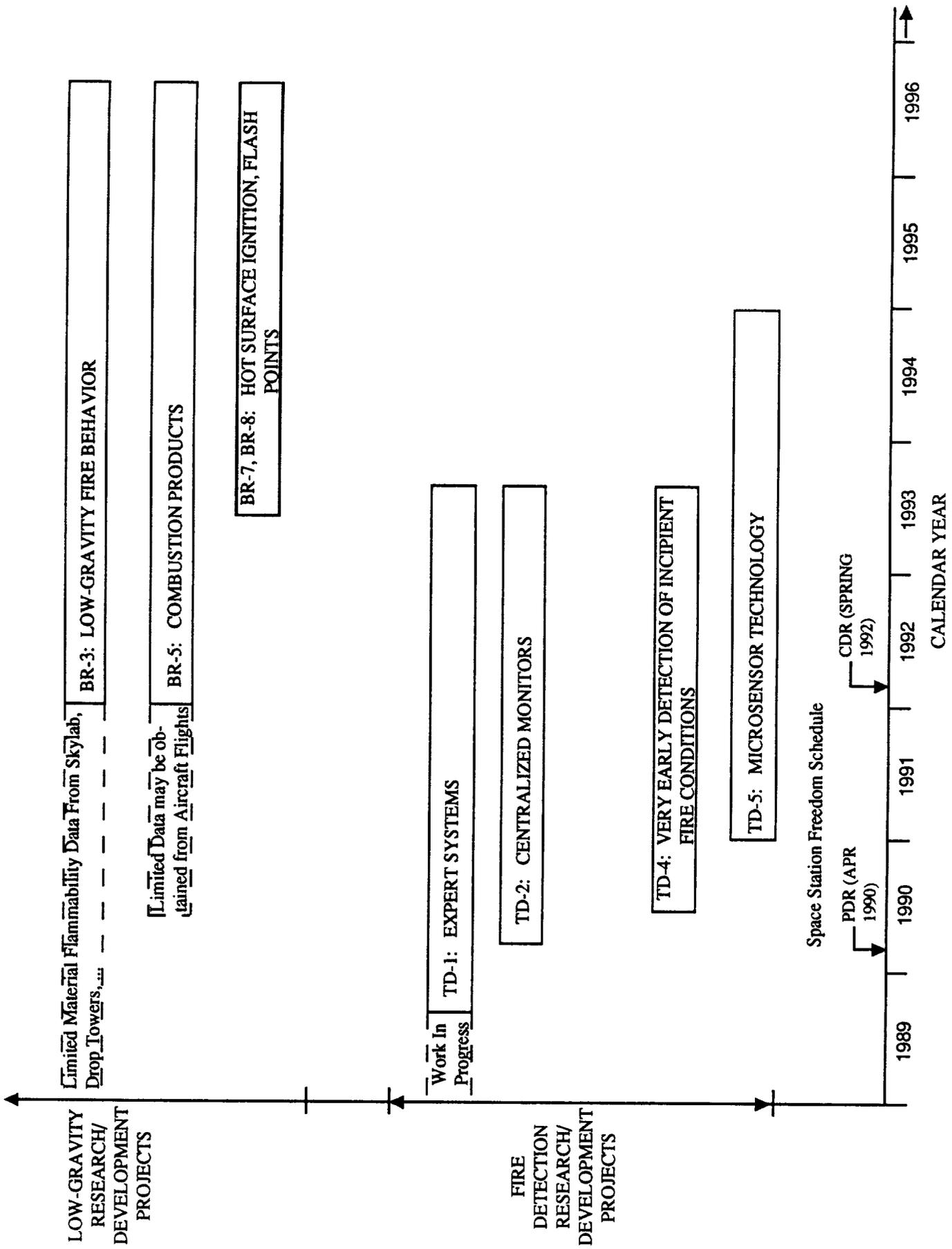


FIGURE 3-2. SCHEDULE FOR FIRE DETECTION PROJECTS

3.3 Development Of Expert Systems For Fire Detection/Alarm/Suppression

3.3.1 Background: The need for highly responsive and reliable fire detection (and suppression) systems is stressed throughout this report. A large number of the respondees to the spacecraft fire-safety survey, conducted as a part of this effort, have endorsed the need for an "expert system" approach to the fire detection suppression (FDS) subsystem. For example, R. Smith of the National Institute for Standards and Technology (NIST) acknowledged that the expert system knowledge base should be developed in a phased approach, since the development of advanced manned spacecraft -- such as Space Station Freedom -- is only now underway. Also, since the effects of microgravity on the various types of combustion is not well understood, Smith and Kashiwagi (Reference 7) suggested that the knowledge base should include a basic fire-signature data base for size distribution and constituency of particles produced in both the flaming and non-flaming cases. This fire signature data base will then be upgraded as low-gravity data becomes available.

The development of "expert" and "distributed intelligence" fire detection and suppression systems is taking place at a rapid pace for earth-based applications (see References 8-13). The use of microprocessor-based systems permits higher levels of fire detector signal evaluation and processing. In general, control tends to be moved away from the detector sensor to a central "panel" or control system. According to R. Von Tomkewitsch (Reference 13), the fundamental functions of a fire-protection system that needs a certain level of intelligence are as follows:

1. Processing of signals from automatic fire detectors.
2. Annunciation of an alarm condition.
3. Automatic initiation of defense measures (i.e., fire extinguishment, closing of vents, switching on escape route indicators, etc.).

Depending on the level of complexity desired and limited by the knowledge base available, an expert system should have at least the following attributes:

1. Identification of individual detectors by type and precise physical location.
2. Continuous and rapid functional checks of all connected detectors.
3. Ability to store and utilize appropriate algorithms (e.g., calibration, fire signature data, etc.).

4. Automatic notification of failed detectors.
5. Uniform response sensitivity unaffected by "drift" from the nominal operating points of the detectors.
6. Greater protection against false alarms.

Finally, a very important aspect of automated, or semi-automated, expert fire detection and suppression systems is that of fail-safe reliability and/or system redundancy. This includes considerations of both the system hardware and software (e.g., see Reference 11).

3.3.2 Proposed Efforts: The proposed project is described on the basis of work breakdown structure (WBS) tasks directed toward the development of fire detection and suppression (FDS) "expert" systems for advanced, manned spacecraft. A review of the literature to date suggests that ground-based applications of microprocessor-based fire detection/alarm systems have outpaced those for aircraft and spacecraft. Thus, the starting point for this effort should be the performance of a critical review of the commercially available ground-based systems and those utilized on commercial and military aircraft. The organization of the project WBS is illustrated in Figure 3-3.

Task 1.0: Review Current State-of-the-Art Fire Detection/Alarm Expert Systems

Subtask 1.1: Evaluate Commercially Available, Ground-Based Systems. There are a number of complex, multiple detector fire detection/alarm systems available on the commercial market. These should be reviewed to evaluate their attributes and applicability to advanced spacecraft.

Subtask 1.2: Review Current Status Of Aircraft And Spacecraft Fire Detection And Suppression Control Systems. Fire alarm and control systems used on commercial and military aircraft may have little relevance to advanced spacecraft. An exception may be the recent (Reference 14) Federal Aviation Study on advanced fire alarm systems. The systems used on the STS Space Shuttle and Spacelab are not highly complex and are not fully automated (i.e., crew action is required). Current design efforts for SS Freedom's FDS subsystem should be made a part of this review.

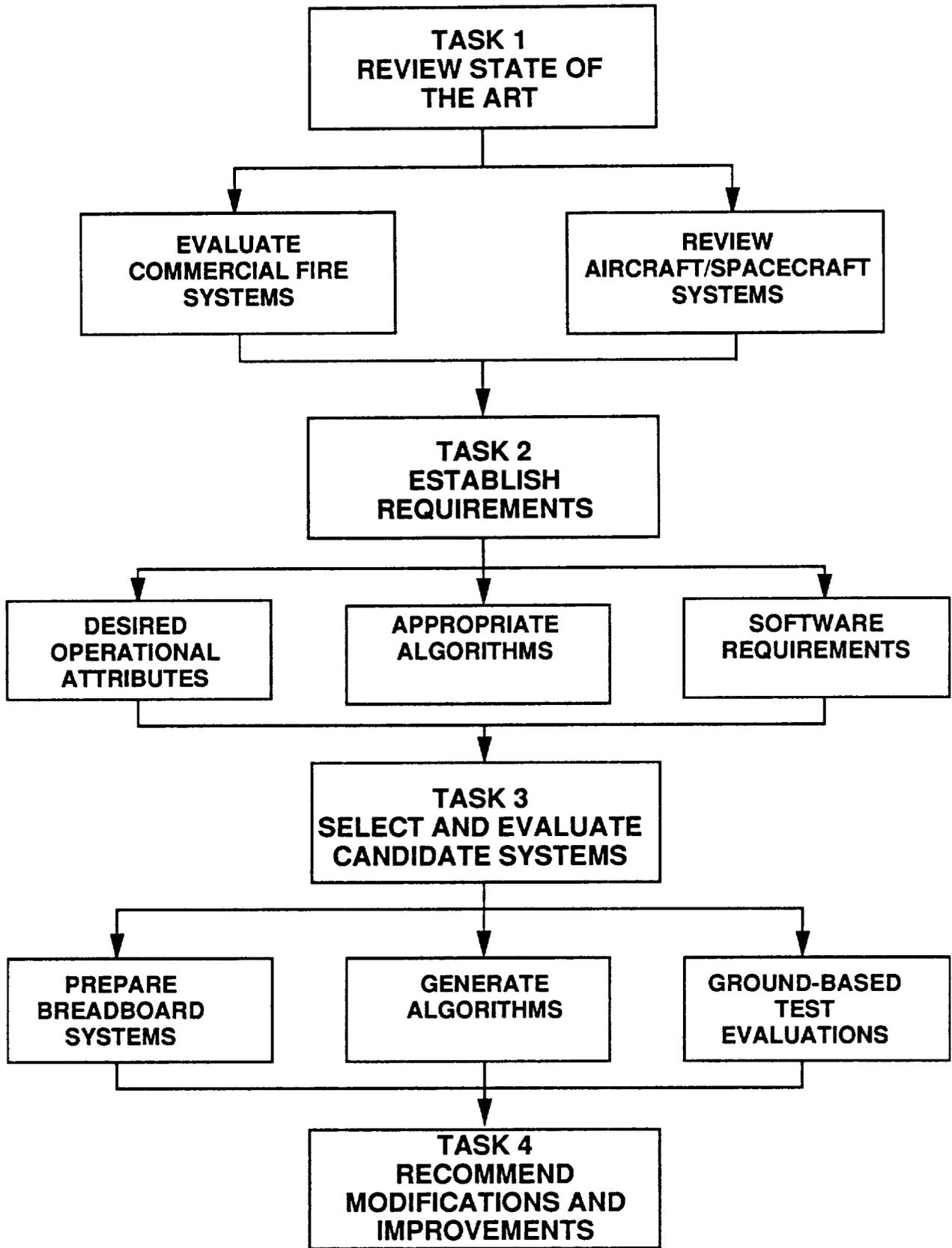


FIGURE 3-3. WORK BREAKDOWN STRUCTURE FOR DEVELOPMENT OF EXPERT SYSTEMS FOR FIRE DETECTION/ALARM/SUPPRESSION

Task 2.0: Establish A Requirements List For Advanced Spacecraft Expert Systems

Subtask 2.1: Tabulate Desired Operational Attributes. The level of complexity of an advanced spacecraft's FDS subsystem will strongly impact on the subsystem's operational attributes. Some of the most commonly desired features and attributes were outlined above in the background section. The use of multiple types of detectors in any specific region of the spacecraft will increase the level of fire detection but only to the extent that the appropriate algorithms are available to the expert system.

Subtask 2.2: Identify The Fire Detection Algorithms To Be Incorporated. As a minimum, the expert system knowledge base shall require the following algorithms:

1. Type and location of all detector sensors.
2. Calibration set points and/or curves.
3. Response versus known fire signature.
4. Long-term detector sensor drift.

In addition, there may be a need for a number of operational protocols concerning communication, alarm annunciation, and system control (i.e., vents, lighted markers, etc.)

Subtask 2.3: Review And Identify Software Requirements. The FDS subsystem's expert system software requirements will follow the level of complexity and desired features outlined in Subtask 2.1 and 2.2. The software reliability and fail-safe requirements must be given proper attention.

Task 3.0: Select And Evaluate Candidate Expert Systems For Advanced Spacecraft

Subtask 3.1: Prepare Operational Breadboards of Candidate Expert Systems. The intent of this subtask is to assemble ground-based breadboard FDS subsystems and appropriately configured expert systems for test and evaluation. The use of existing commercially available hardware and software is recommended. Minor modification and up-grades to the hardware may be appropriate.

Subtask 3.2: Generate And Incorporate Desired Algorithms Into Breadboards. The software for an expert system to be used with spacecraft FDS subsystems may be significantly different from that used in ground-based expert systems. Thus, based on the requirements established in Task 2.3, there may be significant changes in the software and algorithms incorporated into existing expert systems.

Subtask 3.3: Perform Ground-Based Tests And Evaluations Of Candidate Breadboards.

The intent of these tests is to exercise the candidate FDS subsystem expert systems for evaluation. Therefore, artificially generated fire signatures may be used unless it is the test and evaluation of the fire detector sensors that is specifically desired. A limitation of these tests is that, by necessity, the bulk of them must be performed under normal, sea-level gravity conditions. Thus, the low-gravity response of the fire detector sensors cannot be readily simulated until a more extensive knowledge base of low-gravity fire signatures has been established.

The tests and evaluations of the candidate expert systems shall be measured against the desired features and attributes outlined in Task 2.0.

Task 4.0: Recommend Modifications And Improvements To The Expert System Designs

The purpose of this task is to summarize and organize the modifications and improvements deemed necessary for the candidate expert systems tested in Task 3.0. Assuming that there is no commercially available expert system that meets all of the desired attributes for spacecraft application, the breadboards should be modified and retested.

3.4 Development Of Centralized Fire Detector/Monitors With Distributed Sensors

3.4.1 Background: The use of a small number of centralized fire detector monitors in a spacecraft is attractive in the potential savings in weight, power, and usable space. Each centralized monitor would accommodate multiple sensors arranged in the most appropriate ways for reliability, redundancy, etc. The discussion herein for this project is, therefore, devoted to the development of centralized monitors that utilize some type of optical-based radiation sensors (including fiber optics) and/or the sensing of smoke particles and aerosols through pumped or aspirating tubes.

Several respondees to the Wyle spacecraft fire-safety survey recommended that NASA should give consideration to the use of some types of radiation sensors for advanced spacecraft. Some of the more specific of these recommendations included the use of combined ultraviolet/infrared (UV/IR) radiation sensors, the use of near-field infrared imaging and signal processing, and the use of infrared-transmitting fiber optics. UV and IR detectors are commonly specified for use where very rapid response (milliseconds) is necessary, i.e., in hypo-and hyperbaric chambers, munitions and other explosives handling areas, inside of certain military vehicles, etc. The NASA Skylab spacecraft (1973-74) utilized some 22 UV radiation flame detectors. The development and test evaluation of these Skylab flame detectors have been described by R.M.F. Linford (References 15 and 16). The advantages and disadvantages of the use of UV and IR radiation detectors are reasonably well understood, and their application to highly controlled environments reduces some of the causes of false alarms. Techniques for minimizing certain types of false alarms through special signal processing measures have been discussed by H. Luck and K.R. Hase (Reference 17).

Most applications of UV and IR flame and overheat detectors have, to date, required that the radiation sensing element and any associated optics be located at the site being monitored. This requirement often places the delicate sensing elements in adverse environments. The use of fiber-optic technology promises to aid in allowing the detector sensing element and associated electronics to be located remotely from the site of interest. For example, the U.S. Air Force funded studies over ten years ago relative to the use of UV fiber optic sensors for aircraft engine fires (e.g., Reference 18) and more recently (1982) to advanced UV aircraft fire detection systems (Reference 19). In 1988, the NASA White Sands Test Facility (WSTF) published an

investigation into the applicability of infrared (IR) fiber-optic sensors for use as distributed fire detectors on Space Station Freedom (Reference 20). Ultimately, low-gravity testing of UV and IR radiation detectors will be required to evaluate their response to various fire scenarios when compared to similar fire scenarios under normal gravity.

Another method for creating a centralized fire-detection system is that whereby the smoke particles (i.e., any smoke gases and aerosols) are transported rapidly from the fire source to the fire detector by pumping the smoke through tubes. The use of pumped tubes for the transport of combustion products to centralized detectors has been used for several years in underground mines, road- and subway tunnels, etc. (References 21 and 22). A comparable system was developed in Australia for early detection of fires in computer facilities (Reference 23). This system has been given the generic name VESDA (Very Early Smoke Detection Apparatus) and is now marketed in the United States by Fenwal Incorporated, Ashland, Mass. An advantage of centralized fire-detection systems is that the centrally located smoke detector sensor, usually of the light scattering type, can be made more sensitive than conventional smoke detectors. This is because the centralized detector is not as restricted in size and power and can, therefore, use a higher intensity light source, a larger scattering chamber, and a highly responsive photo receiver.

There are obvious disadvantages to the use of pumped tubes. Their size, although small, is non-trivial, and there is a response time associated with the length of each tube and the forced-convection flow rate. Also, there is a pump and scanning valve system required to multiplex the multiple tubes.

Wyle did not find any reference in the literature that indicates that any studies have been performed regarding the use of the pumped-tube (i.e., VESDA type) centralized fire-detection system for spacecraft. However, its use could be attractive for portions of a large, manned spacecraft such as monitoring un-powered racks and storage bins, especially those that are not supplied with circulating air. The central detector unit could be based on the standard detection principles used in ionization and light scattering smoke detectors, or the unit could be enhanced by the addition of some relatively new technologies such as that used by the condensation nuclei fire detector (CNFD, Reference 24).

3.4.2 Proposed Efforts: The proposed project is described on the basis of WBS tasks directed toward the technology development and application of promising fire-detection system concepts that may have specific application to advanced, manned spacecraft. The emphasis is placed on centralized fire detection systems, especially those that include fiber-optic technology (radiation detectors) as shown in Figure 3-4 and pumped tubes (smoke particle/aerosol detectors). The organization of the project WBS is illustrated in Figure 3-5.

Task 1.0: Establish Knowledge Base From The Past Applications Of Centralized Fire Detection Systems: Radiation And Smoke Monitors

Subtask 1.1: Review Documented Application Of Radiation Detectors (UV, IR, And UV/IR) For Fires And Explosions. This subtask will consist of a detailed review of the past application of these fire detectors. The literature indicates that there has been a significant amount of experience with UV and IR detectors for ground-based applications, in military tanks and munitions plants, and for aircraft, in engine nacelles and fuel compartments, but only limited experience in space applications (e.g., Skylab).

Subtask 1.2: Review Documented Application Of Centralized Fire Detection Systems Based On Pumped-Tube Smoke Sensors. This subtask will consist of a review of the past applications of centralized fire detection systems that use pumped or aspirating tubes to sense smoke particles and aerosols. As described in the background material for this project, these types of smoke detectors have been used in a variety of earth-based applications (mines, underground roadways and subways, computer facilities, etc.). Their use in other applications should be reviewed for details regarding type of smoke detector, response time, power requirements, etc.

Task 2.0: Assess The Applicability Of Centralized Fire Detection Systems For Use On Advanced Spacecraft

Subtask 2.1: Analyze The Advantages And Limitations Associated With The Use Of Radiation-Type Fire Detectors. As described in the background material for this project, the advantages associated with UV and/or IR detectors are understood to include rapid response (milliseconds), high sensitivity to certain types of explosions, and ability to monitor large, open areas. The limitations are also reasonably well

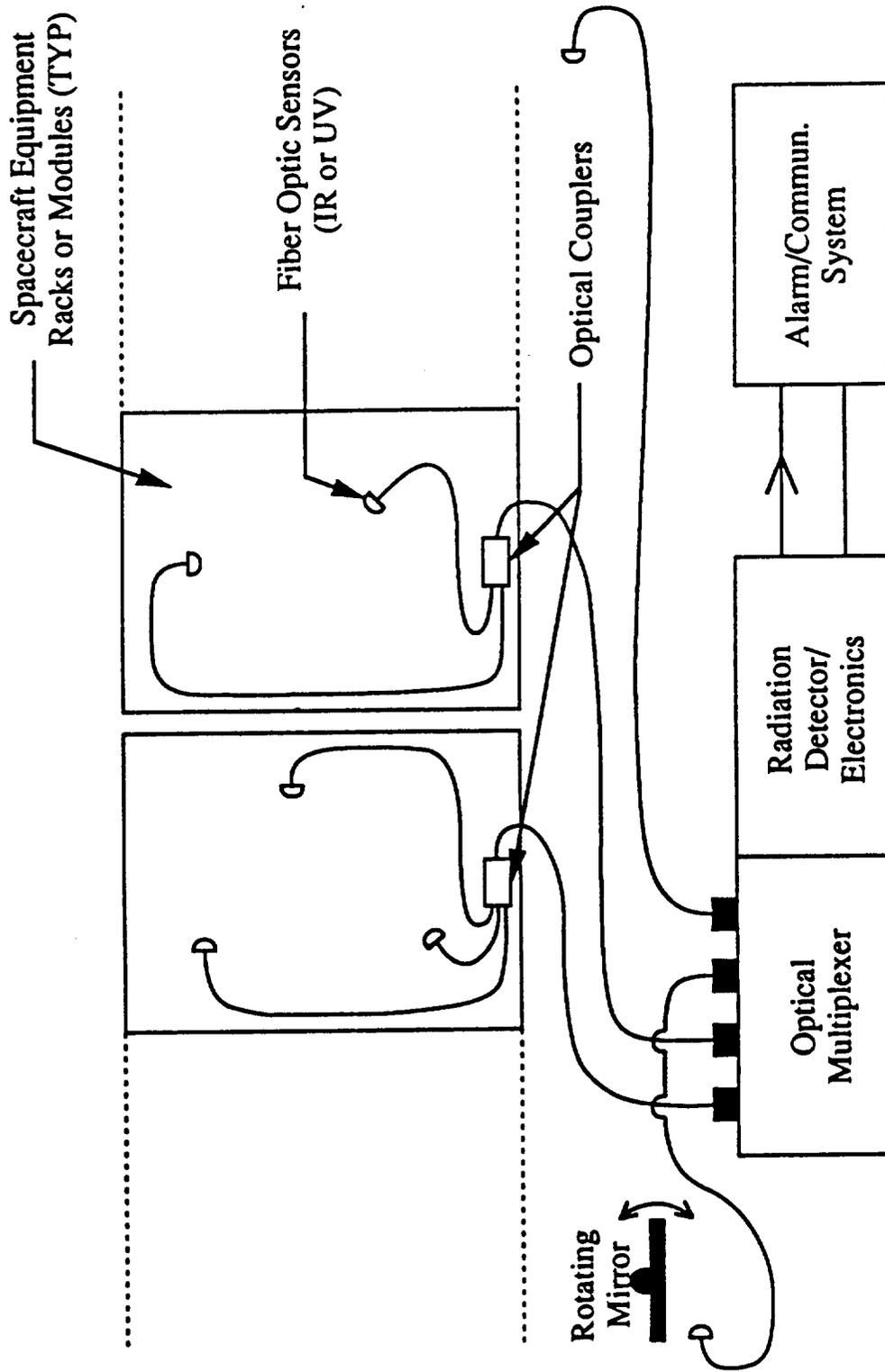


FIGURE 3-4. SIMPLIFIED CONCEPT OF FIBER-OPTIC BASED FIRE-DETECTION SYSTEM FOR SPACECRAFT

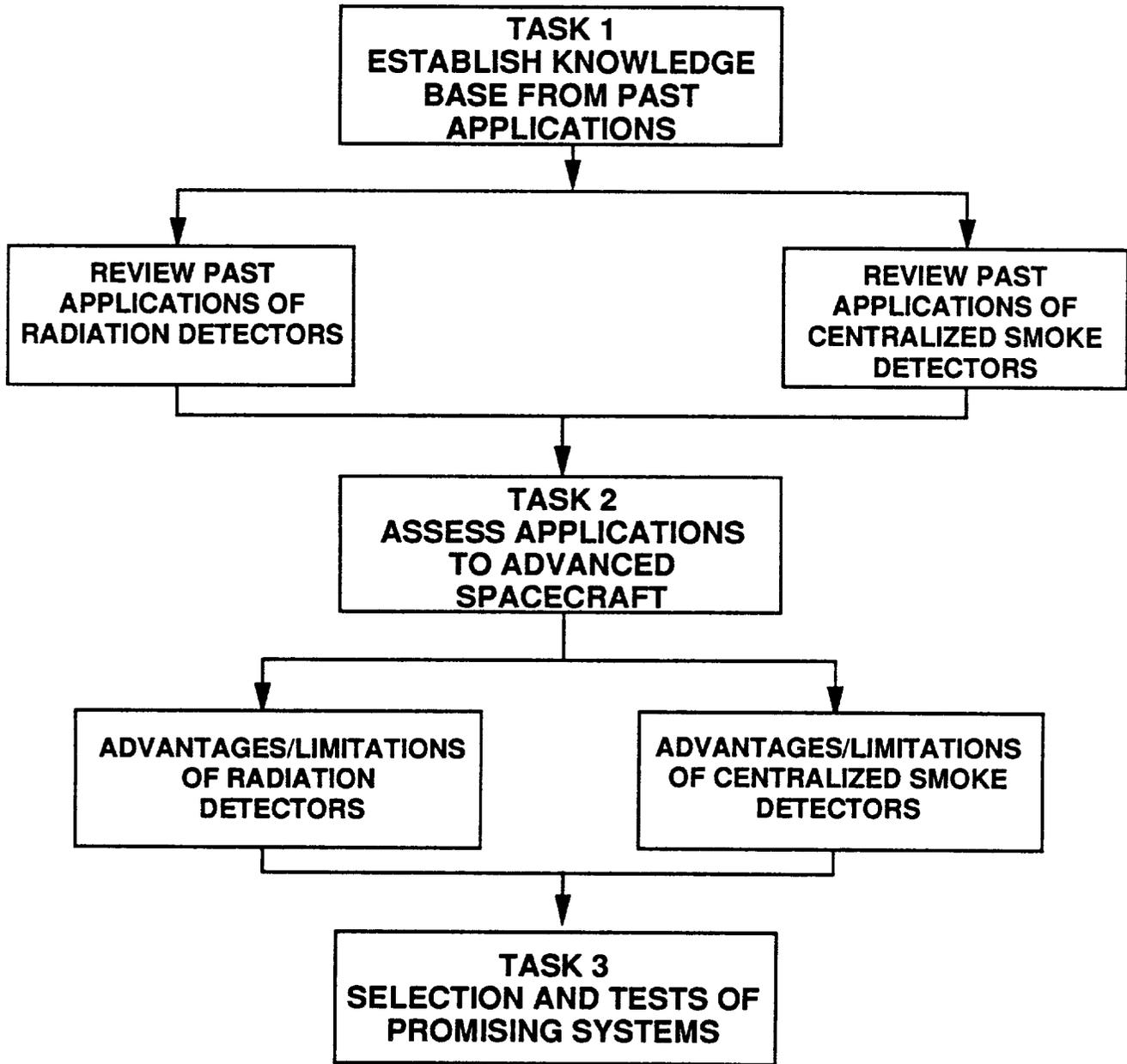


FIGURE 3-5. WORK BREAKDOWN STRUCTURE FOR DEVELOPMENT OF CENTRALIZED FIRE-DETECTION MONITORS WITH DISTRIBUTED SENSORS

understood and include the following: 1) The optical radiation sensors are line-of-sight devices and may require special enhancement for a wider viewing area; 2) False alarms due to stray light have been reported; and 3) Response to deep-seated and/or smoldering combustion may be inadequate. Additional advantages and limitations must be assessed to meet the requirements of advanced spacecraft designs.

Subtask 2.2: Analyze The Advantages And Limitations Associated With The Use Of Pumped Tube Smoke Sensors. For spacecraft applications, where the absence of buoyancy induced convection will limit movement of smoke to the air circulation system, the use of pumped or aspirating tubes to sense smoke particles and aerosols appears to hold promise. Thus, in addition to sensing smoke in quiescent regions of a spacecraft, such systems may be lighter due to the reduced number of detectors, the detector sensitivity can be very high, and a large number of sensing tubes may be supported by each detector. Some system limitations include the following: 1) There is limited spacecraft and aircraft application experience; 2) The detector response time will depend largely on the sensing tube lengths and pumping speed; and 3) A pump and scanning valve system may be required.

Task 3.0: Select And Test Promising Centralized Fire Detection Systems That Use Multiple, Distributed Sensors

This task implies that the review and analysis of fiber optic-based radiation (UV and IR) sensors and pumped tube smoke sensors indicate some applicability to advanced, manned spacecraft. Although much development work may be required for spacecraft application, this task is intended to provide the preliminary selection, design definitions, and possible breadboard testing to establish promising systems for further development.

3.5 Development Of Techniques For Early Detection Of Incipient Fire Conditions By Selective Monitoring Of Gases

3.5.1 Background: Materials, especially nonmetallics, tend to release significant amounts of gases as they are heated. This release of gases ("outgassing") depends on the material, its temperature, and the material's environmental history. It is well understood that fires produce gases (i.e., smoke gases) in quantities that are absent in normal air and that the composition of smoke gases depends on the levels of combustion (e.g., smoldering, flaming, etc.) and the fuels and oxidizers involved. Similarly, incipient fire conditions such as very low levels of smoldering or the early stages of pyrolysis, can also result in the release of gases and smoke aerosols. Although such outgassing occurring at temperatures well below the material's ignition temperature does not constitute an unambiguous incipient fire signature, the detection of large amounts of outgassing could indicate abnormal or unwanted overheating and the potential threat of a fire.

It must be noted that a fire in a spacecraft environment may be significantly different than at normal gravity. For some fire scenarios and fuel geometries, the blanketing effect of the products of combustion will tend to inhibit oxygen entry into the flame zone causing fuel-rich smoke, lower burn rates, and alterations in flame size and shape. The chemical makeup of the combustion products may include more carbon monoxide, aldehydes, ketones, and organic acids than in normal gravity.

Given our current understanding of outgassing and smoke gas composition, the use of these phenomena as fire signatures appears encouraging. Dr. Robert Hager, a consultant, suggested the establishment of a database of those gases most common to the outgassing of aerospace materials (especially nonmetallics) at temperatures from ambient to approximately 250°C (482°F). If a particular gas, or group of gases, can be identified as an unambiguous signature of overheating, then an important early warning alarm may be available. The major problem with this suggestion is that false alarms could be excessive unless some gaseous species other than water vapor, carbon dioxide, and hydrogen is selected.

The use of smoke gases as fire signatures has been investigated for many years. In 1969, M. V. Drickman (Reference 25) recommended the development of a fire detection system for the Apollo command module -- and other advanced spacecraft -- based on a combination of a mass spectrometer and overheat detectors. Problems associated with use of mass spectrometers included size and weight, selection of appropriate species to monitor, false signals from background gases, general instrument reliability, etc.

In 1983, G. Pfister (Reference 26) published a review of research activities on the detection of smoke gases by solid-state sensors. He concluded that solid-state gas detection could provide a viable alternative or additional means for the detection of smoldering or pyrolytic fires at an early stage. The type of solid-state gas sensors that were stated to hold the most promise as smoke gas detectors were the solid-state electrolyte, the metal oxide semiconductor, and the silicon semiconductor device element. Progress in the development of these devices for use as oxygen, hydrogen, and carbon monoxide sensors was discussed. Although some of these devices are commercially available (e.g., CO and O₂ detectors), they have not been developed for common use as fire detectors.

The use of a very sensitive ion mobility spectrometer (IMS) has been suggested for development as a smoke gas detector by E. Thomas of Brunswick Defense Company. The IMS can operate at atmospheric pressure and has been used to detect a number of explosive vapors at levels as low as parts-per-trillion in time periods of the order of seconds (e.g., Reference 27).

The use of material additives or temperature sensitive coatings to act as "tags" was suggested by Wyle respoondees. Additives that can be incorporated into textiles, foams, and plastics for the purpose of causing volatile products and distinctive odors when heated can be used as human sensory alarms. This study was reported by J. R. Holker and G. R. Lomax in 1986 (Reference 28). The B. F. Goodrich Company (Reference 29) developed a novel wall covering material designed to emit a colorless and odorless vapor that activates the alarm mechanism of ionization smoke detectors. Tests reported in the literature (Reference 29) showed that the treated wall covering activated an alarm within six minutes upon heating to 130°C (266°F).

3.5.1 Proposed Efforts: The proposed project is described on the basis of WBS tasks performed with the overall objective of developing techniques for early detection of incipient fire conditions and the generation of additional levels of fire signatures. Thus, the proposed effort is divided into three major tasks: 1) development of a data base of aerospace material outgassing species and smoke gases, 2) development of temperature sensitive material coatings (or micro-encapsulated gas "tags") and 3) development of highly sensitive gas detectors. The organization of the project WBS is illustrated in Figure 3-6.

Task 1.0: Develop A Data Base Of Typical Outgassing Data And Production Of Smoke Gases For Aerospace Materials

Subtask 1.1: Review Available Information To Establish Data Base Of Low Temperature Outgassing. Initially, this subtask would consist of a review of available outgassing data versus temperature for selected aerospace nonmetallic materials. As a material is heated, the initial gases emitted will, of course, be those that are loosely adsorbed, i.e., water vapor and carbon dioxide. As the temperature is increased, additional species will be released, including oxygen, hydrogen, and possibly some of the more volatile hydrocarbons. If the results of this review indicate that there may be some unambiguous gaseous species common to the general class of aerospace materials, then the effort should be pursued to fully confirm this incipient fire signature. One of the immediate sources of data may be the outgassing data taken by NASA during the screening of materials in accordance with the requirements of NHB 8060.1B (Reference 30), although present outgassing tests are performed at ambient conditions only.

