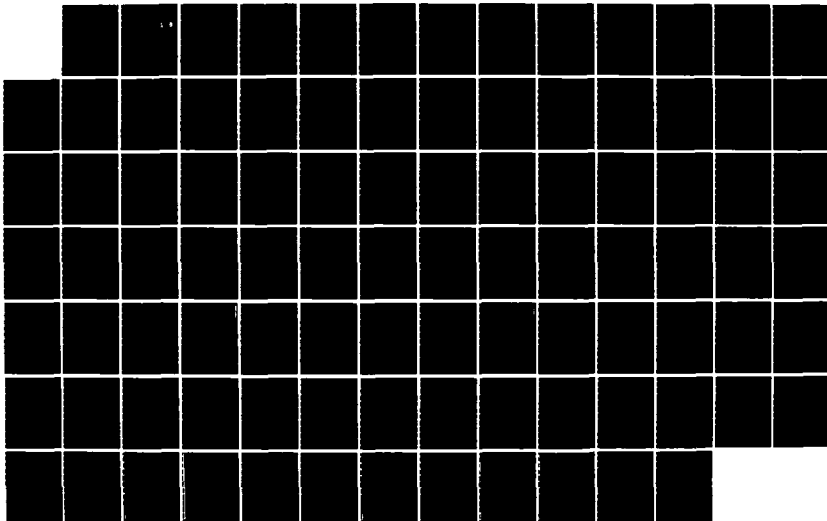
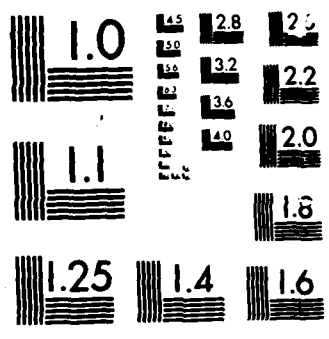


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UNCLASSIFIED F33615-76-C-2127 F/G 13/12 NL





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NOVEL FIRE SUPPRESSION MATERIALS
FOR ADVANCED AIRCRAFT

FINAL REPORT

S. ATALLAH
D. P. CROWLEY



REPORT JTCG/AS-76-T-011

MARCH 1978

PREPARED FOR

THE JOINT LOGISTICS COMMANDERS
JOINT TECHNICAL COORDINATING GROUP
ON

AIRCRAFT SURVIVABILITY

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FOREWORD

The work reported herein was performed by Arthur D. Little, Inc., under United States Air Force Contract F33615-76-C-2127. Mr. R. E. Cretcher of the Air Force Wright-Patterson Aeronautical Laboratories, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, was the technical project officer.

This study is part of Phase II of a four-phase program sponsored by the Joint Technical Coordinating Group for Aircraft Survivability (JTCG/AS). Phase I of the program addressed the definition of the environmental and operating requirements for extinguishing systems on advanced aircraft. Phase II addresses the selection and testing of candidate extinguishing agents. Under Phase III, an engine bay fire test simulator is being constructed to be used for conducting more realistic fire suppression tests. Phase IV is expected to result in the development of advanced, more effective fire extinguishing systems for aircraft of the 1980's.

This technical report was submitted by the authors 16 March 1978. The report has been reviewed and is approved.



Note: Product trade names are used in this report. The use of trade names does not constitute U.S. Air Force or Arthur D. Little, Inc. endorsement of these products.

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powders (-325 mesh) and a 0.8:1 lithium chloride/water solution were selected on the basis of tests in a tunnel in which air was allowed to flow at 18 fps. The test surface was a 6 x 6-inch (15 cm x 15 cm) square heated to about 1700°F (927°C) with JP-4 impinging on it at about 100 cc/s.

A comparison was made among the requirements for a Halon 1301 versus a potassium bicarbonate automatic extinguishing system. The analysis showed that the latter system, with a reliability of only 80% (thus necessitating the use of three redundant systems to achieve 99.2% total reliability) demands smaller volume and weight penalties than a system utilizing Halon 1301.

54. *Salix glauca* L.
 55. *Salix glauca* L.
 56. *Salix glauca* L.
 57. *Salix glauca* L.
 58. *Salix glauca* L.
 59. *Salix glauca* L.
 60. *Salix glauca* L.

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1.0 INTRODUCTION

1.1 BACKGROUND

Fires in engine/nacelle and dry bay areas of advanced military aircraft are expected to occur under environmental conditions which differ markedly from those that prevail on subsonic or low-Mach number supersonic aircraft. The present and projected flight envelopes of advanced military aircraft pose severe limitations on the effectiveness of halon-base fire extinguishing systems currently employed in many aircraft. Maximum suppressant temperatures encountered during storage are very high; so are ambient and bleed air temperatures as well as the temperatures of the engine surface and the outside skin of the aircraft. Furthermore, combat wounds may result in air flow into the fire area at speeds ranging between 350 fps (107 ms^{-1}) in advanced engine/nacelle enclosures to 150 fps (46 ms^{-1}) in dry bay areas. Such high air velocities quickly dilute and exhaust the vaporizing halon agents and provide a continuous supply of oxygen to the fire. The fire may be the result of the accidental release and ignition of the aircraft fuel, hydraulic fluid or engine oil. The hot engine surface and bleed air temperatures as well as incendiary projectiles and electrical sparks are potential ignition sources.

To reduce the potential for aircraft damage and loss of mission due to fire, the United States military services have been interested in selecting and utilizing effective fire suppression agents which are capable of extinguishing and controlling fires in engine/nacelle areas (primarily) and dry bay enclosures under the extreme environmental conditions that may prevail in current and advanced military aircraft. Since there are no commercially available fire extinguishing agents that can economically cope with fires under these conditions, a research program was conducted at Arthur D. Little, Inc. to develop, test and select novel effective extinguishing agents for fires aboard military aircraft of the 1980's.

1.2 OBJECTIVES

The objectives of this program were to select and test a number of novel candidate fire suppression and control agents and to identify one or two materials that may be effective in controlling fires for a period of five minutes, primarily in engine/nacelle areas under conditions similar to those that may prevail on current and advanced military aircraft.

1.3 SCOPE OF WORK

To achieve these objectives Arthur D. Little, Inc. planned to conduct a program consisting of the following tasks:

Task 1 - State of the Art Review and Selection of Candidate Agents

The state of the art of fire extinguishing technology and the chemical and physical properties of such materials as polymeric foams, gelled halons, intumescent materials and low-melting point inorganic hydrates, salts, clays and glasses were to be reviewed. About a hundred candidate materials or combinations of materials were to be selected for experimental evaluation. This selection was to take into consideration published data on the compatibility of the materials with aircraft components, ease of storage and application, toxicity and thermal stability.

Task 2 - Research and Development Plan

A detailed research and development plan for testing the candidate materials in the laboratory and for selecting the most promising materials for final testing at NASA-Ames was to be prepared and approved by the Contract Monitor. The plan was to include the proposed design of a preliminary screening fire test facility and the criteria to be used for rejecting or selecting candidate materials. Also to be included in the plan were details of exposure, environmental, and material compatibility tests to which candidate suppressants were to be subjected.

Task 3 - Preliminary Experimental Screening of Suppressants

A laboratory bench-top engine simulator and agent dispersing device were to be designed, constructed and used to conduct the preliminary screening of candidate materials. Selected tests were to be documented with still and ciné photography. A few agents were to be selected for further evaluation at NASA-Ames' test facility.

Task 4 - Environmental and Compatibility Consideration

An experimental evaluation of the compatibility of the selected agents with aircraft materials under the extreme conditions encountered during storage was to be conducted. Pertinent physical, chemical and toxicological properties of the materials were to be collected from the literature.

Task 5 - Suppressant Systems Concepts and Trade-Off Analysis

Potential systems concepts for the storage, distribution and application were to be developed for the material(s) that appeared most promising by the NASA-Ames tests. A trade-off analysis was to be conducted to identify optimum systems taking into consideration such factors as weight and volume penalties, initial and maintenance costs, mechanical complexity, improvement in fire control effectiveness over present systems, advantages and disadvantages over present systems and anticipated reliability.

2.0 TECHNICAL DISCUSSION

2.1 DEFINITION OF THE PROBLEM

2.1.1 The Fire Environment

The anticipated conditions surrounding the ignition of flammable liquids aboard advanced military aircraft and the growth and propagation of the resulting fire differ considerably from the conditions surrounding fires in subsonic or low-Mach number aircraft. An analysis conducted by General Dynamics [1] for the U.S. Air Force delineated these conditions for vulnerable dry bay and engine/nacelle areas of current and advanced aircraft. Basically, the following combination of conditions which are expected to prevail on advanced aircraft define the worst environment in which a fire suppression system must be able to operate effectively:

1. Suppressant storage temperature range of -65 to 500°F , (-54 to 260°C),
2. Engine case temperature of 1500°F (816°C) and dry bay skin temperature of 550°F (288°C),
3. Bleed air temperature of 1300°F (704°C),
4. Ambient air temperature range of -65 to 650°F (-54 to 343°C), and
5. Air flow velocities of 350 fps (107 ms^{-1}) in advanced engine/nacelle areas and 150 fps (46 ms^{-1}) in dry bay areas.

In addition to the above operating conditions, air flow in the various engine nacelle areas may be significantly altered as a result of combat damage. In such an event, localized air temperatures and velocities may increase. Incendiary projectiles or fragments may become sources of ignition where combustible fuel and hydraulic oil lines or components are damaged.

Vented or nonvented dry bay areas which contain combustible fluid components or are located adjacent to fuel tanks do not normally contain a source of ignition. However, a incendiary projectile, high velocity fragments, hot aircraft surface fragments or damaged bleed air ducting may become sources of ignition.

A projectile impact can cause a significant change in the level of hazard. Holes of up to 2 ft^2 ($.18 \text{ m}^2$) can be expected. These penetrations can affect air flow in vented compartments and induce airflow in nonvented compartments. In addition to providing an ignition source, the projectile may damage combustible fluid components, causing leakage, it may also damage electrical components providing additional sources of ignition, and carry the effects of a fire in one compartment to an adjacent one. Moreover, changes in air flow patterns and velocities can lead to a rapid dissipation of the extinguishing agents thus substantially diminishing its effectiveness.

Flammables of primary concern include JP-4 fuel, hydraulic fluid (MIL-H-5606) and engine oil (MIL-L-7808).

2.1.2 Limitations of Present Fire Suppression System

Fire suppression systems on most aircraft presently employ a halon system which is either manually or automatically activated. Continuous line heat detectors are generally used to indicate the presence of a fire. Regardless of the type of halon used (typically Halons 1301, 1011, 1202), flame extinguishment is achieved as a result of the vaporization of the halon, its dissociation in the flame, and the interference of the generated free radicals with the flame chain reactions.

To achieve continuous extinction of the flame, the halon agent must be present in the proper concentration (typically 5-10%), until ignition sources, the fuel, or the supply of oxygen are eliminated. Such conditions cannot be easily met on advanced or combat damaged aircraft where high air flow rates and high wall and bleed air temperatures are expected to be present for a prolonged period of time. An

excessive amount of halon would be required to keep the fire extinguished for an adequate period of time capable of allowing the walls to cool down and/or for the fuel supply to be shut off. Other traditional extinguishing agents such as water, aqueous foams, carbon dioxide and dry chemicals suffer from similar drawbacks. In addition, some of these agents cannot be used or stored at the temperature extremes expected in advanced aircraft.

2.1.3 General Considerations for Selecting Candidate Fire Suppressants

An effective agent for extinguishing fires in the engine/nacelle and dry bay areas of advanced aircraft must operate under a number of very severe conditions which have already been discussed. Ideally, it would be desirable if the agent is either a liquid or solid powder that withstands the anticipated high storage temperatures, operates at low temperatures, expands immediately upon application to the fire area and forms an inert solid matrix that cannot be swept away by the high air velocities. Organic and inorganic foaming systems immediately suggest themselves as potential candidates. However, there is always a time delay for any foaming system to operate. During the time period that foaming agents are still in their liquid or solid form and are expanding, they may be carried away by the high velocity air stream. A potential solution would be to use a liquid or solid agent that can adhere to the hot surfaces of the fire area, melt (if it is a solid), generate relatively inert, preferably non-toxic gaseous products, froth and eventually produce a solid insulating foam. Such a foam would separate the fuel from the hot walls, flow around, cover, and smooth out many obstructions which serve as flame holders and may also result in reducing the size of the opening in the damaged wall.

A review of currently available fire extinguishing agents was made to see if any could behave in this fashion and at the same time meet the environmental and operational requirements of advanced aircraft. In addition, many chemicals were selected and screened, first by examining their published properties and later through experimental observations. The results of these efforts are described below.

2.2 APPLICABILITY OF CONVENTIONAL EXTINGUISHANTS

Commercially available extinguishing systems are designed to take advantage of the capabilities of relatively inexpensive chemicals to extinguish specific types of fires encountered in industrial, institutional, and residential occupancies. These agents are:

- Water, sometimes modified with anti-freezing agents,
- Foams of various kinds such as protein, fluorocarbon, high expansion and aqueous film forming foams,
- Dry Chemicals: monoammonium phosphate, potassium bicarbonate, sodium bicarbonate/urea base agent,
- Halons^{*}: 1211, 1301, 2402, 1011,
- Carbon Dioxide, and
- Extinguishing agents for metallic fires.

The use of water or aqueous foam systems for the proposed application in advanced aircraft presents certain problems. Because of the high temperature differential between the engine surface and the water or aqueous foam, film boiling will take place where a film of vapor will separate the agent from the hot surface. Like a drop of water applied to the surface of a hot stove, the water forms globules which run off without cooling the hot surface because of poor contact. A specific problem encountered by aqueous foam systems is that there are no commercial foams capable of operating at -65°F (-54°C). Lithium Chloride (LiCl) has been used to lower the freezing point of water to -65°F (-54°C) but at the concentrations it is used, it will destroy any

* Halon numbers indicate the numbers of carbon, fluorine, chlorine and bromine atoms present in the molecule in this order.

foaming agent. Since the presence of LiCl may alter the behavior of water on a hot metallic surface LiCl/water solutions were chosen for testing in this program even though it was recognized that at a storage temperature of 500°F (260°C), all water-base systems will vaporize into steam generating a pressure of about 680 psi (4688 KPa) and thus requiring thick walled storage containers. It was assumed that if a water-base system is adequate for the proposed use, insulating the container against 500°F (260°C) might be economically feasible for the short durations that such temperatures are reached during a typical flight mission.

Some of the dry chemicals had already been tested by NASA-Ames for the proposed application with promising results. Since dry chemicals will operate at -65°F (-54°C) with no problem and because they are capable of withstanding exposures to relatively high storage temperatures, they were all recommended for testing in this program.

As indicated earlier, halons are presently used in engine nacelles of military aircraft. However, the anticipated operating conditions in advanced aircraft are such that any halon used will be quickly dissipated by the high air velocities expected. Unless a continuous supply of halon is available, the fuel impinging on the hot engine surface will reignite as soon as the halon is exhausted. The only possibilities for halons may be if certain additives were used to enhance contact with the hot surface and to supplement the capability of the halon either by cooling the surface or forming a solid insulating foam. Such possibilities are discussed in paragraph 2.3 below.

Unlike halons which extinguish fires by reaction inhibition, carbon dioxide extinguishes fires by inerting. A large concentration of CO₂ (typically 30-40% vs. 5-10% for halons) is needed to reduce the oxygen concentration to a point which will not support combustion. Thus, for protecting a given volume against fire, a much larger volume of CO₂ must be present in air than any halon agent. For this reason and because CO₂ tends to solidify and choke the delivery system when applied at low temperatures, CO₂ has not found much use in engine nacelles of present day aircraft.

Extinguishing agents that have been tested or used on metal (e.g., magnesium) fires include eutectic mixtures of salts which melt at the burning metal surface excluding it from air and cooling it below the ignition temperature. Such an approach was considered to have a potential application to advanced aircraft engine nacelle fires where high wall temperatures are encountered. Another agent used for extinguishing metal fires is trimethoxyboroxine (TMB) which burns and leaves a glassy deposit of boric oxide (borax) on the surface of the metal. This and other chemicals which behave in a similar manner were also considered for the proposed application although burning agents like TMB were not considered particularly desirable for in-flight aircraft.

2.3 NOVEL APPROACHES TO FIRE SUPPRESSION

Several approaches were considered for extinguishing fires in engine nacelle areas of advanced aircraft. As a result of these considerations, a long list of candidate chemicals and combinations of chemicals was generated. As screening tests progressed, some agents were eliminated from the list without testing because tests on chemicals having a similar structure indicated that that category of chemicals was not adequate for the proposed application. On the other hand, other chemicals were added to the list as suggested by the results of tests on related chemicals. Table 2.1 is a comprehensive list of all chemicals considered for testing. The rationale for selecting these agents and categories of chemicals is discussed below.

2.3.1 Modified Halons

As indicated earlier, pure halons are not adequate for the proposed application. However, because of the potential for retrofitting existing halon systems if modified halons can be used and because of the familiarity of the aircraft industry with halons, it was deemed worthwhile to consider the potential for modified halons for this application.

