AFWAL-TR-83-2021, Vol II



# INTEGRATED AIRCRAFT FUEL TANK INERTING AND COMPARTMENT FIRE SUPPRESSION SYSTEM

## Volume II - Evaluation of Nitrogen-Enriched Air as a Fire Suppressant

Boeing Military Airplane Company
P.O. Box 3707
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April 1983

Final Report for period August 1979 —— October 1982





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Aircraft onboard generation of nitrogen-enriched air (NEA) for fuel tank inerting offers significant advantages over the stored nitrogen concept currently in use. Additionally, the excess NEA generated in flight offers a potential fire extinguishing agent. To evaluate this potential, a small scale test apparatus was designed based on a survey of actual aircraft fires. Two configurations were used to simulate fires dominated by either forced convection or free convection. The fire types investigated were pool, spray, hot surface and combat damage. Test variables included air temperature, fuel type, (cont.)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) fuel flow rate and surface temperature. Prior to developing conclusions on the effectiveness of NEA, verification tests were run using other common extinguishing agents ($CO_2$, $LN_2$, and Halon 1301). The quantity of agents required corresponded well with accepted levels based on previous tests.

Several important findings were made. The data, presented in terms of volume percentage (air + extinguishant flow) of extinguishing agent required for fire knock-down, indicates the hot surface fire type to be the most severe. A volume concentration of 72% $NEA_9$ (9% oxygen by volume) was found to be effective in knocking down the hot surface fire. While this concentration is high, when compared on a weight basis, NEA compares favorably with other agents. Extinguishant application time, an important parameter in fire protection system design, was found not to strongly influence agent concentration requirements. In effect, agent applied in bursts as short as one second were as effective as a steady flow of agent when the proper average concentration was provided.

The test data confirms that NEA is a viable fire extinguishing agent. Aircraft systems work was subsequently performed, including the design of an inert gas generating system, high pressure storage system, and NEA inerting and fire suppression systems. This work is reported in Volume I.

## PREFACE

This final report is submitted by the Boeing Military Airplane Company, Seattle, Washington. This work was conducted under F33615-79-C-2027. Dates of research were 15 August 1979 through 29 October 1982. Program sponsorship and guidance were provided by the Aero Propulsion Laboratory (AFWAL/POSH), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 07 and Work Unit 30480789. Terrell D. Allen was the government project engineer.

Work reported in this volume is the experimental evaluation of nitrogen-enriched air (NEA) as an aircraft fire extinguishant. Since the work was essentially of a scientific nature, SI units were used throughout. The purpose of this work was, should NEA prove feasible and effective, to provide background data for the preliminary design of an NEA-based, integrated fuel tank inerting and fire suppression system. The outcome of the test program was that NEA did prove to be effective, and the integrated NEA system design was pursued. The system design, and the development of the inerting and fire suppression system design requirements, are reported in detail in Volume 1 of this document.

Key Boeing contributors to the NEA evaluation phase of this work were: F. F. Tolle, program manager, L. A. Desmarais, principal investigator, T. N. Taylor, P. G. Lichon, and H. M. Fuglvog, test engineers.

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## LIST OF ABBREVIATIONS AND SYMBOLS

### FUELS

| | |
|---|---|
| JP-4 | Military Jet Fuel |
| Jet A | Commercial Jet Fuel (Military Jet Fuel Equivalent JP-8) |
| MIL-H-5606 | Hydraulic Fluid |
| MIL-L-7808G | Lubricant (Turbine Oil) |

### EXTINGUISHANTS

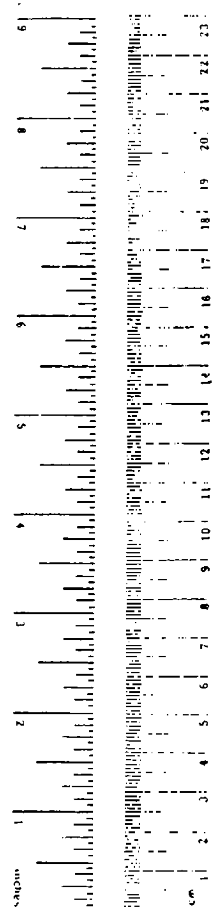
| | |
|---|---|
| $GN_2$ | Gaseous Nitrogen |
| $LN_2$ | Liquid Nitrogen |
| $CO_2$ | Carbon Dioxide |
| Halon 1301 | Bromotrifluoremethane |
| $NEA_3$ | Nitrogen-Enriched Air (3% $O_2$ Content) |
| $NEA_6$ | Nitrogen-Enriched Air (6% $O_2$ Content) |
| $NEA_9$ | Nitrogen-Enriched Air (9% $O_2$ Content) |

| | |
|---|---|
| AENFTS | Aircraft Engine Nacelle Fire Test Simulator |

*Approximate Conversions From Metric Measures*

## METRIC CONVERSION FACTORS

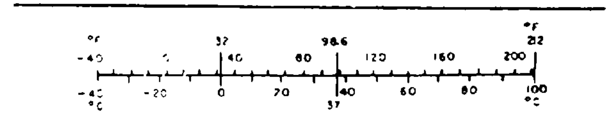
| Symbol | Given | Multiply by | To find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| CM | Centimeters | 0.39 | Inches | in |
| M | Meters | 3.3 | Feet | ft |
| KM | Kilometers | 0.62 | Miles | mi |
| | | **AREA** | | |
| $CM^2$ | Square centimeters | 0.16 | Square inches | $in^2$ |
| $M^2$ | Square meters | 11 | Square feet | $ft^2$ |
| | | **MASS** | | |
| Kg | Kilogram | 2.2 | Pound (mass) | $lb_m$ |
| | | **VOLUME** | | |
| L | Liters | 0.26 | Gallons | gal |
| L | Liters | 0.036 | Cubic ft | $ft^3$ |
| | | **DENSITY** | | |
| $KG/M^3$ | Kilograms/cubic meter | 0.063 | Pounds (mass)/cubic foot | $lbm/ft^3$ |
| | | **TEMPERATURE** | | |
| C | Celsius | 1.8C + 32 | Fahrenheit | F |
| | | **FORCE** | | |
| N | Newton | 0.22 | Pound (force) | $lb_f$ |




| Symbol | Given | Multiply by | To find | Symbol |
|---|---|---|---|---|
| | | **PRESSURE** | | |
| Pa | Pascal | 0.021 | Pounds (force)/square foot | $lbf/ft^2$ |
| $N/M^2$ | Newton/square meter | 0.021 | Pounds (force)/square foot | $lbf/ft^2$ |
| $N/M^2$ | Newton/square meter | $1.45 \times 10^{-4}$ | Pounds (force)/square inch | $lbf/in^2$ |
| | | **ENERGY** | | |
| J | Joule | 0.74 | Foot pounds (force) | ft lbf |
| J | Joule | $0.95 \times 10^{-3}$ | BTU | btu |
| | | **PLANE ANGLE** | | |
| RAD | Radian | 57.3 | Degree (angle) | ( )° |

**TEMPERATURE (exact)**

| | | | | |
|---|---|---|---|---|
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



# 1.0 INTRODUCTION

The overall objective of this contractual effort was the investigation of an advanced protection system that would enhance the fire safety and survivability of aircraft. The system visualized was one that would integrate aircraft fuel tank inerting and compartment fire suppression requirements. Fuel tank inerting investigations in the past have explored the use of on-board generated inert gas, and demonstrated technological potential. Among the features of the fuel tank inerting system is the availability of inert gas in excess of the need of the airplane during the cruise portion of the flight profile. This excess could be used for compartment fire fighting, and provided the basis for this effort.

This program was broken into three tasks to be performed sequentially:

- o Tests were to be conducted to determine the effectiveness and feasibility of NEA as a fire extinguishant. A small scale test apparatus was to be designed for this purpose, and plans to verify the small scale results in a larger simulator were to be formulated (Task I). This work has been completed.

- o Preliminary design and penalty tradeoff evaluation were conducted using NEA and comparisons made with existing compartment fire protection systems (Task II).

- o Optimization of an integrated subsystem to reduce weight and provide multi-function on-board fire protection was accomplished (Task III). Task II and III work is reported in Volume 1 of this report.

## 1.1 OBJECTIVE

This report presents the results of the Task I study, which was designed to evaluate the use of nitrogen-enriched-air (NEA) produced by an on-board inert gas generator in extinguishing aircraft fires. It contains:

- a literature survey
- a description of the small scale test apparatus
- the results of the small scale tests
- comments on the feasibility of NEA as an extinguishant
- a recommendation to proceed with Task II.

## 1.2 APPROACH

Clearly the first step, and a key one, was to demonstrate the utility of NEA as a fire suppressant. The work began with a study to develop realistic scenarios for normal and combat related in-flight fires and in that context, to develop realistic design quantity measurements for the effectiveness of on-board generated inert gas for fire protection. Valuable background information was provided by Boeing survivability/vulnerability research on normal and combat threats, and on fire safety assessments (both theoretical and experimental) of the use of inert gases (nitrogen and nitrogen enriched air) in aircraft designs. Further, Boeing had been involved as a participant in design effort for the flight test of an on-board inerting system for a C-135. Finally, Boeing exploited knowledge gained under a related contract to operate the AFWAL AENFTS, Aircraft Engine Nacelle Fire Test Simulator, and the Aircraft Fuel Tank Simulator at WPAFB.

The essential new element that is reported in this document is an experimental evaluation of the utility of on-board inert gas generators in fire protection. The data was developed using a small scale test apparatus at Boeing's North Field Test Laboratories located at Seattle, WA. A crucial problem in developing design data in small scale was to assure that it could be extrapolated to large scale. The solution to scaling problems was an iterative modeling strategy (Figure 1).

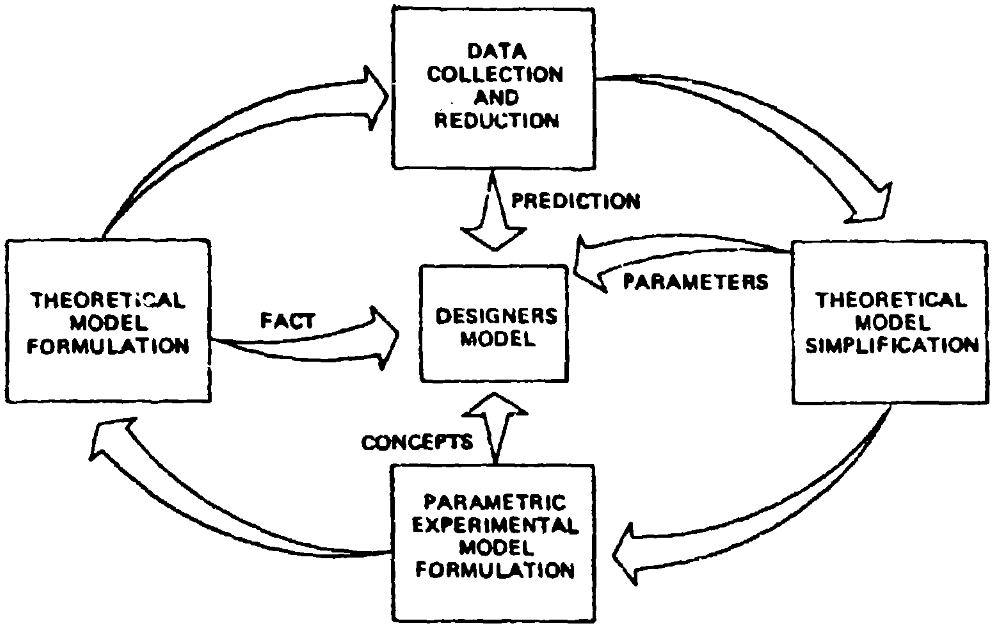



*Figure 1. Modeling Formalism*

The activities depicted in the figure are described in the following:

- Theoretical fire dynamics model formulation brings together concepts from fluid dynamics, heat transfer, combustion chemistry and the boundary conditions for the specific problem. The non-dimensional number of primary concern was determined to be the Damkohler number, which relates to fire stability.

- A small scale test program was formulated to confirm the theoretical formulation of fire dynamics.

- A small scale apparatus was designed, and instrumentation was chosen to collect the necessary data.

- Data was reduced using the concept of the Damkohler number, and processed by computer programs to provide parametric plots and equations.

- The reduced data was formulated to permit evaluation and optimization of design alternatives for fire extinguishment.

In exploring nacelle and compartment fires, a small number of scenarios were used to develop a reasonably comprehensive understanding of fire phenomena using the small scale experimental facility. For a nacelle fire (as distinct from an explosion) to be damaging, a flameholding mechanism is required to prevent fire blowout in the highly ventilated engine compartment; the choice of a flameholder, and modeling of flameholder action was taken from earlier USAF engine flameholding studies (Reference 1). Flameholding is much less significant for compartment fires where the fire is sustained by free convection (because of relatively low ventilation rates); a different type of modeling was therefore required.

Experiments were planned to develop a comparison of several extinguishants (including inert gases) in satisfying fire suppression requirements, and to validate the analysis. Initially it was thought that the differences between forced (nacelle) and free convection (compartment) fires and the dimensions of the compartments, would require the construction of two experimental devices. It was subsequently found that only one test device was needed providing its orientation could be changed. Task I activities extended over a period of fifteen months, providing the time for interplay between literature research, modeling, experiment and reporting.

The predictions of the small scale nacelle fire model were to have been confirmed in the large scale engine nacelle test facility at WPAFB during Task I. Due to facility availability, only limited testing of nitrogen was performed in the large scale nacelle simulator.

## 1.3 BACKGROUND

An extensive survey of the literature was conducted as an initial step. The data gained from this survey were combined with Boeing experience related to fires experienced as a result of combat operations, and those encountered in normal operation. The fire scenarios that developed were used to guide the design of an economical small scale fire test apparatus.

### 1.3.1 Literature Survey

The primary thrust of this survey related to the use of nitrogen and nitrogen enriched air for fire suppression and control. Emphasis was placed on extinguishment characteristics, advantages, limitations and areas of utilization. In total 34 documents were reviewed and summarized; the resultant survey appears in Appendix A, Section A1.0.

### 1.3.2 Fire Scenario Development

A survey was conducted of military and commercial experience in terms of direct causes of aircraft fires, including causes that are encountered in both normal and combat operations. The fire scenarios developed in Appendix A, Section A2.0, were used to guide the design of the small scale test apparatus. Table 1 summarizes the findings on fire sites, fluids involved, fuel phase, and ignition source. Table 2 lists the most likely combat threats and the associated damage.

Table 1. Fire Scenarios

| Type of Fire | Ignition Source |
| --- | --- |
| Engine Nacelle: JP-4, Jet A, hydraulic fluid, lube oil | |
| Pool | Spark |
| Stream | Hot Surface |
| Spray | Spark |
| Spray | Hot Surface |
| Spray and Flameholder | Spark |
| Wheel Well: Hydraulic fluid | |
| Spray | Hot Surface |
| Weapons Bay: JP-4, Jet A (stream); hydraulic fluid (spray) | |
| Stream | Fragment Impact Flash |
| Stream | Incendiary |
| Spray | Fragment Impact Flash |
| Spray | Incendiary |
| Electrical/Electronics Bay: electrical | |
| Electrical Short | Spark |
| Cargo Bay: Cargo load | |
| Standard Cargo | Spark |
| Wing Cavity: JP-4, Jet A, hydraulic fluid, lube oil | |
| Pool | Spark |
| Spark | Spark |
| Spray and Flameholder | Spark |

Table 2. Combat Damage Survey.

| Type of Fire | Ignition Source |
| --- | --- |
| 120 grain fragment | 0.4" x 0.5" |
| 12.7 mm API | 0.509" diameter |
| 14.5 mm API | 0.590" diameter |
| 23 mm API | 0.907" diameter |
| 23 mm HEI | max. attainable |

# 2.0 TEST PROGRAM

This section describes the design of the test facility and the development of test procedures.

## 2.1 Small Scale Simulation Considerations

Simulation of the fires of concern need not duplicate exactly the actual event in all cases. For example, the fire scenarios show a number of short duration ignition sources. For these cases, any experimentally convenient ignition source, such as a spark plug or a hot wire, could be used to initiate the fire, and then turned off. On the other hand, hot surfaces represent continuing sources of ignition energy. The energy could be expected to stabilize a fire by reducing chemical reaction time and the surface provides a re-ignition threat. Thus an actual hot surface was felt to be necessary.

Other factors which appear relevant in the literature cannot be directly simulated in small scale, indicating that scaling would not be feasible. Some of these are:

- hot surface dimensions are likely to exceed those possible in a small scale device
- the air flow passages in engine compartments ventilation spaces are complex; area variations and the presence of multiple flameholders will require large scale test fixtures
- extinguishants are injected into engine compartments from relatively few points (4 to 8); non-uniform agent distribution cannot be well simulated in small scale
- fuel residence times in the small scale apparatus are insufficient to completely vaporize the fuel
- altitude effects due to density and temperature variation

It is apparent that tests designed to investigate these factors should be performed to extend and verify the results of the small scale program. This is the purpose of the follow-on large scale tests to be carried out by the USAF in the Aircraft Engine Nacelle Fire Test Simulator (AENFTS) located at Wright-Patterson AFB. Limited testing in the AENFTS was conducted and the results are discussed in this report.

Drawing on the various fire scenarios described in the literature, a number of observations were made. In an aircraft compartment, release of a variety of fuels is possible. If ignited, a quiescent or turbulent flame may result from any one of several distinct modes of combustion. A crack or leak in a line or container can lead to a spray (high pressure fluid source) or stream (low pressure fluid source) of combustible fluid. The combustible may collect in a puddle, or burn completely within the compartment cavity with or without contact with the walls. A variety of ignition sources were obvious -- electrical, hot surface, incendiary, friction, etc. Since local environmental effects were expected to have a strong influence on extinguishant behavior, the fire test fixture had to simulate a variety of aircraft compartments.

### 2.1.1 Compartment Simulation

The fire scenario study results appeared to require the simulation of two classes of compartments. In the first, forced convection plays a major role, while in the second, free convection plays the major role.

#### 2.1.1.1 Forced Convection Fires

Engine nacelle ventilation was characterized by high primary air flow rates, with total mass flows of up to 16.0 kg/s. Airflow velocities around engine hot sections during takeoff range from 3 m/s on large modern transports (767/CF6-80) to 6 m/s in fighters (F-111/TF-30). At altitude, the fighter ventilation flow velocities can reach 53 m/s at 10,670 m and Mach 0.75 and 75 m/s at 16,760 m and Mach 2.2 (F-111/TF-30). In these spaces, a variety of fires can occur and the following design selections were made for simulation purposes:

- Pool Fire - a square container whose fore and aft walls were of adjustable height and spaced to hold liquid fuels was selected. The wall height arrangement which produced the most stable fire was to be experimentally determined as the standard for extinguishant evaluation.

- Spray Fire - standard home heating oil nozzles provided suitable fuel flow rates in the region of interest. The nozzles faced downstream and a flameholder was required to stabilize the fires. The low vapor pressure of the fuels presented a problem, and considerable effort was expended in achieving an intense stable fire.

- Hot Surface Fire - a small rectangular section heated by calrod units provided the means for investigating the relation of fire stability to the hot surface temperature, fuel flowrate, and primary air flow rate in regions around engine hot sections. The hot section acts as a continuous ignition source, and a "z"-section placed at the upstream end of the surface provided a flameholder.

2.1.1.2 Free Convection Fires

If the dimensions of a compartment are large, and ventilating flow velocities are low ($\leq$ 1 m/s) free convection induced by the fire is the dominant influence in fire stabilization. Free convection velocities can be roughly approximated by

$v_{free} = \sqrt{gl}$, where g = acceleration of gravity, and l = typical vertical dimension.

Wheel Well

Wheel wells exhibit a medium ventilation mass flowrate, roughly 1 kg/s. The heated surface described earlier was used to simulate a hot brake condition. Using the spray nozzle chosen in the nacelle test series, fuel could be sprayed onto the hot surface where it would ignite spontaneously.

Weapons Bay

The ventilation flowrate of the weapons bay is similar in nature to that of the wheel well. However, the weapons bay compartment fire testing was considered tc require combat damage simulation.

Electrical/Electronics Bay

Airflow through this kind of compartment is relatively low, about 1.36 kg/s. Because the principal fuel is expected to be electrical insulation which burns slowly with moderate energy release, it was concluded that agent concentrations capable of handling JP-4 hot surface fires would also handle electrical fires. No specific tests of electrical fires were conducted.

Cargo

The cargo space is a large volume, but experiences a low unit airflow, about 1.1 kg/s. In the past, fire extinguishant tests for cargo aircraft have employed "standard" pieces of cargo such as curled shreds of wood used for packaging. It was felt that these fires were not as severe as liquid fueled fires, and no simulation was carried out.

Wing Dry Bay

Wing dry bays normally experience little or no ventilating airflow except that due to pressure relief. However, damage to the dry bays could result in ambient air entering the bay, thus supplying oxygen to a fire in that area. If bleed air, hydraulic or fuel lines running near or through the dry bays are also damaged, hot air or escaping combustible fluids may contribute greatly to a fire in the bay. High temperature incoming air combined with a fuel spray would create the effect of escaping bleed air in the test chamber, with velocities low enough to simulate a large, poorly vented compartment. Reference 2 notes that compartment pressures resulting from exterior damage, that is, whether a positive or negative pressure is produced, is dependent on the angle of attack and on the type of damage (see Section A2-2). For purposes of this study, air addition to the fire site appeared to be the more severe situation in terms of fire stability and thus was modeled.

### 2.1.2 Simulation of Fuel Variables

The small scale fire test facility was required to be capable of simulating a variety of fuel-related variables. The range of each of the following variables was conditioned by fire scenario specifications and facility size:

- o ventilation rate (normal operation and combat damage)
- o fuel type (JP 4, Jet A, MIL-H-5606, MIL-L-7808)
- o fuel flow rate
- o fuel loading condition (pool, low and high pressure sprays)
- o temperature (air and hot surface)
- o preburn time
- o flameholders
- o ignition sources

### 2.1.3 Simulation of Extinguishants

Fire extinguishants of several types (Halon 1301, $CO_2$, gaseous and liquid nitrogen) were tested to establish a baseline data set against which NEA could be compared. It was found possible to predict NEA performance from $GN_2$ results; the prediction technique was experimentally verified and proved instrumental in greatly reducing the test requirements. The following agent variables were considered in the light of present and future airplane operations:

- o concentration
- o air flow rates
- o test section turbulence
- o time to extinguish
- o dispersal means

## 2.2 SMALL SCALE FIRE TEST FACILITY DESIGN

In engine compartments, there is a need for considerable cooling air flow, with velocities exceeding 3 m/s; engine bay fires are dominated by this air flow. On the contrary, most other compartments are designed for little or no through velocity, and fires are dominated by free convection effects. After considerable study, it was concluded that one test fixture could adequately model all the compartments. (Assembly and installation drawings can be found in Appendix B.) The final configuration involved a rectangular, 15.24 x 30.48 x 60.96 cm, test section. The long axis of the test fixture was aligned horizontally to simulate engine compartment fires, and aligned vertically to simulate other aircraft bays (Figure 2).

Referring to the horizontal orientation of the test section shown in Figure 3, removable plates were provided for the top and bottom surfaces; vertical sides were provided with two windows per side for viewing and photography. The removable top plate gave access for installation of test equipment and instrumentation. The bottom plate was replaceable with one of four interchangeable sections, configured to:

- support a pool container with adjustable height walls and fuel feed
- provide a flameholder and nozzle fittings for spray fire tests
- contain wire wound resistance heater elements with an effective heated area of 15.24 x 22.86 cm
- provide a blank plate for use as necessary

All removable sections and the viewing windows were held in place with spring-loaded clamps (Figure 4) which permitted movement to accommodate thermal expansion. This feature was also intended to provide a measure of emergency pressure relief in the event of incipient explosions. The windows were made of 0.64 cm thick Pyrex, set into individual frames, and isolated from the test section metal by gaskets made of Guard Board (an asbestos substitute) in order to minimize thermal stresses on the glass.

Stainless steel, type 304, was selected for fabrication of the test and transition sections on the basis of its strength, ductility, and corrosion resistance. In addition, austenitic stainless steels, such as 304, retain their desirable mechanical properties at both cryogenic and elevated temperatures (approaching low red heat or 650C), and since both extremes were likely to be encountered durng testing, seemed the most suitable for this application (Reference 3).

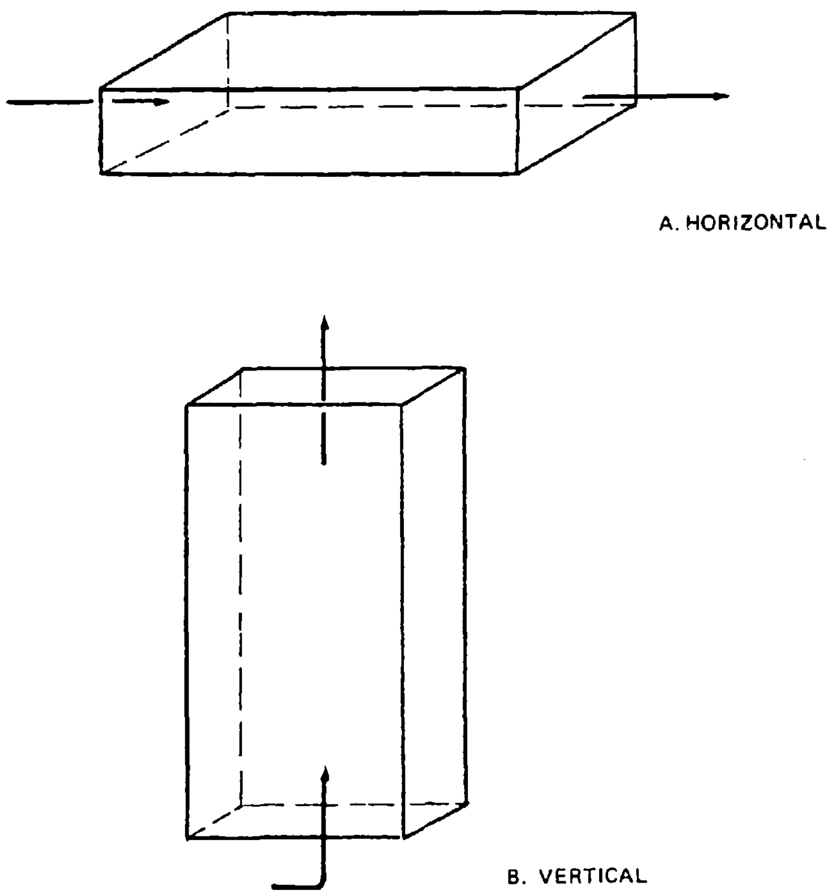



*Figure 2. Compartment Orientations*

*Figure 3. Forced Convection Fire Test Apparatus*

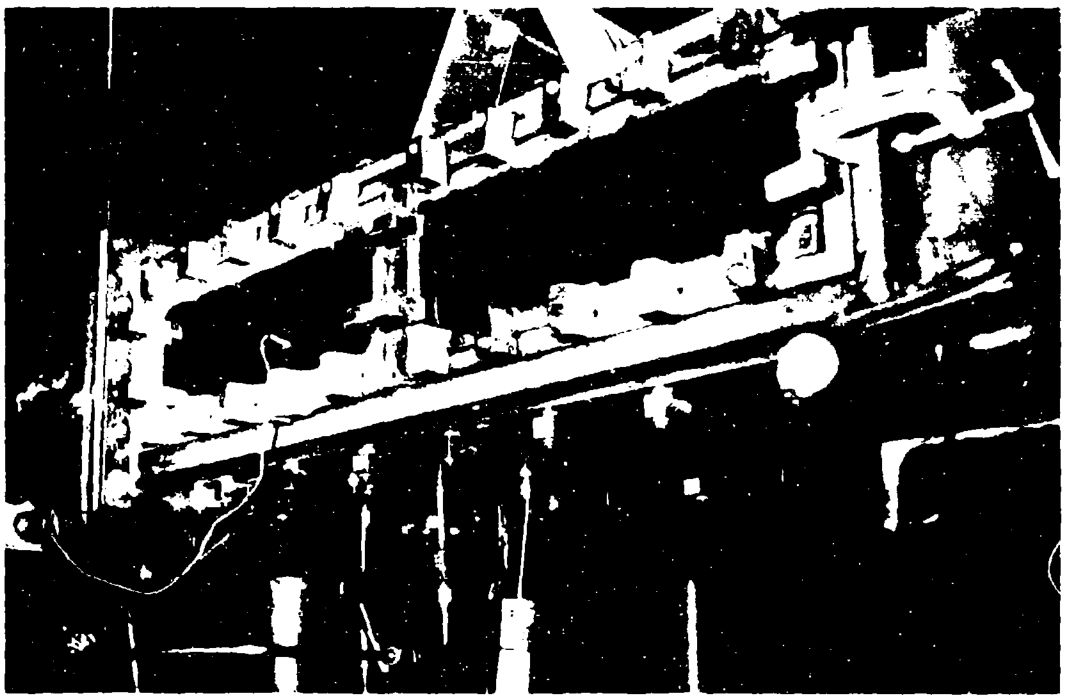


*Figure 4. Test Section Side View*

Two ignition sources were planned -- an electric spark, and the hot surface. With the quantities of fuel involved, and the difficulty of igniting some of the fluids (notably engine lubricating oil) the spark was found unsatisfactory. It was replaced by a coil of Nichrome wire, powered by 50 VDC. During a test sequence, the power was turned on and left on until ignition occurred; this sometimes involved a considerable period of time, as in pool fire tests with lubricating oil where the pool itself had to be heated to a relatively high temperature before ignition took place. The Nichrome coil ignition source was found to be positive, simple and inexpensive.

2.2.1 Forced Convection (Engine Bay) Fire Test Apparatus

The test section was installed in a hazardous test cell at North Boeing Field, and was supplied combustion air from the wind tunnel supply lines at the site. After passing through an array of control valves and flow meters, the air entered the apparatus through a 10.16 cm inside diameter circular pipe, and from there flowed into an extinguishant mixing section. The extinguishant mixing section was 49.64 cm long and 10.16 cm inside diameter; two sets of eight holes were drilled in the mixing section circumference. As finally configured, one set of holes was plugged. The remaining set of holes was connected to a manifold which circled the mixing section (Figure 5); extinguishant was thus injected radially from the manifold into the airstream after flowing 20.32 cm downstream of the manifold, the air entered a 78.74 cm long diffuser/transition section. This section converted the 10.16 cm circular section into the rectangular test cross section, increasing the flow area by a factor of 5.7, and thereby reducing the velocity by the same factor. The test section was supported laterally by two 2.54 cm steel bars welded to the bottom of flanges at either end of the test section. As installed, one bar rested in a notch and the other bar rested on a flat surface, thereby providing opportunity for thermal expansion of the test section. (See Figures 3 and 4, already cited.) The exhaust from the test section flowed through a 1.8 m long duct, turned through a $90^0$ elbow and vented through the test cell roof. A sump and drain were provided to remove liquid fuel accumulations from the exhaust region.

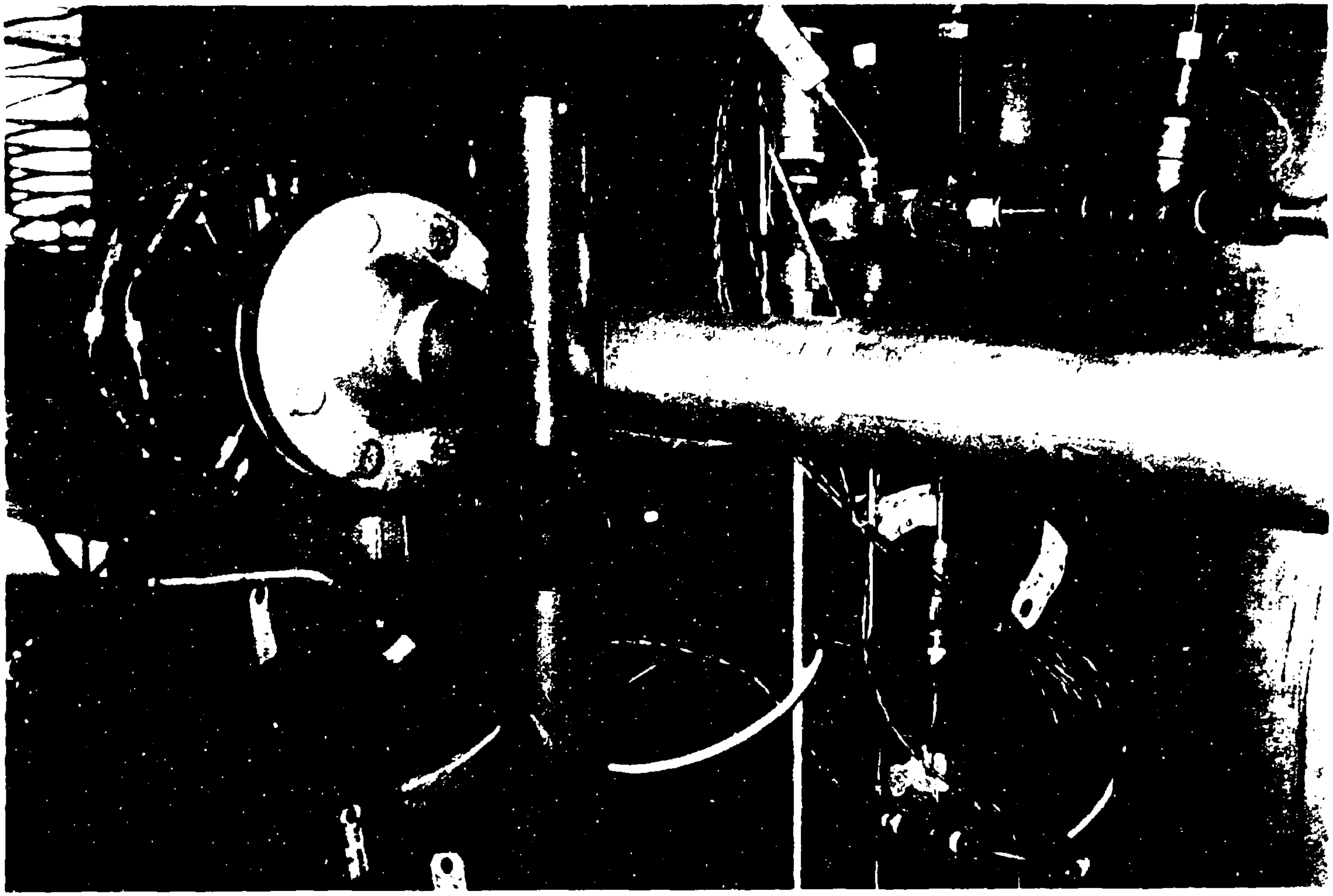


*Figure 5. Air Inlet and Extinguishant Manifold*

2.2.2 Free Convection Fire Test Apparatus

For the simulation of bays other than engine bays, the test section was rotated through $90^{\circ}$ (Figure 6). Air was again introduced into the test apparatus through the 10.16 cm inside diameter circular pipe and the extinguishant mixing section (described in the preceding paragraph). The air then entered a short transition section which turned and at the same time diffused the flow to enter the test section. A floor plate (see Figure 27 in Section 3.2.1) was inserted between the transition section and the test section. The 10.16 x 10.16 cm square pool was located in the center of the floor plate. Twelve slots 0.50 cm wide x 4.00 cm long were cut into the floor plate to simulate compartment ventilation or leakage. The test section was supported by the same bars as described in the preceding; the method of support is shown in the Installation Drawing (Appendix B, Figure B-1).

