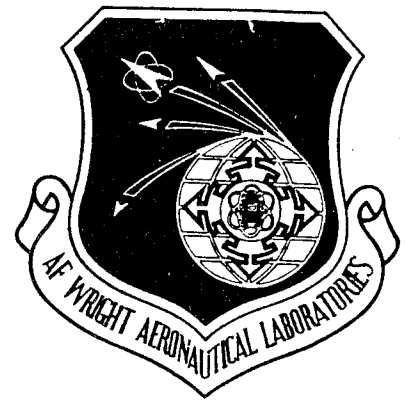


AFWAL-TR-85-2060



Volume II Aircraft Engine Nacelle Fire Test Programs
Part 2 Small Scale Testing of Dry Chemical Fire Extinguishants

VULNERABILITY METHODOLOGY AND PROTECTIVE MEASURES FOR AIRCRAFT FIRE AND
EXPLOSION HAZARDS

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Dry chemical fire extinguishing agents were studied in a simulated small scale aircraft engine nacelle environment to observe the ability of these agents to prevent re-ignition, a known deficiency of the presently used gaseous agents. An injector was developed which effectively dispersed agent into the airstream; a fuel spray behind a flameholder, ignited and sustained by a hot surface, was used as the test scenario. The agents were found to be effective in very small quantities (<30 grams) for initial suppression of the fire, but permanent extinguishment was found to be a function of test conditions. The agents tended to accumulate on test surfaces and cause some corrosion as the result of repeated applications but were easily cleaned from affected surfaces.				
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VULNERABILITY METHODOLOGY AND PROTECTIVE MEASURES FOR AIRCRAFT FIRE AND
EXPLOSION HAZARDS

Volume II Aircraft Engine Nacelle Fire Test Programs

Part 2 Small Scale Testing of Dry Chemical Fire Extinguishants

This report is one of the set of aircraft fire protection reports contained in
AFWAL-TR-85-2060 as listed below:

Volume I Executive Summary

Volume II Aircraft Engine Nacelle Fire Test Program

Part 1 Fire Detection, Fire Extinguishment and Hot Surface
Ignition Studies

Part 2 Small Scale Testing of Dry Chemical Fire Extinguishants

Volume III On-Board Inert Gas Generator (OBIGGS) Studies

Part 1 OBIGGS Ground Performance Tests

Part 2 Fuel Scrubbing and Oxygen Evolution Tests

Part 3 Aircraft OBIGGS Design

PREFACE

Aircraft fire protection research conducted by the Boeing Military Airplane Company under Contract F33615-78-C-2063 is discussed in this report. Most of the research was carried out in newly activated facilities, the Aircraft Engine Nacelle (AEN) simulator, and the Simulated Aircraft Fuel Tank environment (SAFTE) simulator located at Wright-Patterson Air Force Base and was conducted between February 1981 and October 1984. The contract was sponsored by the Air Force Wright Aeronautical Laboratories (AFWAL) and the Joint Technical Coordinating Group on Aircraft Survivability (JTTCG/AS). Guidance was provided by the Fire Protection Branch of the Aero Propulsion Laboratory (AFWAL/POSH), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3043, Task 07, and Work Unit 86. Gregory W. Gandee, Terrell D. Allen, and John C. Sparks were the Government project engineers.

The results are presented in three volumes with Volumes II and III subdivided into parts. Volume I summarizes the research conducted under this program, describes the test facilities used, and highlights important findings. Volume II discusses research related to engine compartment (nacelle) fire protection. Testing was done primarily in the AEN simulator, but some small scale testing was performed at Boeing facilities in Seattle. Volume III discusses fuel tank fire protection research studies performed under this contract. Most of this work was focused on on-board inert gas generator systems (OBIGGS). Much of the testing related to OBIGGS development was conducted in the SAFTE simulator, but again some related small scale testing was done in Seattle. The contents of the three volumes are listed below:

Volume I Executive Summary

Volume II Aircraft Engine Nacelle Fire Test Program

Part 1 Fire Protection, Fire Extinguishant and Hot Surface Ignition
 Studies

Part 2 Small Scale Testing of Dry Chemical Fire Extinguishants

Part 1 OBIGGS Ground Performance Tests

Part 2 Fuel Scrubbing and Oxygen Evolution Tests

Part 3 Aircraft OBIGGS Designs

Boeing acknowledges the contributions of the design and technical personnel of Technical/Scientific Services, Inc. (TSSI) for their support to this program and to R. G. Clodfelter of the Air Force for his technical guidance during the research studies and for his efforts to develop these National facilities for generalized investigations of techniques to improve aircraft fire safety.

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LIST OF ABBREVIATIONS AND SYMBOLS

AEN	Aircraft Engine Nacelle Fire Test Simulator
GPH	Gallons Per Hour
KD+KI+SiO ₂	Potassium Dawsonite plus Potassium Iodide and Silica Flow Agent
MONNEX	Condensation Product of Potassium Bicarbonate and Urea
NaD+SiO ₂	Sodium Dawsonite plus Silica Flow Agent

1.0 INTRODUCTION

Development of fire protection systems for aircraft engine compartments has been an on-going effort for many years. Altman, et al (Ref. 1) trace this development over the past 40 years, review progress, and cite areas that require further research. They point out that the current technique of extinguishing engine fires by fluid (fluid extinguishing agent) injection began with such substances as carbon dioxide and carbon tetrachloride and was followed by the halogenated hydrocarbons or Halons. The fluid based systems were found to have some effectiveness problems, especially for the higher operating temperatures of advanced engines. This deficiency led to the investigation of dry powder extinguishing agents as a means of enhancing engine fire protection. One objective was to develop fire extinguishant materials that would adhere to the walls of a jet engine compartment to help nullify the high airflow effect; the high airflow negates the fire control mechanism of gaseous systems. A second objective was to develop a fire control system which would not only extinguish a fire, but would prevent reignition even with the persistence of conditions that produced the fire initially.

Testing conducted in Ref. 1 was performed using a static test unit and a small scale air flow device. The results revealed that some commercial dry chemical fire extinguishants have a greater weight effectiveness in suppressing hot surface initiated fuel fires than the gaseous or liquid Halons currently in use. Recommendations included testing of dry chemical agents in the Aircraft Engine Nacelle (AEN) at WPAFB to confirm these results. (A bibliography of dry powder extinguishant research is presented at the end of this report.)

The objective of the work discussed in this report was to gain experience with (1) the techniques of handling dry chemical extinguishants and (2) their performance as fire extinguishants in a simulated engine nacelle environment, prior to testing with dry chemical agents in the AEN facility. This objective was accomplished through testing in the small scale fire test facility previously developed for use with gaseous and liquid nitrogen, carbon dioxide, and Halon 1301.

Three agents were evaluated in this program:

- o MONNEX, produced by ICI, Ltd., a condensation product of KHCO_3 (potassium bicarbonate) and the organic compound $\text{CO}(\text{NH}_2)_2$ (urea)
- o $\text{NaD}+\text{SiO}_2$ (sodium dawsonite plus silicon dioxide), consisting of 99 weight percent NaD and 1 weight percent SiO_2 , produced by Chatten Drug and Chemical, and Tullco, Inc., respectively
- o $\text{KD}+\text{KI}+\text{SiO}_2$, encapsulated, (potassium dawsonite plus potassium iodide and silicon dioxide), consisting of 90.1 weight percent KD, 8.9 weight percent KI, and 1 weight percent SiO_2 , produced by the Monsanto Research Corporation.

Dawsonite represents the aluminum carbonate anion, $[\text{Al}(\text{OH})_2\text{CO}_3]^-$; SiO_2 is added as a flow agent, serving to enhance the fluid characteristics of the extinguishing agent.

2.0 EXPERIMENTAL APPARATUS AND PROCEDURES

2.1 Test Facility

The test facility used to perform the dry chemical extinguishant tests is shown schematically in Figure 1. Airflow rates of 10, 20, and 34.5 feet per second were used. The latter velocity was representative of the maximum air velocity that could be used while sustaining combustion in the test section. Since the duct area of the test section was 0.5 square feet, the corresponding volume flow rates were 5, 10, and 17.3 cubic feet per second. The fuel flow rate was 1.08 gallons per hour (GPH). Electrical resistance heaters were used to control the temperature of the hot surface. Initial temperatures (prior to combustion) ranged from about 1100°F to 1450°F; while combustion maximum temperatures as high as 1750°F were observed.

2.2 Hot Surface Characterization

Minimum hot surface temperatures required for ignition with 1.08 GPH fuel spray were determined as a function of test section air velocity (Figure 2). (Thermocouple locations are indicated on the figure). These conditions correspond to temperatures required for re-ignition of hot surface fires following initial extinguishment, and are discussed later in more detail.

Thermocouple (TC) No. 1 consistently proved to be the location of the highest surface temperature prior to initiation of fuel flow, and, as such, was used as the reference temperature. Note that the temperature distribution changes non-uniformly with the test section air flow rate. The temperature distribution also changes after ignition; an example of this behavior for an air velocity of 10 feet per second is shown in Figure 3.

At surface temperatures above those required for ignition, initiation of fuel flow caused the surface temperature to decrease and, then, to recover after a fire was established and the fuel flow was terminated. The initial cooling rates that occur in the vicinity of TC No. 1 just after the fuel was injected, and the final stable temperatures reached by the surface, are given for each of the test air velocities in Table 1.