Subtask 1.2: Perform A Systematic Review Of The Smoke Gases Produced During Different Stages Of Incipient Fire Conditions. The next part of Task 1.0 is to review information on the composition and quantity of smoke gases produced during different stages of incipient fire conditions. Wyle's consultant for toxicology, Dr. H.L. Kaplan, has also suggested that a high priority should be given to the continuous monitoring of the following asphyxiant gases and conditions, i.e., CO, HCN, CO₂, and O₂ depletion. Dr. Kaplan placed emphasis on CO and HCN since these gases are capable of producing rapid incapacitation. Regarding the monitoring of irritant gases — some of which are also highly toxic —, Dr. Kaplan suggested that the following gases be monitored on a less rapid basis; HCl, HBr, HF, NO_x, acrolein, isocyanates, phosphorus compounds, and

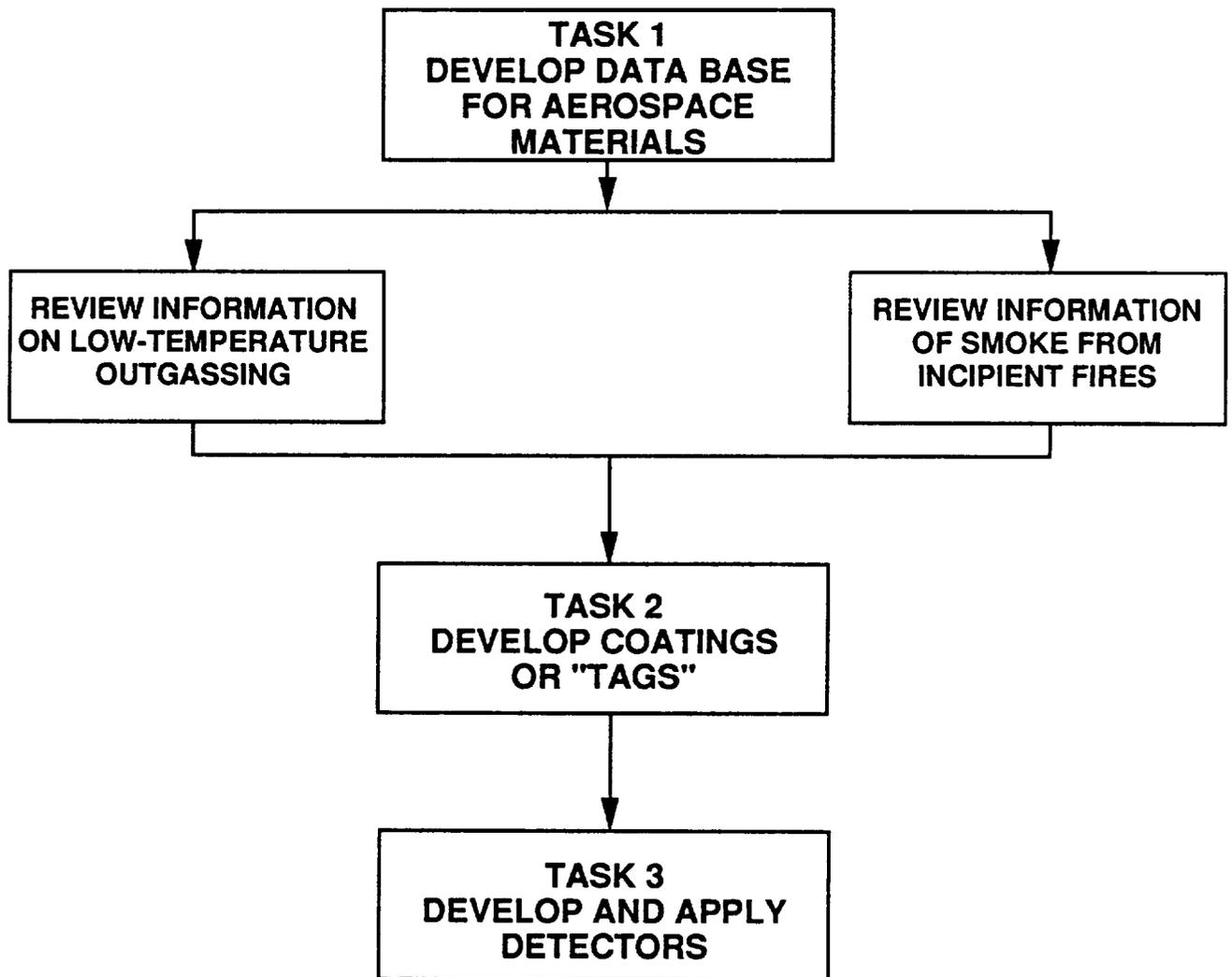


FIGURE 3-6. WORK BREAKDOWN STRUCTURE FOR DEVELOPMENT OF TECHNIQUES FOR EARLY DETECTION OF INCIPIENT FIRE CONDITIONS BY SELECTIVE MONITORING OF GASES

fluorinated organics. It should be noted that the irritant gases (except NO₂) are likely to provide warning to the spacecraft crew (when crew is present) at lower than hazardous concentrations because they irritate the eyes and the respiratory tract.

The output of this subtask is intended to be a limited data base which will summarize the "typical" outgassing species from aerospace nonmetallic materials for temperatures up to approximately 250°C (482°F). Also, this data base shall include a tabulation of "typical" smoke gases resulting from the different stages of incipient fire conditions.

Task 2.0: Develop Temperature Sensitive Coatings Or Micro-encapsulated Gas "Tags"

This proposed task constitutes an effort to determine the viability of the use of temperature sensitive coatings that would enhance early detection of incipient fire conditions without creating other hazards to the spacecraft or crew. Although research and development have been performed relative to the application of this technique to materials for use in homes and offices, it is necessary to ensure that such coatings or material additives are non-toxic and do not adversely affect the base materials' physical and mechanical properties. The use of additives that depend on the production of odors upon pyrolysis may be inappropriate for spacecraft, which may be unmanned for extended periods of time. The proprietary active ingredient reported by the B. F. Goodrich Company for poly (vinyl chloride) coated wall covering (Reference 29) was stated to emit a colorless and odorless vapor that would activate ionization smoke detectors when the wall covering was heated to approximately 150°C (302°F).

Task 3.0: Expand The Development And Application Of Tuned Smoke/Gas Detectors

The types of smoke gas detectors of interest to this task are those that can be tuned to identify the presence and quantity of specific gas species. These instruments include, but are not limited to, the gas chromatograph/mass spectrometer (GC/MS) and the ion mobility spectrometer (IMS). The use of the GC/MS and similar instruments are already in the planning stages for the purpose of monitoring the habitable atmosphere in Space Station Freedom (Reference 31). These plans include rapid sampling of major constituents (i.e., H₂, O₂, N₂, CO, CO₂, H₂O, and CH₄) and the periodic (e.g., 30 minute cycle time) monitoring of a large class of trace contaminants.

The current status of these gas detectors was reviewed recently by R. A. Peters, et al. (Reference 32) and G. Marsh (Reference 33). Although these types of instruments are generally impractical to be used as distributed smoke gas detectors, they can provide an additional level of fire signature to warn operators of problems.

The objectives of this task are to quantify the use of incipient-fire detection systems and to investigate the possibility of designing a centralized fire-detection system using these types of gas detectors as the sensor subsystem. In order to accomplish these objectives, the study may establish standard laboratory test setups to evaluate techniques and provide comparative assessments and tests of detector response, design requirements, potential low-gravity influences, and so on.

3.6 Development Of Smoke Detectors Using Microsensor Technology

3.6.1 Background: Assuming that microsensor gas detectors can be developed to adequate levels of sensitivity and reliability, their use on advanced spacecraft is attractive by virtue of their small size and the additional fire signatures provided. Fundamentally, microsensor fire detectors depend on the research and development of solid-state gas sensors, a field of some activity in the past 15 years (References 34 and 35).

According to G. Pfister (Reference 26), the most promising solid-state sensor principles for use in detecting low concentrations of gases include the following:

1. The Electrochemical Cell (based on sensing the change in cell potential across a solid state electrochemical membrane, i.e., a Nernst cell)
2. The Metal Oxide Semiconductor Gas Sensor (based on sensing the change of the electrical conductivity of metal oxide semiconductors due to surface oxidation)
3. Barrier Type Gas Sensors (based on the change in the electrical characteristics of MOS, MIS, and Schottky barrier devices)
4. Microcalorimeter Gas Sensors (based upon a measurement of the heat of combustion liberated when a gas is oxidized).

Solid-state gas sensors have the general limitations of 1) high working temperature and power consumption of sensors, 2) gas response sensitive to the relative humidity, 3) limited specificity to selected gases, and 4) sensor contamination and drift in time periods of one year or less. Pfister has suggested that many of these limitations can be overcome and that specific solid-state sensors can detect selected gases with sufficient sensitivity to be used as smoke gas detectors. Of course, some of these types of sensors have already been developed commercially for specific applications. One of these is the Taguchi gas sensor manufactured by Figaro Engineering in Japan. The Figaro metal oxide semiconductor gas sensor (see Figure 3-7) is used extensively for explosive vapor monitors, combustion hazard alarms, and breath alcohol meters. Also, probably the most widely used solid state gas sensor is the electrochemical cell used to monitor oxygen.

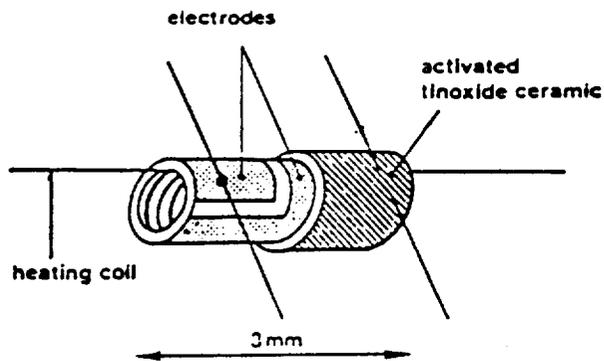


FIGURE 3-7
COMMERCIAL METAL OXIDE SEMICONDUCTOR
SENSOR FOR COMBUSTION GASES

The general class of gas chromatograph/mass spectrometer (GC/MS) gas sensors are not included here since they can hardly be considered "microsensors." However, in a recent paper by G.E. Spangler et al. (Reference 36), a miniature ion mobility spectrometer (IMS) cell is described, which is being developed for field application monitoring of toxic organic vapors in the ambient atmosphere with levels of detection in the range of parts per billion (ppb) or better.

3.6.2 Proposed Efforts: The proposed project is described on the basis of WBS tasks which will require intensive efforts in several technical discipline areas. These discipline areas include chemical microsensor and microinstrumentation development and the involvement of such technologies as the following: 1) integrated optics and surface acoustic wave (SAW) sensors, 2) etched microcapillary tubes, 3) lithographic and thin-film techniques, and 4) many other microfabrication techniques.

NASA cannot be expected to underwrite all of the research and development costs associated with microsensor smoke gas detectors. However, the need for multiple, low-weight, smoke gas detectors for very early fire detection on large, advanced manned spacecraft demands that NASA monitor and adapt the most appropriate emerging technologies. The organization of the project WBS is illustrated in Figure 3-8.

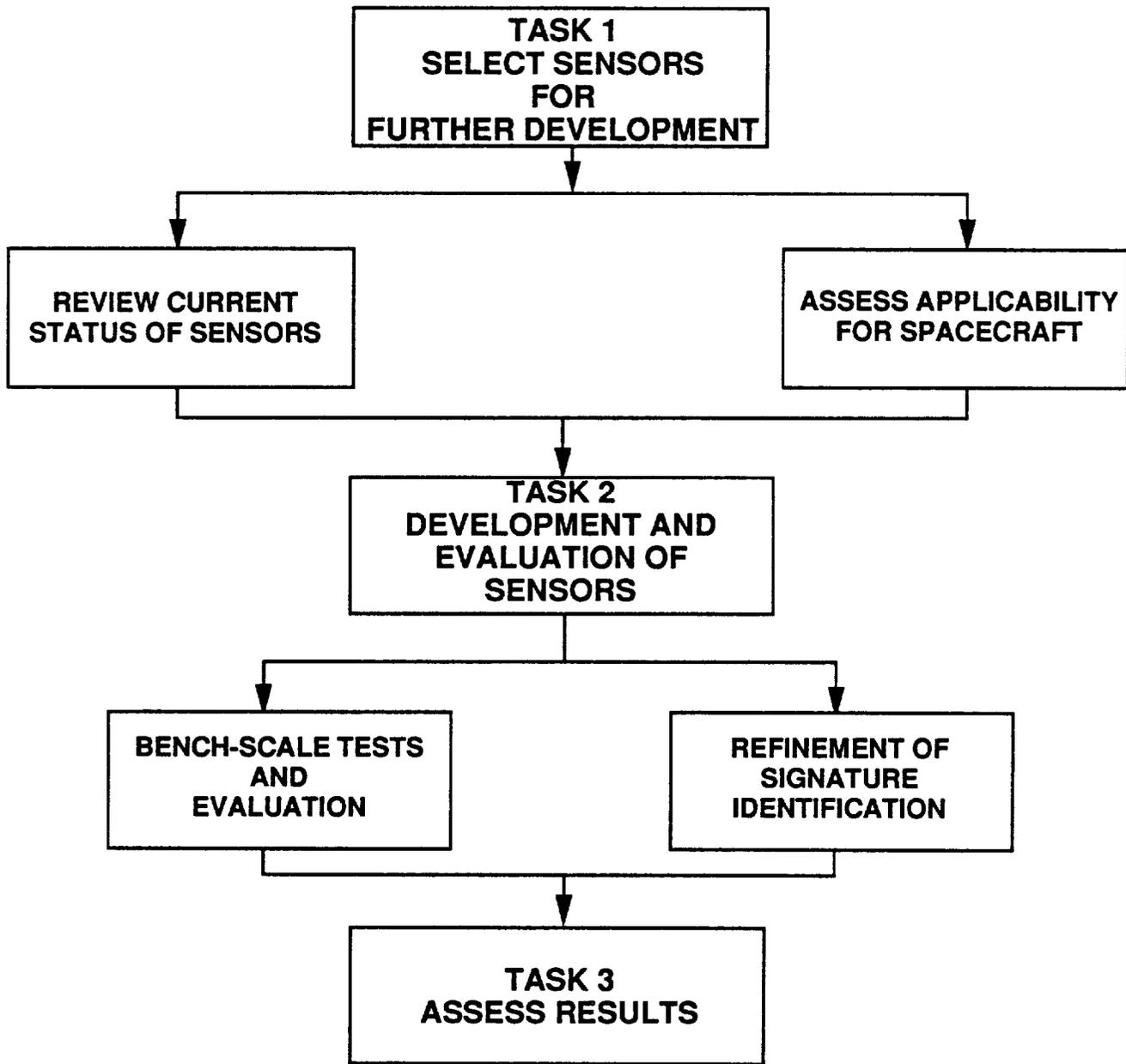


FIGURE 3-8. WORK BREAKDOWN STRUCTURE FOR DEVELOPMENT OF SMOKE DETECTORS USING MICROSENSOR TECHNOLOGY

Task 1.0: Select Appropriate Microsensor Gas Detectors For Further Development

This task shall consist of a critical review of the current status of microsensor gas detector development and an assessment of the applicability of such detectors to advanced manned spacecraft. The following subtasks shall be required to fulfill these objectives.

Subtask 1.1: Review Current Status Of Microsensor Gas Detector Development. This review should include, but not be limited to, those solid-state gas detectors that are either in the commercial development stage or are emerging as highly promising. Desired characteristics should be established that include the following: 1) specific gas(es) monitored, (2) sensor sensitivity, 3) physical and operational parameters, 4) reliability and maintainability, etc. Also, estimates should be made regarding the development time required for flight qualification. The candidate sensors may include the following types:

- 1) Electrochemical (Nerst) Cells
- 2) Barrier Type Devices
- 3) Metal Oxide Semiconductors
- 4) Microcalorimeters
- 5) Surface Acoustic Wave (SAW) Sensors.

Subtask 1.2: Assess Applicability Of Microsensor Fire Detectors For Use On Advanced, Manned Spacecraft. A systems engineering trade study will be necessary to identify the advantages and disadvantages of microsensor smoke gas detectors when compared to currently used, conventional smoke detectors. Also, their applicability as redundant or backup detectors and their ability to provide very early fire signatures must be considered. This review should also consider the achievement of desirable attributes for spacecraft design, including minimum size, mass, and power requirements, and maximum sensitivity and reliability.

Task 2.0: Support Development And Evaluation Of Selected Microsensor Gas Detectors

Subtask 2.1: Perform Bench Scale Tests And Evaluation Of Selected Microsensor Gas Detectors. This subtask is based on the assumption that candidate microsensor gas detectors have been developed to a state of commercial readiness, but are not

necessarily ready for inclusion in a spacecraft fire detection subsystem (FDS). In this subtask, appropriate test requirements and procedures must be devised in order to test and evaluate the candidate detectors based on spacecraft system requirements. Bench-scale tests are to be conducted for comparison of the performance of the microsensors to that of conventional sensors.

Subtask 2.2: Continue Refinement and Evaluation of Smoke Gases as Early Burning Process Fire Signatures. The purpose of this subtask is to perform a critical review of the reliability of smoke gases as signatures for early burning processes. It is essential that an understanding of the nature and quantity of smoke gases is achieved. In this regard, the project on smoke-gas identification described in Section 3.5 is a necessary precursor or complement to the efforts of this subtask.

Task 3.0: Assess Results of Development Program for Application of Microsensor Smoke Detectors to Advanced Spacecraft

The purpose of this task is to review the results of the foregoing development effort to assess the applicability of microsensor smoke detectors to advanced, manned spacecraft. Clearly, there is applicability of these sensors as habitable atmosphere gas monitors and as process monitors, but the requirements for smoke detection -- especially reliability and sensitivity -- need to be established at this point in the overall effort.

3.7 Research On Low-Gravity Fires

3.7.1 Background: Basic research in combustion science impacts almost every aspect of the spacecraft fire-safety problem: prevention, detection/suppression, and recovery. Despite the progress made in the past few decades, the combustion characteristics of fuels in reduced gravity are not completely understood. In the January 25-26, 1989, International Microgravity Combustion Workshop at the NASA-Lewis Research Center (report in preparation), recent advances and future needs in microgravity combustion were discussed by a number of researchers. It has been suggested by several authors that there are essentially two main reasons to pursue low-gravity combustion research: 1) better understanding of normal-gravity combustion processes by eliminating the buoyancy effects, and 2) spacecraft fire safety. However, on-going low-gravity research efforts in the USA, Europe, and Japan have largely focussed on the science aspects of the field rather than on the applied, fire-safety aspects. While it is clear that a fundamental understanding of the low-gravity combustion phenomena will enhance the spacecraft fire safety in the long run, short term benefits could be improved by focussing some of the research efforts toward immediate fire-safety problems, such as low-gravity burning rates, fire detection, and fire suppression.

Fire, in itself, is a very complex phenomenon involving interactions among fluid dynamics, chemical reactions, radiation, and aerosol physics. So, it is understandable that researchers have focussed on a single phenomenon, such as flame spread over a thin solid fuel, and developed theoretical models and simple experimental tests. Also, most of these low-gravity combustion experiments, except those performed aboard Skylab, are performed in ground-based drop towers, or in aircraft flying parabolic trajectories to produce the low-gravity field. These ground-based facilities limit the scope of the experiments in two ways: first, the time available for experiments is limited and, at present, only very thin solid fuels can be used as test materials; and second, sophisticated diagnostic tools cannot be utilized.

From the above introduction, it is clear that for the low-gravity research program to have maximum impact on spacecraft fire safety in the next five year period, it must

aim to:

1. Provide a long duration microgravity environment so that practical material configurations can be tested and the required diagnostic tools can be employed to extract pertinent information from these experiments.
2. Focus more on the fire-safety aspects of combustion science such as burning rates, pyrolysis products, ignition, spread, extinction, and flame radiation characteristics.
3. Obtain data for various fuel geometries including films and sheet materials, foams, bulk materials, as well as particulates (e.g., dusts).

3.7.2 Proposed Efforts: The proposed project is described on the basis of WBS tasks in the field of theoretical and experimental low-gravity combustion of non-metallic solid materials. It must be emphasized that this basic research effort is necessarily an iterative process between theoretical modeling and experimentation, and both of these aspects must progress simultaneously. The organization of the project WBS is illustrated in Figure 3-9.

Task 1.0 Review Solid-Fuel Combustion Literature

This task consists of reviewing all aspects of low-gravity, solid-fuel combustion literature with a view toward identifying the knowledge gap that exists in the fire-safety area. Limitations of currently available theoretical models and experimental data are gathered as a part of this task.

Task 2.0: Define Low-Gravity Tests

Subtask 2.1: Identify Fuel Materials/Configurations To Be Tested In Low Gravity. A material is usually selected as a test fuel based on its burning characteristics and test reproducibility. Drop tower tests (Reference 37) and KC135 flight experiments have produced limited data on flame spread and extinction for thermally thin solid fuels of the two-dimensional and cylindrical configurations. However, realistic applications involve more complex configurations, such as open cell foam, thermally thick surfaces, laminated fuels with thermal properties varying along a given direction, and 3-D effects. Other fuels to be tested will include particulates and even gaseous and liquid fuels. The NASA document NSTS 22648 on flammability configuration analysis

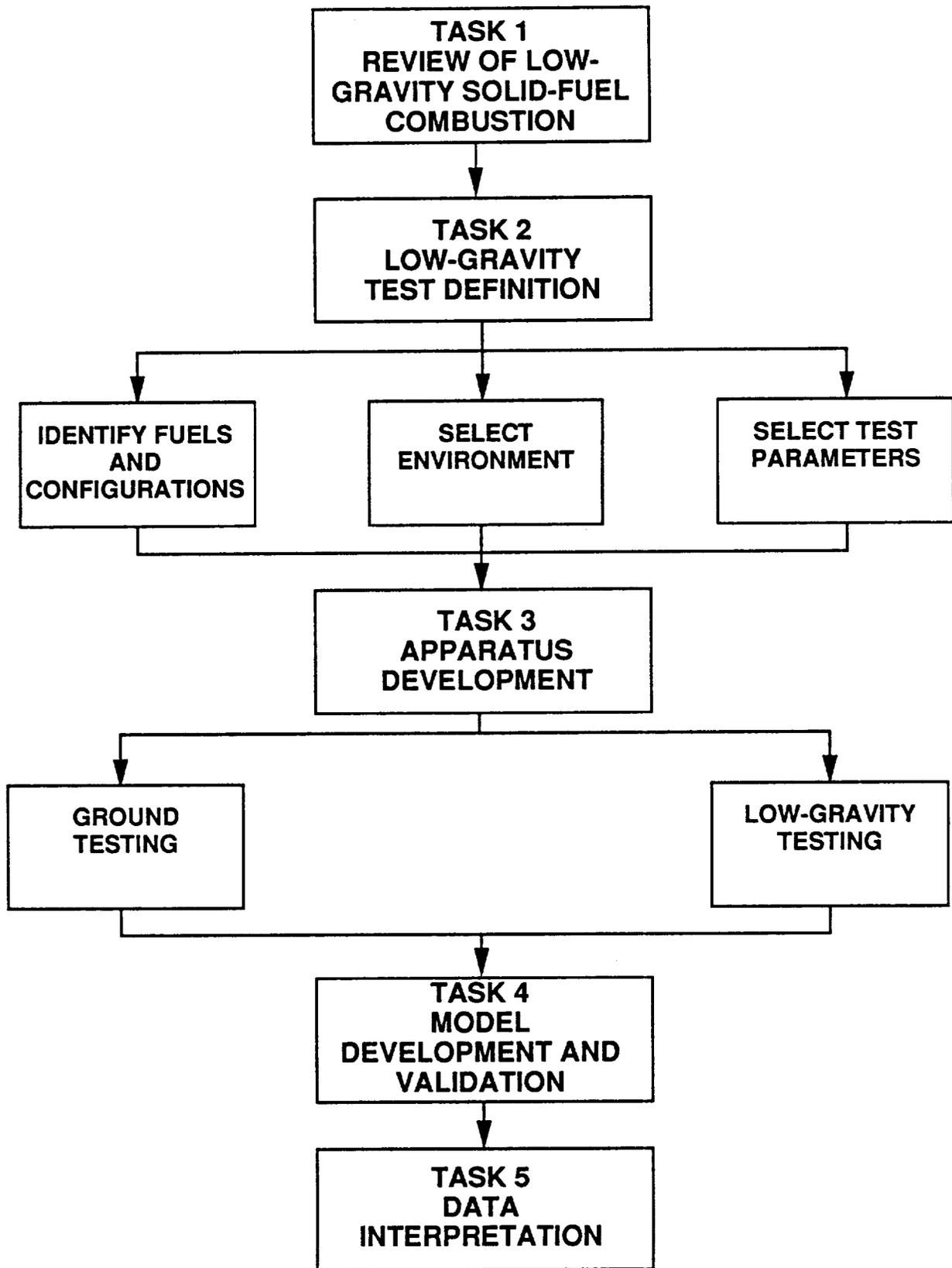


FIGURE 3-9. WORK BREAKDOWN STRUCTURE FOR RESEARCH ON LOW-GRAVITY FIRES

(Reference 38) provides examples of other configurations that are encountered in spacecraft hardware constructions. The intended outcome of this subtask is a set of fuel configurations that have direct bearing on practical applications and test effectivity. Some typical fuel configurations that should be tested in low gravity are shown in Figure 3-10.

Subtask 2.2: Select Environments. The experimental conditions to be determined are as follows:

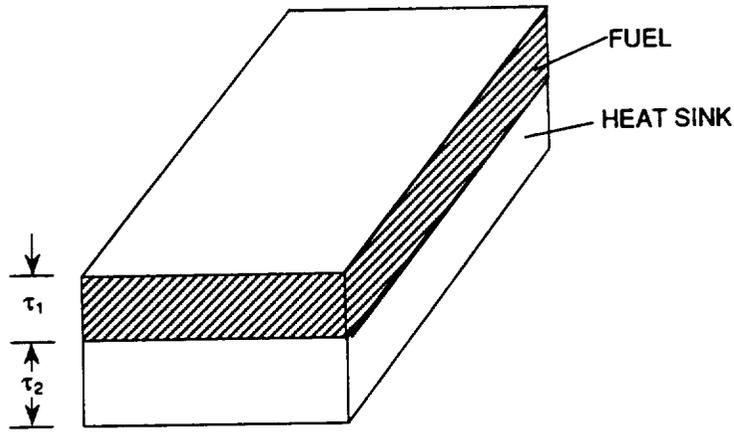
- o O₂/Diluent Concentrations
- o Pressure
- o Flow Velocity (0 to approximately 20 cm/s)
- o Radiation Heating
- o Others

The oxygen concentration and pressure levels are chosen for the experiment to reflect the operating environment of the spacecraft, and they are well established or known. The diluent concentration, however, needs to be selected with some care because recent results (Reference 39) have shown that the diluent properties can affect the flame characteristics. Similarly, flow velocity can have a strong influence on flammability limits and flame-spread rate (Reference 37) and experiments should vary from the quiescent condition to the typical ventilation-generated flow velocities. Radiation heating is used to preheat the fuel sample prior to ignition, as desired. Other boundary and initial conditions are also selected during this subtask, depending upon the experimental apparatus and modeling requirements.

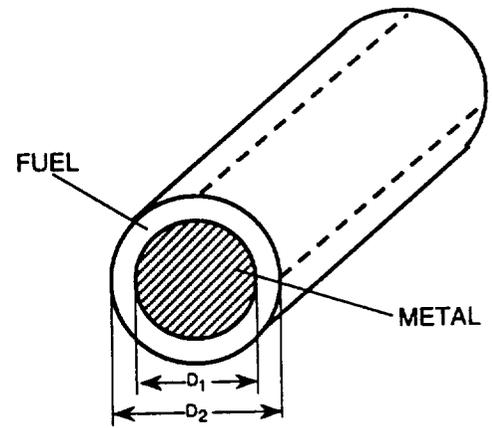
Subtask 2.3: Select Test Parameters. This subtask is to identify the quantities that are to be measured experimentally. The quantities include ignition energy, flame spread rate, extinction conditions, flame radiation characteristics, and mass burning rates. With the availability of long-duration microgravity facilities and sophisticated diagnostic tools, measurements of transient effects, velocity and temperature fields, and burnt-gas particulate characteristics must also be planned.

Task 3.0: Develop Low-Gravity Experimental Apparatus

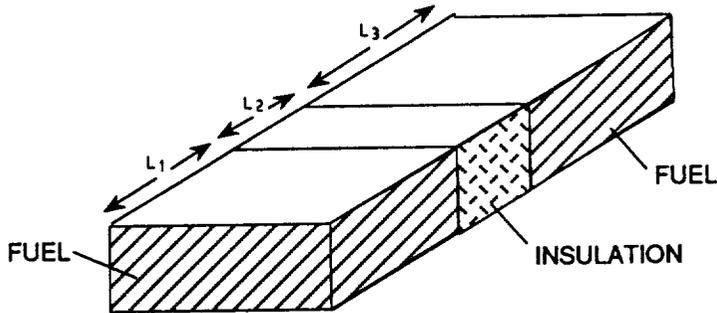
Development of an experimental apparatus for use in a space-based facility is an evolutionary process. However, the scope of the experimental effort envisioned in this



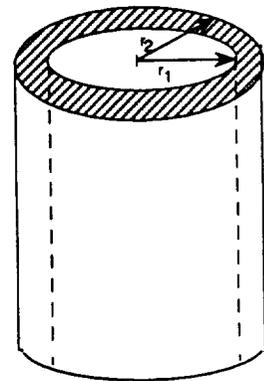
FUEL WITH HEAT SINK
OR LAMINATED FUEL



WIRE/CABLE INSULATION
(HEAT SINK EFFECT)



FUELS SEPARATED BY
FIRE BARRIER



HOLLOW CYLINDER
(RADIATION EFFECTS)

FIGURE 3-10. TYPICAL FUEL CONFIGURATIONS FOR STUDY IN
LONG DURATION MICROGRAVITY TESTS

project allows one to use some of the experimental hardware that is already under development by NASA, perhaps with some minor modifications. The hardware include apparatus in final design, under development, or in active use, such as: the solid surface combustion chamber, the multipurpose drop tower chambers, and the modular combustion facility (Reference 40). It is recommended that as far as possible, one of the existing, already tested, hardware be used for this proposed experimental project.

The diagnostic tools that would be anticipated for the proposed experimental project are:

1. Temperature Measurement - Thermocouples
2. Velocity Measurement - Particle Track, LDV
3. High Speed Movie Camera
4. Radiation Detectors
5. Specie and Particulate Measurement Units

Subtask 3.1: Perform Ground-Based Testing Of The Experimental Apparatus. All aspects of the experimental setup chosen during Task 3.0 is ground tested during this subtask. Any modifications to the experimental apparatus, data acquisition, or diagnostic tools are made when necessary. To some extent, the results obtained during this testing phase could be used to validate the subsequent theoretical models.

Subtask 3.2: Perform Low-Gravity Tests. The ground-tested apparatus is readied for flight aboard the Space Shuttle or Spacelab. This includes integration and other necessary modifications to the data acquisition and automation aspects of the experiment. Stringent safety measures are met during this task period. Finally, the experiments are conducted based on the planned test matrix.

Task 4.0: Develop The Theoretical Model

The objective of this analysis is to provide a theoretical basis to interpret the experimental data obtained in reduced gravity. Analytical and numerical models for ignition, flame spread, and extinction are to be developed. Models are to be validated through low-gravity test data available from the literature and ground-based tests, as applicable, from Task 3.0.

Task 5.0: Interpret And Compare Data To Model Predictions

During this task, the experimental results obtained from low-gravity tests are analyzed and interpreted based on the theoretical models developed in Task 4.0. Model limitations are identified and methods of improvement are outlined. These results are organized and presented in such a form so that they can be incorporated into fire modeling, material screening tests, and other low-gravity fire fighting efforts.

3.8 Other Fire Detection Projects

Several other concepts and suggestions directly related to fire-detection hardware and techniques for advanced spacecraft are worth noting even though they have not been incorporated into the high-priority projects.

Cross-zoning (Topic 5.2, Table 2-1) is a common technique in ground-based fire detection systems wherein the response of fire detectors in regions (zones) adjacent to the alarm detector(s) are interrogated for their level of response. If a fire event has initiated in a specific zone, the response of detectors in adjacent zones or in zones in the downstream path of the ventilation system may aid in determining the validity of an alarm and the severity of the fire event. The applicability of the cross-zoning technique to spacecraft fire-detection systems will depend upon the type, location, and number of fire-detector sensors and the expert system designed to monitor and respond to the detectors. For example, a decision on the degree of response (warning or danger) may be based on whether sensor indications are confined to a single powered-equipment rack or are found in adjacent racks in the common ventilating system.

Another major concern relative to fire-detection systems for advanced spacecraft is that relative to the optimal location of fire-detection sensors in the absence of gravity-induced convection (Topic 5.5). Fire-detection devices that depend upon the transport of combustion products (smoke gases and particulates) and for heat to the detector sensors are likely to not respond readily to a fire condition unless there is an appropriate amount of forced convection. Obviously, the fire-detector sensors must be located in the forced convection flow path and must be downstream of the fire condition. The ventilation modeling of spacecraft volumes and its influence on the transfer of heat, smoke, and combustion products for fire detection and control is an important concern, and it is the basis of a high-priority project described in Section 5.0.

Finally, it must be recognized that ionization and photoelectric fire detectors are the state-of-the-art for aircraft and spacecraft, and they will continue to be used (in STS Shuttle and Spacelab) for the foreseeable future. While no high-priority project addresses the development of these detectors, their improvement for the unique

application in space is clearly desirable. The major limitations of these devices are that they are more responsive to certain ranges of particulate and smoke aerosol sizes (requiring better knowledge of likely space fire and precursor signatures) and they are far from optimum in terms of minimum size and mass and maximum reliability.

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4.0 PROJECT DESCRIPTIONS: FIRE EXTINGUISHMENT AND ATMOSPHERE CLEANUP

4.1 Background

The perceived need and provision for fire-fighting equipment to be used on-board manned spacecraft has changed significantly as spacecraft have grown larger and as the spaceflight missions have increased in duration. The NASA Mercury and Gemini spacecraft were not provided with any dedicated fire extinguishers, except for the crew's hand-held food rehydration (water) guns. Currently, the STS Space Shuttle and Spacelab spacecraft are fitted with crew-activated portable and fixed fire extinguishers that contain pressurized bromotrifluoromethane (Halon 1301). Location of the Halon 1301 extinguishers in the STS Shuttle Orbiter cabin is shown in Figure 4-1. A brief history of NASA's use of fire extinguishants on all manned spacecraft is provided in Reference 41 and in Appendix C. The choice of specific extinguishing agents and the appropriate application techniques for advanced spacecraft is of continuing concern. A general discussion of the advantages and limitations of a number of candidate extinguishants was prepared by Dr. J. de Ris (Reference 42).

The commonly used fire extinguishing agent Halon 1301 is well-recognized as an effective and efficient fire fighting material, especially in the case of superficial fires in ground systems. However, some of the adverse features of the Halon 1301 extinguishants -- and many other bromo- and chlorofluorocarbons -- may prevent their extensive use on future spacecraft. For spacecraft usage, these adverse features are largely associated with their toxicity and their corrosiveness when decomposed in a fire: 1) The decomposition products as a result of interaction with a fire may be unacceptably toxic and corrosive (References 41 and 42); and 2) These extinguishants may not be compatible with various elements of a spacecraft's environmental control system. Certain halons and chlorofluorocarbons (CFCs) have recently been linked to possible future depletion of the Earth's stratospheric ozone layer (Reference 43).