2.2.3 Instrumentation and Control

Figure 7 is a schematic of the flow and instrumentation used in the tests, and contains the key to the symbols; Appendix C lists the instrumentation characteristics.

Air Supply System

Referring to Figure 7, air temperature could be increased by a heat exchanger in the wind tunnel air supply with a capability of raising air temperature to 260C. Depending on mass flow required (Figure 8) the air next transits either a 3.81 cm or a 1.91 cm line, each of which contains a flowmeter (PASS-FN-1A or B). At 20C and 2.0691 MPa line pressure, the smaller pipe provided a mass flow range from 0.1134 to 0.4535 kg/s, while the larger line provided from 0.4535 to 0.7936 kg/s.

Extinguishant Supply System

The $CO_2$, $LN_2$ and Halon 1301 extinguishant supply containers were suspended from 2268 kg load cells, (ESS-W-2,3,4, Figure 7); while the $GN_2$ supply rested on an electronic scale (ESS-W-1, Figure 9) providing mass flow rate measurement of the higher $GN_2$ flow rates. At the lower flow rates, the volumetric flow rate of Halon 1301 was measured by a rotameter (ESS-FI-1,

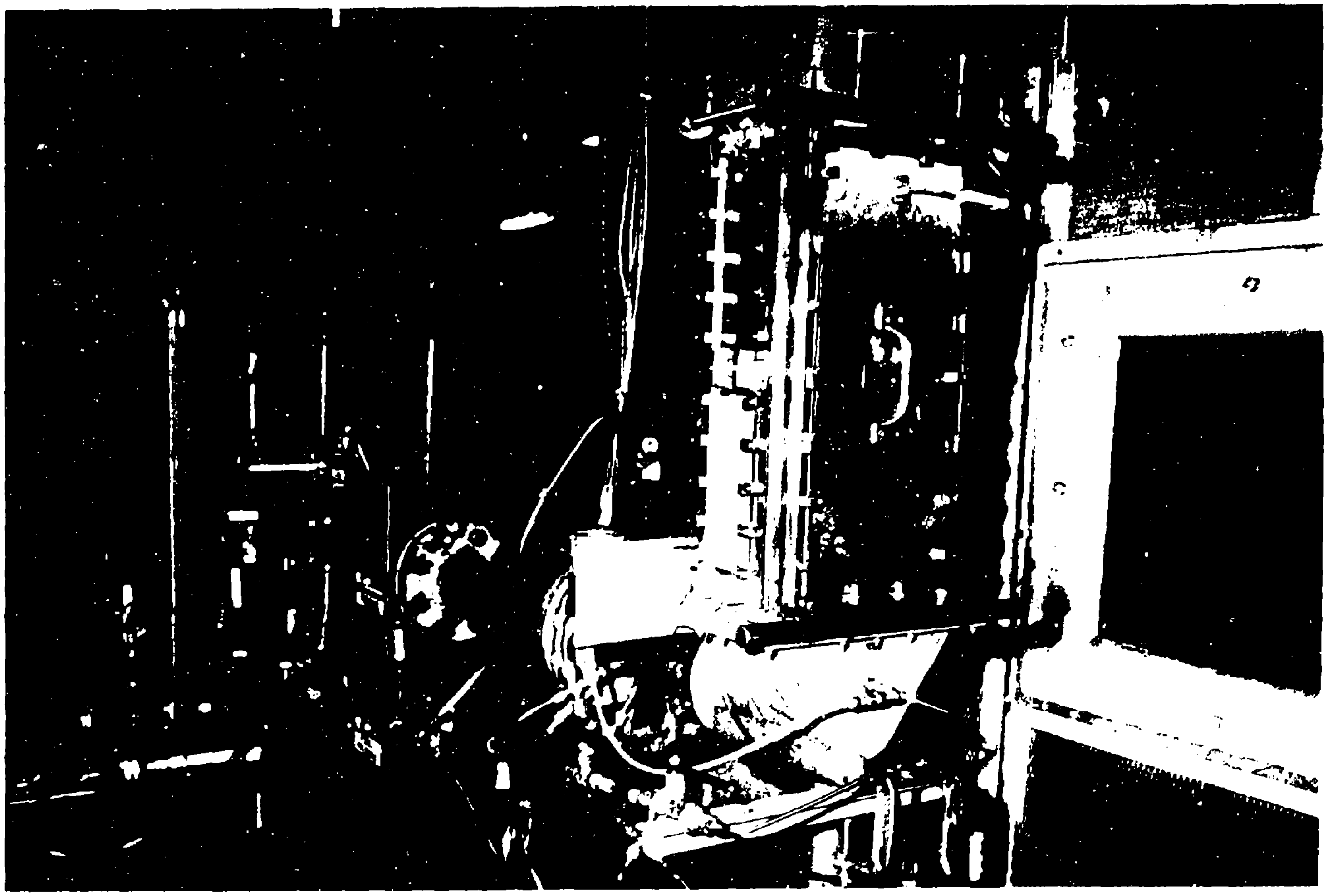


*Figure 6. Free Convection Fire Test Apparatus*

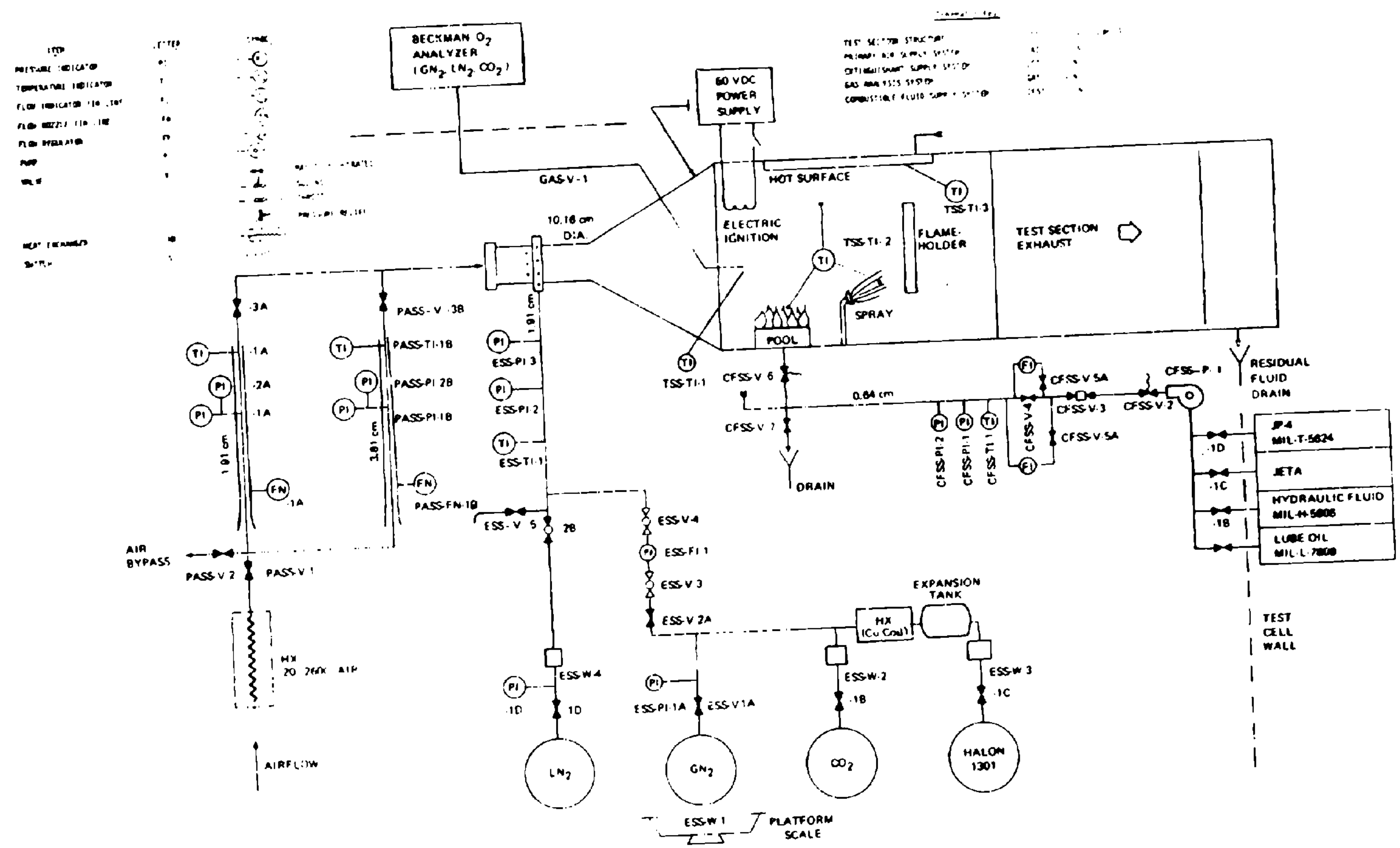



Figure 7. Test Facility Schematic

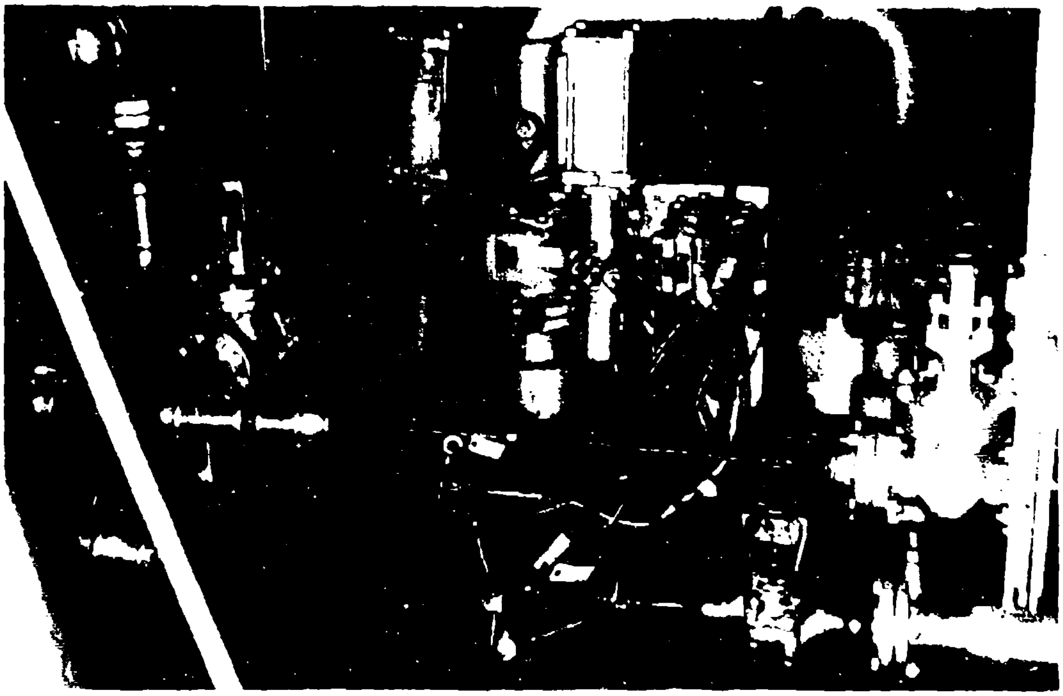


*Figure 8. Airflow Supply*

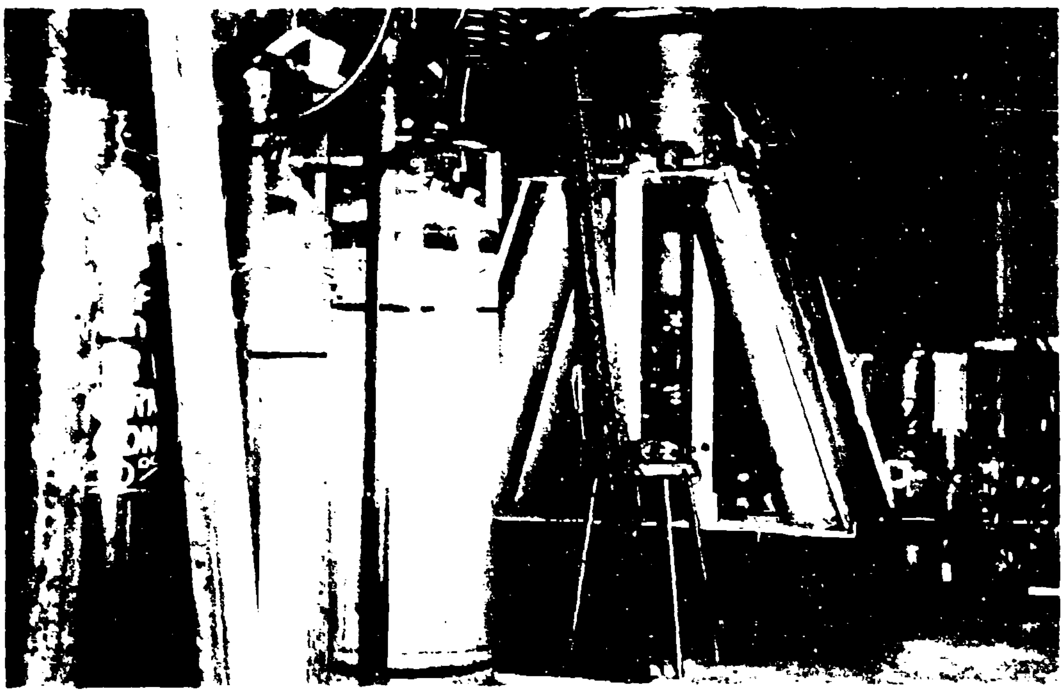


*Figure 9. Extinguishant Supply*

Figure 10). It was also found necessary to employ an expansion tank in series between the Halon 1301 container and the supply line to the extinguishant feed system to insure that the Halon 1301 was in a gaseous state. The bottle (Figure 11) was supported on the Halon 1301 container, so that the load cell could record gas as well as liquid depletion. (If the Halon 1301 was not pre-vaporized, unsteady two phase flow occurred which made it impossible to control or measure flow rate.)

Fuel Supply System

All fuel supplies were located outside the test cell (Figure 12); the hydraulic supply was a standard flight line hydraulic cart. Fuel temperature and pressure were measured with standard instruments. Although a rotameter was provided (Figure 12) to measure fuel volumetric flow for pool flow supply, its capacity was exceeded by the fuel flow rates which were standardized for spray fires. Accordingly, flow rates through the fuel nozzles were calculated, using standard orifice flow techniques to account for viscosity, density and pressure effects. The fuel spray nozzles were calibrated with JP-4 by weighing the volume accumulated over a measured time at a given pressure.

Gas Analysis System

A sampling tube located at the entrance to the test section was used to withdraw samples for analysis. A Beckman Model 0260 Oxygen Analyzer was used to measure oxygen concentration in the flow, while a Miran Model 201 Ambient Air Monitor was used to measure Halon 1301 and $CO_2$ concentration. These instruments were used to establish uniformity of extinguishant mixing at the test section entrance cross-section, and to check other primary methods (flowmeters, electronic balances, etc.) of measuring gas composition.

2.2.4 Data Acquisition

Automatic data recording was used for all essential temperature, pressure and other transducer generated signals. Output was recorded at a station outside the test cell (Figure 13); a heavy armored glass window provided viewing of the test section through the test section windows. Microphones and headsets

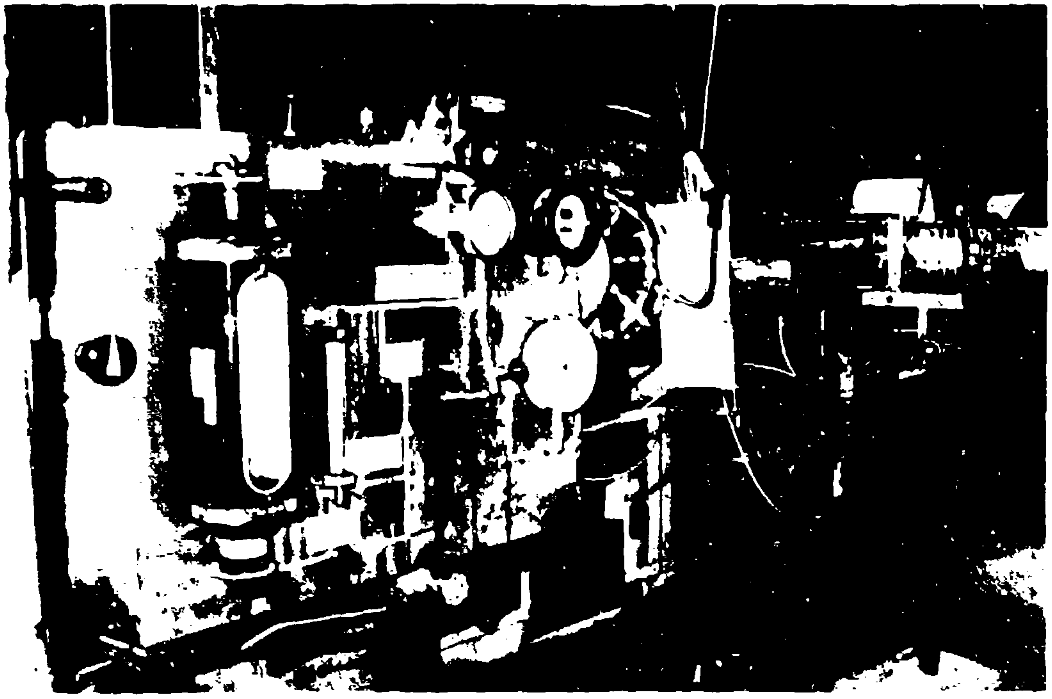


*Figure 10. Fluid Control and Metering*

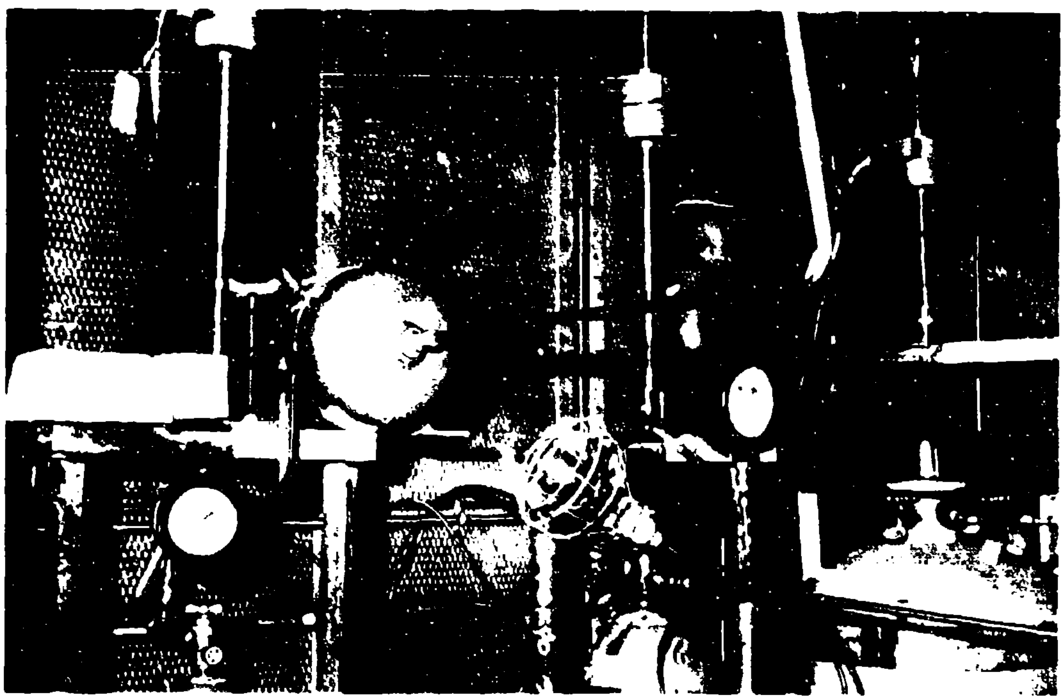


*Figure 11. HALON 1301 Expansion Tank*

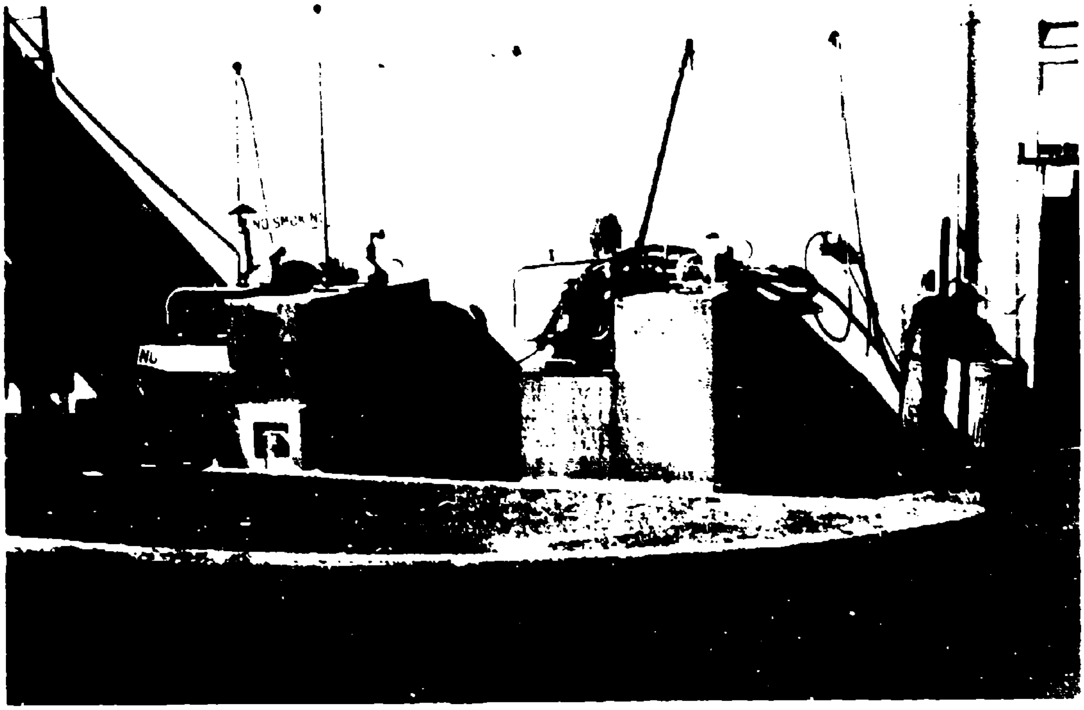



*Figure 12. Fuel Supply*

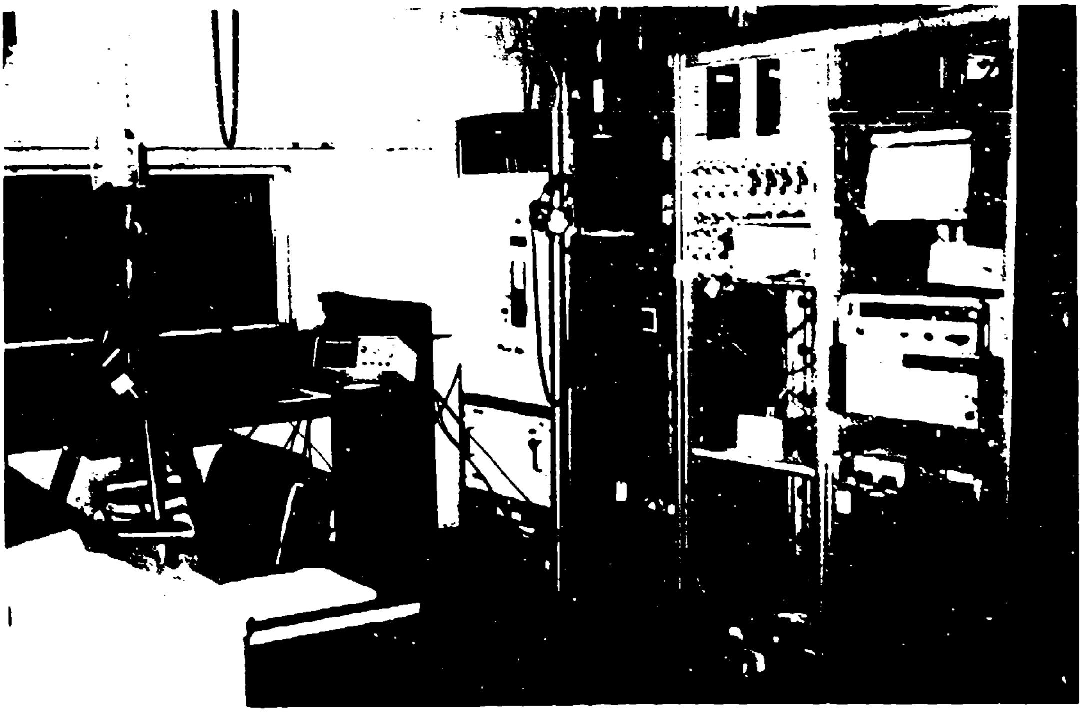


*Figure 13. Data Acquisition System*

allowed communication between the test engineer controlling the experiments and recording data, and his assistant inside the test cell. Automatically recorded data was output in millivolt form on a "grocery tape" for later reduction. Some values, as from rotameters, were recorded manually onto a strip chart which continuously and automatically tracked:

- ignition indication
- temperature on the hot surface
- oxygen percentage
- load cell reading during each test run

2.2.5 Test Procedure

The sequence of events was to start a fire at low primary air velocities and fuel flow rate; increase air flow and fuel flow to desired values; adjust air temperature and gradually build up agent flow rate until the fire extinguished. This starting sequence was used to ease the ignition problem. From a safety standpoint, if ignition did not occur within several seconds of start of fuel flow, fuel flow was cut off and ignition terminated; air flow was continued to purge vapors, and drains were opened to eliminate liquid fuel from the test section.

After determining the agent concentration required to extinguish a fire by gradual increasing flow rate, the fire was re-established and agent was released at the rate previously found to extinguish the fire; fire extinguishment within 4 seconds was required. This step was taken to better simulate actual extinguishing events, where agent flow increases discontinuously from zero to full flow rate. Tests were also performed in which the agent flow time was limited to as little as one second to determine relationships between concentration, flow time and effectiveness.

Prior to actual test initiation, each of the various systems -- air, fuel extinguishant, and data acquisition -- was operated for the purpose of function verification and instrument calibration. Each test point required the selection of a number of conditions, and identification of the test run variable; as an example:

| | |
|---|---|
| Compartment | engine nacelle (forced convection) |
| Ignition Source | hot surface, 788C |
| Flameholder Employed | z-type |
| Combustible Material | JP-4 |
| Fuel Loading Condition | high pressure spray, 3.0 l/s |
| Extinguishant Type | Halon 1301, uniformly mixed |
| Air Temperature | 93C |
| Air Flowrate | 6 m/s |

Typically, these scenario conditions were then repeated for testing of each of the other extinguishants. Data was produced by the test engineer according to instructions as indicated in Table 3. Specifics on the procedure used with different types of fires can be found in Appendix D.

Table 3. Recorded Data.

ENTER:
- Run Number
- Scenario Identification
- Fuel Type
- Extinguishant Type
- Flow Tube Size

RECORD:
- Primary Air
  - delta pressure (PASS-PI-2A/B)
  - static pressure (PASS-PI-2A/B)
  - temperature (PASS-TI-1A/B)
- Test Section Air Temperature (TSS-TI-1)
- Fire Region Temperature (TSS-TI-2)
- Hot Surface Temperature (TSS-TI-3) (if applicable)
- Fuel
  - pressure (CFSS-PI-1)
  - temperature (CFSS-TI-1)

Extinguishant

supply pressure (ESS-PI-1A/B/C/D)

delivery pressure (ESS-PI-2)

temperature (ESS-TI-1)

weight flow (ESS-W-1,2,3,4 or ESS-FI-1)

Extinguishment Time

Percent Oxygen

2.2.6 Facility Safety Features

Due to the potential hazards associated with the combustibles involved, preventative measures were taken to minimize the potential for damage to the facility, and to guarantee the safety of test personnel.

Prevention by Design

Tests were conducted in a hazardous test cell located in the Propulsion Fuel and Engine Test Laboratory. This cell was constructed specifically to house tests of a hazardous nature, and includes a number of built-in safety features

- o a water flooding system
- o an explosion-proof electrical system
- o a large ventilation fan
- o test cell ceiling blowout panels

Prevention by Procedure

Safety precautions taken included:

- o storage of combustibles outside the test building
- o activation of ventilating fans during test runs
- o exclusion of test personnel from the test cell during familiarization activities
- o a minimum of two complete air changes after each test to eliminate fuel vapors
- o drainage of sumps to eliminate residual fluids after each test
- o electrically grounding all metal components to avoid static discharges

In addition, a staff engineer prepared a detailed plan for each test series and a test engineer assured rigorous adherence to the plan.

# 3.0 TEST RESULTS

Data was required which would allow evaluation of a variety of extinguishants in a range of scenarios. The method of evaluation was a comparison of agent concentration versus test section velocity for a given scenario. The essentially limitless number of test conditions had to be narrowed to a number which was manageable. Nine test variables were identified, and the maximum planned number of variations was established (Table 4).

Table 4. Test Variables.

| Variable | Variations |
|---|---|
| Compartment Type | 2 |
| Fire Type | 4 |
| Ignition Source | 2 |
| Flameholder | 2 |
| Fuel | 5 |
| Fuel Flow Rate | 2 |
| Air Temperature | 3 |
| Air Flow Rate | 5 |
| Extinguishant | 5 |

More than $10^4$ data points would be required if all possible combinations had been evaluated. It was possible to reduce the test matrix size, by noting that:

- the primary fuel of concern was JP-4, and extinguishants in the preponderance of the tests were $GN_2$ and Halon 1301
- while five airflow rates were initially necessary to establish trends, three were considered adequate as experience was gained with simulated engine compartment fires
- pool fires required no flameholder and only one ignition source
- spray fires always required a flameholder

- fire intensity and stability were expected to be either insensitive to fuel flow rate, or be maximal at a flow rate that could be experimentally discovered
- free convection tests would be limited to one or two air velocities

The results from the engine fire simulation are discussed first. These fires are characterized by air flow velocities which dominate free convection effects at all but the lowest velocities; extinguishants were mixed into the air flow upstream of the fire site to provide a uniform dispersion of agent. This is followed by a discussion of compartment fires (dry bays, wheel wells, carge compartments) in which free convection plays a dominant role; in these cases, agent was released in two modes -- through a single port in the vicinity of the fire site and also by mixing into the entering air stream.

Eight compartment test variables selected were:

- fire type -- pool, spray, hot surface, combat damage
- fuel type -- JP-4, Jet A, hydraulic fluid, engine oil, propane gas
- fuel flow rate -- 1.0, 2.1, 3.0 and 3.9 l/hr
- air flow rate -- 0.3 to 1.2 m/s (low), and 1.5 to 30.0 m/s (high)
- air temperature -- 20, 93 and 204C
- hot surface temperature -- 677, 732 and 788C
- extinguishant -- Halon 1301, $CO_2$, $LN_2$, $GN_2$, plus premixed $NEA_9$ to a limited extent

As previously noted, not all combinations of variables in the potential test matrix were examined. The principal fuels emphasized were JP-4 and hydraulic fluids, after early tests established that these fuels created the more difficult fires to extinguish. The principal agents were Halon 1301 because of its high volumetric efficiency and $GN_2$ because its performance could be analytically extended to NEA. Other variables were tested on the limited basis necessary to establish their status with regard to the baseline variables.

held constant, and the incoming air velocity adjusted for each increase in volume percent NEA as follows:

$$v_{corrected} = \frac{V\%_{air,\ NEA}}{V\%_{air,\ GN_2}} v_{initial},$$

where

$V\%_{air,\ NEA}$ = calculated volume percent air in the air + NEA mixture

$V\%_{air,\ GN_2}$ = volume percent air in the air + $GN_2$ mixture

A development of these equations is contained in Appendix E5.0.

Data was non-dimensionalized as follows in preparing the data plots:

- o velocity was divided by $v_{max}$ = 30.48 m/s, and
- o stoichiometric flame temperature was divided by a reference flame temperature

The results in the forced convection test results section are broken down into the different fire types investigated. In the analysis that follows, no attempt was made to extrapolate the data to air velocities below 1.5 m/s, where it is felt that the fire is no longer dominated by forced convection. Data in the range below 1.5 m/s more properly falls in the region dominated by free convection, discussed in Section 3.2.

## 3.1 FORCED CONVECTION (ENGINE NACELLE) FIRE SIMULATION

Simulations of four types of engine fires are discussed; pool, spray, hot surface, and combat damage.