TABLE 2.1

CHEMICALS EVALUATED DURING SCREENING PROGRAM

1. HALONS AND MODIFIED HALONS

Halon 2202 (1,2-dibromo 1 difluoroethane)

Halon 2202 + Cab-O-Sil M5
Halon 2202 + boric acid

Halon 2402 (dibromotetrafluoroethane)

Halon 2402 + Cab-O-Sil M5
Halon 2402 + Cab-O-Sil HS5
Halon 2404 + Tullanox 500
Halon 2404 + boric acid

Halon 1011 (bromochloromethane or CB)

CB + Cab-O-Sil M5
CB + boric acid
CB + Fyrol 6

Halon 1002 (dibromomethane)

Dibromomethane + Cab-O-Sil M5
Dibromomethane + boric acid

Halon 1211 (bromochlorodifluoromethane)

Halon 1301 (bromotrifluoromethane)

Halon 2402 Slurries

Halon 2404 (87%): $\text{NH}_4\text{H}_2\text{PO}_4$ (21%):Cab-O-Sil (1%)
Halon 2402 (87%): KHCO_3 (21.1%):Cab-O-Sil (1%)

2. INORGANIC CHEMICALS

Li_2CO_3	Lithium carbonate
Na_2CO_3	Sodium carbonate
K_2CO_3	Potassium carbonate
CaCO_3	Calcium carbonate

TABLE 2.1 (continued)

MgCO_3	Magnesium carbonate
NaHCO_3	Sodium bicarbonate
KHCO_3	Potassium bicarbonate
NaF	Sodium fluoride
NaCl	Sodium chloride
NaBr	Sodium bromide
NaI	Sodium iodide
KF	Potassium fluoride
KCl	Potassium chloride
KBr	Potassium bromide
KI	Potassium iodide
SbF_3	Antimony fluoride
SnI_2	Stannous iodide
Al_2O_3	Aluminum oxide
B_2O_3	Boric oxide
P_2O_5	Phosphoric oxide
SiO_2	Silicon oxide
MgO	Magnesium oxide
NiO	Nickel oxide
CoO	Cobalt oxide
PbO	Lead oxide
SnO	Stannous oxide
SbO_3	Antimony oxide
H_3BO_3	Boric acid

TABLE 2.1 (continued)

Na_2SO_4	Sodium sulfate
K_2SO_4	Potassium sulfate
CaSO_4	Calcium sulfate
$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	Ferrous sulfate (hydrous)
$\text{Fe}_2(\text{SO}_4)_3$	Ferric sulfate
MgSO_4	Magnesium sulfate
$\text{Ca}_2\text{P}_2\text{O}_7$	Calcium pyrophosphate
$\text{Ca}_3(\text{PO}_4)_2$	Calcium phosphate
$\text{Ca}_{10}(\text{OH})_2(\text{PO}_4)_6$	Calcium hydroxiapatite
$\text{Ca}_{10}\text{Cl}_2(\text{PO}_4)_6$	Calcium chloroapatite
$\text{NH}_4\text{H}_2\text{PO}_4$	Ammonium dihydrogen phosphate
KH_2PO_4	Potassium dihydrogen phosphate
$(\text{NH}_4)_2\text{HPO}_4$	Diammonium phosphate
AlPO_4	Aluminum phosphate
$\text{K}_2\text{B}_2\text{O}_4$	Potassium borate
$\text{Na}_2\text{B}_2\text{O}_4 \cdot 10\text{H}_2\text{O}$	Sodium borate (hydrous)
$(\text{NH}_4)_2\text{Cr}_2\text{O}_7$	Ammonium dichromate
K_2CrO_4	Potassium chromate
$\text{K}_2\text{Cr}_2\text{O}_7$	Potassium dichromate
$\text{K}_2\text{Si}_2\text{O}_5$	Potassium silicate
CaCl_2	Calcium chloride
$\text{K}_2\text{B}_4\text{O}_7 \cdot 4\text{H}_2\text{O}$	Potassium tetraborate
SnCl_2	Stannous chloride

TABLE 2.1 (continued)

Ca(OH)_2	Calcium hydroxide
2KCl:PbCl_2	Potassium lead chloride
KCHO_2	Potassium formate
NaCHO_2	Sodium formate
$\text{Pb(CHO}_2)_2$	Lead formate
$\text{Ca(CHO}_2)_2$	Calcium formate
$\text{KC}_2\text{H}_3\text{O}_2$	Potassium acetate
$\text{NaC}_2\text{H}_3\text{O}_2$	Sodium acetate
$\text{Pb [C}_2\text{H}_3\text{O}_2]_2$	Lead acetate
$\text{Ca [C}_2\text{H}_3\text{O}_2]_2$	Calcium acetate
$\text{K}_2\text{C}_4\text{H}_4\text{O}_6 \cdot 1/2\text{H}_2\text{O}$	Potassium tartrate
CaC_2O_4	Calcium oxalate
MgC_2O_4	Magnesium oxalate
CoC_2O_4	Cobalt oxalate
$\text{FeC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$	Ferrous oxalate
$\text{NiC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$	Nickel oxalate
$(\text{NH}_4)_2\text{C}_2\text{O}_4 \cdot \text{H}_2\text{O}$	Ammonium oxalate

Commercial Extinguishing Agents

Purple K[®] (Ansul)
 Foray[®] (Ansul)
 Plus 50B[®] (Ansul)
 Monnex[®] (ICI)
 KO Flame[®] (experimental proprietary agent)
 Super K[®] (Norris)
 Tullanox 500[®] (Tulco)

TABLE 2.1 (continued)

3. INTUMESCENT AND ABLATIVE ORGANIC COATINGS

Albi Clad 890[®] (Albi Mgf.)
Chartek 59[®] (Avco)
FlameMastic 700[®] (Flamemaster Corp.)
Firex RX-2375[®] (Pfizer)
Pyrocrete[®] (Carbolene)
CECO Firehold[®] (Intumescent Paint) (CECO)
 Firehold + Cab-O-Sil M5
 Firehold + Tullanox
 Firehold + boric acid
Exting 130[®] (Touraine)
#777[®] Intumescent Varnish (Ocean)
#432[®] Flat FR Varnish (Ocean)

4. POLYMERIC FOAMS

Polyurethane Foam Stafoam System AA1604
Fire Retardant Silicone Foam Q3-6548/Pr855 (Dow Corning)

5. EUTECTIC MIXTURES AND INORGANIC SOLUTIONS

Purple K-KH ₂ PO ₄	Potassium bicarbonate - potassium dihydrogen phosphate
Na ₂ B ₄ O ₇ -Na ₂ CO ₃	Sodium tetraborate - sodium carbonate
KCl-PbCl ₂	Potassium chloride - lead chloride
KF-H ₂ O	Potassium fluoride aqueous solution
LiCl-H ₂ O	Lithium chloride aqueous solution
KC ₂ H ₃ O ₂ -H ₂ O	Potassium acetate aqueous solution

6. MISCELLANEOUS AGENTS

FC 77 (3M-Fluorinert)
FC77 + Cab-O-Sil HS5
FC77 + Cab-O-Sil M5

TABLE 2.1 (continued)

FC77 + Tullanox 500
FC77 + boric acid
FC77 + Cab-0-Sil + boric acid
FC77 + Aluminum octoate

FC48 (3M-Fluorinert)

FC48 + Cab-0-Sil HS5
FC48 + Cab-0-Sil M5
FC48 + Tullanox 500
FC48 + boric acid
FC48 + boric acid + Cab-0-Sil M5
FC48 + Aluminum octoate
L-3407 (3M-Fluorinert + glass microballoons)

DC-200 (Methyl Silicone) (Dow Corning)

DC-200 + Cab-0-Sil HS5
DC-200 + Cab-0-Sil M5
DC-200 + Cab-0-Sil M5 + boric acid
DC-200 + Aluminum octoate

DC-510 (Methyl Phenyl Silicone) (Dow Corning)

DC-510 + Cab-0-Sil M5
DC-510 + Cab-0-Sil M5 + boric acid
DC-510 + Aluminum octoate

DC-550 (Methyl Phenyl Silicone) (Dow Corning)

DC-550 + Cab-0-Sil M5
DC-550 + Cab-0-Sil M5 + boric acid
DC-550 + Aluminum octoate

DC-710 (Methyl Phenyl Silicone) (Dow Corning)

DC-710 + Cab-0-Sil M5
DC-710 + Cab-0-Sil M5 + boric acid
DC-710 + Aluminum octoate

SF-1154 (Methyl Phenyl Silicone) (GE)

SF-1154 + Cab-0-Sil HS5
SF-1154 + Cab-0-Sil M5
SF-1154 + Tullanox 500
SF-1154 + boric acid

TABLE 2.1 (continued)

SF-1154 + Cab-O-Sil M5 + boric acid
SF-1154 + Aluminum octoate

FS-1265 (Fluoro Silicone) (Dow Corning)

FS-1265 + Cab-O-Sil HS5
FS-1265 + Cab-O-Sil M5
FS-1265 + Tullanox 500
FS-1265 + boric acid
FS-1265 + Tullanox + Halon 2402
FS-1265 + Cab-O-Sil M5 + boric acid
FS-1265 + Aluminum octoate

SF-1147 (Methyl Alkyl Polysilicone) (GE)

SF-1147 + Cab-O-Sil M5
SF-1147 + Cab-O-Sil M5 + boric acid

ENJ-2065 (di-isonylphthalate) (Exxon)

ENJ-2065 + Cab-O-Sil HS5
ENJ-2065 + Cab-O-Sil M5
ENJ-2065 + Tullanox 500
ENJ-2065 + boric acid
ENJ-2065 + boric acid + Cab-O-Sil M5
ENJ-2065 + Aluminum octoate

Tetraethylsilicate

Tetraethylsilicate + Cab-O-Sil HS5
Tetraethylsilicate + Cab-O-Sil M5
Tetraethylsilicate + Tullanox 500
Tetraethylsilicate + boric acid
Tetraethylsilicate + Cab-O-Sil M5 + boric acid
Tetraethylsilicate + Aluminum octoate

Trimethylborate

Trimethylborate + Cab-O-Sil HS5
Trimethylborate + Cab-O-Sil M5
Trimethylborate + Tullanox 500
Trimethylborate + boric acid
Trimethylborate + Cab-O-Sil M5 + boric acid

TABLE 2.1 (continued)

Trimethoxyboroxine

Trimethoxyboroxine + Cab-0-Sil M5
Trimethoxyboroxine + Cab-0-Sil HS5
Trimethoxyboroxine + Tullanox 500
Trimethoxyboroxine + boric acid

Tributylborate

Tris 2,3-dibromo propyl phosphate

Tris + Cab-0-Sil HS5
Tris + Cab-0-Sil M5
Tris + Tullanox 500
Tris + boric acid
Tris + boric acid + Cab-0-Sil M5

Potassium Silicate

Potassium Silicate + Cab-0-Sil
Potassium Silicate + boric acid
Potassium Silicate + CB

Tetra Ris (Hydro Oxymethyl) Phosponium - (Hooker Chemical)

Bis (Beta Chlorethyl) Vinyl Phosphate - (Stauffer)

Fyrol 6 (Stauffer) + CB

Phosgard C-22-R (Monsanto)

Tetrabromoethane (Acetylenetetrabromide)

Tween 80 (ICI)

Disflamoll TCF (Naftone)

Flame Out 5600-B1 (Halby)

The gelling of liquid halons can be achieved by the addition of metal octoates and stearates [2] and fumed silica. It was anticipated that the gelled halon, when applied to the fire region, would adhere to the hot walls, boil slowly, cool the surface, extinguish the fire and leave a protective glassy metal oxide deposit on the surface. Another modification for halons includes slurring with inorganic dry chemical extinguishants such as potassium bicarbonate [3].

The problems foreseen with such approaches were that most halons begin to decompose at 500°F (260°C) generating corrosive halogens and hydrogen halides. The toxicity of some halons and of their products of decomposition when applied to a fire has always been of concern. Furthermore, the stability of the gellants at 500°F (260°C) is not known. Another problem that could arise with gelled halons is the lack of fluidity at -65°F (-54°C) since one would expect an increase in viscosity at that temperature. All common halons boil at temperatures well below 500°F (260°C) which is also higher than their critical temperature. Therefore, the storage container must be able to withstand the very high vapor pressures (> 700 psi [4826 KPa]) of the selected agents at 500°F (260°C). Insulation of the suppressant container against the anticipated maximum storage temperature of 500°F (260°C) which only occurs for a relatively short period during a flight mission will be necessary but may be economically feasible.

2.3.2 Inorganic Chemicals

Some dry chemical extinguishing agents such as potassium bicarbonate had already been tested at NASA-Ames facility with some success [4]. Although automatic dry chemical systems used for industrial fire protection lack reliability [5], such a consideration will have to be addressed during the design phase of the delivery system and was not a criterion for the selection of agents in this program.

All commercial dry chemical extinguishing agents and similar compounds were selected for testing. Of particular interest were lithium salts since they were predicted to have better extinguishing capabilities than potassium salts. The reasoning for this prediction was that potassium salts are known to be more effective than sodium salts

and lithium supercedes potassium in the electro motive series. Thus lithium has a greater tendency to lose electrons and interfere with the free radical formation in the combustion reaction.

Alkali and other metal halides which decompose easily upon heating such as iodides and bromides were also selected as candidate agents.

Other inorganic chemicals selected for testing included metallic oxides and salts which decompose easily into metallic and non-metallic oxides such as phosphates, borates and silicates. It was hoped that some of these oxides would melt and glaze the hot surfaces. The heat of fusion would cool the surface and the resulting smooth surface would prevent the presence of nucleation sites and promote film boiling of the fuel.

Another group of chemicals consisted of metalo-organic acid salts (e.g., formates, oxalates, acetates and tartrates) which were expected to generate CO_2 and water vapor upon decomposition.

2.3.3 Intumescent and Ablative Organic Materials

When certain compositions are heated, they soften, decompose and generate a gaseous product which provides a foam-like fluffy matrix. Such compositions have been used in the formulation of commercial coatings and paints (e.g., Albi Clad[®] - Albi, Flamarest[®] and Chartek[®] - Avco) to protect surfaces against fires. Protection is primarily due to the insulating effectiveness of the intumesced coating. Other coatings ablate by charring or decomposition in the fire at a very slow rate thus delaying heat penetration to the protected surface, (e.g., Thermo-Lag[®] - TSI).

Although intumescent and ablative coatings have been basically used for fire protection rather than suppression, it was believed that by themselves, or in combination with other materials they may be able to extinguish aircraft fires effectively.

One problem expected to be associated with these materials is their instability at 500°F (260°C), since many begin to decompose at that temperature. Their lack of fluidity at low temperatures is another problem. In addition, intumescent coatings are known to produce a foam-like matrix which is generally very friable and could thus be swept away by high air flow rates expected in the engine nacelle of an advanced aircraft. Whether or not these materials (particularly if they are applied as a powder) would adhere to the hot surfaces was another problem. The toxicity of the gases released upon decomposition has also been of some concern. Nevertheless, some of these paints were recommended for testing under this program.

2.3.4 Polymeric Foams

Cellular plastics are usually generated upon mixing two reactive components. The heat of reaction releases a gaseous product which, in turn, foams the mixture. Once the reaction is completed, a solid foam is produced. Additives are generally included in the foam mixture to inhibit the flammability of the final product. Polymeric foams such as isocyanurate polyurethane, urea-formaldehyde and phenolics have excellent fire retardant capabilities and were considered as candidates for the proposed application. However, there are several potential problems associated with organic polymeric foams. Most organic materials begin to decompose at or below 500°F (260°C) and an insulated container may have to be used to protect the foaming agents for the duration of a flight mission.

The reaction between some foam components at -65°F (-54°C) is expected to be very slow and accelerants may have to be used if the fire area is to be quickly inundated with foam. The fluidity of the foam components at -65°F (-54°C) is also a problem. Another is the inherent delay in the chemical foaming reaction during which period a high velocity air stream in the fire area may sweep the liquid components to non-affected areas. Furthermore, most fire-retarded polymeric foams include chemical additives which could produce highly toxic gases upon pyrolysis or charring. One particular polymeric foam,

Dow Corning[®] 3-6548 Silicone RTV Foam, was considered worthy of serious attention because of its noncombustibility and stability at high temperatures. It was recognized that it too required the mixing of two proprietary components the behavior of which at -65°F (-54°C) and 500°F (260°C) was not known.

2.3.5 Inorganic Foaming Materials

Inorganic foams were considered but eliminated without testing because they are generally produced from aqueous slurries and are thus subject to freezing at low temperatures. The freezing point of water may be lowered with organic and inorganic additives but the effect of these additives on the resulting foam (if foaming is still possible) is not known. Organic additives such as propylene glycol (60% in water) can lower the freezing point to only -60°F (-51°C), while 4.93 lb CaCl₂/gal (590 m/l) of water reduces the freezing point to about -50°F (-46°C). Only a lithium chloride solution can be made to freeze at -65°F (-51°C) but the presence of lithium chloride would interfere with the foaming reaction of magnesium oxychloride foaming systems. Foamed gypsums and concretes were also considered and discarded for similar reasons.

A more promising approach to foaming inorganic compositions was through the selection of materials which were expected to adhere to the hot wall surfaces, decompose releasing a gaseous product or water of hydration, soften or melt, produce a froth or a foam as the gaseous bubbles rise through the melt and finally solidify. Eutectic mixtures of two or more inorganic compounds were formulated to produce low-melting point materials and these are included in Table 2.1.

2.3.6 Miscellaneous Candidate Agents

Several chemicals and commercial products were also considered and recommended for testing either individually or in combination with other materials. Examples of chemicals with special properties are ammonium dichromate which dissociates upon heating and expands several times its volume to produce an inert insulating material (chromium oxide). An organic silicate such as ethyl silicate, although combustible, was also recommended for testing because it can produce a silicon oxide layer on the hot surface.

Commercial synthetic high-temperature lubricants, silicone oils and fluorinated inert liquids were also among those examined either individually or in combination with other powdered agents.

3.0 EXPERIMENTAL PROGRAM

3.1 PURPOSE

The purpose of the experimental program was to evaluate the behavior of the many agents identified during the initial phase of the program upon exposure to a variety of screening tests. The tests were representative of specific conditions likely to be encountered in advanced aircraft applications. The screening tests were designed to evaluate such characteristics as the behavior of the agents upon contact with a hot metal surface, their capability to extinguish a fire involving a fuel impinging on the hot surface both with and without air-flow, and the compatibility of the candidate agents with materials expected to be encountered in advanced aircraft.

3.2 TEST APPARATUS AND PROCEDURES

3.2.1 Simple Hot Plate Apparatus

Preliminary tests were conducted in a quiescent environment to determine the behavior of various candidate agents when applied to a heated metal surface. A small hot plate was used (see Figure 3.1). The apparatus which was placed under a laboratory hood consisted of a 2" x 2" x 1/16" (5.1 x 5.1 x .16 cm) plate, type 304 stainless steel, supported on a laboratory ring stand and positioned over a natural gas/oxygen torch. The distance between the plate and the torch, approximately three inches, was adjusted to achieve uniform heating of the plate.