The choice of a new fire extinguishant for use on an advanced spacecraft, such as SS Freedom, is constrained by the requirements for low toxicity (in both the neat and decomposed states), high effectiveness per pound, low corrosivity, compatibility with the spacecraft environmental control and life support system (ECLSS), etc. Also, special considerations and uncertainties are added when there is a need for the extinguishants to be used in a hyperbaric airlock (HAL) facility or in an oxygen-enriched atmosphere.

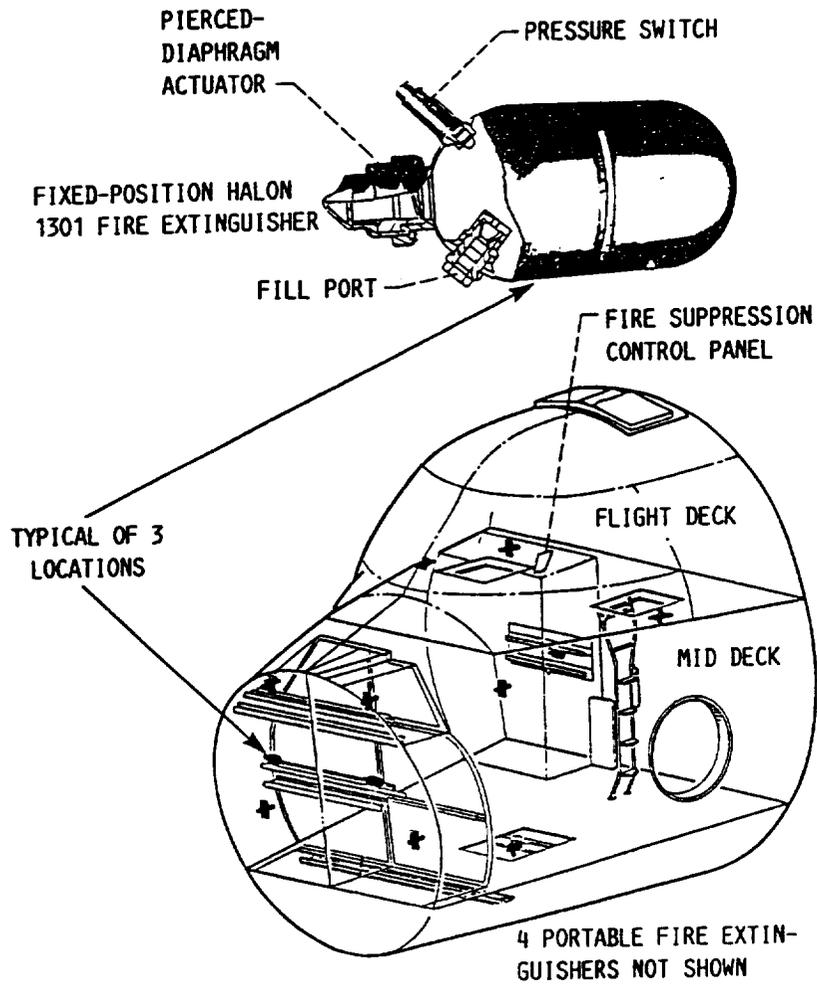


FIGURE 4-1. HALON 1301 FIRE EXTINGUISHERS IN THE U.S. SHUTTLE ORBITER CABIN

Special demands for "rapid" atmosphere cleanup are required if a fire event -- or a major spill -- occurs in the confines of an orbiting spacecraft. Obviously, the demands for crew involvement during the cleanup or the need to provide safe exit and refuge for the crew will depend upon the severity of the event. The capacity of most spacecraft atmosphere revitalization systems (ARS) is limited, and a significant fire event (or spill) would most likely require mission termination. This is not an acceptable scenario for an advanced, long-duration mission spacecraft.

4.2 Proposed Fire Extinguishment And Atmosphere Cleanup-Related Projects

All of the concerns expressed above regarding fire extinguishment and atmosphere cleanup on board manned spacecraft were identified repeatedly during the course of this effort. Specifically related topics are tabulated in Table 2-1 under the headings "Fire Extinguishants and Suppression Techniques" and "Post-Fire Cleanup." These suggested topics include tests and evaluations of extinguishants for use in hypo-and hyperbaric atmospheres, development of a replacement extinguishant for Halon 1301, development of a high capacity environmental cleanup (auxiliary) unit, and several others.

The final selection of highest-priority projects has provided three projects to be included in the thematic area of fire suppression, listed below in the order of descending priority and identified by the discipline number shown in Figure 2-2.

<u>Priority Discipline No.</u>	<u>Project Title</u>
AR-3	Evaluation of Fire Extinguishants And Techniques For Use In Hypobaric And Hyperbaric Atmospheres
TD-3	Development of High-Capacity Environmental Cleanup Auxiliary Unit
BR-1	Research On Candidate Extinguishants For Low-Gravity Fire Scenarios

Figure 4-2 illustrates a proposed schedule for the highest-priority fire-extinguishment projects. Included on the schedule is the project to develop expert systems already described in Section 3.3, since the expert system will encompass fire-suppression subsystems. The schedule also includes the lower-priority advanced project on post-fire corrosion and the technology development project on fire blankets.

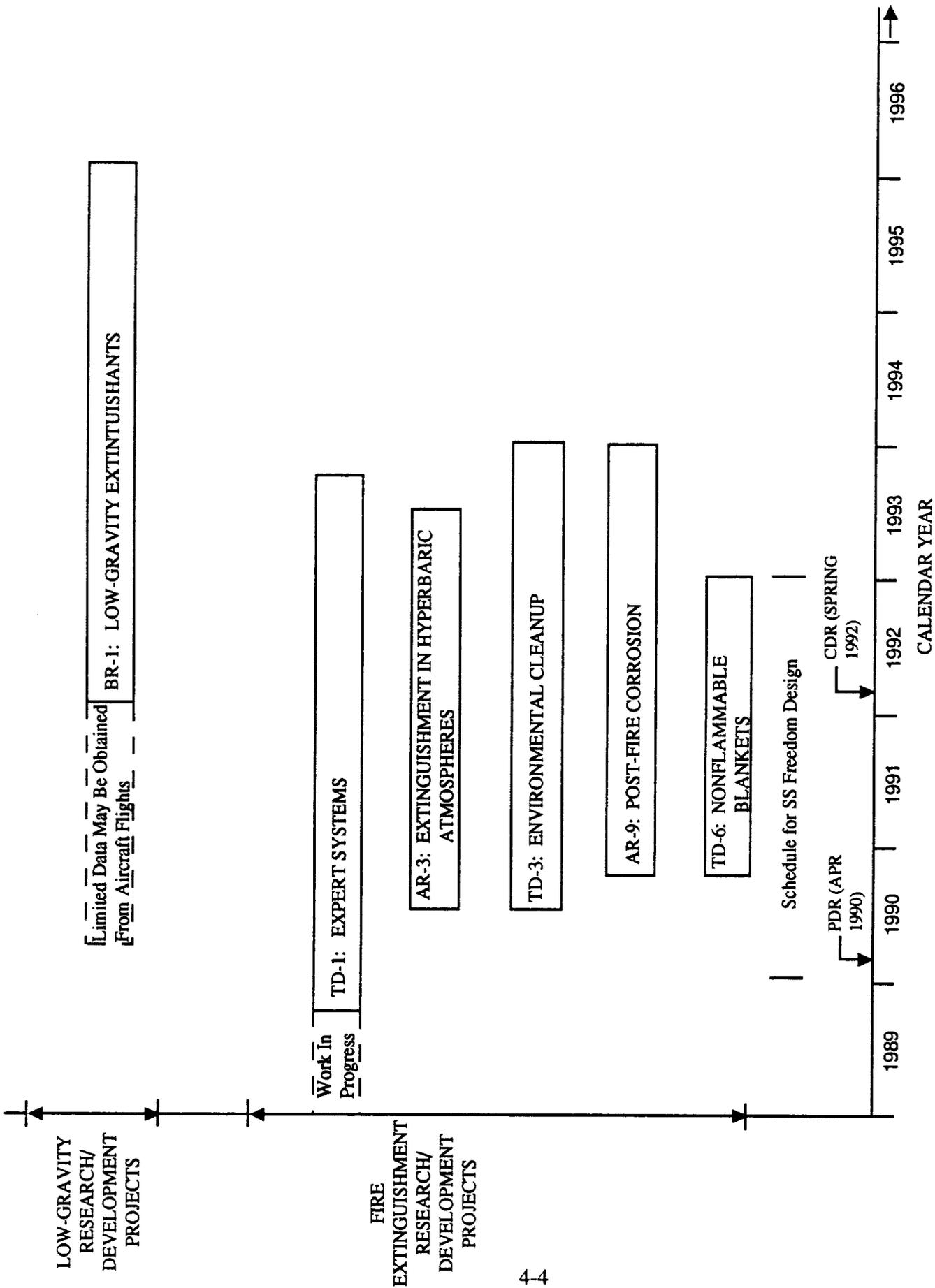


FIGURE 4-2. SCHEDULE FOR FIRE EXTINGUISHMENT AND ATMOSPHERE CLEANUP PROJECTS

4.3 Evaluation Of Candidate Fire Extinguishants And Application Techniques For Use In Spacecraft Hyperbaric And Hypobaric Atmospheres

4.3.1 Background: The use of specially designed, artificial atmospheres has been a major part of manned space flight since its inception. Initially, concern about potential cabin leaks in flight resulted in the requirement for the crew to wear full pressure suits for their protection. The total pressure within the suits had to be low enough to permit mobility of the suit joints and gloves. The requirement of a normal oxygen quantity, or partial pressure, in the atmosphere dictated a high concentration of oxygen (i.e., a hypobaric environment). For these reasons, early manned spacecraft were designed to use a pure oxygen atmosphere at 0.34 ATA (atmospheres absolute, or 34 kPa).

NASA's designs for early manned spacecraft -- Mercury, Gemini, and Apollo -- followed this low pressure, pure oxygen philosophy. For the Skylab spacecraft, the need to be pressure-suited at a low pressure applied only to crew transfers in the Apollo spacecraft (0.34 ATA and pure oxygen) and the occasional extra-vehicular activity (EVA). The balance of the crew time in Skylab was in a shirt-sleeve environment which consisted of 65 percent oxygen/35 percent nitrogen at 0.35 ATA (35 kPa).

Manned spacecraft have not been equipped with "hyperbaric" chambers to date. However, the need for these facilities for application to advanced, long-duration space missions such as Space Station Freedom (SS Freedom), lunar bases, missions to Mars, etc. is now recognized. Recommendations prepared by the SS Freedom Hyperbaric Medicine Ad Hoc Committee (NASA/Johnson Space Center (JSC), January 9-10, 1989, Dr. Joe Boyce, Chairman) support the need for a Hyperbaric Airlock (HAL) and the incorporation of a hyperbaric Health Maintenance Facility (HMF) within HAL. The Ad Hoc Committee endorsed the need for the HAL/HMF facility to alleviate risk due to decompression sickness during EVA and to respond to any illnesses requiring hyperbaric treatment on SS Freedom.

Due to this need for a HAL/HMF and due to the very long duration missions planned for SS Freedom, much thought has been given to the selection of the breathable atmosphere for both the STS Space Shuttle and SS Freedom. The current consensus relative to the shirt-sleeve environment outside of the HAL is that the breathable atmosphere should be as nearly like that at normal sea level as possible. The

spacecraft fire-safety community would prefer a much reduced percentage of oxygen in both the shirt-sleeve environment and in the HAL. The fire-safety materials community is concerned with the on-going difficulty of providing non-flammable (i.e., rapidly self-extinguishing) materials, especially those used in quantity: paper, clothing, electrical wire insulation, thermal insulation, etc., and the very high risk to life if an accidental fire were to start in the confines of crew spaces. The dichotomy between human breathing effectiveness, which is primarily determined by the partial pressure of oxygen, and the flammability characteristics of materials which are essentially a function of oxygen concentration is illustrated by Figure 4-3. Recent tests performed by the NASA Johnson Space Center's White Sands Test Facility at high pressures (References 44 and 45) on various commonly used materials such as paper, cotton cloth, etc., confirm this trend.

Even today in 1989, there still does not exist a full consensus as to what the nominal hyperbaric environment should be for SS Freedom. The Space Station Projects (SSP) Requirements Document (JSC 31000, Revision C) (Reference 47) specifies that the hyperbaric environment shall have an oxygen concentration no greater than 16 percent at 4 to 6 atmospheres (400 to 600 kPa). However, the SS Freedom Hyperbaric Medicine Ad Hoc Committee (see above) has recommended a hyperbaric environment of 2.8 ATA (280 kPa) with an oxygen concentration of no less than 20 percent and no more than 23 percent at all pressures.

Clearly, adoption of the above recommendations by the SS Freedom Hyperbaric Medicine Ad Hoc Committee (January 1989) may severely limit the type and quantity of non-metallic materials used in the HAL/HMF if the requirements of NHB 8060.1B (Reference 30) are adhered to rigorously. In any case, a significant amount of additional flammability testing is indicated.

Fire detection and extinguishment in artificial atmospheres, especially oxygen-enriched atmospheres, can be problematic. In ground-based hyperbaric and hypobaric facilities, the NFPA Technical Committee on Hyperbaric and Hypobaric (Health Care) Facilities (Reference 48) has established recommendations for the use of deluge type, wet pipe sprinkler systems in Class A hyperbaric chambers (i.e., those designed for human use, multiple occupancy). For the extinguishment of fires in hypobaric facilities, the NFPA recommends that only water or water-containing thickening or wetting agents are to be used.

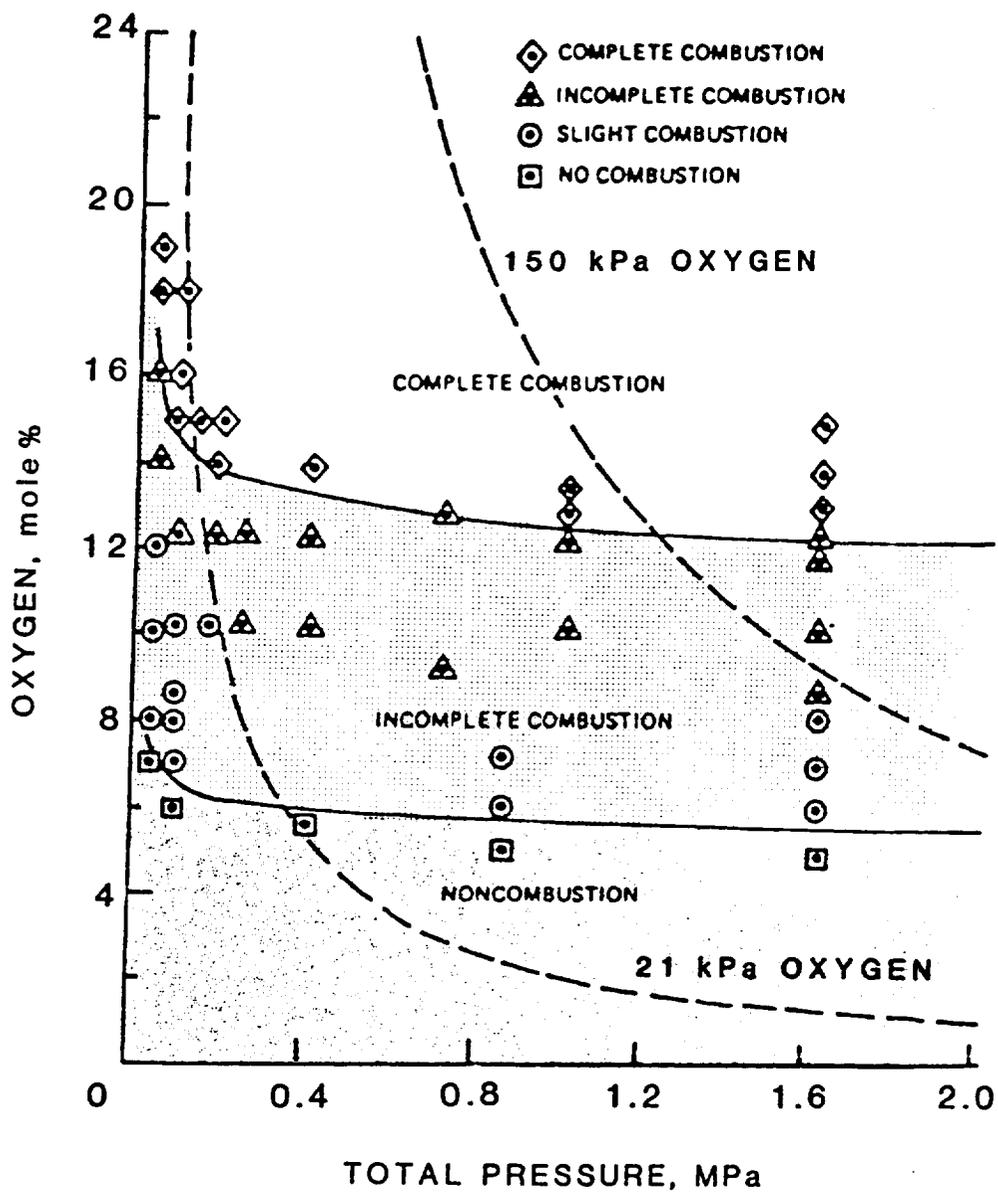


FIGURE 4-3. VARYING DEGREES OF COMBUSTION IN AN OXYGEN-NITROGEN ATMOSPHERE (REFERENCE 46)

NASA has performed a limited series of fire extinguishment tests in hyperbaric and hypobaric atmospheres. The tests often cited (Reference 49) were performed at the NASA Johnson Space Center and included highly oxygen-enriched hypobaric atmospheres and moderately oxygen-enriched hyperbaric atmospheres. Suppression of combustion by the direct application of gaseous extinguishants (e.g., Halon 1301) to open fires in open-cell polyurethane foam was relatively ineffective at oxygen concentrations above 30 percent and unsuccessful when the oxygen content was greater than 77 percent at total pressures of 0.34 and 1.0 ATA (34 and 101 kPa). The hypobaric test extinguishants included other gases (helium, nitrogen, argon, and carbon dioxide), solids (sodium bicarbonate and potassium bicarbonate), and liquids (foam, ethylene glycol solution and a water-based gel).

4.3.2 Proposed Efforts: Based on the background discussion provided above, it is apparent that there will be strong requirements for additional testing of hypobaric and hyperbaric environments for application to advanced space missions — beyond those efforts currently underway at the NASA Marshall Space Flight Center (MSFC) and NASA JSC's White Sands Test Facility (WSTF). The proposed project is described on the basis of work breakdown structure (WBS) tasks directed to the concerns regarding extinguishment in these atmospheres, but the effort must clearly be coordinated with materials screening, materials selection and design, fire detection and alarm annunciation, post-fire cleanup, and human factors. The organization of the project WBS is illustrated in Figure 4-4.

Task 1.0: Update Current Knowledge Base Relevant To Space Applications Of Hypo- And Hyperbaric Environments

Subtask 1.1: Establish Current Knowledge Base And Perceived Requirements For Hypobaric Environments And Extinguishants. The current knowledge regarding the use of, and fire hazards associated with, ground-based hypobaric facilities may be obtained largely from the open literature and published reports. Slightly to moderately oxygen-enriched hypobaric atmospheres are currently experienced in STS Space Shuttle pre-EVA conditioning, post-EVA desuited (in airlocks), and in the EVA spacesuit itself. The current recommendations relative to fire safety in hypobaric environments may be obtained from a number of sources, including the materials screening test data published in MSFC 527/JSC 09604 (Reference 50), the various studies and tests upon which the NFPA standards are based, limited NASA tests, and others.

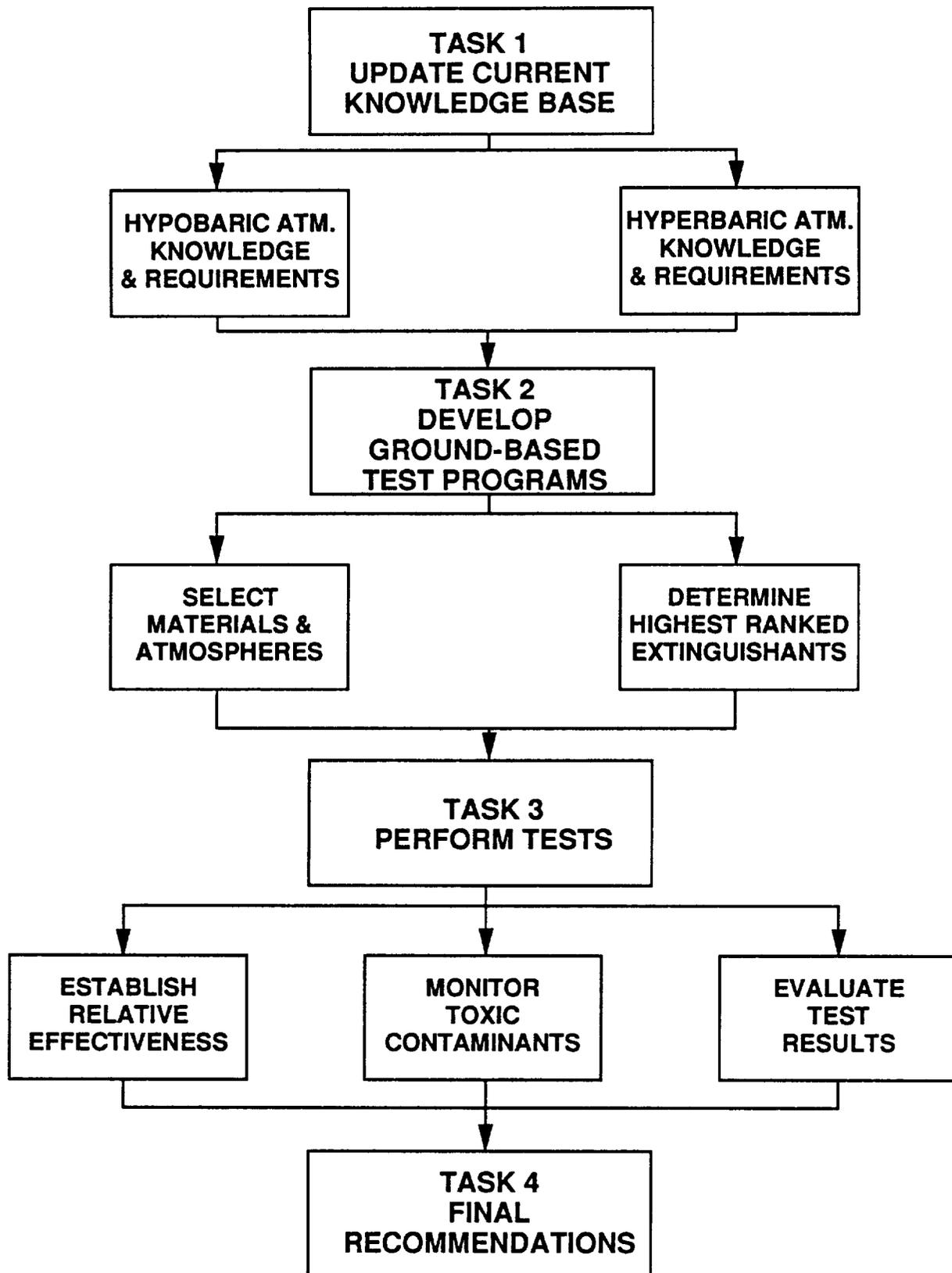


FIGURE 4-4. WORK BREAKDOWN STRUCTURE FOR EVALUATION OF FIRE EXTINGUISHANTS AND APPLICATION TECHNIQUES FOR USE IN SPACECRAFT HYPOBARIC & HYPERBARIC ATMOSPHERES

Oxygen-enriched spacesuits will continue to be used in the foreseeable future with the current 4.3 psia (30 kPa) limitation, and oxygen masks or hoods will be required for use in space-based Health Medical Facilities (HMF). An advanced 8 psia (55 kPa) hard suit under design will permit reduced oxygen concentration, however. Also, pre- and post-EVA procedures and protocols are likely to include oxygen-enriched environment scenarios. Other hypobaric requirements should be established.

Subtask 1.2 Establish Current Knowledge Base And Perceived Requirements For Hyperbaric Environments And Extinguishants. Although there is a significant amount of information from Navy, NFPA, and other literature relevant to fire safety in hyperbaric environments, this effort will concentrate on test data and studies at or slightly below the normal-atmosphere mole fraction of oxygen. It is likely that a substantial amount of flammability-screening tests and extinguishant evaluation and selection tests will be performed under these hyperbaric atmospheres.

Future uses of hyperbaric atmospheres in space will certainly include those associated with health medical facilities (e.g., for treatment of air embolism and decompression sickness (DCS) suffered by crew members). Also, as man learns to better adapt to artificial atmospheres, the use of hyperbaric environments consisting of very low percentages of oxygen (less than 10-12 percent) may appear promising to fire protection engineers but are unlikely to be well received by physiologists. Thus, another purpose of this subtask is to tabulate some of these requirements, especially those that would most likely impact materials use and fire safety.

Task 2.0: Develop A Ground-Based Test Program For The Evaluation Of Candidate Extinguishants For Use In Hypo- And Hyperbaric Environments

Subtask 2.1: Establish A List Of Candidate Materials (Fuels) And Worst-Case Hypo- And Hyperbaric Atmospheres That May Be Encountered. Test materials will include not only thick and thin aerospace construction materials but also waived flammable materials likely to be encountered, such as cotton cloth or paper. The test atmospheres will cover the expected range of oxygen concentrations and hypo- to hyperbaric total pressures.

Subtask 2.2: Select The Highest Ranked Candidate Extinguishants And Application Methods For Test And Evaluation.

The list of candidate extinguishants can be imaginative, to include water, water-based foams, gas-based foams, and conventional gaseous extinguishants. For space applications, it is also important to investigate application techniques, to include sprays, mists, deluge and flooding, and portable hand-held units.

Task 3.0: Perform Ground-Based, Fire Extinguishment Tests In Hypo- And Hyperbaric Environments

Subtask 3.1: Establish Relative Effectiveness Of Fire Extinguishment Systems.

Relative effectiveness is, in general, a measure of the mass of extinguishant necessary to suppress the tested fire scenario. Other factors to be weighed in the comparison may be cost, volume, containment and pressurization, etc.

Subtask 3.2: Monitor Tests For Production Of Toxic Contaminants.

Some extinguishants, particularly the halogenated agents, generate toxic and corrosive byproducts. Of some importance, also, is the disposal of nontoxic contaminants from the extinguishant; for example, excess water collection, foam disposal, or gas venting.

Subtask 3.3: Evaluate Test Results In Terms Of Perceived Crew Activities.

The proposed efforts tabulated under Tasks 2.0 and 3.0 are largely an extension and expansion of work currently underway at NASA (MSFC and JSC/WSTF). Among the new aspects of this effort is the need to clearly define acceptable (and unacceptable) extinguishants and to evaluate crew activities and procedures. For example, certain gaseous extinguishants may be acceptable for use in the lower oxygen concentration (e.g., less than 20 percent) hyperbaric environments, but not in the general hypobaric environments. Also, since hyperbaric chamber environments have not been used on manned spacecraft to date, the capability of the crew members involved to respond to and safely handle a fire event is a critical issue. One or more of the hyperbaric facility occupants on board an actual spacecraft may, in fact, be patients who are already incapacitated to some level prior to a fire event.

Task 4.0: Make Recommendations For The Selection Of Extinguishants And Application Techniques To Be Used In Hypo- And Hyperbaric Environments

These recommendations shall proceed from results emanating from the preceding tasks, Tasks 1.0 through 3.0. The recommendations shall cover not only the appropriate extinguishants and application techniques but also an assessment of missing data and verification tests to be performed in low gravity. Again, the close relationship of this project to the basic research project on low-gravity combustion, described in Section 3.7, is stressed.

4.4 Development Of A High-Capacity Environmental Cleanup Auxiliary Unit

4.4.1 Background: One of the highest safety-related priorities for any manned spacecraft is to provide the crew with a clean, comfortable, and relatively contaminant-free breathable atmosphere. The overall system used to perform this function is referred to as the ECLSS (Environmental Control and Life Support System). An overview of the Space Station Freedom's ECLSS is presented in Reference 31. The Atmosphere Revitalization Subsystem (ARS) of the ECLSS is charged with the function of maintaining the spacecraft's breathable atmosphere and removing contaminants so that they do not exceed the SMAC (Spacecraft Maximum Allowable Concentrations) values for the intended mission (Reference 30). However, the ECLSS units used in current NASA spacecraft such as the STS Space Shuttle and Spacelab are not designed to accommodate any significant fire events or major spills -- such as a microbial spill. Small quantities of typical combustion products (e.g., HF, HCl, CO, HCN, and COCl₂) would be removed by the STS Space Shuttle LiOH canisters, charcoal beds and/or catalytic oxidizers, but other toxic combustion products that may be present may be much more difficult to remove.

Among the highest ranked and most often repeated concerns by fire-safety experts contacted in the Wyle survey were those relevant to post-fire recovery of the breathable atmosphere and restoration of "normal" on-orbit operations. However, the Space Station Freedom may have very limited amounts of LiOH if current plans are continued to provide removal of atmospheric carbon dioxide (CO₂) by trapping on molecular sieves. Thus, sufficient LiOH may not be available to remove acidic combustion products unless some research is done to show that it is effective in removing them. The need for a portable, high-capacity device to clean up smoke and microbial spills was identified by Charles D. Ray of NASA/MSFC and Dr. Hiroaki Sasaki of The Fire Research Institute of Japan, who suggested that such a vacuum cleanup device might also include an internal extinguishant to quench any burning materials, including liquids.

It is Wyle's understanding that NASA does not currently have a fully developed auxiliary unit that could be used for rapid decontamination and cleanup of a spacecraft module's atmosphere after a fire event or a microbial spill. However, there are a number of organizations that have been involved in the design and development of systems and devices whose purpose it is to remove and/or neutralize toxic gases.

In 1984, the Hamilton Standard Division of United Technologies Corporation (UTC) developed and demonstrated a smoke removal unit (SRU) for shipboard use in closed compartments (Reference 51). This Hamilton Standard SRU was developed specifically to clear and maintain the atmosphere of a sealed compartment following various ship fire scenarios, by utilizing a series of filters and chemical beds to remove smoke particulates and toxic gases to a level that permits a safe and comfortable work environment (Figure 4-5). Visual observations indicated rapid clean-up of dense smoke within 10 minutes.

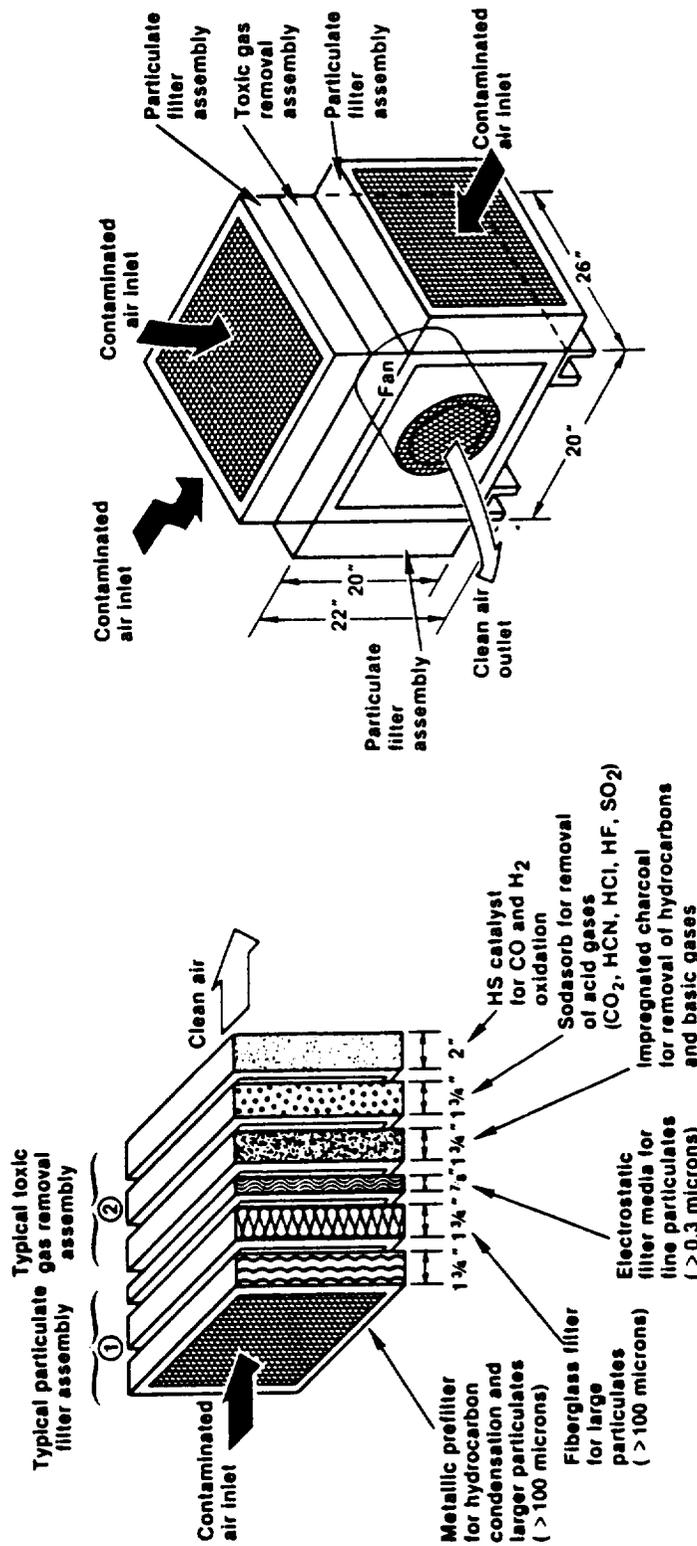
In a separate effort, the Plasma Group at the U.S. Army Chemical Research, Development and Engineering Center (CRDEC, Aberdeen Proving Ground, Maryland) is developing an invention referred to as the Reactive Bed Plasma (RBP) reactor (References 52 and 53). The RBP (Figure 4-6) is based on the technology of a plasma (or ionized gas) and catalytic packing materials. The main function of the catalytic packing material is to provide an increased amount of time for contaminant molecules in a flowing air stream to reside in the active plasma region. The high energy electrons generated by the plasma produce decomposed species of the toxic materials. The CRDEC is currently analyzing the scale-up of the RBP device and the addition of a ceramic High Efficiency Particulate Aerosol (HEPA) filter for potential application to Space Station Freedom.

Efforts similar to those described above are underway at other organizations and these efforts should be investigated for applicability to advanced spacecraft. For example, toxic substance decontamination efforts are underway at the National Institute for Standards and Technology's Center for Chemical Technology, Boulder, Colorado.

4.4.2 Proposed Efforts: The need for a high-capacity, auxiliary atmosphere cleanup unit for fire events in advanced manned spacecraft is generally acknowledged, assuming that sufficient excess capacity is not available in the spacecraft's environmental control and life support system (ECLSS). The proposed project is described on the basis of the following WBS tasks whose organization is illustrated in Figure 4-7.