### 3.1.1 Pool Fires

Data was taken at the test conditions shown in Table 5; test run numbers are indicated in parenthesis for reference to the data plots in Appendix G, Figures G-1 through G-9. The parenthesis notation will be used throughout Section 3.0, indicating test number.

held constant, and the incoming air velocity adjusted for each increase in volume percent NEA as follows:

$$v_{corrected} = \frac{V\%_{air,\ NEA}}{V\%_{air,\ GN_2}} v_{initial},$$

where

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Simulations of four types of engine fires are discussed; pool, spray, hot surface, and combat damage.

### 3.1.1 Pool Fires

Data was taken at the test conditions shown in Table 5; test run numbers are indicated in parenthesis for reference to the data plots in Appendix G, Figures G-1 through G-9. The parenthesis notation will be used throughout Section 3.0, indicating test number.

Table 5. Engine Pool Fire Matrix.

| FUEL/AIR TEMP. | 20C | 93C | 204C |
|---|---|---|---|
| JP-4 | $GN_2$ (106,114)<br>$CO_2$ (105)<br>Halon 1301 (104)<br>$LN_2$ (113) | $GN_2$ (115) | $GN_2$ (116)<br>$CO_2$ (117) |
| JET A | $GN_2$ (101)<br>$CO_2$(102)<br>Halon 1301 (103) | | |
| MIL-H-5606 | $GN_2$ (107)<br>$CO_2$ (111)<br>Halon 1301 (109) | | |
| MIL-L-7808G | $GN_2$ (112)<br>$CO_2$ (111)<br>Halon 1301 (110) | | |

Pool fire simulation was accomplished using a 10.16 cm x 10.16 cm pool (see Figure 14) which was fastened to the floor of the test section, just downstream of the test section entrance. The height of the fore and aft walls of the pool was 1.27 cm, and the side walls 2.54 cm. Fuels were introduced to the pool through a 5 mm diameter opening in the pool floor. When air velocity was increased, fuel burning rate also increased, and thus fuel had to be supplied at nominal pressure in order to prevent fuel depletion during any given test run. Little difficulty was experienced in ignition of the fuels using the hot wire ignited as shown, except that the MIL-L-7808G (engine lubricating oil) required heating to a relatively high temperature (about 200C) before ignition would occur. Once ignited, a stable fire could be

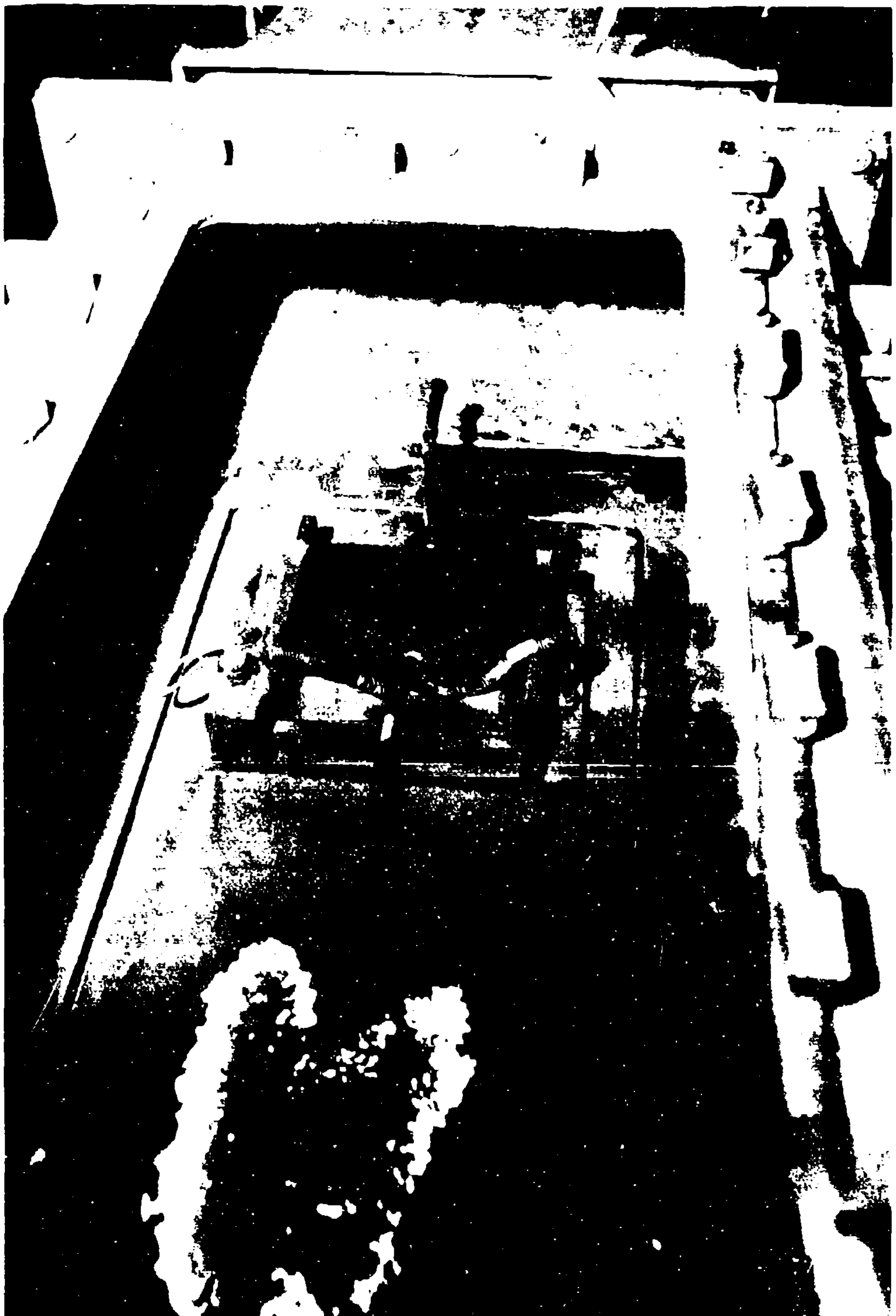

Figure 14. Engine Compartment Pool Configuration

maintained at air velocities up to approximately 16 m/s. Figure 15 shows JP-4 fire with air velocity set at 13 m/s. The length of the flame varied with air velocity becoming shorter as velocity increased. The appearance of the flame did not change greatly for different fuels, always yellow in color, but became white as air velocity was increased. The fires became unstable at velocities above 16 m/s; blow-out velocities of 21, 25, and 18 m/s were determined for JP-4, and Jet A, and MIL-H-5606, respectively. It is noted that the blow-out velocity of Jet-A is higher than that of JP-4, when the reverse had been expected. This suggests that while Jet-A fires are more readily extinguished in the presence of fire extinguishing agents, they tend to be slightly more persistent than JP-4 fires in the air velocity range where both fires are quite unstable. The blow-out velocity for MIL-L-7808G was essentially the same as that of MIL-H-5606. When elevated air temperatures were used in conjunction with JP-4, blow-out velocities of 26 and 30 m/s were encountered for 93C and 204C air, indicative of reduced reaction time as air temperature was increased.

Based on the volume percent of agent required to extinguish JP-4 pool fires in a 20C airstream with a velocity of 1.5 m/s, the ranking of agents (from least to most required) is shown in the second column of Table 6. Assuming equal times during which agent concentration must be sustained to extinguish a particular fire, the third column of the table reflects relative extinguishment weights required compared to Halon 1301 as a base.

Table 6. Agent Effectiveness in Extinguishing Pool Fire.

| AGENT | VOLUME PERCENT | RELATIVE WEIGHT |
|---|---|---|
| Halon 1301 | 3.5 | 1.0 |
| $CO_2$ | 18 | 2.0 |
| $LN_2$ | 28 | 1.8 |
| $GN_2$ | 37 | 2.3 |

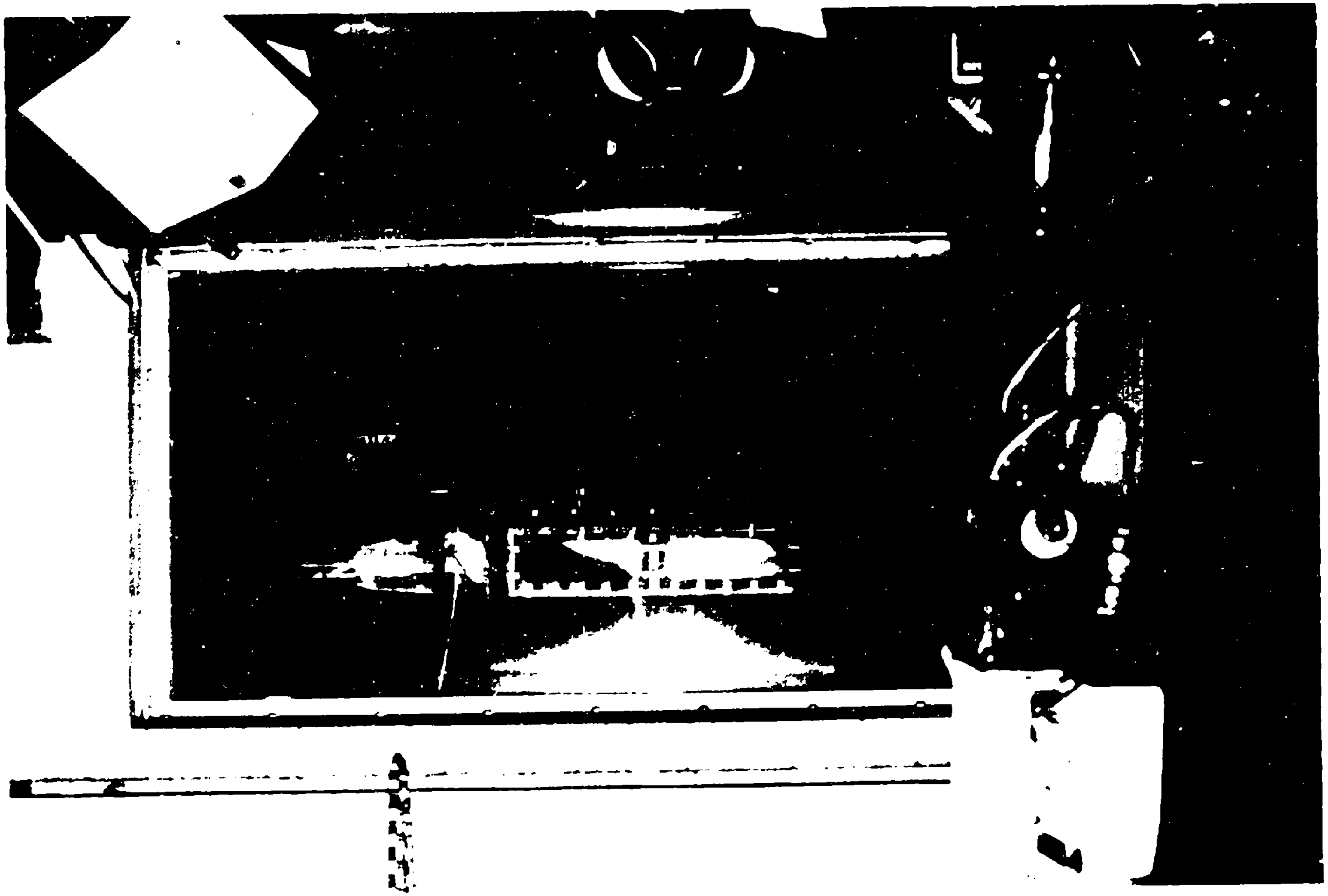

Figure 15. Pool Fire

The distinction between $CO_2$ and $LN_2$ is based on effectiveness tests with JP-4 fuel in a 20C airstream. Studies at higher air temperatures, where the cooling action of $LN_2$ might be more noticeable, could cause a reversal of the placement of $LN_2$ and $CO_2$.

Halon 1301 extinguishant requirements for the four fuels combusted in a 20C air stream indicate a maximum requirement of 3.5 ± 0.5 volume percent when the results are extrapolated to an air velocity of approximately 1.5 m/s, independent of fuel type. Lack of dependence on fuel type follows from the fact that all of the test fuels are hydrocarbons, and from the chain-breaking action of Halon 1301 in the complex of intermediate products, especially free radicals, which sustain these fires. Dependence of Halon 1301 requirements on air temperature was not explored for pool fires.

$CO_2$ extinguishant requirements for the four fuels in a 20C air stream shows 18.0 ± 1.0 volume percent to be the maximum at 1.5 m/s air velocity. When the airstream temperature was increased to 204C, the $CO_2$ requirement showed no significant increase. The primary action of $CO_2$ as an extinguishant is as a diluent, which reduces the adiabatic flame temperature, and thereby increases the chemical reaction time.

$LN_2$ experiments were limited to JP-4 in a 20C airstream, where a 28 volume percent concentration was shown necessary. The action of $LN_2$ results from two effects -- that of an inert diluent, and that of a coolant. Both actions tend to reduce the adiabatic flame temperature, and increase the chemical reaction time.

$GN_2$ was the most extensively studied extinguishant, and the experimental data were extrapolated to equivalent NEA flows as shown in Appendix G. The amount of $GN_2$ required at 1.5 m/s is in the range of 37%, with no statistically significant dependence on fuel type. Similarly, no significant trend of $GN_2$ as a function of air temperature was noted; it is likely that the large quantities of $GN_2$ required reduces the temperature of the air/$GN_2$ mixture entering the fire site so as to render fire intensity a very slowly changing variable with respect to air temperature at the extinguishment condition. NEA results were obtained by extrapolation of $GN_2$ results. Calculations were made for 3, 6, and 9% oxygen content NEA, denoted $NEA_3$, $NEA_6$, and $NEA_9$, respectively. Working from the values of $GN_2$ required, the following were obtained for a 20C airstream.

Table 7. NEA Required to Extinguish Pool Fires (20C Airstream)

| Agent Vol % | Air Velocity (m/s) | | |
|---|---|---|---|
| | 1.5 | 2.0 | 3.0 |
| $GN_2$ | 37 | 32 | 37 |
| $NEA_3$ | 41 | 37 | 31 |
| $NEA_6$ | 48 | 43 | 35 |
| $NEA_9$ | 57 | 51 | 41 |

3.1.2 Spray Fires

Two developmental steps were required prior to spray fire test initiation, which were (1) to choose a spray/flameholder configuration, and (2) to establish a matrix of test conditions. Candidate flameholder shapes included a cylinder, 1.27, 2.54, and 3.81 cm solid $90^o$ angle iron sections, and perforated angle irons of varying thickness. All flameholders were mounted vertically in the center of the test section. Flameholders were tested in combination with fuel nozzles of varying capacity and spray angle to determine a configuration which would sustain a stable flame at the highest test section velocity. When the nozzles were located upstream of the flameholders at distances of 7.6 and 15.2 cm, no configuration could be found that would sustain a stable flame at velocities greater than 4 m/s, much lower than those encountered in the pool testing. It was concluded that insufficient quantities of fuel were able to reach the flameholder recirculation zone. The last configuration tested was one in which the spray nozzle was inserted through an opening in the apex of the flameholder (see Figure 16). It was found that fires became very stable and that when a fuel flow rate of 4.21 l/hr was used, the flame could not be blown out at any velocity within the capacity of air supply system. Thus on the basis of flame stability this configuration was selected for the spray fire extinguishant investigation.

The matrix of test conditions, including the test fuel flow rates, was next determined. Although the fire could not be blown out at the 3.0 l/hr fuel flow rate (nozzle capacity rating), blow-out could be achieved at lower fuel flow rates. The procedure used to determine blow-out velocity of JP-4 and MIL-H-5606 as a function of fuel flow rate was as follows:

- o air velocities were established at intervals between 2 and 22 m/s
- o at each air velocity setting, a fire was established at the maximum fuel flow rate (4.29 l/hr fuel)
- o fuel flow rate was lowered by reducing fuel delivery pressure until the blow-out occurred.

Results of this procedure are shown in Figure 17 for the two fluids tested, JP-4 and hydraulic fluid.

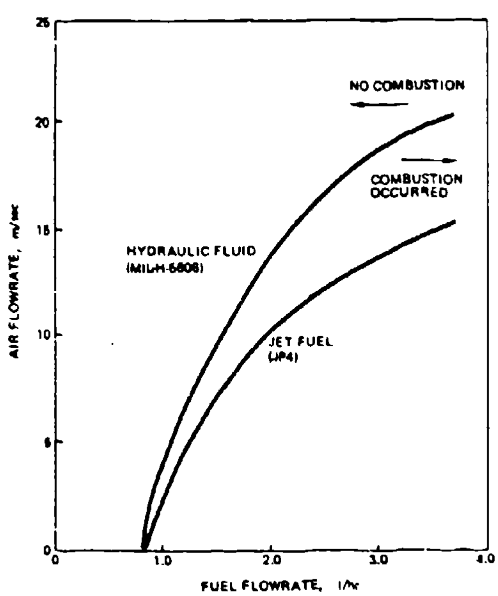


*Figure 17. Blow - Out Test Results for JP - 4 and MIL - H - 5606*

*Figure 16. Spray Flameholder Configuration*

Four fuel flow rates were selected within the test section blow-out range: 1.04, 2.12, 3.04, and 3.90 l/hr. At each of the selected fuel flow rates, potential air velocity test points were selected at 20, 50, and 80% of the blow-out velocity. As an example, the selected test points for JP-4 are shown in Figure 18.

The appearance of the spray fires was similar at each of the upper three fuel flow rates, but at the 1.04 l/hr flow rate the fire appeared unstable. Flames filled the full height of the flameholder; it was not possible to determine visually (Figure 19) the width of the fire plume. Observation of the hydraulic fluid fires was hindered because considerable unburned fluid accumulated on the windows. Inspection showed that partially combusted fluid deposits adhered to the test section surfaces (Figure 20). No such accumulation was noted during the combustion of JP-4.

Data was taken at the test conditions shown in Table 8, plotted data is contained in Figures G-10 through G-21.

Table 8. Engine Spray/Flameholder Fire Test Matrix

| FUEL | AIR TEMPERATURE | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 20C | | | | | | 120C | |
| | FUEL PRESSURE (kPa) | | | | | | | |
| | 34.5 | 138 | 276 | 448 | 1690 | 2760 | 276 | 448 |
| JP-4 | $GN_2$ (201) | $GN_2$ (202) | $GN_2$ (203) | $GN_2$ (204) | | | $GN_2$ (211) | |
| | | | $CO_2$ (205) | | | | | |
| | | | Halon 1301 (206) | Halon 1301 (207) | | | Halon 1301 (212) | Halon 1301 (213) |
| MIL-H-5606 | | | | | $GN_2$ (208) | | | |
| | | | | | Halon 1301 (209) | Halon 1301 (210) | | |

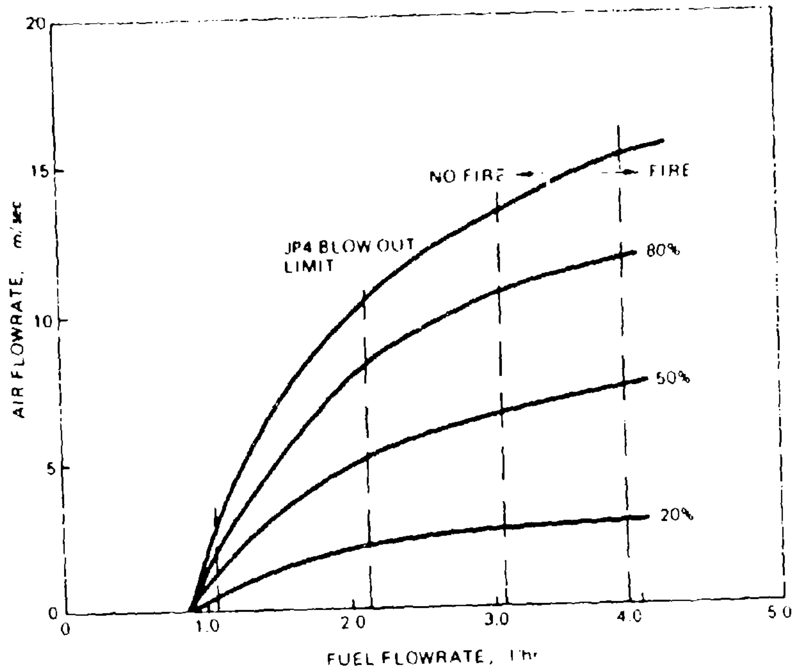


*Figure 18. JP-4 Spray Test Air Velocity Selection*

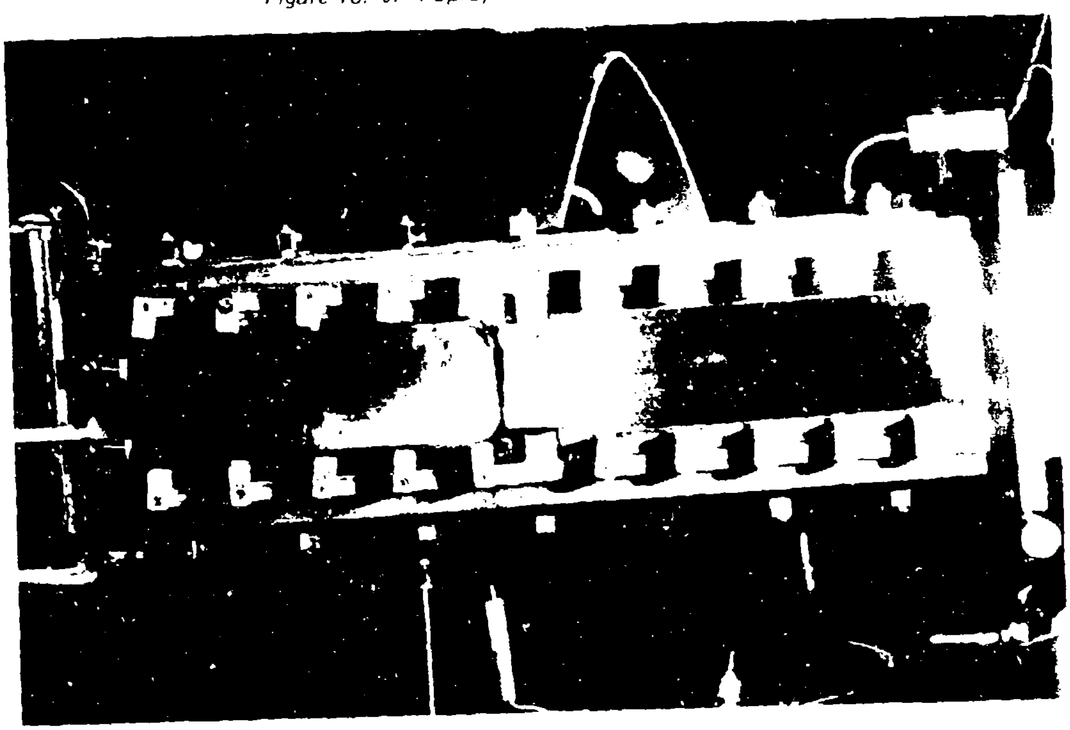

*Figure 19. Hydraulic Fluid Spray Fire*

*Figure 20. Test Section Appearance Following Hydraulic Fluid Spray Test*

Based on the volume percent agent required to extinguish JP-4 spray fires in a 20C airstream and at 1.5 m/s test action velocity, the ranking of agents is shown in the second column of Table 9. Assuming equal times to extinguish a particular fire, the third column of the table reflects relative extinguishant weights required compared to Halon 1301.

Table 9. Agent Effectiveness in Exinguishing JP-4 Spray Fire.

| AGENT | VOLUME PERCENT | RELATIVE WEIGHT |
|---|---|---|
| Halon 1301 | 3 | 1 |
| $CO_2$ | 25 | 2.5 |
| $GN_2$ | 48 | 3.0 |
| $LN_2$ | Not tested | -- |

The Halon 1301 data indicates agent requirements nearly identical to those required for pool fires, with no significant variation with fuel/air ratio, fuel type or airstream temperatures. The chain-breaking action of Halon 1301 dominates any possible diluent effect which might arise from agent concentration increase.

Limited testing of $CO_2$ was conducted at a fuel flow rate of 3.0 l/hr in a 20C airstream. The agent concentration requirment was 25% higher than required to extinguish a JP-4 pool fire. The difference probably derives from the larger fire volume and higher temperatures achieved in the case of the spray fire.

$GN_2$ requirements to extinguish JP-4 in a 20C airstream were some 33% greater than for the pool fire. The volume percent of oxygen in the mixed air/$GN_2$ stream was some 11% higher than the level of 9% generally considered necessary for ignition or sustenance of a fire, indicating that reduction of residence time is of assistance in extinguishing fires.

There is some evidence of dependence of fire stability on fuel flow rate. Using JP-4 at 1.0 l/hr, the fire appeared to be unstable on the basis of visual observation and the data plots of run 201. The slope of the line (which is usually indicative of activation energy) on the plots is obviously different. At 2.1 l/hr, the fire was much more stable, although the data plots for run 202 show a slope discrepancy compared to higher fuel flowrates. At fuel flows greater than 3.0 l/hr, the slopes were normal, and extinguishant requirements showed only small increases with further fuel flow increase. Hydraulic fluid tests showed similar tendencies at flow rates of 3.0 and 3.9 l/hr. In this regard, comparison of runs 203 (JP-4) and 208 (MIL-H-5606) in air velocity/reciprocal temperature coordinates shows similar slopes, indicating similar activation energies. These runs also indicate that hydraulic fluid fires are harder to extingush, although differences in spray pattern due to viscosity may be the cause.

Air temperature increase from 20 to 121C increases fire stability; blow-out velocity was increased from 12 m/s to 21 m/s. However, the amount of $GN_2$ required to extinguish fires at air velocities of 2 to 3 m/s was not greatly changed -- the large amounts of $GN_2$ required to extinguish fires at this condition (some 50% of the total flow) reduces the temperature of the air/$GN_2$ mixture approaching the fire site, and masks the effect of temperature. Halon 1301 requirements were essentially invariant as temperature was changed.

To obtain NEA data, $GN_2$ data were converted to equivalent flows of 3, 6, and 9% oxygen content NEA, and the results are presented in Table 10 for a range of airstream velocities.

Table 10. NEA Required to Extinguish Spray Fires (20C Airstream)

| | AIR VELOCITY (m/s) | | |
|---|---|---|---|
| AGENT (VOL %) | 1.5 | 2.0 | 3.0 |
| $GN_2$ | 48 | 41 | 33 |
| $NEA_3$ | 54 | 46 | 36 |
| $NEA_6$ | 59 | 51 | 40 |
| $NEA_9$ | 66 | 57 | 44 |

The data should not be extrapolated to lower velocities because of potential changes in the fire physics.

3.1.3 Hot Surface Fires

A high temperature surface presents a continuous ignition source, and as well contributes energy to a fire sited on the surface. The flameholder for this fire was fastened to the bottom of the test section, overhanging the hot surface; it combines with the hot surface to provide a very stable fire site. As might be expected, the resultant fires are very difficult to extinguish. The tests were conducted at surface temperatures of 371, 677, 732 and 788C and at air temperatures of 20 and 93C, using JP-4 fuel as shown in Table 11; data plots are contained in Figures G-22 through G-29.

Table 11. Engine Hot Surface Fire Test Matrix.

| FUEL | AIR TEMPERATURE | | | | |
|---|---|---|---|---|---|
| | 20C | | | | 93C |
| | SURFACE TEMPERATURE | | | | SURFACE TEMPERATURE |
| | 371C | 677C | 732C | 788C | 788C |
| JP-4 | $GN_2$ (304) | $GN_2$ (301) | $GN_2$ (302) | $GN_2$ (303) | $GN_2$ (311) |
| | | $CO_2$ (305) | | $CO_2$ (306) | |
| | | Halon (307) 1301 | | Halon (308) 1301 | Halon (312) 1301 |
| | | $LN_2$ (304) | | $LN_2$ (310) | |

The hot surface energy source was constructed with eight 26.04 cm x 0.95 cm diameter Chromalox high watt density heater elements, each capable of dissipating 7.29 $w/cm^2$ at a maximum surface temperature of 816C (see Figure 21). Each rod was secured in a semi-circular slot and electrically connected to a variable voltage, 30A source. Power to the heater elements was controlled by a VARIAC, whose voltage could be adjusted to obtain a selected temperature at any test air flow rate. Fuel was supplied through the same 3.90 l/hr nozzle used in the spray test, with the nozzle oriented perpendicular to, and directed toward, the hot surface. The nozzle head was placed slightly below the edge of the flameholder to prevent fuel droplets from being blown downstream before contacting the hot surface (see Figure 22). Attempts to introduce the fuel upstream of the flameholder introduced the same difficulty as in the spray configuration, in which the fuel vapor was not entrained behind the flameholder in sufficient quantity to allow a stable fire to develop.

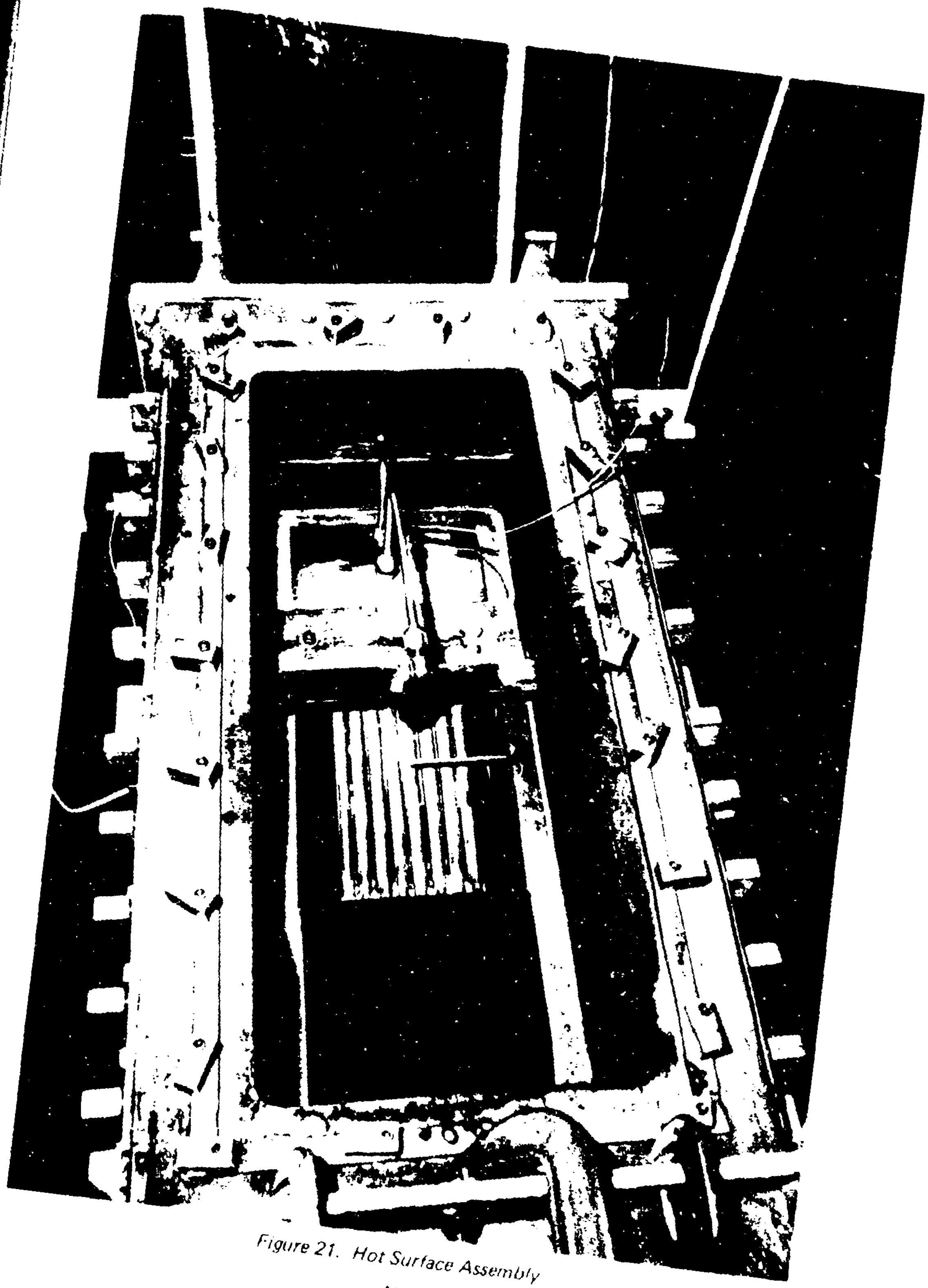

Figure 21. Hot Surface Assembly

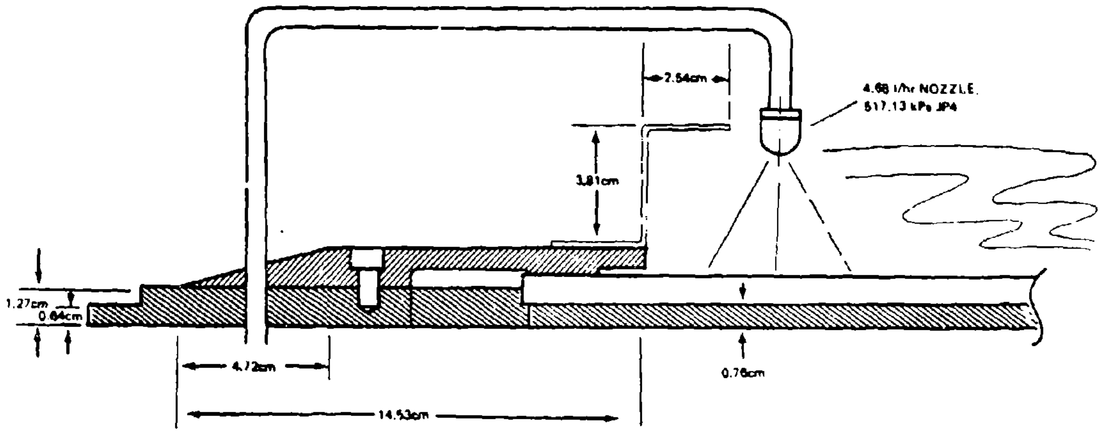


*Figure 22. Hot Surface Spray/Flameholder Configuration*

It was found that ignition of fuel by the hot surface could be readily obtained at test airflow conditions by initiating the spray of fuel onto the surface, provided the surface temperature was sufficiently high. It was also found that the minimum surface temperature for ignition increased with airflow. An investigation to determine the magnitude of the ignition temperatures required yielded results shown in Figure 23.