A 30 gage chromel/alumel thermocouple was attached to the upper surface of the plate and connected to a recording potentiometer. The temperature monitoring system was used for establishing a repeatable plate temperature of 1400°F (760°C) throughout this initial screening phase. When steady state was achieved, a small amount of the agent was placed on the heated surface and its behavior observed and recorded. Of particular interest were the following:

- agent combustibility,
- its capability to wet the hot plate,

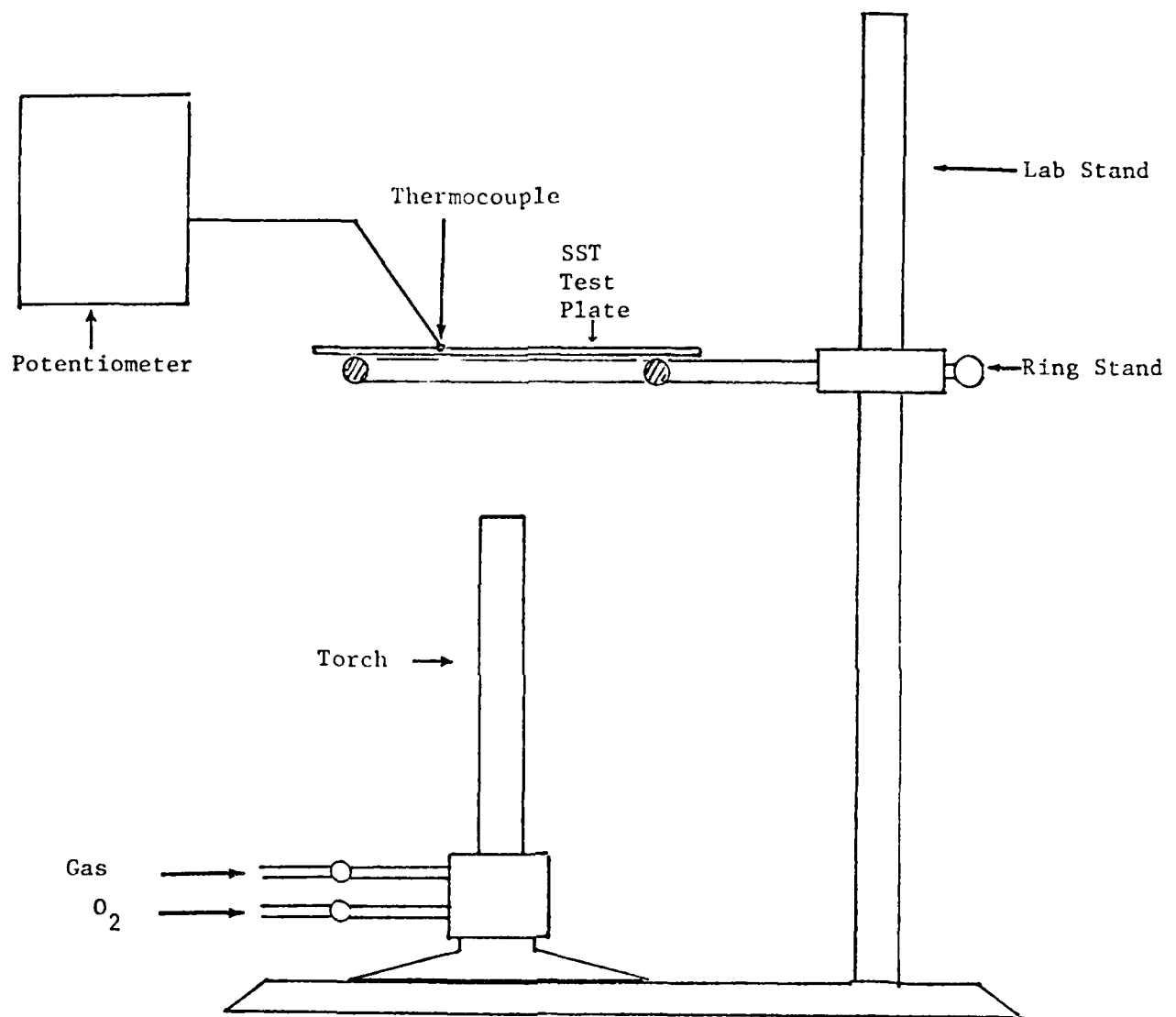


Figure 3.1: Simple Hot Plate Apparatus

- boiling characteristics of liquid agents,
- amount and nature of residue, (e.g., powder, glaze, crust, tar, char, froth, molten mass), and
- chemical reactivity with the test plate.

To evaluate the flame extinguishment capability of selected agents in a quiescent atmosphere, the test apparatus was modified as shown in Figure 3.2 to allow the simultaneous application of the agent and fuel. The apparatus consisted of a separatory funnel containing a supply of JP-4 fuel. The funnel was positioned over a 6 inch (15.2 cm) diameter shallow stainless steel dish. The dish was supported by a ring stand above a natural gas/oxygen torch.

The fuel control valve was regulated to achieve a constant flow rate sufficient to maintain continuous flaming before agent application. The temperature of the dish was kept at 1700°F (927°C) to achieve fuel autoignition. In a typical test, when steady flaming was reached, the agent was applied to the hot plate and observed for its extinguishing capability and other characteristics such as agent contribution to the flame, generation of substantial smoke and prevention of reignition of the falling drops of fuel.

3.2.2 Engine/Nacelle Simulation Apparatus

An apparatus simulating an engine/nacelle was designed and fabricated to permit the testing of powdered, liquid and gelled extinguishing agents in a high-speed flaming environment. The apparatus consisted of four major components: a rectangular tunnel, a heated test plate section with an observation window, a fuel delivery system, and an extinguishing agent injection system.

During the initial tests, the apparatus suffered extensive damage through distortion attributed to localized heating and the reaction of the interior metal surfaces with the various chemicals used. After a careful analysis of the cause of the damage, a second apparatus was fabricated along the same general design of the first

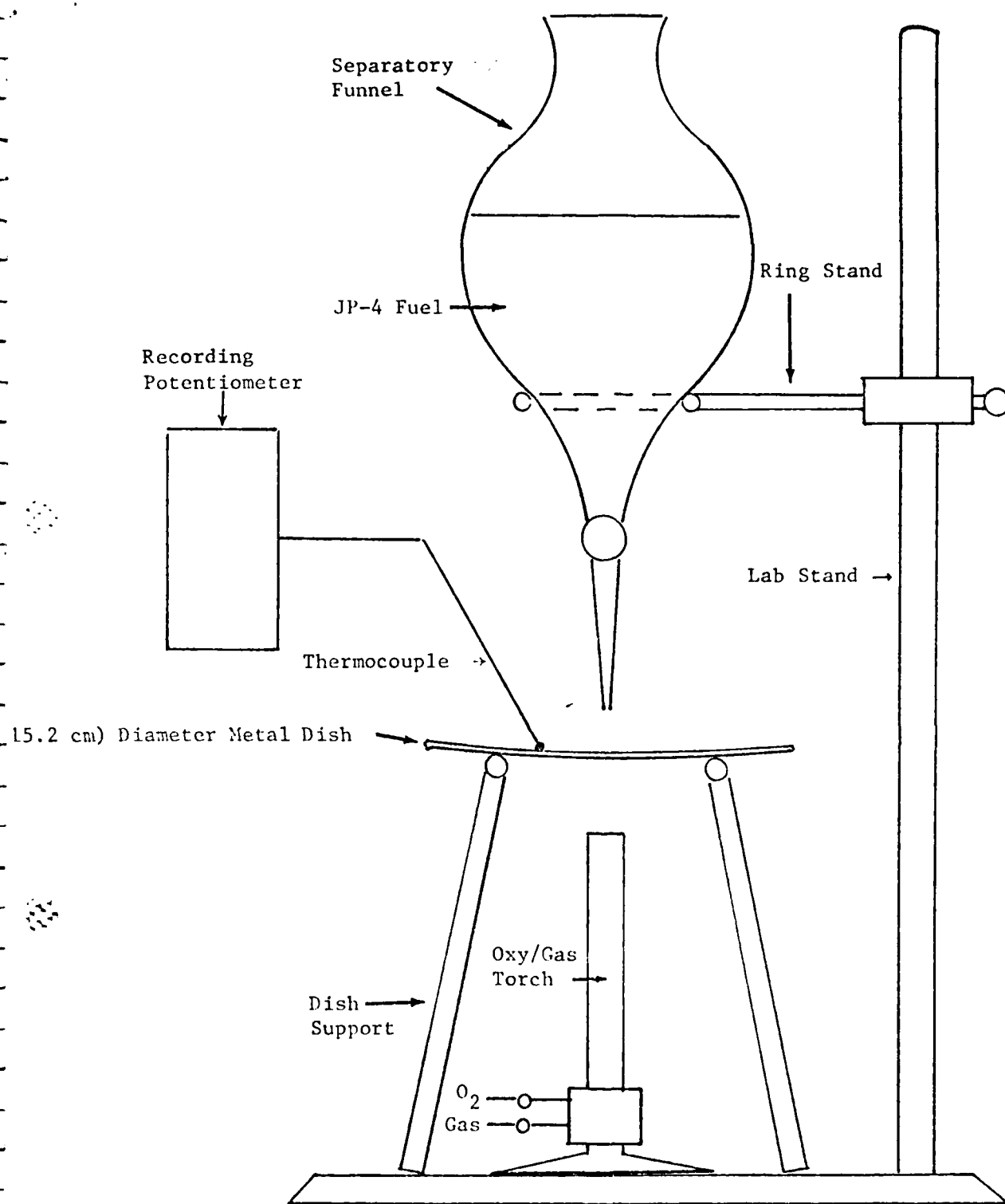


Figure 3.2: Modified Hot Plate Apparatus

apparatus utilizing .125-inch (0.31 cm) stainless steel plate instead of .0625-inch (0.16 cm) cold rolled steel used in the first tunnel. Additional refinements were made to the apparatus in the form of extensive bracing and reinforcement of the heated section of the tunnel and the addition of thermal insulation beneath the test area. Figure 3.3 is a photograph of the apparatus.

The test tunnel was 3 inches (7.6 cm) high by 8 inches (20.5 cm) wide by 8 feet (2.44 m) long. It was connected to a blower which was capable of achieving air velocities of up to 100 fps (30.5 ms⁻¹). The test section of the tunnel was located at its midpoint. It consisted of a 6" x 6" (15.2 x 15.2 cm) area on the tunnel floor designed to accept specially designed test plates. Two 2 1/2" x 18" (6.3 x 45.7 cm) long Pyrex windows were installed in the front and rear walls of the test section to permit observation of the extinguishment tests. The windows were held in place by metal clamps. High temperature gaskets were placed between the window plates and the tunnel. An 8" x 12" (20.3 x 30.5 cm) steel plate was bolted directly over the region occupied by the test plates. It served to support the JP-4 discharge nozzles and to provide access to the interior of the tunnel.

Air flow velocities were measured using an Alnor velometer located 12 inches (30.5 cm) upstream of the test zone. The air velocity could be adjusted by varying the inlet area of the air blower.

The test plates were made of stainless steel and measured 6" x 6" x 0.062" (15.2 x 15.2 x 0.16 cm). Three flame-holding fins were welded to each plate as shown in Figure 3.4. The plates were placed on the floor of the test tunnel using eight hold-down tabs secured by bolts fastened through the tunnel floor as shown in Figure 3.5.

The fins were 6" (15.2 cm) in length, approximately 3" (7.6 cm) apart and 0.625" (1.6 cm) high. The fins were inclined about 60° from normal on the downwind side and were oriented to 90° to the airflow direction in the duct. Three holes measuring 0.125" (0.32 cm) in diameter and 1" (2.5 cm) apart, were drilled in each fin to provide additional turbulence which enhanced the combustion of JP-4.