Task 1.0: Review Current Status of Breathable Atmosphere Cleanup Units

Subtask 1.1: Review Status of NASA ECLSS Atmosphere Revitalization Units. STS Space Shuttle and Spacelab ECLSS units rely basically upon LiOH canisters and



Self-contained smoke/toxic gas clean up concept
 (1500 cfm unit provides total visibility in
 <10 min. for a 5000 ft³ smoke-filled space)

Typical sections-particulate and toxic gas removal

FIGURE 4-5. HAMILTON STANDARD SMOKE-TOXIC GAS REMOVAL UNIT

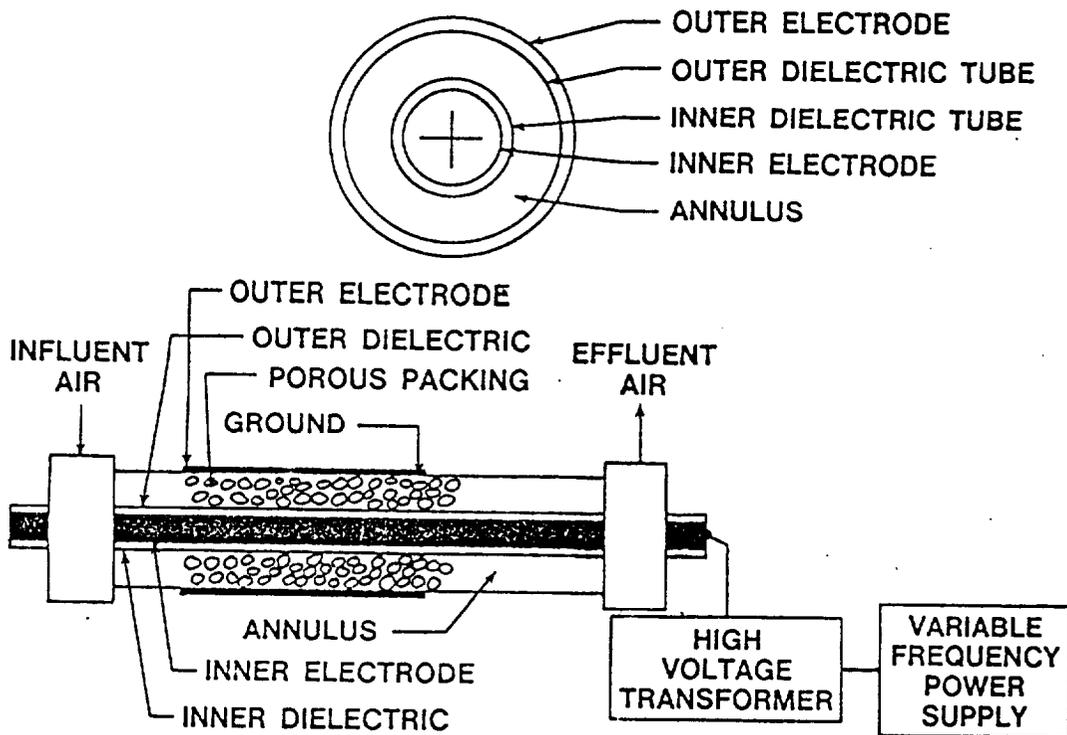


FIGURE 4-6. U.S. ARMY CRDEC REACTIVE PLASMA BED FOR DECONTAMINATION OF TOXIC GASES

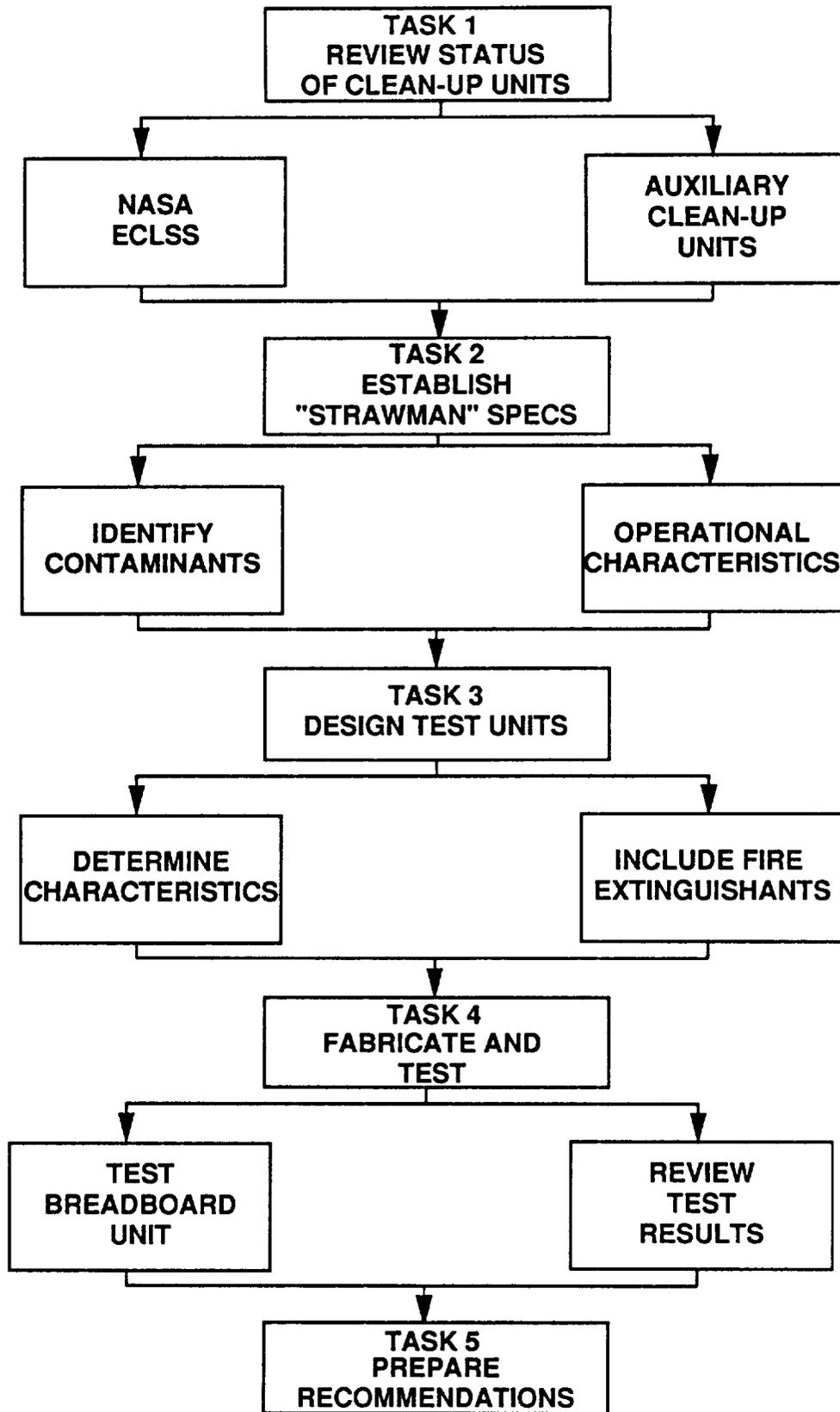


FIGURE 4-7. WORK BREAKDOWN STRUCTURE FOR DEVELOPMENT OF HIGH CAPACITY ENVIRONMENTAL CLEAN-UP AUXILIARY UNIT

charcoal absorbent beds to cleanse the spacecraft atmosphere. The capacity of these systems generally do not permit accommodation of any significant fire event or hazardous spill. Design efforts for the Space Station Freedom ECLSS acknowledge the need for a more sophisticated, higher capacity system. However, there are a number of combustion-produced (smoke) gases and other toxic (and irritant) gases that may poison and/or exceed the capacity of nominal ECLSS units. A short list of some of the contaminants anticipated on Space Station Freedom is presented in Table 4-1. It is the purpose of this subtask to identify those contaminant gases that would quickly exceed the capacity of the current ECLSS units in the event of a fire or hazardous spill.

Subtask 1.2: Identify And Review Capabilities Of Candidate Auxiliary Cleanup Units.

The purpose of this subtask is to review and tabulate the capabilities and advantages/disadvantages of candidate auxiliary units for breathable atmosphere cleanup. Candidate cleanup units may include those described above in the background discussion (e.g., Hamilton Standard's SRU and the RPB under development by the U.S. Army CRDEC) and others. In addition to their ability to provide acceptable decontamination of challenge gases, their operational characteristics are to be tabulated (i.e., operating temperature, power, EMI shielding requirements, size, ease of regeneration, post-treatment requirements, etc.).

Task 2.0: Establish Strawman Specifications For Spacecraft Applicable Auxiliary Units

Subtask 2.1: Prepare Priority List Of Combustion Produced (Smoke) Gases And Other Contaminants To Be Accommodated. Since the purpose of the auxiliary cleanup unit is to clean up the spacecraft breathable atmosphere rapidly and safely after a fire event or hazardous spill, it may be stated that the unit should be able to accommodate acid and other gases from fire events, extinguishments, and spills, as well as significant quantities of particulate material and aerosols. This task shall be devoted to the quantification of the contaminants to be accommodated and to the establishment of the allowable time — for a given event — until the SMAC values (Reference 30) are approached and/or until the spacecraft ECLSS can accommodate the load.

**TABLE 4-1. TYPICAL CONTAMINANT SOURCES ANTICIPATED
FOR SPACE STATION FREEDOM
(Reference 31)**

SOURCE	CONTAMINANT
<ul style="list-style-type: none"> • MAN 	<ul style="list-style-type: none"> - METABOLIC PRODUCTS: CO₂, NH₃, CO, H₂S, H₂, CH₄, ORGANIC ACIDS, MERCAPTANS - BACTERIOLOGICAL CONTAMINANTS
<ul style="list-style-type: none"> • SPACECRAFT SUBSYSTEMS, NON-ISOLATED EXPERIMENT EQUIPMENT AND PAYLOADS 	<ul style="list-style-type: none"> - WIDE VARIETY OF ALCOHOLS, ALDEHYDES, AROMATICS, ESTERS, ETHERS, CHLOROCARBONS, FLUOROCARBONS, HALOCARBONS, HYDROCARBONS, KETONES, ACIDS, etc.
<ul style="list-style-type: none"> • EMERGENCY SITUATIONS: FIRE, SPILLS, EQUIPMENT FAILURES 	<ul style="list-style-type: none"> - CO, CO₂, HYDROCARBONS, AROMATICS, ACID GASES, OXIDES OF N₂, SO₂, NH₃, SMOKE, ALCOHOLS, FORMALDEHYDE, etc.
<ul style="list-style-type: none"> • NON-ISOLATED ANIMAL AND PLANT EXPERIMENTS 	<ul style="list-style-type: none"> - METABOLIC, BACTERIOLOGICAL
<ul style="list-style-type: none"> • FOOD PREPARATION (NOTE 1) 	<ul style="list-style-type: none"> - AEROSOLS, DRY SOLIDS, ACROLEIN, etc.
<ul style="list-style-type: none"> • GARBAGE (NOTE 1) 	<ul style="list-style-type: none"> - H₂, CH₄, BACTERIOLOGICAL CONTAMINANTS (CADAVERINE AND PUTRESCINE)

NOTE 1: These contaminant sources were added by J.H. Kimzey, Consultant.

Subtask 2.2: Outline Desired Range Of Operational Characteristics. The purpose of this task is to establish a practical range (or ranges) of auxiliary unit characteristics for spacecraft application. These characteristics include the removal or filtration limits of contaminants (time and maximum discharge), and, in addition, specify limits on power usage, size and weight, high-voltage and EMI shielding, etc.

Task 3.0: Design Breadboard Test And Demonstration Unit(s)

The overall purpose of this task is to prepare a design (or designs) of an engineering breadboard unit based upon the reviews and assessments performed during Task 1.0 and, where possible, to meet the strawman specifications outlined in Task 2.0. Where the advantages or disadvantages of competing technologies are unclear, the design of more than one breadboard unit may be warranted.

Subtask 3.1: Select Configuration(s) For Design. It is the purpose of this subtask to perform trade studies and component assessments in sufficient detail to permit choosing a limited subset of designs that will approach the strawman specifications of Task 2.0. A variety of alternative configurations may be established from existing units, modifications, and innovative concepts.

Subtask 3.2: Investigate Inclusion Of An Internal Fire Extinguisher In Auxiliary Cleanup Unit. The incorporation of a fire extinguishing device internal to an auxiliary cleanup unit may have merit if burning materials (solids or liquids) are vacuumed into the unit for rapid fire response. The investigation must also include the means of storage, quantity required, delivery, and application technology of selected extinguishing agents.

Task 4.0: Construct And Test Breadboard Demonstration Unit

Subtask 4.1: Challenge Breadboard Unit With Simulated And/Or Actual Fire Scenarios. The purpose of this subtask is to evaluate the operational capability of the breadboard auxiliary atmosphere cleanup unit(s). Since the main purpose of the high capacity auxiliary unit is to provide rapid cleanup of the spacecraft module atmosphere after a fire event, the breadboard unit may be initially challenged by a series of real or simulated fire scenarios. This series of tests could be formulated similar to those performed by Hamilton Standard during the evaluation of their Smoke

Removal Unit (SRU) (Reference 51). The SRU was challenged with particulates, aerosols, and toxic gases simulating combustion products from Class A and Class B fires. Since the auxiliary cleanup unit may also be required to accommodate toxicants and irritants other than those resulting from "typical" spacecraft fire scenarios, the breadboard units may be challenged with these gases as well.

Subtask 4.1: Review Test Results And Recommend Appropriate Modifications/Upgrades To The Breadboard Unit.

The purpose of this subtask is to perform critical evaluations of the ability of the unit(s) to meet, or approach, the strawman specifications developed in Task 2.0. Also, it will be important to assess the capacity of the unit(s) in terms of the amounts of contaminants that can be accommodated prior to regeneration and/or reconstitution. It is quite likely that preliminary reviews will require additional challenge testing in order to assess the value of recommended modifications or upgrades.

Task 5.0 Prepare Recommendations For The Development Of A Prototype Auxiliary Cleanup Unit

After a sufficient and appropriate amount of challenge tests and modifications are made to the breadboard auxiliary cleanup unit, a prototype unit (or units) should be designed and developed. The development schedule for the prototype units may be appropriately shortened if prior test efforts are judged successful.

4.5 Research On Candidate Extinguishants For Use In Low-Gravity Atmospheres

4.5.1 Background: The effective and efficient suppression of unwanted fires in spacecraft is clearly a high-priority issue and has been stressed in the preceding sections. The requirements for acceptable fire extinguishants to be used in manned spacecraft can be more demanding than in ground-based facilities. Since a manned spacecraft is a closed environmental system, a fire extinguishing agent should possess the following attributes: 1) low toxicity in both the neat and decomposed states, 2) high effectiveness in fire suppression on a unit-mass basis, 3) low corrosivity of the post-fire products, 4) compatibility with the spacecraft's ECLSS, and 5) no major problems in post-fire cleanup.

Some of the desired attributes of candidate extinguishants listed above can be evaluated in ground-based testing and many of these evaluations and recommendations have been published (References 42, 49, 54 and 55). An attribute that cannot be fully evaluated in ground-based facilities is the effect that the low-gravity environment may have on an extinguishant's efficiency. These issues of concern in fire/extinguishant interaction in microgravity have been discussed by W. Youngblood and K. Seiser (Reference 56). One of the respondees to the Wyle survey, Dr. James Reuther, has addressed some of the anticipated problems with regard to spacecraft fire suppressions (Reference 57). Dr. Reuther included the following concerns: 1) combustion in low gravity can actually be intensified by the convection induced via delivery of a suppressant, and 2) fire suppressants whose effectiveness depend on chemical activity may not be as effective in the presence of the cooler burning, low-gravity flames.

4.5.2 Proposed Efforts: The proposed project is described on the basis of WBS tasks directed at performing extinguishant/fire interaction experiments in low gravity. The organization of the project WBS is illustrated in Figure 4-8.

Task 1.0: Establish A Recommended Group Of Extinguishants For Testing

Subtask 1.1: Review Available Data For Effectiveness Of Candidate Extinguishants.

The purpose of this subtask is to collect and review the available literature and test data on extinguishants. This will assist in establishing which extinguishants should be evaluated further.

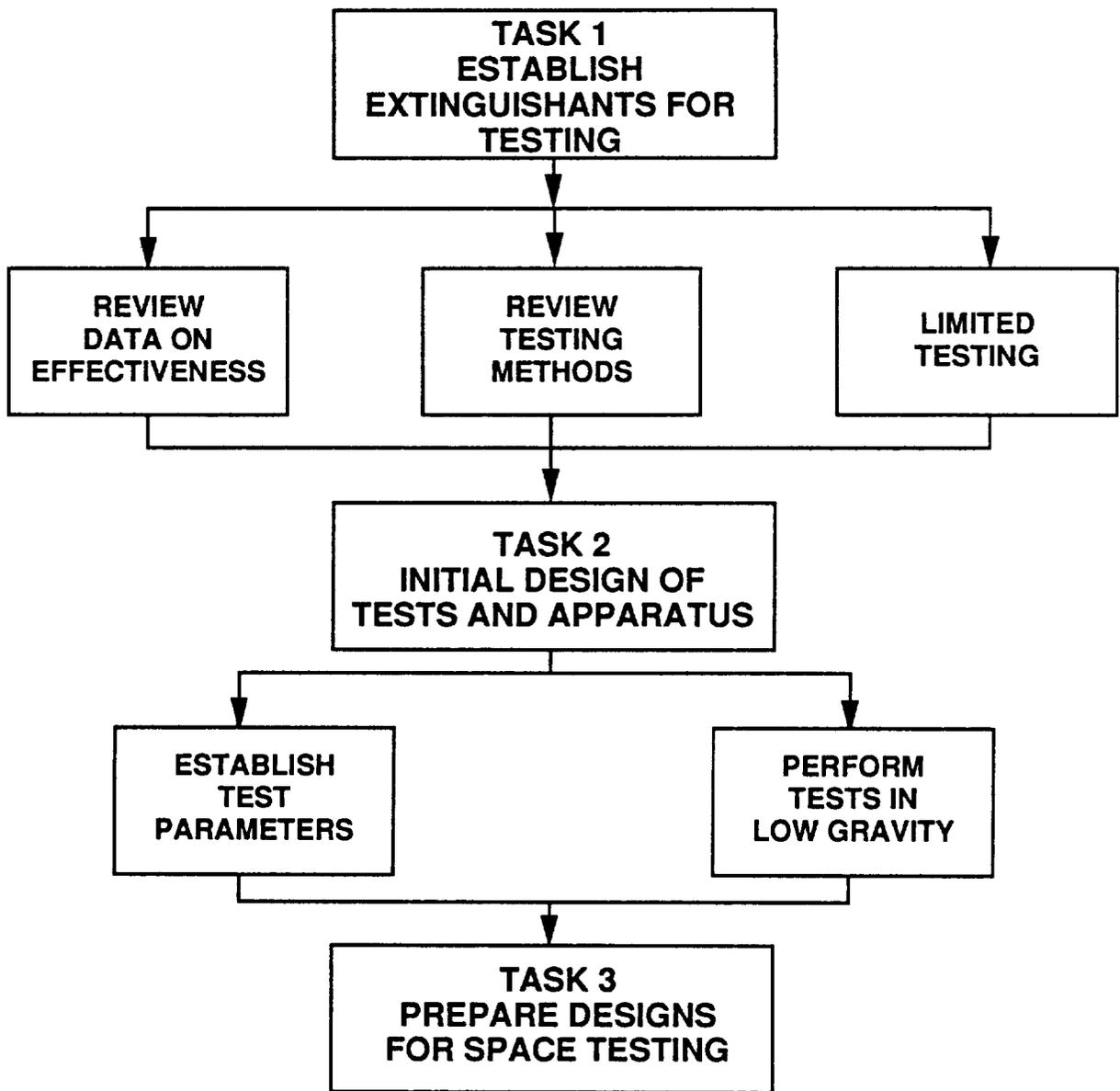


FIGURE 4-8. WORK BREAKDOWN STRUCTURE FOR RESEARCH ON CANDIDATE EXTINGUISHANTS FOR USE IN LOW GRAVITY ATMOSPHERES

Subtask 1.2: Review The Appropriate Methods And Procedures For Testing And Evaluating Extinguishants. This subtask shall consist of a trade study for the review of industry standards and accepted procedures for methods of evaluating fire extinguishant materials and means of application. For example, is a specific extinguishant inappropriate for smoldering combustion, yet fully adequate for NFPA Class A and Class B fires? Does it appear that normal-gravity testing is sufficient -- no low-gravity testing is required?

Subtask 1.3: Perform Limited Ground-Based Testing On Candidate Extinguishants. If necessary, ground-based tests will aid in creating a data base of extinguishant/fire interaction results for later comparisons with low-gravity tests. The type and quantity of test data desired should be determined from the reviews performed in Subtasks 1.1 and 1.2. The data should include the following as a minimum:

- 1) Concentration of extinguishant necessary to suppress combustion.
- 2) Effect of material type on extinguishant effectiveness.
- 3) Toxicity and other characteristics of extinguishant.
- 4) Soot, toxic and corrosive products of extinguishment process.
- 5) Compatibility with design features of spacecraft ECLSS.

Task 2.0: Initiate Design Of Low-Gravity Tests And Test Apparatus For Extinguishant Evaluation

Subtask 2.1: Establish Desired Test Parameters. Some general comments provided by J.H. Kimzey, a Wyle consultant, that apply to extinguishant tests in any spacecraft environment are appropriate here, as well as to the hyperbaric testing described in Section 4.3.

1. Careful consideration should be given to the selection of materials to be used as candidate test fuels. Include samples of the following materials:
 - o Highly flammable (e.g., paper, cotton cloth)
 - o Low melting point (e.g., sheet nylon, nylon cordage)
 - o Thin materials (e.g., mylar films, various coatings)
 - o Other materials (e.g., thick solids, foamed materials, liquids, metals(?)).

2. Select materials that tend toward self-extinguishment in normal gravity and evaluate these materials in low gravity.
3. Select a test chamber whose size will provide realistic results for the material and material configuration selected.
4. Consider tests using different material spacings to investigate low-gravity ignition from material to material.
5. Investigate realistic disturbances to the atmosphere in low gravity caused by the spacecraft ventilation system, crew movement, and flow induced by application of the extinguishing agent.

Subtask 2.2: Perform Limited Tests in Sub-Orbital Low-Gravity Facilities. These fire/extinguishant interaction tests are intended to be precursor tests to any such tests on STS Shuttle or Spacelab. Although the short duration of the drop tower tests are unlikely to produce the desired data for full extinguishant evaluation, some information may be gained relevant to the suppression of ignition by inerting. The longer duration aircraft flights (following Keplerian parabolic trajectories) and the much longer sounding rocket flights promise much useful fire/extinguishant data. It must be noted that, for such tests to be of value, the test chamber must be scaled appropriately for the test combustion process.

Task 3.0: Prepare Designs For Fire Extinguishment Apparatus To Be Evaluated On Spacelab And/Or Space Station

This task would require the development of flight qualified hardware to be flown on manned spacecraft missions. This task should only be contemplated if the issues and concerns regarding low-gravity fire/extinguishant interaction and extinguishant effectiveness remains unresolved.

4.6 Other Fire Extinguishment Projects

Several other concepts and projects directly related to fire extinguishment are worth noting even though they have not been incorporated into the highest-priority projects.

Figure 4-2 includes schedules for two lower-priority projects: post-fire corrosion and non-flammable blankets for smothering crew-accessible fires. A brief review of post-fire corrosion effects in ground-based fire scenarios is described by W.W. Youngblood (Reference 58), and long-range research has been initiated at the Factory Mutual Research Corporation relevant to post-fire corrosion and mitigation methods.

The development of "nonflammable" blankets to be used by the spacecraft crew to smother accessible fires was also suggested by Factory Mutual Research Corporation. Blankets of this type are commercially available.

Topic 4.2 (Table 2-1) calls for the development of an appropriate replacement for the commonly used Halon fire extinguishants. This topic was not developed into a priority project since this corresponds to studies already underway at several private-sector organizations with oversight from the Environmental Protection Agency (EPA) and the U.S. Department of Defense (Reference 43). Obviously, candidate replacement agents are major concerns of the three priority projects already described in this section.

5.0 PROJECT DESCRIPTIONS: RISK AND HAZARD ASSESSMENT

5.1 Background

A thorough understanding of the risks and hazards associated with any spacecraft must be of the highest priority. The advent of advanced, manned spacecraft such as Space Station Freedom poses new risks and hazards that must be identified and accommodated in the most efficient and safest manner. The responses to the survey conducted by Wyle as a part of this study suggest that the risk and hazard assessment of threats from fires and explosion-induced fires requires additional and detailed attention. It should be noted that the recommended projects described herein for fire risk and hazard identification and assessment are intended to supplement and expand existing NASA guidelines and requirements. For example, the "Threat Strategy Technique" prepared for Space Station Freedom by Rockwell International (References 59 and 60) and the nuclear power industry's Probabilistic Risk or Safety Assessment (PRA or PSA) methodology (Reference 61) represent organized means for addressing a variety of threats to a spacecraft, including those threats involving fires.

5.2 Proposed Risk And Hazard Assessment Projects

The final selection of highest-priority projects has provided three projects to be included in the thematic area of risk and hazard analysis, listed below in the order of descending priority and identified by the discipline number shown in Figure 2-2.

<u>Priority Discipline No.</u>	<u>Project Title</u>
AR-1	Evaluation of New Fire-Analysis Tools for Advanced Manned Spacecraft
BR-2	Research on Numerical Modeling of Spacecraft Fire Scenarios
AR-4	Evaluation of Ventilation Flow Models for Spacecraft

Figure 5-1 illustrates a proposed schedule for the highest-priority risk and hazard assessment projects. The schedule also includes the lower-priority basic research projects on engineering models for evaluation of end-use material flammability. Note that for the two numerical modeling projects (BR-2 and AR-4), a single schedule is shown. These are more or less parallel projects; and, in fact, only one detailed project description is given in this section.

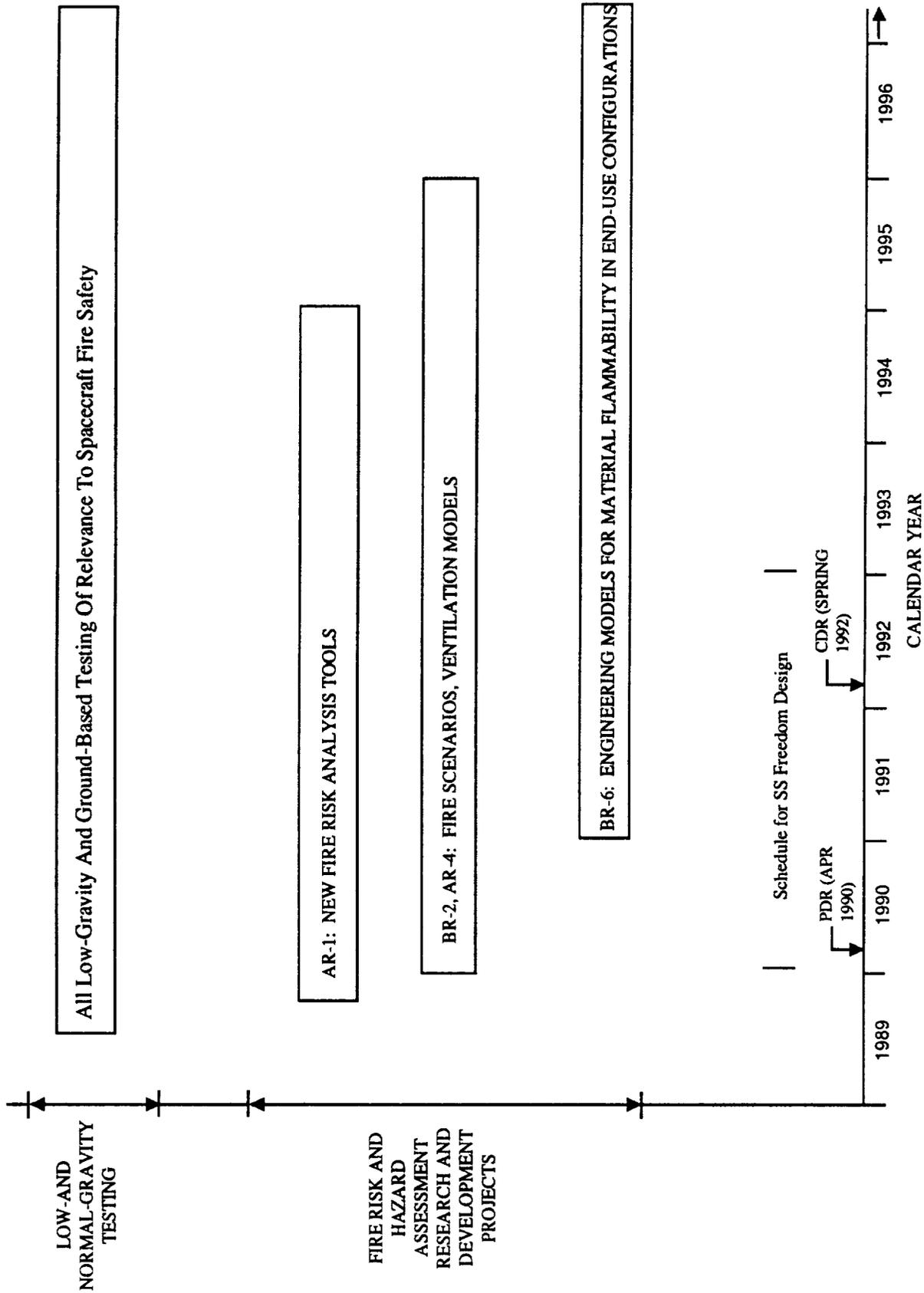


FIGURE 5-1. SCHEDULE FOR FIRE RISK AND HAZARD ASSESSMENT PROJECTS

5.3 Development Of New Fire Risk Analysis Tools For Advanced, Manned Spacecraft

5.3.1 Background: A detailed, methodical system safety analysis tool has been identified as a prime requirement for use at all stages of spacecraft design to preclude, control and otherwise mitigate threats, including those threats due to fires and explosions on-board spacecraft. Such a system safety analysis tool (or tools) suitable for application to Space Station Freedom and other advanced spacecraft will most likely require development from the best features of existing fire risk analysis tools and methodologies. This review and assessment must start at concept design and continue throughout the life of the spacecraft. It is because of this need to recognize the importance of spacecraft fire and fire-related threats and the associated risk analyses that this project has been assigned a high priority.

A list of the typical risk assessment tools and techniques that represented the state-of-the-art in the 1970's was prepared and assessed by Peercy and Raasch (Reference 59). These risk assessment tools included the following: 1) Fault tree analysis, 2) Checklists, 3) Sneak circuit analysis, 4) Failure mode and effects analysis (FMEA or FMECA), 5) Vehicle hazard analysis, and 6) Mission phase hazard analysis. Although each of these analysis tools have specific strengths, Peercy and Raasch stated that they are normally applied to spacecraft after requirements definition, i.e., not nearly early enough in the design cycle. Thus, they identified the need for new threat assessment and threat mitigation techniques as a requirement for all design stages of a spacecraft.

A system safety analysis tool referred to as the "Threat Strategy Technique" was prepared for the NASA Space Station by Rockwell International (Reference 60) well before the Phase B Work Package 1 design efforts. In an early presentation of this overall effort, Witcofski (Reference 62) outlined the study's subobjectives:

- 1) Develop a crew-safety philosophy and criteria,
- 2) Assess potential threats to crew safety, potential Space Station design and operational concepts, and the range of potential in-space activity scenarios, and
- 3) Assess the potential for various crew-safety strategies to meet desired criteria.

As part of the Rockwell International Threat Strategy Technique development effort, a "baseline" safety philosophy for the Space Station was prepared by Peercy and Raasch (Reference 60) and is illustrated in Table 5-1.

TABLE 5-1. SPACE STATION SAFETY PHILOSOPHY PRECEDENCE (HOW MUCH SAFETY?)

CURRENT OPTIONS	COMMENTS
<ul style="list-style-type: none"> • Cause no damage whatsoever to Space Station and no injury to crew. • Cause no damage to Space Station beyond routine maintenance capability. 	Desirable: cost trade Cost Trade
<ul style="list-style-type: none"> • Cause no damage to Space Station or injury to crew that will result in a complete suspension of operations. 	Baseline Philosophy
<ul style="list-style-type: none"> • Space Station repairable and operational within a specified period of time. • Crew survival at expense of the Space Station. 	May require escape/rescue. Implies evacuation and rescue as a minimum.

The Rockwell effort identified 23 separate categories of threats to the Space Station and ranked the threats of fire and explosion/implosion among the highest. The overall approach used in the Rockwell effort to deal with the identified threats included the following sequence of hazard mitigation efforts:

1. Design To Preclude.
2. Design To Control.
3. Provide Protective Devices And Design Operational Work-Arounds.
4. Design An Appropriate Crew Retreat To A "Safe Haven" Or Module (Assuming Incomplete Mitigation Of The Threat).

Based on probabilistic risk assessments developed by the nuclear power industry (Reference 61), another methodology for the definition of risk due to fire in manned spacecraft can be stated as follows:

1. Define the critical locations in the spacecraft where fire could result in substantial damage, or lead to loss of life,
2. Model the propagation of a fire event as well as its detection and suppression, and
3. Assess the system response for the identified critical fire scenarios.

Some of the limitations in this methodology include the difficulty in modeling fire scenarios due to incomplete knowledge of the effects of low gravity on ignition, combustion, flame propagation, etc.

J. H. Kimzey and others have identified secondary causative factors of ignition of materials within a spacecraft pressurized module as a result of an impact by space debris and those due to materials incompatibility, especially those failures caused by storage container release of reactive materials.

As used herein, a threat is defined as any situation that endangers either the crew or the spacecraft. A potential hazard is a threat that has been determined to have a combination of probability, frequency, and/or severity for a given scenario and that must be dealt with. Throughout this report, the phrases "risk assessment" and "hazard assessment" will be used interchangeably. These phrases generally imply that the probability and frequency of the threat may be determined, along with the severity of the event for a given scenario.

5.3.2 Proposed Efforts: The proposed project is described on the basis of work breakdown structure (WBS) tasks directed to develop and refine a technique for identifying threats to spacecraft due to fires and fire-induced explosions. Further, the effort is intended to outline methods for developing acceptable solutions to the fire threats such that they may be rendered benign. The organization of the project WBS is illustrated in Figure 5-2.

Task 1.0: Establish Data Base Of Fire/Explosion Threats Of Potential Hazard To Manned Spacecraft

The purpose of this task is to establish a data and knowledge base of "lessons learned" from past spaceflight missions, existing risk analyses and "threat-strategy" techniques, and knowledge of low-gravity effects on fire and fire safety.