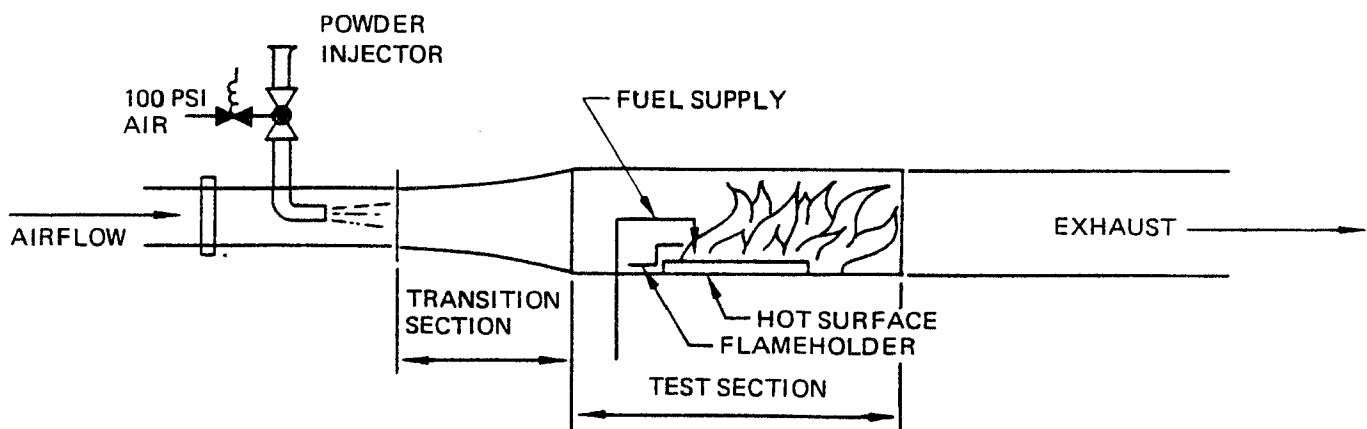


Figure 1. Test Section Diagram

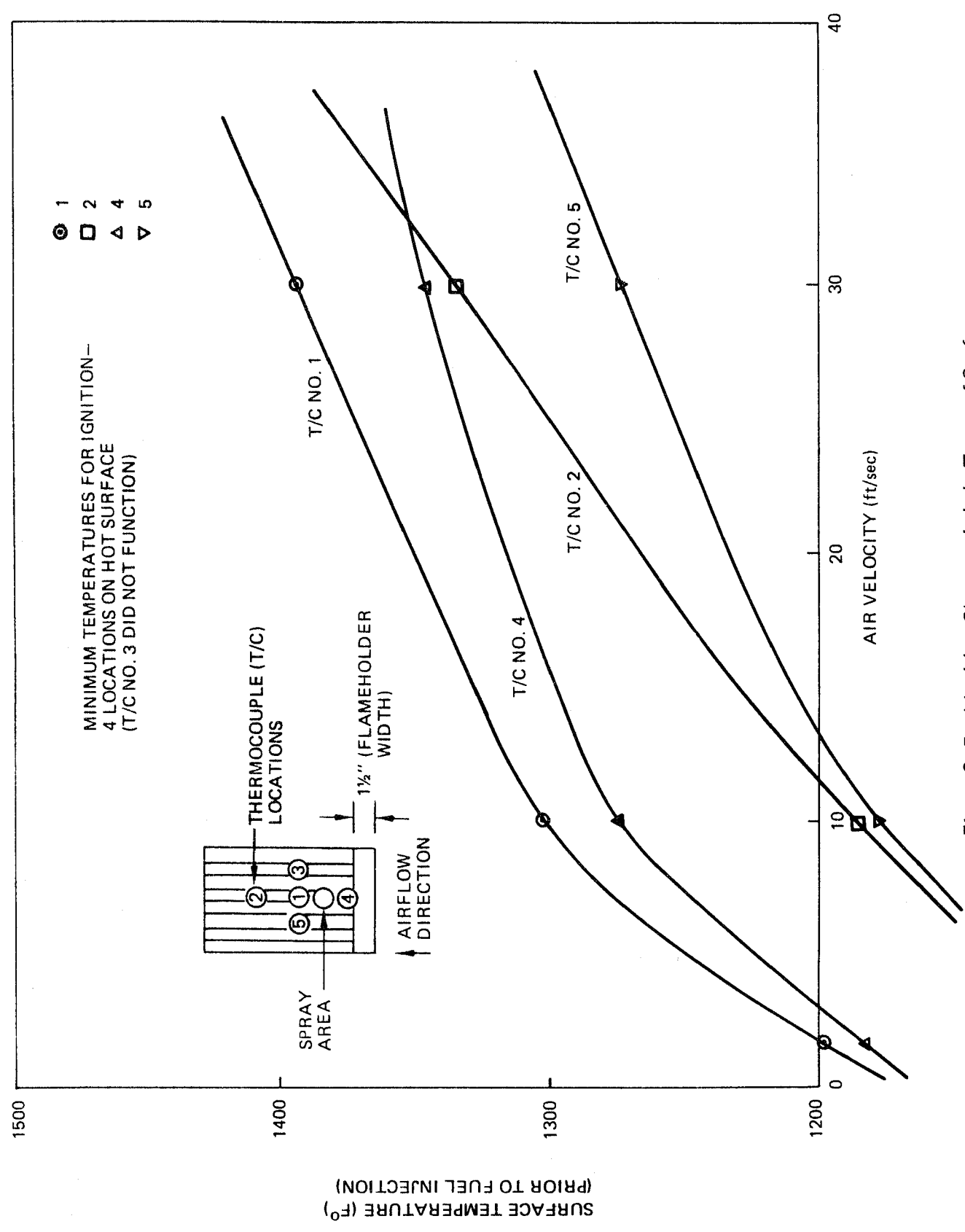
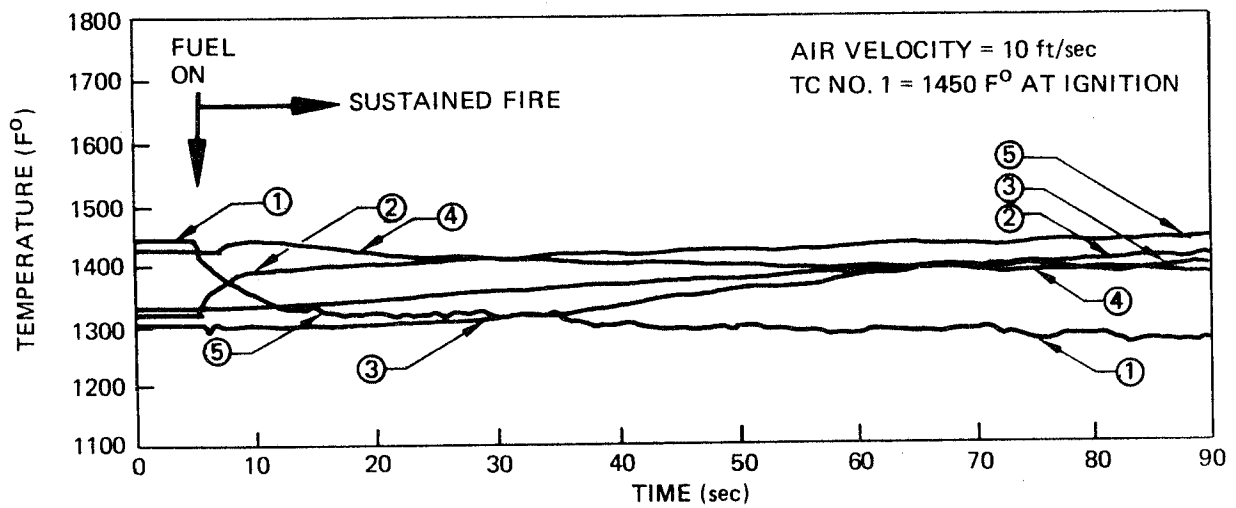
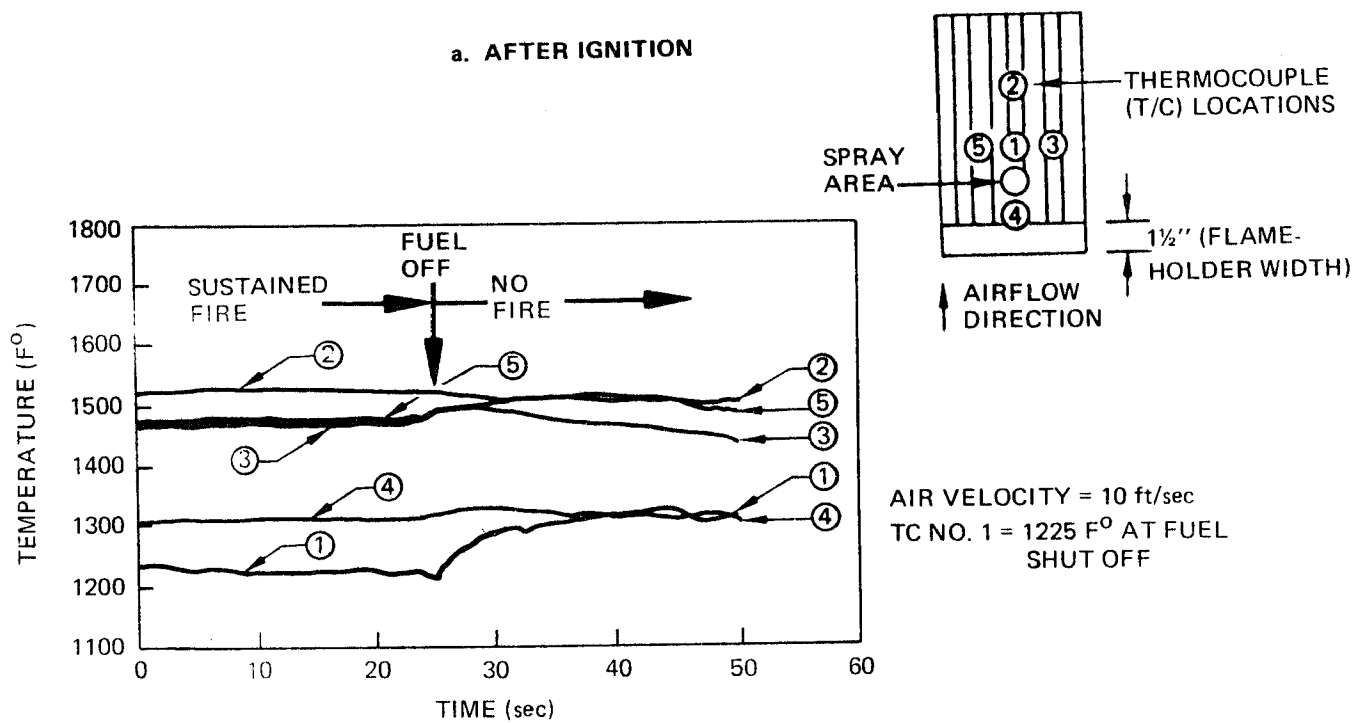


Figure 2. Fuel Ignition Characteristic in Terms of Surface Temperature and Air Velocity



a. AFTER IGNITION



b. AFTER FUEL SHUTOFF

Figure 3. Hot Surface Temperature Traces

Table 1. Fuel Cooling Effects

<u>Air Velocity</u> (ft/sec)	<u>Cooling Rate</u> (oF/sec)	<u>Surface Temperature</u> oF
10	13.0	1338
20	7.5	1400
34.5	1.5	1430

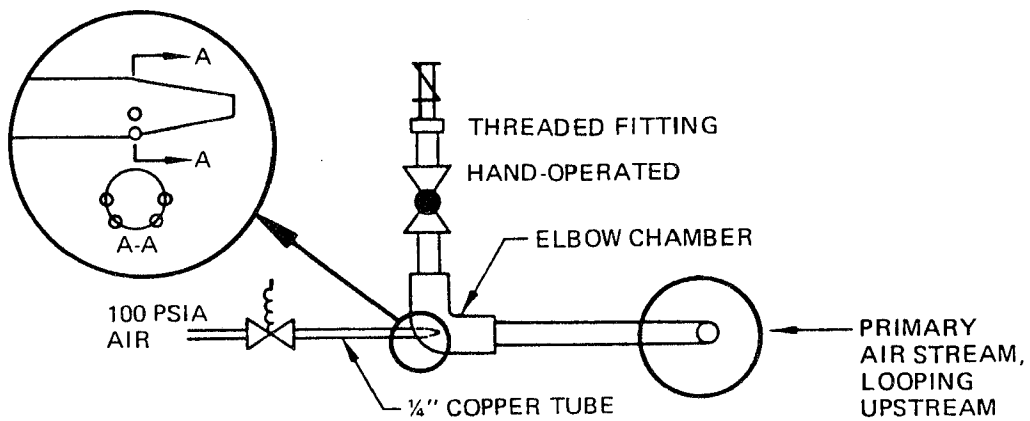
(The initial temperature in each case was 1450^oF, as measured at TC No. 1; ignition occurred in all cases.)