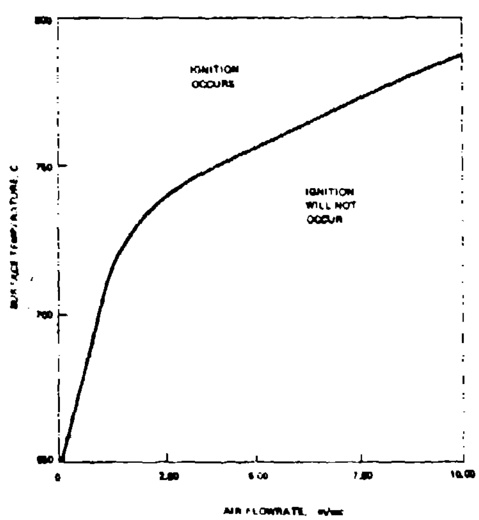


*Figure 23. Hot Surface Temperature vs Air Flow Rate*

The re-ignition phemonenon was also investigated. Reference 4 indicates great difficulty in re-igniting a fire after agent application when fuel flow is maintained. In the present investigation, when extinguishant flowed for 20 to 30 seconds, it was observed that re-ignition would occur if the hot plate temperature exceeded ignition conditions when the agent flow was stopped. The probability of re-ignition was determined, as in initial ignition, by the surface temperature versus air flow rate relationship shown in Figure 23. The physical location of the fuel spray and the shape of the flameholder both played a role in determining whether a sufficiently high surface temperature could be maintained, following initial extinguishment of the fire, to allow re-ignition.

For example, at low velocities the air velocity had no significant effect on the fuel spray due to protection by the flameholder, and since the fuel flow was not reduced on fire extinguishment, the fuel spray impinged on and cooled the surface below the required ignition temperature. As air velocity was increased, the airflow was finally able to carry a major portion of the fuel vapor downstream before it could contact the hot surface. Surface cooling was reduced, and the probability of re-ignition increased.

The fire was localized, filling the flameholder laterally and covering the entire hot surface area (see Figure 24). In reducing the data, it was not possible to correlate the data on ln v versus 1/T plots because of the unknown energy contributed to the fire by the hot surface. It was also found that hot surface fires supplied with spray fuel were so persisent that blow-out velocity could not be obtained at fuel flow rates of 3.90 l/hr, since maximum test section velocity was limited to 25 m/s. Since blow-out velocity is needed for data interpretation, it was necesary to extrapolate the data to zero agent concentration. Blow-out velocity was expected to increase with surface temperature, but this was not immediately observable in the data plots (Figure G-22A). A procedure was established to correct this problem.

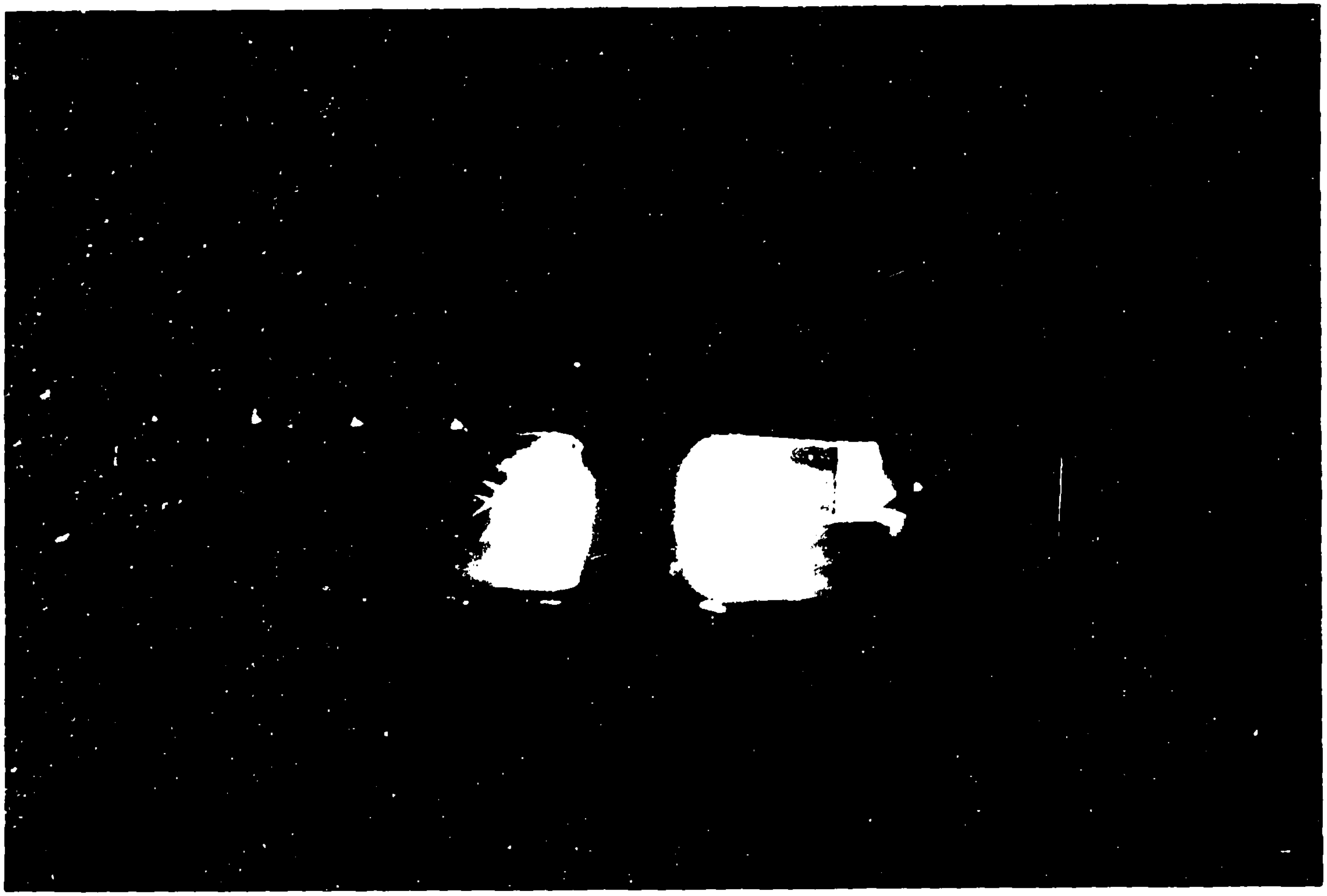

*Figure 24  Hot Surface Fire*

First, it was observed that the slopes of runs 301 and 302 (Figure G-22A) were essentially identical. Run 301 was arbitrarily chosen as representative of the correct slope which all runs should exhibit. Then, since test data at each of the other surface temperatures were expected to parallel data from run 301, the data of runs 302, 303 and 304 were fit to lines of the same slope as run 301. The plots of runs 301, 302, 303, and 304 were then extended to the y-axis ($v/v_{max}$), and the y-intercepts taken to be the representative blow-out velocities for each condition (Table 12). Blow-out velocities now display the expected behavior with surface temperature. These blow-out values were inserted into the hot surface data and used for the purpose of data correlation.

Table 12. Extrapolated Hot Surface Blow-out Velocity

| | BLOW-OUT VELOCITY (m/sec) | |
|---|---|---|
| SURFACE TEMPERATURE (C) | 20C AIRSTREAM | 93C AIRSTREAM |
| 371 | 19.7 | -- |
| 677 | 25.8 | -- |
| 732 | 28.8 | -- |
| 788 | 34.0 | 35.2 |

A check of this technique was made following modification of the air supply system to increase capacity. At 788C surface, 20C air condition, the blow-out velocity was measured to be 32 m/sec thus confirming the validity of the procedure described above.

The second column of Table 13 lists the volume percent of agent required (at 1.5 m/s in a 20C airstream), while the third column (assuming equal times for which agent concentration must be sustained) shows the extinguishant weight required compared to Halon 1301.

Table 13. Agent Effectiveness in Extinguishing Hot Surface Fires (20C Airstream, 788C Hot Surface).

| AGENT | VOLUME PERCENT | RELATIVE WEIGHT |
|---|---|---|
| Halon 1301 | 3.5 | 1.0 |
| $CO_2$ | 34 | 2.9 |
| $LN_2$ | 34 | 1.8 |
| $GN_2$ | 56 | 3.0 |

Halon 1301 concentrations of approximately 3.5% were effective in controlling hot surface fires, essentially independent of surface or air temperature. This is a further indication that the extinguishant mechanism is chemical rather than physical in nature.

$CO_2$ requirements in 20C airstreams ranged from 32% at 677C surface temperature to 34% at 788C. $LN_2$ results fall into the same range as $CO_2$. $GN_2$ requirements were 47% at 677C, and 56% at 788C surface temperature.

NEA requirements varied with air temperature and surface temperature. Data are presented in Table 14 at 20C airstream and 677C surface temperature; for contrast, data are also shown at 20C airstream and 788C surface temperature.

Table 14. NEA Requirements to Extinguish Hot Surface Fires.

| | 20C AIR/677 SURFACE | | | 20C AIR/788C (m/s) | | | 93C AIR/788C SURFACE | | |
|---|---|---|---|---|---|---|---|---|---|
| | AIR VELOCITY (m/s) | | | AIR VELOCITY (m/s) | | | AIR VELOCITY (m/s) | | |
| AGENT V% | 1.5 | 2.0 | 3.0 | 1.5 | 2.0 | 3.0 | 1.5 | 2.0 | 3.0 |
| $GN_2$ | 47 | 43 | 35 | 56 | 51 | 44 | 58 | 53 | 46 |
| $NEA_3$ | 52 | 47 | 39 | 62 | 57 | 53 | 64 | 59 | 55 |
| $NEA_6$ | 59 | 54 | 45 | 68 | 62 | 54 | 70 | 64 | 56 |
| $NEA_9$ | 67 | 61 | 50 | 70 | 64 | 55 | 72 | 66 | 57 |

### 3.1.4 Combat Damage Fires

Combat damage was simulated by a 1.91 cm diameter hole in the test section floor. A 1.91 cm diameter steel pipe was inserted through the hole, and flared on the inside of the test section to simulate the petalling caused by combat damage (Figure 25); the top of the flare was 0.95 cm above the floor. The pipe was connected through a rotameter and a valve to the shop air supply system. Air injected through the pipe models air flow from the exterior to the interior of an engine compartment. The test fuel was JP-4 at a flow rate of 3.9 l/hr, injected through a spray nozzle located upstream of the combat damage site. It was experimentally found that the nozzle had to be aimed so that the test section floor was wetted to insure that fuel could enter the separated zone created by the combination of flared pipe and injected air (Figure 26). The hot wire igniter was located aft of the damage site.

The pattern of the fire can be seen in Figure 26. At the low airflows used during ignition, the fire extended to the fuel nozzle, but as the airflow was increased to the test condition, the flame moved to the rear of the air injection port as shown by the heavier deposits on the floor.

The test matrix is shown in Table 15, the plotted data, in Figures G-30 through G-35.

Table 15. Combat Damage Fire Test Matrix
(JP-4 Fuel at 3.9 l/hr, Airstream Temperature 20C).

| INJECTED AIR VOLUMETRIC FLOW RATE (l/s) | | 0 | 6.1 | 8.8 | 11.8 |
|---|---|---|---|---|---|
| INJECTED AIR PRESSURE DIFFERENTIAL (kPa) | | 0 | 3.4 | 7.0 | 12.7 |
| AGENTS | $GN_2$ RUN NO. | (401) | (402) | (403) | (404) |
| | Halon RUN NO. | (405) | (406) | (407) | (408) |

Generally speaking, these fires were less stable than the pool, spray or hot surface fires previously discussed. The flared pipe which protruded into the

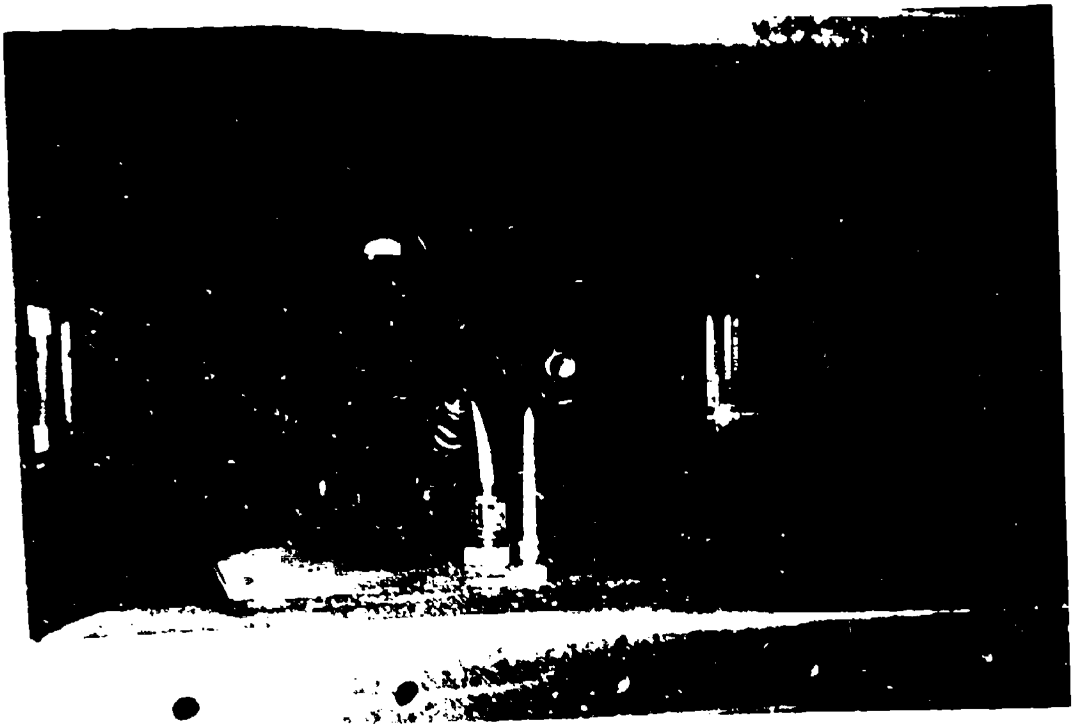

Figure 25. Combat Damage Configuration

Figure 26. Combat Damage Simulation Separated Zone

test section to simulate petalling of a surface due to ballistic penetration served as a moderately effective flameholder, with a blow-out velocity of 9 m/s when no air was injected. As air was injected through the pipe at progressively higher rates, the flame became more stable; the blow-out velocity increased to 10.5 m/s at the highest injection rate, 11.8 l/s, which corresponds to a differential pressure of 12.7 kPa between the interior and exterior of the test section. This pressure differential is considered typical of the static pressure difference between the interior and exterior of a nacelle. As usual, Halon 1301 was the more effective agent. Considering the agent required to extinguish the most persistent combat damage simulation fire, Table 16 compares the agents at 1.5 m/s test section velocity.

Table 16. Agent Effectiveness in Extinguishing Combat Damage Fires.

| AGENT | VOLUME PERCENT | RELATIVE WEIGHT |
|---|---|---|
| Halon | 6 | 1 |
| $GN_2$ | 42 | 1.32 |

The Halon 1301 concentration required is higher than that for pool, spray, or hot surface fires, because the fire is supplied with a considerable amount of air at its site. This air, of course, contains no Halon 1301, and on mixing with the test section flow considerably reduces the agent concentration. On the other hand, $GN_2$ requirements are relatively unaffected. Evidently, the large amount of $GN_2$ present and the small amount of injected air are such that the $GN_2$ concentration is nearly constant.

NEA data were obtained by conversion of the $GN_2$ data, and are shown in Table 17.

Table 17. NEA Required to Extinguish Combat Damage Fires.

| AGENT (VOL %) | AIR VELOCITY (m/s) 1.5 | 2.0 | 3.0 |
|---|---|---|---|
| $GN_2$ | 42 | 35 | 26 |
| $NEA_3$ | 44 | 37 | 28 |
| $NEA_6$ | 49 | 41 | 31 |
| $NEA_9$ | 54 | 46 | 35 |

## 3.2 FREE CONVECTION FIRE SIMULATION

Free convection compartment fire tests included pool, spray and hot surface fires. The fires are characterized by the dominance of free convection velocities induced by the fire over the velocities associated with air entering the compartment. In the configuration of the test article, with its long axis vertical (see Figure 3, Section 2.2.2) the free convection velocities could reach 2.4 m/s; the ventilating air velocity at the higher flow rates approximately 1.0 m/s. Blow-out velocity is a meaningless term for this type of fire because, by definition, all characteristic velocities are very low. Air to sustain the fire was introduced through slots around the pool circumference.

Two modes of extinguishing agent introduction were used. In the first mode (pre-mixed), the agent was uniformly mixed into the ventilating air stream using the extinguishant manifold and mixing section from the engine fire tests. This permitted simulation of engine compartment zones where very low ventilation velocities are encountered. In the second mode (injected), agent was introduced through a single 1.27 cm diameter port located 0.23 m above the floor of the test section. In an actual airplane system, agent would be introdu d into compartments such as wheel wells or dry bays through one or more such ports.

### 3.2.1 Pool Fires

The same 10.16 x 10.16 cm square pool and electric igniter used in the forced convection testing, were attached to the floorplate of the test section (Figure 27). The ventilating air slots can be seen around the pool circumference, and the single port extinguishant injection hole can be seen above the pool. The fuel in the pool was replenished through a hole in the pool's center. The test fuel was JP-4, the test extinguishants were $GN_2$ and Halon 1301, and two test section velocities were evaluated. Run numbers are shown in Table 18, data plots in Figures G-36 through G-39.

Table 18. Free Convection Pool Fire Test Matrix (JP-4 Fuel, Airstream Temperature 20C).

| AIR VELOCITY (m/s) | | | 0.30 | .055 |
|---|---|---|---|---|
| AGENT | Premix | $GN_2$ | (501) | |
| | | Halon | (502) | |
| | Inject | $GN_2$ | (503) | |
| | | Halon | (504) | |

The appearance of the free convection pool fire differed greatly from the engine compartment pool, in that the fire burned not only within the boundaries of the pool as might be expected, but also traveled to and was sustained above the incoming air slots. This was thought to occur because the oxygen supply above the pool became depleted; vaporized fuel then mixed with the incoming airstream to sustain the fire at one or more of the incoming air slots.

These fires are relatively easy to extinguish. Halon 1301 at 3% by volume is sufficient whether pre-mixed or injected. Nitrogen requirements showed unusual behavior in the pre-mixed case, in that the percentage required increased as ventilating velocity increased. There is considerable scatter in the data at the lowest velocity, where the fire appeared relatively unstable once nitrogen flow began. It can be surmised that incipient oxygen starvation

Figure 27. Free Convection Pool Configuration

in combination with nitrogen mixed with the airstream made the fire easy to extinguish. When nitrogen is injected above the fire, the fire is replenished by air with standard oxygen content, and nitrogen must diffuse or be convected to the fire site. At the higher velocities, test section turbulence may be more effective in bringing agent to the fire site.

NEA requirements are generally modest, as shown in Table 19.

Table 19. NEA Required to Extinguish Free Convection Pool Fires.

| AGENT (VOL %) | AIR VELOCITY (m/s) | | | |
|---|---|---|---|---|
| | (PREMIXED AGENT) | | (INJECTED AGENT) | |
| | 0.30 | 0.55 | 0.30 | 0.55 |
| $GN_2$ | 10 | 20 | 42 | 12 |
| $NEA_3$ | 12 | 25 | 45 | 13 |
| $NEA_6$ | 15 | 30 | 48 | 15 |
| $NEA_9$ | 20 | 39 | 50 | 18 |

3.2.2 Spray and Hot Surface Fires

The spray and hot surface fire simulations were conducted using a common configuration. The hot surface panel, as constructed for the engine hot surface fire test, was installed initially with the spray nozzle/flameholder unit at the upper (exhaust) end of the test section. However, a very unstable flame resulted in tests conducted both with and without power to the high temperature surface. As in the earlier spray tests, it appeared necessary that a flameholder be positioned between the air supply and the spray to insure that sufficient quantities of fuel vapor were entrained. For this reason, the position of the panel was reversed, placing the spray/flameholder unit at the lower end of the test section as shown in Figures 28 and 29. The resulting fires were quite stable. Ignition of the fuel was followed by an intense fire which filled the entire test section. After 1-2 minutes excess oxygen became depleted, and the fire size reduced and was concentrated in the

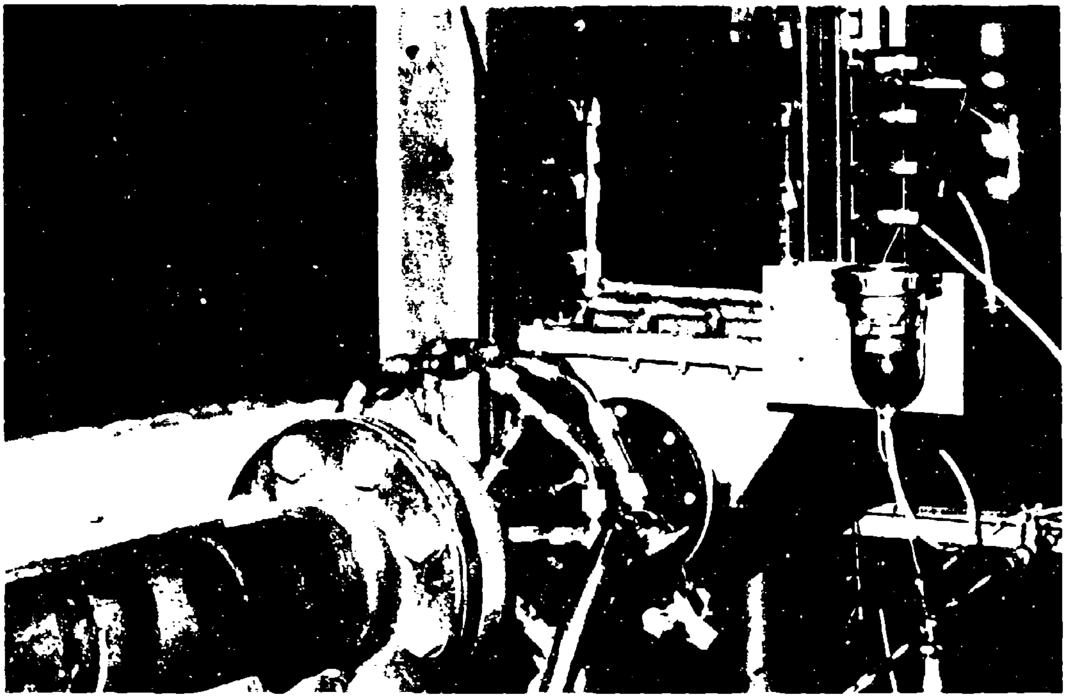

*Figure 28. Free Convection Spray/Hot Surface Assembly*

*Figure 29. Free Convection Hot Surface/Spray/Flameholder Configuration*

space above the flameholder and adjacent to the hot surface. Test conditions were as detailed in Table 20, using a JP-4 fuel flow rate of 3.90 l/hr; plotted data is contained in Figures G-40 through 48.

Table 20. Free Convection Spray/Hot Surface Test Matrix.

| FUEL | SURFACE TEMPERATURE | | | | | |
|---|---|---|---|---|---|---|
| | 20C (SPRAY) | | | | 788C (HOT SURFACE) | |
| | AIR TEMPERATURE | | | | | |
| | 20C | | 205C | | 20C | |
| | PREMIX | INJECT | PREMIX | INJECT | PREMIX | INJECT |
| JP-4 | $GN_2$(601)<br>Halon(602) 1301 | $GN_2$(603) | $GN_2$(604)<br>Halon(605) 1301 | | $GN_2$(606)<br>Halon(607 1301 | Halon(608) 1301 |

Comparison of the spray and hot surface data in Table 21 indictes, as expected, that the free convection hot surface fire is the more difficult to extinguish than either free convection pool or spray fires. In terms of agent quantity, however, the forced convection hot surface fire still appears to represent the worst case. In each test, extinguishant was pre-mixed with air. NEA data presented was obtained by analysis.

Table 21. Agent Concentration Required to Extinguish Free Convection Spray and Hot Surface Fires

| PRE-MIXED AGENT | $20^{\circ}$C AIR/$20^{\circ}$C SURFACE | | $20^{\circ}$C AIR/$788^{\circ}$C SURFACE | |
|---|---|---|---|---|
| | AIR VELOCITY (m/s) | | AIR VELOCITY (m/s) | |
| | 0.30 | 0.55 | 0.30 | 0.55 |
| Halon 1301 | 4 | 3 | 7 | 3 |
| $GN_2$ | 42.5 | 25 | 45 | 31 |
| $NEA_3$ | 47.5 | 29 | 51 | 35 |
| $NEA_6$ | 53 | 33 | 57 | 39 |
| $NEA_9$ | 60 | 39 | 62 | 46 |

## 3.3 NEA ANALYSIS VERIFICATION AND ADDITIONAL TESTING

Throughout the preceding discussion, the quantity of NEA required to accomplish fire extinguishment has been reported in terms of percentages calculated from gaseous nitrogen test results. The procedure for converting the $GN_2$ to the NEA, however, is based on the assumption that the air and extinguishant flows are thoroughly mixed, as was accomplished in the extinguishant testing discussed thus far. Based on the speculation that such an ideal condition might not occur in an actual test situation, further tests were conducted to determine whether the effectiveness of NEA could indeed be predicted by calculation. Deviation from the calculated NEA requirement would indicate lower mixing efficiency than was encountered with the other agents tested.

In addition to the NEA verification tests, it was of interest to establish the dependence of agent effectiveness on application rate and duration, given that existing fire suppression systems typically employ high rate, short term discharge (HRSTD) of agent. For example, it could be hypothesized that a one second pulse application of agent at a given flow rate would not have the same fire extinguishing capability as the same flow rate applied in a steady state mode. The basis for the argument would be that one second may not be a sufficiently long period of time for mixing of the agent and the incoming air, or for interaction of the agent with the fire.

The tests showed this hypothesis is to be incorrect. The crucial quantity is agent concentration achieved, independent of time of application down to a minimum application time of one second (the shortest time tested) or less.

In the earlier discussion of testing with the hot surface configuration, surface cooling in the vicinity of the fuel spray was suggested as the reason why, in some cases, re-ignition of a fire failed to occur on shutoff of the extinguishing agent. The possibility that this cooling factor may quantitatively influence the test results prompted a series of tests to be performed using a pre-vaporized fuel which in effect, would not provide the same cooling as the liquid.

Finally, an important part of this extinguishant effectiveness investigation was to be, as previously mentioned, confirmation of the small scale test results, in the Aircraft Engine Nacelle Fire Test Simulator (AENFTS). A series of tests was conducted in the AENFT simulator during March 1981, to which some of the small scale results can be compared.

### 3.3.1 NEA Verification

Again using the hot surface test setup configured to model the engine compartment as described in Section 3.1.3, test runs 303 and 304 were repeated using premixed $NEA_9$ as the extinguishant in place of $GN_2$. The $NEA_9$ used for this work was commercially obtained in 2200 psi cylinders in order to

- o ensure the correct quality of the gas (for $NEA_9$, an oxygen content of 8.82 - 9.18% was guaranteed), and to
- o minimize the test set-up activities required

Hardware improvements made prior to the execution of these test runs included the replacement of manual valves ESS-V-2A and 3 (see the test facility schematic, Figure 7) with a timer-controlled solenoid valve and a throttle valve with an adjustable regulator, respectively.

These changes were made for two purposes: first, to allow conservation of the extinguishants, and second, to enable the time of extinguishant application to be controlled. Previously, the test approach called for the agent concentration to be found at which the fire was extinguished in 4 seconds or less. After the fire was extinguished, the agent flow was allowed to continue for 20-30 seconds while temperature, pressure, and flowrate data was recorded. As an alternative approach, the solenoid valve timer was set at 4.0 seconds, and the regulator setting adjusted each time agent was applied until the proper agent flowrate was found. This also conserved agent and it was possible to perform many more test runs from one extinguishant bottle.

Results of the test performed to confirm the validity of the $NEA_9$ requirement calculation are shown in Figures 30 and 31, for heated (788C) and unheated (371C) surface conditions. The dashed lines are the calculated

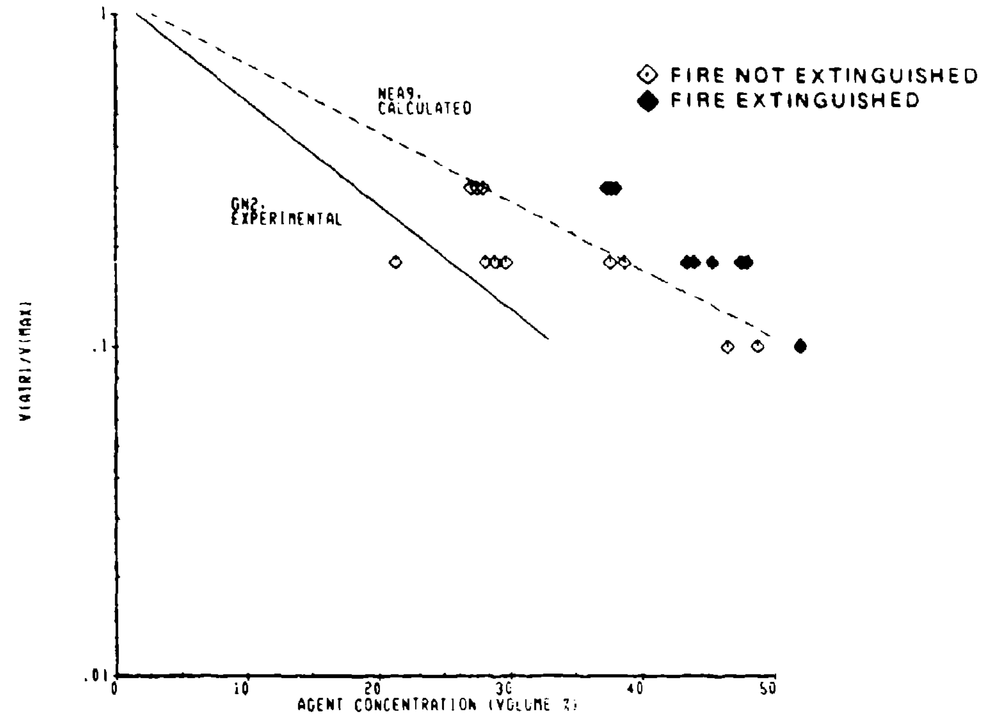


*Figure 30. NEA Verification Tests, 788C Surface*

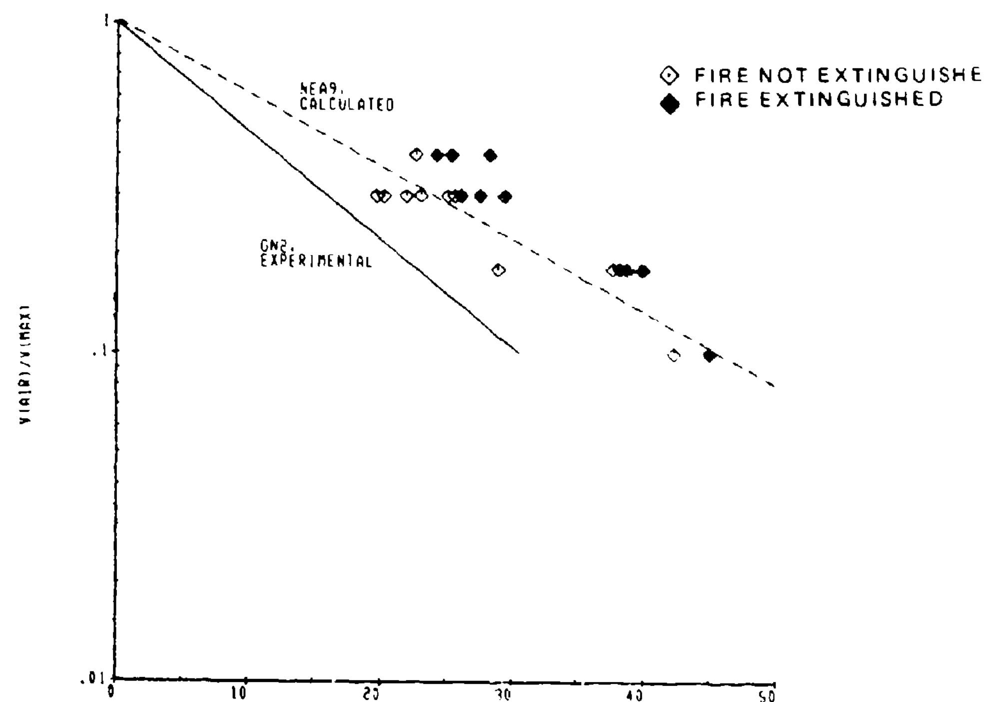


*Figure 31. NEA Verification Tests, 371C Surface*

$NEA_g$ requirement; the solid symbols represent fire knock-downs, the open symbols, unsuccessful knock-down attempts. In both cases, good agreement was obtained between the calculated and experimental $NEA_g$ requirements.

An interesting result of this series of tests was the discovery that, unlike the previous tests in which agent was allowed to flow for 20-30 seconds and re-ignition of the hot surface fires on agent shut-off was uncommon, permanent hot surface fire keep-down when the agent was applied in short bursts never occurred. In effect, the cooling process was too short to allow reduction of the hot surface temperatures (in the vicinity of the fuel spray) below the minimum temperature required for re-ignition. Shown in Figure 32 are traces of temperatures at 5 locations on the surface.

As might be expected, test runs in which power was not supplied to the hot surface showed no re-ignition tendency once the fires were initially extinguished. Surface temperatures prior to extinguishant application were already far below the minimum required for re-ignition. In effect, it can safely be assumed that the same would occur for the other fire types investigated earlier in the test program, i.e., the pool, spray, and combat damage fires, in which the ignition source was deactivated prior to the agent application.