Subtask 1.1: Review Documented Fire/Explosion Events and Alarms From Past Missions. There is a need to gather fire and explosion-related information from past space flight missions and to organize this information to be readily accessed by designers, safety personnel, crew training specialists, etc. The long-duration missions of both the United States (especially Apollo, Skylab and Spacelab) and the Soviet Union

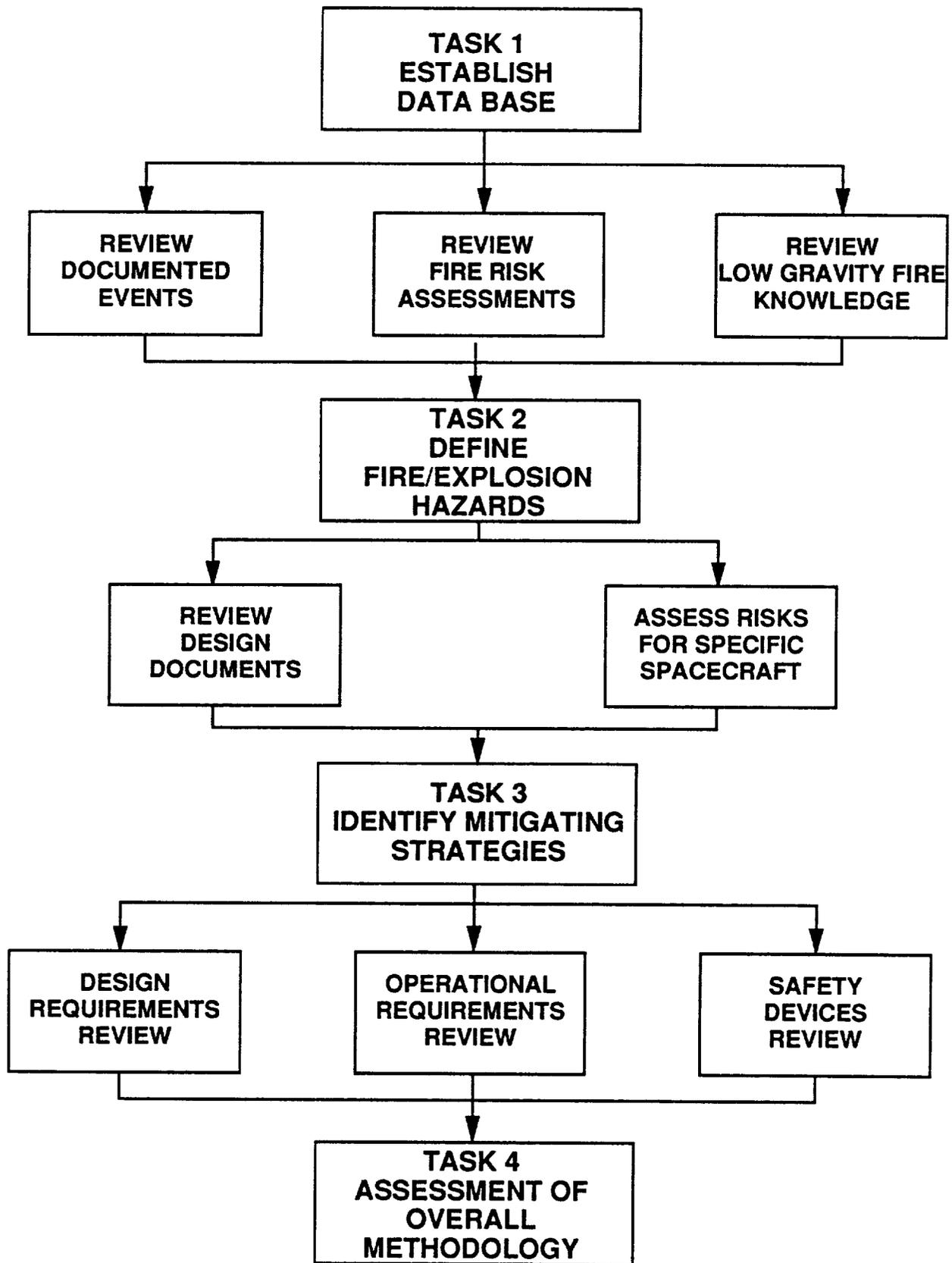


FIGURE 5-2. WORK BREAKDOWN STRUCTURE FOR EVALUATION OF NEW FIRE RISK ANALYSIS TOOLS FOR ADVANCED, MANNED SPACECRAFT

(Salyut through Mir) will be of highest use. Evidences of overheated motors, clogged filters, inappropriate use of materials, etc. have all been documented or alluded to in mission reviews.

Subtask 1.2: Review Existing Fire Risk Assessments Relative To Advanced Spacecraft. The purpose of this subtask is to identify and review available risk assessments and studies relative to advanced, manned spacecraft such as those developed for Space Station Freedom, covering those of fire, fire-induced explosions and related threats.

Subtask 1.3 Review Knowledge Base Of Microgravity Effects On Fires. Although the knowledge base relative to the effects of low gravity on ignition, combustion, and extinction of fires is limited, the intent of this subtask is to collect available information for efficient application. Over the long term, new information will be made available from several sources, including the results of the basic research project described in Section 3.7.

Task 2.0 Define Potential Hazards From Fire And Explosion Threats For Specific Spacecraft

The purpose of this task is to apply the knowledge base developed in Task 1.0 to a specific spacecraft. As discussed above, the review and definition of specific threats to a spacecraft should be performed very early in the design cycle and then updated as the design proceeds.

Subtask 2.1: Review Spacecraft Design Documents At Each Review Step. NASA's safety requirements for payloads, payload integration, carrier spacecraft and all associated hardware and operating procedures are very stringent. This subtask is intended to supplement existing safety requirements from an overall review perspective, i.e., to apply the knowledge developed during Task 1.0 to identify potential threats for fire and explosions. The review should examine material usage, location, quantity, and compatibility, and it should also identify locations of highest threat, for example, hazardous experiments, waste storage, fluid handling, power concentrations, etc.

Subtask 2.2 Assess Risks Associated With Potential Threats For The Specific Spacecraft Under Review. The intent of this subtask is to assess the risk associated with the threats identified in Subtask 2.1. This would entail an estimate and review of probabilities of exposures and consequences of the threatened event. Such an assessment would include a study of the proximity or isolation of identified fuels and likely ignition sources, probability of spillage, human errors, and probability of outside events, such as meteoroid or space debris impact.

Task 3.0: Identify And Recommend Strategies For Fire Risk Minimization By Mitigation Or Elimination Of Threats

This task is devoted to the preparation of strategies for eliminating or rendering benign any fire or explosion threats identified for the specific designs reviewed in Task 2.0. The overall results of this task will be a set of strategies that apply to specific fire and explosion threats, but may also apply to similar threats associated with other designs.

Subtask 3.1: Review Design For Adherence To Established NASA Safety Requirements. Existing NASA safety requirements are intended to "preclude" and "control" threats by adherence to stringent design considerations. The appropriate selection and limitation on the use of materials is inherent to these safety requirements. Wherever possible, one leg of the fire triangle should be eliminated and in the case of reactive fluids, both ignition sources and fuels should be eliminated for a fail-safe design. However, in the case of advanced, manned spacecraft this cannot always be done. This is especially true of some experiment racks where fuels and oxidizers are present and where containment and isolation from ignition sources becomes the only way to preclude the threat of fire or explosion.

Subtask 3.2: Review Operational Requirements For The Minimization Of Threats. This task is to be devoted to the development of operational strategies designed to "preclude" and/or "control" threats of fire and explosions. An obvious example of such a strategy is that of timelining experiments such that power usage is well distributed in both time and location on the spacecraft. Another example is that where the discharge of waste materials to the process materials management subsystem (PMMS) is timelined to keep incompatible reactive materials from mixing or accumulating. Handling and storing general refuse (foodstuff, wipes, etc.) is also a common, but important spacecraft activity.

Subtask 3.3: Review Of The Provision Of Safety Devices And Contingency Equipment And Procedures.

This subtask is included in recognition of the importance of the safety devices and contingency measures required in the event that a fire hazard due to a specific threat or group of threats is not mitigated. Thus, early design reviews of the locations and types of fire detection and suppression systems, early warning and communication systems, provisions for egress of crew to safe havens (e.g., adjacent modules), and post-fire cleanup are all important aspects of the risk analysis.

Task 4.0: Assess The Impact Of Threat Mitigation Strategies On Fire And Explosion Risks

After selected threat mitigation strategies have been defined and recommended, they must be critically reviewed for anticipated effect and appropriateness. Threat mitigation and the accompanying risk assessment is an iterative process to insure that the solution to one threat will not create a worse solution for other threats. The cost and schedule impacts must also be addressed for all threat mitigation strategies.

5.4 Research On Numerical Modeling Of Fire Scenarios In Spacecraft

5.4.1 Background: In the event of a fire inside a spacecraft, the smoke and fire spread are essentially controlled by the ventilation flow. Established fire-detection and suppression procedures developed for the buoyancy-dominated, normal-gravity conditions are not applicable in the microgravity environment. Detailed flow and fire modeling are necessary to determine the optimum locations for the fire detection and extinguishment systems and to develop fire control procedures. The information obtained from spacecraft fire models is also important during the design phase of the spacecraft to formulate appropriate rescue, escape, and recovery procedures. The need to create comprehensive mathematical models to enhance fire safety of a spacecraft during its design phase as well as operational stage has been identified as one of high priority by several experts surveyed by Wyle.

Fire modeling involves the solution of the field equations for temperature, velocity, and species concentrations with basic combustion models providing the flame dynamics as the driving boundary conditions. Fire spread, growth and smoke-gas transportation in enclosures have been modeled with some success under normal-gravity conditions using numerical solution techniques of the governing conservation equations. Both zone models and field models have been used to analyze the smoke spread, flashover and other fire related phenomenon in a variety of enclosed geometries such as buildings, aircraft cabins, and ships. In zone modeling, the burning enclosure is divided into several distinct regions characterized by a dominant fire behavior and these zones are coupled together using interface conservation conditions to simulate the entire fire scenario. Typical zones employed in a zone model are the flaming combustion zone, the thermal plume zone, the hot-gas layer accumulation, and the ventilation flow region.

In the field-modeling approach, the entire region of interest is treated as one unit and the governing Navier-Stokes equations and energy and species conservation equations are solved along with the appropriate initial and boundary conditions. While field modeling provides accurate flow-field results and avoids the empiricism involved in the zone modeling, it demands large amounts of computer-memory storage and time to resolve small scale flow structures in space and time which may be of importance in certain fire scenarios associated with large enclosures.

The modular construction and well defined geometry of most spacecraft, such as the Space Station Freedom, eliminates some of the statistical aspects of a normal-gravity building fire code and lends itself to realistic field calculations. Individual units such as equipment racks, open cabin areas, air-locks, etc. can be analyzed separately, treating the inlet and exit conditions as parameters, and an overall model for the entire spacecraft can be developed by combining these separate results.

Both the European (ESA) and Japanese (NASDA) space agencies have started preliminary numerical modeling studies for the Columbus Lab and the JEM (References 63 and 64). The Japanese effort includes numerical flow field calculations as well as functional model tests to validate the codes. However, at present, their objective is essentially to determine the ventilation flow parameters and is not directly related to the fire-safety problem. The proposed effort by ESA is directly aimed at fire modeling with a view toward finding optimal locations to place the fire detectors. Numerical modeling has also been sponsored by NASA to study the dispersal of contaminants in the cabin area of the Space Station Freedom (Reference 65).

5.4.2 Proposed Efforts: The proposed project is described on the basis of WBS tasks directed at developing and formulating a numerical model of fire spread in the low-gravity environment of Freedom modules. The organization of the project WBS is illustrated in Figure 5-3.

Task 1.0: Select A Suitable Mathematical Model For The Flow Processes

In microgravity, as in the normal gravity conditions, the fluid flow field is determined by the conservation equations for mass, momentum, and energy and these equations are well known. However, certain special considerations need to be taken into account in formulating a fire model. Materials burning under microgravity is known to produce more soot, and radiation heat transfer plays a major role in fire growth and smoke spread. A suitable radiation exchange model has to be adopted to simulate the highly non-gray combustion products. Hottel's "mixed gray masses" model has been used in the past for building fires (see Reference 66). Another important factor that is of interest from the fire-detection point of view is the smoke transportation and coagulation process. In the past, the Smoluchowski equation, which governs the

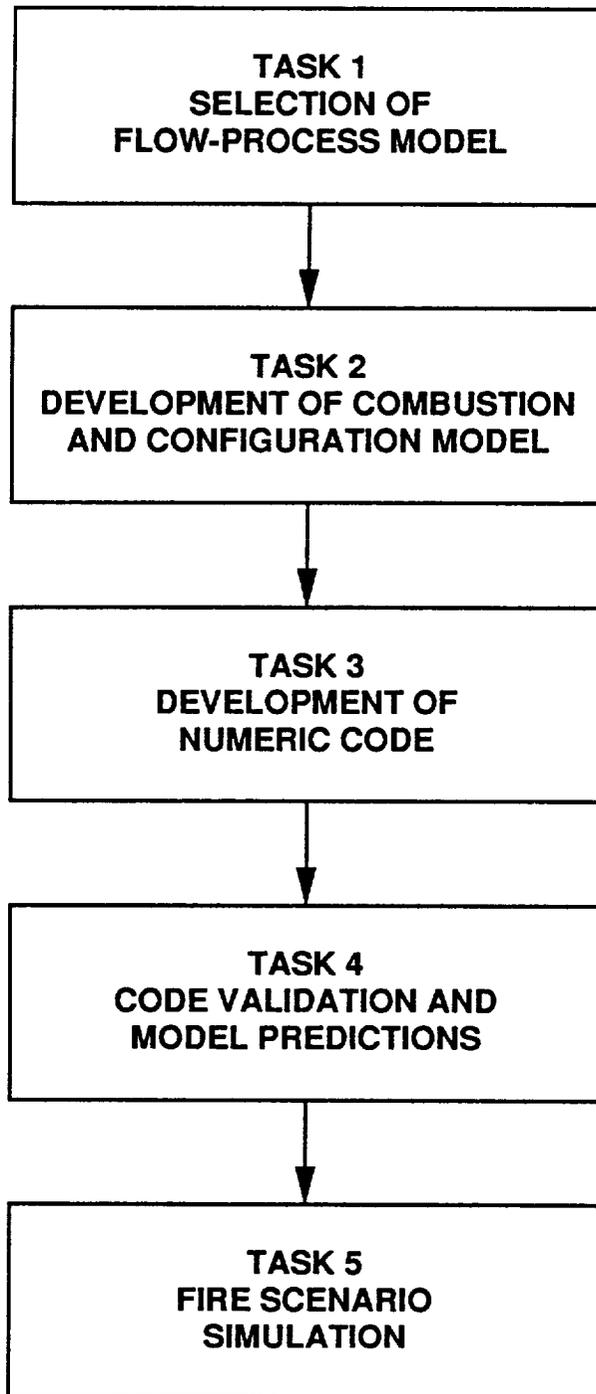


FIGURE 5-3. WORK BREAKDOWN STRUCTURE FOR RESEARCH ON NUMERICAL MODELING OF FIRE SCENARIOS FOR SPACECRAFT

particle size distribution, has been solved using a Lagrangian reference frame and particle tracking procedures along with the hydrodynamic equations to predict smoke properties (Reference 67). A similar approach could be used to analyze the fire-generated aerosol transportation inside spacecraft compartments. A suitable turbulence model also needs to be incorporated into the flow conservation equations.

Task 2.0: Develop Models For Basic Combustion Processes And Configuration Effects

Basic combustion models for ignition, flame spread, burning rate, and extinction are necessary components for a physically realistic fire modeling effort. No matter how accurately the field equations are solved, without physically realistic materials combustion models, the overall performance of the simulation will be unsatisfactory. The current state of knowledge on microgravity solid fuels combustion is still in its infancy (see Section 3.7). The limited information that is available in the literature is focused toward understanding the basic physical phenomena and is not directly applicable to numerical simulation models.

Basic combustion science experiments on solid fuels and theoretical analysis consider simple geometrical configurations and boundary conditions. However, the flammable materials that are used in a spacecraft form a part of the complex configurations. Guidelines to evaluate potentially flammable configurations are presented in the NASA/JSC document NSTS 22648 (Reference 38) which is based on NASA's past experience in fire safety and extensive test results conducted according to NHB 8060.1 (Reference 30). The need to place this empirical knowledge on a strong scientific basis has been recognized by a number of fire safety experts. The primary methods recommended in NSTS 22648 are 1) to limit the flammable materials by replacement with nonflammable materials and 2) to restrict the flame propagation paths, either by covering flammable materials with a nonflammable material or by separation of flammable materials by fire breaks, which are gaps, openings, nonflammable materials, or heat sinks.

At the present time, it may be necessary to consider a semi-empirical approach. This approach would be based on available experimental and theoretical results to extract information relevant to fire models from fundamental combustion science

investigations, where empirical and/or analytical models for microgravity combustion of solid fuels are developed that provide fire-related parameters such as burning rate, smoke production rate, energy release rate, etc. These models must be able to account for the energy interactions that are encountered in an actual end-use geometrical configuration of a spacecraft interior.

Task 3.0: Develop Numerical Codes

The numerical code selected must be able to solve three-dimensional, transient problems for arbitrarily shaped bodies (racks, electronic cabins, open cabin area, etc.). Body fitted co-ordinate systems may need to be implemented to model complex interior shapes of a spacecraft. A list of requirements for a microgravity fire-model code is given in Table 5-2. There are a number of powerful codes that are commercially available that seem to meet most of the requirements, namely the PHOENICS, FLUENT, FLUENT/BFC, FIDAP, etc. There are also several Navier-Stokes solvers developed by NASA (e.g., ARC3D, INS3D) which may be modified to suit the present problem. A review of the literature pertaining to combustor modeling and aerosol dispersion may be valuable in selecting relevant transport equation solver and smoke particle tracking procedures respectively.

This task involves the selection of numerical schemes that are capable of solving the field equations, radiation transfer and particle transport equations accurately in the region of interest. The results of the previous tasks will be combined to produce a unified numerical program. The field equations are coupled with the proper boundary and initial conditions and a program flow logic is developed.

Task 4.0: Code Validation And Model Predictions

Any numerical code developed to simulate a spacecraft fire scenario must be validated first. Experimental validation of microgravity fire scenario simulation is very difficult, if not impossible, on earth. Full scale tests similar to building fires and aircraft cabin fires are not possible for spacecraft fires in ground-based facilities due to the ever present buoyancy forces. However, it is possible to model the smoke spread and the flow patterns caused by ventilation inside a spacecraft using isothermal, liquid systems in normal gravity. A scale model of the spacecraft can be

TABLE 5-2. REQUIREMENTS FOR A NUMERICAL CODE USED IN MICROGRAVITY FIRE MODELING

• FLOW TYPE	- INCOMPRESSIBLE - SUBSONIC
• FLUID TYPE	- VISCOUS - NEWTONIAN - LAMINAR/TURBULENT
• ANALYSIS TYPE	- STEADY - TRANSIENT
• FLUID PHASE COMPONENT	- SINGLE - DISPERSED SECOND PHASE OF PARTICLES
• REACTION OF FLUID	- REACTING
• CIRCULATION TYE	- RECIRCULATION
• BOUNDARY	- FIXED - COMPLEX INTERIOR GEOMETRIES - 3D
• EQUATIONS SOLVED	- CONSERVATION OF MASS - CONSERVATION OF MOMENTUM - CONSERVATION OF ENERGY - CONSERVATION OF CHEMICAL SPECIES - RADIATION - PARTICLE TRANSPORT/COAGULATION

fabricated using transparent materials and the flow circulation inside could be visualized using, for example, water as the flow medium and a neutrally buoyant dye as the smoke generated by a fire source. It may be possible to use some other fluid with neutrally buoyant particles in an isothermal system to model the hydrodynamic effects under microgravity.

The validated fire code could then be used to predict a number of factors influencing the fire safety of the spacecraft. Some of these parameters are:

1. Flow and temperature field.
2. Particle size growth and distribution.
3. Transient fire development times.

The simulation code can also provide input to the risk and hazard analysis by simulating various fire events at different locations and times inside a spacecraft. Results from simulated fire events can also be incorporated into the knowledge-base of an expert system used in the spacecraft fire control. Since full-scale tests under microgravity are not possible, even crude simulation results are of great value to the designer and may help in designing future test methods.

Task 5.0 Simulate Fire Scenarios

This task identifies critical fire scenarios and simulates them on a computer to assess the potential risk levels and provide the designer with alternatives. Optimum locations to install fire detectors and suppressants are also identified. One must be aware that such use of the computer simulations must be used with caution and good judgement.

The modeling program outlined above is quite ambitious and it may not be possible to include all the physical details into a single computer code which can be run in a reasonable length of time. Part of the challenge, then, is to make the necessary approximations without losing the predictive capabilities of the overall program.

It must be noted that the program outlined above considers flammable solid materials as the potential sources of fire hazards. However, flammable and reactive liquids and gases when spilled or leaked into an area could act as sources of fire spread. On-going research on the combustion characteristics of these fuels must be continued.

5.5 Other Risk And Hazard Assessment Projects

The third-ranked project in this thematic area on the evaluation of ventilation flow models is not discussed further. It is parallel to the project on numerical modeling of fire scenarios just described and would have a similar WBS. One of the most useful results of a ventilation-flow model would be a forced convection map that would guide the optimal locations of fire detectors for sensing through means of both temperature and smoke-particle distribution.

A lower-priority topic of interest deals with the threats associated with spacecraft impact by orbital debris and meteoroids (Topic 6.4, Table 2-1). The potential damages that may be caused by such impacts and the methods of mitigating those damages are being studied extensively by NASA and its contractors. Of concern to fire safety, the radiant energy release from hypervelocity impacts (Project GT-5), along with molten debris from the impact, has been shown to easily ignite flammable materials (this was reported by WSTF personnel). The proposed oxygen transfer system for Freedom has utility trays that contain flexible oxygen lines as well as coolant and electrical lines. The study would evaluate the penetration and flame propagation initiated by hypervelocity particle impact on the utility tray. Possible experiments could use CO₂ lasers to measure critical energy for ignition of standard materials.

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6.0 PROJECT DESCRIPTIONS: TOXICOLOGY, HUMAN RESPONSE AND ATMOSPHERE CONTROL

6.1 Background

The maintenance of a safe, clean and comfortable atmosphere for crew habitation in any spacecraft is of the highest priority. Originally, in the Mercury and Gemini spacecraft, the breathable atmosphere was 100 percent oxygen at 34.5 kPa (5 psia). This evolved finally to the shirt-sleeve, sea level air environment (21 percent oxygen at 1 atmosphere total pressure) for the STS Space Shuttle Orbiter and Spacelab. The equipment devoted to maintaining the spacecraft atmosphere is referred to as the Environmental Control and Life Support System (ECLSS). The ability of the ECLSS to maintain the spacecraft environment free from toxicants and irritants is somewhat limited, and the system is generally not designed for off-nominal occurrences such as a fire or toxic spill (see Section 4.4). Even in the state-of-the-art ECLSS units used in the Shuttle Orbiter and in the planned units for Space Station Freedom, toxic contaminants and irritants can exceed acceptable human tolerance levels if an off-nominal event occurs and is undetected in sufficient time to use auxiliary cleanup devices.

Monitoring a spacecraft atmosphere continuously for selected gases, including toxic contaminants and irritants, will be essential for the much longer-duration mission spacecraft such as Freedom. The universality of the need for real-time contamination monitoring was emphasized by Astronaut Dr. Bonnie J. Dunbar in her presentation at the Space Station Freedom Toxic and Reactive Materials Handling Workshop (Reference 68).

6.2 Proposed Efforts

The final selection of highest-priority projects has provided a single project to be included in the thematic area of toxicology, human response, and atmosphere control listed below and identified by the discipline number shown in Figure 2-2.

<u>Priority Discipline No.</u>	<u>Project Title</u>
AR-2	Evaluation Of Contaminants and Continuous Monitoring On-Orbit And Material Screening For Toxicity

However, a number of lesser-priority projects were identified during the course of this effort, which addresses concerns regarding threats to spacecraft crew from fire-produced toxicants and irritants, the provision of off-nominal "fire-safe" atmospheres, and the long-term physiological response of crew members to these off-nominal environments. Figure 6-1 illustrates a schedule for the priority project and two other projects in these human factors.

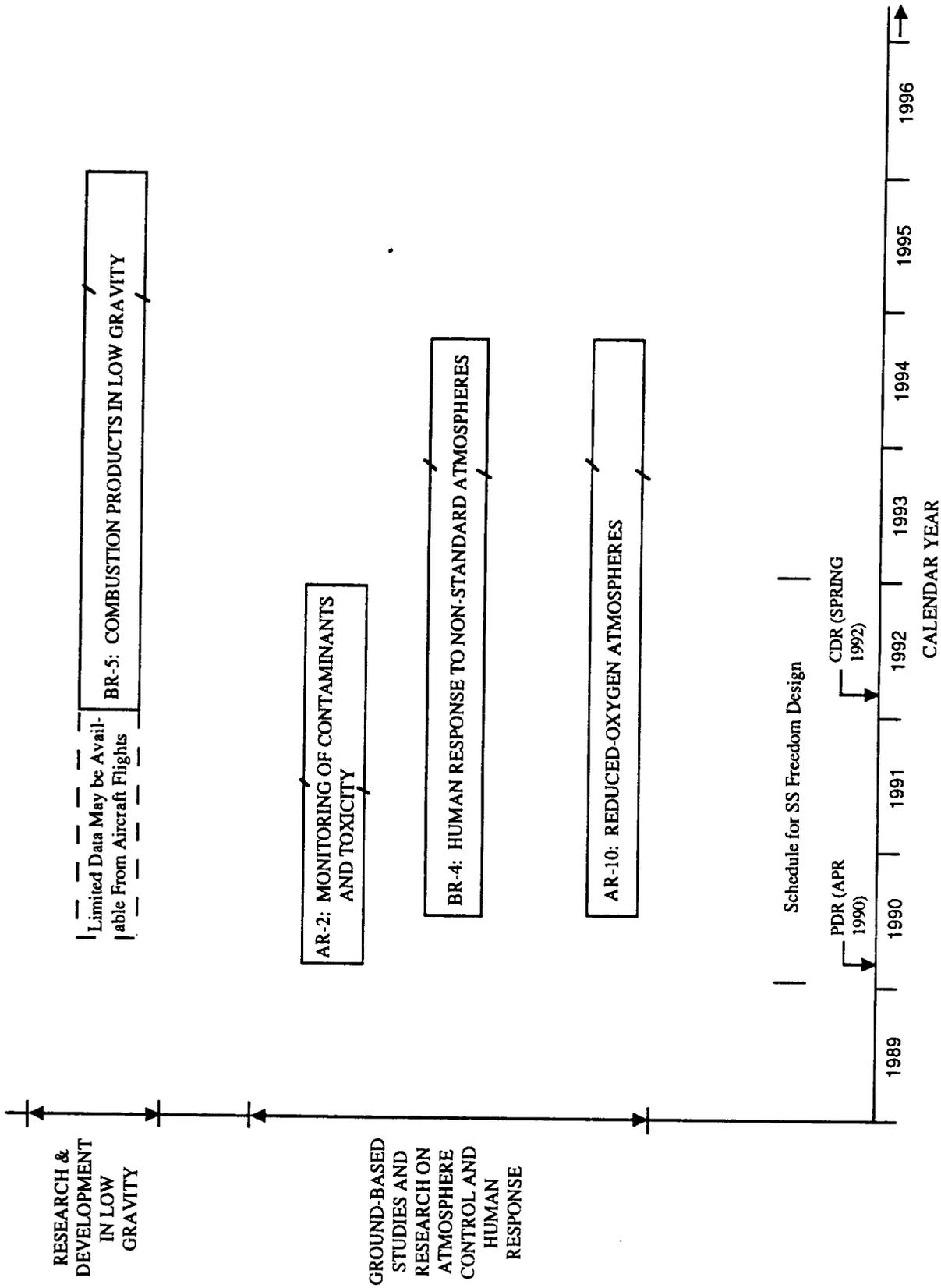


FIGURE 6-1. PROJECT SCHEDULE FOR SPACECRAFT ATMOSPHERE CONTROL, HUMAN RESPONSE, AND TOXICOLOGY PROJECTS

6.3 Evaluation Of Requirements For Continuous Monitoring Of Contaminants On-Orbit And Materials Screening For Toxicity

6.3.1 Background: With the advent of NASA's Space Station Freedom, there is a renewed concern regarding the potential hazard from toxicants and irritants in the spacecraft habitable atmosphere. Of course, a major source of toxic gases would be from a spacecraft fire event, or to a lesser extent from a severely overheated component.

During the Wyle survey conducted as a part of this effort, several topics were suggested that involve toxicants and irritants in various contexts. These suggested topics may be identified as follows (from Table 2-1):

- Topic 1.6 Identify Those Gases Which Should Be Monitored Continuously For Spacecraft Atmosphere Toxicity And Irritants
- Topic 7.1 Perform Toxicity Analyses Of The Offgassed Products From Overheated Components
- Topic 7.2 Establish A Policy Position Relevant To The Toxicological Hazards Associated With The Pyrolysis Products Of Spacecraft Materials

These topics have been combined into the single highest-priority project described in this section.

Continuous and rapid monitoring of toxic contaminants has not been routinely performed on past NASA-manned spacecraft. Further, the detailed screening of materials for the production of toxicants and irritants resulting from any stage of combustion has been essentially abandoned. Although seven-day Spacecraft Maximum Allowable Concentration (SMAC) values have been established for a limited number of the major combustion products (e.g., CO, HCN, SO₂, and the nitrogen oxides (Reference 30)), these values are not applicable to the much longer missions planned for the future. Work is currently underway to define 90-day SMAC values.

An overview and assessment of the proposed research and technology projects relevant to spacecraft smoke gas toxicity (and irritants) was prepared by a Wyle

Consultant, Dr. H.L. Kaplan. Some of the comments from that overview are highly relevant to this proposed effort and are summarized in the remainder of this section.

According to Dr. Kaplan, materials screening and selection and the development of toxic hazard/risk assessment models based on the results of toxicity bioassay tests have not been productive because of constraints and limitations such as the following:

1. The combustion products and the quantities thereof generated by any material are variable and depend on several factors, i.e., temperature, rate of heating, O₂ availability, material configuration, etc. In addition, the results obtained under normal gravity conditions do not represent those of low gravity.
2. With few exceptions, the LC₅₀ (toxicity index -- see Note 1) values of most materials fall within a narrow range despite marked differences in the combustion products generated and their potential toxicity to humans. One notable exception is polytetrafluoroethylene (PTFE).
3. In general, the LC₅₀ index of lethality values does not measure the potential of the smoke gas to impair performance, impair or delay escape, or incapacitate humans.
4. The relevance of the animal models, used in toxicity test methods, has not been fully established, particularly in the case of irritant gases, because it is not known whether any of the laboratory test methods replicates the combustion of materials in actual fires and the resultant generation of toxicants.
5. In one series of tests (Reference 70), the National Institute for Standards and Technology (formerly NBS) N-gas model failed to predict the lethality of approximately 30 percent of the materials tested.
6. New York State is nearing completion of its mandatory three-year program requiring the submission of LC₅₀ values for certain building and finishing materials. To our knowledge, the hundreds of LC₅₀ values filed will not be used for approval/disapproval of materials since there is no means to apply them.

Note 1: The term LC₅₀ may be defined as "... the concentration of combustion products needed to cause 50 percent of the test animals to die from these concentration measurements after a specified exposure time." (Reference 69)

The combustion of materials and the generation of toxicants may be considerably different in low gravity than in normal gravity. Consequently, the data base accumulated during years of testing in normal gravity is questionable when used to assess the potential toxicity of spacecraft materials. Resolution of this concern implies the need for a research and test program that includes testing in low gravity.

The fundamental question, therefore, is what strategy should NASA assume with regard to the potential for toxicity-related incapacitation and/or death of spacecraft crews that may result from fires during a mission? Monitoring of toxicants and irritants is planned for Space Station Freedom, but to what extent and how timely the monitoring should be has not been fully established. Regarding the combustion toxicity of spacecraft materials, should all candidate materials be screened for their potential to produce lethal or incapacitating quantities of toxicants and irritants? If such screening is performed, on what basis and against what criteria should the screening be performed? Alternatively, should such screening be abandoned and full reliance be placed on the screening provided by flammability tests and enhanced fire detection/suppression techniques? It should be noted that the techniques used to make a material less flammable generally introduces increased toxicity. Thus, selecting a material which is less likely to propagate a fire (the criterion generally used throughout the manned spacecraft program) has reduced the total gas load from an accidental fire while admitting a small amount of more toxic gases. The Spacecraft Columbia teleprinter incident of 12 August 1989 (STS-28) illustrates this. If electrical insulation had been selected for minimum toxic gases, it probably would have been polyethylene, cotton or paper, and parafin, and the fire would have spread producing a total gas load which would be far more damaging -- or total results that were catastrophic.

These arguments have been assessed by Kaplan to determine the priority and overall cost of three strategies for spacecraft material selection based on combustion toxicity (Table 6-1). The most practical approach appears to be largely in experience-based material selection (Strategy 3, Table 6-1), with limited bioassay testing (Strategy 1) and analytical toxicity assessment (Strategy 2). This philosophy underlies the project described in this section.

**TABLE 6-1. CANDIDATE STRATEGIES FOR SPACECRAFT MATERIALS SELECTION
BASED ON COMBUSTION TOXICITY**

APPROACH	PRIORITY	COST
1. Extensive combustion toxicity testing, including bioassay tests (e.g., NIST N-gas method as a minimum). (Selected low gravity confirmation required.)	Low	Over \$100 Million (10+ year period)
2. Extensive analytical toxicity assessment based on evaluation of smoke gases produced by a material and toxic hazard assessment from available human toxicological data. (Low gravity comparison of smoke gas production required.)	Medium	Over \$25 Million (5+ year period)
3. Avoidance of potentially hazardous (i.e., toxicant producing) materials based on their chemical content and industry experience. (Limited tests as in Approaches 1. and 2. may be required.)	Highest	\$2-5 Million (5+ year period)

6.3.2 Proposed Efforts: The proposed project is described on the basis of work breakdown structure (WBS) tasks directed toward the applied research and engineering associated with the monitoring of combustion (smoke) gases for crew safety (and possibly fire detection) and the need for and merits of candidate methods for the screening and selection of materials based on combustion toxicity. The need for continuous monitoring for crew safety and warning may be judged to be well-established. The need for material screening is not well-established for the technical and cost reasons discussed above. The organization of the project WBS is illustrated in Figure 6-2.