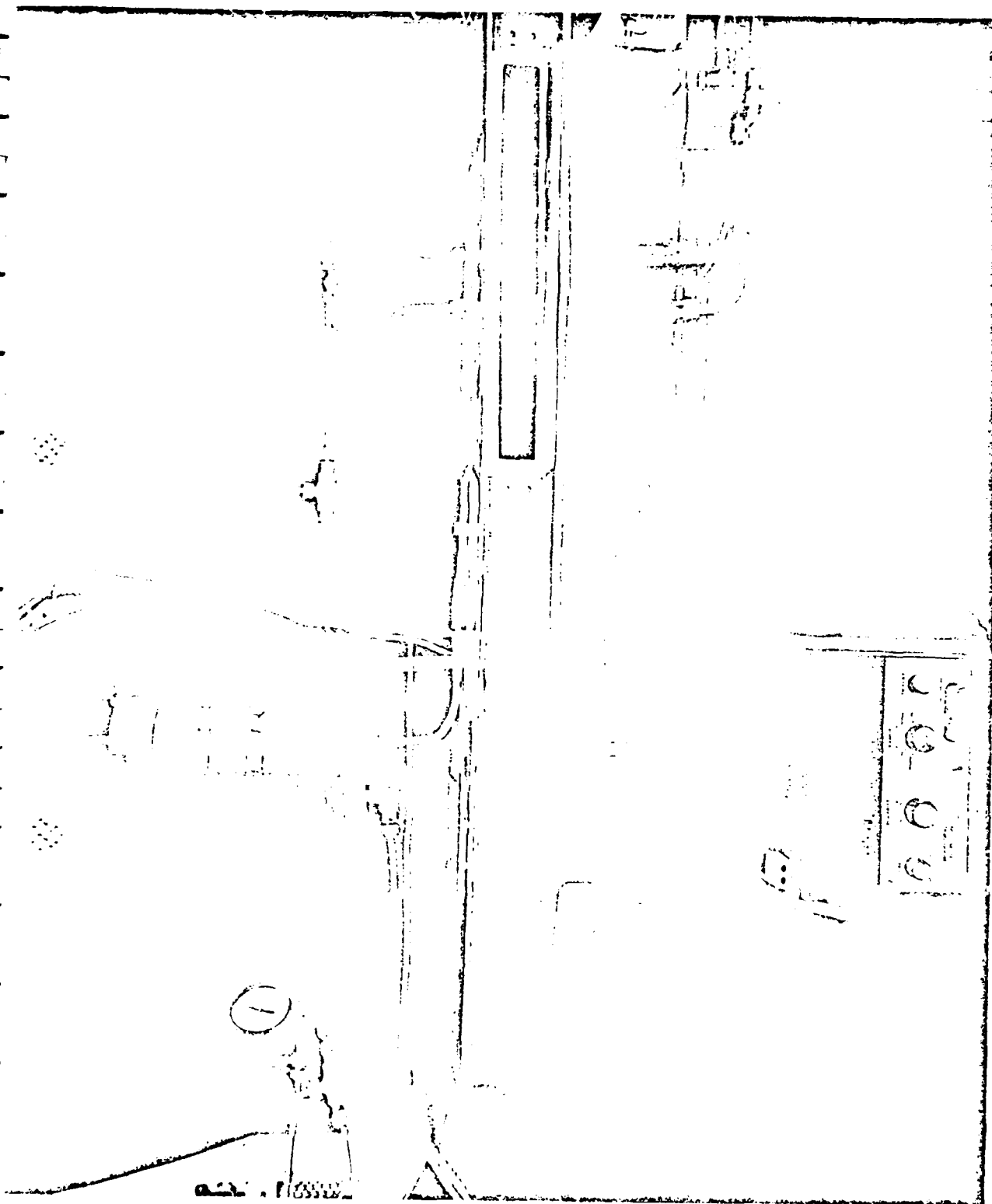


Figure 3.3: Photograph of Tunnel Apparatus

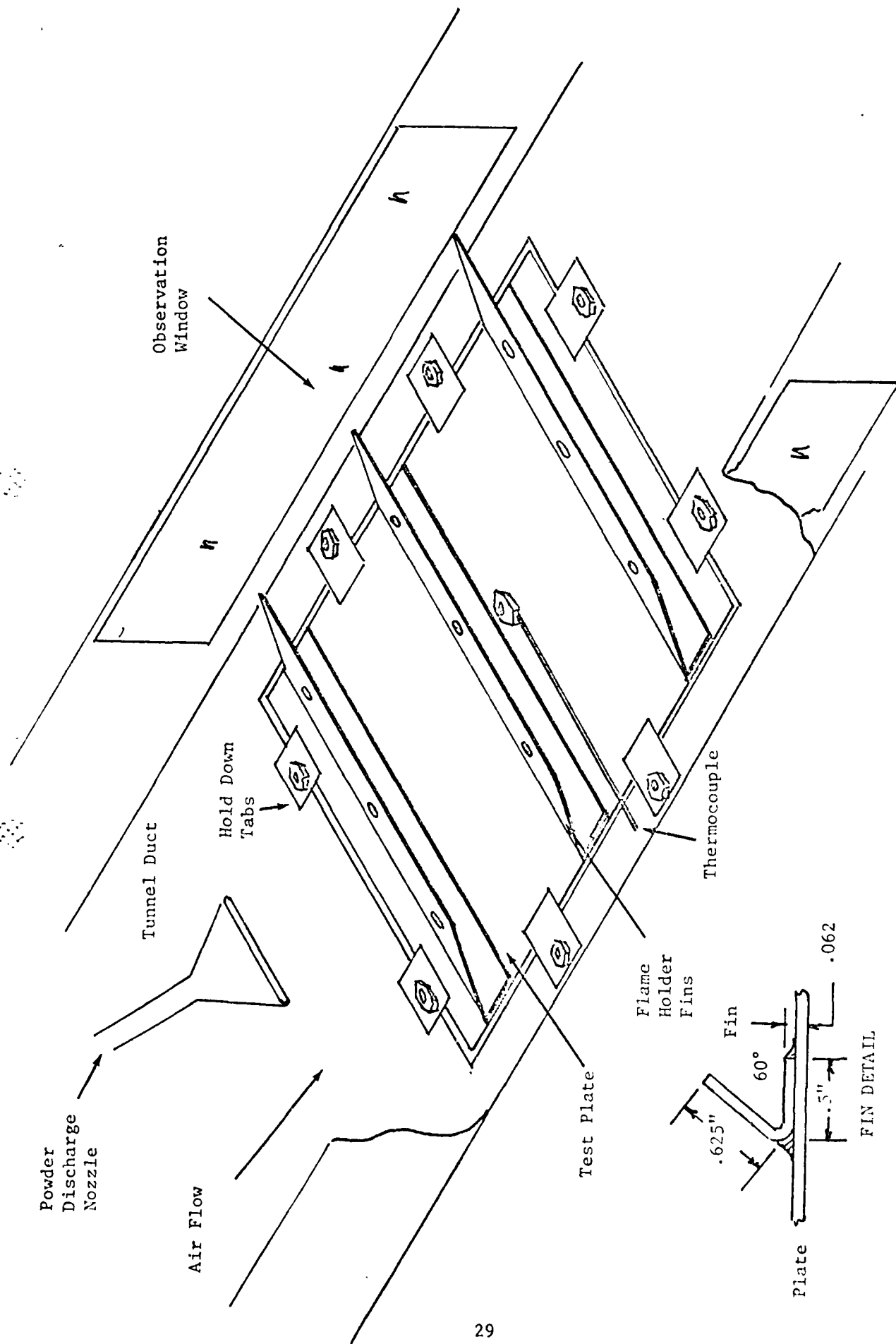


Figure 3.4: Flame-Holding Fins on Test Plate

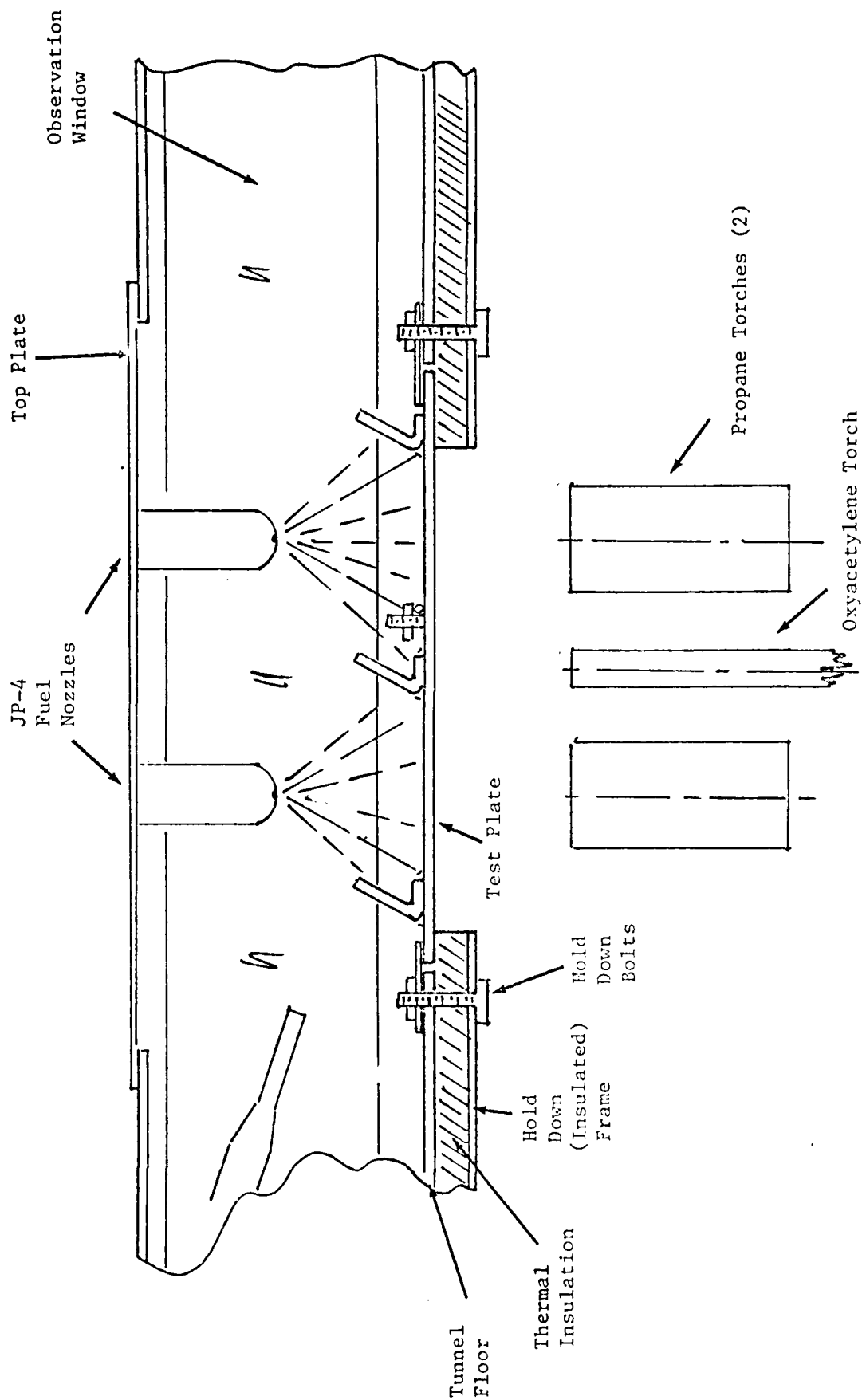


Figure 3.5: Test Plate Hold-Down Method

A sheathed chromel/alumel thermocouple which was bolted to the test plate was used to monitor the stagnation zone surface temperature approximately 0.5 inch (1.27 cm) downstream from the center of the middle flame holder. The signal generated by the thermocouple was recorded on a continuous single channel recorder. A direct readout digital voltmeter was used as an alternate temperature indicator during startup.

The heat source for the test plate consisted of two 1-inch diameter propane burners and one acetylene torch. The acetylene torch insured that the central plate temperature of 1700°F (927°C) was attained, while the additional propane burners insured uniformity of temperature distribution over the test plate.

The heating system was capable of yielding a steady-state temperature of 1700°F (927°C) over a circular plate surface area of approximately 6 square inch when the air velocity in the duct was 18 fps (6 ms^{-1}). Under these conditions, the JP-4 spray was shown to self-ignite consistently upon impingement on the test plate and without any detectable delay time. Autoignition could also be achieved at air velocities of up to 100 fps (33 ms^{-1}), but the luminous flame zone was reduced in size to a small region on the downwind side of the flameholders.

JP-4 fuel was used in all of the tests. Compared with other combustible liquids such as hydraulic fluid or engine oil, JP-4 is by far, the most flammable. Thus, the results of any tests involving JP-4 should be applicable to fuels with lesser flammability.

The fuel was directed onto the test plate using two .85-gph ($8.9 \times 10^{-4} \text{ s}^{-1}$), 60° solid cone nozzles positioned downward from the tunnel cover plate. The spray cones were directed approximately 1 inch (2.5 cm) behind each of the two front fins along the centerline of the tunnel. The fuel was supplied to the two nozzles, which were arranged in a parallel circuit, by a fuel pump rated at 100 psi (689 KPa).

Flow control to the two nozzles was achieved through the use of a needle valve and flowmeter. The fuel flow rate was kept at 50 ml/min from each nozzle. Adjustments in the height of the nozzles with respect to the test plate were necessary to ensure that under the test air velocity (18 fps) [6 ms^{-1}], the fuel impinged on and wetted the test plate and ignited. A closeup view of the plate during a test is shown in Figure 3.6.

A sketch of the agent discharge system is shown in Figure 3.7. For powdered agents, it consisted of a reservoir connected to a nitrogen pressurizing system. The latter consisted of a high pressure gas cylinder, pressure regulator, manual shut-off valve and an electrically timed solenoid valve for effecting the pressurization of the reservoir. The discharge end of the reservoir was connected to a smooth bore tube which extended through the wind tunnel. It terminated with a fish-tail shaped discharge nozzle, with an exit opening $1 \frac{1}{4}$ " (3.1 cm) long x .05" (0.1 cm) high. The nozzle was located one inch upstream of the leading edge of the test plate and one inch above the tunnel floor. It was oriented downward at approximately 45° to disperse the agent uniformly over the test plate. A mechanical vibrator was attached to the upper section of the agent reservoir. The vibrator insured a consistent discharge of the powder out of the reservoir. It was activated simultaneously with the high pressure solenoid valve.

The dispensing system for liquid agents was mounted alongside the powdered agent system. It also incorporated an agent reservoir, high pressure nitrogen discharge system, flow shut-off valve, a timer-activated discharge solenoid valve at the exit and a square pattern discharge nozzle. As can be seen in Figure 3.7, ready selection of the discharge system was possible for the various tests.

The square pattern spray nozzle was positioned to achieve a direct application of liquid agent over the entire surface of the test plate with a minimum of overspray.

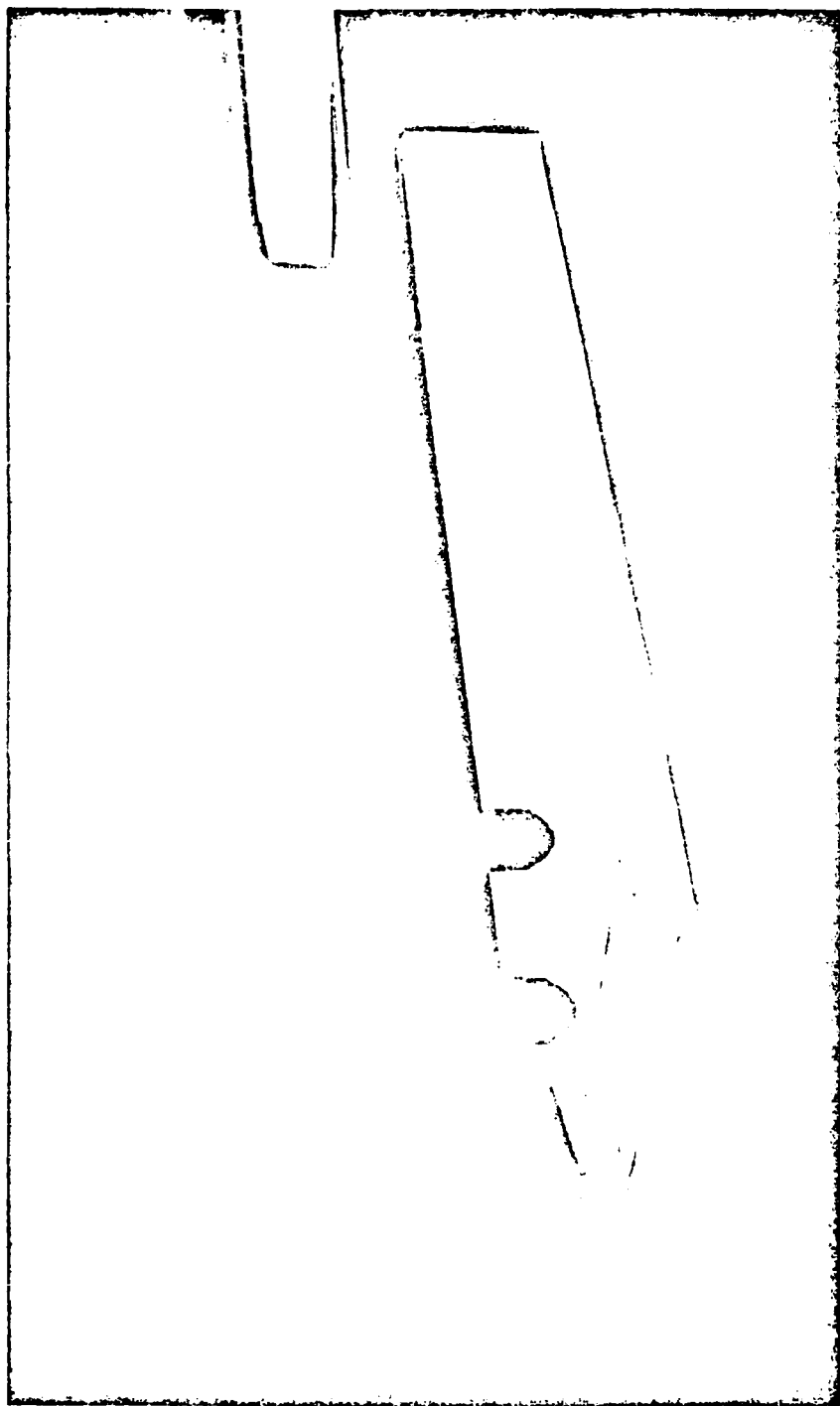


Figure 3.6: Close-up of Test Plate During a Test

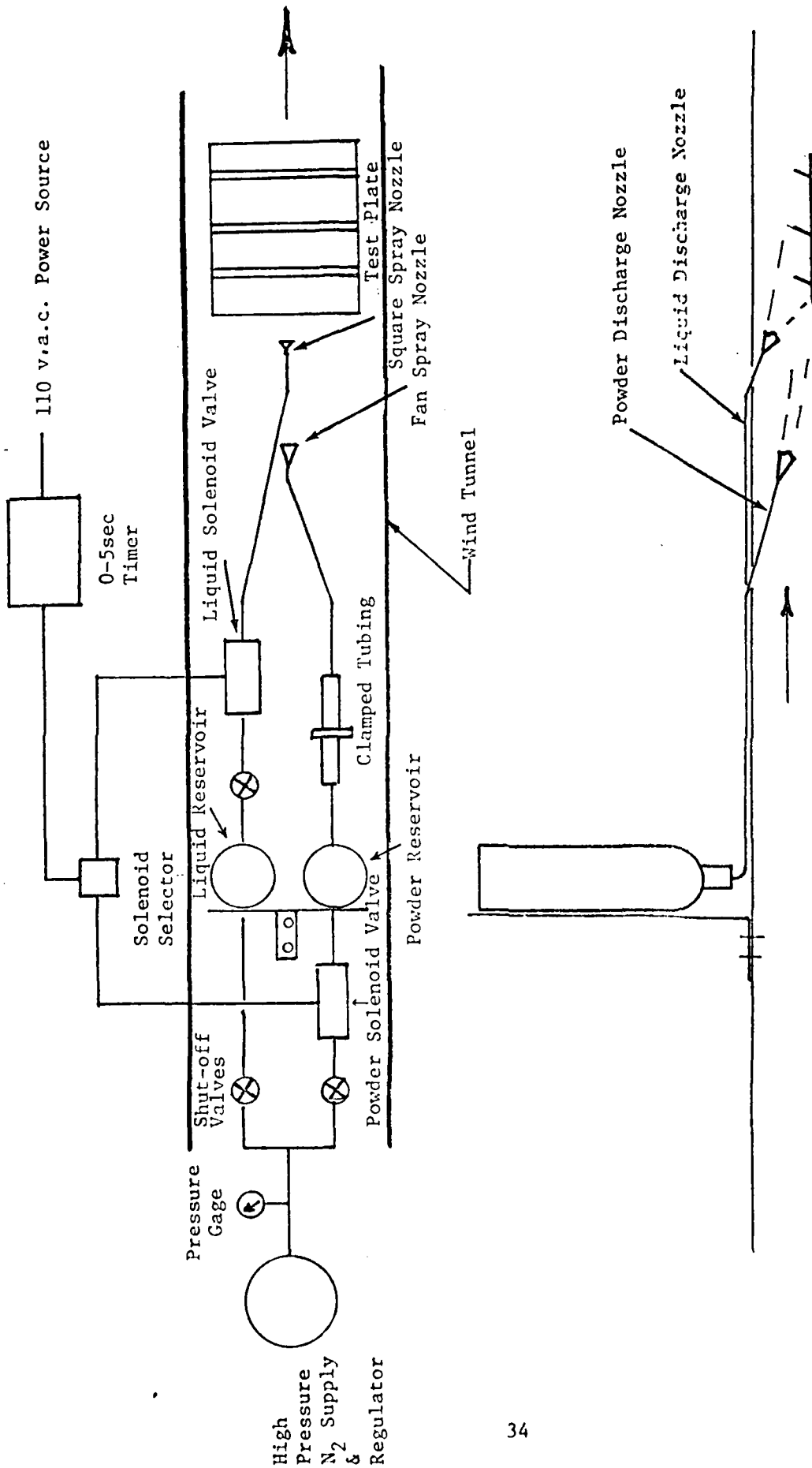


Figure 3.7: Agent Discharge Systems

For each test, a constant nitrogen pressure head was applied to the fluid in the agent reservoir. The electronic timer, which could be set between zero and five seconds, controlled the length of time the agent dispensing solenoid was opened. To measure the quantity discharged, separate calibrations were conducted using the same test conditions (i.e., N_2 pressure, nozzle, timer setting) as the routine screening tests. Several nozzles were utilized to achieve various discharge rates with fluids of different viscosities and densities.

Powdered agents were prepared for testing by first grinding and/or ball milling the chemicals. This was followed by sieving them through a -325 mesh screen. The sieved powders were then oven-dried at approximately 160°F (71°C) for a period of no less than 24 hours. The powders remained in the oven until tested.

In preparation for a typical test, a sand-blasted test plate was attached to the tunnel and the air blower turned on. The thermocouple was also bolted to the plate and connected to the recorder. The propane burners and acetylene torch were ignited and the temperature of the plate monitored until a steady temperature of about 1700°F (927°C) was reached. The JP-4 fuel sprays were then turned on. The propane and acetylene torch control valves were then readjusted to regain a steady temperature of about 1700°F (927°C).

A preweighed charge of the candidate agent was then placed in the appropriate reservoir. The valve to the nitrogen pressurizing tank was opened. The solenoid valve was opened and the behavior of the flame in the tunnel observed. In most tests, the flame would be extinguished momentarily but the fuel vapors would reflash after a few seconds.

After repeated preliminary tests, it was found that successful permanent extinguishment (i.e., up to five minutes) could be achieved if the fuel vapors did not reflash within a minute after flame extinguishment. Apparently air cooling of the plate for one minute was sufficient to lower its temperature below the ignition point of the fuel.

A commercial grade of potassium bicarbonate extinguishing agent (PKP[®] - Ansul) was found to be able to achieve permanent extinguishment when 5 grams were used. Since this agent was also being used at NASA-Ames for comparison purposes, it was selected as the control agent for these tests as well.