3.3.2 Injection Time Comparison

Earlier, the installation of a timer-controlled solenoid valve to control the duration of agent application was discussed. This modification permitted a series of tests to be conducted to compare the effect of short term versus long term extinguishant applications.

The results of these tests are summarized in Table 22; the plotted data can be found in Figures G-49 through 54. All volume percentages are calculated from the average volumetric flowrates over the specified time interval.

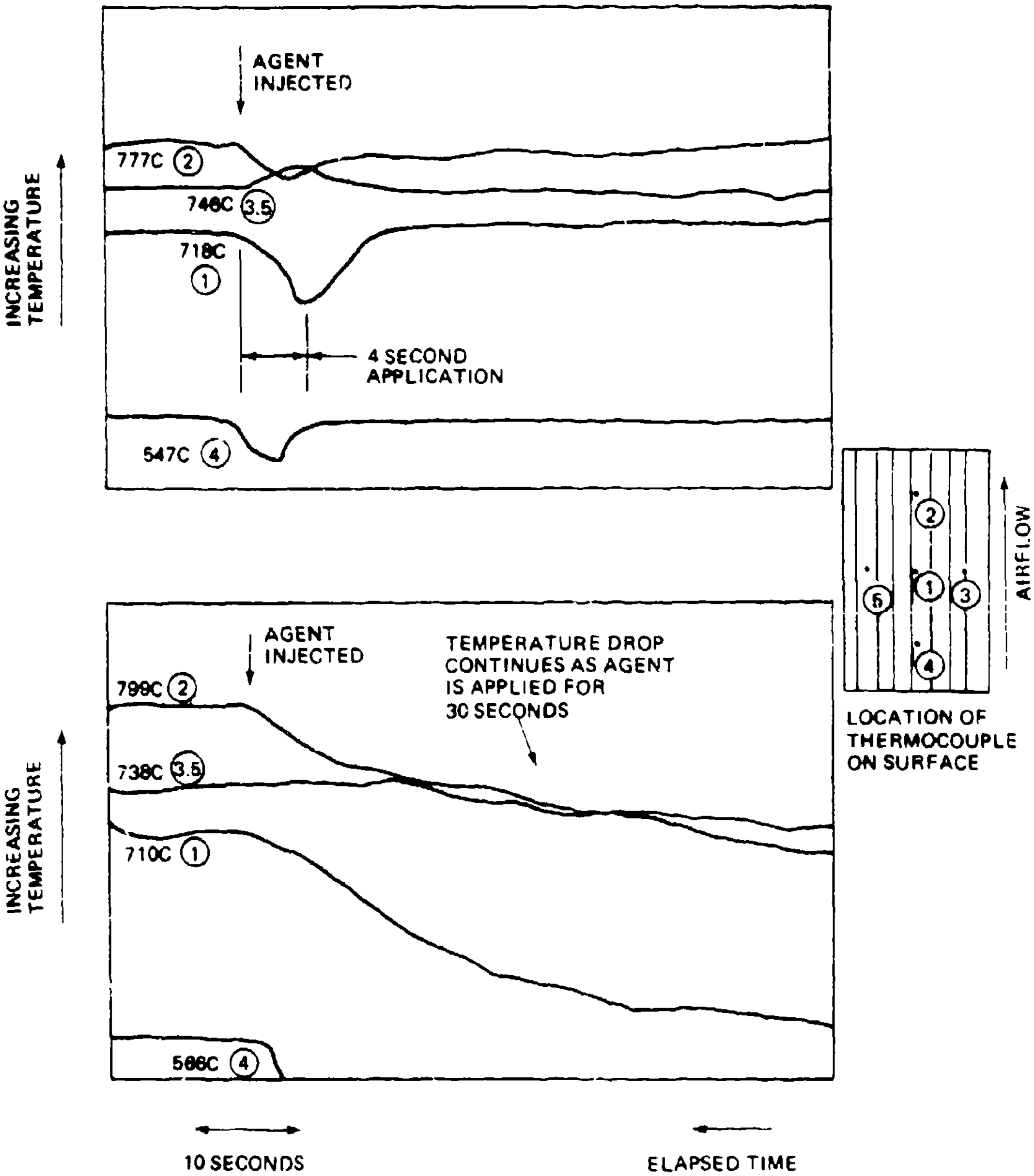


*Figure 32. Surface Temperature Traces*

Table 22. Agent Requirement at $v_{air}$ = 3.0 m/s.

| INJECTION TIME (SEC) | | 1.0 | 2.0 | 3.0 | 4.0 |
|---|---|---|---|---|---|
| $GN_2$ | 788C SURFACE | 35.5% | --- | --- | 34.0% |
| | 371C SURFACE | 31.0 | --- | --- | 30.0 |
| $NEA_9$ | 788C SURFACE | 48.0% | 48.0 | 47.0 | 51.0 |
| | 371C SURFACE | 45.0 | 48.0 | 47.0 | 43.0 |
| Halon 1301 | 788C SURFACE | 5.5 | --- | --- | 2.5 |
| | 371C SURFACE | 5.0 | --- | --- | 2.5 |

It appears that the difference in agent requirement for varying extinguishant injection times is not statistically significant in the case of $GN_2$ and $NEA_9$; percentage variation (no more than 2 or 3%) between the different injection times is very small. These results indicate that an inertant's effect is the same, once the required minimum concentration is reached, whether its presence is brief or extended. The same does not appear to be true of Halon 1301, however, which may be due to the difference in its mechanism of fire suppression. In particular, the volume percent of Halon 1301 required for suppression of fire on the 788C on the 371C surface with the 1.0 second application was twice that of a 4.0 second application.

As noted in the previous section (3.3.1), permanent fire suppression of the hot surface fires could not be accomplished when the gaseous extinguishing agents were applied in single short bursts. As an added item of interest, test runs were performed with multiple bursts of agent applied - one after another with a delay of several seconds between each burst. Agent flows were of sufficient concentration to cause fire knock-down. The result was that while the fire re-ignited after the first and possibly the second burst of extinguishant, it was extinguished permanently after a small number of these repetitions. Surface temperatures monitored during this process indicated that each time the agents were applied, surface cooling continued for the duration of the agent flow, but heating resumed on re-ignition. The heating process, however, takes place at a slower rate than the cooling. Therefore, each time the agent was applied, the temperature of the surface was at a lower level than the previous application. After several bursts of agent, the surface temperatures were below the minimum required for re-ignition. In effect, this approach achieves the same result as a single application of agent of extended duration (20-30 seconds), but requires a much smaller quantity of agent.

3.3.3 Propane-Fueled Hot Surface Fire

In addition to the liquid fuel (primarily JP-4) used throughout this test program, propane was used as the test fuel in order to explore the effect of fuel vaporization from a hot surface on some of the observed instances of permanent fire keep-down. The tests were conducted with a surface temperature of 788°C, and an air temperature of 20°C. The flow rate of propane used was that providing the same heating value as the JP-4.

Little difference is evident in the minimum concentration of nitrogen required for fire extinguishment, as shown in Figure 33, indicating that the degree of fuel vaporization was not a strong variable in influencing the extinguishant requirements. Neither was any difference evident in the re-ignition tendency of propane compared to JP-4. Given a hot surface ignition source and agent applied in a short (1-4 second) bursts, re-ignition always occurred on agent shut-off.

3.3.4 Large Scale/Small Scale Data Comparison

Based on results obtained in the small scale test program, tests were to be performed in the large scale, Aircraft Engine Nacelle Fire Test Simulator (AENFT) located at Wright-Patterson Air Force Base. The purpose of these tests was to verify results produced in the small scale testing. Though the large scale simulator was unavailable for use at the scheduled time, a series of tests performed later, during the facility checkout period was similar in nature to the small scale work, and the data is presented here for comparison.

Shown in Figure 34 is interior configuration of the large scale test section. The AEN cross section is one-third of an annulus formed by two

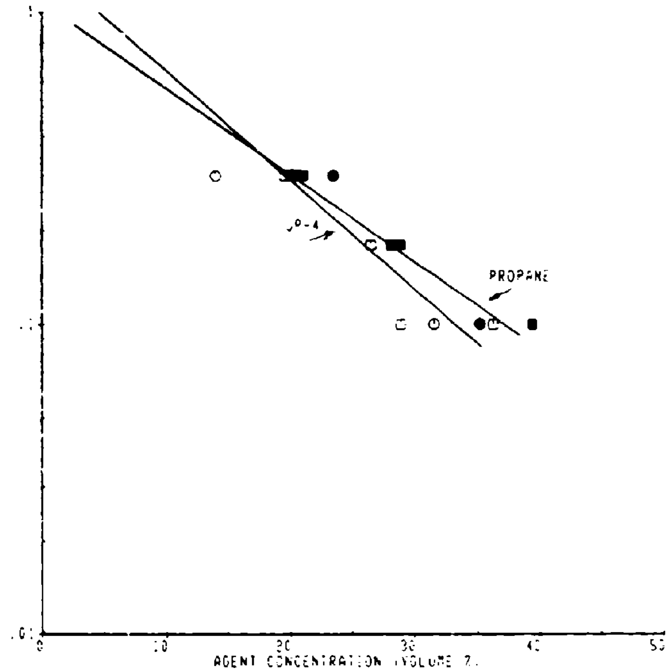


*Figure 33. $GN_2$ Extinguishant Requirements for Propane and JP - 4*

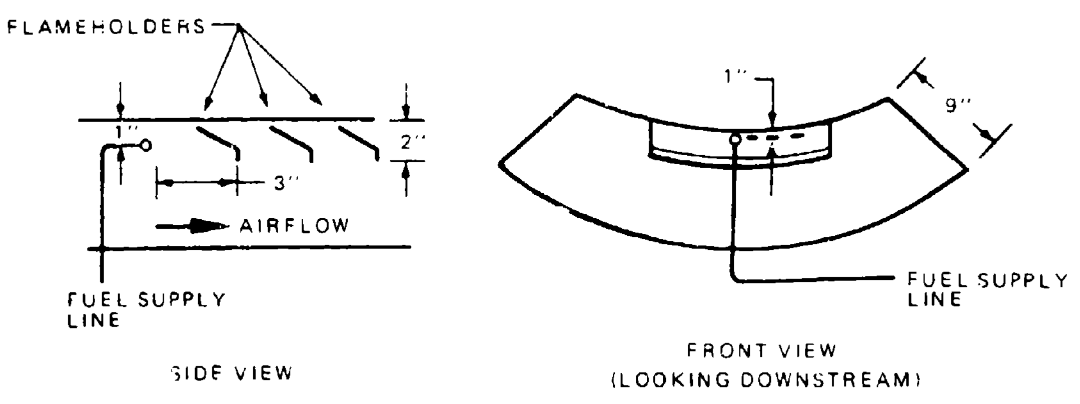


*Figure 34. AENFT Test Section Configuration*

each time the agent was applied, the temperature of the surface was at a lower level than the previous application. After several bursts of agent, the surface temperatures were below the minimum required for re-ignition. In effect, this approach achieves the same result as a single application of agent of extended duration (20-30 seconds), but requires a much smaller quantity of agent.

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Shown in Figure 34 is interior configuration of the large scale test section. The AEN cross section is one-third of an annulus formed by two cylinders, the inner cylinder being 0.76 m diameter and the outer cylinder 1.22 meters in diameter, and has an area of 0.23 $m^2$. This section approximates the full-sized engine cavity formed between the engine case and the nacelle. For the small scale simulator, a rectangular cross-section was used because the width of the test section represented such a small "wedge" of the annulus that it would be well approximated without curved surfaces. The depth of the simulators was more similar - the small scale, 15.2 cm, and the large scale, 22.9 cm. The effective length of the large scale test section is 0.52 meters, compared to the 0.61 m, small scale section. Three flameholders were mounted in series on the upper test section surface as shown in the figure, and the fuel nozzle positioned about 7.6 cm upstream of the first flameholder. A single flameholder was used in the small scale facility.

Tests were performed in the AEN using $GN_2$, $NEA_6$, and $NEA_9$. A sufficient number of data points were taken using $GN_2$ (in the AEN) to allow trends to be visualized in the same manner as the small scale test data, again, by plotting test section air velocity as a function of the concentration of extinguishant (Figure 35). Too few data points were taken with $NEA_6$ and $NEA_9$ for any trends to be seen. Geometric dissimilarities prevent a true comparison of results obtained in the two facilities. Lines were drawn on the figure for clarity, separating the regions where extinguishment did and did not occur, and do not represent mathematical curve fits. Tests were performed at velocities of approximately 2.1, 3.0, 5.5, 7.6, and 9.1 meters per second; agent was discharged into the air stream in about one second.

To make a better comparison, small scale data was taken with the test section in the configuration most similar to that of the large scale is plotted together with the large scale data. The same flameholder/not surface configuration was used as described in Section 3.1.3. The surfaces in the large scale simulator on which the fire stabilized reached temperatures around 370C, and the small scale hot surface was also heated to this temperature prior to agent application. Fuel flows of 4.5 l/hr and 33.8 l/hr, and air temperatures of 21C and 38C were used in the small and large scale test, respectively.

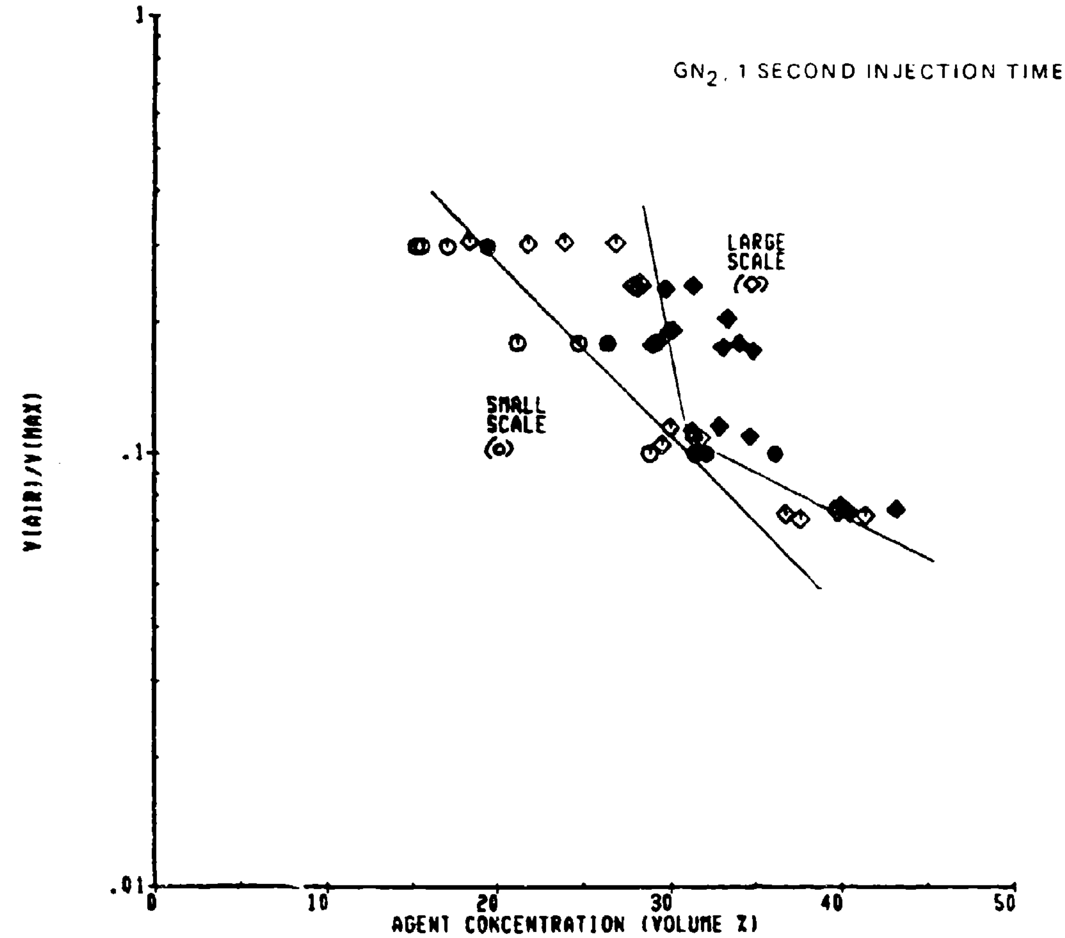


*Figure 35. Comparison of Large and Small Scale Test Results*

As is obvious from Figure 35, an inflection exists for the large facility data in the concentration requirement at air velocities of 2-3 meters per second. Without a characterization of the flow patterns in the AEN test section, yet to be performed, no explanation is offered for the apparent discontinuity in slope. The blowout velocity of a fire was found in the small scale work to be geometry dependent; geometry effects have yet to be determined in the AEN, and may contribute to the behavior of the fire.

## 3.4 SUMMARY OF RESULTS

In general, Halon 1301 was the most effective agent from the standpoint of volume percent required to extinguish any of the fires studied. Next most effective were $CO_2$ and $LN_2$, while the least effective agents were $GN_2$ and its NEA derivatives. From a relative weight standpoint (assuming equal times to extinguish a fire are required for the various agents), the same conclusions hold, but the differences are much reduced. It is important to note that the quantity of NEA required for fire extinguishment was found experimentally to match the requirement that can be calculated based on the proportion of nitrogen in the NEA.

Drawing on the various fire scenarios described in the literature, several scenarios were modeled and the relevant fuel, air, and ignition source variables simulated. Two airflow ranges were investigated:

- o high air flow ($v/v_{max} > 0.05$), characteristic of engine nacelle ventilation flows, in which forced convection governs fire stability, and

- o low air flow, ($v/v_{max} < 0.05$), characteristic of large fuselage compartments and wing dry bays, in which free convection induced by the fire is the dominant influence in fire stabilization

Fire types modeled included

- o pool
- o spray
- o hot surface, and
- o combat damage

Fuel related variables were fuel type, flow rate, and loading condition (pool, low and high pressure sprays). Two ignition sources were used - a hot wire and a hot surface.

As might be expected, the hot surface fires were the most difficult to extinguish in almost every case. Higher agent concentrations were required to knock-down the fires initially because of presumably higher reaction temperatures, and extinguishing agent had flow that had to be sustained for long enough to allow surface cooling or re-ignition would occur.

Forced convection fires appear to require the highest agent concentrations. Table 23 lists the highest agent requirement for the several types of fires modeled. NEA design criteria may well be dictated by these requirements; the agent concentrations required would, of course, depend on the oxygen content of the NEA.

Table 23. Agent Requirement for Most Difficult Fire.

| AGENT | FIRE TYPE | VOL % | RELATIVE WEIGHT COMPARED TO Halon 1301 SAME FIRE |
|---|---|---|---|
| Halon 1301 | Engine Fire (Combat Damage) | 6 | 1 |
| $LN_2$ | Engine Fire (Hot Surface) | 34 | 2.9 |
| $CO_2$ | Engine Fire (Hot Surface) | 34 | 1.8 |
| $GN_2$ | Engine Fire (Hot Surface and Hot Air) | 58 | 2.7 |
| $NEA_3$ | | 64 | 3.1 |
| $NEA_6$ | | 70 | 3.4 |
| $NEA_9$ | | 72 | 3.5 |

Testing of $GN_2$ and NEA was performed in the large scale nacelle simulator (AEN) but the extent of the tests was too limited to allow reasons to be identified for the differences between the small and large scale test results.

## 4.0 UTILITY OF NEA IN INTEGRATED INERTING/FIRE FIGHTING SYSTEMS

Solely on the basis of fire fighting capability, the fire tests results present NEA in a relatively unfavorable light compared to other agents. However, if the basis of judgement were a combined fuel tank inerting/fire suppression system, a different conclusion might be reached. The study of integrated inerting/fire suppression systems should be conducted in the light of existing inerting systems and concepts, and existing fire fighting systems. System trades could then be conducted which would consider improvements in

- o safety
- o cost
- o airplane performance

These trade studies would go far towards determining the utility of NEA.

Some conclusions can be drawn at this time, based on previous studies and order of magnitude estimates. Generally, they indicate combined inerting/fire fighting to be feasible, and in some instances, advantageous.

### 4.1 REMARKS ON ENGINE FIRE FIGHTING AGENT REQUIREMENTS

Most engine compartment are protected by Halon extinguishing systems. A variety of halogenated hydrocarbons are used, but the most commonly used type in the United States is Halon 1301 ($CF_3Br$), and it was for this reason that it was used in this study. The amount of agent required to extinguish an engine fire varies with engine size; as reported in various documents, the agent amounts are:

| AIRCRAFT | ENGINE | AGENT (kg) |
|---|---|---|
| T-39 | JT-12 | 0.9 |
| DC-10, 767 | CF6-6, 50, 80 | 3.4 |

Most airplanes have two-shot extinguishing systems, so the amount of agent aboard is twice that noted. While Halon is a very effective agent, it is one of a class of compounds whose release into the environment has been criticized by the EPA.

If its use were barred, the USAF might or might not be required or elect to abandon its use. Also, with the higher air flowrates in advanced engine nacelles, Halon agents have been found to lack the staying power required to prevent re-ignition where persistent ignition sources exist because they are dispersed so rapidly. In any case, alternatives should be studied.

$LN_2$ was proposed at one time as an engine fire extinguishant for the Boeing 747; in their proposal for the 747, Parker-Hannifin estimated that 1.8 kg would be required to extinguish JT-9D fires, and that this amount would produce an agent concentration of $\sim$ 33% for 2-3 seconds. Parker-Hannifin based their requirement estimates on experimental results obtained in a wind tunnel test of an operating JT-12 engine with cowling; these reported results (Reference 5) are consistent with the findings in the small scale test apparatus for pool fires (28%) and hot surface fires (33%).

On this basis, estimates were made on the amount of $GN_2$ and $NEA_9$ needed to extinguish an engine fire on a large airplane. Since Boeing 767/CF6-80A data were readily available, this size engine compartment was considered. Ventilating flow is 0.77 kg/s at takeoff, derived from fan bleed air. Flow area around the high compressor is approximately 1.8 $m^2$ and around the compressor/turbine section, approximately 0.4 $m^2$. From this, flow velocities can be estimated at 0.4 m/s around the compressor, and 1.6 m/s around the hot section. Conservatively, 60% by volume $GN_2$ and 100% $NEA_9$ were assumed to be concentrations required per fire extinguishant application; it was also assumed that these concentrations would have to be sustained for 5 seconds. Under these assumptions, 2.3 kg of $GN_2$, or 3.9 kg of $NEA_9$ per application would suffice. For the 747's JT-9D engines (with a cooling flow 3 times that required by the CF6-80), an upper limit of 7 kg of $GN_2$ or 11.7 kg of $NEA_9$ per application would be needed for a single, 5 second application.

## 4.2 REMARKS ON INERTING SYSTEMS

Fuel tank inerting systems using on-board generator inertant are in a development stage. Several small generating systems have been experimentally evaluated under Boeing IR&D programs. The Air Force is also funding the procurement of advanced generators of the size needed to inert a KC-135 airplane. Based on the data that has been developed up to the present time, design studies were conducted on several aircraft, one of which was a conventional manned penetrating bomber. The concept which evolved (Figure 36) used a 6.9 MPa stored gas system to minimize overall system weight. Several pressurization schedules examined are listed in Table 24, with results as shown in Table 25. Depending on the pressurization allowable in the fuel tanks, the amount of stored gas (NEA) was in the range of 52 to 61 kg. A similar study was done for the Boeing YC-14 airplane, using a 20.7 MPa stored gas system; the amount of stored gas required was 65 kg, stored in a 73 cm diameter sphere weighing 19 kg empty.

The C-5 uses an $LN_2$ fuel tank inerting system, hence the performance of an $LN_2$ system is quite well known. Weight, cost and logistic data are available for trade purposes.

## 4.3 REMARKS ON COMPARTMENT FIRE FIGHTING

Other agents such as $CO_2$ and $LN_2$ are used to protect various airplane zones. $CO_2$ is often used in inhabited zones, where it is discharged from hand held bottles directly onto fires. $LN_2$ from the fuel tank inerting system is used to fight fires in the C-5's wheel wells, dry bays, and underfloor areas, while Halon 1301 is used in the cargo area.

If NEA is to be used to fight fires, it seems clear that the maximum oxygen content must be reduced to $\leq$ 9% at the fire site. To achieve a 9% oxygen level, very high NEA agent concentrations would be required and passenger safety was cursorily examined. The concern is that if $NEA_9$ were used in habited zones at a concentration of 100% and at atmospheric pressure, oxygen

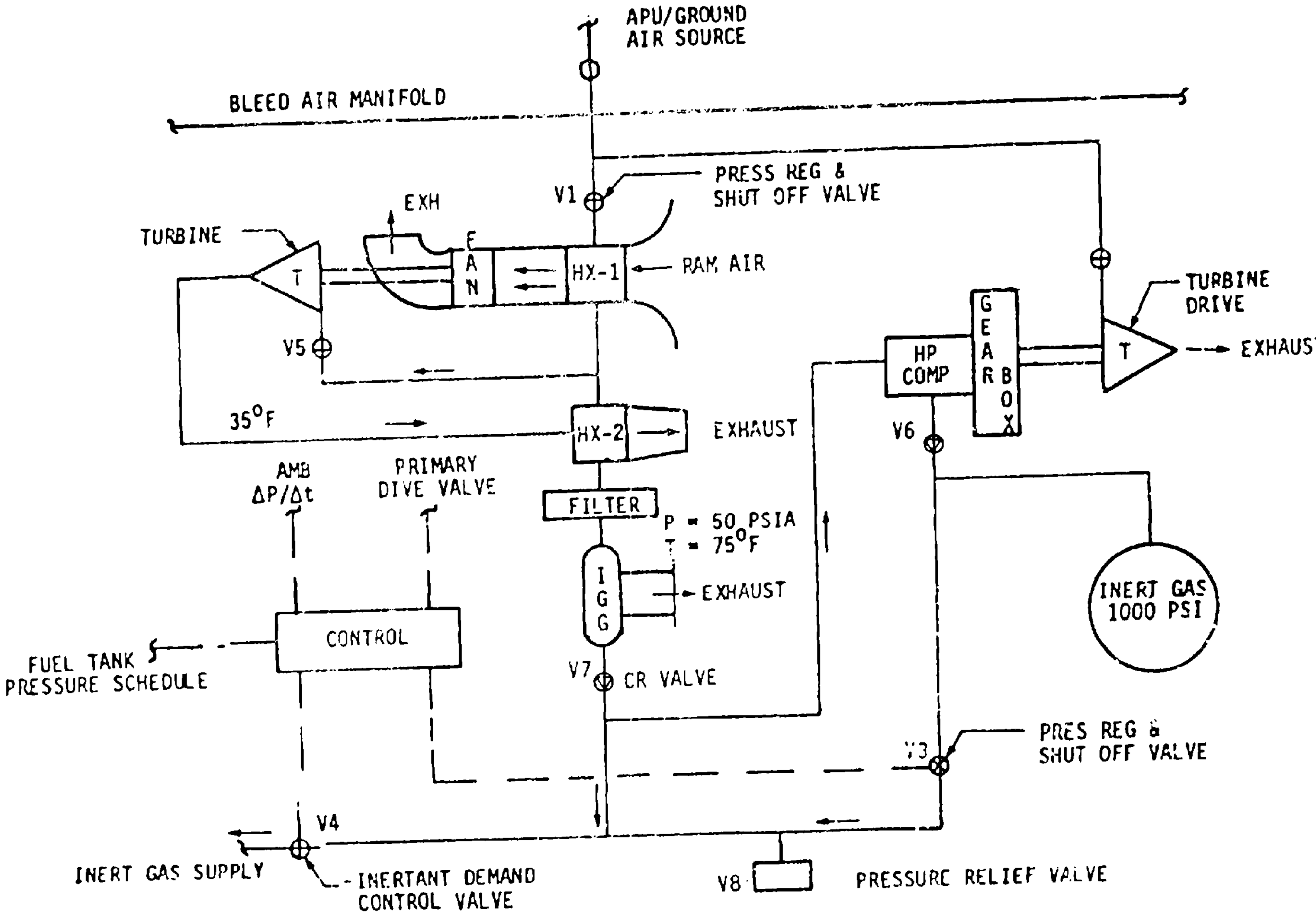


*Figure 36. Manned Penetrating Bomber Fuel Inerting System*

Table 24. Fuel Tank Inerting Flow Rate Requirements, Lbs - Min Standard Day

| PRESSURE SCHEDULE CONCEPTS | TAKE-OFF / CLIMB | CRUISE | | DASH | DESCENT [1] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | FROM 25,400 FT | | | FROM 42,595 FT | | |
| | | 25,400 FEET | 42,595 FEET | | PEAK | AVG | [2] N2 | PEAK | AVG | [2] N2 |
| LINEAR 5 PSIG MAX | 1.74 / .75 | .263 | .085 | .47 | 10.6 | 9.44 | 46 | 25.3 | 20.5 | 175 |
| CONSTANT 5 PSIG | 2.33 / .635 | .263 | .085 | .63 | 37.4 | 24.8 | 126.6 | 63.8 | 33.4 | 284.5 |
| VENTED AMBIENT PRESSURE | 1.74 / 1.16 | .136 | .027 | .47 | 39.4 | 26.[illegible] | 13[illegible] | 66.7 | 35.2 | 300 |
| LINEAR 10 PSIG MAX | 1.74 / .77 | .337 | .142 | .47 | -.39 | -.83 | -4.2 | 13.5 | 3.09 | 25.6 |
| CONSTANT 10 PSIG | 2.92 / .695 | .390 | .143 | .79 | 35.6 | 23 | 117.3 | 60.8 | 31.6 | 269 |
| LINEAR 7.5 PSIG MAX | 1.74 / .67 | .325 | .113 | .47 | .89 | .85 | 4.3 | 23.6 | 13.3 | 113.4 |

[1] RATE OF DESCENT = 5000 FT/MIN

[2] TOTAL INERT GAS REQUIRED - LBS

Table 25. Inerting System: Component Weight Summary

| PRESSURE SCHEDULE | HEAT EXCHANGERS/ EQUIPMENT | VALVES (7) | IGG | HIGH PRESSURE SYSTEM | | | CONTROLS | DISTRIBUTION SYSTEM | CLIMB/DIVE VALVES | INSTALLED WEIGHT |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | INERT GAS | HP SYS TOTAL | VOLUME ($FT^3$) | | | | |
| A | 9.2 | 7 | 65 | 48 | 143 | 9.1 | 5 | 67 | 17 | 338 |
| B | 15.5 | 11.8 | 110.6 | 126.6 | 278 | 24 | 5 | 67 | 17 | 549 |
| C | 14.2 | 10.8 | 101 | 136 | 293 | 26 | 5 | 118 | 17 | 603 |
| D | 10.5 | 5.0 | 74 | 0 | 0 | 0 | 5 | 63 | 17 | 186 |
| E | 17 | 12.9 | 121 | 117.3 | 263 | 22 | 5 | 63 | 17 | 543 |
| F | 12.3 | 9.3 | 87 | 0 | 0 | 0 | 5 | 65 | 17 | 209 |

PRESSURE SCHEDULES

A LINEAR (5 PSIG MAX)

B CONSTANT 5 PSIG

C VENTED (AMB)

D LINEAR (10 PSIG MAX)

E CONSTANT (10 PSIG)

F LINEAR (7.5 PSIG MAX)

(1) INCLUDES 10% INSTALLATION FACTOR

vapor pressure would fall to 43% of normal. This corresponds to the partial pressure of oxygen at an altitude of 6600 m; loss of consciousness on sustained exposure would probably occur after a few minutes. Since agent would only be required for a few seconds, and most cabin pressurization systems produce an air change every 4 to 5 minutes, it appears that passenger compartment fires might be safely fought with NEA. If only crew members were involved, or if passenger oxygen were available, standard procedures would call for use of oxygen in the event of fire. In these cases, oxygen availability and use would remove any limits on the time of use of NEA.

## 4.4 INTEGRATED NEA INERTING/FIRE FIGHTING SYSTEMS (ORDER OF MAGNITUDE ANALYSIS)

To establish the plausibility of an integrated NEA inerting/fire fightng system, an order of magnitude analysis was accomplished. To be conservative, $NEA_9$ is assumed to be the best quality material available.

### 4.4.1 IGG Sizing

The IGG must be of a size to accommodate both inerting and fire fighting requirements. Airplanes of the size of a KC-135 require some 4 kg/minute of $NEA_9$ production to re-pressurize fuel tanks during descent, in the absence of a stored gas reservoir. Engine fire fighting for a CFM-56 engine (being incorporated into the KC-135 fleet) is estimated to require some 23 kg/minute of $NEA_9$ to achieve effective agent concentration. The only way this requirement could be accommodated would be to increase the size of the IGG by a factor of six. This weight penalty was judged unacceptable.

On the other hand, the YC-14 inerting system design (using stored NEA at 20.7 MPa) had a capacity of some 65 kg of inertant when fully charged. For its CF6-80 engines, an additional 8 kg of NEA would provide the same protection as the present two-shot Halon 1301 extinguishing system, without prejudice to the inerting system. At the worst, the entire IGG/inerting system weight would increase 15% to provide this fire fighting capability. In such a system, if an engine fire were to occur, its extinguishment would have priority over inerting, and 18 extinguishant applications become available.

It appears that an integrated inerting/fire fighting system would require a stored gas system to be feasible.

4.4.2 Airplane Ducting

Ducts would be required to move NEA to potential fire sites. These ducts would compete for space with hydraulic, bleed air and fuel lines, and with control and electrial cables. High pressure ducts might be required to solve the space problems.

4.4.3 Life Cycle Cost and Other Considerations

The cost of installing the IGG, storage systems, and controls, and cost of ducting would have to be traded against costs for alternative systems such as

- o NEA inerting/Halon fire extinguishant
- o $LN_2$ inerting/Halon fire extinguishant

Survivability/vulnerability improvements, airplane performance penalties (due to engine bleed and system weight), and logistic and maintainability considerations all need to be assessed. An order of magnitude analysis cannot differentiate between the many alternatives, and detailed trade studies are needed.