Task 1.0: Establish A Priority List Of Combustion (Smoke) Gas Toxicants And Irritants To Be Monitored Continuously On-Orbit

Subtask 1.1: Review Past Experience In Spacecraft Atmosphere Monitoring. On-orbit monitoring of the spacecraft breathable atmosphere has been generally limited to measurements of the partial pressure of oxygen and carbon dioxide (e.g., in Skylab, STS Space Shuttle and Spacelab). Any other detailed assessment of the spacecraft breathable atmosphere was accomplished by taking "grab-samples" and returning them to earth for analysis. This past experience should be reviewed.

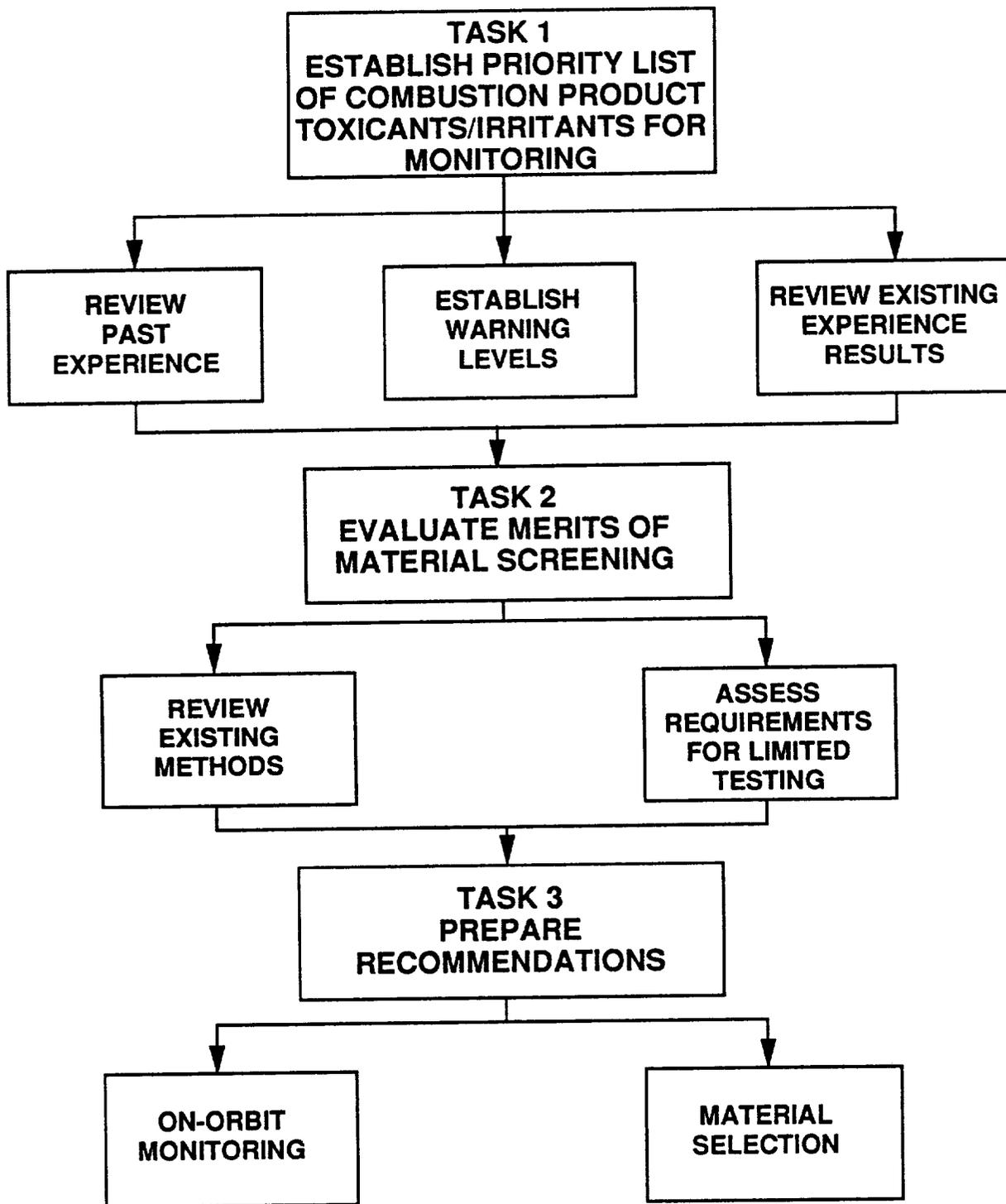


FIGURE 6-2. WORK BREAKDOWN STRUCTURE FOR EVALUATION OF REQUIREMENTS FOR CONTINUOUS MONITORING OF CONTAMINANTS ON-ORBIT AND MATERIAL SCREENING FOR TOXICITY

Subtask 1.2: Establish Warning Levels For The Major Smoke Gas Toxicants And Irritants. Current plans for the Space Station Freedom include the continuous monitoring of the atmosphere in the habitable areas for several major constituents and a wide range of trace contaminants (Reference 31). What is currently missing is a quantitative identification of the most toxic combustion products (i.e., the "bad actors") and a means for rapidly identifying these compounds in the event of a fire and for determining when the atmosphere is again safe for normal breathing. Rapid monitoring of only such gases as carbon monoxide (CO), carbon dioxide (CO₂) and oxygen (O₂) may be inadequate in the presence of other smoke gases such as HCl, HBr, HCN, HF, NO_x, acrolein, and isocyanates. Also, there may be value in monitoring phosphorous compounds and fluorinated organics. The first purpose of this subtask is to determine which of these asphyxiant and irritant gases should be monitored rapidly, i.e., in time periods of seconds to a few minutes. The Federal Guidelines of IDLH (Immediately Dangerous to Life or Health) concentrations may be appropriate (Reference 71).

The second purpose of this subtask is the selection and assessment of simple and compact -- preferably portable -- analytical sensors for monitoring major toxicants to determine, e.g., when it is safe for crew members to remove their respirators. These sensors could be the standard Draeger tubes or some combination of battery-powered smoke gas detectors under development (Reference 32).

The third purpose of this subtask is to develop recommendations for new Spacecraft Maximum Allowable Concentration (SMAC) values needed for application to long-duration manned spaceflight missions to ensure that continuous, prolonged exposure to combustion products and fire/extinguishant breakdown products do not result in incapacitation of crew members. Seven-day SMAC values have been developed and are listed in NHB 8060.1B (Reference 30) for some major combustion products, including CO, HCN, nitrogen oxides, and SO₂. However, these values are not applicable to the much longer missions planned for advanced, manned spacecraft.

Subtask 1.3: Review Existing Experimental Results To Establish Those Gases That Should Be Monitored For Use In Smoke Gas Fire Detection Systems. The interpretation of experimental results is an important subtask in the project. The scope of this subtask, however, falls within the project discussed in Section 3.5 on the

development of techniques for early detection of incipient fire conditions by monitoring outgassing, smoke gases, etc. Precursor or concurrent activities in these two projects must be assumed.

Task 2.0: Evaluate The Need For Adopting An Approach For Screening Materials For Combustion Product Toxicity

Subtask 2.1: Review Existing Methods For The Evaluation Of The Toxicity Of Smoke Gases. All three material-selection strategies listed in Table 6-1 are based on methods to assess combustion-product toxicity of candidate materials. In addition, but not discussed here, is the growing number of mathematical models being developed for the prediction of toxic hazards (e.g., the Fractional Effective Dose Model (Reference 72)). These models depend upon the availability of appropriate toxicological and flammability data. Adoption of any of these methods will require careful consideration by toxicologists who are sensitive to the limitations and merits of the individual methods.

The costs in time and money associated with any detailed, thorough methodology for the screening of materials for combustion toxicology can be substantial. Even the costs of the NIST (formerly NBS) "N-gas" model methodology (Reference 69) are not insignificant if a large number of materials are to be screened. The rough order of magnitude costs listed in Table 6-1 would need to be re-defined.

Subtask 2.2: Assess The Requirements For A Limited Test Program. This subtask depends largely upon the results of the assessment performed in Subtask 2.1. For example, the evaluation of Strategy No. 3 of Table 6-1 may involve use of limited bioassay tests (e.g., the N-gas method) to verify that a material is or is not potentially hazardous.

Task 3.0: Prepare Formal Recommendations

Subtask 3.1: Prepare Recommendations Relevant To The Monitoring Of Combustion Products On Orbit. Based on the results of the reviews and assessments of Tasks 1.0 and 2.0, recommendations will be made for the resolution of the following issues:

1. What combustion or pyrolysis products should be monitored continuously and rapidly on-orbit?

2. What simple, compact analytical sensors can be used by the crew for post-fire hazard monitoring?
3. What SMAC values are appropriate for combustion products predicted for long-duration manned spaceflight.
4. What should be monitored for fire detection?

Subtask 3.2: Prepare Recommendations Relevant To The Screening And Selection Of Materials For Combustion Toxicity. This subtask constitutes the preparation of a NASA policy position regarding the need to perform screening tests for the evaluation of the potential hazards associated with combustion product toxicity. The importance of establishing such a policy should not be underestimated.

6.4 Other Toxicity, Human Response, And Atmosphere Control Projects

Several other projects in this thematic area are worthy of note, although they were not ranked among the highest-priority projects. For example, Priority Discipline No. AR-10, "Evaluation of the Merits of Providing Breathable, 'Fire-Safe' Atmospheres in Advanced Spacecraft," investigates the advantages of providing a safer, reduced-oxygen atmosphere for spacecraft crews (see References 73 and 74). According to Dr. D.R. Knight (Reference 73), atmospheric-control studies sponsored by the Navy showed that spacecraft crews can live and work in enclosed environments with 11 percent oxygen if the total pressure is adjusted to maintain the partial pressure of oxygen above 16 kPa (0.16 atm.). The reduced oxygen concentration would prevent or retard most types of fires. Reduced-oxygen atmospheres are unlikely to be adopted for Space Station Freedom for two fundamental reasons: 1) An off-nominal atmosphere that is unlike the normal sea-level earth atmosphere would interfere with a number of life-sciences experiments and some physical experiments; and 2) Human tolerance to long-term exposure to such atmospheres in low gravity is not well defined. It may be envisioned, however, that the use of off-nominal "fire-safe" atmospheres will be used for other long-duration spaceflight missions in the future.

Project BR-4, "Research Relevant to the Effects on Human Physiology Due to Long-Term Exposure to Non-Standard Atmospheres," covers the basic research pertinent to the fire-safe atmospheres just discussed. Dr. Knight (Reference 73) cautioned that the expanded research required must include assessments of the long-term physiological limitations of decompression sickness, acute hypoxia, and chronic hypoxia. Dr. John Orr of the Southwest Research Institute, a Wyle respoondee, recommended the expansion of research into the effects of combustion products on cognitive functions such as perception, memory, and decision making of spacecraft crews.

Finally, BR-5, "Research on Low-Gravity Investigations Relevant to the Pyrolysis and Combustion Products of Selected Materials," was compiled from several recommendations of the respoondees. The production of toxicants and irritants in various low-gravity fire scenarios is poorly understood. There is a strong possibility that a fire event in low gravity may result in smoke gases that are more toxic than if the same fire scenario were to take place at normal gravity. This supposition is supported by the observation that the burning process of various materials in a nearly quiescent, low-gravity environment tends to result in a slower flame spread rate and

the flame tends to be cooler and sootier than in a normal-gravity environment (References 75 and 76). If these observations are correct, then a low-level combustion process (i.e., smoldering, pre-pyrolysis, etc.) or even an actual flaming condition may proceed undetected for a substantial period of time in a spacecraft with a resultant buildup of highly toxic gases.

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7.0 PROJECT DESCRIPTIONS: GROUND-BASED TESTING AND STANDARD TEST METHODS FOR FLAMMABILITY

7.1 Background

The ground-based testing and evaluation of spacecraft materials and configurations for flammability are among the most important efforts in NASA's safety program. No material or component is permitted to be used on a manned spacecraft in any configuration until it has been judged to meet stringent safety requirements. The test procedures and guidelines for flammability are among the most demanding, with the result that materials selection and component design are fundamentally conservative.

The development of advanced spacecraft, such as Space Station Freedom, and the increased use of the STS Space Shuttle Orbiter and Spacelab for hazardous experimentation has placed new demands on all safety requirements. Regarding fire safety, materials screening for flammability is receiving renewed attention within NASA, especially at the NASA Marshall Space Flight Center (MSFC) and NASA Johnson Space Center (JSC) (including JSC's White Sands Test Facility). NASA's flammability requirements outlined in NHB 8060.1B, "Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environments That Support Combustion" (Reference 30) are currently being revised and materials testing for flammability has continued to expand. NASA's guidelines for the assessment of flammability hazards associated with STS payload hardware (NSTS 22648, Reference 38) have been recently revised (October 1988) and provide conservative requirements for component end-use configurations.

In view of the attention given to safety and the generally successful record of U.S. space missions, criticism of both NHB 8060.1B and NSTS 22648 and other NASA requirements and guidelines for spacecraft fire safety may seem unjustified. However, there are special problems that are not adequately addressed by the current test methods and guidelines. Also, the intentional conservatism of current requirements may be too restrictive for full access to advanced spacecraft. In addition, there have been strong recommendations for adopting new test methods that hold promise for placing flammability testing on a firmer scientific and engineering basis (e.g., see Reference 77). Current flammability tests are basically "pass/fail" and do not permit, therefore, direct comparison and correlation with existing low-gravity flammability data and new data that are beginning to emerge. Further, a number of

variables exist that could permit one material batch to pass, while another batch (or batches) may fail.

Examples of some special problems relating to material flammability testing have been cited in the Wyle survey responses, for example:

- 1) The phenomenon of arc-tracking may contribute to starting a wire insulation fire.
- 2) Tests used to qualify materials for use in high pressure oxygen systems are inadequate.
- 3) The effect on the flammability of non-metallic materials due to long-term aging is not adequately addressed.
- 4) Some inconsistencies have been noted in the results of comparisons between NASA and ESA flammability tests for Group I materials.

7.2 Proposed Ground-Based Testing And Standard Test Methods For Flammability Projects

The final selection of the highest-priority projects has provided two projects to be included in the thematic area of ground-based testing and standard test methods for flammability, listed below in the order of descending priority and identified by the discipline number shown in Figure 2-2.

<u>Priority Discipline No.</u>	<u>Project Title</u>
GT-1	Test Procedures And Pass/Fail Criteria For Special Problems Relevant To Electrical Wire/Cable Insulation Flammability
GT-2	Critical Review Of Relevant Test Methods For The Screening Of Non-Metallic Materials For Flammability

Figure 7-1 illustrates a proposed schedule for the highest priority ground-based testing and standard test methods for flammability projects. The schedule includes additional lower-priority in ground testing for flammability in hyperbaric atmospheres (GT-3) and advanced research on aging and degradation (AR-8).

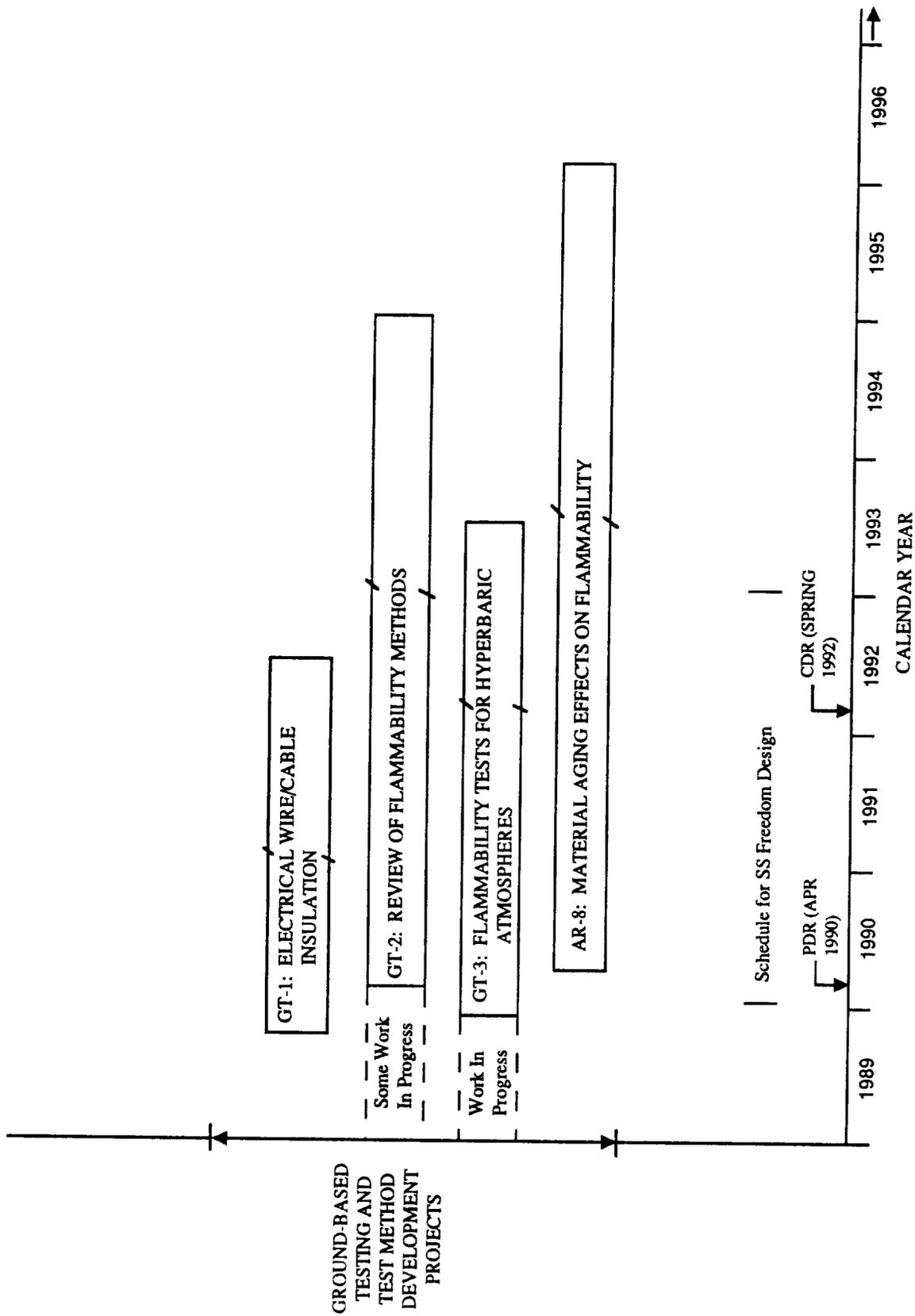


FIGURE 7-1. SCHEDULE FOR GROUND-BASED TESTING AND STANDARD TEST METHODS FOR FLAMMABILITY PROJECTS

7.3 Test Procedures And Pass/Fail Criteria For Electrical Wire/Cable Insulation Flammability

7.3.1 Background: NASA's specifications for electrical wire and cable material selection, design, and installation are stringent, especially in the case of manned spacecraft applications. Many of these NASA specifications incorporate, by reference, other demanding standards and procedures (e.g., MIL-STD and IEEE). With regard to flammability requirements, electrical wire insulation and electrical connector pottings and conformal coatings must adhere to Tests 1, 4 and 5 of NHB 8060.1B (Reference 30).

The survey of fire-safety workers, conducted as a part of this effort, identified two special problems related to the flammability of electrical wire and cable insulation. The first of these concerns was the specific phenomenon known as "Arc Tracking," the formation of carbon on the insulation surface, caused by electrical arc overheating, which reduces the electrical insulating value of the wire covering and will contribute to starting a fire. Unpublished tests at the NASA Kennedy Space Center have shown that sustained arc tracking can be initiated at a voltage of 28V (with sustaining currents less than 4 A). The concerns relative to wire insulation arc tracking, especially as the phenomena might adversely affect STS Shuttle wire insulation, are being actively reviewed by NASA and various contractors. The standard NASA tests for wire insulation flammability, NHB 8060.1 Tests 1 and 4, do not test specifically for arc tracking resistance. It was pointed out that the ASTM D-9 Committee is currently developing a standard test procedure the purpose of which is to quantify the tendency of wire insulation materials to arc track at low voltages.

The second major concern relative to electrical wire and cable insulation is the general issue of the long-term effect that environmental aging may have on flammability. Although NASA has long recognized the need to address time-related changes along with other material property requirements (i.e., corrosion, stress corrosion, fracture control, vacuum stability, etc.), the advent of advanced, long-duration mission spacecraft such as SS Freedom demands that renewed emphasis be placed on material aging. The planned design life of 30 years for a spacecraft such as Freedom is much more demanding in terms of material aging than, for example, the original 10-year design life of the STS Shuttle Orbiter vehicle. A recent report

(Reference 78) has been prepared by the Southwest Research Institute for the NASA JSC that addresses the long-life assurance of materials for future, long-duration mission spacecraft.

7.3.2 Proposed Efforts: The proposed project is described on the basis of work breakdown structure (WBS) tasks directed to address some of the special problems related to the flammability of electrical wire and cable insulation. The concern relative to the effect of lifetime aging on flammability is included. The organization of the project WBS is illustrated in Figure 7-2.

Task 1.0: Review The Special Problem Of Arc Tracking As Related To Spacecraft Electrical Wiring

Portions of this effort are already in progress within NASA. Assessments are being made relative to the arc tracking concerns as applied to STS Shuttle Orbiter electrical systems — especially the Kapton wire insulation. This effort should be expanded to develop a test procedure that would properly address the arc-tracking problem for all advanced spacecraft electrical wire and cable insulation and provide an appropriately conservative pass/fail criterion.

Task 2.0: Establish Material Aging Protocols For Electrical Wire And Cable Insulation

Subtask 2.1: Review Current Knowledge and NASA Requirements Relative To Accelerated-Life Aging. The purpose of this subtask is to perform a critical review of NASA's current specifications and requirements as they apply to long-life assurance of materials. The emphasis shall be on non-metallic materials, especially those whose flammability properties may be affected by long-term aging. This effort shall require an extensive review of the literature and may require a significant test program.

Subtask 2.2: Develop Test Procedures For Material Aging Of Electrical Wire And Cable Insulation. This subtask follows from the critical review and testing called for in Subtask 2.1. Where possible, the test procedures (aging protocols) to be developed should be based on well-established industry methods. Examples of industry standards that require environmental aging are IEEE Std. 323-1988 (IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations, dated September 30, 1983)

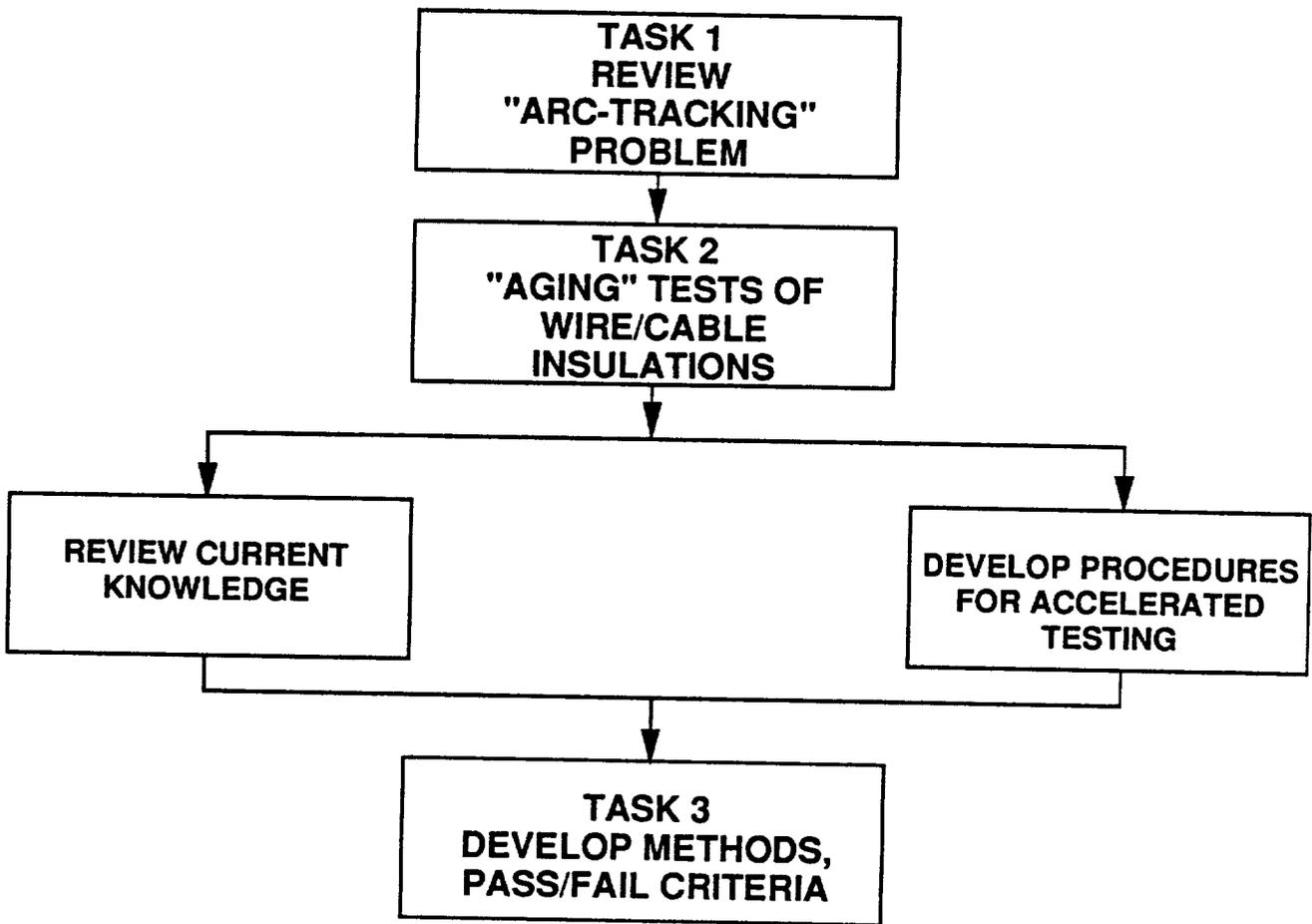


FIGURE 7-2. WORK BREAKDOWN STRUCTURE FOR TEST PROCEDURES AND PASS/FAIL CRITERIA FOR ELECTRICAL WIRE/CABLE INSULATION FLAMMABILITY

and UL-746B (UL Standard for Polymeric Materials - Long Term Property Evaluations, dated December 14, 1978). These industry standards typically address the electrical insulation properties of wire, cable, and other component coverings and coatings. However, the present effort places additional emphasis on the flammability of the wire insulation after aging.

Task 3.0 Prepare Draft Test Procedures And Pass/Fail Criteria For The Arc Tracking Phenomenon And For Material Aging

The test procedures, pass/fail criteria, and material aging specifications (protocols) prepared during Tasks 1.0 and 2.0 shall be formally documented in draft form for release. Review should be performed by all NASA design, materials, and safety personnel concerned with the failure or degradation of electrical wire insulation. Since this type of internal review does not constitute full industry consensus, it is important that well-recognized industry test standards and test procedures be incorporated where possible.

7.4 Critical Review Of Relevant Test Methods For The Screening Of Non-Metallic Materials For Flammability

7.4.1 Background: Test personnel from the NASA/JSC White Sands Test Facility (WSTF) have recommended this review for at least two reasons. First, there are two current test methods for the selection of non-metallic materials for use in the pressurized regions of spacecraft: 1) the European Space Agency (ESA) oxygen index test (Reference 79) and 2) the NASA upward propagation test (Test 1 of Reference 30). The ESA test (Figure 7-3) determines a limiting oxygen concentration for non-propagation using a vertical sample mounted in a flow chamber and ignited at the top

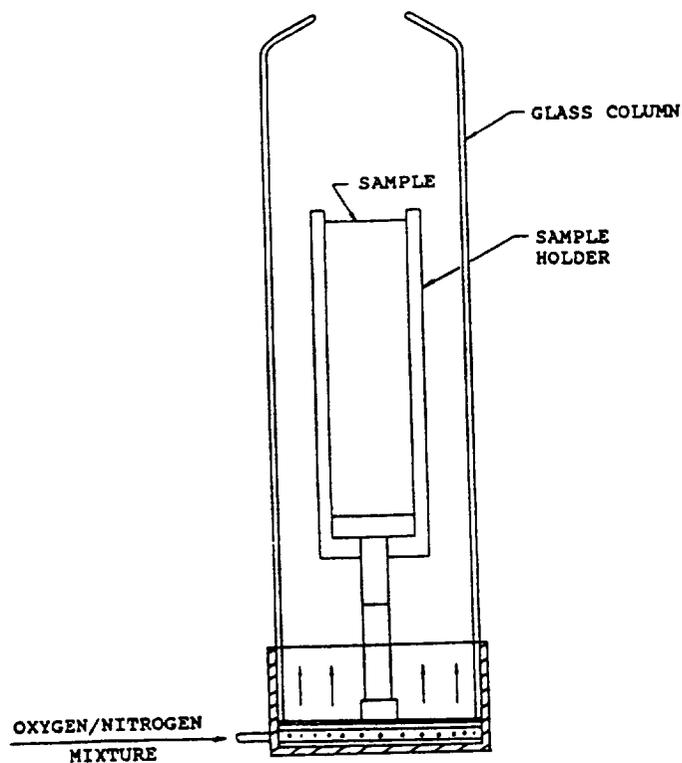
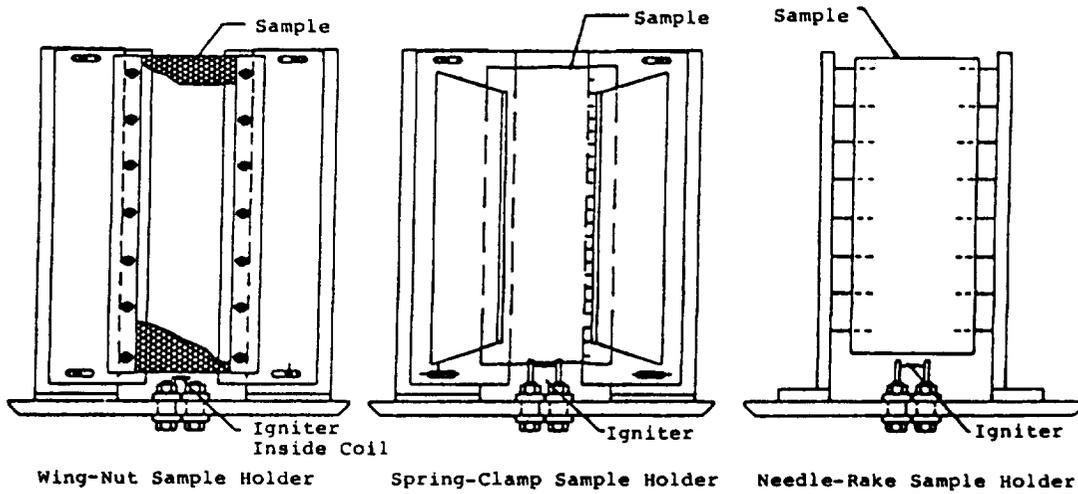


FIGURE 7-3. ESA OXYGEN INDEX APPARATUS

surface. The NASA test (Figure 7-4) determines non-propagation also using a vertically mounted sample, but in a quiescent atmosphere chamber with ignition at the bottom surface. In both tests, non-propagation is the self-extinguishment of the flame before it spreads beyond a specified reference length. Both tests provide a pass/fail criterion for materials that can have unrestricted use in spacecraft pressurized atmospheres (i.e., Group I materials). While the bulk of the flammability testing for



Sample Holders for NASA Upward Propagation Test

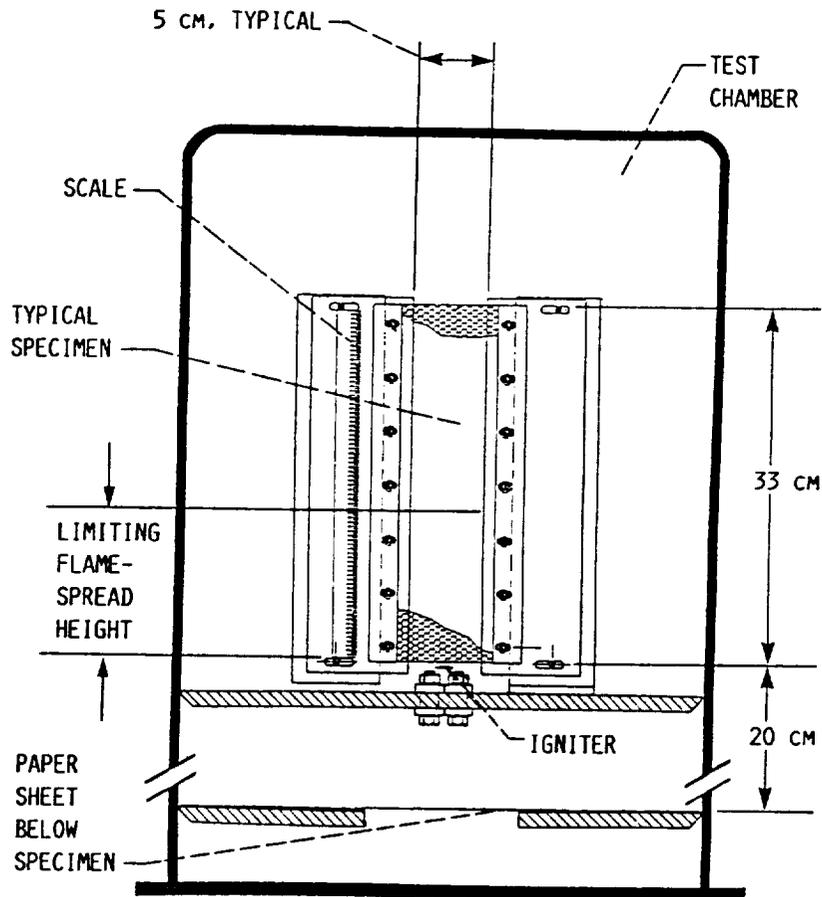


FIGURE 7-4. NASA STANDARD UPWARD BURNING TEST APPARATUS

Group I criteria performed for ESA by the European Space Research and Technology Center (ESTEC) is conducted in accordance with the NASA upward burning test, it is recognized that there exist two different standard tests that may yield different acceptance criteria. Recently, controlled experiments comparing the two methods (Reference 80) were performed on a variety of materials, including rigid plastics, foams, elastomers, films, fabrics, and coatings. Nearly 20 percent of the materials either passed the ESA test for Group I acceptance but failed the NASA test in the same Space Shuttle simulated atmosphere or vice versa.

A second reason given (Reference 81) for supporting this critical review of methods is that the NASA test (Reference 30) remains essentially unchanged since its original use for the screening of materials in atmospheres containing up to 100 percent oxygen. The NASA test is essentially a pass/fail screening that produces little or no correlatable information. Similarly, although the ESA oxygen index test is based on a more widely accepted ASTM test (referred to as the "Critical Oxygen Index," ASTM D2863), the ESA test does not produce much information for the spacecraft designers.