A typical test sequence for a candidate powdered agent would begin with a test using 10 grams. If the test failed, the test would be repeated. If it failed again, no further testing was conducted with the candidate agent. If it succeeded in extinguishing the flame on the first or second attempts, the charge was reduced to 5 grams and the tests were repeated. Depending on whether or not successful extinguishment was achieved, repeat tests were then carried out utilizing 5-gram charges. The few successful powdered agents finally selected were those capable of extinguishing the flames for a period of 60 seconds using a charge of 5 grams.

The procedure for testing liquid agents was similar to that for testing powders except that the liquid agent dispensing system was used. Activation of the liquid dispensing system was accomplished by the operation of the solenoid selector switch.

For certain liquids and solutions, the nitrogen pressure was adjusted to achieve a discharge rate of 54 ± 3 grams/sec as measured by timing the collection of a fixed volume of the agent. When this was established, the timer was set to discharge approximately 40 grams. Depending on the outcome of the fire extinguishment test, the timer was reset to deliver 30 grams and the test repeated. Forty grams was selected because it was a typical quantity of water that would effect a 60-second reignition delay repeatedly when applied at the same rate.

In all tests, temperature records were kept to document successful extinguishment. Typical temperature records are shown in Figure 3.8 for a case of flame reflash after initial extinguishment and Figure 3.9 for the case of a successful extinguishment.

Millivolts

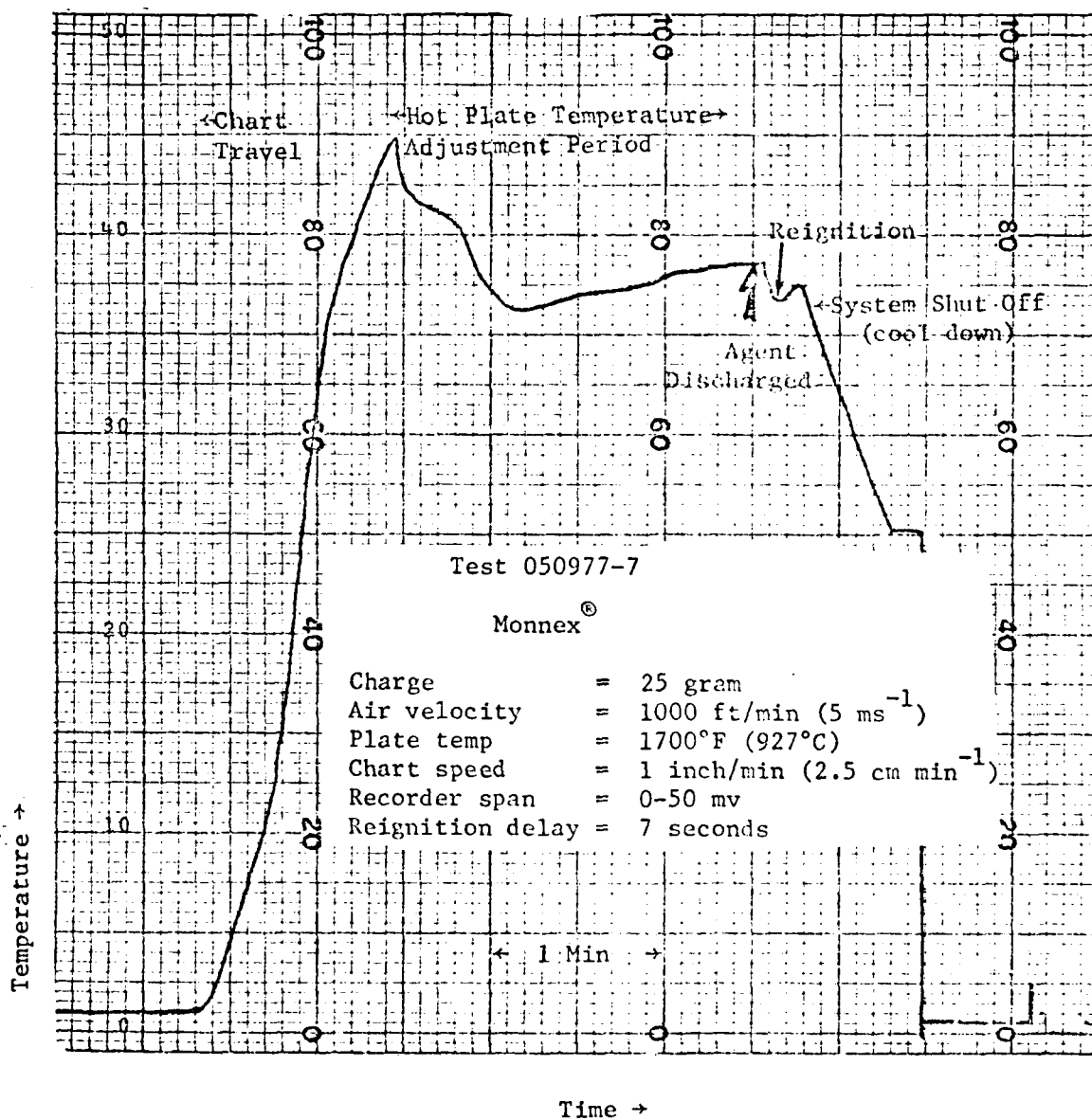


Figure 3.8: Typical Plate Temperature History for Unsuccessful Extinguishment with Monnex®

Millivolts

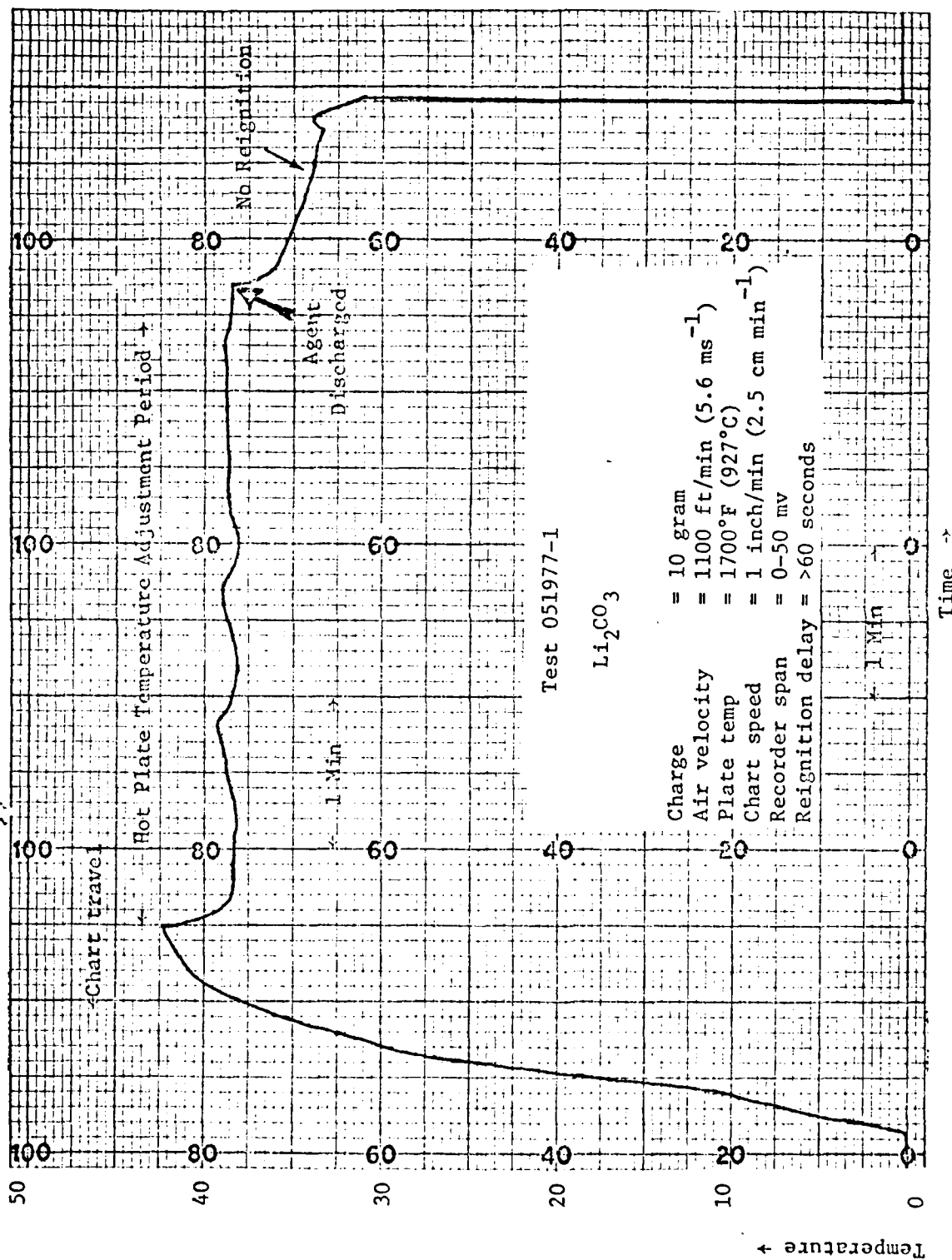


Figure 3.9: Typical Plate Temperature History for
Successful Extinguishment with Li_2CO_3

3.2.3 Material Compatibility Tests

Nonmetallic materials were exposed to candidate powdered agents for a period of 33 days in air at 100°F (38°C). In preparation for the exposure, a one-inch (2.5 cm) square coupon of each nonmetal was cut, polished, rinsed in acetone, flushed with water and then placed flat on the bottom of a Petri dish. Each powdered agent was then poured into the dishes to cover the coupon completely. The undersides of the coupons were not in contact with the agent, except around the periphery of the coupon.

After pouring the agent over the coupons, each dish was covered and placed in an automatic temperature controlled oven which had been preheated to 100°F (38°C). Nonmetal coupons without agents, were also placed in Petri dishes, covered and placed in the oven for comparison. An additional, unexposed set of nonmetal test coupons was retained outside the oven for reference.

Metallic coupons were similarly prepared and placed in an automatic temperature controlled oven that was preset at 500°F (260°C). Following exposure, the coupons were examined for evidence of chemical reaction with the powdered agents. Comparisons were made with the reference set of test coupons.

Compatibility tests between an aqueous solution of LiCl and metallic and nonmetallic coupons were conducted at room temperature. The coupons were completely submerged in the solution for 19 days and partially submerged for a period of 43 days. Partially submerged samples were suspended in the solution so that one half of the coupon was below the liquid surface. A set of metallic and nonmetallic coupons was retained for comparison purposes. At the conclusion of the immersion tests, the coupons were examined for evidence of chemical reactions with the LiCl solution. Special attention was given to the region of the test coupons that was located at the solution/air interface.

3.2.4 Flow Enhancement

Some difficulty was encountered during tests conducted at NASA-Ames on the candidate agents selected under this program. These difficulties were attributed to a lack of agent fluidity. Consequently, attempts were made to increase the fluidity of the powdered agents using various flow-enhancing agents. The agents were Cab-O-Sil M-5, Cab-O-Sil MS-7, Cab-O-Sil HS-5, Tullanox 500, and Talcum powder.

Various amounts of each agent were blended with the three powdered agents ranging from 10% to .5% by weight. It was found that the best flow enhancement of KI, Li_2CO_3 and Na_2CO_3 powders was achieved using .5% Tullanox 500. Moreover, no degradation in fluidity, as determined by timing the flow of a known quantity of agent through a long stemmed glass laboratory funnel, was observed after exposure of the agents containing Tullanox 500 for one hour at 500°F (260°C).

4.0 RESULTS

4.1 HOT PLATE TEST RESULTS

As indicated in paragraph 3.1, an initial screening of single solid and liquid compounds was conducted in a quiescent air environment using the hot plate apparatus. The screening program consisted of applying small quantities (< 1 gram) of selected materials to the plate and recording their physical and chemical behavior. Compounds which underwent no transformation were judged to be less capable of adhering to hot surfaces in sufficient quantities than other substances which fused and/or decomposed. Fuel autoignition delay times were expected to be greater for the latter substances. Substances which melted to form globules or which subsequently vaporized were judged to be less likely to effect prolonged extinguishment than substances which spread over the hot plate and vaporized more slowly. The results for single solid and liquid compounds are summarized in Table 4.1.

Another series of tests were conducted utilizing liquids which had been blended with thickening or gelling agents to determine if the addition of such agents would improve the adhesiveness of the liquids to the hot metal plate. The results are given in Table 4.2. Except for gelled Halon 2402, Fluorinerts[®] (3M), and Tris - compounds, all other liquids flamed upon contact with the hot plate, thus losing their desirability as extinguishing agents. Tests with Fluorinert[®] 48 showed that it burns when applied to a plate at 1500°F (816°C) but not when the temperature is 1400°F. Agents which did not burn and left a viscous residue on the surface were:

- Fluorinert[®] 48 with anhydrous boric acid
- Tris 2,3-dibromopropylphosphate with anhydrous boric acid
- Dibromotetrafluorethane (Halon 2402) with anhydrous boric acid

However, since Fluorinert[®] appeared to be temperature-sensitive and because Tris 2,3-dibromopropylphosphate has been linked to cancer, Halon 2402 with anhydrous boric acid was judged to be the most promising from this series of tests.

TABLE 4.1

HOT PLATE TEST RESULTS

(Stainless Steel Plate at ~ 1400°F, 760°C)

Solids

Substance	No Change	Melts	Vaporizes	Reacts*	Burns	Remarks
Lithium Carbonate, Li_2CO_3		X				
Sodium Carbonate, Na_2CO_3		X				Forms glassy coating.
Potassium Carbonate, K_2CO_3	X					Slight tendency to adhere.
Calcium Carbonate, CaCO_3	X					
Magnesium Carbonate, $4\text{MgCO}_3 \cdot \text{Mg}(\text{OH})_2 \cdot 4\text{H}_2\text{O}$	X					
Sodium Bicarbonate, NaHCO_3		X			X	
Potassium Bicarbonate, KHCO_3		X			X	
Sodium Fluoride, NaF	X					
Sodium Chloride, NaCl		X			X	Wets plate.
Sodium Iodide, NaI		X			X	Wets plate; fumes.
Potassium Fluoride, KF		X				Wets plate; forms dark residue.
Potassium Iodide, KI		X			X	
Calcium Chloride, CaCl_2		X			X	
Magnesium Oxide, MgO	X					
Cobalt Oxide, CoO	X					
Lead Oxide, PbO		X				Wets plate.
Calcium Hydroxide, $\text{Ca}(\text{OH})_2$	X					
Potassium Chloride, KCl		X			X	Vaporizes slowly, wets plate.

* Reacts with plate or decomposes visibly.

TABLE 4.1 (continued)

Substance	No Change	Melts	Vaporizes	Reacts*	Burns	Remarks
Potassium Phosphate, KH_2PO_4		X		X		Wets surface; forms glassy coating.
Monoammonium Phosphate, $\text{NH}_4\text{H}_2\text{PO}_4$		X	X		X	Forms globules
Calcium Phosphate, $\text{Ca}_3(\text{PO}_4)_2$	X					
Calcium Pyrophosphate, $\text{Ca}_2\text{P}_2\text{O}_7$	X					
Ammonium Dichromate, $(\text{NH}_4)_2\text{Cr}_2\text{O}_7$				X		Expands to dark powder without adhering. Decrepitates.
Potassium Chromate, K_2CrO_4		X				Wets plate; spatters.
Potassium Dichromate, $\text{K}_2\text{Cr}_2\text{O}_7$		X		X		Glowing combustion; forms dark residue.
Ferrous Oxalate, $\text{FeC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$				X		Forms dark powder-like residue. Leaves residue.
Ferric Sulfate, $\text{Fe}_2(\text{SO}_4)_3 \cdot \text{XH}_2\text{O}$				X		Tendency to form globules.
Lead Acetate, $\text{Pb}(\text{C}_2\text{H}_3\text{O}_2) \cdot 3\text{H}_2\text{O}$		X	X	X	X	Flames.
Sodium Acetate, $\text{NaC}_2\text{H}_3\text{O}_2 \cdot 3\text{H}_2\text{O}$		X	X		X	Foams, wet surface, vitrifies.
Stannous Stearate,						Melts with frothing to form viscous liquid.
Sodium Borate, $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$		X			X	Melts slowly.
Boric Acid, B_2O_3		X				
Magnesium Sulfate, MgSO_4	X					
Sodium Sulfate, Na_2SO_4		X				
Calcium Sulfate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	X					

TABLE 4.1 (continued)

Liquids

Substance	No Change	Melts	Vaporizes	Reacts *	Burns	Remarks
3M [®] CO-FC 48				X	X	Forms globules (film boiling).
3M [®] CO-FC 77				X		Forms globules (film boiling).
Dow Corning [®] DC 510				X	X	Vigorous flaming combustion.
Dow Corning [®] DC 550				X	X	Vigorous flaming combustion.
Dow Corning [®] DC 710				X	X	Vigorous flaming combustion.
Dow Corning [®] FS 1265				X	X	Vigorous flaming combustion.