# 5.0 CONCLUSIONS AND RECOMMENDATIONS

## 5.1 CONCLUSIONS

The primary purpose of this task was to evaluate the effectiveness of nitrogen-enriched air (NEA) as a fire extinguishant. A review of typical aircraft inflight fire scenarios was conducted, and a small scale test apparatus was designed and built based on the outcome of this review. A review was also conducted of past and present efforts to use nitrogen and nitrogen air mixtures for fire suppression, and of state-of-the-art fire extinguishants ($LN_2$, Halon 1301, and $CO_2$), as well as NEA, to verify known concentration requirements in the small scale facility. Conclusions reached from the test program are:

o the most difficult fire to extinguish for agents other than Halon 1301 was the hot surface (with flameholder) used in conjunction with heated air; for Halon 1301, the most difficult situation was that of combat damage; the maximum agent requirements discovered for any fire scenario during these tests are shown in Table 26 at an air velocity of 1.5 m/s

Table 26 Maximum Agent Requirements.

| AGENT | SCENARIO | VOLUME % | RELATIVE WEIGHT |
|---|---|---|---|
| Halon 1301 | Combat Damage | 6 | 1 |
| $CO_2$ | Hot Surface | 34 | 2.9 |
| $LN_2$ | Hot Surface | 34 | 1.8 |
| $GN_2$ | Hot Surface | 58 | 2.7 |
| $NEA_9$ | Hot Surface | 72* | 3.5 |

* Calculated

- the concentration requirements determined for each agent were found to be consistent with known requirements used in fire suppression system design

- confidence was developed in the principle of oxygen dilution as a means of fire extinguishment, and in the analytical means developed for predicting agent concentrations required for extinguishment, in particular for the forced convection cases

- NEA effectiveness in terms of volume percent required for extinguishment can be accurately calculated from the known performance of gaseous nitrogen

- the concentration of inert gas required is not strongly dependent on the time of application of the agent; the same fire knock-down capacity was observed, whether a short burst (one second, for example) or a steady flow of agent was used, when the same average concentration was provided

- the order of magnitude difference between Halon 1301 and $NEA_9$ on a volume percent basis is reduced by a factor of three on a relative weight of agent basis

- on the basis of these studies, $NEA_9$ is a plausible extinguishing agent at concentrations of $\leq$ 72%, somewhat less than might be supposed from flammability limits alone; the difference arises from velocity effects in the forced convection case, and instability of fires in free convection cases

- the data obtained in the large scale, nacelle simulator (AENFTS) was of a preliminary nature, and is insufficient to provide a detailed comparison or verification of the results obtained in the small scale simulator

- the plausibility of an Integrated NEA Fuel Tank Inerting/Fire Suppression System was established assuming:
  - an NEA inerting system would be aboard
  - NEA is stored under high pressure

## 5.2 RECOMMENDATIONS

With the potential of nitrogen-enriched air as an aircraft fire extinguishant successfully demonstrated, the following recommendations were made:

- that the Task II and III studies be performed to design an NEA fire suppression system, integrate the NEA fire fighting and fuel tank inerting systems, and perform system trade-off studies; the transport airplane recommended for the study is the C-5A. It is a relatively modern airplane, has an installed $LN_2$ inerting system, and was familiar to the engineers who performed the study. This study has been performed, and the results are reported in Volume 1 of this document - see the Preface on page iv for further explanation)

- that further testing of NEA be done in the Aircraft Engine Nacelle Fire Test Simulator so that the small scale test data can be verified, and the contents of Section 3.3.4 re-evaluated as needed.

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## A1.0 LITERATURE SURVEY

The purpose of this literature survey was to review and evaluate literature related to the use of nitrogen and nitrogen-enriched air as fire extinguishants. Past and present efforts were to be examined to gain useful information about the fire extinguishant characteristics, limitations, advantages, and areas of utilization. References were selected primarily for their value in summarizing past work and in reporting technological advances in each subject area.

### A1.1 Inert Gases - Fire Suppressant Characteristics

Inert gases have been used for fire suppression purposes since World War II in capacities ranging from laboratory studies to full-scale system applications. Strictly speaking, inert gases are those which fall in the farthest right column of the periodic table of elements, Group 0. Shown here is the average composition of air, with the inert components denoted by an asterisk.

| COMPONENT | PER CENT BY VOLUME | COMPONENT | PER CENT BY VOLUME |
|---|---|---|---|
| Nitrogen | 78.03 | Neon* | 0.0012 |
| Oxygen | 20.99 | Helium* | 0.0005 |
| Argon* | 0.94 | Krypton* | 0.0001 |
| Carbon Dioxide | 0.035-0.04 | Ozone | 0.00006 |
| Hydrogen | 0.01 | Xenon* | 0.000009 |

However, in the context of combustion processes the term "inert" has a broader meaning in which it refers to the presence or addition of a gaseous substance which acts to prevent a potentially combustible environment from developing, or to suppress a combustion reaction by reduction of the proportion of oxygen in the ambient air. Thus nitrogen is termed an inert gas.

The usefulness of inert gases in fire suppression is based on the dilution of the oxygen present in air, 20.99% by volume, to some level at which combustion cannot occur. Determination of this level has been a point of study for the past 40 years, and is generally accepted to be between 9-12% by volume. Figure A-1 depicts the results of experimental programs conducted by various agencies to isolate the safe oxygen limit (Reference A-1) as a function of air temperature.

Comparison of the inert gases on the basis of their ability to control combustion by limitation of oxygen content indicates that

helium > > nitrogen > argon

in terms of effectiveness in identical situations, because the weight of helium required is far less than that required of the other gases (Reference A-2).

The term inerting has also come to be used in another context, in reference to the use of Halons (halogenated hydrocarbons) as fire suppression agents. Although the mechanism of fire control by Halons is quite different from that of inert gases, the similarity of application in aircraft systems has brought about this extension of the definition.

Since the introduction of Halon agents, studies have typically been oriented toward comparison of their effectiveness with that of inert gases, based on their relative abilities to prevent or extinguish hydrocarbon fires. Of concern when Halons are used, much more so than for inert gases, is the creation of potential harmful concentrations of toxic and/or corrosive decomposition products (HF and HBr). The highest concentrations of harmful decomposition products are thought to be produced from fires with high burning rates (Reference A-3).

The summary of data in Table A-1, taken from numerous references, illustrates the typically accepted ranking of extinguishants in order of increasing effectiveness. These values represent the minimum concentrations of agent required to prevent flame propagation through mixtures of hydrocarbon fuels and oxidants, for a single spark ignition source.

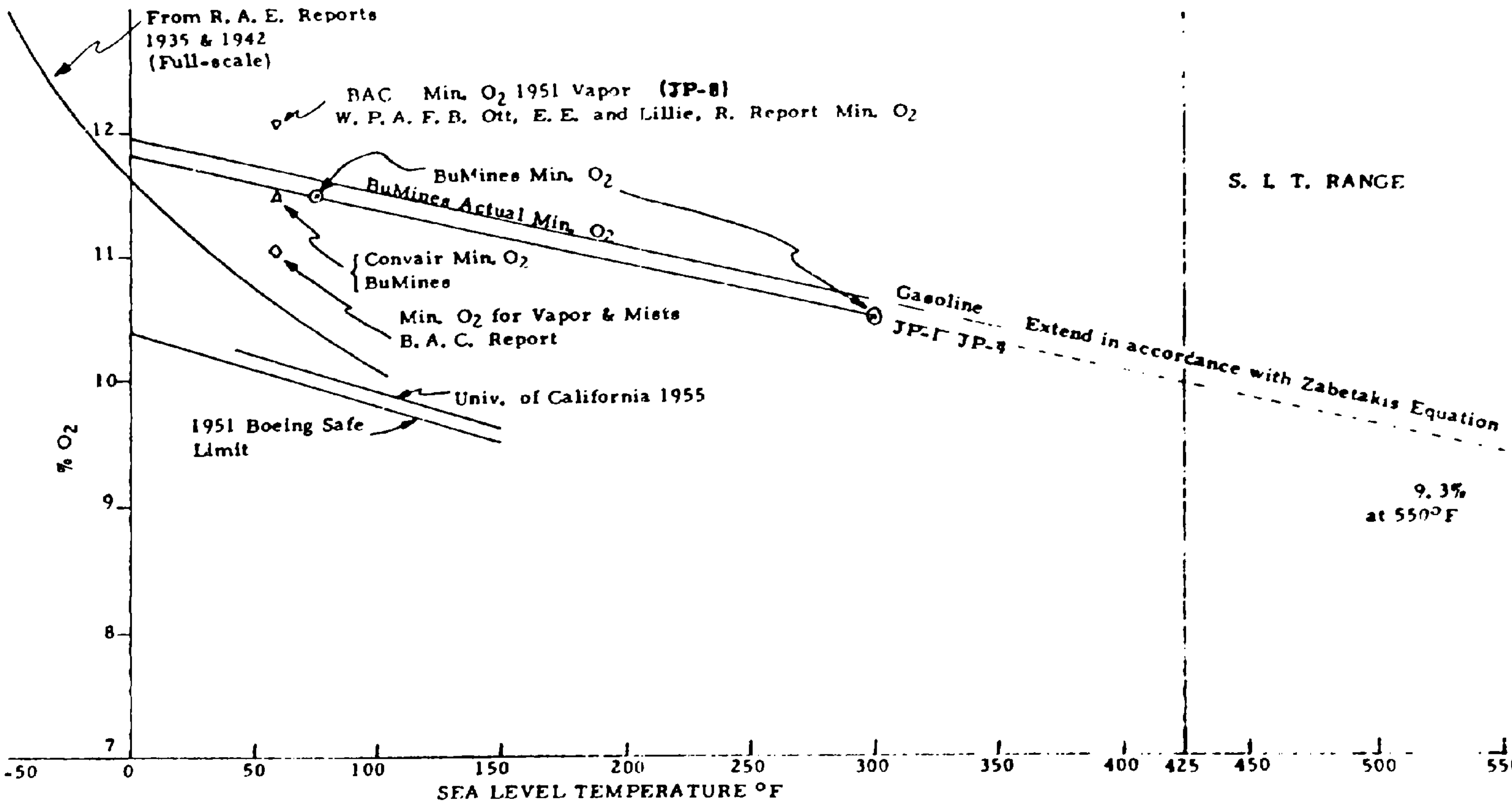



*Figure A-1 Composite Chart of Inerting Requirements*

Table A-1. Summary of Extinguishant Concentrations (by volume percent added) from Literature Survey. (References A-3, A-4, and A-5).

| | |
|---|---|
| Halon 1202 ($Br_2CF_2$) | 3.8% |
| Halon 1301 ($CF_3Br$) | 4.7% |
| Halon 1211 ($CF_2ClBr$) | 5.3% |
| Halon 1001 ($CH_3Br$) | 7.8% |
| Halon 1130 ($CFCl_3$) | 11% |
| Halon 1220 ($CF_2Cl_2$) | 12.3% |
| Halon 1120 ($CHFCl_2$) | 15.5% |
| Carbon Dioxide ($CO_2$) | 29% |
| Water Vapor, Engine Exhaust Gases | 36% |
| Gaseous Nitrogen ($GN_2$) | 42% |

A ten percent safety factor has been included in each of the Halon values, and it is recommended that 20% be added to $N_2$ and $CO_2$ if these values are to be used for design concentrations. Ignition source energy influences inerting requirements, which tend to be higher for more severe sources due to increases in temperature and heat flux throughout the combustible mixture. For example, as much as 10% Halon 1301 is required to extinguish a mixture ignited by incendiary devices, where 5% would normally be required (Reference A-4).

The primary zones of concern for fire suppression on an aircraft are the engine/nacelle, fuel tanks, and airplane compartments. The first zone is a dynamic environment and the second and third quasi-static, each requiring a different approach to fire control. Examination of particular fire hazards associated with each area requires that attention be given to airflow quantity and distribution, and to potential ignition sources.

A1.2 Fuel Tank Inerting

Fuel tanks represent a significant fire hazard on aircraft, and thus have stimulated the creation of protection devices - both passive and active types. Passive means of protection include fuel tank explosion suppression foams or bladder cell tank design, while active protection includes the concept of fuel tank inerting (replacement of all or part of the oxygen in air by a non-combustible gas).

While explosion suppression foam protection systems have had and will continue to have applications in many Air Force aircraft, the use of foam is impractical in some aircraft because of tank size (weight penalty or tank configuration- installation penalties) and high environmental temperatures. Inerting systems represent the most promising of the alternative protection systems (Reference A-6).

The B-57, SR-71 and B-70 all have used nitrogen inerting systems and experimental systems have been tried on an XB-70, a B-50, a B-36, and a B-52. Prototype inerting systems were installed and flight tested on the C-141 and C-135, as well as on an FAA DC-9. The C-5A transport fleet has had a full-time inerting system installed and operating successfully for several years (References A-6 and A-7).

Sources of ignition to which aircraft are potentially vulnerable include (Reference A-8):

- o lightning strikes, where ignition of the fuel-air mixture occurs directly as the result of a strike hitting an open vent or burning a hole through a tank wall, or indirectly by induced arcing in the fuel tanks
- o takeoff, flight, and landing mishaps, in which fire resulting from a mishap causes ignition and explosion of fuel tanks, greatly magnifying the severity of the mishap consequences;
- o military battle damage

The concept of fuel tank inerting was first investigated in the mid-1950's when it was found during the development of the XB-70 (a Mach 3 vehicle) that aerodynamic heating would raise the temperature of the fuel tank walls well above the fuel vapor ignition point. The function of the inerting system, which employed stored liquid nitrogen, included dilution of the initial oxygen present in the fuel tank ullage and also that evolved from the fuel inflight, by pressurization of the vapor space with gaseous nitrogen (Reference A-9). The Parker-Hannifin Corporation of Irvine, California developed the XB-70 system, and in 1968, contracted to develop inerting systems for the C-141 and C-135. Following successful flight testing of the C-141 system, the accidental loss of two C-5A aircraft due to fire and explosion prompted the USAF to retrofit the C-5A fleet with extensive fire fighting capability, including a fuel tank inerting system (References A-6 and A-7).

Major design requirements met by the C-5A inerting system are that (Reference A-7),

- the $O_2$ concentration in the fuel tank ullage and vents must be maintained below a nominal 4% except during climb when a maximum of 9% is allowable
- temperatures and pressures must be within aircraft design limits under all conditions, including failure modes
- $LN_2$ service capability must be 76 kilograms per minute or greater
- enough $LN_2$ must be stored for two maximum range, maximum altitude flights, and for a 48 hour ground reserve (a 136 kg reserve was also included for fire fighting)
- it must incorporate provisions to insure maximum safety to the aircraft and personnel during all phases of flight and ground operation

Parker-Hannifin was selected to perform the C-5A inerting system retrofit subsequent to the FAA flight worthiness certification of their DC-9 $LN_2$ fuel tank inerting system. Extensive flight testing of the DC-9 installation showed that the inerting system (Reference A-10),

- maintained a mixture in the fuel tank vapor space and vent system having a volumetric $O_2$ concentration less than 8 percent under all normal and emergency flight conditions, and did so without causing excessive pressure differentials
- could maintain positive tank pressure under the most demanding descent conditions

A total of 122.5 kg of $LN_2$ was stored on the DC-9 for inerting purposes, and the nitrogen consumption ranged from 8 to 11 kg per hour (Reference A-11).

In addition to repressurization of the ullage space with nitrogen, a second factor must be considered in rendering a fuel tank inert. Fuel dissolves an amount of air, depending on the total pressure, and as the aircraft gains altitude and the pressure drops, some of the dissolved gases will be evolved. The solubility coefficients are such that the gases in JP-4 fuel contain 35% oxygen, and when these gases are evolved, oxygen enrichment of the vapor space occurs. In an un-inerted fuel tank the resultant $O_2$ concentration can approach 35% (Reference A-12).

Fuel must therefore be "scrubbed" to reduce the concentration of oxygen in the evolving gases by nitrogen dilution, and encourage the evolution of dissolved gases to prevent supersaturation of the fuel. Two methods of fuel scrubbing, climb scrubbing and aspiscrubbing, have been developed and are currently in use on the C-5A transport (Reference A-13). In the older climb scrub system, nitrogen is introduced to the fuel during climb through nozzles and bubbles through the liquid, reducing the amount of oxygen dissolved in the fuel. In the newer aspiscrub system, nitrogen and fuel are fed into an aspirator, in which dissolved oxygen is removed from the fuel. With either scrub system, the fuel tank ullage will remain inert during climb.

### A1.3 Compartment Fire Suppression

The previous section on fuel tank inerting was included primarily because the bulk of nitrogen inerting technology has been developed for fuel tank inerting applications. Once full-scale fuel tank inerting systems were proved to be feasible, interest was stimulated in extension of the inert gas fire suppression concept to other zones of the aircraft susceptible to fire. This extension would increase the overall efficiency of the inerting system, but provide a level of fire protection not previously available. Within the last 10 years a number of studies have been conducted to determine the practicality of using nitrogen as an aircraft compartment fire suppressant, when applied in a manner similar to the currently used extinguishants. Typically, $LN_2$ is tested and compared to HALON effectiveness on the basis of volume percent of extinguishant needed to suppress a fire.

In 1971 two studies were conducted at NAFEC (National Aviation Facilities Experimental Center) using $LN_2$. The first was an extensive test program aimed at determining the feasibility of using $LN_2$ as a turbo jet engine fire extinguishant. Nacelle volume and airflow were varied to enable study of $LN_2$ effectiveness as a function of the nacelle environmental factors. Additional work was done to investigate the extinguishant quantities required, behavior and properties, and the effect of extinguishant application on the engine components and structure. Overall, the use of $LN_2$ was shown to be feasible for engine fire suppression, with little difference in quantity required when airflow was increased by creating artificial structure damage. The main advantage of using $LN_2$ over conventional Halon systems was found to be the relatively long application duration - in the time during which $LN_2$ suppresses a fire, cooling of re-ignition sources reduces the probability of re-ignition (Reference A-14).

The second study was performed to investigate $LN_2$ effectiveness for use in controlling cargo bay fires, in comparison to Halon 1301. Variables were the size of the cargo load and the ventilation airflow. Results showed that very large quantities of gaseous nitrogen (75% by volume), were required to suppress the same fire that could be handled by a 3% by volume concentration on Halon 1301. Again, however, $LN_2$ was better than Halon in preventing re-ignition (Reference A-15).

The following year, work was conducted by the Army to survey helicopter fires and extinguishing methods. In addition, design criteria were developed, and fire simulation done in model engine, oil cooler, and electronics compartments to test extinguishants (Reference A-16).

Another study was a detailed review of extinguishing system requirements on advanced aircraft. The F-111 was used as the baseline aircraft, but information was also presented for a number of commercial and military aircraft on the engine nacelle, and other compartments; the environments encountered in each zone, and an overview of the fire suppression systems currently in use were described (Reference A-17).

### A1.4 Inert Gas Generation

Onboard generation of inert gas from air has been investigated in the hope that the weight and logistics penalties associated with liquid nitrogen could be reduced. Various means exist by which the oxygen in air can be reduced, and the remaining gas can be used for fire suppression in a similar fashion to liquid nitrogen.

Many schemes for generating inerting quality nitrogen on-board aircraft have been investigated. These include (References A-12 and A-18):

- separation of nitrogen and oxygen in air by selective diffusion using a permeable membrane
- physical adsorption of oxygen from air using molecular sieve materials
- catalytic combustion of $O_2$ from air using aircraft fuel
- chemical absorption of $O_2$ from air
- air rectification (liquification and separation)

The first two types of systems listed above emerged as the most feasible, and will be discussed in more detail. Catalytic combustion of low temperature jet fuel and conditioned bleed air in a 700C reactor serves to remove the oxygen from the bleed air, yielding combustion products rich in inert gas and suitable for use in fuel tanks. Disadvantages are that the inert gas must be further conditioned -- cooled and decontaminated -- prior to use, and that the presence of the reactor itself presents an additional ignition hazard. Chemical absorption is accomplished by removing oxygen from the air by a metal chelate, fluomine. The basic system consists of two sorbent-beds; one absorbs oxygen from the air stream directed into the fuel tank ullage, and the other simultaneously desorbs oxygen overboard. When the sorbent beds become fully loaded (or depleted) of oxygen, the air streams are reversed. The desorption process takes place at a high temperature, which is known to cause degradation of the sorbent material. Also, thermal cycling is required to complete the transition between the two processes, which has a questionable impact on the life of the system. Complex valving, the number of rotating turbines, and complex functional controls result in a low reliability system compared to the liquid nitrogen storage system. Physical adsorption processes, such as molecular sieve, are less temperature sensitive and could be used in place of chemical sorbents in a similar inert gas generating system.

Serious efforts to determine the feasibility of inert gas generation for the fuel tank inerting application began as recently as 1972. The AiResearch Manufacturing and General Electric Companies conducted roughly concurrent programs which involved feasibility studies and laboratory demonstrations of potential generating systems.

AiResearch used the DC-10 as a representative transport aircraft, defined typical system requirements, and concluded that both the catalytic combustion and permeable membrane systems were viable candidates. Both systems were demonstrated capable of generating a product containing less than 9% oxygen. In addition, preliminary design indicated that an IGG system would weight a fraction of a liquid nitrogen system designed to DC-10 fuel tank inerting requirements. Although the permeable membrane system was determined to be slightly heavier than the catalytic reactor, the subsystem offers the potential for reliable operation without the addition of new ignition sources on the generation of potentially harmful by-products which could collect in the fuel tanks. Weight of the permeable membrane system was estimated at 145 kg. Consideration of the permeable membrane system represented an adoption of new technology. The material selected for the laboratory test program was polymethyl pentene polymer, which was formed into tubes, and the tubes encased in a cylinder through which air could pass and undergo the nitrogen-oxygen separation process (Reference A-18).

The General Electric study also indicated the suitability for aircraft fuel tank application of a permeable membrane inert gas generating system (using engine bleed air) in terms of the quality and quantity of product, system size, and weight. The configuration of the IGG used for testing was somewhat different than the one developed by AiResearch but again, the DC-10 was used as the representative aircraft. Sheets consisting of three thicknesses of permeable membrane material, bonded to a backing for support, were bonded to each side of a thin aluminum plate. The plates were stacked ten per 2.54 cm. A rectangular module was constructed for testing, however, developmental work indicated that a circular one would be structurally superior. A system sized for high-speed descent as the design condition was estimated to weigh 159 kg; the gas generator module was 152 cm long, 56 cm in diameter and had hemispherical ends (Reference A-19).

Following a demonstration that inert gas generation was a feasible alternative to using a stored liquid nitrogen fuel tank inerting system, AiResearch conducted an extensive program beginning in 1975 to design, fabricate, and test a fuel scale breadboard permeable membrane IGG. The DC-9 was used as the design baseline. Based on the data and experience gained from the development program, a preliminary system design was completed (Reference A-20).

The inert gas generator design and fabrication process yielded a mechanism which, when fed with conditioned air, produced nitrogen-enriched (or oxygen-depleted) air of 9% or less oxygen content. The membrane material was formed into tubes of a diameter on the order of 50 microns, the tubes packed into a circular bundle (shown in Figure A-2), and the bundle encased in a 30 cm diameter module. Approximately 10 million tubes would be required for a module of the size shown. Generation of the nitrogen-enriched air (NEA) was accomplished by internal pressurization of the polymer tubes with air (Figure A-3). The air underwent a selective diffusion process; oxygen diffused across the membrane and was exhausted from the module, while nitrogen passed through the tube length and was collected. The efficiency of the oxygen removal process was dependent upon the inert gas flow rate demand. If low NEA flow rates were practial, a product stream containing as little as 2 or 3% oxygen could be obtained (Table A-2).

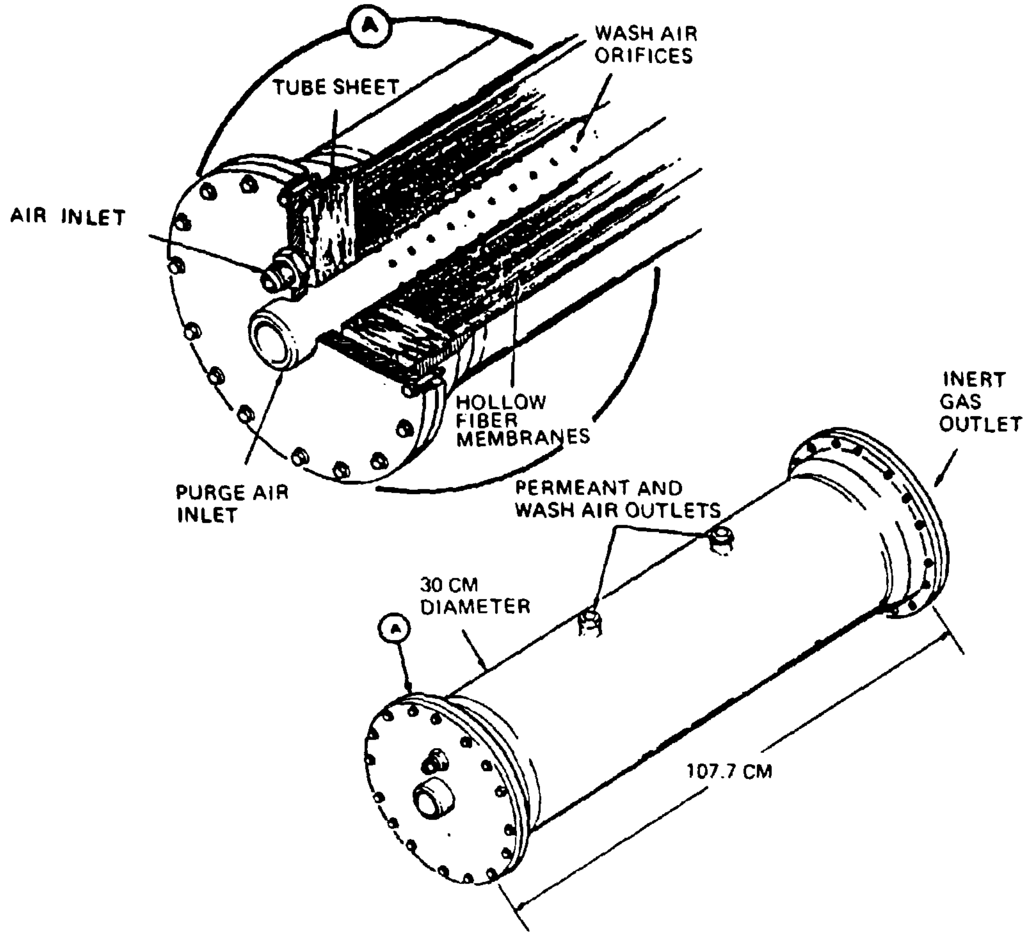



*Figure A - 2 Breadboard PM - IGG Module Design*

Table A-2. IGG Performance

| | INERT GAS FLOW RATE (kg/min) | RESULTANT OXYGEN CONCENTRATION |
|---|---|---|
| Design Point Flowrate | 1.06 | 9% |
| Reduced Flowrate | 0.45 | 5.0 - 5.4% |
| Cruise Condition Flowrate | 0.11 | 5% |

A block diagram of the fuel tank inerting system design using an IGG as the source of inertant is shown in Figure A-4. System weight was estimated at 149 kg, including a 30% uncertainty factor. An equation was provided from which a first order approximation can be made of fuel tank inerting system weight, for aircraft other than the baseline DC-9 used in this study. It appears as:

SYSTEM WEIGHT (kg) = 34.24 X + 42.70

where X = inert gas flow (lb/min)

Expressions are also given from which to estimate the required system supply airflows:

BLEED AIR = 1.80 X

RAM AIR = 6.85 X

ECS PRIMARY AIR = 4.30 X

The Clifton Corporation has also developed an air separation device which operates on the principle of physical adsorption, called a molecular sieve. The sieve material retains a large portion of the oxygen in the input air while the nitrogen constituent of the air passes through the sieve and becomes the oxygen-depleted output gas (Reference A-21).

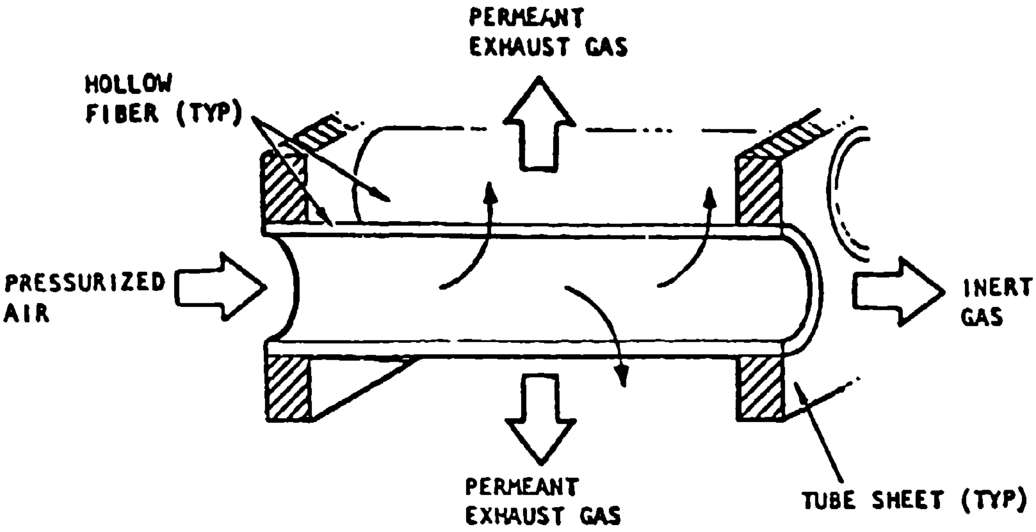



*Figure A-3 Internal Pressurization of IGG Hollow Fiber*

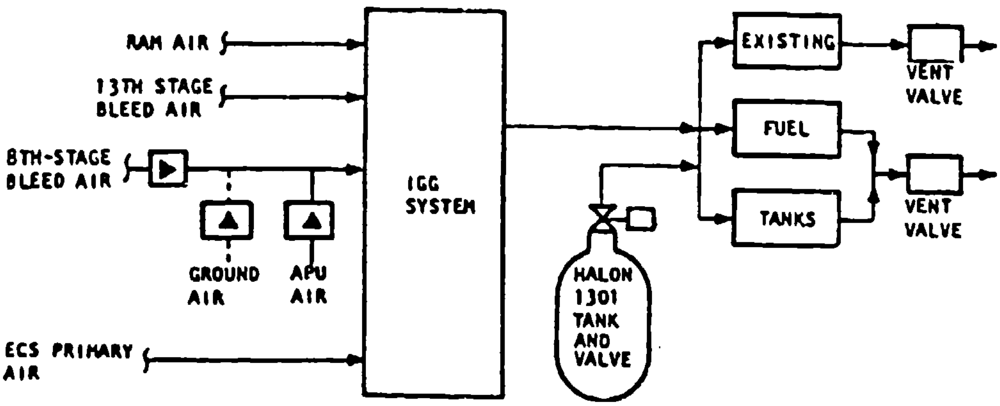



*Figure A-4. Inerting System Block Diagram*

A two-part cycle is used (Figure A-5); while one "bed" of the molecular sieve module is being used to adsorb oxygen, the other is being regenerated by discharging (desorbing) waste gas to the atmosphere. Periodically, the function of the beds is reversed. The molecular sieve can produce gas with less than 1% oxygen content by volume, although this purity is not generally required for fuel tank inerting purposes. A fuel tank inerting system using a molecular sieve inert gas generator would be of the same design as the system shown in Figure A-4. Both the permeable membrane and the molecular sieve generator require temperature and pressure conditioning of the air supplied to them to insure efficient operation; the conditioning equipment and generator combined are referred to as the inert gas generating system.

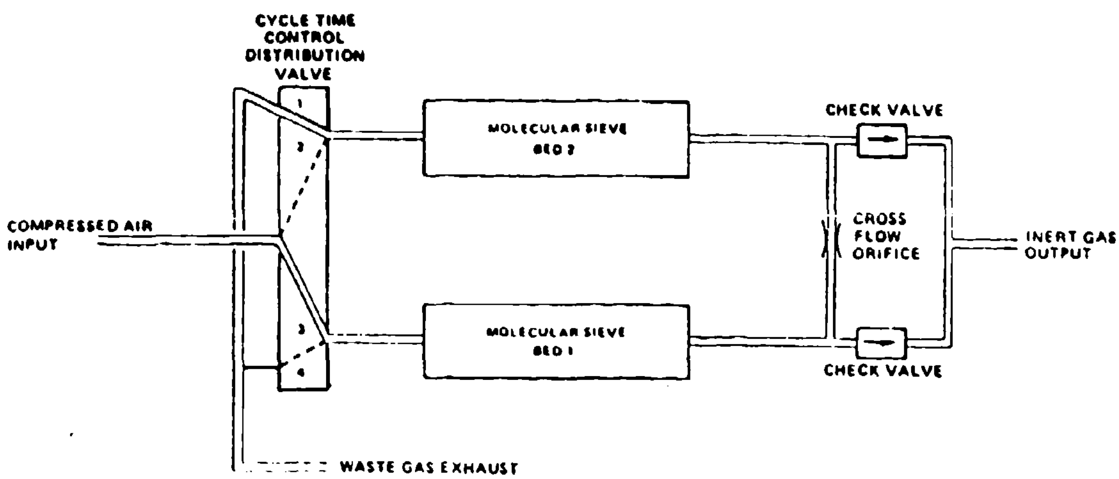



*Figure A-5. Molecular Sieve Air Separation Module (ASM)*

# A2.0 FIRE SCENARIO DEVELOPMENT

The basis for the design of the small scale test apparatus, to be employed in Task I of this contractual effort, was a comprehensive analysis of "typical aircraft normal and combat-related, inflight fire scenarios." This and the following section (A2.2) document the results of the scenario reviews.

## A2.1 Non-Combat Fire and Explosion Hazards

This (non-combat) study was pursued in the context of the goals of this contract, and not as an all-inclusive analysis. In particular, the potential application of nitrogen-enriched air as a fire suppressant in zones other than fuel tanks was investigated. It was assumed that the fuel tank fire hazard is sufficiently well-documented and fuel tank protection requirements clearly defined under separate studies so as not to need additional attention.