An often stated goal of NASA's microgravity combustion research program is to obtain an enhanced understanding of the flammability of materials in various microgravity environments so that a better assessment of their fire safety attributes in spacecraft use may be made from necessarily limited ground-based testing. The need to perform a number of material flammability tests in low gravity was emphasized by several of the fire-safety experts responding to Wyle's spacecraft fire safety survey. The ability, however, to correlate such flammability data obtained in microgravity with ground-based test results will require more fundamental information than that which can be supplied by the current NASA tests.

Examples of test parameters and conditions to be considered for flammability correlations were outlined by Dr. V. Babrauskas (Reference 77) as follows:

- 1) Planar, thermally thick specimens.
- 2) The testing of composites as composites, instead of testing individual layers.
- 3) Simulated fire exposure to consist of a uniform, adjustable radiant flux.
- 4) Design of tests to give one-dimensional heat transfer.

- 5) Design of apparatus such that specimens do not melt out of holder or retreat from their ignition sources.
- 6) The measurement of heat, species, soot and smoke on a per-gram basis.
- 7) Use of oxygen consumption for measuring heat release rates.
- 8) The selection of both irradiance conditions and test times to predict full-scale data.
- 9) The focus on predicting volume-integrated full-scale variables (e.g., heat release rate) instead of point variables (e.g., temperature at a given station).

One of the recent pieces of test apparatus developed for the bench-scale determination of combustion heat release rate, mass loss rate, smoke production, and toxic product formulation is the Cone Calorimeter (Reference 82) illustrated in Figure 7-5, which is under review at present as an ASTM test method (Committee E-5, Proposal P-190).

7.4.2 Proposed Efforts: The proposed project is described on the basis of WBS tasks directed to culminate in a new or revised methodology for testing nonmetallic materials for flammability, especially for NASA Group I criteria. The effort will be aided if established and/or generally accepted test methods are adopted where possible. The organization of the project WBS is illustrated in Figure 7-6.

Task 1.0: Perform A Critical Review Of Relevant Test Methods For Evaluating The Flammability Of Nonmetallic Materials

Subtask 1.1: Compare And Evaluate Available Test Results Performed For The NASA Space Shuttle And Spacelab. The purpose of this subtask is to expand upon the test results described in Reference 80 in which the NASA and ESA tests for meeting Group I criteria materials requirements were compared. A thorough review of the background (genesis) of both the NASA test (Test 1 of Reference 30) and the ESA test (oxygen index test of Reference 79) will be performed, and additional data from both tests should be obtained and compared, if possible. The advantages, disadvantages, and limitations of the tests will be identified.

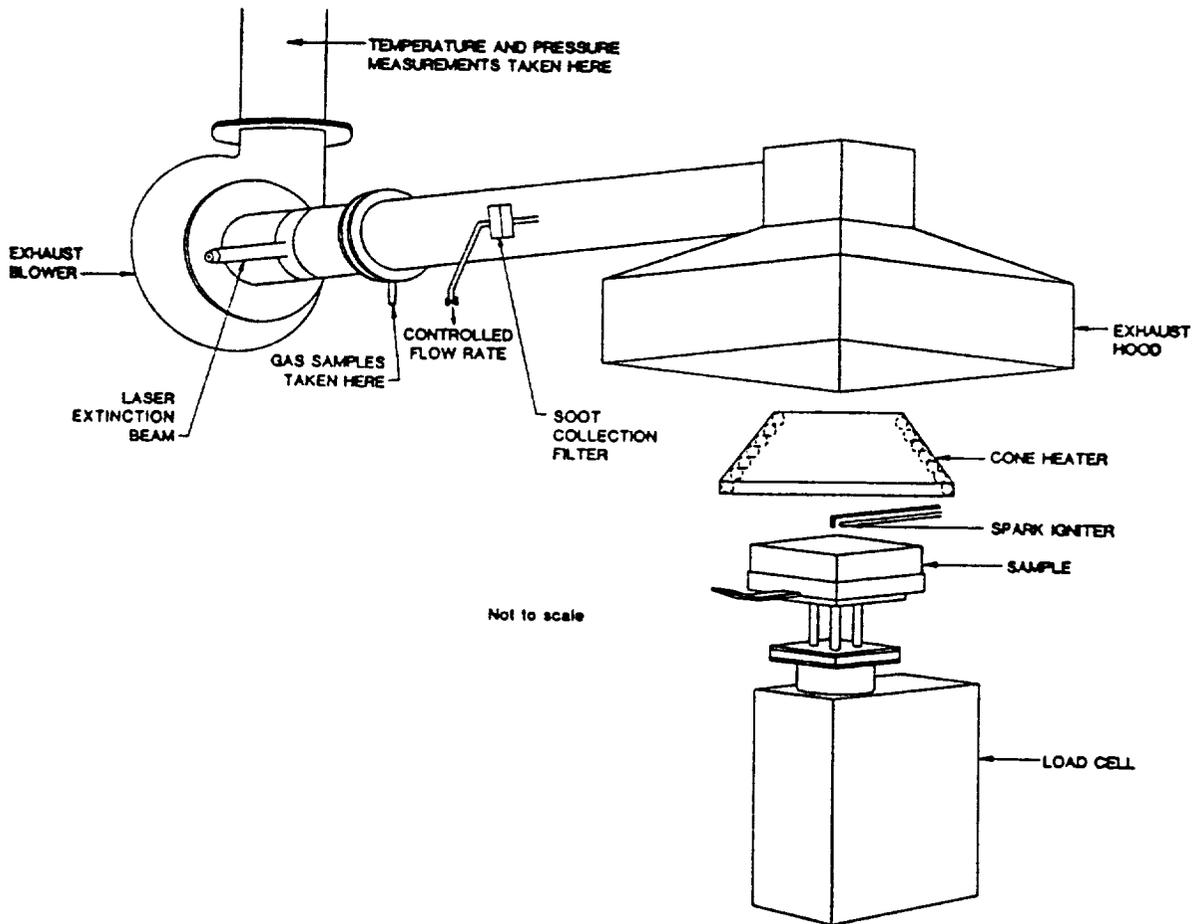


FIGURE 7-5. CONE CALORIMETER

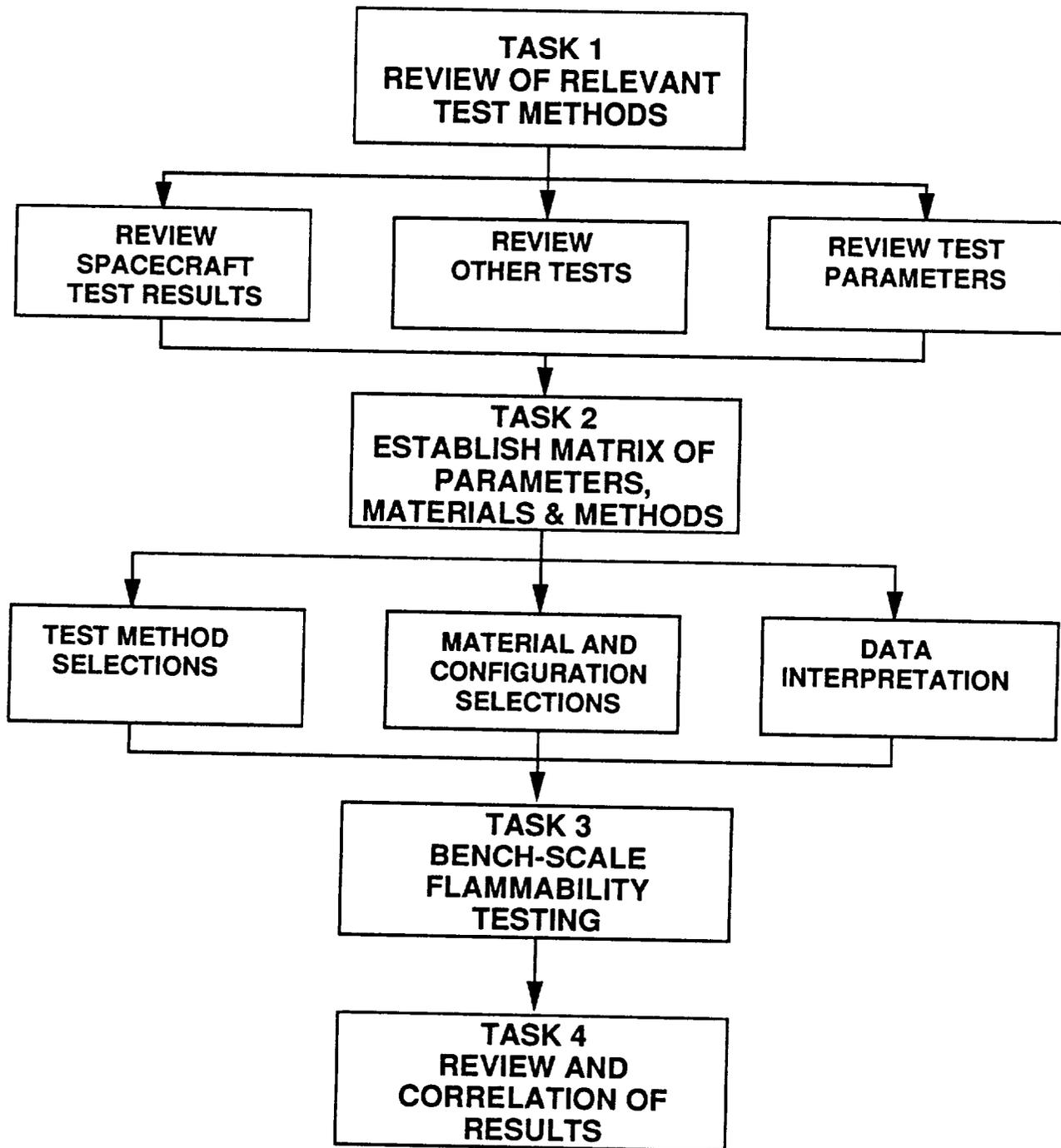


FIGURE 7-6. WORK BREAKDOWN STRUCTURE FOR CRITICAL REVIEW OF RELEVANT TEST METHODS FOR SCREENING NON-METALLIC MATERIALS FOR FLAMMABILITY

Subtask 1.2: Review Other Potentially Applicable Test Methods. Specific test methods that may be potentially applicable to the determination of selected components of the physics of flammability will be reviewed in this subtask. A proposed starting point for this effort would be based on the recommendations prepared by Dr. V. Babrauskas (Reference 77).

During this subtask, it is also recommended that a review be made of the tests and requirements used by the commercial airline industry to rank and/or screen nonmetallic materials for use in the interiors of transport category airplane cabins. For example, the Federal Aviation Association (FAA) flammability tests set out in the recently amended version of FAR 25.853 (Reference 83) include requirements and recommended methods for determining material heat release rates and smoke emission, using the Ohio State University rate-of-heat-release test apparatus (ASTM E906). Europe's Airbus Industrie has adopted its own fireworthiness regulations, i.e., the Airbus Test Specification ATS 1000.001. This specification defines material requirements regarding allowable limits for toxicity -- requirements not currently adopted by the FAA. A brief discussion of the FAA and Airbus Industrie specifications is presented in Reference 84.

Subtask 1.3: Establish Desired Test Parameters For Flammability Testing. This subtask will be devoted to the preparation of a realistic list of the parameters associated with flammability physics that should be measured and/or adhered to during testing. Although the anticipated fire scenarios for NASA spacecraft may be considerably different than those for aircraft and ground-based facilities and vehicles, the fundamental requirements for obtaining meaningful and repeatable measurements of ignition, flame spread, and burning and product generation rates is universal for all of the fire conditions. A preliminary list of the desirable test parameters was presented above in the background discussion.

Task 2.0 Establish Matrix Of Desired Flammability Test Parameters, Materials, And Candidate Test Methods

After the knowledge base preparation and reviews performed in Task 1.0 have been completed, this task will be devoted to the preparation of a test matrix for use in evaluating the applicability of selected tests and test parameters for screening and/or ranking nonmetallic materials for flammability.

Subtask 2.1: Select Candidate Test Methods For Use In determining Specific Flammability Parameters. A subset of flammability test methods will be selected based on the review performed during Subtask 1.2. The selected procedures may include more than one of the reviewed methods, with modifications and combinations as appropriate to meet the demanding specifications for spacecraft use. The selection will also cover test conditions and ranges of experimental parameters.

Subtask 2.2: Select A Limited Number Of Nonmetallic Materials And Material Configurations For Testing. The materials selected for test method development should have the following characteristics:

- 1) Relevancy to manned spacecraft use in pressurized volumes.
- 2) Variety of specific materials and material configurations (foams, composites, laminations, films, etc.)
- 3) Unique qualities for research, such as marginal flammability or inconsistent prior test results (e.g., Reference 80).

Subtask 2.3: Develop Data Interpretation Models. Existing and/or new material flammability models will be selected or developed to interpret the planned test results in terms of ignition, flame spread, extinction, burning rates, etc. Such data interpretation models shall include the selection of dimensionless parameters for correlation of test data, numerical simulations of the flammability process, and the selection or development of fundamental analytical models.

Task 3.0: Perform Bench-Scale Flammability Tests Based On Prepared Test Matrix

This task will be devoted to the set-up and conduct of the test matrix prepared in Task 2.0. Test procedures will be prepared for each portion of the flammability test methodology and an appropriate number of test specimens shall be submitted for testing.

Task 4.0: Review Test Results And Correlate With Data Interpretation Models

The results of the flammability tests will be reviewed and correlated with the appropriate models. Where possible, material rankings from the tests will be

compared with the results of the NASA and ESA pass/fail results for Group I criteria materials. If necessary, the test matrix will be altered and additional tests will be performed.

Finally, recommendations will be made relevant to the adoption of new or revised flammability test methods.

7.5 Other Ground-Based Testing And Standards Development Projects

Several other suggestions and potential projects related to ground-based testing and standards development are worth noting even though they have not been incorporated into the highest-priority projects.

Priority Discipline No. GT-3 (see Figure 2-2), "Expansion Of Flammability Tests On Materials For Use In Hyperbaric Atmospheres," extends work already underway at both the NASA MSFC and NASA JSC White Sands Test Facility (WSTF). This effort is clearly complementary to the highest-priority project on fire extinguishment in these atmospheres, described in Section 4.3. Among the suggestions of the Wyle sources are recommendations for detailed testing to determine the relative reactivity of air versus selected oxygen-inert gas mixtures at increasing levels of pressure. This is in recognition that the addition of some inert gases such as argon or nitrogen to high-pressure oxygen tends to increase the energy required for ignition.

The project described in Section 7.2 already covers, in part, studies on wire insulation aging effects. Attention is called to AR-8, "Evaluation Of The Effects Of Long-Term Aging On The Degradation And Flammability Of Spacecraft Materials," which is a project concerned with the more general aspects of aging effects, an important concern in the long-term operations planned for the Space Station Freedom.

Several other suggestions involving metals ignition in high-pressure oxygen and ignition and detonation of spacecraft fuels were contributed by WSTF personnel. For the former, minimum ignition energy tests and criteria would permit future spacecraft system designers to control the energy levels of ignition sources in proximity to potential fuel sites. For the latter, experiments to determine the detonation parameters on all spacecraft fuels should be performed at the actual operating conditions because detonation parameters depend on the initial state of the fuel. Priority should be given to determining the detonation parameters for proposed high pressure, propulsion system fuels for the Space Station.

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8.0 SUMMARY OF OTHER FIRE-SAFETY TOPICS AND PROJECTS

Several other topics and projects that did not fit into the previous thematic areas or priority groupings are worthy of some comments. Included are the suggestions on post-fire cleanup, preparation of a spacecraft fire safety handbook, spacecraft crew training, prevention or mitigation of spontaneous ignition, materials compatibility with chemically reactive gases and liquids, and design of fire-safe appliances for crew use on advanced spacecraft. The identification and investigation of these subjects was largely through the efforts of J.H. Kimzey, based on his many years of dealing with materials problems and spacecraft fire-safety issues at the NASA Johnson Space Center (JSC).

8.1 Additional Comments On Post-Fire Cleanup

Rapid cleanup of a spacecraft's habitable atmosphere must be accomplished immediately after a fire event has been identified and extinguished. This was partially addressed in the project on the development of an environmental cleanup unit (Section 4.4). The time, power, and materials required to restore the habitable atmosphere will depend upon the severity of the fire event and the equipment and procedures available. Mr. Richard T. Congo of the NASA MSFC and Mr. J.H. Kimzey emphasized the need for the development of procedures, cleaning techniques, and crew training for the additional cleanup that is likely to be required after the habitable atmosphere has been restored and the crew is allowed to re-enter the affected spacecraft module (Topic 1.7, Table 2-1).

8.2 Preparation Of A Spacecraft Fire Safety Handbook

There is not currently available a single handbook devoted to spacecraft fire safety. The need for such a handbook was suggested as Topic 6.2 by Mr. Robert Clodfelter of the Wright Patterson Air Force Base. This handbook would contain much of the material developed in this report, but would exhibit more detail in terms of accepted practice for spacecraft fire safety (material selection, configuration design, fire detection and suppression, etc.). A new fire safety handbook would not be intended to replace existing spacecraft fire safety related documents. In this handbook, various chapters and topics would be prepared in detail by appropriate personnel at each of the NASA field centers, other government agencies, and outside organizations.

8.3 Spacecraft Crew Training

The establishment of an intensive fire-safety training program for spacecraft crews is an absolute requirement for long-duration flights of advanced spacecraft such as Space Station Freedom. Although astronaut training currently includes procedures relative to the spacecraft fire detection and suppression (FDS) subsystem, it is recommended that such training be expanded to enable crew to respond to the increased number of fire scenarios that could occur on advanced spacecraft. It is recommended that fire "drills" be continued during long-duration spaceflights. Other aspects of the expanded crew training would include those activities involving post-fire cleanup and restoration of normal operational conditions. Such training is not currently a part of the crew requirements for the STS Shuttle Orbiter or Spacelab, since any fire event in those spacecraft that would require a release of extinguishant (i.e., Halon 1301) is cause for mission abortion and return to earth.

8.4 Prevention Or Mitigation Of Spontaneous Ignition

Threats of an explosion or fire due to the spontaneous ignition of a combustible atmosphere in the low-gravity environment within a spacecraft may be possible, but such threats are poorly understood at present. This subject has been assembled into Project AR-5, "Evaluation Of The Mitigation Of Spontaneous Ignition Of Waste." Mr. Kimzey has suggested a research project, initiated by a review of the literature on spontaneous ignition and combustion, to learn more on how these phenomena occur in normal gravity and how to apply this knowledge, as possible, to low gravity.

Space for the storage of on-board space vehicle supplies is always at a premium. Thus, supplies are packed together in a dense manner. Even in a ventilated storeroom or cabinet, there will be a reduced air flow. The proposed study would investigate whether a hazard exists when materials are stored for long periods in low gravity, for example: dry foods, moist food items, frozen foods, condiments, extra clothing, towels, tissue paper, alcohol wipes, cleaning materials, spare parts and maintenance items, and medical supplies, etc.

It is clear that actual experimental research into the fire hazard, or lack thereof, posed by spontaneous ignition in low gravity will not be resolved easily or in a manner timely enough for Space Station Freedom design. Thus, it is recommended that methods of mitigation be adopted. It may be necessary to adopt some or all of the

following measures: 1) chemical or thermal inerting of stored waste, especially organic waste; 2) cooling or freezing of stored waste; 3) active ventilation of storage areas; and 4) careful segregation of stored supplies.

8.5 Long-Term, On-Orbit Storage Of Chemically Reactive Liquids And Gases

Topic 8.1 covers the establishment of a data base relevant to materials compatibility for long-term storage of chemically reactive gases, liquids, and solids. This technical issue is included in this assessment of fire-safety topics due to the threat of explosion and/or fire from improper or inadequate storage of various chemically reactive materials, particularly the propellants nitrogen tetroxide, hydrazine, and derivatives, halogens and oxygen on orbiting spacecraft.

For example, hydrazine, as a monopropellant, will break down in the presence of a catalyst at some critical temperature producing the gases hydrogen, nitrogen, and ammonia. Above the critical temperature, which is characteristic of each metal, ceramic, and polymer, the exothermic reaction starts and continues at an accelerating rate until an explosion occurs, unless immediate action to cool the system is provided. As the Space Station will have on-board tanks for storing hydrazine used in propulsion systems, in recharging the unmanned satellites or, later on, interplanetary vehicles, it is necessary to evaluate the various materials which are wet with hydrazine in order to learn the critical threshold temperature for each material.

Mr. Kimzey also recommended that an investigation be undertaken to evaluate the effect that a major solar flare might have on the integrity of on-orbit hydrazine storage/handling systems.

8.6 Design And Development of Fire-Safe Appliances For Crew Use

With the advent of long-duration spaceflight missions, the crew will need appliances for their convenience and comfort -- appliances such as those used on earth that include microwave ovens, clothes washers/dryers, televisions, etc. Although it is obvious that these devices must be rendered safe for crew use, their use in microgravity may pose some new problems.

Mr. Kimzey has recommended a test and development project on earth to evaluate the appropriate design and use of on-orbit clothes dryers (Topic 10.5). A background

review would be conducted based on ground investigations of appliance fires. The study would identify fabrics and processes to be used in Freedom and would provide guidelines for designing a fire-safe clothes dryer, considering all aspects of human psychology; overloading equipment, impatience, neglect of maintenance, etc.

9.0 RECOMMENDATIONS FOR PROGRAM MANAGEMENT AND OVERSIGHT

The importance of spacecraft fire safety demands appropriate management and oversight of the projects underway as well as those identified in this study to be initiated or expanded. The absence of adequate attention to the important functions of project management and oversight would most certainly result in a number of potentially disastrous situations which could include: (1) inappropriate prioritization, (2) unnecessary project duplication, (3) reduced level of interest in safety and safety technology, and (4) inefficient use of limited resources.

The technical management of any spacecraft fire-safety program within NASA will most likely continue to flow from each major program office (i.e., Space Station Freedom, STS Shuttle, etc.) through the project offices and technical staffs at each relevant NASA field center. At each of the major field centers (especially MSFC and JSC), there are technical organizations who have responsibility for various aspects of spacecraft fire safety, including materials screening and selection, materials compatibility, fire detection and suppression, toxicology and contaminant monitoring, etc. To a large extent, these are ongoing technical efforts that have been in place for many years. When a new program is initiated, these technical groups are asked to respond accordingly. In general, this organization of technical disciplines has worked very well, as judged by NASA's spacecraft fire safety record from the early 1970s to date.

However, two serious deficiencies regarding NASA's overall spacecraft fire-safety efforts have been identified. These two deficiencies have become quite apparent with the advent of the Space Station Freedom (SS Freedom) program and are as follows:

1. There is currently no overall NASA program in spacecraft fire safety, especially as regards advanced spacecraft. An earlier, intercenter Spacecraft Fire Hazards Steering Committee met from 1968 through 1971.
2. Communication among the technical groups working in various aspects of fire safety has been somewhat weak and could be significantly improved.

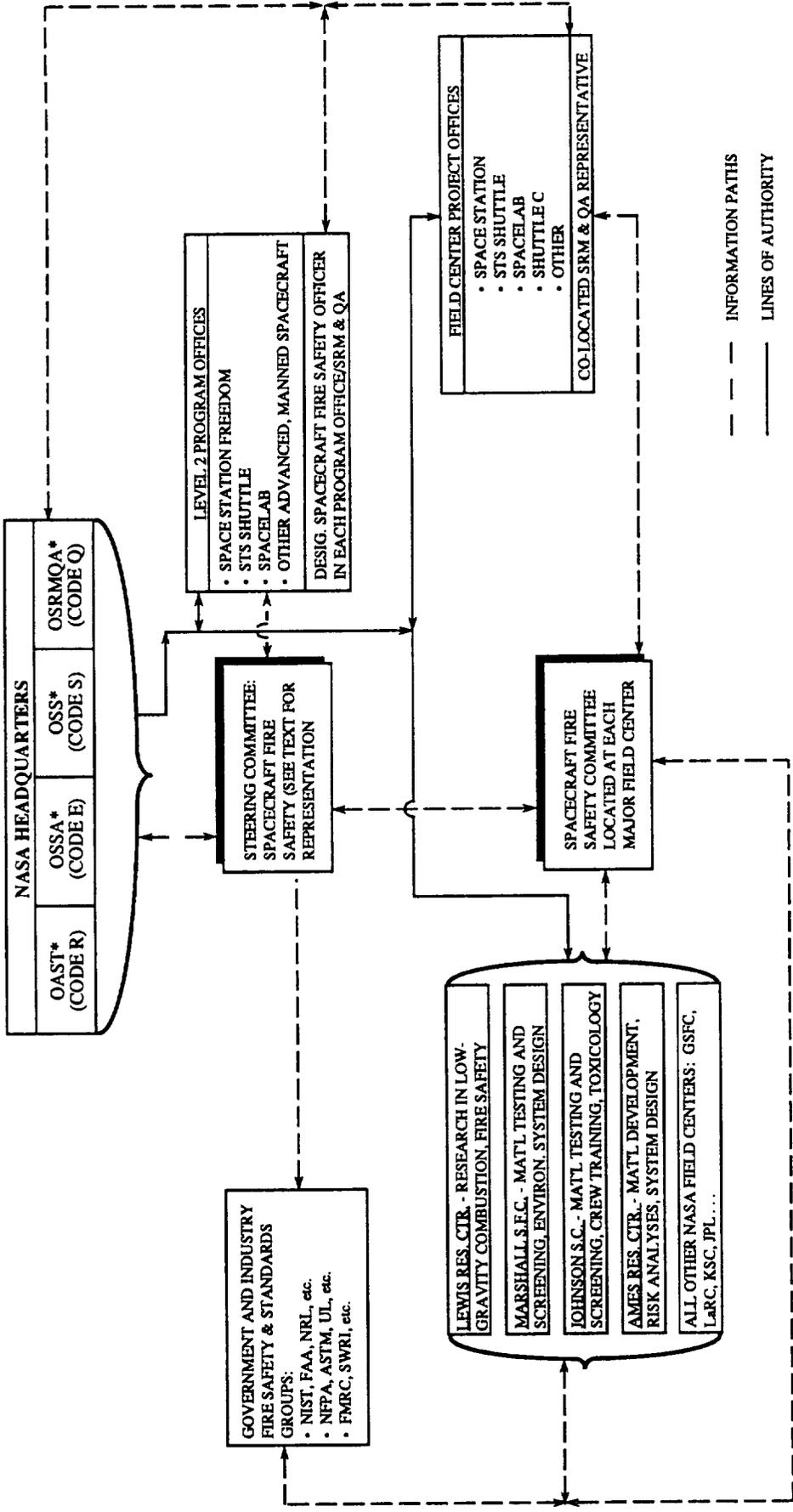
With regard to the lack of an overall NASA program in fire-safety efforts relevant to SS Freedom, the division of responsibilities between the NASA field centers has resulted in the assignment of the Fire Detection and Suppression (FDS) subsystem to the Marshall Space Flight Center (MSFC). Traditionally, the technical studies and tests relevant to fire detection and suppression had been a function of the Johnson

Space Center (JSC) and JSC's White Sands Test Facility (WSTF). This shift in responsibility has resulted in some lost motion and coordination difficulties. The problem has been intensified by the retirement of several of NASA's most experienced fire-safety experts at both JSC and MSFC.

Recently, the NASA Lewis Research Center (LeRC) has taken an active role in providing means for overcoming the perceived deficiencies in the spacecraft fire-safety program that were identified above. In addition to the two major spacecraft fire-safety workshops held at LeRC (August 1986 and January 1989) and several technical publications (e.g., References 1, 85 and 86) on spacecraft fire safety, the efforts described in this report leading to a research and technology development program in fire safety for advanced spacecraft were monitored by the LeRC under NASA Headquarters sponsorship. The LeRC is well recognized in basic and applied research in microgravity combustion science, and the Center possesses unique facilities in drop towers and research aircraft dedicated to these studies. The microgravity combustion effort now supports applications to various aspects of spacecraft fire safety (Reference 40).

The adoption of any or all of the proposed fire-safety projects described in this report depends on the recognition of the importance of such a program by the advanced spacecraft program offices and field centers. The implementation is clearly the responsibility of NASA Headquarters. Further discussion of the management efforts is embedded in the following comments on program organization and communications.

With regard to the second of the perceived deficiencies, the role of excellent communications and technical oversight in any program as important as spacecraft fire safety cannot be overemphasized. Figure 9-1 illustrates a scenario that is designed to take advantage of NASA's current organization to improve communications. Stated simply, it is recommended that overall authority should be maintained by NASA Headquarters -- say in the Office of Safety, Reliability, Maintainability and Quality Assurance (SRM & QA). A "Spacecraft Fire-Safety Steering Committee" should be formally established at the Headquarters level under SRM & QA, with representatives from the other Level 1 offices, the advanced spacecraft program offices, and the NASA field centers. In addition, it is recommended that an Ad Hoc "Spacecraft Fire Safety Committee" be re-established at those NASA field centers having some direct involvement with manned spaceflight systems, crew training,



* SEE TEXT FOR THESE ACRONYMS.

FIGURE 9-1
RECOMMENDED NASA ORGANIZATION FOR MANAGEMENT AND OVERSIGHT: SPACECRAFT FIRE SAFETY

and/or design, fabrication and testing of manned spacecraft hardware. Members of each of these committees should be selected from directly involved personnel from that field center's project offices, engineering directorates and divisions, and the center's safety office (SRM & QA). Each NASA field center's Ad Hoc "Spacecraft Fire-Safety Committee" should meet periodically to discuss issues and concerns of most relevance to its projects. The chairperson of each field center's committee must be willing to see that minutes of the meetings are kept and must communicate routinely with the chairpersons of the other NASA field center committees and with the Headquarters level Steering Committee. Other NASA Headquarters offices shown on Figure 9-1 are the Office of Aeronautics and Space Technology (OAST), responsible for applied research and development, the Office of Space Science and Applications (OSSA), responsible for low-gravity combustion science, and the Office of Space Station (OSS).

The illustrated organization (Figure 9-1) shows that, although the responsibility for SRM & QA flows from NASA Headquarters (Code Q) and the Level 2 program offices for manned spacecraft, the fire-safety related information will flow in both directions. The Spacecraft Fire-Safety Committee chairperson at each NASA field center would maintain oversight of all spacecraft fire-safety activities through contact with his or her counterpart at the other field centers. Recommendations for other duties and responsibilities of the Ad Hoc Spacecraft Fire-Safety Committees at each field center include those activities outlined in the following paragraphs.

Fire-safety workshops should be organized by the "Steering Committee," along with members of the Ad Hoc "Spacecraft Fire Safety Committees" as deemed necessary — probably no less frequently than every two years. In addition to the directly involved NASA personnel and their contractors, these larger workshops should be attended by experts from industry, academia, and other government agencies.

While overall authority should be maintained by NASA Headquarters (SRM & QA), each NASA field center should exert a lead role in those areas of spacecraft fire safety where they possess unique expertise and program responsibility. For example, the following lead roles may be indicated:

NASA/MSFC	Material selection and data basing, system design and testing
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NASA/JSC/WSTF Material screening and selection, combustion toxicology,
crew training

NASA/LeRC Current and advanced fire-safety concepts supported by
microgravity combustion research, ground-based micro-
gravity testing, liaison with microgravity combustion
research community

NASA/Ames RC Development of new and improved "fire-safe" materials,
risk analyses, and expert system applications.

In addition, the knowledge and research capabilities resident in the Langley Research Center, Goddard Space Flight Center, and the Jet Propulsion Laboratory may also contribute to the spacecraft fire-safety program.

The above recommendations are believed to have merit because they take advantage of one of NASA's most important functions, i.e., Safety, Reliability, Maintainability, and Quality Assurance. The suggested activities are all based on responsibilities already established in the organization.

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10.0 CONCLUDING REMARKS

The advent of long-duration, manned spacecraft and permanently orbiting structures, such as Space Station Freedom, poses new challenges to the fire-safety community. Although material screening and configuration control as done in the past by NASA is likely to continue, greater emphasis on fire protection for these more advanced, manned spacecraft is needed. It is evident that all aspects of fire mitigation, i.e., prevention, detection/suppression, and recovery must be considered and a balanced approach be taken in a fire-safety program development. This will not only increase the fire safety of future spacecraft, but it will also make the spacecraft and its facilities more accessible to the user community.

The results of the present study have identified a large number of fire-safety concerns, some major, that are relevant to future spacecraft. Based on a prioritization of these concerns, a comprehensive spacecraft fire safety program plan is presented. The recommended fire safety program contains the highest priority projects in the following thematic areas:

1. Advanced Fire Detection Techniques and Hardware
2. Fire Extinguishment and Atmosphere Cleanup
3. Risk and Hazard Assessment
4. Toxicology, Human Response and Atmosphere Control
5. Ground-Based Testing and Standard Test Methods For Flammibility.

Detailed descriptions and Work Breakdown Structures of selected projects within each one of these categories are presented. The overall program plan and the individual projects stress the adoption and refinement of fire-safety techniques and hardware already in use or under development by the fire-safety community as a whole. For example, the research and development of expert systems applied to the fire detection/suppression system hardware of spacecraft is imperative. Also, the program plan may be considered pragmatic in that it does not insist that NASA alone underwrite all advanced fire safety techniques, materials and systems.

Throughout the course of this study, it became apparent that a fundamental lack of understanding of how fires might be initiated, propagated, and extinguished in a low-gravity spacecraft environment is a major obstacle to the spacecraft designers. This lack of understanding of the differences between fire events in normal gravity and low

gravity has forced the use of ground-based technology which may or may not be appropriate. It is for this reason that several projects have been included that recommend a significant amount of testing of materials in low gravity for ignition, flame spread, extinction, etc.

Finally, the importance of program management and oversight cannot be underestimated. This study, having performed a cursory review of the current fire safety organizations within NASA, recommends a decentralized, project-oriented organizational structure with the ultimate responsibility residing with the NASA Headquarters. It is further recommended that each NASA field center establish a "Spacecraft Fire Safety Committee" composed of cognizant and responsible personnel working with manned spacecraft design and development. At least one member of each of these committees should be from that field center's Safety Office (SRM & Q/A).

It is recommended that the program plan developed in this report be implemented as soon as possible so that the fullest benefits possible are obtained during the development phase of the Space Station Freedom.

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APPENDIX A
RESPONDEES TO SPACECRAFT FIRE SAFETY SURVEY



APPENDIX A
RESPONDEES TO SPACECRAFT FIRE SAFETY SURVEY

During the efforts reported herein for spacecraft fire safety analysis and planning, the authors contacted numerous experts and workers in the fire safety and combustion research community. Table A-1 is a tabulation of those individuals who responded formally to requests for fire safety issues and concerns and/or information in various forms. Several of the respondents assembled material from their organizational colleagues and submitted multiple and, in some cases, extensive responses. For example, multiple and extensive responses were obtained from Joseph L. Buckley (FMRC), Richard W. Bukowski (NIST), Jack Stradling (JSC/WSTF), Dr. Arthur F. Grand (SwRI), and several others. The authors are very appreciative of the time and effort provided by all of the respondents.