TABLE 4.2

RESULTS OF HOT PLATE TESTS ON LIQUIDS AND GELS

(Stainless Steel Plate at ~ 1400°F, 760°C)

Candidate	Adhesion to Plate (✓ = good)	Behavior on Plate				
		Smokes	Flames	Froths/ Bubbles	Leaves Residue	Type of Residue
1. Exxon, ENJ-2065 (di-isonyl phthalate)		✓	✓			
" + Cab-O-Sil M5		✓	✓		✓	powder
" + Cab-O-Sil HS5		✓	✓		✓	powder
" + Tullanox 500			✓	✓	✓	powder
" + boric acid anhydrous		✓	✓	✓	✓	viscous char
2. 3M Co., "Fluorinert" FC77 (Fluorocarbons)						
" + Cab-O-Sil M5					✓	powder
" + Cab-O-Sil HS5					✓	powder
" + Tullanox 500				✓	✓	powder
" + boric acid anhydrous						
3. 3M Co., "Fluorinert" FC48 (Fluorocarbons)						
" + Cab-O-Sil M5					✓	powder
" + Cab-O-Sil HS5					✓	powder
" + Tullanox 500					✓	powder
" + boric acid anhydrous				✓	✓	viscous layer
4. Trimethyl borate						
" + Cab-O-Sil M5		✓	✓		✓	powder
" + Cab-O-Sil HS5		✓	✓		✓	powder
" + Tullanox 500		✓	✓		✓	powder
" + boric acid anhydrous		✓	✓		✓	powder

TABLE 4.2 (continued)

Candidate	Adhesion to Plate (✓ = good)	Behavior on Plate			
		Smokes	Flames	Froths/ Bubbles	Leaves Residue Type of Residue
5. Trimethoxyboroxine			✓		
" + Cab-O-Sil M5		✓	✓		✓ viscous layer
" + Cab-O-Sil HS5		✓	✓		✓ viscous layer
" + Tullanox 500		✓	✓		✓ viscous layer
" + boric acid anhydrous			✓		
6. Tetraethyl Silicate			✓		
" + Cab-O-Sil M5			✓		✓ powder
" + Cab-O-Sil HS5			✓		✓ powder
" + Tullanox 500			✓		✓ powder
" + boric acid anhydrous			✓		✓ powder
7. Tris 2,3-dibromopropyl phosphate					
" + Cab-O-Sil M5		✓		✓	✓ powder
" + Cab-O-Sil HS5		✓		✓	✓ powder
" + Tullanox 500		✓		✓	✓ powder
" + boric acid anhydrous		✓		✓	✓ viscous layer
8. Dow Corning 200 (Methyl Silicone)					
" + Cab-O-Sil M5	✓	✓	✓	✓	✓ film
" + Cab-O-Sil HS5	✓	✓	✓	✓	✓ powder
" + Tullanox 500	✓	✓	✓	✓	✓ powder
" + boric acid anhydrous	✓	✓	✓	✓	✓ viscous layer

TABLE 4.2 (continued)

Candidate	Adhesion to Plate (✓ = good)	Behavior on Plate				Type of Residue
		Smokes	Flames	Froths/ Bubbles	Leaves Residue	
9. Dow Corning FS-1265 (Fluoro Silicone) " + Cab-0-Sil M5 " + Cab-0-Sil HS5 " + Tullanox 500 " + boric acid anhydrous	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	film char layer char layer char layer viscous layer
10. General Electric SF-1154 (Methylphenyl Silicone) " + Cab-0-Sil M5 " + Cab-0-Sil HS5 " + Tullanox 500 " + boric acid anhydrous	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	oily layer powder moist layer powder viscous layer
11. Dibromotetrafluoroethane (Halon 2402) " + Cab-0-Sil M5 " + Cab-0-Sil HS5 " + Tullanox 500 " + boric acid anhydrous	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	char char char viscous layer
12. 1, 2-dibromodifluoroethane (Halon 2202) " + Cab-0-Sil M5 " + Cab-0-Sil HS5 " + Tullanox 500 " + boric acid anhydrous	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓	char char char powdery

TABLE 4.2 (continued)

Candidate	Adhesion to Plate (✓ = good)	Behavior on Plate			
		Smokes	Flames	Froths/ Bubbles	Leaves Residue
13. Exting 130, Touraine (Intumescent Paint)		✓	✓	puffs up	✓ powder
" + Cab-O-Sil M5		✓	✓	puffs up	✓ powder
" + Cab-O-Sil HS5		✓	✓	puffs up	✓ powder
" + Tullanox 500		✓	✓	puffs up	✓ powder
" + boric acid anhydrous		✓	✓	puffs up	✓ char
14. CECO, Firehold 10, White (Intumescent Paint)		✓	✓	puffs up	✓ powder
" + Cab-O-Sil M5		✓	✓	puffs up	✓ powder
" + Cab-O-Sil HS5		✓	✓	puffs up	✓ powder
" + Tullanox 500		✓	✓	puffs up	✓ powder
" + boric acid anhydrous		✓	✓	puffs up	✓ char

4.2 FLAMING HOT PLATE RESULTS

The extinguishing effectiveness of liquid agents and liquid agents containing gelling and residue-forming additives was investigated using the modified flaming hot plate screening apparatus described in 3.1 and shown in Figure 3.2. The results are shown in Table 4.3. As can be seen, certain liquid and halon gels, Fluorinert[®] liquid blends and Dow Corning[®] silicone foam extinguished the flames effectively. All other agents either contributed to flaming or did not have any significant beneficial effect.

4.3 TUNNEL TEST RESULTS

4.3.1 Powders

Preliminary tests on powdered materials were performed in which the quantity of the candidate agents, reservoir discharge pressures and test plate temperatures were varied. The tests were performed using the first tunnel which eventually had to be discarded. The results of these tests are shown in Table 4.4. From these data it appeared that commercial potassium bicarbonate (Purple K[®]-Ansul), Monnex[®] (ICI Ltd.) and monoammonium phosphate were the most effective agents. Potassium chloride (Super K[®]-Norris) showed marginal but promising performance.

Table 4.5 summarizes the results of powdered agents when tested in the rebuilt tunnel. In most cases, reignition delays fell either within the ranges of 10 seconds or less or 60 seconds or more. Li_2CO_3 , Na_2CO_3 and KI were notable in that they successfully prevented reignition for 60 seconds or more in quantities of 5 grams. In addition, Li_2CO_3 and KI left a glassy residue on the test plate, evidently due to melting. Li_2CO_3 , Na_2CO_3 and KI were selected for further testing at NASA-Ames. Purple K[®] was not sent because it had already been tested successfully on NASA-Ames' test apparatus.

4.3.2 Gaseous CO_2 and Halon 1301

Simple extinguishment tests were performed in which CO_2 was introduced in the tunnel by injecting it from a commercial portable unit

TABLE 4.3

Flaming Hot Plate Test Results

<u>Agent</u>	<u>Successfully Extinguishes</u>	<u>Burns</u>	<u>Does Not Burn or Extinguish</u>
<u>CB (Bromochloromethane or Halon 1011)</u>			
CB + Cab-0-Sil M5	x		
CB + boric acid	x		
<u>Dibromomethane (Halon 102)</u>			
Dibromomethane + Cab-0-Sil M5	x		
Dibromomethane + boric acid	x		
<u>FC77 (3M-Fluorinert[®])</u>			
FC77 + Cab-0-Sil HS5	x		
FC77 + Cab-0-Sil M5	x		
FC77 + Cab-0-Sil M5 + boric acid	x		
FC77 + Aluminum octoate	x		
<u>FC48 (3M-Fluorinert[®])</u>			
FC48 + Cab-0-Sil HS5	x		
FC48 + Cab-0-Sil M5	x		
FC48 + boric acid + Cab-0-Sil M5	x		
FC48 + Aluminum octoate	x		
L-3407 (3M-Fluorinert + glass microballoons)	x		
<u>DC-200 (Methyl silicone) - Dow Corning[®]</u>			
DC-200 + Cab-0-Sil HS5		x	
DC-200 + Cab-0-Sil M5		x	
DC-200 + Cab-0-Sil M5 + boric acid		x	
DC-200 + Aluminum Octoate		x	

TABLE 4.3 (continued)

Agent	Successfully Extinguishes	Burns	Does Not Burn or Extinguish
DC-510 (Methyl phenyl silicone) - Dow Corning [®]			
DC-510 + Cab-O-Sil M5		x	
DC-510 + Cab-O-Sil M5 + boric acid		x	
DC-510 + Aluminum octoate		x	
DC-550 (Methyl phenyl silicone) - Dow Corning [®]			
DC-550 + Cab-O-Sil M5		x	
DC-550 + Cab-O-Sil M5 + boric acid		x	
DC-550 + Aluminum octoate		x	
DC-710 (Methyl phenyl silicone) - Dow Corning [®]			
DC-710 + Cab-O-Sil M5		x	
DC-710 + Cab-O-Sil M5 + boric acid		x	
DC-710 + Aluminum octoate		x	
SF-1154 (Methyl phenyl silicone) GE [®]			
SF-1154 + Cab-O-Sil HS5		x	
SF-1154 + Cab-O-Sil M5		x	
SF-1154 + Cab-O-Sil M5 + boric acid		x	
SF-1154 + Aluminum octoate		x	
FS-1265 (Fluoro silicone) - Dow Corning [®]			
F-1265 + Cab-O-Sil HS5		x	
FS-1265 + Cab-O-Sil M5		x	
FS-1265 + Cab-O-Sil M5 + boric acid		x	
FS-1265 + Aluminum octoate		x	
SF-1147 (Methyl alkyl polysilicone) GE [®]			
SF-1147 + Cab-O-Sil M5		x	
SF-1147 + Cab-O-Sil M5 + boric acid		x	
ENJ-2065 (di-isonylphthalate) Exxon [®]			
Exxon 2065 + Cab-O-Sil HS5		x	
Exxon 2065 + Cab-O-Sil M5		x	
Exxon 2065 + boric acid + Cab-O-Sil M5		x	
Exxon 2065 + Aluminum octoate		x	

TABLE 4.3 (continued)

Agent	Successfully Extinguishes	Burns	Does Not Burn or Extinguish
<u>Tetraethyl silicate</u>		x	
Tetraethyl silicate + Cab-O-Sil HS5		x	
Tetraethyl silicate + Cab-O-Sil M5		x	
Tetraethyl silicate + Cab-O-Sil M5 + boric acid		x	
Tetraethyl silicate + Aluminum octoate		x	
<u>Trimethyl borate</u>			
Trimethyl borate + Cab-O-Sil HS5		x	
Trimethyl borate + Cab-O-Sil M5		x	
Trimethyl borate + Cab-O-Sil M5 + boric acid		x	
<u>Trimethoxyboroxine</u>			
Trimethoxyboroxine + Cab-O-Sil M5		x	
Trimethoxyboroxine + Cab-O-Sil HS5		x	
<u>Tris 2,3-dibromo propyl phosphate</u>			
Tris + Cab-O-Sil HS5	x		
Tris + Cab-O-Sil M5	x		
Tris + boric acid + Cab-O-Sil M5	x		
<u>Potassium silicate</u>			x
Potassium silicate + Cab-O-Sil			x
Potassium silicate + boric acid			
Potassium silicate + CB			
<u>Tetrakis (Hydroxymethyl) phosphonium</u> (Hooker Chemical)		x	
Bis (Beta chloroethyl) Vinyl phosphate - (Stauffer)		x	
<u>Fyrol[®] 6 (Stauffer)</u>			
Fyrol 6 + CB		x	x
Phosgard [®] C-22-R (Monsanto)			x

Boric acid was not compatible with potassium silicate.
Did not mix. Formed separate layers.

TABLE 4.3 (continued)

Agent	Successfully Extinguishes	Burns	Does Not	
			Burn or	Extinguish
Tributyl borate		x		
Tetrabromoethane (Acetylenetetrabromide or halon 104)	x			
Tween 80 (ICI) ^②		x		
Disflamoll TCF (Naftone)		x		
Flame Out 5600-B1 (Halby)		x		
Stafoam AAl604 (Polyurethane)		x		
Flame Retardant Silicone Foam - Dow Chemical ^⑥	x			
Firehold 10 (Intumescent Paint) CECO ^②		x		
Exting 130 (Intumescent Paint) Touraine ^⑥				x
#777 Intumescent Varnish - Ocean ^②		x		
#432 Flat FR Varnish - Ocean ^②				x

Preliminary Powder Extinguishment Tests

(Air Velocity $\sim 15 - 19$ fps, $4.6 - 5.8 \text{ ms}^{-1}$)

Agent*	Weight of Agent Discharged (g)	N ₂ Pressure in the Discharge Reservoir (psig)	Plate Temperature (°C)	Reignition Delay Time (sec)
Purple K [®]	20	20	915	>60
Purple K [®]	20	20	970	< 1
Purple K [®]	20	20	890	>60
Purple K [®]	20	20	930	2
Purple K [®]	20	20	925	>60
Monnex [®]	20	20	930	>60
Monnex [®]	10	20	930	>60
Monnex [®]	10	20	905	>60
Monnex [®]	5	20	925	>60
CaCO ₃	20	20	915	0
CaCO ₃	20	18	925	0
MgO (-200 mesh)	30	20	915	0
K ₂ CO ₃	30	30	945	~ 1
K ₂ CO ₃	20	20	905	0
KCl	30	30	915	>60
KCl	20	20	895	0
NaHCO ₃	30	30	945	3
NH ₄ H ₂ PO ₄	30	30	865	>60
NH ₄ H ₂ PO ₄	20	20	865	25
Na ₂ CO ₃	30	30	930	4
Li ₂ CO ₃	30	30	930	0
K ₂ Cr ₂ O ₇	30	30	930	0
K ₂ CO ₃ /B ₂ O ₃ (67/33)	30	30	930	4
NaBr/Na ₂ CO ₃ /K ₂ CO ₃ /KBr (30/15.5/20/34.5)	30	30	930	5
K ₂ CO ₃ /B ₂ O ₃ (45/55)	30	30	930	2
SiO ₂ /K ₂ CO ₃ (58.2/41.8)	30	30	930	0

* All chemicals with the exception of Purple K[®] and Monnex[®] were sieved and the -325 mesh fraction used except where indicated.

TUNNEL TEST RESULTS

Test Conditions:

Air velocity, 18 fps (5.5 ms^{-1})

Plate temp $\approx 1700^\circ\text{F}$ (927°C)

N_2 Pressure* ≈ 20 psig (138 KPa)

Test Agent	Amount of Agent (grams)	Number of Tests With Reignition of			Condition of Residue on Plate
		>60s	10s < t < 60s	<10s	Powder Glaze
KHCO_3	20	2	0	2	✓
K_2CO_3	20	0	0	1	✓
Monnex [®] (ICI)	20	0	0	4	✓
	20	0	0	2	✓
	25	2	0	4	✓
	30	0	0	2	✓
	30	1	0	0	✓
	40	0	0	1	✓
	40	1	0	0	✓
	20	7	0	5	✓
Purple K [®] (Ansul)	10	5	0	1	✓
	5	2	(36 sec)	5	✓
	4	0	0	1	✓
	3	0	0	3	✓
Foray [®] (Ansul)	20	0	0	3	✓
Monoammonium phosphate base					
Plus 50-B [®] (Ansul)	5	0	0	2**	✓
NaHCO_3 base	10	2	0	1	✓
Na_2SO_4	10	0	0	2	✓
NaCl	5	0	0	2	✓
	10	2	0	0	✓
CaCO_3	20	0	0	2	✓
	10	0	0	2	✓

* Agent discharge gas

** Flame leakage past plate noted for one test.

TABLE 4.5 (continued)

Test Agent	Amount of Agent (grams)	Number of Tests With Reignition of			Condition of Residue on Plate
		>60s	10s < t < 60s	<10s	
Na_2CO_3	5	1	0	2	✓
	10	1	0	0	✓
SiO_2	10	0	0	20	✓
MgO	10	0	0	2	✓
NaHCO_3	10	0	0	2	✓
KHCO_3	10	0	0	2	✓
KCl	10	1	0	0	✓
	5	0	0	2	✓
$\text{NaC}_2\text{H}_3\text{O}_2$	10	0	0	2	sooty
KH_2PO_4	10	0	0	2	✓
MgCO_3	10	0	0	2	✓
PbO	10	0	0	2	✓
CaCl_2	10	0	0	2	✓
Al_2O_3	10	0	0	2	✓
K_2CrO_4	10	0	0	2	✓
$\text{Ca}_2\text{P}_2\text{O}_7$	10	0	0	2	✓
CaC_2O_4	10	0	0	2	✓
MgC_2O_4	10	0	0	2	✓
$(\text{NH}_4)_2\text{HPO}_4$	10	0	0	2	✓
KI	10	1	(25 sec)	0	✓
$\text{Ca}_3(\text{PO}_4)_2$	10	0	0	2	✓
CoC_2O_4	10	0	0	2	✓
$\text{Ca}(\text{CHO}_2)_2$	10	0	0	2	none left
$\text{FeC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$	10	0	0	2	none left
$(\text{NH}_4)_2\text{Cr}_2\text{O}_7$	10	0	0	2	✓
Li_2CO_3	10	2	(25 sec)	0	✓
	5	1	0	0	✓
MgSO_4	10	0	0	2	✓

TABLE 4.5 (continued)

Test Agent	Amount of Agent (grams)	Number of Tests With Reignition of			Condition of Residue on Plate	
		>60s	10s < t < 60s	<10s	Powder	Glaze
$K_2Cr_2O_7$	10	0	0	2	✓	
$Fe(SO_4)_3$	10	0	0	2	plate discolored	
$NH_4H_2PO_4$	10	0	0	2	sooty	
$(NH_4)_2C_2O_4 \cdot H_2O$	10	0	0	2	sooty	
$Ca(OH)_2$	10	0	0	2	✓	
NaF	10	0	0	2	✓	
NaBr	10	0	0	2		✓
NaI	10	0	0	2		✓
$K_2B_4O_7 \cdot 4H_2O$	10	0	0	2		✓
K_2SO_4	10	0	0	2	✓	
$Ca_{10}(OH)_2(PO_4)_6$	10	0	0	2	✓	
(Calcium Hydroxiapatite)						
$NiC_2O_4 \cdot 2H_2O$	10	0	0	2	✓	
KBr	10	0	0	2		✓
$FeSO_4 \cdot 7H_2O$	10	0	0	2	✓	
Sb_2O_3	10	0	0	2	char	
$CaSO_4$	10	0	0	2	✓	
SnO	10	1	0	0	✓	
	5	0	0	2	✓	
$Na_2B_4O_7 \cdot 10H_2O$	10	0	0	2		✓
NiO	10	0	0	2	✓	
$Pb(CHO_2)_2$	10	0	0	2		✓
$Ca(C_2H_3O_2)_2$	10	0	0	2	✓	
KO Flame [®] (a proprietary	10	2	0	1	✓	
Aluminum Phosphate Complex)	5.5	0	0	1	✓	
CoO	11	0	0	2	✓	
$C_4H_4O_6K_2 \cdot 1/2H_2O$	11	0	(25 sec)	1	✓	

TABLE 4.5 (continued)

Test Agent	Amount of Agent (grams)	Number of Tests With Reignition of			Condition of Residue of Plate
		>60s	10s < t < 60s	<10s	
$\text{Pb}(\text{C}_2\text{H}_3\text{O}_2)_2$	11	0	0	2	✓
NaCHO_2	11	0	0	2	✓
AlPO_4	11	0	0	2	✓
	15	0	0	1	✓
Super K [®]	11	0	(21 sec)	0	✓
SbF_3	11	0	0	1	frothy
SnCl_2	11	0	0	1	✓
B_2O_3	11	0	0	1	crust
P_2O_5	11	-	-	1	char
SnI_2	11	0	0	2	char
Purple K [®] / KH_2PO_4 (1:1 by wt)	11	0	(24 sec)	1	✓
$\text{Na}_2\text{B}_4\text{C}_2/\text{Na}_2\text{CO}_3$ (1:1 by wt)	11	0	(16 sec)	1	✓
KCl/PbCl_2 (1:1 by wt)	11	1	0	0	✓
	5.5	0	(15 sec)	1	✓

into the tunnel blower entrance. Similarly, Halon 1301 was injected using the fan nozzle normally used for distributing powdered agents. In both cases, extinguishment was achieved temporarily during the injection period. However, reignition took place within a few seconds after agent application had been stopped.