2.3 Powder Injector Development

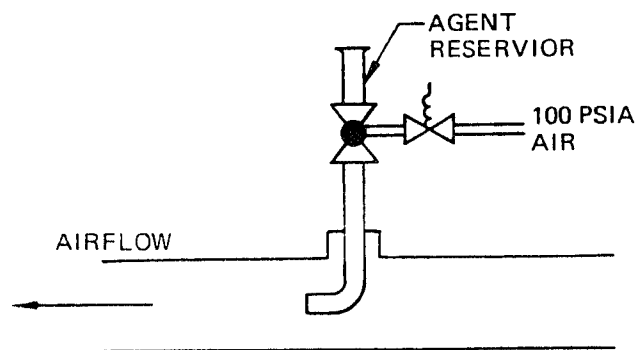
The powder injection mechanism was designed to: (1) contain the powder load until ready for injection into the test section, and (2) on command, disperse the powder as evenly as possible into the airstream before the powder entered the fire region.

Initially, the injector was designed to be similar to the device used by Myronuk (Ref. 1) at NASA-Ames (Figure 4a). This injector worked well for up to 30 gram loads of agent; for agent amounts larger than 30 grams a redesign was required. The size of the elbow-shaped chamber was insufficient, and the agent re-loading procedure was excessively complicated for repetitive testing. The injector was modified to the configuration shown in Figure 4b.

Loading the agent into the modified injector was a single-step operation - agent was simply loaded into the reservoir. It was not necessary to cap the opening of the reservoir. The agent was injected by activating a remote switch, opening the solenoid valve, which actuated a ball valve. As the ball valve opened, agent fell downward and was entrained into the airstream. This configuration worked well by giving acceptable injection times throughout testing for all except the largest quantities of agent. For those cases, the agent reservoir was pressurized (in particular, for test samples of NaD+SiO₂ of 30 grams or more due to its lower density) to give positive injection in an acceptably short time (< 1 second). Air entering the test section through the injector had no visible effect on the fire. The test section and injector as configured during testing are shown in Figures 5 and 6.



a. ORIGINAL DESIGN



b. MODIFIED DESIGN

Figure 4. Agent Injector Design

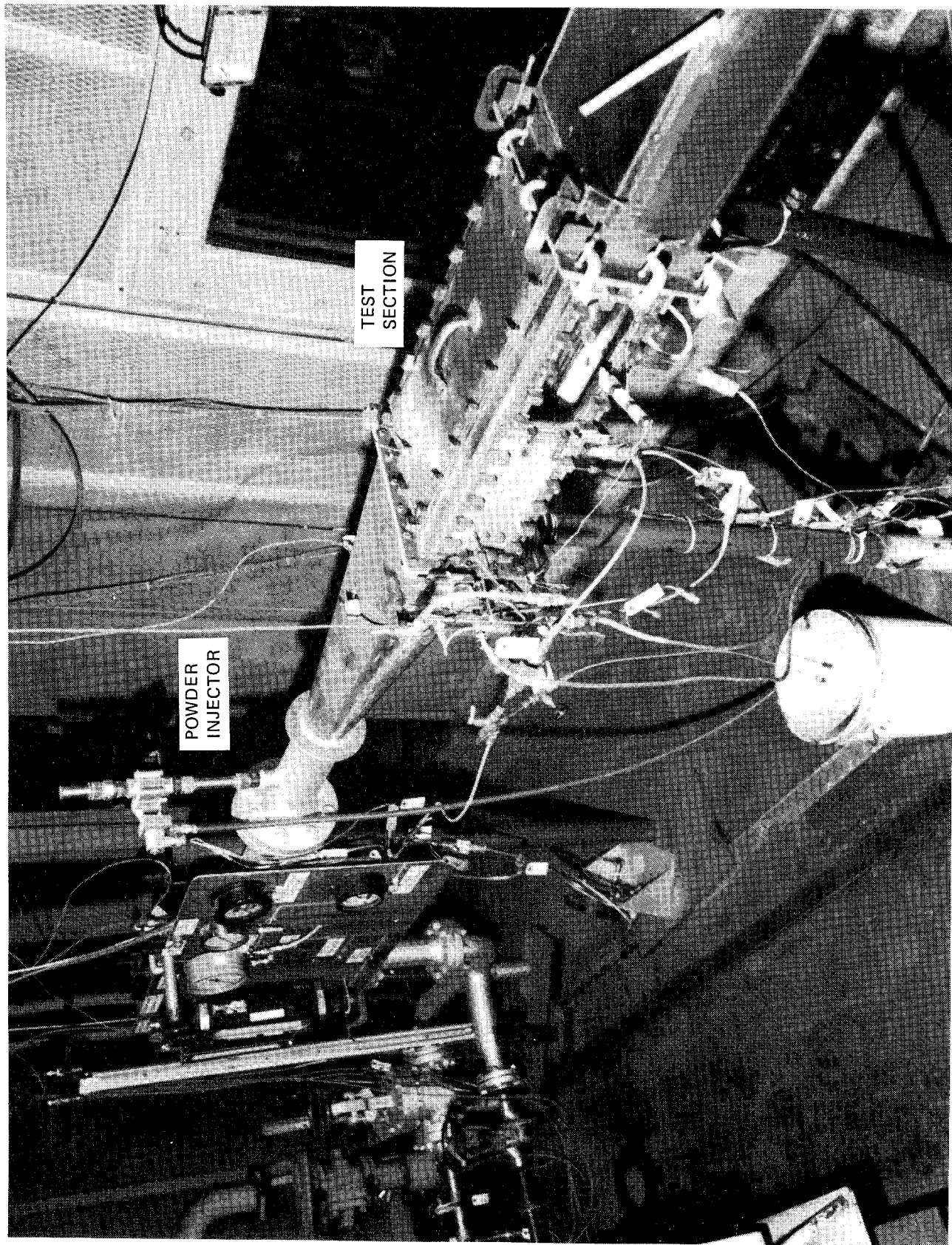


Figure 5. Test Section and Injector as Installed

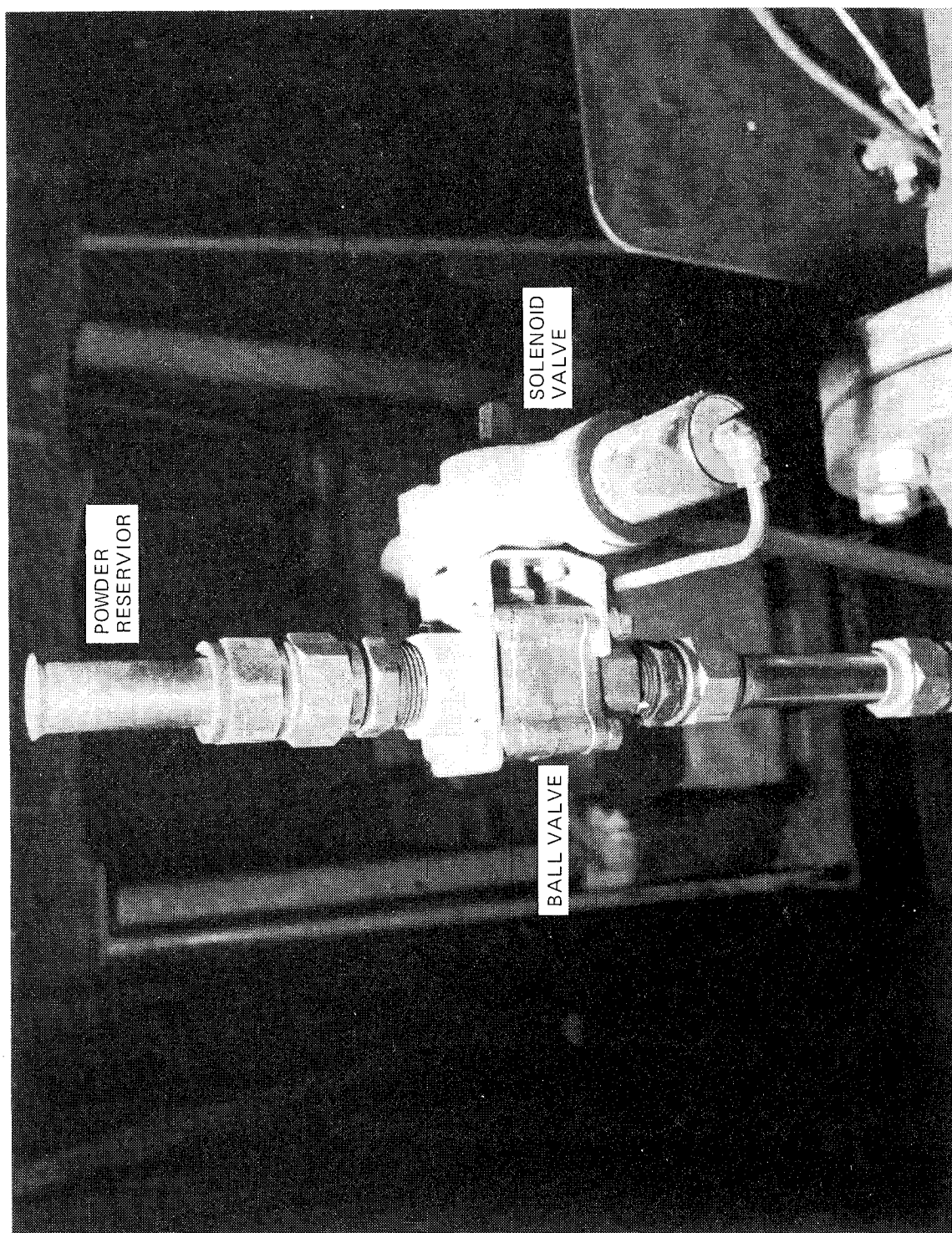


Figure 6. Injector Mechanism

2.4 Basic Test Procedures

The variables addressed in the test program were:

<u>VARIABLE</u>	<u>DESCRIPTION</u>
fire type	hot surface with flameholder (see Figure 1)
fuel type and flowrate	JP-4, 1.08 GPH
air temperatures	70 and 330 ⁰ F
air flowrates	10, 20, and 34.5 ft/sec
dry chemical extinguishing agents	MONNEX, NaD+SiO ₂ , and KD+KI+SiO ₂ (encapsulated)

Using ambient temperature air, test series were conducted for each of the three agents, at each of the three selected air velocities. Test series were limited to the 20 ft/sec air velocity when elevated air temperatures were used.

Testing of an agent at a selected velocity proceeded as follows:

- (1) The air velocity and temperature were established.
- (2) Electrical power was applied to the hot surface, and adjusted as required to obtain the desired pre-flame surface temperature.
- (3) Fuel was applied, and a stable flame established.
- (4) Powder was injected:
 - (a) If extinguishment did not occur, the powder weight was increased and the attempt repeated. All test series were begun with a powder weight of 5 grams; the largest weight used in any test series was 50 grams.
 - (b) If extinguishment did occur, the knock-down time and the keep-down time, if re-ignition occurred, were observed. If extinguishment was not permanent, the powder weight was again increased and the run repeated.