The first column in Table A-1 tabulates individual "Source Codes" for each respondent. Each project listed in Table 2-1 in Section 2.0 includes the Source Code(s) of the respondents who recommended or supported that specific project.

TABLE A-1. RESPONDEES TO SPACECRAFT FIRE SAFETY SURVEY

SOURCE CODE	RESPONDEE AND ORGANIZATION	TELEPHONE
1.0	Dr. George Apostolakis (University of California, Los Angeles)	(213) 825-1300
2.0	Dr. Robert A. Altenkirch (Mississippi State University, Mississippi)	(601) 325-2270
3.0	Harlan Burke (Boeing Aerospace, Huntsville, Alabama)	(205) 461-2487
4.0*	Dr. Homer Carhart (Naval Research Laboratory, Washington, D.C.)	(202) 767-2262
5.0	Robert G. Clodfelter (Wright-Patterson Air Force Base, Ohio)	(513) 255-4208
7.0	Matthew B. Cole (NASA Johnson Space Center, Houston, Texas)	(713) 483-4285
8.0	Dr. Martin E. Coleman (NASA Johnson Space Center, Houston, Texas)	(713) 483-7187
9.0	Joseph L. Buckley, et al. (Factory Mutual Research Corporation, Norwood, Mass.)	(617) 762-4300
10.0	Richard L. P. Custer (Worcester Polytechnic Institute, Worcester, Mass.)	(508) 831-5562
11.0	Dr. Robert N. Hager, Jr. (Consultant, Franktown, Colorado)	(303) 688-8958
13.0	Dr. Harold L. Kaplan (Consultant, San Antonio, Texas)	(512) 492-9985
14.0*	Dr. Takashi Kashiwagi (National Institute for Standards and Technology, Gaithersburg, Maryland)	(301) 975-6699
15.0	C. Frank Key (NASA Marshall Space Flight Center, Alabama)	(205) 544-2487
17.0	J. Howard Kimzey (Consultant, Houston, Texas)	(713) 333-2246
18.0*	Dr. Anil K. Kulkarni (The Pennsylvania State University, University Park, Penn.)	(814) 865-7073 (814) 865-1345
19.0	Paul W. Ledoux (McDonnell Douglas Space Systems Company, Houston, Texas)	(713) 280-1602
20.0	Dr. Douglas R. Knight, M.D. (Naval Submarine Medical Research Laboratory, Groton, Conn.)	(203) 449-2508
21.0	Richard W. Bukowski, et al. (National Institute for Standards and Technology, Gaithersburg, Maryland)	(301) 975-6881
22.0	Jennifer D. Noelke (NASA, Johnson Space Center, Houston, Texas)	(713) 483-3661
23.0	Dr. John B. Opfell, et al. (AiResearch Los Angeles Division, Allied-Signal Aerospace Company, Torrance, Calif.)	(213) 512-1488
25.0	Charles D. Ray (NASA, Marshall Space Flight Center, Alabama)	(205) 544-7227
27.0*	Dr. James J. Reuther (Battelle Columbus Laboratories, Columbus, Ohio)	(614) 424-7916
28.0	Dr. K. Saito (University of Kentucky, Lexington, Kentucky)	(606) 257-1685
29.0	Dr. Hiroaki Sasaki (Fire Research Institute, Tokyo, Japan)	(0422) 44-8331
31.0	Dr. William A. Sirignano (University of California, Irvine)	(714) 856-6002
32.0	Jack Stradling, et al. (NASA Johnson Space Center, White Sands Test Facility, Las Cruces, New Mexico)	(505) 524-5732
33.0	Dr. Roger A. Strehlow (University of Illinois, Urbana)	(217) 333-3769
34.0*	Dr. Martin Summerfield (Princeton Combustion Research Laboratories, Inc., Monmouth Junction, New Jersey)	(609) 452-9200
35.0	Dr. James S. Tien (Case Western Reserve University, Cleveland, Ohio)	(216) 368-4581
36.0	Dr. Robert E. Tapscott, et al. (New Mexico Engineering Research Institute, Albuquerque, New Mexico)	(505) 768-7578
37.0	Emory Thomas (Brunswick Corporation, Defense Division, Costa Mesa, California)	(714) 546-8400
39.0	Dr. Forman A. Williams (University of California, San Diego, LaJolla, California)	(619) 534-5492
41.0	Workshop Proceedings, Spacecraft Fire Safety (NASA CP-2476)	
42.0	Gus Sarkos (Federal Aviation Administration, FAA Technical Center, Atlantic City Airport, New Jersey)	(609) 484-5620
43.0	Dr. Arthur F. Grand, et al. (Southwest Research Institute, San Antonio, Texas)	(512) 522-2012
44.0	Richard T. Congo (NASA Marshall Space Flight Center, Alabama)	(205) 544-2629

*Supplementary information was obtained from presentations by these respondents at the International Microgravity Combustion Workshop, January 25-26, 1989, NASA Lewis Research Center, Cleveland, Ohio.

APPENDIX B
PRIORITIZATION PROCESS DESCRIPTION



APPENDIX B

PRIORITIZATION PROCESS DESCRIPTION

B.1 DEVELOPMENT OF THE PRIORITIZATION PROCESS

A project prioritization process was developed to rank the 58 spacecraft fire safety-related suggestions and topics to produce the select group of high-priority projects described in this report. Care was exercised to minimize any institutional or subjective bias in the process, although such bias can never be fully eliminated. To assure the reader that objectivity was indeed sought, the priority philosophy and ranking factors are explained in this Appendix. All of the contributed suggestions and topics listed in Table 2-1 (Section 2.0) were considered in the prioritization process; moreover, project rankings were updated in successive iterations. This permitted adjustment and refinement of the prioritization rankings performed under this effort as new information was obtained. Also, at any time in the future, the rankings may be adjusted as new technology emerges or projects are completed and/or otherwise resolved.

The basic fire-safety philosophy for the prioritization process is derived from assumptions and guidelines applied to Space Station Freedom and other advanced spacecraft. These assumptions and guidelines are as follows:

1. A minor fire event, or at least an ignition, is likely to occur on a future space mission (consensus opinion).
2. Baseline Safety Philosophy: No event (e.g., fire) would cause damage to the spacecraft or injury to the crew that would result in complete suspension of operations (Reference B-1).
3. Spacecraft fire-safety management is a risk optimization based on a trade-off of practical fire-safety approaches against small but tolerable risks (Reference B-2).

A full understanding of the above listed assumptions and guidelines demands a careful review of References B-1 and B-2 and supporting documentation. Reference B-2 identified some of the practical reasons for not being able to ensure complete

B-1. Peercy, R.L. Jr. and Raasch, R.F., "Threat-Strategy Technique: A System Safety Tool for Advanced Design," *Journal of Spacecraft and Rockets*, Volume 23, No. 2, 1986, pp. 200-206.

B-2. Friedman, R. and Sacksteder, K.R., "Fire Behavior and Risk Analysis," NASA TM-100944, December 1988.

elimination of the fire-causing elements in spacecraft (i.e., fuel, ignition, and oxygen) and, further, outlined the generally accepted fire-safety strategies. Figure B-1 shows pictorially a representation of the increasing levels of on-orbit fire damage (risk). The lowest two levels suggest that a fire event is precluded, or, if a fire event does occur the response is successful (i.e., there is little or no injury to the crew and the spacecraft mission can continue).

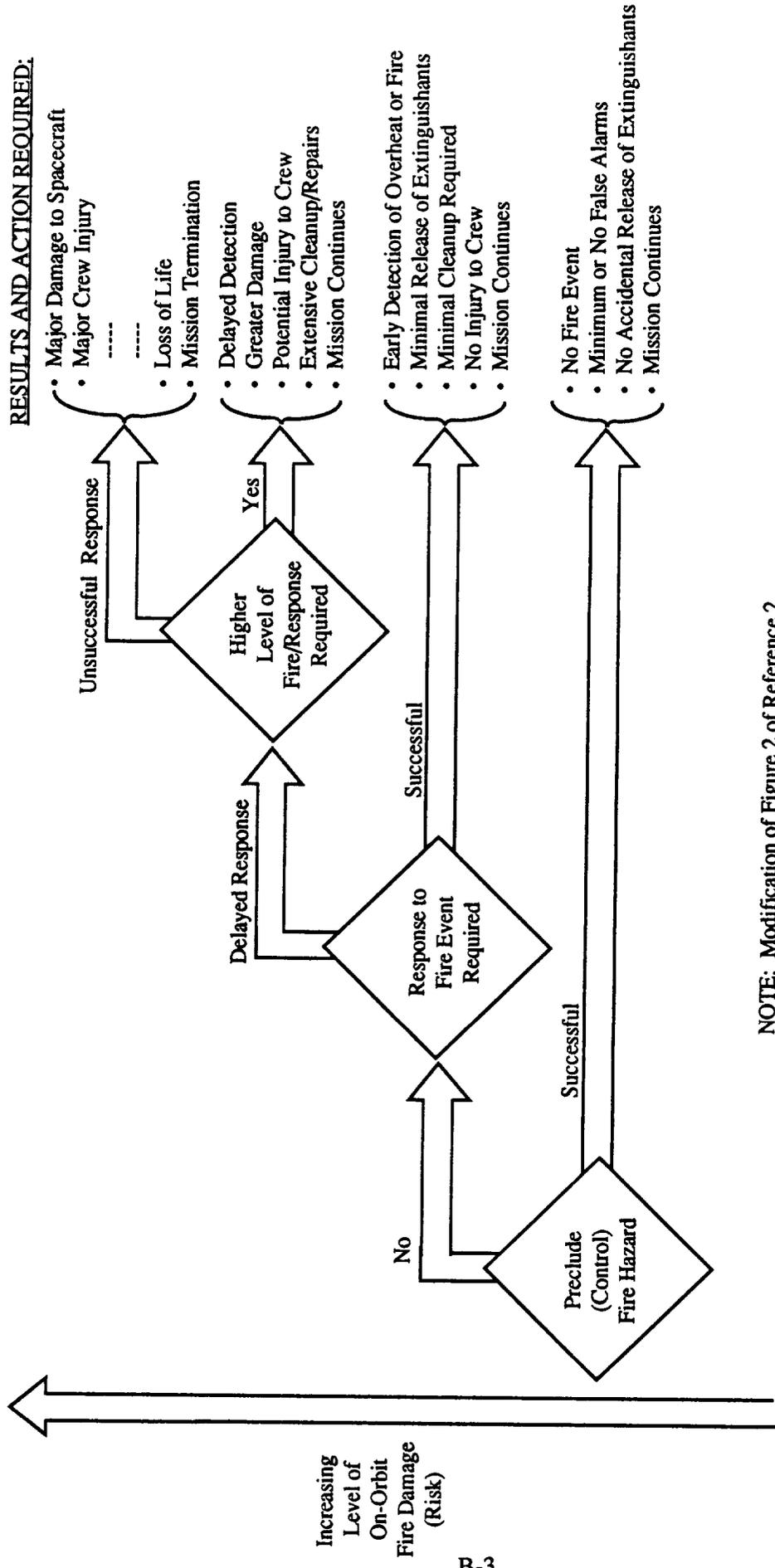
Obviously, the upper two levels of on-orbit fire damage (risk) in Figure B-1 are deemed unacceptable and, conversely, the lowest level of risk cannot be ensured. It is, therefore, a fundamental objective to enhance the fire safety of spacecraft by concentration on the strategy of responsive techniques for mitigation of fire and its precursors through appropriate recognition of the proposed research studies and technology development topics. It is with this objective that the following prioritization process steps were developed for the present effort.

B.2 STEPS IN THE PRIORITIZATION PROCESS

Step 1. Collect and assimilate technical concerns, issues and recommendations from survey of experts, in-house information, and other sources.

Step 2. Condense collected material into clearly defined recommendations for action (specifically 58 identified topics) and organize same into categories of interest. Eleven such categories were identified and include the following:

- 1.0) Atmosphere Control, Monitoring, and Post-Fire Cleanup
- 2.0) Low-Gravity Ignition, Flame Spread, and Flame Characteristics
- 3.0) Expert Systems Development (Hardware/Software)
- 4.0) Extinguishants and Fire Suppression Techniques
- 5.0) Fire Detectors and Fire Detection Systems
- 6.0) Fire Risk/Hazard Assessment
- 7.0) Human Effects and Toxicity
- 8.0) Materials and Material Configurations



NOTE: Modification of Figure 2 of Reference 2.

FIGURE B-1.

REPRESENTATION OF SPACECRAFT FIRE SAFETY STRATEGIES

9.0) Modeling of Fire Scenarios

10.0) Other Fire-Safety Related Issues

11.0) Testing and Test Standards (Ground-Based)

- Step 3. Apply the prioritization rating factors (R) and criticality weighting factors (C) listed in Table B-1 to each of the identified fire safety research studies and technology development topics. The priority factors are explained in the following section.
- Step 4. Review the rankings accomplished in Step 3. and flag those items which are a) purely programmatic, b) already in progress, and/or c) require no significant funds to complete.
- Step 5. Combine and eliminate topics and assemble into priority projects, iterate Steps 3. and 4. as necessary, and derive the prioritized array (work breakdown structure) of priority projects, presented in Figure 2-2 in the body of this report.

B.3 COMMENTS ON THE FIRE-SAFETY PRIORITY PARAMETERS

The Fire-Safety Priority Parameters outlined in Table B-1 are intended to be relatively free of institutional or subjective bias and should be easy to understand and use.

It is clear that not all of the suggested topics cover issues that can be resolved within the next approximately five years, and many of the topics cannot be fully resolved or developed to meet Space Station Freedom's Critical Design Review (May 1992). Thus, the first priority parameter (No. 1) addresses the urgency of the item relative to SS Freedom's design/development schedule. Note that a low rating factor doesn't mean that effort shouldn't be initiated immediately but simply provides a measure of schedule urgency.

The intent of Priority Parameters Nos. 2 and 3 should require no explanation. Priority Parameter No. 4 considers the status of technology as an impediment to resolution and/or development of a fire-safety topic. For example, the full acceptance of solid-state fire detection devices (micro-sensor technology) is unlikely in less than five

TABLE B-1

FIRE SAFETY PRIORITY PARAMETERS AND RATING FACTORS

FIRE SAFETY PRIORITY PARAMETER	RATING FACTOR DEFINITION (Lowest Priority, R = 1 to 2 Up to Highest Priority, R = 9 to 10)
1. Urgency to Meet Space Station Freedom Schedule	<ul style="list-style-type: none"> • Schedule to meet Space Station Preliminary Design Review: R = 9 to 10 • Schedule to meet Space Station Critical Design Review: R = 6 to 8 • Schedule important to Space Station, but cannot meet PDR/CDR: R = 3 to 5 • Urgency not high for Space Station: R = 1 to 2
2. Perceived Relevance to Other Advanced Spacecraft, Current and Future	<ul style="list-style-type: none"> • High relevance to all advanced spacecraft designs: R = 9 to 10 • Modest relevance to advanced spacecraft designs: R = 6 to 8 • Low relevance to advanced spacecraft designs: R = 3 to 5 • No relevance to advanced spacecraft designs: R = 1 to 2
3. Anticipated Value to Micro-gravity Combustion Science: Fire Safety Emphasis	<ul style="list-style-type: none"> • Highest scientific value: R = 8 to 10 • Modest scientific value: R = 5 to 7 • Lower scientific value: R = 2 to 4 • Little or no scientific value: R = 1 to 2
4. Perceived Status of Enabling Technologies (As An Impediment to Issue Resolution)	<ul style="list-style-type: none"> • No new technology required: R = 9 to 10 • Very little new technology required: R = 6 to 8 • Required technology available in two-three years: R = 3 to 5 • Required technology unlikely to be available in less than 5 years: R = 1 to 2
5. Extent of Low-Gravity Testing Required	<ul style="list-style-type: none"> • Little or no low-gravity testing required: R = 8 to 10 • Short duration, low gravity tests required (e.g., drop tower, aircraft, suborbital rocket, etc.): R = 5 to 7 • Extended duration low-gravity testing required (e.g., STS Space Shuttle, Spacelab, etc.): R = 1 to 4
6. Anticipated Cost of Effort (May Include New Capital Equipment)	<ul style="list-style-type: none"> • Low cost (no new capital equipment): R = 9 to 10 • Modest cost (including modest equipment): R = 5 to 8 • High cost (extensive manhours and/or major capital equipment costs): R = 1 to 4
<p>Criticality Weighting Factor, C: Highest Criticality, C = 7 to 10 Lowest Criticality, C = 1 to 3</p>	
<p>NOTE: Apply weighting factors only to Fire Safety Priority Parameters 1 and 2.</p>	

years. Although this technology may be highly desirable, NASA should not be required to fully underwrite its development since there are acceptable alternative detectors.

Fire-Safety Priority Parameter No. 5 (Extent of Low-Gravity Testing Required) requires some explanation. The high value of the rating factor ($R = 8$ to 10) defined for the case where "little or no low-gravity testing is required" is simply a recognition of the limited access to the test environment of low gravity. Priority Parameter No. 5 is also indirectly related to cost (No. 6). The greater the need for low-gravity testing (e.g., via Spacelab), the greater the cost.

Finally, the Criticality Weighting Factor (C) is to be applied to Priority Parameters Nos. 1 and 2, only. These factors are intended to allow judicious recognition of the urgency and relevance of selected items. For example, the development of "expert" fire detection/suppression systems (Topic No. 3.2 of Table 2-1) is clearly one of the most important and relevant fire-safety efforts. The technology is available, little low-gravity testing is required, and the development cost should be modest.

APPENDIX C

REVIEW OF SPACECRAFT FIRE PROTECTION



APPENDIX C
REVIEW OF SPACECRAFT FIRE PROTECTION

Kimzey, John Howard
Consultant

Several philosophies have guided the design of systems in manned spacecraft during the last 27 years. Some approaches have been well thought out, using an appropriate balance of engineering and physiological guidelines. Others have at times been somewhat arbitrary. The items discussed here include the atmosphere of the cabin, the crew requirements (clothing, hygiene, rest and work schedules, etc.), material selection, fire detection, fire extinguishment, caution and warning systems, and crew attitude and housekeeping. Table C-1 shows how in-flight protection varied as dictated by the various design requirements.

C.1 ATMOSPHERE

Conservatism dictated a pure oxygen atmosphere for the cabin of Mercury, and this atmospheric composition was continued in subsequent programs, Gemini and Apollo. But conservatism is a valid description from only one perspective, not from all viewpoints. Above the earth's atmosphere, the probability of a meteoroid hit was considered to be unacceptably high. So, if the assumption is that a hit would puncture the cabin wall and violate the pressure integrity, the crew needed a pressurized suit to survive. And, if suited, the crewman needed sufficient oxygen to sustain normal breathing, but at a low enough total pressure to enable mobility of arms and legs. This resulted in the need for the atmosphere to be pure oxygen.

Subsequent experience showed that damaging hits from space debris were not the problem that was anticipated, and so the shirt sleeve environment necessitated for long duration flights (starting with Gemini 4) gradually became the norm for space crewmen.

Skylab was the first vehicle to baseline a two-gas system, although Apollo launched with a two-gas atmosphere and went to pure oxygen on orbit. The Skylab environment was 65 percent oxygen and 35 percent nitrogen at 5.2 psia (36 kPa) even though the Apollo Command Module, used for crew transfers, still had pure oxygen as its atmosphere.

TABLE C-1
SPACECRAFT FIRE PROTECTION

SPACECRAFT	IN-FLIGHT ATMOSPHERE*	CREW CLOTHING	MATERIAL SELECTION (Flammability Standpoint)	FIRE DETECTION**	FIRE EXTINGUISHMENT
Mercury, MR-3, 4, MA-6, 7, and 8	Oxygen at 5 psia (34 kPa)	Pressure suited	Good	Human Senses	Dump Atmosphere
Mercury, MA-9	Oxygen at 5 psia (34 kPa)	Partially unsuited	Good	Human Senses	Dump Atmosphere
Gemini GT-3, 8	Oxygen at 5 psia (34 kPa)	Pressure suited	Good (except for sponge cloth)	Human Senses	Dump Atmosphere
Gemini GT-4, 5, 6, 7, 9, 10, 11, and 12	Oxygen at 5 psia (34 kPa)	Pressure suited for launch and entry	Good (except for sponge cloth)	Human Senses	Dump Atmosphere (after suiting)
Apollo 7, 8, 9, 10 and 13	Oxygen at 5 psia (34 kPa)	Pressure suited for launch and entry	Very good	Human senses	Foam
Apollo 11, 12, 14, 15, 16, and 17	Oxygen at 5 psia (34 kPa)	Pressure suited for launch and entry	Very good	Human Senses	Foam
Lunar Module	Oxygen at 5 psia (34 kPa)	Pressure suited for lunar surface travel	Very good	Human Senses	Foam and water gun
Apollo-Soyuz	Oxygen at 5 psia (34 kPa)	Pressure suited for launch and entry	Very good	Human Senses	Foam
Skylab	65 oxygen, 35 nitrogen at 5.2 psia (36 kPa)	Pressure suited for launch, EVA, and entry	Very good	Thirty ultra-violet	Foam and water hose
Orbiter 1-4	Sea level air (21% O ₂ at 14.7 psia) Typically 22-25%	Pressure suited for launch and entry	Very good	Nine ionization type smoke detectors	Halon 1301 3-fixed, Avionics 2-portable
Orbiter 5-25	Sea level air	Shirt sleeve	Very good	Nine	Halon 1301
Orbiter STS-26	Sea level air	Pressure suited for launch	Very good	Nine	Halon 1301

- NOTES:**
- *The atmosphere inside the spacecraft during some ground operations is increased to more than atmospheric (as much as 21 psia or 145 kPa) pressure with pure oxygen. Mercury, Gemini, and Apollo 1 applies.
 - **Human senses implies smell, sight, sound, and touch in whatever combination. For spacecraft with electronic fire detection, these still apply, particularly when the crew disables the system for preventing false alarms.

The Orbiter made the final change by selecting 21 percent (nominal) oxygen at 14.7 psia (101 kPa) with nitrogen as the inert gas. For the Space Station Freedom, the consensus of the scientific community insists on an atmosphere similar to sea level air in order that normal-gravity ground data can be compared directly with low-gravity in-flight observations.

C.2 CREW REQUIREMENTS

Clothing was selected primarily for comfort. Pressure suits selected for Mercury were modified somewhat for Gemini as one of the mission requirements involved an EVA (extra-vehicular activity) with severe radiation levels not found on earth. Apollo suits had the additional requirement, in the case of those who would explore the moon, of longer periods of self-sufficiency plus the added protection from abrasion by the use of extra gloves and footwear. But, it wasn't until the fifth Orbiter flight that sufficient confidence was established to have the crew perform launch and landing operations without a full pressure suit and ejection seats. That confidence was abruptly shaken by the Challenger accident, however, with the result that the STS-26 Discovery crew had to have very elaborate (and heavy) suits with life support aids designed for an open-ocean recovery: a life raft and two liters of drinking water, etc.

Flight suits (coveralls with long sleeves), underwear, socks, caps, and various footwear have been used. Apollo in-flight clothing was PBI and Durette. The Shuttle started out with flame-retardant cotton and switched to Nomex in STS-25 because of linting. Shorts and T-shirts are worn when possible. Materials include cotton (underwear and socks), Nomex, beta-cloth (fiberglass), and a variety of materials for EVA suits: neoprene-coated nylon, teflon fabric, aluminized mylar, dacron, silicone rubber, polycarbonate, polysulfone, etc. Some of these were selected for their non-flammable characteristics in a selected atmosphere; others were selected with a waiver as no acceptable substitute was available.

Sleep periods were scheduled as close as possible to match those the crew had grown accustomed to, and all slept at the same time. In such confined quarters, it was felt the activity of some would disturb the sleep of others. Hygiene facilities were somewhat primitive. Only on Skylab was a shower provided. The Shuttle has a private toilet and provision for a wet cloth bath. Shaving was waived by some men while others apparently shaved at the last minute before a public appearance. Highly

flammable paper (tissue, notebooks, etc.) and highly flammable cotton towels and face cloths were on-board and in use.

Crew preference items were also allowed, such as the "Hello Mom" and "Ajax Delivery Service" signs of earlier flights and the five Hawaiian shirts of STS-26, with no attempt to meet material selection criteria.

C.3 MATERIAL SELECTION

Engineering properties formed the basis for selecting a given material, with toxicity and flammability placing a close second in the priority system. In addition, for metals, their fracture corrosion and stress corrosion properties were a guide as well.

Testing a material for acceptability was done in accordance with a NASA Headquarters document, NHB 8060.1 from November 1971 to February 1974, NHB 8060.1A from February 1974 to September 1981, and a B-revision after that. A C-revision, now under review, will undoubtedly apply for the Space Station. For materials that do not pass or qualify according to the approved testing, a waiver is granted. Historically, the majority of these have been granted for flammable materials to be located inside the crew cabin. The Orbiter has had two toxicity waivers and about thirty Rockwell and sixty GFE (government-furnished equipment) flammability waivers. For example, the face plate of the EVA suit is made of polycarbonate, an impact resistant transparent polymer which is highly flammable in oxygen. Also, among the EVA helmet construction materials is polysulfone, which is also flammable in air. Similarly, the use of cotton, as previously stated, was waived as synthetic substitutes do not have the water absorbency or comfort characteristics, and most are flammable as well. The major flammability waivers are for suits, towels, data files, foam cushions in lockers, velcro, and PVC (polyvinyl chloride) used in medical wiring harnesses and tubing.

In addition to selecting the proper material for specific environments, there has been a variety of constraints on the materials. Thus far, the philosophy is that if a potentially catastrophic occurrence initiates, the system is designed to contain the problem. If, for example, a motor overheated and a fire started, it would self-extinguish before heat or toxic effects would disable the crew. This is exactly what happened when a wire shorted and charred in STS-6, but no propagation of a fire took place.

An instance of how this design constraint is applied is in the placing of velcro (hook) on the cabin walls. In order to prevent a fire path of the nylon, which is flammable in air, velcro is limited to four square inches (25 cm²) at a time with at least a two-inch (5-cm) gap between it and other flammables. Food wrappers, paper, towels, etc. are also managed in such a way as to minimize fire propagation. In the Gemini, however, this was not a strict design constraint. Most interior surfaces were "carpeted" with a water absorbent maze of cellulose acetate called "sponge cloth" to reduce the effects of annoying spills (water, fruit juice, urine, etc.). This material burned extremely rapidly in the spacecraft's oxygen environment. In the case of Apollo, the design was far more fire-safe, yet the large block of polyurethane foam that was used for ground testing of the Command Module to cushion the hatch of Apollo 204 greatly contributed to that January 1967 catastrophe. This happened as a result of emphasizing in-flight safety in a far more rigid manner than pre-flight activities. An excellent critique of that accident and its consequences is documented in "Apollo Expeditions to the Moon," a publication designated NASA SP-350. George M. Low, the Program Director, listed "Three Mistakes" on page 73 of that publication, concluding that they "added up to a spark, fuel for a fire, and an environment to make the fire explosive in its nature. And three fine men died."

C.4 ELECTRICAL SYSTEMS

The use of circuit breakers as a means to prevent accidental ignition has its own potentially conflicting design considerations. From a reliability standpoint, there is a built-in allowable overload capability which is designed to prevent circuit interruption from a momentary power surge. But, from a fire safety standpoint, any overload is highly undesirable. Thus, a tension exists between safety and continued performance.

Another design conflict that has an effect on accidental fire is the practice of combining several circuits with a single circuit breaker. The advantages from a weight and reliability standpoint are obvious. But, a short in a minor circuit that draws less than five amperes may cause localized overheating to the point where the conductor melts before a fifteen or twenty ampere circuit breaker responds and opens the circuit.

C.5 FIRE DETECTION

The human senses provide an excellent means of identifying an accidental fire nearby in a confined space such as the Mercury, Gemini, and Apollo spacecraft, provided the human is healthy and alert. Thus, when the mission plan involved sleep, as in the last Mercury flight, Gemini 4, and subsequent flights, this means of fire detection is inadequate. A survey of possible types of fire detectors was prepared by the Manned Spacecraft Center, J.H. Kimzey, on 12 January 1971 and forwarded to the Apollo Office. Skylab provided the first in-flight fire detector, using thirty ultra-violet, line-of-sight, devices placed throughout the vehicle. The Orbiter uses nine ionization-type smoke detectors, which respond to particulates of flame precursors.

C.6 FIRE EXTINGUISHMENT

For crewmen already in a pressure suit in a spacecraft and breathing pure oxygen, the atmosphere can be vented to space in the event of an accidental fire. But man cannot live very long in such confinement. Eating, using the toilet, and other mundane chores such as exercise or performing experiments cannot be done efficiently that way.

Apollo had a fire extinguisher, consisting of a pressurized can that delivered upwards of four cubic feet (0.1 M^3) of foam, which displaced the oxygen surrounding a blazing electrical component when its nozzle is inserted into the selected opening in the instrument panel. The Lunar Module had a water "gun" for reconstituting dehydrated food, which was designated a fire extinguisher.

Obvious limitations of the Apollo foam extinguisher destined it to oblivion. For Skylab, one of the ten water tanks (lightly pressurized) was fitted with a long garden-type hose so water could be directed in ample quantity to extinguish a fire, or keep it from spreading.

Weight considerations resulted in the selection of Halon 1301 for the Orbiter. Water is provided in very limited amounts, and the decreased concentration of oxygen in the atmosphere make this gas an excellent choice, particularly in the Avionics Bay. Portable extinguishers holding a 2-1/2 pound (1.1 kg) charge are provided in the crew cabin. Tests recently completed with human subjects in normal gravity show no measurable effect from breathing this gas (bromotrifluoromethane) in one percent

concentrations for twenty-four hours. That concentration represents the maximum which would result if all on-board extinguishers were emptied in the absence of a fire. If used in a fire, the breakdown of that material when added to the smoke of the consumed material would produce a variety of toxic and extremely corrosive gases.

C.6 CAUTION AND WARNING SYSTEMS

Automatic on-board monitoring of the atmosphere and means to alert the crew for off-nominal conditions has long been a major design consideration. Various items have been included throughout the space program. In addition to a drop of cabin pressure, a drop in oxygen partial pressure, a rise in carbon dioxide, and the presence of various contaminants in the atmosphere are examples. During the Apollo 11 Lunar Module descent to the moon, at six thousand feet (1800 M) above the lunar surface, a yellow light came on "and we encountered one of the few potentially serious problems in the entire flight" reports Michael Collins who was flying the Apollo at the time and who heard Aldrin say, "program Alarm. It's a 1202." Collins decoded that to mean "executive overflow," meaning simply that the computer has been called upon to do too many things at once and is forced to postpone some of them (NASA SP-350, page 210).

C.7 CREW ATTITUDE

The crew's role in fire protection cannot be over-emphasized. Each individual has his or her own background with an accidental fire, as well as experience level in fighting fires. We all have thousands of hours (specifically 8766 hours per year) living, sleeping, and working in surroundings that are typically quite flammable, yet only moderately hazardous considering the options. For one thing, we normally can leave the area - whether a residence, an office, a hotel room, an industrial shop, or an automobile - and leave the situation for the experts to deal with. For ships and aircraft, escape is not always an option, and the situation becomes more complex, but very few of us have crises like this in our personal experiences. So, we have a relatively casual attitude about accidental fires.

In space, there are several things lacking that we have previously taken for granted. With no fire department to summon and with no life boats or parachutes for crew exit, the isolation results in total dependence on just those on board who are available to help. At least in the Orbiter, as well as other low altitude orbiting vehicles, a landing is possible in about two hours or less.

For the Space Station Freedom, the likelihood of a shuttle vehicle being available on standby for months at a time is highly unlikely or, to put it another way, very expensive. Thus, the crew awareness of the criticality of their situation must be faced early in their training, in the selection of items brought on board, and in the scheduling of activities on board the Station.

C.8 SPACE STATION HOUSEKEEPING

Special concern in the mind of fire protection engineers is the area of housekeeping. Included here is the orderly placement of things, the general cleanliness of living and working areas, and the identification and disposal of trash. Much material is packed into every spacecraft: work items, sustenance items, recreation items, backup system items, etc. For many spaceflights, no doubt, there is an in-flight orientation needed. "Where is locker D-19?" and "Isn't there supposed to be a thing-a-ma-jig to turn this?" And with as many as seven or eight people sharing such confined spaces, there is much room for creativity, such as in finding a better place to store the mustard. Then, there is the eternal problem of unpacking an optic, using it, and restoring it for return to earth. Everybody over five years old has experienced the frustration of simply putting the several items back in the carton recently opened and which appeared to be so logically fitted together. Add to that the zero gravity environment and we have the wonderment expressed by Skylab crewmen when things carefully placed where they could be found later had simply disappeared.

Short spaceflights tended to impress the crew with the fact that there would soon be a day of reckoning when everything had to be stowed for the re-entry. For longer stays, as expected in the Space Station, it will become tempting to include "Mañana" in the priority system.

Cleanliness is another area that has to be addressed directly. The design of interior surfaces must preclude those out-of-sight dark areas where an item can and will nest for months. In addition, crew training must include appropriate reasons why fluids, food residues, chemicals from experiment packages, soiled tissues, etc. can cause corrosion, damage electrical insulation, interfere with thermal control, and otherwise contribute to starting an accidental fire.

The identification and stowage of trash is probably the most significant area in which we have learned little in the twenty-seven years of spacecraft use. Spontaneous ignition is mysterious enough in earthly spaces. In zero gravity, we may learn the hard way what it means to simply toss our discards into the trash-master and leave the packages in the designated place for pickup in as much as three months when the next crew transfer takes place. Perhaps for a dead test rodent or other biological specimen, the inevitable odor will dictate special handling. But other more subtle items may escape optimum treatment. Food scraps, alcohol wipes, film wrappers, adhesive tape, torn fabrics, paper, old batteries, monkey feces, and unknown gunk from some experiment may prove to be relatively incompatible.



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16. Abstract A detailed review identifies spacecraft fire-safety issues and the efforts for their resolution, particularly for the threats posed by the increased on-orbit duration, size, and complexity of the Space Station Freedom. Suggestions provided by a survey of Wyle consultants and outside fire-safety experts were combined into 30 research and engineering projects. The projects were then prioritized with respect to urgency to meet Freedom design goals, status of enabling technology, cost, and so on, to yield 14 highest-priority projects, described in this report in terms of background, work breakdown structure, and schedule. These highest-priority projects can be grouped into the thematic areas of fire detection, fire extinguishment, risk assessment, toxicology and human effects, and ground-based testing. Recommendations for overall program management stress the need for NASA Headquarters and field center coordination, with information exchange through spacecraft fire-safety oversight committees.					
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