4.3.3 Liquids and Slurries

As indicated in 3.2.2, numerous tests were conducted using water as an extinguishing agent so as to provide a reference base for comparing the performance of other liquids and solutions. More than fifty extinguishment attempts were made with water while varying nozzle type, water flow rate and discharge period.

The results for water were very erratic. This was attributed to changes in the plate surface due to sudden quenching, buckling and the formation of small puddles of water and/or fuel on the test plate. Nevertheless, it was generally found that extinguishment of the flames could be achieved repeatedly with 40 g of water when applied at a rate of about 54 g/s. This rate and total mass were used to check the relative performance of other liquids and solutions. The results of these tests are shown in Table 4.6. The results show that LiCl/water solution (0.8:1) performed better than water. Because such a solution does not freeze at -65°F (-54°C), it was recommended for testing at NASA-Ames.

Three Halons: 1011, 2402 and 1211, were tested extensively utilizing a variety of nozzles, nitrogen pressures (which control discharge rate) and discharge periods. It was generally found that the halons will extinguish the flames during application to the test plate and sometimes for a few seconds after application depending on the amount of agent accumulated on the test plate. Halon slurries with potassium bicarbonate and monoammonium phosphate did not perform significantly better than the pure halons. Table 4.7 summarizes the results of these tests.

TABLE 4.6
LIQUID, GEL AND SLURRY RESULTS

<u>Agent</u>	<u>Amount of Agent (ml)</u>	<u>Discharge Period (sec)</u>	<u>Reignition Delay (sec)</u>
KC ₂ H ₃ O ₂ /H ₂ O (2:1)	30	1.0	>60
3M Fluorinert FC 77	24.5	1.25	5
	19	1.0	5
3M Fluorinert FC 77	22	1.6	1
	22	1.6	4
3M Fluorinert FC 48	22	1.2	2
	22	1.2	3
LiCl/H ₂ O (.8:1)	25.5	.7	>60
	34	0.5	>60
KF/H ₂ O (1:1)	32	0.66	>60
	23.5	0.5	9
Halon 1011/Fyrol 6 (1:1)	27	0.60	5
	14.8	.5	0
Tetraethyl Silicate	26	1.0	0
	48	2.	0
	48	2.	0

TABLE 4.7

HALONS AND HALON SLURRY RESULTS

	Amount of Agent (ml)	Discharge Period (s)	Reignition Delay (s)
Halon 1011 (in nozzle no. 33041704 Sprayco®)	10	.5	7
	15	.75	7
	15	.75	7
	19.4	1	9
	19.4	1	7
	19.6	1	6
	19.6	1	7
	20	1	>60
	20	1	7
	28	1.5	9
	32	2	9
	32	2	9
	36	2	8
	36	2	11
	45	15	0
	48	2	11
	51	3	16
	58	2	11
	65	4	15
	165	30	210
Halon 1011 (in nozzle no. 33051504 Sprayco®)	22	.5	8
	22	.5	7
	67	1.5	12
	67	1.5	18
	135	3.0	28
	225	5.0	49

TABLE 4.7 (continued)

	Amount of Agent (ml)	Discharge Period (s)	Reignition Delay (s)
Halon 2402	182	60	0
(in nozzle no. 33041704	21	.5	3
Sprayco®)	24	.5	5
	72	1.5	7
	96	2.0	8
Halon 1211	1.1	6	0
(in powder nozzle)	4.9	6	0
	15	10	0
	40.5	2	2
	64	2.5	2
	93	4	2
Halon 2402 (78%) KHCO ₃ (21%) Cab-O-Sil (1%)	35.7 g	~ 1	10
} slurry			
Halon 2402 (78%) NH ₄ H ₂ PO ₄ (21%) Cab-O-Sil (1%)	25 g	~ 1	4
} slurry			
	40 g	~ 1	1

4.3.4 Silicone Foam Tests

During the flaming hot plate tests, Dow Corning[®] Q3-6548 silicone foam exhibited desirable properties as an extinguishing agent. As a result, tests were performed in the tunnel apparatus in which this foam was injected on the test plate immediately following manual mixing of its two components in a cartridge specifically designed for this purpose by the manufacturer.

As soon as mixing was completed in a period of approximately 15 seconds, the unexpanded foam was extruded out of the cartridge onto the flaming test plate.

The flames were extinguished as the mixture foamed and spread across the test plate preventing the JP-4 fuel from reaching the hot surface. A layer of about 3/4-inch (1.9 cm) thickness was formed. Due to an insufficient supply, the foam covered only one-half of the plate and flaming continued at the downstream half of the test plate. Flames did not propagate upstream where JP-4 fuel continued to spray onto the silicone foam surface. The post-test condition of the silicone foam is shown in Figure 4.1.

This foam was not selected for subsequent testing at NASA-Ames because of the expected difficulties in mixing the two components at low temperatures. It is also very doubtful that the gas-generating reaction would take place at temperatures approaching -65°F (-54°C). Nothing is known about the stability of the individual components at 500°F (260°C). However the excellent behavior of this material in a fire involving a fuel impinging on a hot plate warrants special mention. It is conceivable that it may find application as a fire extinguishing agent elsewhere where the temperature restrictions are not as severe as they are for the proposed application. Also, it may be possible to design a system that can operate effectively at the two temperature extremes.

Arthur D. Little, Inc

0 1 2 3 4 5
| | | | | | |
Centimeter Scale

Figure 4.1: Post Test Condition of Dow Corning[®] Silicone Foam

4.4 COMPATIBILITY TEST RESULTS

Nonmetallic materials (neoprene, Teflon, PVC and Buna-N Rubber) were tested for their compatibility with KI, Li_2CO_3 , Na_2CO_3 and LiCl powders. The results of these tests are shown in Table 4.8. As can be seen, there was no apparent incompatibility between the test materials and powders under the conditions of the test.

Several metals were tested for their compatibility with the same powders in a 500°F (260°C) oven for one week. The results of this exposure are summarized in Table 4.9.

It should be noted that LiCl was recommended as a candidate agent in an aqueous solution. However, when applied to a heated surface during a fire, the water will evaporate leaving a LiCl residue that may react with the metal surface. Thus, it was important to know the effect of solid LiCl on various aircraft metals.

A separate test was performed to evaluate the compatibility of both metals and nonmetals with a 0.8:1 solution of LiCl in water. The metallic and nonmetallic materials were completely submerged for 19 days and partly submerged for 43 days. The results are given in Table 4.10.

4.5 NASA-AMES TEST RESULTS

Samples of -325 mesh KI, Li_2CO_3 and Na_2CO_3 which were flow-enhanced with .5% fumed silica (Tullanox[®] 500) were sent to NASA-Ames for testing. In addition, a 0.8:1 LiCl/water solution was also sent.

None of the agents sent to NASA-Ames were able to extinguish the flames on NASA-Ames' apparatus.

TABLE 4.8

COMPATIBILITY TEST RESULTS

Condition after exposure to 100°F (38°C) air for 33 days:

<u>Test Material</u>	<u>No Agent</u>	<u>KI</u>	<u>Li₂CO₃</u>	<u>Na₂CO₃</u>	<u>LiCl</u>
Neoprene	unaffected	unaffected	unaffected	slightly less flexible than normal	unaffected
Teflon	unaffected	unaffected	unaffected	unaffected	unaffected
PVC	color darkened, distorted	color darkened, distorted	color darkened, distorted	color darkened, distorted	color darkened, distorted
Buna-N Rubber	unaffected	unaffected	unaffected	unaffected	unaffected

TABLE 4.9

COMPATIBILITY TEST RESULTS

(Exposure: 1 week at 500°F, 260°C)

Sample	POWDERED AGENT			
	<u>Li₂CO₃</u>	<u>KI</u>	<u>Na₂CO₃</u>	<u>LiCl</u> *
Aluminum 5052	very slight reaction ⁽¹⁾	no reaction	no reaction	surface reacted ⁽²⁾
Aluminum 6061	no reaction	no reaction	no reaction	very slight reaction ⁽¹⁾
Brass	no reaction	surface reacted ⁽²⁾	no reaction	surface reacted ⁽²⁾
Copper	surface reacted ⁽²⁾	surface reacted ⁽²⁾	surface reacted ⁽²⁾	surface reacted ⁽²⁾
Nickel	no reaction	no reaction	no reaction	very slight reaction ⁽¹⁾
Mild Steel	no reaction	slight reaction ⁽³⁾	no reaction	surface reacted ⁽²⁾
Stainless Steel 304	no reaction	no reaction	no reaction	surface reacted ⁽²⁾
Titanium	no reaction	no reaction	no reaction	surface reacted ⁽²⁾

Note:

- (1) Surface of coupon showed evidence of some chemical reaction beyond the normal oxidation resulting from exposure to air at 500°F (260°C)
- (2) Surface of coupon had a thin removable crust.
- (3) Surface of specimen coupon showed evidence of some chemical reaction greater than (1) but less than (2).

* LiCl is a candidate agent only in a 0.8:1 aqueous solution.

TABLE 4.10

COMPATIBILITY TEST RESULTS WITH LiCl SOLUTION

Agent: Room temperature, 0.8:1 LiCl/water solution.

Exposure: Coupons totally submerged 19 days, coupons half submerged 43 days.

<u>Test Coupon</u>	<u>Submerged Portion</u>	<u>Liquid/Air Interface</u>	<u>Zone Above Interface</u>
Mild Steel	local greenish deposits - easily removed but left etch marks	greenish deposits, heavier than in submerged portion - leaves definite etch marks	coupon etched lightly approximately 1/4" above water line
Brass	greenish discoloration not removable from surface	greenish deposits, heavier than in submerged portion - not removable	coupon etched lightly approximately 1/4" above water line
Titanium	unaffected	unaffected	unaffected
Nickel	light green deposits -	very slightly etched	unaffected
Copper	light green to blue surface discoloration - can be partially rubbed off	slightly etched	slight oxidation layer can be rubbed off
Stainless Steel 304	unaffected	unaffected	unaffected
Aluminum 5052	surface deposits - can be rubbed off - slight residual etching remained	slightly heavier surface deposits than submerged portion - indistinct etch patterns exist	slightly etched approx. 1/4" above water
Aluminum 6061	slight surface deposits formed - can be rubbed off - slight residual etching remained	very slightly etched	surface discoloration no etching evident

TABLE 4.10 (continued)

<u>Test Coupon</u>	<u>Submerged Portion</u>	<u>Liquid/Air Interface</u>	<u>Zone Above Interface</u>
Teflon	unaffected	unaffected	unaffected
Rubber	unaffected	unaffected	unaffected
PVC	unaffected	unaffected	unaffected
Neoprene	unaffected	unaffected	unaffected

5.0 DISCUSSION OF RESULTS

5.1 IGNITION AND EXTINGUISHMENT MECHANISMS

A review of the results given in the previous section, the progress reports on work being carried out at NASA-Ames [6] and a study conducted at the Bureau of Mines [7] leads to the following observations:

1. Three powdered chemicals, Li_2CO_3 , Na_2CO_3 and KI, were found to extinguish the flames in the tunnel apparatus at Arthur D. Little, Inc. However, the same agents failed when tested at NASA-Ames tunnel facility.
2. Some agents such as potassium bicarbonate and Monnex[®] successfully extinguished the flames in both systems under certain operating conditions. However, the reignition delay times were dependent on the quantity of the agent applied and the air velocity.
3. Tests at NASA-Ames also showed that the ease of ignition of JP-4 was highly dependent on the type of hot surface on which it impinged.
4. Tests at the Bureau of Mines showed that the ignition temperature of aircraft fuels increased with increasing air velocity. Ignition temperatures were also found to depend on the geometry of the hot surface on which the fuel impinged.

These observations and the apparently erratic extinguishment results may be explained by postulating mechanisms for fuel ignition and flame extinguishment on a hot surface.

When a fuel such as JP-4 is sprayed in the form of small droplets on a horizontal surface heated above the boiling point of the fuel, two types of boiling may take place depending on the temperature difference between the droplet and surface. At low temperature differences, nucleate boiling takes place. In this case the droplet wets the surface. Irregularities and scratches in the surface serve as nucleating sites for vapor bubbles to form. Heat transfer rates

are high and boiling is rapid because of the agitation generated by the bubbles (see Figure 5.1a). If the surface temperature is very high, as is the case in the tests described in this report, a layer of vapor is formed around each fuel droplet or fuel layer and film boiling takes place (see Figure 5.1b). The film serves as an insulating layer which slows the rate of heat transfer to the fuel. If the air is blowing against the surface, the fuel droplets or film will be swept away easily because the vapor layer acts like an air bearing and friction with the surface is minimal.

The temperature profile within the vapor layer separating the liquid fuel and the hot surface will vary between the boiling point of the liquid at the surface of the fuel and the hot surface temperature. Whether or not a combustible vapor/air mixture is formed, and whether such a mixture ignites, is a function of the hot surface temperature, the ambient air temperature and the air velocity. This, in turn, determines the rate of heat loss from the vapor layer, the droplet residence time in the heated zone, and the degree of turbulence. The degree of turbulence determines the ease by which a combustible vapor/air mixture becomes available to ignite. Thus, fuel droplets impinging on a hot surface may or may not ignite depending on many interdependent variables.

The extensive studies that have been made to date on film and nucleate boiling [8] have also shown that the incipience of boiling is highly dependent on the condition of the surface to which the liquid is applied. Polished surfaces tend to promote film boiling and to superheat the droplets above their boiling point whereas rough surfaces encourage nucleate boiling and quick vaporization. This may explain the differences in hot surface ignition temperatures of the same fuel when various metallic surfaces were used [6].

Assuming that all of the necessary conditions exist for fuel ignition on a hot surface, initial extinguishment of the flame may be achieved by traditional means (e.g., inerting, chemical inhibition, cooling). However, if after extinguishment all conditions are restored

to their original status, the fuel can be expected to reignite. To prevent reignition, at least one of the conditions needed to ignite the fuel must be removed. One possibility is to keep the flame extinguished long enough for the air stream to cool the hot surface to a temperature below the minimum needed to reignite the fuel. Another is for the extinguishing agent to melt and glaze the rough hot surface. The agent and its propellant gas tend to quench the hot surface momentarily. The agent absorbs first the sensible heat needed to raise its temperature to its melting point and next its heat of fusion. If it melts, it may smooth the surface so as to promote film boiling of the fuel. The fuel droplets or layer will then tend to run off more easily with the air stream (see Figure 5.2).

In summary, the ignition and extinguishment mechanisms of a fuel impinging on a hot plate are far from being simple, repeatable events. They are dependent on many factors such as:

- the heated surface: its temperature, geometry, material and roughness,
- the fuel atomizing system: fuel droplet size, impingement velocity and rate of application,
- the agent/dispersing system: the chemical and physical properties of the agent, rate of application, fraction impinging on the surface,
- the propellant gas: its flow rate, heat capacity, thermal conductivity, and
- the air velocity.

It is not surprising then that there were differences in behavior of specific agents between the two test systems. It is predicted that differences in agent behavior will also be encountered between the NASA-Ames test facility and the engine simulator being constructed at Wright-Patterson Air Force Base.