The aircraft zones which were candidates for fire protection were selected on the basis of: cause and frequency of fire occurrence; types of fires encountered; and environments.

### A2.1.1 Hazard Definition

Throughout the numerous studies reviewed for the purpose of developing aircraft fire scenarios, the trend has been to identify fire hazards in terms of general cause, severity, and the human factors involved. A noticeable weakness occurs in most studies in the lack of information presented on the direct cause and nature of aircraft fires. This usually occurs because such data is either unavailable or not determinable. However, this is precisely the type of information that is needed if efforts to develop effective fire protection systems are to be pursued in the most meaningful manner.

To remedy this lack of data, an analysis of mishap data was conducted using information obtained from the Air Force Safety Center with the expectation that this data would reveal more detail than could be obtained from the other analyses. ("Mishap" is a collective term referring to incidents, minor accidents, and major accidents and excludes combat incidents.) The mishaps considered were only those in which fire was a direct factor in the occurrence of the mishap. Data relating the number of fire-related mishaps to the total number of mishaps will be discussed in the next section.

In general, two things emerged from this effort; first, the definition of a sequence of events in which fire-related mishaps typically occur, and second, isolation of a series of common factors which, if identified specifically, define in detail the factors affecting a given fire environment.

The sequence of events leading to a fire related mishap appears in Figure A-6. The first event in the sequence is marked by the occurrence of a component or system failure, and can occur either in an actual equipment failure mode or be induced by some external cause.

The second event in the sequence, following an equipment failure, is the development of an unsafe condition - unsafe in the sense that normal operation of an aircraft component or system has been interrupted, thus creating a potential (or actual) fire hazard. The length of time between a failure and the resultant developments is situation dependent, and is an important factor to consider in the design of fire protection features. This "interaction" time can be very short, as in the situation where a cracked line or fitting allows fuel to spray on a hot engine surface, or very long, as when defective wiring or electrical components are allowed to smolder for some time before a fire develops and is detected. Listed in the figure are examples of combustible materials and ignition sources commonly encountered in the mishap reports. In each mishap the combustible and ignition source combine to impair the functioning of the aircraft, to a degree dependent on the local environmental conditions.

Once combustibles and ignition sources begin to interact, local environmental conditions determine whether or not a fire be initiated, the degree of the fire, and how long it may be sustained. A significant number of the mishaps reviewed were cases in which a potential fire condition existed, but a fire did not occur; these are referred to as "overheat" conditions.

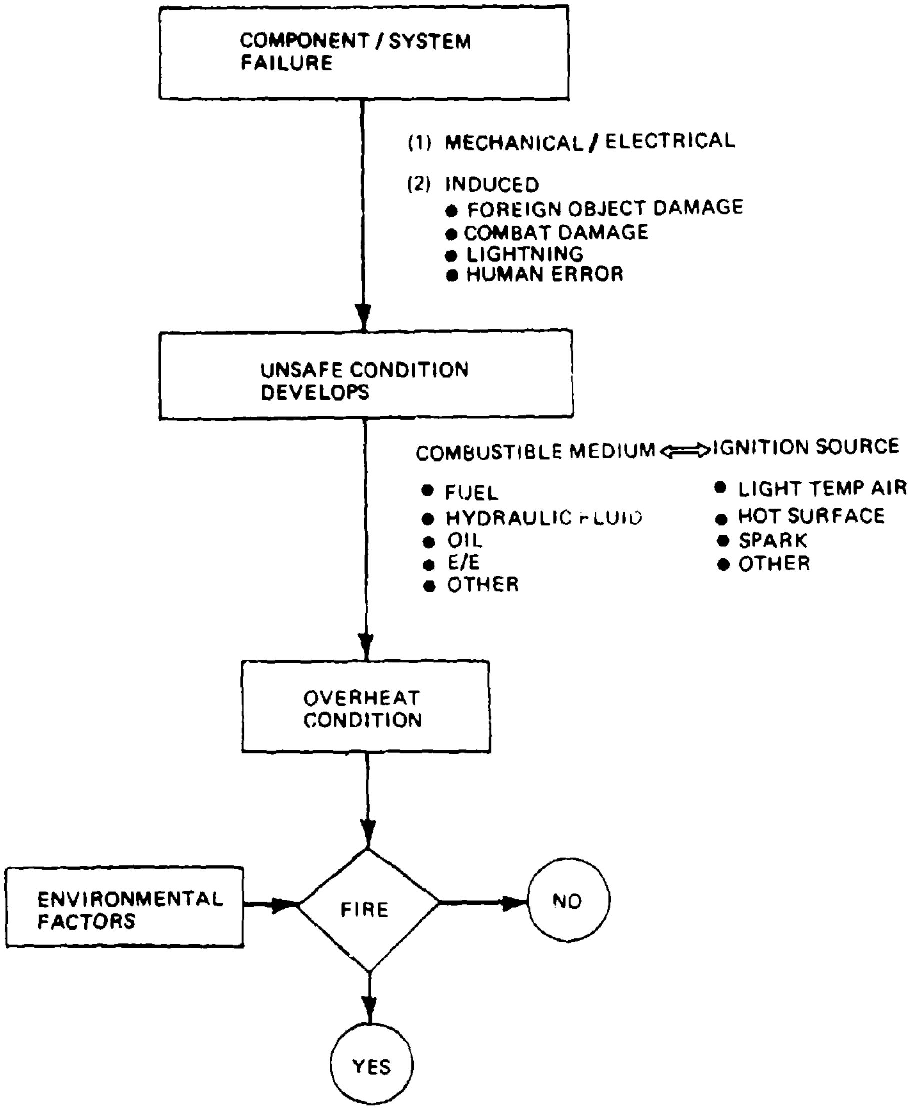



*Figure A-6. Mishap Sequence Of Events*

Finally, if detailed information can be obtained on each of the items listed

- o component/system involved
- o combustible and ignition source involved
- o environmental factors
- o extent of the resulting overheat/fire condition

then sufficient data is available from which to identify the most relevant approach to development of a fire suppressant technique.

A2.1.2 Past Studies fo Non-Combat Mishaps

A thorough investigation of the fire protection problem as it is related to mishap experience requires that a broad range of aircraft types be studied. Sources of information included in this review are listed in Table A-3:

Table A-3. Scenario Review Data Sources.
(Reference A-22 through A-25)

| SOURCE | ACCIDENTS MAJOR | ACCIDENTS MINOR | INCIDENTS | PERIOD COVERED | FIELD OF STUDY |
|---|---|---|---|---|---|
| Commercial | X | X | | 1959-68 | Significance of Fire in Commercial Jet |
| Navy | X | X | | 1965-75 | Hydraulic Fluid Induced Fires |
| Air Force | X | X | X | 1965-79 | Hydraulic Fluid Fires |
| NATO | X | X | X | 1964-76 | Civil and Military Fire Related Mishaps |

A study of free-world commercial jet aircraft accidents (Reference A-22) occurring between 1959 and 1968 revealed that, out of 340 total accidents, 116 involved fire (Figure A-7). Fire was the primary cause of damage or loss of the aircraft in 33 of the 116 fire-related accidents (Figure A-8); and in 19 of the accidents, fire was an initial event rather than a post-crash occurrence (Figure A-9).

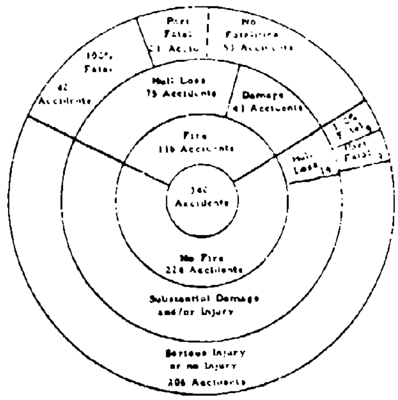



*Figure A - 7. Fire Incidence*

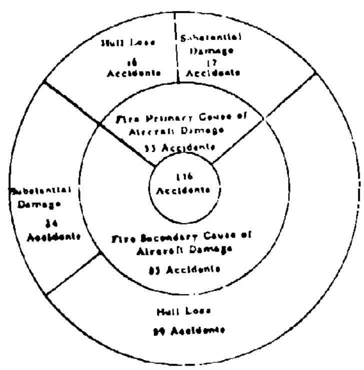



*Figure A - 8. Airplane Fire Damage*

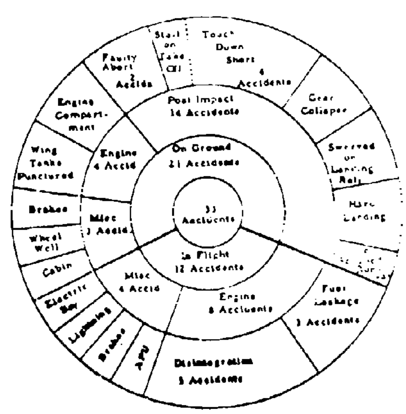



*Figure A - 9. Fire Primary Cause of Accidents*

Of these 19 accidents,

- o 13 were due to engine disintegration, fuel leakage, or APU fire
- o 3 were due to brake and wheel well fires
- o one each were due to cabin and electrical bay fires
- o one was the result of a lightning strike

In another study which included both civil and military aircraft operated in most of the NATO countries, data on 1,141 fire-related mishaps were reviewed (Reference A-25). The aircraft types included civil and military transports and helicopters, as well as military trainers and tactical aircraft. The mishaps included 212 impact survivable post-crash fire accidents, 38 fatal inflight accidents and 495 non-fatal inflight incidents, and 396 accidents and incidents on the ground (at airports). A ranking of the severity of the fire threats was developed, both in terms of potential for injury and probability of occurrence. The ranking is shown in order of decreasing severity; types of aircraft damage or the operational modes are included as appropriate to each hazard.

Table A-4 Fire Hazard Ranking

1. Post-crash massive fuel spill fires.
   A. Wing/partial wing separation
   B. Major fuel tank damage

2. Fuel tank explosions.
   A. Inflight
   B. Post-crash

3. Post-crash moderate fuel spill fires.
   A. Minor fuel tank damage
   B. Fuel line damage

4. Cabin material fires.
   A. Inflight
   B. Post-crash

5. Propulsion system fires.
   A. Non-contained titanium fires
   B. Non-contained rotor fragment initiated fires

6. Landing gear system fires.
   A. Maintenance
   B. Inflight

7. Fuel tank explosions.
   A. Maintenance
   B. Refueling

Two studies were obtained from the Navy and from the Air Force which provided data on hydraulic fluid fires in military aircraft (References A-23 and A-24). For the eleven year period between 1965 and 1975, 101 accidents and incidents occurred in Navy aircraft and 126 in Air Force aircraft which could be attributed directly to hydraulic fluid ignition.

Table A-5. Hydraulic Fluid Fire Mishaps 1965-1975

| | Navy | Air Force |
|---|---|---|
| Major Accidents | 29 | 46 |
| Minor Accidents | 26 | 8 |
| Incidents | 46 | 72 |
| Total | 101 | 126 |

Fighters, bombers, and attack aircraft were the most susceptible to hydraulic fluid fires, accounting for 60% of the total number of accidents and incidents; more than 30% of the totals were engine-related, and most took place on the ground rather than in-flight. Most of the fluid release resulted from high pressure line failures; other important causes were seal and fitting failures. Two-thirds of the hydraulic fluid fires were ignited by a hot surface ignition source.

A2.1.3 Analysis of Air Force Mishaps

Aircraft types used in the USAF mishap review included the following bomber, fighter, and transport aircraft: B-52, FB-111, F-4, F-15, F-111, C-135, C-130, C-141, and C-5. Incidents during the year 1978 were reviewed, and major and minor accidents occurring from 1975 through 1978 provided useful statistics. These data were obtained from detailed mishaps descriptions as supplied by the Air Force Safety Center and from the annually published USAF Accident Bulletins (References A-26 and A-27). Table A-6 indicates the percentage of mishaps in which fire was involved.

Table A-6. Percentage of Mishaps Involving Fire.

| | 1975-1978 | | 1978 |
|---|---|---|---|
| | Major Accidents | Minor Accidents | Incidents |
| Involving Fire | 143 (91.67%) | 74 (13.33%) | 180 (9.52%) |
| Total Mishaps | 156 | 555 | 1890 |

The percentages indicate the more severe the mishap, the higher the probability that fire was involved. Table A-7 further categorizes the 397 accidents and incidents reviewed.

Table A-7. Tabulation of Mishaps by Fire Category

| CATEGORY | 1975-1978 MAJOR ACCIDENTS | 1975-1978 MINOR ACCIDENTS | 1978 INCIDENTS |
|---|---|---|---|
| 1. Fire occurred before accident/incident | 40 (25.64%) | 42 (7.57%) | 57 (3.02%) |
| 2. Fire occurred after accident/incident* | 100 (64.10%) | 19 (3.42%) | 1 (0.05%) |
| 3. No fire occurred | 13 (8.33%) | 481 (86.67%) | 1710 (90.48%) |
| 4. No fire but overheat condition existed | 3 (1.92%) | 13 (2.34%) | 122 (6.46%) |
| TOTAL | 156 | 555 | 1890 |

* including crash fires

Certain category 2 mishaps are relevant to fire protection studies (foreign object damage, or explosion of gases accumulated in engine compartments); however, post crash fires were not within the scope of this study.

Categories 1 and 4 are therefore of primary interest. 138 of the 397 mishaps reviewed fall into Category 1, in which fire occurs and is the major factor in the outcome of the mishap. An equal number, 138, fall into Class 4 in which no fire occurred although the conditions required for combustion existed.

The tendency toward fire-related mishaps is identified by aircraft type in Table A-8.

Table A-8. Tabulation of Fire-Related Mishaps by Aircraft Type.

| | 1975-1978 | | | | 1978 | |
|---|---|---|---|---|---|---|
| | MAJOR ACCIDENTS (CLASS A) | | MINOR ACCIDENTS (CLASS B) | | INCIDENTS (CLASS C) | |
| | TOTAL | FIRE-RELATED | TOTAL | FIRE-RELATED | TOTAL | FIRE-RELATED |
| B-52 | 3 | 3(100%) | 77 | 26(33.77%) | 168 | 19(11.31%) |
| FB-111 | 6 | 6(100%) | 14 | 1(7.14%) | 31 | 2(6.45%) |
| C-5A | 3 | 3(100%) | 8 | 0(0%) | 47 | 6(12.77%) |
| C-130 | 11 | 9(81.82%) | 51 | 3(5.88%) | 182 | 22(12.09%) |
| C-135 | 5 | 5(100%) | 68 | 10(14.71%) | 109 | 16(14.68%) |
| C-141 | 10 | 7(70%) | 10 | 2(20%) | 104 | 3(2.88%) |
| F-4 | 78 | 72(92.31%) | 246 | 21(8.54%) | 759 | 61(8.04%) |
| F-15 | 15 | 14(93.33%) | 15 | 6(40%) | 356 | 41(11.52%) |
| F-111 | 25 | 24(96%) | 36 | 5(13.89%) | 134 | 10(7.46%) |

The first step in the development of typical fire scenarios was to identify the locations of fire occurrence. These are the engine nacelle, dry bays, wheel wells, electrical/electronics bays, and cargo areas. Table A-9 contains, a breakdown by fire location for the 397 mishaps reviewed.

Table A-9. Tabulation of Fire-Related Mishaps by Aircraft Compartment.

| COMPARTMENT | FIRE CLASS | 1975-1978 MAJOR ACCIDENTS | 1975-1978 MINOR ACCIDENTS | 1978 INCIDENTS |
|---|---|---|---|---|
| Engine Nacelle | 1 | 24 | 38 | 39 |
| | 2 | 4 | 10 | 0 |
| | 4 | 1 | 11 | 57 |
| Dry Bay | 1 | 2 | 0 | 2 |
| | 2 | 0 | 0 | 0 |
| | 4 | 1 | 1 | 9 |
| Wheel Well | 1 | 2 | 2 | 4 |
| | 2 | 4 | 2 | 0 |
| | 4 | 0 | 0 | 5 |
| Electrical/ Electronic Bay | 1 | 3 | 1 | 6 |
| | 2 | 0 | 0 | 0 |
| | 4 | 0 | 1 | 8 |
| Cargo Area | 1 | 0 | 0 | 1 |
| | 2 | 0 | 0 | 0 |
| | 4 | 0 | 0 | 0 |
| All Others | 1 | 9 | 1 | 5 (4) |
| | 2 | 92 (2) | 7 | 1 |
| | 4 | 1 | 0 | 43 (3,4) |
| | TOTAL | 143 | 74 | 180 |

(2) All others, major accidents, Category 2: in 87 mishaps aircraft were destroyed by ground impact and 5 were by mid-air collisions.

(3) All others, incidents, Category 4: 33 mishaps involving lighting strikes.

(4) All others, incidents: 2 mishaps in Category 1, and 4 in Category 4 involved failure of windshield anti-icing wiring.

A2.1.3.1 Engine Nacelle

Table A-9 shows that 29 major accidents were engine fire related, as were 59 minor accidents and 98 incidents. These represent 47% of the 397 mishaps reviewed, therefore, identification of the failure which caused the engine fires is an important step in the fire scenario development (Table A-10).

Table A-10. Tabulation of Engine-Related Mishaps by Cause

| CAUSE | MAJOR | MINOR | INCIDENT |
|---|---|---|---|
| Bleed Duct | 2 | 7 | 19 |
| Turbine | 4 | 5 | 16 |
| Fuel Leak (lines, fittings, etc). | 4 | 9 | 9 |
| Engine Stagnation | 0 | 0 | 16 |
| Starter | 1 | 5 | 9 |
| Compressor | 6 | 4 | 3 |
| Combustor | 2 | 5 | 3 |
| Afterburner | 1 | 2 | 4 |
| Fuel Pump | 1 | 2 | 6 |
| Foreign Object Damage | 0 | 6 | 0 |
| Unknown | 2 | 2 | 1 |
| Valve | 1 | 0 | 2 |
| Bearing | 1 | 0 | 1 |
| Propeller | 1 | 0 | 1 |
| Gear Box | 0 | 1 | 0 |
| Hydraulic Pump | 0 | 1 | 0 |
| Hydraulic Leak (lines, etc.) | 0 | 1 | 0 |
| Generator | 0 | 0 | 1 |

The most frequently occurring mishaps were of Category 4 type, those relating to failure of bleed air ducts. Although in no case did fire result directly, substantial heat damage from escaping bleed air usually occurred. In a typical accident which occurred on an F-111D, a weld failed on a sixteenth stage bleed air duct venting bleed air directly against the heat shield and activating the fire detection system. Heat shields and bonded panels in the vicinity were buckled and deformed by the heat. In an incident on a B-52G, a 16th stage bleed air duct also failed; the engine cowling, fuel lines and an oil tank were damaged by shrapnel from the failed line; the engine was shut down as a precaution, and no fire resulted.

Next most frequent were turbine-related mishaps. Turbine failures usually result in extensive damage to the aircraft, often including fire. In a representative F-15A accident, a second stage turbine blade failed, followed by disintegration of the turbine. Debris-severed lines released fluids which created a severe fuel/oil fire and resulted in damage to the airframe and flight controls. Fire extinguishing agent was discharged, but airflow patterns in the damaged engine bay diverted the agent and the fire persisted until the flammable fluids were consumed.

Fuel leaks also result in frequent fire and explosion mishaps. In a C-130B accident, a leak developed in a fuel line from corrosion on the surface of the line. Substantial quantities of fuel leaked from the line and pooled in the engine hot section around a drain hole that had become obstructed. When the leak was detected, the engine was shut down. Disruption of the engine airflow (from the shut down) caused fuel to contact hot engine surfaces and ignite. The fire extinguishers were discharged, but in this case did not extinguish the fire because the fire was located aft of the fire wall. In another instance involving an F-4C, a fuel filter developed a leak, and leaking fuel was ignited when it came into contact with the afterburner. Engine shutdown alone was sufficient to extinguish the fire.

Starter failures are also a fairly common cause of fire. In an F-4E accident, a bearing failure resulted in disintegration of the starter turbine. Segments of the turbine severed main fuel, oil, and hydraulic lines, and the liquids were ignited by hot gases which were also escaping from damaged lines. Major fire damage was sustained.

Most of the other mishap reports were similar in nature to those described above; fuel, oil, and hydraulic fluid are usually the combustibles involved, either individually or in combination, sometimes aggravated by escaping bleed air. Several instances were noted where extinguishing agent was ineffective due to air flow pattern interference.

A2.1.3.2 Dry Bays

Though uncommon in comparison to the incidence of engine fires, fires in the pylon and wing dry bay areas are often related to engine nacelle fires due to the close proximity of fuel lines, hydraulic lines, and bleed air ducting routed from the engine.

In a mishap occurring on a C-5A transport, unsupported generator cables in the left inboard pylon came into contact with a hydraulic line. Chafing between the cable and line over an extended period of time resulted in wearing of the cable's insulation and electrical arcing. Arcing eventually eroded the steel hydraulic line to a degree that internal pressure blew a hole in the line during flight, and subsequently, the arcing ignited the escaping hydraulic fluid. Pilots observed the bleed duct hot warning light, the engine overheat light, and the fire suppression system warning light, prompting them to pull the fire control handle, and then to apply three 45 second shots of $LN_2$. By this time, the main fuel inlet line in the pylon had ruptured due to the extremely hot blow-torch type flame concentrated against it, thus adding JP-4 to the fire. Although the fire suppression system failed to contain the fire, the aircraft landed safely with major damage sustained by the inboard wing and pylon. On investigation, it was determined that an insufficient quantity of $LN_2$ was available due to under-sized nitrogen discharge lines, and that the discharge lines in the vicinity of the fire had melted because they were not made of fire-resistant material.

In a fighter aircraft incident, a bolt failure allowed a coupling to be forced open and the joint of a bleed air duct to separate. Adjacent components and wiring were overheated or burned by the escaping hot air. Similar incidents were reported in which bleed ducts failed between the engine and wing bleed air manifold. In one case it was noted that 125 psi, 600$^{o}$F air from a ruptured bleed duct had caused heat damage to electrical bundles, fluid lines, and sheet metal. A single incident involved damage from the collision of a bird with the leading edge of a C-130, 18 inches inboard of the number four engine. Tears of 15 by 6 inches in the leading edge skin, and 18 inches of bleed ducting were caused; the bleed air released damaging adjacent wiring and lines.

The remaining mishaps associated with dry bay regions were all associated with the failure of boundary layer control valves, which typically resulted in heat damage to external flap surfaces and to adjacent hydraulic components.

A2.1.3.3 Wheel Wells

Fires occurring in wheel wells nearly always involve the combination of hot brake surfaces and the ignition of hydraulic fluid escaping from damaged hydraulic lines under high pressure. (Hydraulic fluid (MIL-H-5606) has a flash point of 200F and an auto-ignition temperature of 468F.) In a typical incident, overheating of the brake assemblies on a C-130 fused the brake pads to the rotor disc, caused the failure of an actuating piston and subsequent release of hydraulic fluid. The escaping hydraulic fluid was ignited and fire caused the rupture of other hydraulic lines. The fire was extinguished by a ground crew.

None of the mishaps (1975 to 1978) of military aircraft involved inflight wheel well fires. However, this possibility is not excluded. A commercial aircraft accident in 1963 and a C-5A accident in 1974 were caused by delayed ignition of combustibles in the main wheel well. Brake surfaces had been heated by heavy braking, and a failure of wheel components from stress occurred resulting in the leaking of hydraulic fluid. Ignition of the fluid did not occur until the aircraft had taken off and the wheel well doors had been closed. Other hydraulic lines, as well as fuel lines in vicinity of the fire, were damaged by the wheel failure and/or melted by the primary fire, adding further combustibles to the fires.

A2.1.3.4 Electrical/Electronics Bays

The infrequent fires in aircraft electrical/electronics bays most often result from damaged electrical equipment which provides an ignition source. In one severe mishap involving a fighter aircraft, chafing of a generator power lead against a liquid oxygen supply line occurred and eventually ignition of the electrical equipment resulted from arcing between the power lead and oxygen line. The fire was intensified by escaping oxygen and the flow of cabin air through an adjacent regulator.

In another, less severe, but more typical incident, a cooling turbine failed, damaging the cooling duct and allowing hot air to circulate in the equipment compartment. Equipment was damaged in the compartment, though no fire resulted.

A2.1.3.5 Cargo Areas

Fires reported in cargo bays are most often not the result of an aircraft failure, but are caused by some external factor. Only one mishap of the group surveyed reported a fire in a cargo bay. The seat frame of a truck, which had been loaded onto a cargo aircraft, came into contact with a battery terminal and sparking occurred. The sparks eventually started a fire, which was quickly suppressed with a portable fire extinguisher.

In another in-flight incident, actually classified as an engine-related mishap, a turbine disk failed, and a large portion of the disk penetrated the fuselage and subsequently entered a cargo container. A smoldering fire resulted which was extinguished by ground rescue personnel after the airplane landed. It was noted in the report of this incident that the standard A-20 (Halon 1011) fire extinguisher used prior to landing was not effective in fighting the fire.

## A2.2 Combat Fire and Explosion Hazards

The development of "typical combat-related inflight fire scenarios" requires answers to the following questions: What is the physical nature of combat damage? How can the environments created by combat damage be simulated?

Combat data (References A-28 through A-35) were reviewed by Survivability/Vulnerability personnel. The data focussed on Southeast Asia (SEA) combat loss and damage data for airplanes operating at approximately 35,000 feet subjected to high altitude threats and and in ground support missions subjected to low altitude threats. Data from eleven aircraft types were reviewed, and provided the basis for small scale simulation of battle damage conditions resulting from skin/dry bay/fuel tank penetrations by fragments and projectiles. The simulated damage conditions derived were generalized representations of the nominal and extremes of damage and do not consider the many variations in dry bay geometry, structural design and fuel loading conditions.

A2.2.1 Combat Loss/Damage Data Analysis

Data from one source indicate that approximately 60% of the high altitude aircraft losses attributed to damage from surface to air missile fragments resulted from penetration of wing and fuselage tanks and subsequent fuel fires. Similarly, low altitude combat loss data indicate that approximately 50% of the aircraft losses surveyed occurred as a result of fuel fire damage.

Low altitude combat damage data accumulated from returning aircraft indicated the following non-lethal damage distributions:

- fueled regions of the aircraft accounted for an average of 16% of the total bottom view projected area (Ap) and took 15% of the total hits to the aircraft

- seventy-two percent (72%) of total hits were taken to the front at azimuth angles of $\pm 45^{0}$ and elevation angles of $45^{0}$ off the vertical axis; nearly all remaining hits were taken at elevation angles of 45 to $90^{0}$ to the front, and to the rear at azimuth angles of $\pm 45^{0}$ and elevation angles of 0 and $90^{0}$ (Figure A-10)

- seventy-three percent (73%) of all hit incidents to the aircraft surveyed were single hits; 27% were two or more hits per incident

- seventy-six percent (76%) of all low altitude hits surveyed occurred at altitudes of 2000 feet and less

- approximately 95% of all hits to the aircraft were taken from 7.62, 12.7, 14.5 and 23 mm gun fired projectiles frequently having incendiary characteristics

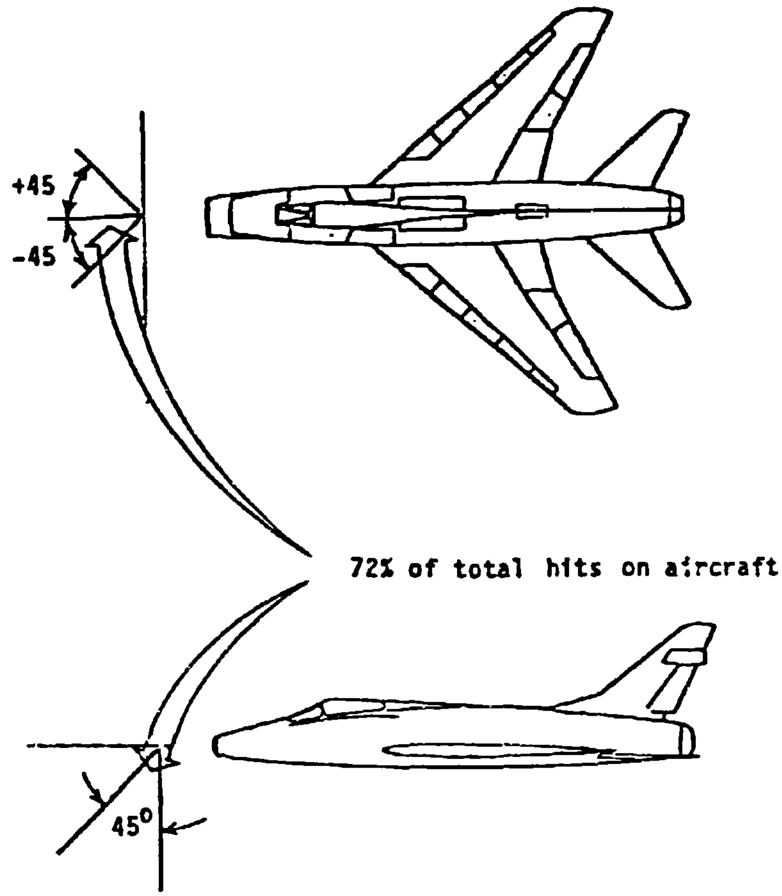



*Figure A - 10. Combat Damage - Direction of Hits*
*Aircraft Performing Ground Support Mission*

As shown by the results of the data analysis, 15% of the total aircraft hits impacting fueled regions did not result in subsequent aircraft loss through fuel-fire damage. One or more of the following circumstances may have existed:

- o projectiles penetrating fuel tanks passed through su ficient liquid fuel to quench incendiary effects

- o projectiles penetrating fuel tanks did not first pass through dry bay areas

- o projectiles entering fuel tank ullage regions did not cause explosion due to ullage rich or lean conditions

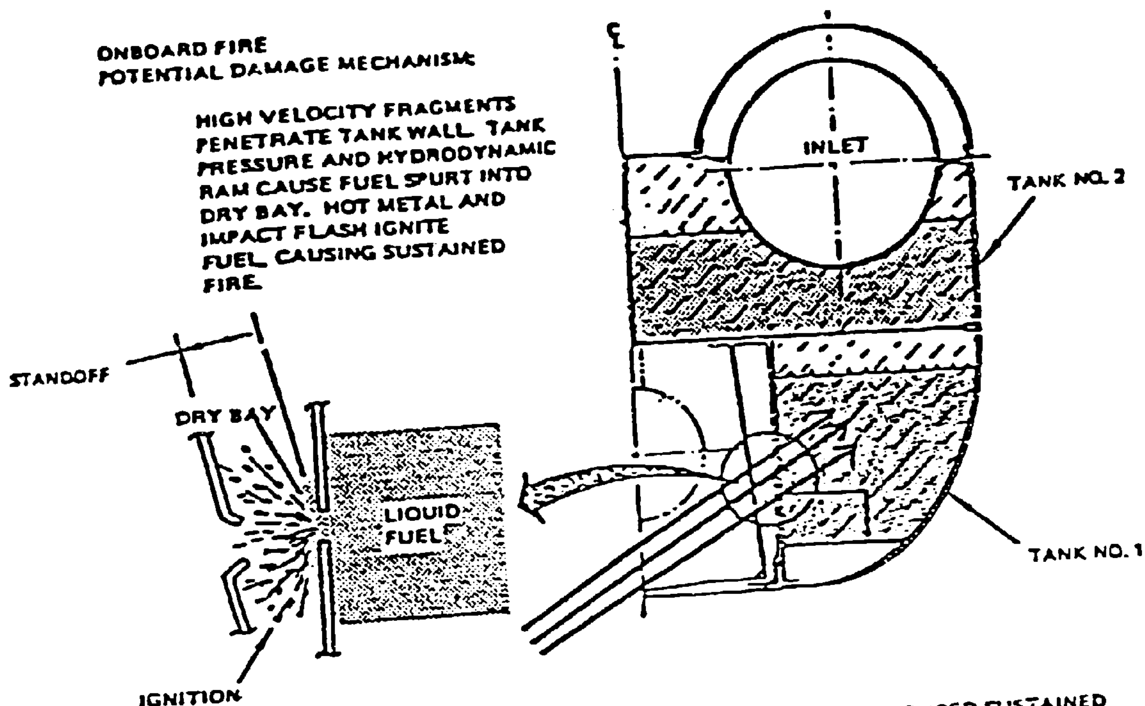
- o projectiles penetrating structure and/or tank walls, prior to entering the fuel tank volume may not have encountered sufficient resistance to strip the projectile jacket to and release incendiary material

- o fuel tank protection (reticulated foam, self-sealing bladders) or dry bay foam may have suppressed fuel fires

A2.2.2 Combat-Related Inflight Fire Scenarios

From the combat loss data presented, it is apparent that the hazards of fuel-fire related aircraft damage are significant. Analysis of fuel tank conditions shows that aircraft in a combat environment are likely to operate with flammable ullage during some portion of their mission. Fuel tank ullage conditions analyzed in the literature for representative fighter and strategic aircraft mission scenarios are similar to those encountered by aircraft identified in the combat loss and damage statistics show substantial probability for ignition.