Prior to testing of the dry chemical agents, several means of filtering the exhaust air to remove the unabsorbed agent were considered, as required by

industrial hygiene regulations. Boeing industrial hygiene personnel were consulted, and the following determinations were made:

- o The component of the dry chemical agents considered most immediately threatening to the health of persons in contact with the chemical agents were the SiO_2 (silica).
- o The silica, used as an additive to improve the fluidity of the agents, is amorphous and not crystalline in structure. Only the crystalline silica is known to cause pulmonary fibrosis (silicosis) in instances of prolonged inhalation.
- o The toxicological effects of the MONNEX and the dawsonite compounds have not been determined.
- o Considering the minute particle size of the agents, and the small quantities used in testing, their presence was considered equivalent to that of nuisance dust. No filtering system was required, although handling precautions, such as using dust masks, were observed.

3.0 TEST RESULTS

The purpose of this test program was to evaluate the performance of each of three powders in terms of its relative ability to knock-down, and to keep down, a stable hot surface fire. Knock-down time (T_{kn}) is defined as the length of time required to extinguish a fire from the time the agent is injected; keep-down time (t_{ke}) is the length of time a fire remains extinguished.

3.1 Test Approach

The initial test approach was to evaluate the effectiveness of the agent on a hot surface after stable hot surface fire temperatures were reached. Comparisons were made between agents relative to their ability to suppress a fuel fire initiated on a 1450°F surface. However, variations in surface temperature influenced the ability of an agent to keep-down the fire. Thus, in a number of cases, additional runs were performed with a single powder weight at a variety of surface temperatures to determine the effectiveness boundaries of a particular sample concentration.

One means of comparing agents of similar effectiveness is to observe the difference in fire keep-down time accomplished by identically tested agents. This comparison indicates the difference in the persistence of one agent compared to another. When dry chemical agents are applied to a burning fire with a continual fuel spray, complex reactions occur which are not only difficult to describe but also contribute to the data repeatability problem.

Agent quantity was varied in 5 gram increments from 5 grams to as high as 50 grams in some cases, depending on agent effectiveness. Even though mixed units are involved, an agent concentration in terms of grams per cubic foot was a good measure of effectiveness. In this context agent concentration is determined by

$$\frac{\text{Agent qty (gm)}}{\text{Test Section Area (ft}^2\text{) x Airflow Velocity (}\frac{\text{ft}}{\text{sec}}\text{) x contact time}} = \frac{\text{gm}}{\text{ft}^3}$$

The contact time that the agent affects the fire volume (the time from initial powder cloud contact with the fire to the time that the trailing edge of the cloud passes out of the fire zone). This time did not vary significantly with powder type or amount, in spite of different densities, but did vary with test section air velocity - primarily because the suction effect occurring in the injector line increased with increasing velocity. The contact times for each velocity, as determined from test runs recorded on high speed film, are as follows:

<u>Air Velocity</u> <u>(ft/sec)</u>	<u>Agent Contact Time</u> <u>(seconds)</u>
10	0.72 - 0.80
20	0.56 - 0.64
34.5	0.40 - 0.56

As mentioned in Section 2.3, the agent reservoir was pressurized for tests with high agent volumes to ensure that all of the agent was transferred into the airstream. In those tests, all conducted with NaD+SiO_2 at 10 ft/sec air velocity, the contact time was decreased to 0.34 seconds. (A few test runs were made using low agent quantities conducted with and without pressurization. Without pressurization, the effect on the fire was minimal, but when repeated with pressurization, extinguishment was permanent. Resolution of how much agent quantity could be reduced and still cause permanent knock-down, and further, once the minimum quantity was found, could the injection pressure be increased to extend the region of effectiveness of the agent, was not pursued in this study. This should be included in future testing in the AEN facility.)

The extinguishing capability of the dry chemical agents, as described in the following sections, was found to be primarily a function of surface temperature and to some extent, test configuration factors. In summary, noticeable effects on the fires were observed even with very small agent concentrations; larger concentrations took longer to be dispersed into the airstream, and in turn, were in contact with the fire longer and allowed time for surface cooling to take place. In most cases, the probability of achieving permanent extinguishment was clearly related to the surface conditions after the physical effects of the agents had passed; in particular,

how much the surface had cooled during the time the fire was extinguished. In some cases high concentrations caused permanent extinguishment of the fire by blanketing the surface, as the example described in the previous paragraph. These results occurred more randomly and were not as repeatable as those which were temperature dependent.

3.2 Observations

In all cases, even at concentration quantities as small as 1 gram per cubic foot, the dry chemical agents injected into the test section airstream had a visible effect on the fire. While small amounts did not cause knockdown, these amounts did cause the flame volume to contract and recede behind the flameholder. When amounts were used that were sufficient to cause knockdown of the fire for brief periods of time, instantaneous suppression of the flame occurred, followed by an equally sudden re-ignition. Permanent extinguishment (infinite keep-down time) initially appears the same as brief suppression but is not followed by re-ignition. Permanent keep-down is believed to occur when the mass concentration of the agent is sufficient to (a) blanket the fire to cause initial extinguishment, and (b) keep the fire down long enough to allow the fuel flow to cool the surface below the re-ignition temperature.

An example is described in detail to illustrate the interaction of the extinguishing agent and the fuel and ignition sources. With an air velocity of 10 feet per second, and a hot surface of 1450°F initial temperature, quantities of 20, 25, 30 and 35 grams of $KD+KI+SiO_2$ were applied (Table 2).

Table 2. Surface Temperature Response to Application of Various Agent Concentrations

Powder Weight (gm)	Powder Concentration (gm/ft ³)	Temp ¹ Before Agent Inj. (°F)	Keep-down Time (sec)	Time to Reach Lowest Temp. (sec)	Lowest Temperature (°F)
20	5.26	1338	0.4	4	1299
25	6.58	1335	4.4	6	1214
30	7.89	1337	3.8	5	1247
35	9.21	1336	25.0	22	1195 ²

1 Temperatures are taken at TC No. 1 for convenience.

2 Temperature at re-ignition = 1225°F.

When 20 grams of the agent were applied, the concentration caused knock-down of the fire for only 0.4 seconds. However, even this brief period was sufficient to allow surface cooling by the fuel flow. The temperature decrease at the reference point continued for about 4 seconds from the time of initial knock-down, until the temperature reached 1299°F. At that point, the powder was no longer effective, and reignition occurred. The combined effect of combustion and surface heating caused the temperature at TC No. 1 to begin rising toward its steady-state temperature of 1338°F. Little difference was observed between the effectiveness of the 25 and 30 gram amounts except for the temperatures at which re-ignition occurred; keep-down times were 4.4 and 3.8 seconds, times to reach the lowest temperatures were 6 and 5 seconds, occurring at temperatures of 1214 and 1247°F, respectively. When 35 grams of agent were applied, the temperature decrease continued for 22 seconds until a minimum of 1195°F was reached and an increase in temperature began. After three seconds of temperature increase, re-ignition occurred at 1225°F.

In each case, re-ignition occurred at a reference point temperature substantially lower (~50-100°F) than the 1300°F shown in Figure 2 as the required re-ignition temperature. It is suspected that, even though the temperature at the reference point was between 1200 and 1250°F, the temperature necessary for re-ignition existed at some other point on the surface not as strongly influenced by fuel cooling. The basis for this supposition is the observed change in surface temperature distribution when fuel is applied as shown in Table 1. In other words, in order for permanent extinguishment of a hot surface fire to occur, the temperature of all points on the surface must be reduced to levels below the re-ignition temperature corresponding to the air velocity.

3.3 Test Results

Data taken at test section velocities of 10, 20, and 34.5 feet per second and using MONNEX as the extinguishant are shown in Figure 7. Temperatures are the hottest monitored point on the surface just prior to agent application, and not necessarily taken at the reference point, TC No. 1. As established earlier, the hottest point is most likely to influence re-ignition potential, regardless of its location.

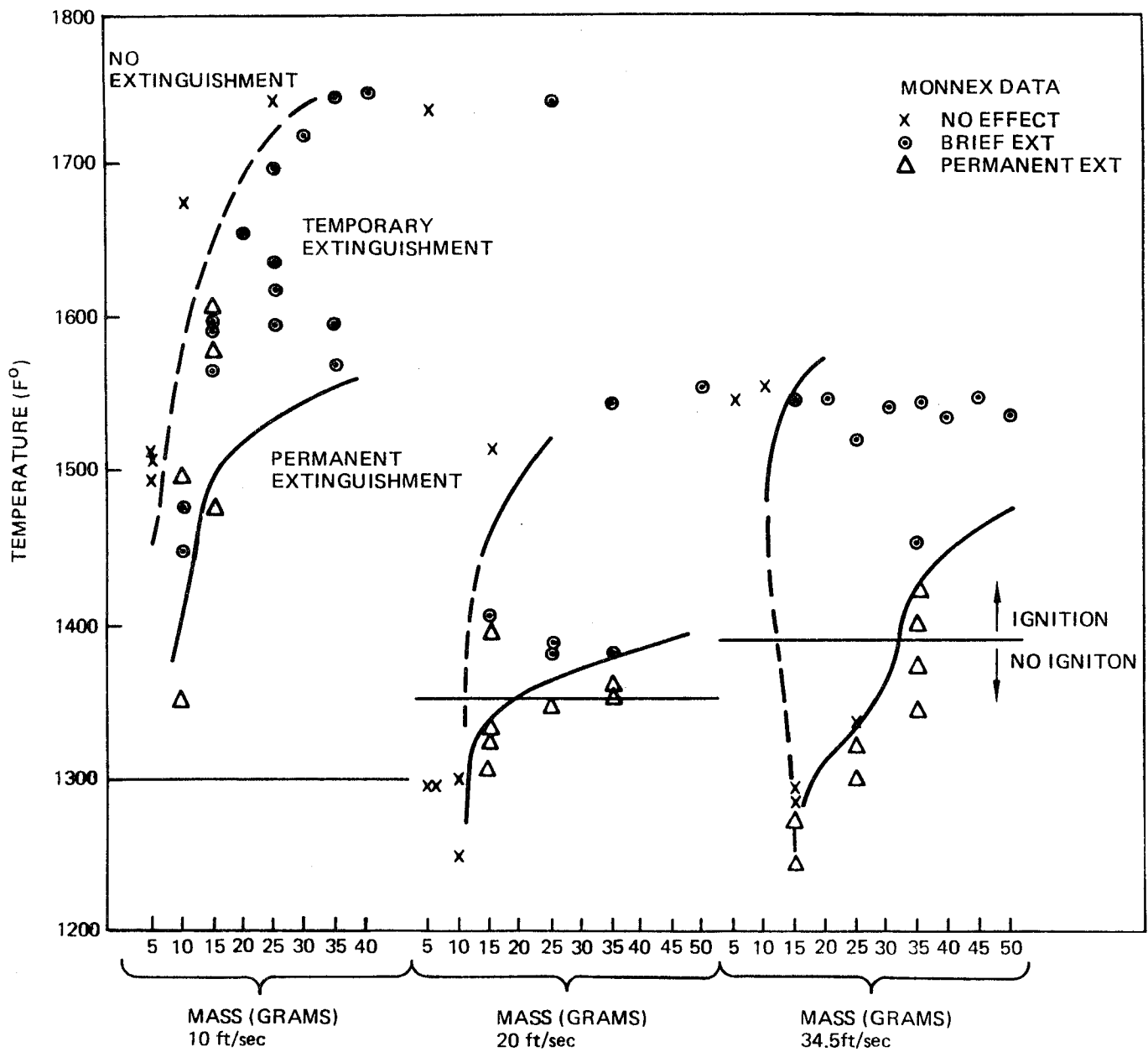


Figure 7. MONNEX Test Data (Grams Versus Surface Temperature)

The test data revealed that regions were established which appeared to separate the three types of fire response (no extinguishment, momentary extinguishment, and permanent extinguishment) in a regular manner.