5.2 COMPARATIVE EFFECTIVENESS OF AIRCRAFT EXTINGUISHING SYSTEMS

Of the new agents that were tested on both the Arthur D. Little,

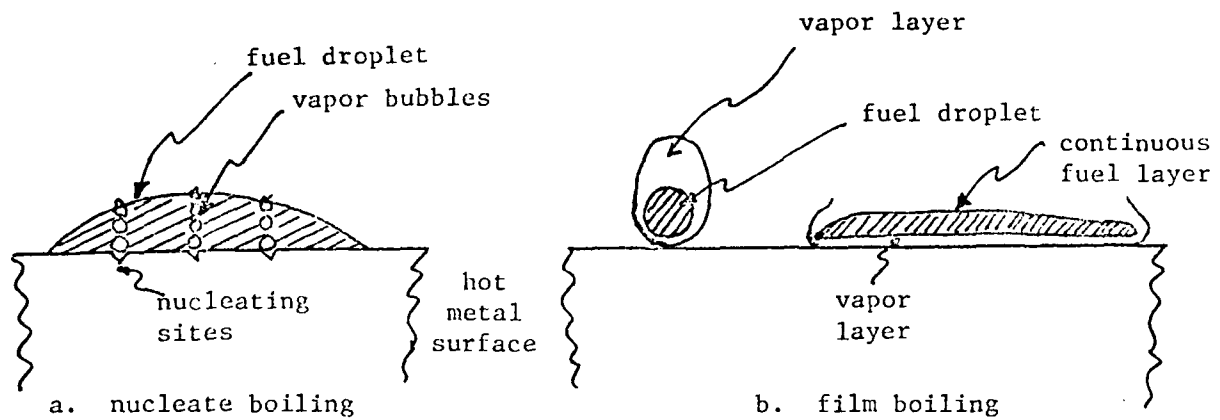


Figure 5.1: Behavior of Fuel Droplets on Hot Surfaces

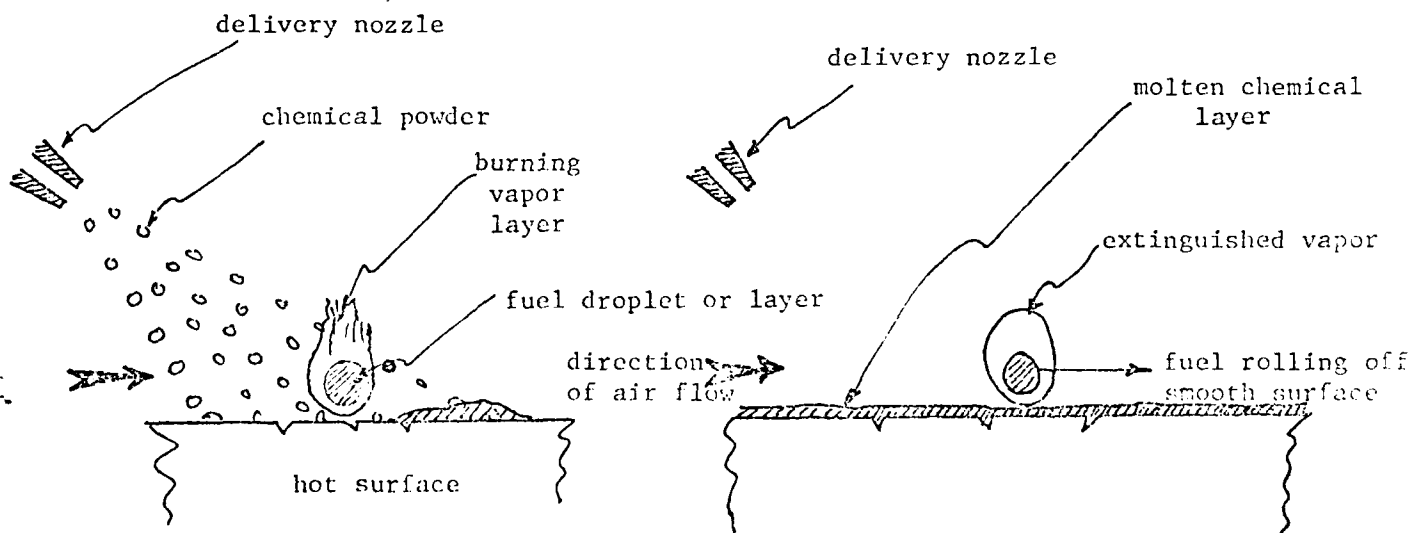


Figure 5.2: Postulated Extinguishment Mechanism

Inc. and NASA-Ames systems to date, only dry chemical agents appear to hold some promise. The data developed under this program indicate that a minimum of about 5 g is needed of a dry chemical agent such as potassium bicarbonate to provide permanent extinguishment of a flame from a JP-4 fuel impinging on a 6 x 6-inch (15 cm x 15 cm) surface placed in a duct which is 3" x 8" (7.6 cm x 20.3 cm) in cross section when the air velocity is about 18 fps (6 ms^{-1}). In comparison, a concentration of 6% of a typical Halon such as 1301 is needed continuously in the air stream to effect extinguishment. To compare requirements for a dry chemical system versus a Halon system, the worst conditions postulated for a fire in a highly simplified engine nacelle were considered.

The simplified engine was assumed to have the dimensions shown in Figure 5.3. It was desired to compare agent requirements for a one-minute extinguishment.

5.2.1 Calculation of Dry Chemical Requirements

Minimum dry chemical requirements can be calculated using the data developed under this program. Since a minimum of 5 grams is needed to extinguish a fire on a .25 sq ft (232 sq cm) 6" x 6" (15.2 x 15.2 cm) plate when air velocity is 18 fps (6 ms^{-1}), one can estimate minimum requirements to extinguish a fire involving the larger area of the simplified engine nacelle of Figure 5.3 when air is blowing at the maximum anticipated rate of 350 fps (107 ms^{-1}).

$$\begin{aligned}
 \text{The maximum potential heated surface, given a fire} &= 12 (2\pi \times 1.25) \\
 &= 94.25 \text{ sq ft } (8.8\text{m}^2) \\
 \text{Minimum agent quantity needed} &= 5 \text{ g} \times \frac{350 \text{ fps}}{18 \text{ fps}} \times \\
 &\quad \frac{94.25 \text{ sq ft}}{0.25 \text{ sq ft}} * \\
 &= 36,651 \text{ gram} \\
 &= 80.73 \text{ lb}
 \end{aligned}$$

*This calculation assumes that the quantity of the dry chemical agent needed is directly proportional to the air velocity and the hot surface area. It further assumes that the whole engine surface has been heated to the ignition temperature.

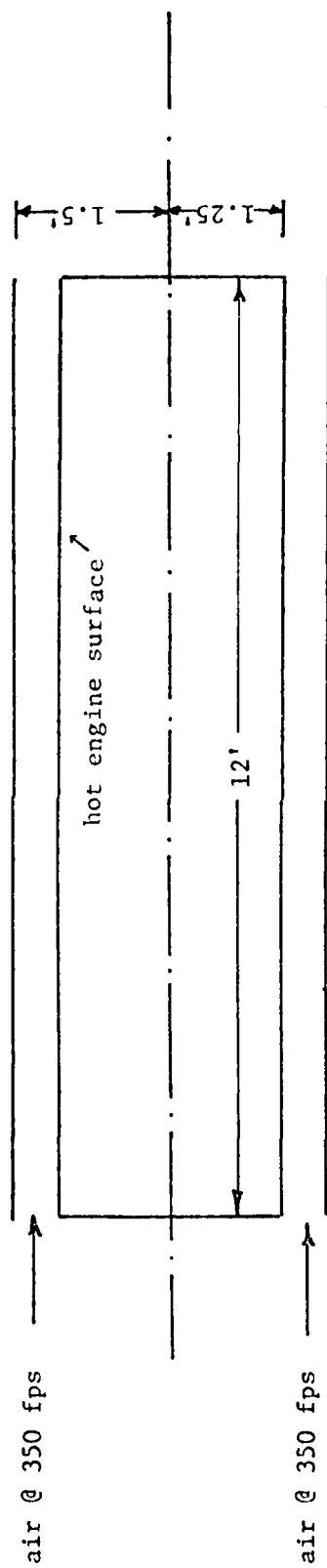


Figure 5.3 Simplified Engine Nacelle Used in Calculations

The 5-gram requirement was the minimum based on laboratory test data. To insure extinguishment, twice that charge should probably be applied. Thus, assuming a 100% reliable dry chemical agent dispensing system, the mass of the dry chemical needed to extinguish the worst engine nacelle fire will be approximately 161.5 lb (73.2 kg).

Commercially available automatic dry chemical systems are known for their unreliable performance. Factory Mutual's experience with industrial dry chemical systems shows that they are 27% reliable [5]. There are several reasons for this low reliability figure:

1. Vibration tends to pack the dry chemical in its storage container.
2. Any moisture present during filling operations will tend to cake the chemical over long storage periods.
3. The flow of a solid/gas mixture in long tortuous tubes often results in plugging at sharp bends or fittings.
4. Maintenance and testing of dry chemical systems are extremely difficult.

Even if the reliability of an automatic aircraft dry chemical system can be raised to 80%, three completely redundant delivery systems will be needed to achieve an overall reliability of 99.2%.

The total volume and weight penalties associated with three redundant dry chemical systems each containing 161.5 lb (73.2 Kg) of dry chemical are approximately 7.5 cu ft ($.21 \text{ m}^3$) and 1215 lb (551 Kg). Based on data from industrial system, each container was assumed to weigh approximately 1 1/2 times the weight of its contents (i.e., ~ 224 lb; 102 Kg).

5.2.2 Calculation of Halon 1301 Requirements

To extinguish a fire in the engine nacelle of an aircraft using Halon 1301, a concentration of approximately 6% halon must be present in the air stream continuously. The total volume of Halon 1301 necessary to extinguish a fire under the worst conditions discussed above can be calculated as follows:

The volumetric flow of air in the nacelle = $350 \text{ fps} \times \pi \times (1.5^2 - 1.25^2)$

The volume of Halon 1301 needed for one minute extinguishment =

$$6\% \times 350 \times \pi(1.5^2 - 1.25^2) \times 60 \frac{\text{sec}}{\text{min}} \approx 2721 \text{ cu ft } (77 \text{ m}^3)$$

$$\text{The mass of Halon 1301 needed} \approx \frac{2721 \text{ cu ft}}{2.5 \text{ cu ft/lb}} \approx 1090 \text{ lb } (494 \text{ Kg})$$

Note that, unlike the calculation for dry chemical quantities, the Halon calculations are based on volumetric flow rate of air in the engine nacelle area and are not a function of surface area.

Because Halon systems are not subject to the unreliabilities encountered by automatic dry chemical systems, a single storage system is needed.

The total volume and weight requirements are approximately 12 cu ft ($.34 \text{ m}^3$) and 2725 lb (1236 Kg). An empty halon container was also assumed to weigh one and a half times the weight of its contents.

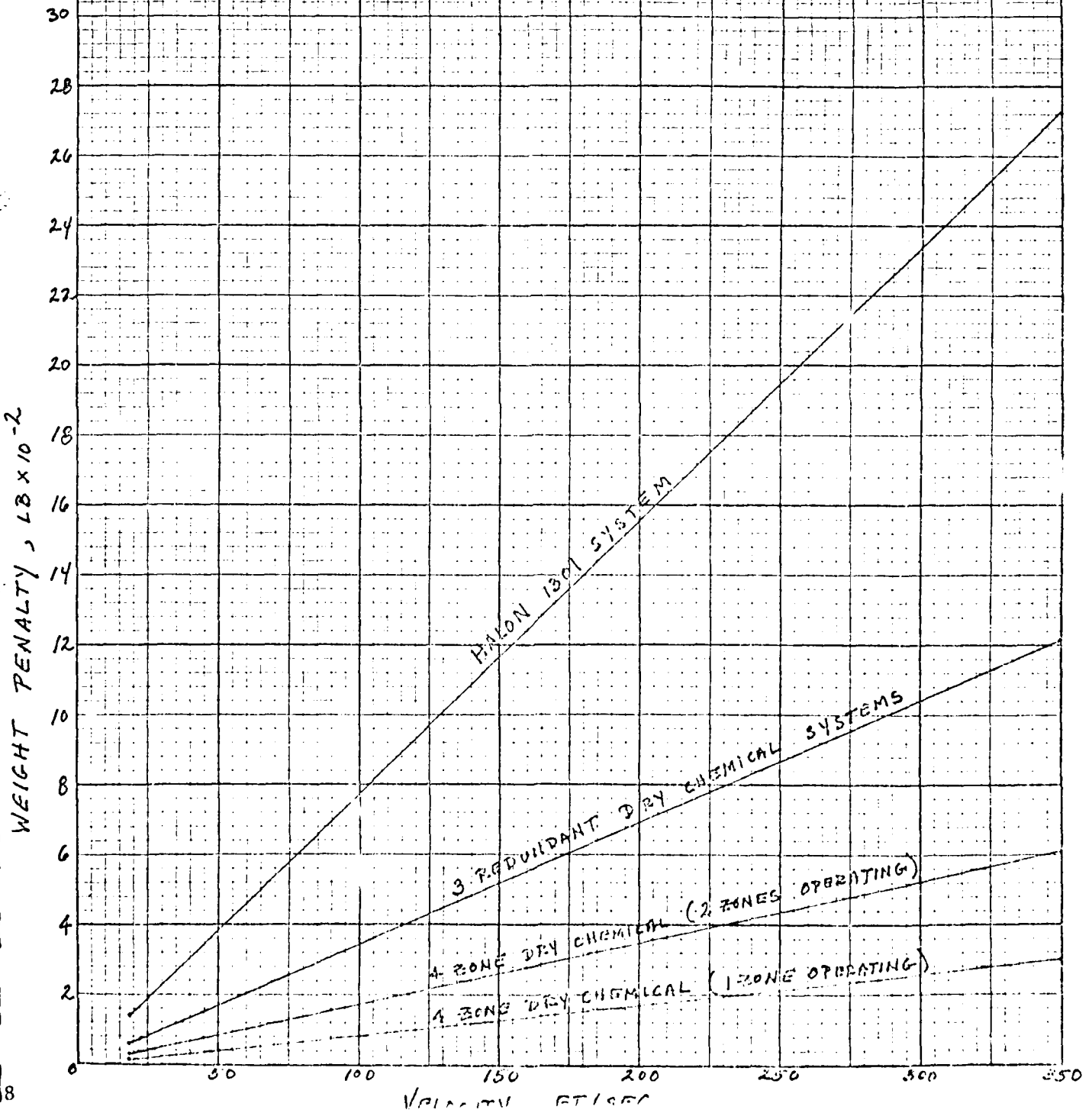
5.2.3 Comparison Between the Two Systems

Based on these calculations and the assumptions made, it appears that three redundant dry chemical systems each having a reliability of only 80% will have 37.5% smaller volume requirements and 44.4% smaller weight penalties than a single 99% reliable Halon 1301 system needed for the proposed application.

These comparisons between the two systems will be true regardless of air flow velocity because both weight penalties are directly proportional to air velocity. See Figure 5.4. However, as noted above the calculation of the dry chemical weight penalty assumed that the total engine surface is heated to ignition which may be too conservative. The dry chemical weight penalty will be proportionally reduced depending upon the actual surface area heated to ignition temperature (e.g. if the heated surface is 1/5th of the total engine surface, the weight penalty will be 1.5 cu ft, (0.04 m^3) 243 lb (110Kg) respectively). Since the halon calculation is not dependent upon the heated surface area the halon weight does not change, if the area is reduced.

FIGURE 5.4

WEIGHT PENALTY OF VARIOUS EXTINGUISHING SYSTEMS
AS A FUNCTION OF AIR STREAM VELOCITY



Further reduction in dry chemical and halon system weight penalties may be effected by zoning the engine nacelle area, i.e. zoning entails separate detection and agent distribution system in each zone but only one storage container. A four zone engine for example would require one half of the agent capacity assuming that two contiguous zones operate.

The feasibility of zoning must await the design, development and testing of detection and dispensing systems that are compatible with specific engine configurations.

If total protection against reignition were not required, the Halon 1301 system weight penalty would be reduced to about 450 lb (204 Kg) assuming a 10 sec discharge period and an air stream velocity of 350 fps. The dry chemical system weight penalties will not change because of the short system discharge period, e.g., 1 to 5 sec.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The results of experiments involving the extinguishment of flames from a JP-4 fuel spray impinging on a hot plate at about 1700°F (927°C) in the presence of air at a velocity of 18 (6 ms^{-1}) fps can be summarized as follows:

1. Carbon dioxide and common fire extinguishing halons will extinguish the flames only while the agent is being applied. Reignition of fuel is established immediately or within a few seconds after agent application is stopped.
2. Several powdered (-325 mesh) chemical agents performed equally well under the test conditions by being capable of extinguishing the flame for more than 60 seconds upon the application of only 5 grams. These agents were potassium bicarbonate (KHCO_3), lithium carbonate (Li_2CO_3), potassium iodide (KI), and sodium carbonate (Na_2CO_3).
3. A 0.8:1 lithium chloride (LiCl)/water solution was also found effective in extinguishing the flames for more than 60 seconds when applied at the rate of 51 g/s for half a second. This agent would not freeze at -65°F (-54°C), however, it will have to be contained in an insulated container to withstand exposure to 500°F (260°C) during a flight mission.
4. With the exception of potassium bicarbonate, none of the agents selected performed satisfactorily at the NASA-Ames test facility. It is postulated that fuel ignition and extinguishment mechanisms are dependent on many apparatus and procedure-related factors. This makes it difficult to guarantee that the results on one apparatus can be duplicated on another.
5. The presence of 0.5% of a commercial fumed silica (Tullanox[®] 500) was found to enhance the fluidity of all chemical powders.

6. Dow Corning[®] silicone foam was a very effective agent in insulating the hot surface and preventing fuel ignition. It is doubtful, however, that this two-component agent will be capable of foaming or flowing at -65°F (-54°C) or of surviving prolonged exposure to 500°F (260°C).
7. Compatibility tests at 100°F (38°C) showed that the candidate powders did not have any significant deleterious effects on neoprene, Teflon, PVC and Buna-N Rubber. Similarly, LiCl solution had no effect on the same materials when tested at room temperature. Prolonged exposure of aluminum (5052, 6061), brass, copper, nickel, mild steel, stainless steel 304 and titanium to the dry powders at 500°F (260°C) resulted in surface reactions between dry LiCl and all metals, Na₂CO₃ and copper, KI and brass, copper and mild steel, and Li₂CO₃ and copper. Lithium chloride solution in water reacted in various degrees with all metals except titanium and stainless steel 304.

6.2 RECOMMENDATIONS

1. It is important to understand the controlling factors for fuel ignition and extinguishment in the presence of very hot metallic surfaces. It is recommended that a basic research program be conducted to study the mechanisms for fuel ignition and extinguishment on a hot surface. High speed photography may be a useful tool for such an investigation.
2. Because of the dependence of extinguishment test results on the test apparatus and conditions, all candidate extinguishing agents selected under this study and by NASA-Ames should be tested in the aircraft engine simulator being constructed at Wright-Patterson Air Force Base before a final selection is made.
3. The tests conducted to date and the simplified cost-effective analysis indicate that dry chemical powders such as a commercial potassium bicarbonate fire extinguishing agent may be

the best solution for advanced aircraft. A program to design highly reliable automatic dry chemical systems for advanced aircraft should be of immediate interest.

4. An investigation should be conducted on the potential for the adaptation of Dow Corning[®] silicone foam so that it may be utilized for the proposed application.

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