Considering Figure 7, some minimum weight, in this case 5-10 grams, was needed for either momentary or permanent extinguishment to occur for surface temperatures up to 1500°F (T/C temperature with fire, just prior to agent injection). The minimum amount required increased with increasing surface temperature, becoming 10-15 grams at 1675°F and 23-30 grams at 1740°F. The horizontal lines are the fuel ignition temperatures characteristic of each velocity, as given in Figure 2.

Considering a constant temperature of 1500°F (Figure 7), increasing the agent amount yielded points at which extinguishment occurred for some brief period of time; further increases produced permanent extinguishment. Also, in the zone of temporary extinguishment, increased agent amount tended to increase keep-down time.

At constant agent concentration (Figure 7), a surface temperature decrease of only 20-30°F is sufficient to shift agent effectiveness from temporary to permanent extinguishment. The proximity of this boundary to the fuel ignition temperature characteristic of the 20 feet per second air velocity, 1350°F, is also significant. If knock-down of a fire occurred on a hot surface whose temperature at its hottest point is near the temperature initially required for ignition, the agent only had to knock the fire down for a brief time. Re-ignition was prevented by fuel flow cooling the surface. At temperatures below the fuel ignition temperature, a definite minimum agent quantity is required to affect the fire. Further, if knock-down of a fire occurs at a surface temperature lower than that required for ignition, knock-down is always permanent. Data for the other two agents is presented in a similar manner in Figures 8 and 9.

The probability of permanent extinguishment at a given surface temperature can be estimated if cooling rates such as those given in Table 1 are known for the expected hot points on the surface. For example, if agent applied to a fire in a 20 feet per second airflow, at a surface temperature 1400°F, keeps the fire down for 5 seconds, and the cooling rate is 7.5°F per second, the final surface temperature can be calculated.

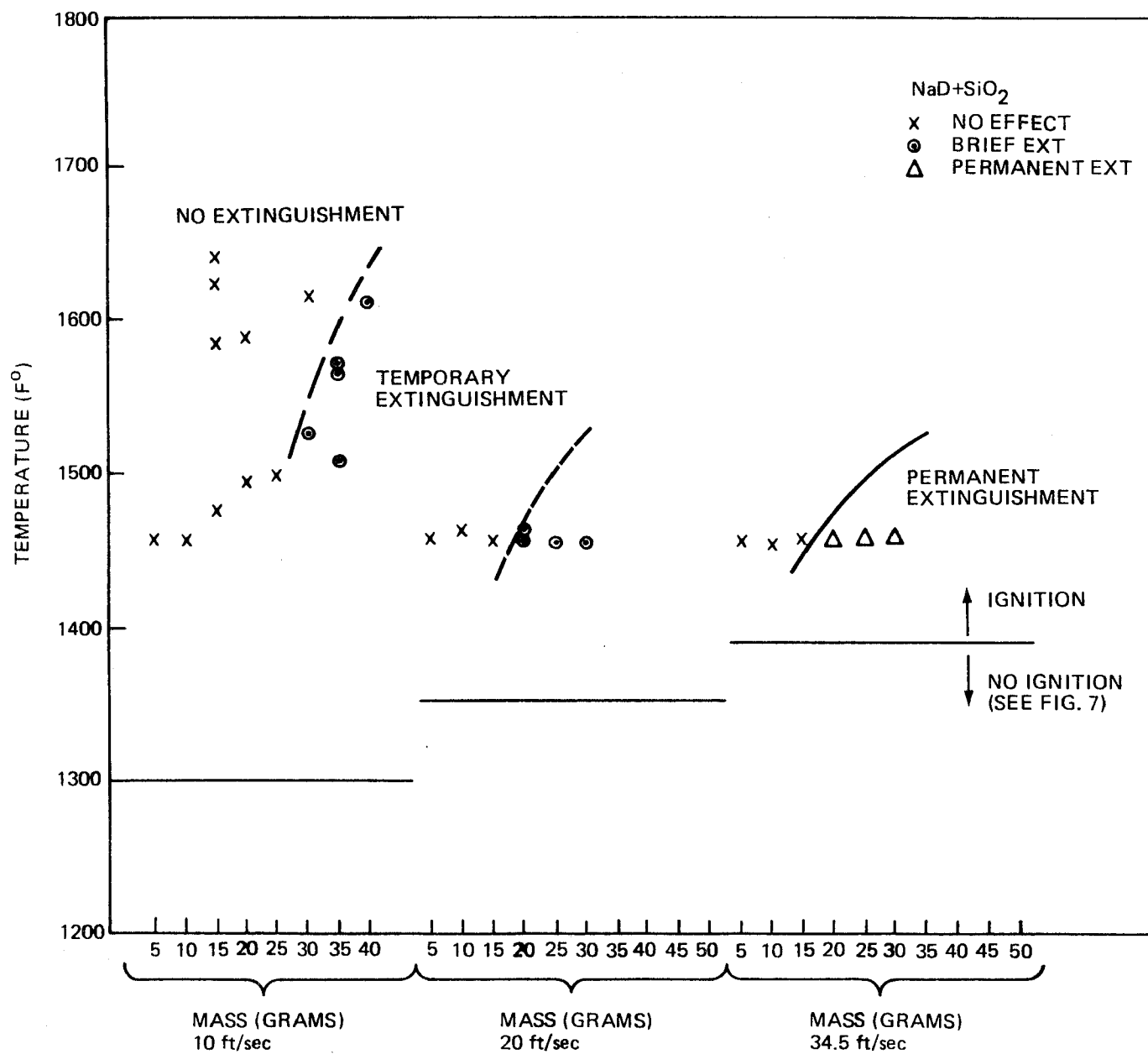


Figure 8. NaD+SiO₂ Test Data (Grams Versus Surface Temperature)

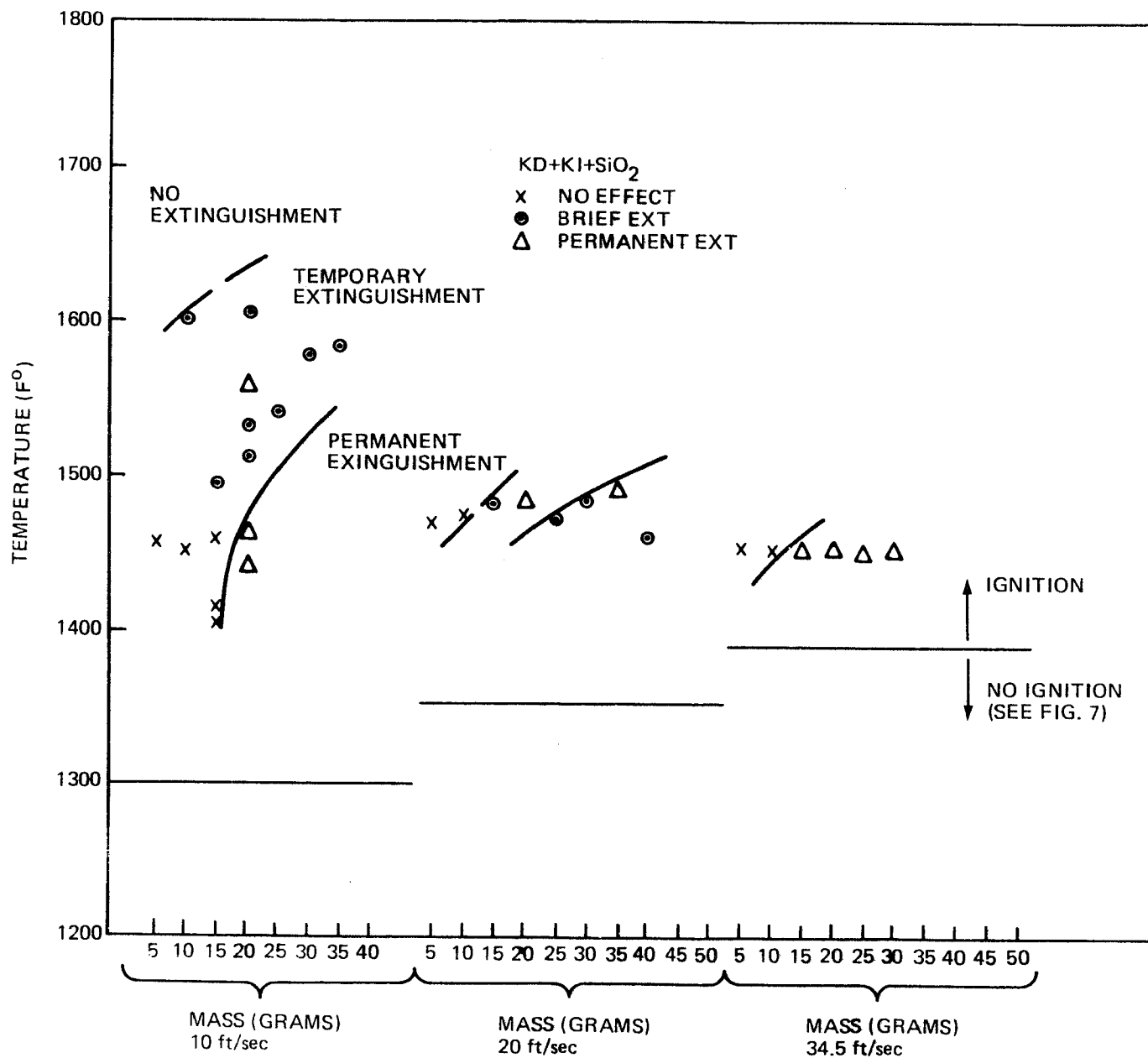


Figure 9. KD+KI+SiO₂ Test Data (Grams Versus Surface Temperature)

$$\Delta T = (7.5^{\circ}\text{F/sec})(5 \text{ sec}) = 37.5^{\circ}\text{F}$$

$$T_{\text{final}} = (1400 - 37.5)^{\circ}\text{F} = 1362.5^{\circ}\text{F}$$

This calculation suggests that the final temperature will not be low enough for permanent extinguishment to be possible; the experiments confirmed this calculation. If the temperature before agent application had been near 1390°F and the same cooling had occurred, permanent knock-down would have been very probable.

It has been established that when using dry chemical agents, permanent extinguishment occurs (at or above the fuel ignition surface temperature) due primarily to fuel cooling following initial knock-down of the fire. Permanent knock-down will be dependent, given an agent concentration sufficient for initial knock-down, on:

- o air velocity and temperature at the time of agent application;
- o hot surface size;
- o temperature;
- o heating rate;
- o flameholder geometry;
- o location of the fuel supply; and
- o degree of fuel vaporization on contact with the surface.

3.4 Comparison of Agents

Data taken on each of the three agents is presented in Figures 10, 11, and 12 in the form of surface temperature versus agent concentration. Surface temperature is non-dimensionalized by dividing the test surface temperature (at the hottest point on the surface just prior to agent application) by the fuel ignition temperature characteristic of the air velocity (always taken at TC No. 1).

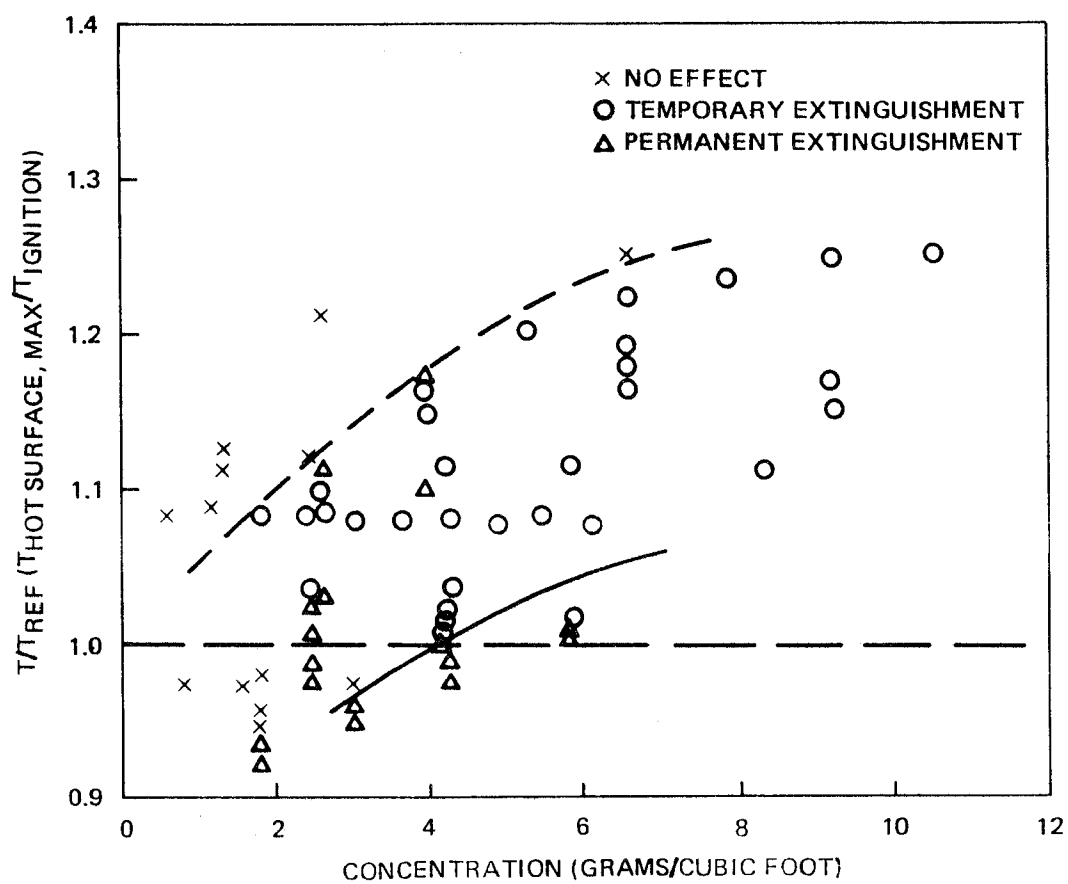


Figure 10. MONNEX Test Data
(T/T_{ref} versus Concentration)

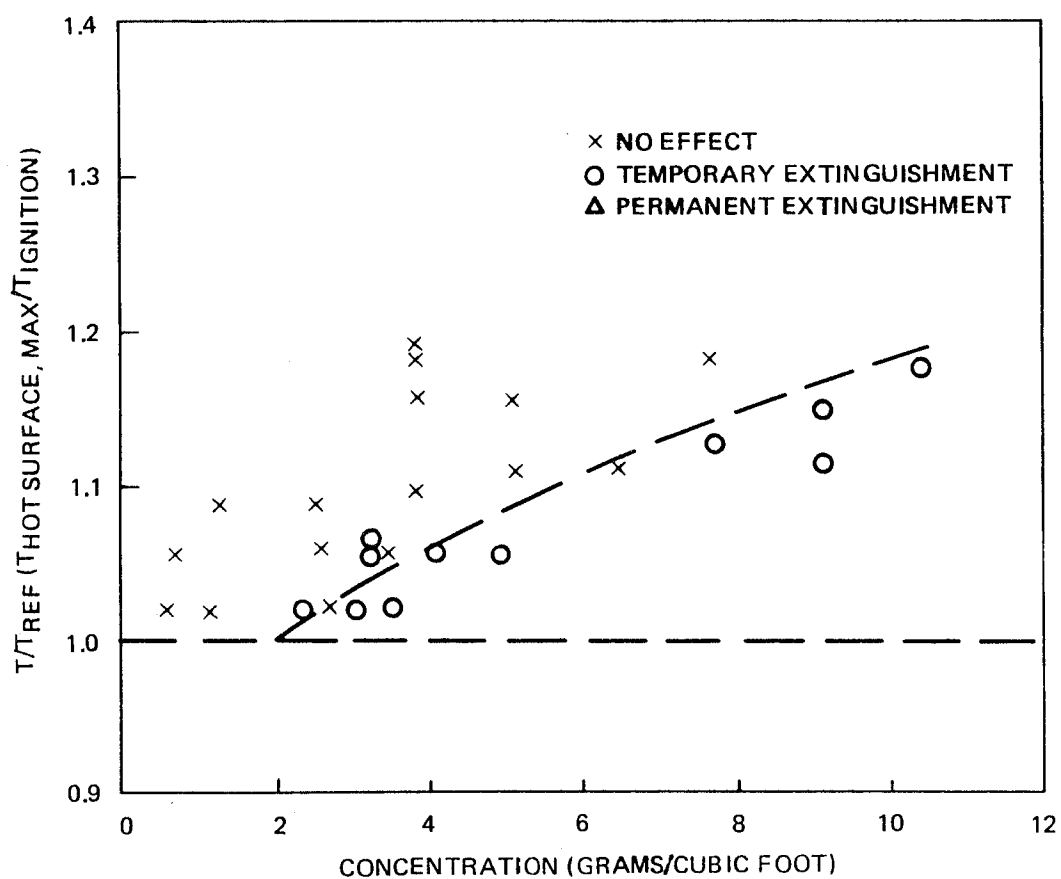


Figure 11. $NaD+SiO_2$ Test Data
(T/T_{ref} versus Concentration)

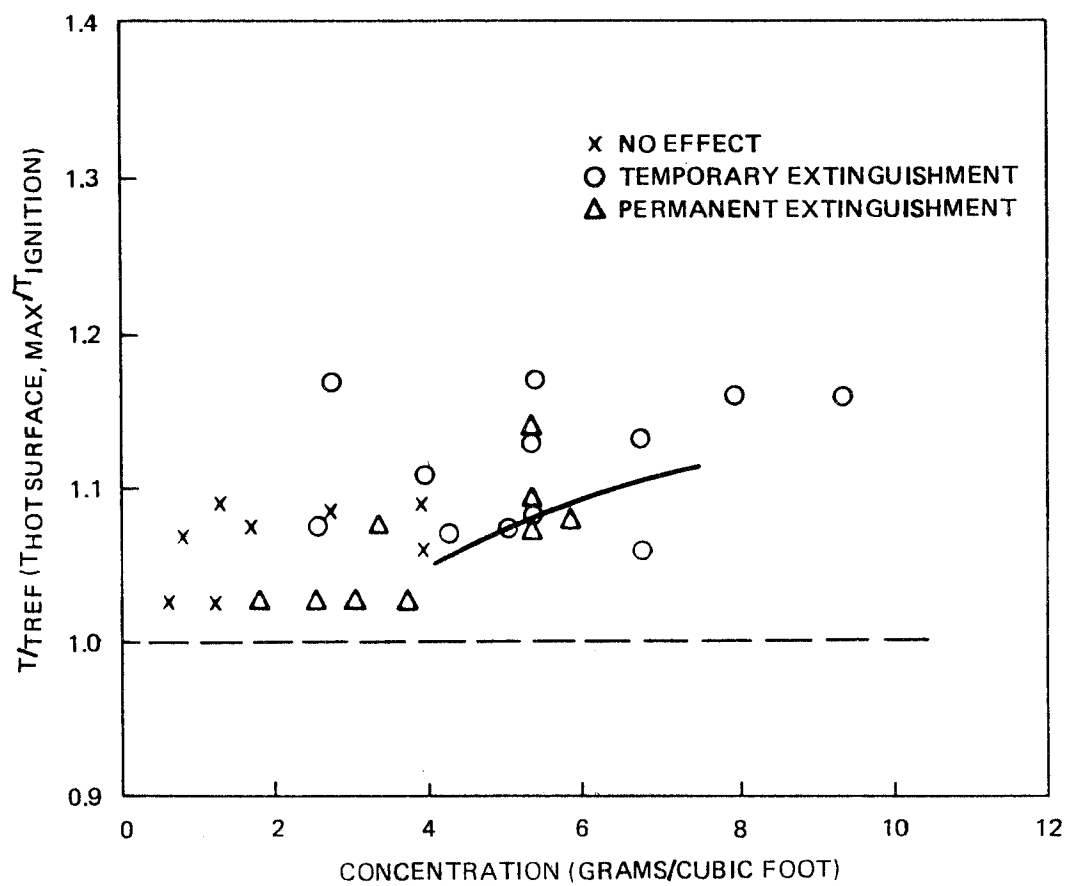


Figure 12. $KD+KI+SiO_2$ Test Data
(T/T_{ref} versus Concentration)

For comparison, agent concentrations required for initial knock-down of the fire for the case where $T_{\text{surface}}/T_{\text{ignition}}$ was equal to 1.10, are shown below:

<u>Agent</u>	<u>Air Velocity</u>		
	<u>10 ft/sec</u>	<u>20 ft/sec</u>	<u>34.5 ft/sec</u>
MONNEX	2.3 g/ft ³	3.0 g/ft ³	1.6 g/ft ³
NaD+SiO ₂	7.25	3.3	2.7
KD+KI+SiO ₂	4.2	2.2	1.85

On this basis, MONNEX appears slightly more effective than the potassium dawsonite compound, whereas sodium dawsonite was the least effective of the three on a weight basis, particularly at the 10 ft/sec air velocity. This trend of effectiveness of the agents with respect to one another continues for all the other $T_{\text{surface}}/T_{\text{ignition}}$ values. Little difference is seen between MONNEX and KD+KI+SiO₂, in terms of keep-down time at a given agent concentration and surface temperature.

Minimum agent concentrations required to obtain fire knock-down are given in the following table:

<u>Agent</u>	<u>Air Velocity</u>		
	<u>10 ft/sec</u>	<u>20 ft/sec</u>	<u>34.5 ft/sec</u>
MONNEX	2.0 g/ft ³	2.0 g/ft ³	1.5 g/ft ³
NaD+SiO ₂	6.9	2.6	1.75
KD+KI+SiO ₂	4.25	2.0	1.25

Again, MONNEX appears more effective, though only slightly, than the potassium dawsonite; the potassium dawsonite is in turn slightly better than the sodium dawsonite.

The lines separating the zones of momentary and permanent fire extinguishment converge at the point where either the agent concentration is too low to cause any interference with the combustion process, or the surface temperature is too low to re-ignite the fire once the fire is knocked-down.

It is not clear whether the line denoting momentary extinguishment reaches a maximum and then remains at a constant value, as shown in Figure 7, or continues to increase with increases in temperature and agent concentration. It is conceivable that surface temperatures can become so high that no amount of agent could cause permanent knock-down, such as in the event of a major failure condition. Under ordinary operating conditions, surface temperatures in the range used in this test program would not occur due to design surface temperature limitations. F-111 data, for example, indicate that the maximum TF-30 engine case temperature is 700°F (Ref. 2).

3.5 Effect of Powder Agents on Test Equipment

The total quantity of each agent expended in the test program was:

MONNEX	1.88 kg
NaD+SiO ₂	1.145 kg
KD+KI+SiO ₂	0.825 kg

The three agents varied greatly in their effect on the test section surfaces. MONNEX, which has a fine granular texture, had no tendency to adhere to test surfaces or to accumulate on the hot surface itself. The initial assumption that the dry chemical agents would cool the surfaces and thereby prevent a sustained fire, was not verified in this test sequence. The minor surface coolings appearing after prolonged testing become only a minor clean-up problem. After about a week of continuous testing, agent accumulation also caused some corrosion and roughening of the upstream side of the flameholder and the ramp just downstream of the hot surface (Figure 13). The rough surfaces were cleaned of agent residue and loose scale by scrubbing with a wire brush and vacuuming; Figure 14 shows the surface after cleaning. The white areas in the picture are residual sodium dawsonite.

The sodium dawsonite compound was the worst of the three agents from a test surface contamination standpoint, as seen in Figures 15 and 16. Any NaD agent entering the vicinity of the fire zone or contacting the surfaces heated by the fire apparently adhered to the surface. However, residual powder was cleaned fairly easily by scrubbing and vacuuming. There was no apparent corrosion. It was not necessary to use a solvent to loosen residual agent

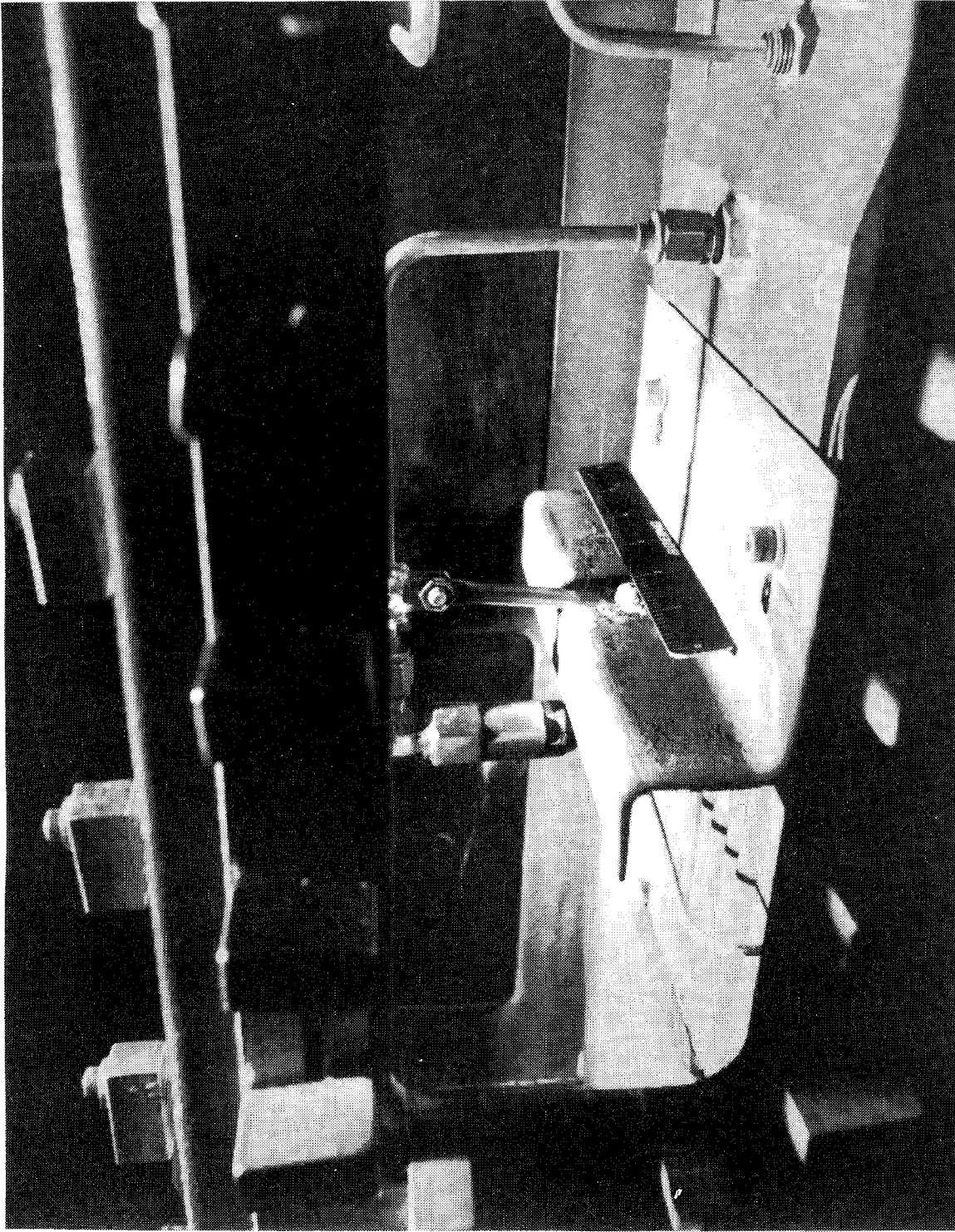


Figure 13. Metal Surface Roughening from Exposure to MONNEX

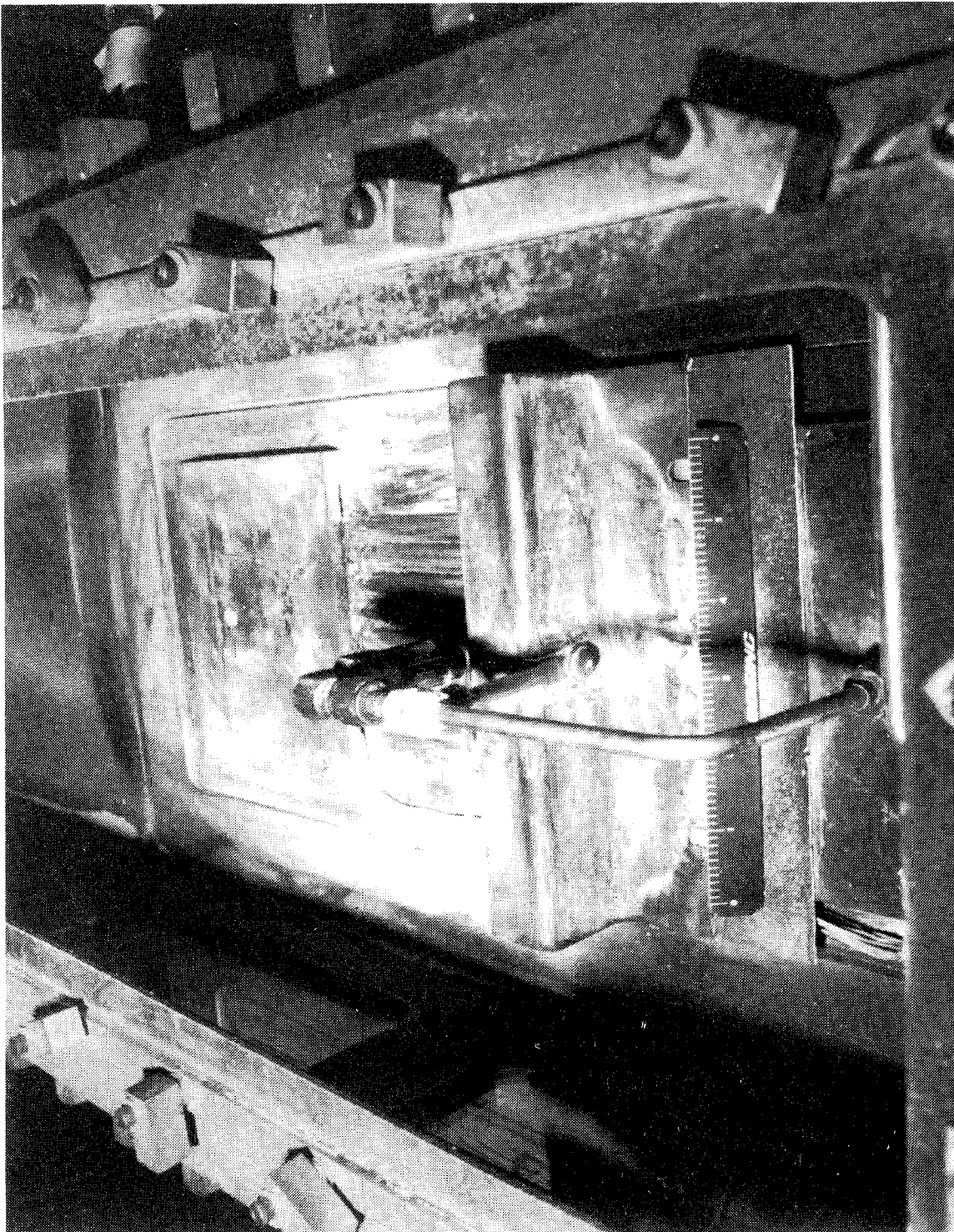


Figure 14. Metal Surface After Cleaning

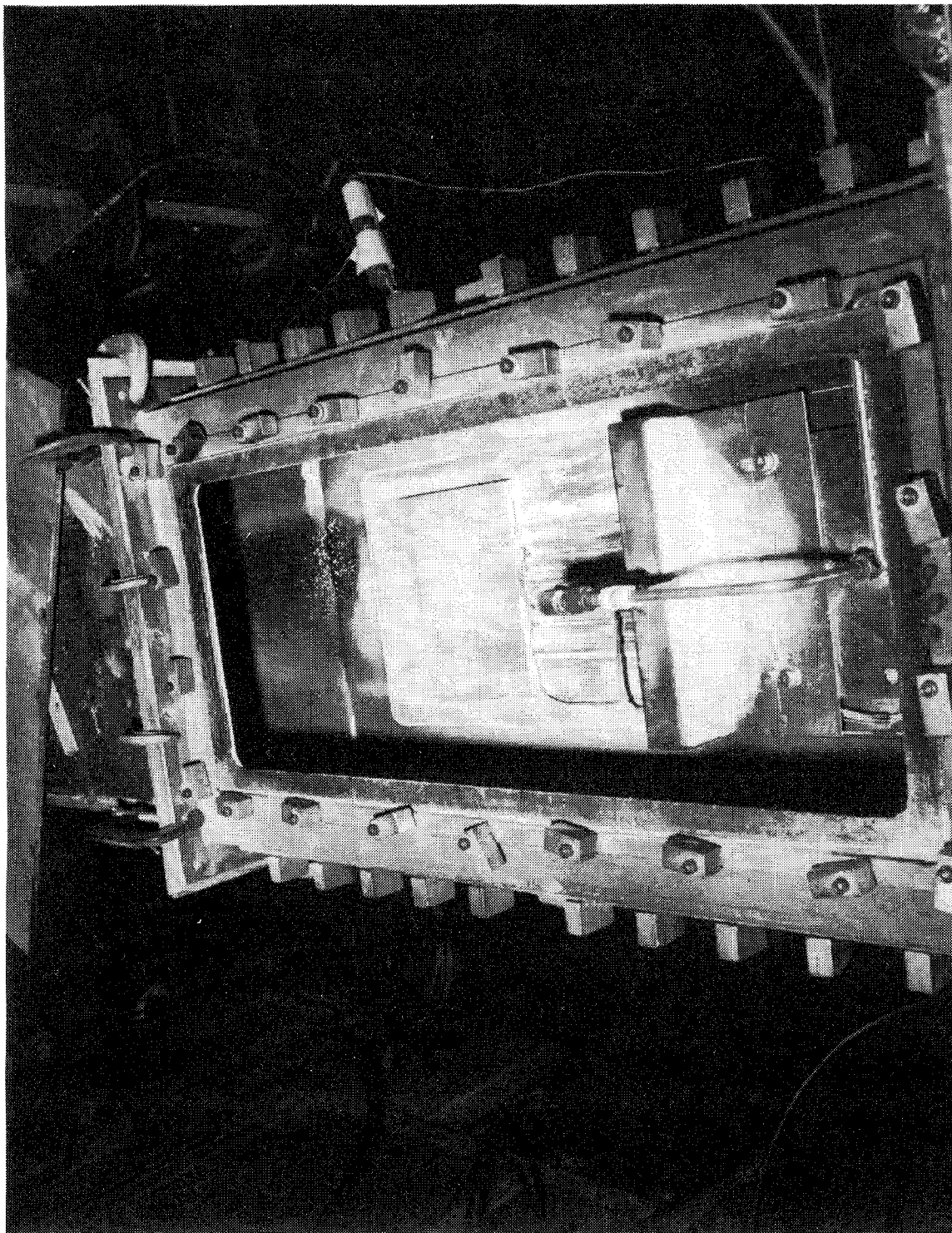


Figure 15. Accumulation of Sodium Dawsonite



Figure 16. Close-up of Sodium Dawsonite Accumulation

prior to vacuuming. The potassium dawsonite posed a lesser cleanup problem than the sodium compound because the potassium dawsonite tended to accumulate on the floor of the test section in two places (just inside the test section entrance and on either side of the hot surface) as shown in Figures 17 and 18. The only peculiarity was that the residual powder on the hot surface itself was green in color rather than white as with sodium dawsonite.

In summary, dry chemical agents have a tendency toward corrosion and agent accumulation on the surfaces they contact, though only as the result of repeated applications in high temperature environments. This problem will always be an inconvenience in test situations but may not be a major disadvantage in applications.

Neither the results of this testing nor those of Altman, et al, (Ref. 1) are directly applicable to an engine compartment fire. In both of these studies the hot surface was at the bottom of the facility where the benefits of fuel cooling following knock-down tend to be maximized. Fuel cooling would not be expected to be nearly as beneficial in a typical annular engine nacelle where fire could occur at other locations besides the bottom of the nacelle. Hot spots not cooled by the fuel or the extinguishant are quite likely to cause reignition of fuel vapors, but this hypothesis has not been substantiated by test data. Perhaps the largest uncertainty is how the powder becomes distributed in a compartment that contains a substantial amount of equipment. Intuitively, one would expect the distribution of Halons to be much more uniform than that of the dry powder extinguishants. Again, test data are lacking to check this assumption. It is also possible that the dry powders may lose much of their effectiveness in the presence of sprays from broken fuel or hydraulic lines. This is another area which should be studied.

The inadvertent release of dry powder extinguishant in an engine compartment and potential subsequent corrosion would be a serious concern, if dry powder systems were implemented. In this regard, the suggestion by Altman, et al, of a hybrid system in which extremely small quantities of Halon would be injected continuously upstream of a potential fire zone, has merit. The dry powder would not be expelled until a halide detector detected by-products of a Halon/fire interaction.

The conclusion by Altman, et al, that dry powder extinguishants have greater weight effectiveness in suppressing hot surface initiated fuel fires than Halons currently in use is not disputed. However, a number of questions with respect to compatibility and effectiveness in a nacelle fire environment need to be answered before dry powders are implemented as engine fire protection systems.

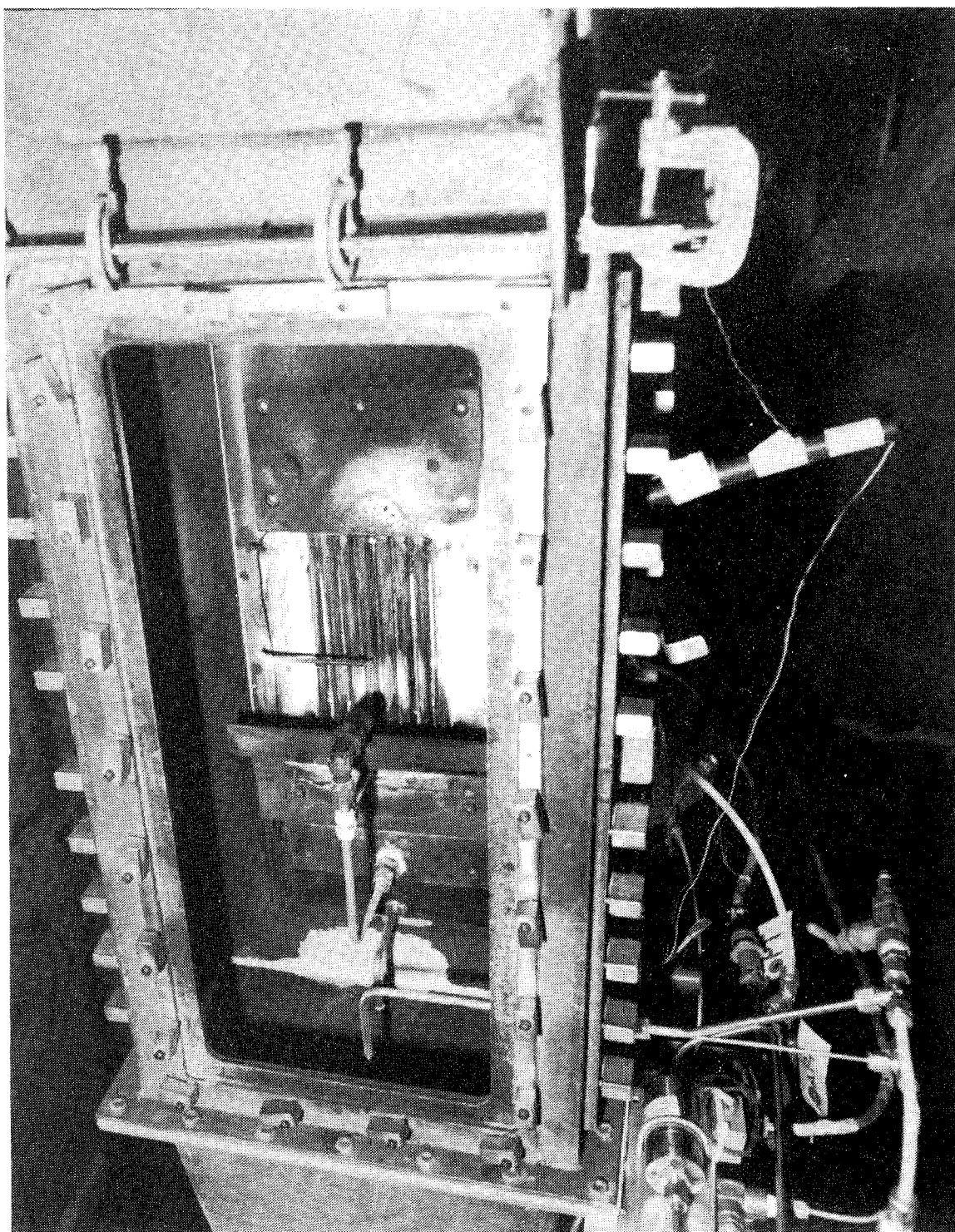


Figure 18. Potassium Dawsonite Accumulation

4.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions made based on the results of these tests were that

- o some degradation of interior test surfaces would occur in the AEN if dry chemicals are used in fire tests unless the surfaces are cleaned regularly;
- o cleaning of the test surfaces can be easily accomplished without any special equipment; no long term effects appear to result when surfaces are cleaned;
- o effective injection of dry chemical agents into the airstream was accomplished with a device of relatively simple design and construction;
- o the dry chemical agents examined do not coat the hot surface to affect fire suppression;
- o all three agents tested were effective in achieving knockdown of the hot surface fuel fires; permanent knock-down capability was found to be a strong function of test conditions, such as the level of surface temperature above the ignition temperature and the air velocity; and
- o above well defined temperature limits (corresponding closely with the temperature required for ignition of the fuel spray), the ability of the agents to suppress the fire was a stronger function of surface temperature than agent concentration.

Because of the potential of dry powder extinguishants, they should be evaluated in the dynamic, engine simulated environment available in the AEN facility at WPAFB. Specific recommendations are to study:

- o the distribution of powder in equipment filled compartments at various ventilation airflow rates

- o the relative effectiveness of powders for fires at different locations in the engine compartment annulus
- o the tendency of spraying fluids to cause the powder to clump and reduce its effectiveness
- o techniques which would promote the ability of the powder to stick to surfaces in the fire zone to help avoid reignition.

If dry powders are tested in the AEN facility, special provisions should be made to simplify cleaning the facility, and cleaning should occur after each test.

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