Another classic combat condition leading to serious on-board fuel fires is illustrated in Figure A-11. The projectile passing through the dry bay penetrates a fuel containing region. Fuel spurts back through the hole and is ignited within the bay by impact flash, incendiary effects or other ignitions




- DRY BAYS ADJACENT TO LIQUID FUEL TANKS ARE PRIME SITES FOR WEAPON-INDUCED SUSTAINED FIRES.
- PROBABILITY OF SUSTAINED FIRE DEPENDS ON:
  - PROJECTILE TYPE
  - VELOCITY
  - OBLIQUITY
  - DAMAGE SIZE (LEAKAGE RATE)
  - ALTITUDE
  - STANDOFF DISTANCE
  - SKIN THICKNESS
  - DRY BAY VENTILATION
  - TANK PRESSURE (LEAKAGE RATE AND ATOMIZATION)

*Figure A - 11. Typical Dry Bay Fire Damage/Failure Mode* sources from aircraft systems. Increased air flow through the skin damaged area provides an oxygen supply, and skin deformation provides a flame holder. Sustained burning is possible only if the proper proportion of fuel-to-air ratio is maintained. Lean, flammable or rich fuel/air ratios within the dry bay are dependent upon the following factors:

- o volume of the dry bay
- o rate of fuel flow into the dry bay
- o rate of air flow into the dry bay
- o fuel and ambient air temperature

The amount of damage to fuel tank and adjoining dry bay structure from a specific threat is dependent upon the following:

- o fuel loading of the tank which influences the degree of damage caused by hydrodynamic ram
- o overpressures created by explosive type projectiles if detonation takes place within the dry bay or within the fuel tank (stand off distance)
- o tank volume and dry bay volume
- o tank construction

The amount of airflow through a damaged skin depends upon the location of the damage where a given damage hole size in one location may tend to supply too much air, driving the fuel/air ratio into a lean condition, and the same damage in another location may supply insufficient air supply driving the fuel/air ratio into a rich condition.

When considering small scale dry bay simulation of combat damage, the wide variations that exist between high altitude and low altitude damage mechanisms made some simplifications necessary.

The following threats were suggested as simulation candidates:

- o a single 120 grain SAM fragment or 50 caliber API projectile penetrating a 0.40 to 0.50 inch skin into a dry bay, and then through a 0.40 to 0.50 inch tank wall into a fuel tank

- a single 20 mm HEI projectile penetrating 0.40 to 0.50 inch skin, detonating within the dry bay, with resultant fragments penetrating a fuel tank

- a single projectile penetrating a dry bay and damaging a pressurized fuel, oil, or hydraulic fluid line

Skin damage size predictions were based on zero degree obliquity penetrations of the skin. Some data (Ref. 2) are available on air flow in fuselage compartments, either for venting and cooling, or because of skin damage (Figure A-12):

- a clean hole in the forward part of the fuselage will induce air flow into the compartment and raise the pressure
- a hole in the rear part of the fuselage, or one that is parallel to the airflow, will cause air to be drawn from the compartment and decrease the pressure

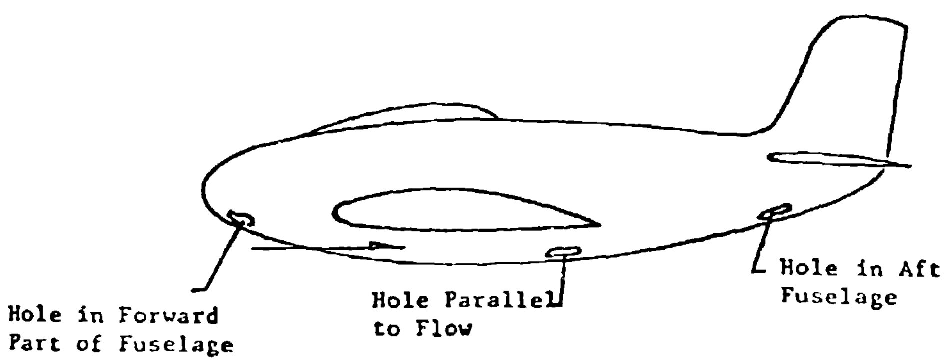



*Figure A-12. Hole Damage Locations*

In a series of experiments, the type and location of hole damage was tested using five "damaged" panels which simulated

- o a clean, 5/8 inch diameter hole
- o a clean, 2-1/4 inch diameter hole
- o a small projectile penetration
- o small and large holes with petalling, as would be induced by hydraulic ram damage

Each panel was positioned at four angles of attack with three different air velocities flowing over the panel (Table A-11). Clean holes produced positive gauge pressures for angles of attack greater than $10^0$, while negative gauge pressures were produced for damaged surfaces with exterior petaling at all angles tested. The differential pressure may cause combustible vapors to be drawn through the aircraft toward potential ignition sources.

For the purpose of establishing small scale test requirements for simulated combat damage, the following conclusions were reached:

- o modeling the large release of fuel from a tank into a dry bay was impractical because of the small volume and airflow in the test facility
- o the simulation of a negative gauge pressure difference in a compartment would draw air containing combustible vapors from controlled environment of the small scale simulator, and was not practical since the fire would be external to the test section
- o simulation of a compartment pressure increase due to induced ram air flow would effectively model a combat damage fire scenario in a safe, controlled manner

### A2.3 Summary of Small Scale Simulation Selection

Following review of typical aircraft inflight fire scenarios, both normal and combat-related, design of the small scale test apparatus was undertaken. Airflow considerations necessarily included

Table A - 11. Compartment Pressures in High Velocity Air Flow

| Panel Damage | Angle of attack | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 Degrees | | 10 Degrees | | 20 Degrees | | 30 Degrees | |
| | Duct Velocity (Knots) | Compartment Pressure (psi) | Duc Velocity (Knots) | Compartment Pressure (psi) | Duct Velocity (psi) | Compartment Pressure (psi) | Duct Velocity (Knots) | Compartment Pressure (psi) |
| 5/8 inch diameter clean hole | 17[illegible] | -.031 | 174 | +.001 | 173 | +.042 | 174 | +.053 |
| | 254 | -.059 | 226 | +.010 | 239 | +.082 | 243 | +.187 |
| | 338 | -.120 | 327 | +.012 | 329 | +.162 | 335 | +.354 |
| 2 1/4-inch diameter clean hole | 174 | -.011 | 176 | +.029 | 174 | +.076 | 174 | +.130 |
| | 255 | -.029 | 254 | +.053 | 245 | +.152 | 245 | +.271 |
| | 353 | -.075 | 347 | +.086 | 346 | +.310 | 345 | +.591 |
| Projectile penetration, small | 174 | -.045 | 174 | -.011 | 170 | +.026 | 173 | +.076 |
| | 237 | -.077 | 236 | -.0[illegible]1 | 234 | +.050 | 238 | +.140 |
| | 338 | -.166 | 332 | -.047 | 335 | +.110 | 329 | +.333 |
| Hydraulic ram, small | 176 | -.273 | 178 | -.258 | 176 | -.217 | 178 | -.151 |
| | 240 | -.517 | 246 | -.501 | 240 | -.356 | 230 | -.241 |
| | 339 | -.936 | 343 | -.937 | 348 | -.667 | 345 | -.359 |
| Hydraulic ram, large | 175 | -.260 | 176 | -.239 | 176 | -.187 | 172 | -.131 |
| | 240 | -.483 | 240 | -.458 | 233 | -.390 | 234 | -.211 |
| | 342 | -.947 | 339 | -.926 | 337 | -.683 | 342 | -.428 |

- o low ventilation rates with large vertical spacing to allow free convection fires
- o high ventilation rates to simulate forced convection in an engine nacelle
- o leakage flow into the test section in addition to the primary flow

Combustibles to be tested were sprays or pools of

- o jet fuels (JP-4, JP-8)
- o hydraulic fluid (MIL-H-5606)
- o lubricating oil (MIL-L-7808)

Flowrates of the combustibles were to be varied to determine the effect of fuel flow rate on fire severity.

Precise simulation of ignition sources did not appear necessary, with the exception of hot surfaces, which provide a continuous source of energy for ignition. For all other fire scenarios, a single positive ignition source (removed once the fire was established) was selected.

Flameholding devices were to be developed as needed to insure fire stabilization.

# APPENDIX B SMALL SCALE TEST FACILITY
## ASSEMBLY AND INSTALLATION DRAWINGS

Major structural elements of the test facility were manufactured to Boeing specification by Aircraft Engineering, 45500 Texaco Avenue, Paramount, CA 90723.

Assembly and installation of these elements was as illustrated on drawings B-1 and B-1.

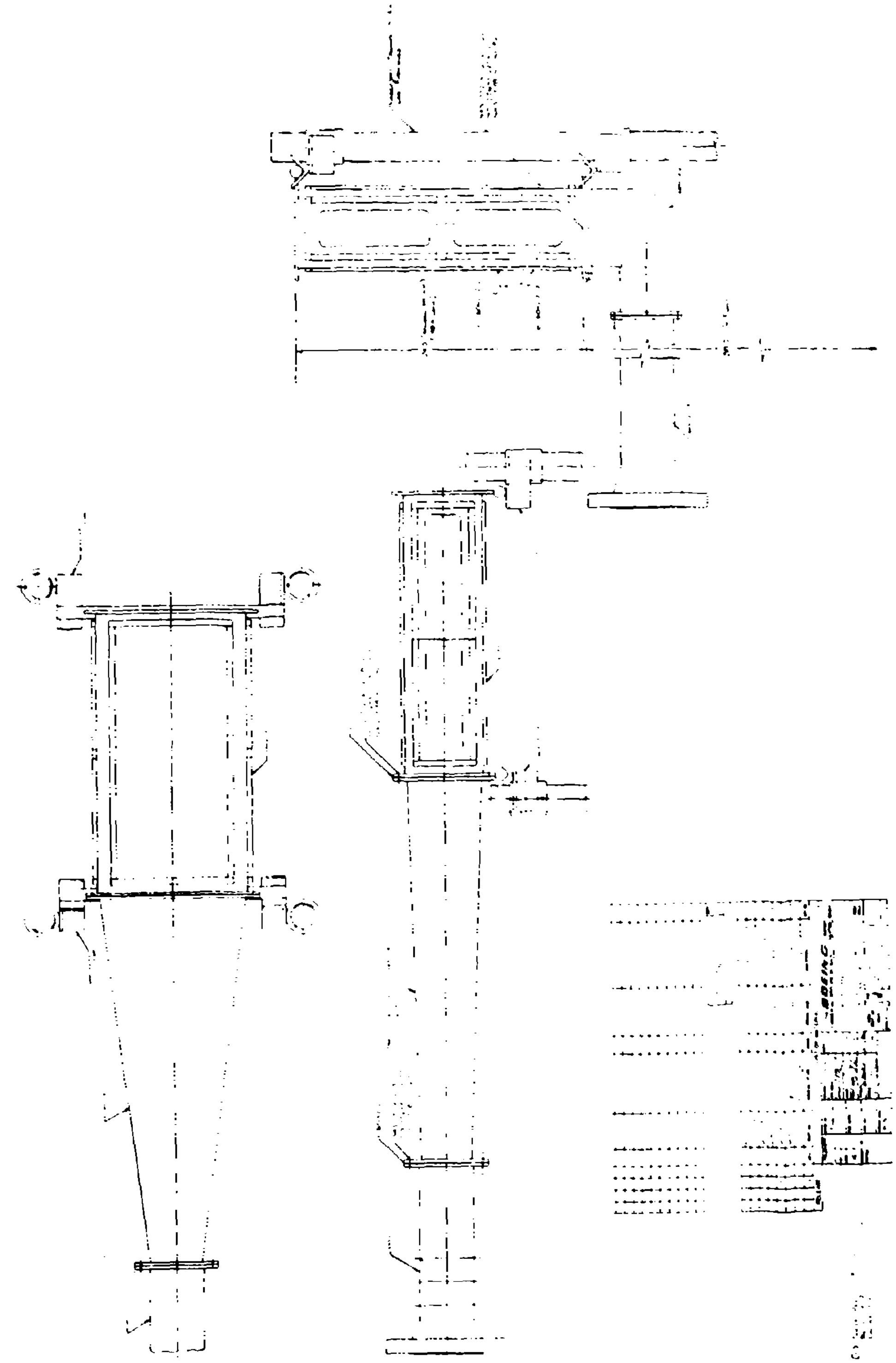


Figure B-1. Test Section Installation Drawing

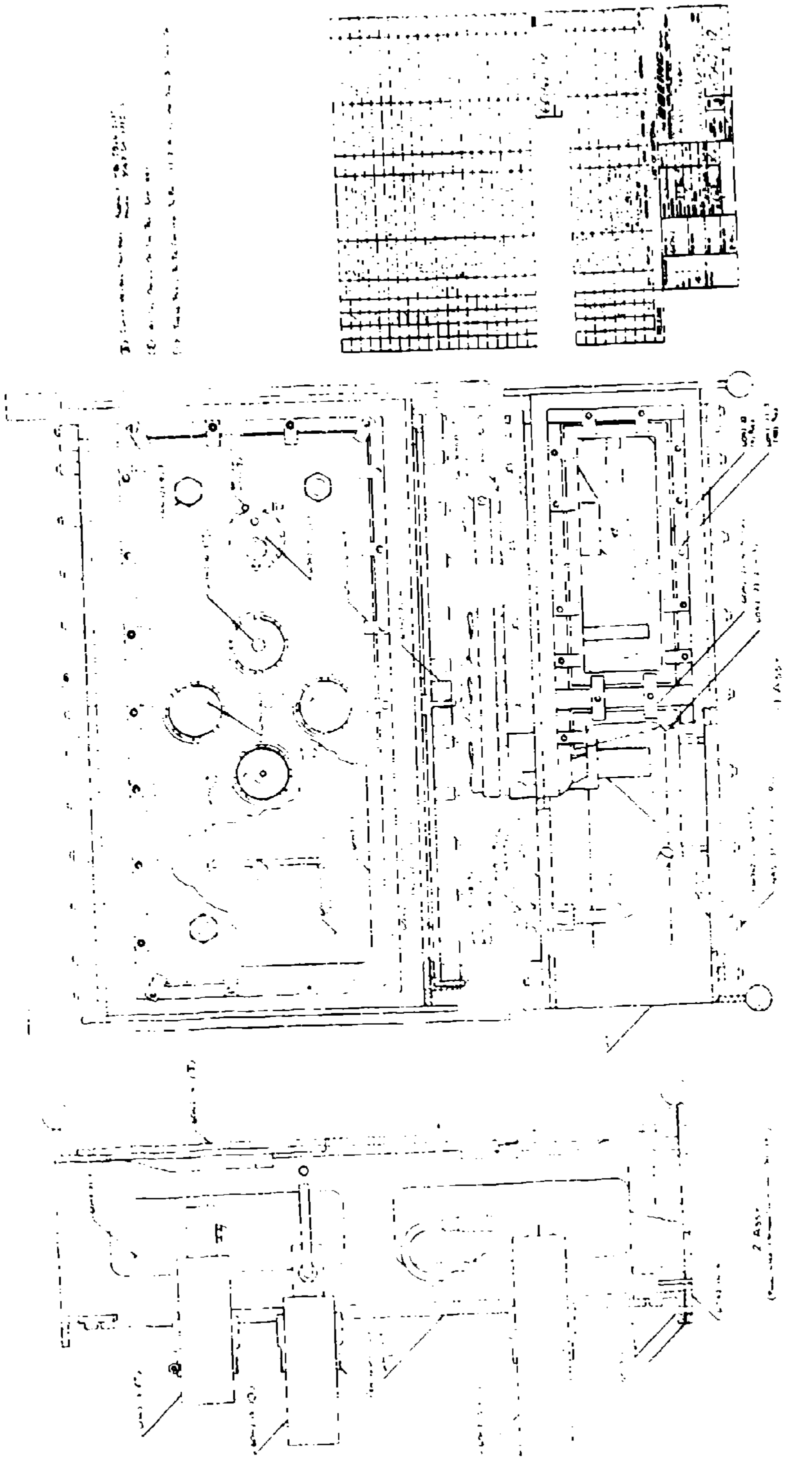


*Figure B-2. Test Section Assembly Drawing*

## APPENDIX C INSTRUMENTATION

### C1.0 DATA ACQUISITION

John Fluke Data Logger, Model #2240B

Minneapolis/Honeywell Temperature Strip Chart

Hewlett Packard 3460 Voltage Monitor

Hewlett Packard 7100 Strip Chart Recorder

### C2.0 SENSORS

All pressure measuring channels were system-calibrated using an air deadweight tester; the force channels were calibrated using certified deadweights. The accuracies of these standards are traceable to the Bureau of Standards.

The temperatures were sensed by thermocouples fabricated from premium grade Chromel/Alumel wire which was certified by the manufacturer to be within $\pm 2^0$ or 3/8% of full scale (whichever is greater).

TABLE C-1. Small Scale Test Instrumentation

| SYMBOL | SENSOR | DESCRIPTION, MAKE & MODEL | |
|---|---|---|---|
| PASS-PI-1A | 1.91 cm Flow Tube Delta Pressure | Transducer, 20 psi | Statham PM60TC |
| PASS-PI-2A | 1.91 cm Flow Tube Static Pressure | Transducer, 200 psi | Senolec 7-1182 |
| PASS-PI-1B | 3.81 cm Flow Tube Delta Pressure | Transducer, 20 psi | Statham PM60TC |
| PASS-PI-2B | 3.81 cm Flow Tube Static Pressure | Transducer 200 psi | CEC4-326 |
| ESS-PI-2 | Extinguishant Delivery Pressure | Transducer, 100 psi | Statham PA731TC |
| CFSS-PI-1 | Fuel Supply Pressure | Transducer, 300 psi | Statham PA731TC |
| PASS-TI-1A | 1.91 cm Flow Tube Temperature | C/A TC | Conax |
| PASS-TI-1B | 3.81 cm Flow Tube Temperature | C/A TC | Conax |
| ESS-TI-1 | Extinguishant Delivery Temperature | C/A TC | Conax |
| CFSS-TI-1 | Fuel Temperature | C/A TC | Conax |
| TSS-TI-1 | Test Section Entrance Temperature | C/A TC | Conax |
| TSS-TI-2 | Flame Region Temperature | C/A TC | Boeing-made |
| TSS-TI-3 | Hot Surface Temperature | C/A TC | Conax |
| | Oxygen Volume Percentage | 0-21% | Beckman 0260 |
| ESS-W-1 | Extinguishant Weight ($CN_2$) | Platform Scale | BLH |
| ESS-W-2 | Extinguishant Weight ($CO_2$ | Load Cell | BLH |
| ESS-W-3 | Extinguishant Weight (HALON) | Load Cell | BLH |
| ESS-W-4 | Extinguishant Weight ($LN_2$) | Load Cell | BLH |

## C3.0 SIGNAL CONDITIONING

All pressures and force channels used NLS Power and Balance Units for signal conditioning. In addition, two channels used Preston 8300 Amplifiers to drive strip chart pens.

The settings and sensitivities of the signal conditioners are listed below:

TABLE C-2. Signal Conditioner Settings

| SYMBOL | BRIDGE VOLTS | AMP. GAIN | SENSITIVITY |
|---|---|---|---|
| ESS-PI-2 | 2.210 | - | 100 cts/psi |
| CFSS-PI-1 | 1.930 | - | 100 cts/psi |
| PASS-PI-1A | 5.170 | - | 100 cts/psi |
| PASS-PI-2A | 8.330 | - | 1000 cts/psi |
| PASS-PI-1B | 5.460 | - | 100 cts/psi |
| PASS-PI-2B | 7.220 | - | 1000 cts/psi |
| ESS-W-4 | 1.66 | 200 | 100 cts/psi |
| ESS-W-3 | 1.66 | 200 | 10 cts/lb |
| ESS-W-2 | 1.68 | 200 | 10 cts/lb |
| ESS-W-1 | 5.00 | 200 | 10 cts/lb |

## APPENDIX D. TEST FACILITY OPERATING PROCEDURES

The task of evaluating, fire extinguishant effectiveness was accomplished by simulating the dynamic environments of each of several aircraft-type compartment under controlled test conditions. For each test, selections were made with respect to environmental factors which characterize the particular fire scenario being employed. For example, the selection process may have appeared as follows:

| | |
|---|---|
| Compartment | engine nacelle (forced convection) |
| Ignition Source | hot surface, 788C |
| Flameholder Employed | yes |
| Fuel Type | JP-4 |
| Fuel Loading Condition | high pressure spray, 3.0 l/s |
| Extinguishant Type | Halon 1301, uniformly mixed |
| Air Temperature | 93C |
| Air Flowrate | 6 m/s |

Following execution of the test runs as described in Section 2.2.5, another air flowrate was selected from the range of interest, and this process repeated until series was complete for the extinguishant being considered. These scenario conditions were then repeated for testing of the other extinguishants. Individual test runs were conducted in the manner described in the following typical instructions to the test engineer:

Record compartment configuration details; run number, fuel type and loading conditions, extinguishant type and dispersal mode. Select the appropriate ignition sequence:

<u>Ignition Sequence A</u>

Application: pool fire, hot wire igniter.

a. Establish pool depth of 1/4" using fuel flow throttle valve, and set fuel flowrate to maintain this depth throughout test. Establish a minimal airflow.

b. Activate electric ignition source, de-activate after positive ignition is achieved. Allow flame to stabilize. Check burn rate against supply rate.

c. Increase airflow to setpoint; adjust air temperature as required.

Ignition Sequence B

Application: spray fire, hot wire igniter.

a. Activate electric ignition source and establish a minimal airflow.

NOTE: When vaporized fuels are used, it is necessary to first activate the ignition source, and then slowly introduce the fuel to prevent explosion.

b. Initiate fuel spray; if ignition has not occurred within several seconds, shut off fuel supply and ignition source. Check test section and exhaust duct for accumulated fuel, drain if necessary. Repeat until a stable flame is established.

c. De-activate ignition source when stable ignition has been achieved.

d. Increase airflow and fuel flow to setpoint; adjust air temperature as required.

Ignition Sequence C

Application: spray fire, hot surface ignition.

a. Establish full test air flowrate required.

NOTE: This action is possible because, unlike the pool and spray cases, it is possible to achieve ignition at any air flow using the hot surface. Test set-up time can therefore be reduced by eliminating the need to adjust power input to the hot surface. (Power input required to obtain a given surface temperature is a function of air flowrate.)

b. Activate hot surface, allow time for warm-up to required surface temperature.

c. Initiate fuel spray at minimal pressure. If ignition occurs immediately, increase fuel flow to the required rate. If ignition has not occurred within a few seconds, shot off the fuel supply, allow time for any accumulated fuel to vaporize, and then repeat the ignition attempt.

e. Adjust air temperature if required.

Briefly activate the data recorder to obtain a description of condition within the test section prior to fire extinguishment. If motion picture footage of a particular test run is desired, the camera will be activated at this point.

Introduce extinguishant either gradually, or instantaneously at the predetermined rate, as described in Section 2.2.5.

Activate the data recorder again to obtain a description of the conditions following extinguishment, keeping the extinguishant flow constant while data is recorded.

Shut off fuel supply, drain any uncombusted fluids.

At the end of each test series, maintain air flow to allow cool-down of hot test surfaces. Inspect the interior of the test section and remove any excessive residue.

## APPENDIX E. SAMPLE CALCULATIONS

### E1.0 CONVERSION OF AIR MASS FLOWRATE TO VELOCITY

$v = \dot{m}/\rho A$, where $\dot{m}$ = mass flowrate (kg/sec)

$\rho = 1.2104\ kg/m^3$ (at 293K, 101 kPa)

$A = 0.0465\ m^2$

Sample Calculation:

$\dot{m} = 0.08$ kg/sec

$$v = (0.08\ kg/sec)/(1.2104\ kg/m^3 \times 0.0465\ m^2)$$
$$= 1.50\ m/sec$$

### E2.0 CALCULATION OF EXTINGUISHANT VOLUME PERCENTAGES

$$V\%_{ext} = (\dot{V}_{ext} \times 100)/\dot{V}_{ext} + \dot{V}_{air})$$

where $\dot{V}_{ext}$ and $\dot{V}_{air}$ are volumetric flowrates in $m^3$/sec of extinguishant and air, respectively.

Sample Calculation:

$$\dot{V}_{ext} = \dot{m}_{ext}/\rho_{ext} \text{ (considering nitrogen)}$$
$$= (0.05\ kg/sec)/(1.1819\ kg/m^3)$$
$$= 0.04\ m^3/sec$$

$$\dot{V}_{air} = \dot{m}_{air}/\rho_{air}$$
$$= (0.08\ kg/sec)/(1.2104\ kg/m^3)$$
$$= 0.07\ m^3/sec$$

$$V\%_{ext} = (0.04 \times 100)/(0.04 + 0.07)$$
$$= 37.00$$

NOTE: Actual extinguishant densities <u>were</u> corrected for extinguishant temperature during data reduction.

## E3.0 TEST SECTION VELOCITY CORRECTION

$$v_{air} = \dot{m}_{air}/\rho_{air}\,A$$
$$= (0.08\ \text{kg/sec})/(1.2104\ \text{kg/m}^3 \times 0.0465\ \text{m}^2)$$
$$= 1.50\ \text{m/sec}$$

Total (product) flowrate:

$$v_{air + ext} = v_{air} + v_{air}\left(\frac{\dot{V}_{ext}}{\dot{V}_{air}}\right)$$
$$= v_{air}\left(\frac{\dot{V}_{air} + \dot{V}_{ext}}{\dot{V}_{air}}\right)$$
$$= v_{air} / \left(\frac{\dot{V}_{air}}{\dot{V}_{air} + \dot{V}_{ext}}\right)$$

Sample Calculation:

$$v_{air + ext} = v_{air}/(1 - \text{V\% EXT})$$
$$= 1.50\ \text{m/sec}/(1 - 0.37)$$
$$= 2.38\ \text{m/sec}$$

## E4.0 % OF EXTINGUISHANT CONVERSION TO % $O_2$

V% AIR = 100 - V% EXTINGUISHANT

V% $O_2$ = 0.2099 (V% AIR)

Sample Calculation:

V% EXT = 37.00

V% AIR = 63.00

V% $O_2$ = 13.22

E5.0 TRANSFORMATION OF $GN_2$ DATA TO EQUIVALENT NEA PERCENTAGES

Since the primary purpose of this test program was to quantitatively determine the effectiveness of nitrogen-enriched air (NEA), it was necessary to devise a procedure to generate the plotted NEA data from the reults of the $GN_2$ tests.

Extrapolation of the $GN_2$ (100% gaseous nitrogen) data to any NEA quality was made holding the following quantities constant:

- o the experimentally measured oxygen percentage (this insures that the chemical reaction time at the fire site is constant)
- o the total volume of flow air + extinguishant (this insures that the residence time at the fire site is constant)

It is first necessary to develop an expression relating $GN_2$/air data to NEA/air data in terms of

- o the experimentally determined $O_2$ percentage
- o the NEA quality (expressed in terms of $\%O_2$)

The basis for the transformation procedure lies in conservation of oxygen and nitrogen quantities, together with adjustment of air flow velocity (Figure E-1).

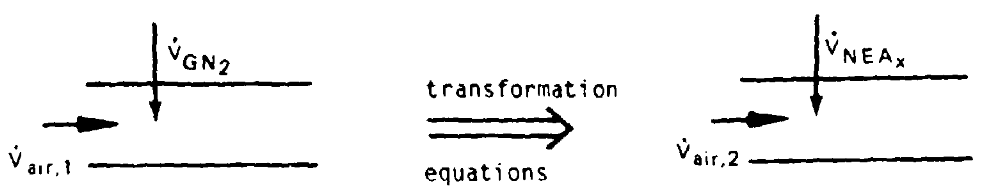



*Figure E - 1. Transformation Relationship*

The volumetric flow rates are constant, thus:

$$\dot{V}_{air,1} + \dot{V}_{GN_2} = \dot{V}_{air,2} + \dot{V}_{NEA_x} \qquad \text{Equation (E-1)}$$

Converting this equation to volume fractions of $GN_2$ and $O_2$,

$$cO_2 + (1-c)\,N_2 = v(0.2099O_2 + 0.7808N_2) + (1-v)(fO_2 + (1-f)N_2) \qquad \text{Equation (E-2)}$$

where,

$c$ = volume fraction of $O_2$ in the product stream (from Figure E-1)

$f$ = volume fraction of $O_2$ in NEA (NEA quality, 0-0.2099)

$v$ = volume of air in (Air + NEA) stream

$1-v$ = volume fraction of NEA in (Air + NEA) stream

Since volumes of $O_2$ and $N_2$ are individually conserved, equation (E-2) may be broken into two equations. For $O_2$,

$$c = 0.2099v + (1-v)f \qquad \text{Equation (E-3)}$$

For $N_2$, the results are redundant:

$$\begin{aligned} 1-c &= 0.7808v + (1-v)(1-f) \\ &= 0.7808v + 1 - v - f + vf \\ c &= -0.7808v + v + f - vf \\ &= 0.2099v + (1-v)f \end{aligned}$$

Solution of equation (E-3) for v provides a means to calculate the volume fractions of air and NEA, given only c and f.

$$v = \frac{c - f}{0.2099-f}$$

and

$$\begin{aligned} 1-v &= 1 - \frac{c - f}{0.2099-f} \\ &= \frac{0.2099-c}{0.2099-f} \end{aligned}$$

Sample calculations:

3% NEA; $c = 0.1322$, $f = 0.03$

$$\begin{aligned} 1-v &= \frac{0.2099-c}{0.2099-f} = \frac{0.2099-0.1322}{0.2099-0.03} \\ &= 0.4319 \end{aligned}$$

6% NEA; c = 0.1322, f = 0.06

$$1-v = \frac{0.2099-0.1322}{0.2099-0.06}$$

$$= 0.5183$$

9% NEA; c = 0.1322, f = 0.09

$$1-v = \frac{0.2099-0.1322}{0.2099-0.09}$$

$$= 0.6480$$

In summary, for 13.22% $O_2$ (by mass) in product stream,

| Quality | 0% NEA | 3% NEA | 6% NEA | 9% NEA |
|---|---|---|---|---|
| Quantity | 37% | 43.19% | 51.83% | 64.80% |

It can be easily seen, however, that these calcuated values of NEA quality represent increasingly larger fractions of the total test section (air + extinguishant) volumetric flow rate, thus reducing the effective air flow, and in turn, the effective air velocity. To maintain constant residence time at the fire site, it is necessary to correct the test section entrance air velocity before the $GN_2$ data can be replotted as NEA data. Since velocities are small, the air can be treated as an incompressible fluid, and:

$$\frac{v_{air,\ reduced}}{v_{air,\ initial}} = \frac{(V\%\ air)NEA}{(V\%\ air)GN_2}$$

where,

(V% Air)NEA = calculated volume % air in the Air + NEA mixture
(V% Air)$GN_2$ = volume % air in the Air + $GN_2$ mixture

Sample Calculation:

$$(V\%\ Air)NEA = 100 - V\%\ NEA$$

$$(V\%\ Air)GN_2 = 100 - V\%\ GN_2$$

3% NEA; $$v_{reduced} = \frac{100 - 43.19}{100 - 37.00}\ 1.5\ m/s$$

$$= 1.35\ m/s$$

6% NEA; $$v_{reduced} = \frac{100 - 51.83}{100 - 37.00}\ 1.5\ m/s$$

$$= 1.15\ m/s$$

9% NEA; $$v_{reduced} = \frac{100 - 64.80}{100 - 37.00}\ 1.5\ m/s$$

$$= 0.84\ m/s$$

In summary, oxygen content and residence time are both constant at the fire site under the calculational procedures:

Data to be used in the sample calculation are shown in Figure E-2.

Sample Calculation:

At a test air velocity of 1.5 m/s (v/vmax = 0.0492), 37% $GN_2$ is required for fire extinguishment, which corresponds to a test section concentration of 13.22% $O_2$. The volume percent of 3, 6 and 9% quality NEA that would be required to provide the same level of effectiveness as the 37% $GN_2$ can be calculated. (NOTE: Effectiveness is defined in terms of the % $O_2$ and the air velocity at which an extinguishant will cause fire extinguishment.)

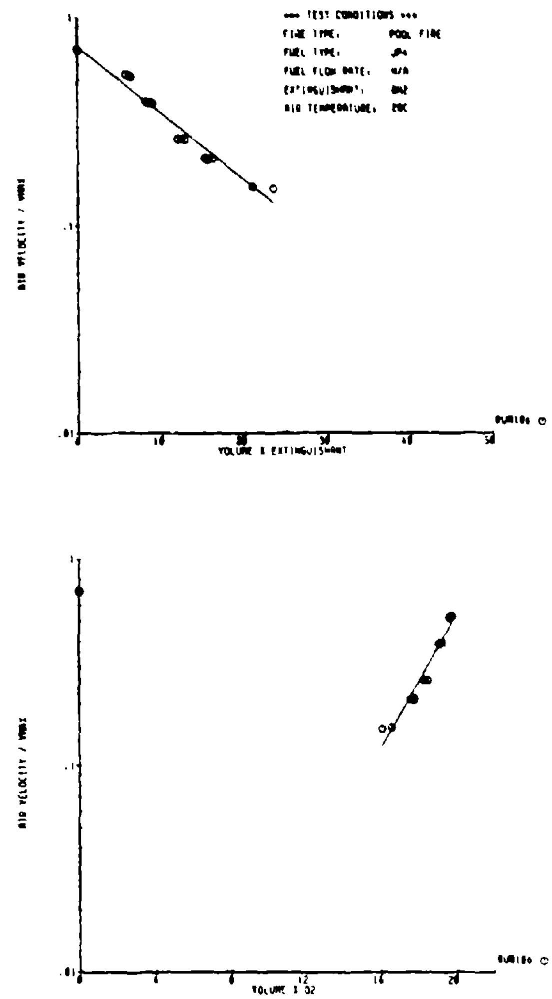



*Figure E - 2. Percent $GN_2$ (Above) and Percent $O_2$ (Below), Data Taken from JP - 4 Pool Fire Test Results, 20C Air*

| Quality | 0% NEA | 3% NEA | 6% NEA | 9% NEA |
|---|---|---|---|---|
| Quantity | 37% | 43.19% | 51.83% | 64.80% |
| $V_{air}$, m/s | 1.5 | 1.35 | 1.15 | 0.84 |

For the purpose of plotting the calculated NEA data from the $GN_2$ test results, this procedure was used to transform each $GN_2$ data point within the test run, and then a linear least squares curve fit applied (as with each of the other agents).

The figures that follow depict each step of the conversion process:

- o Figure E-3 Conversion calculated repeated for each $GN_2$ data point for 3, 6, and 9% equivalents
- o Figure E-4 Least squares curve fit for generated points
- o Figure E-5 Same curve fit with NEA points deleted for clarity.

Values of NEA concentration (used throughout this report) can now be obtained at any constant velocity.

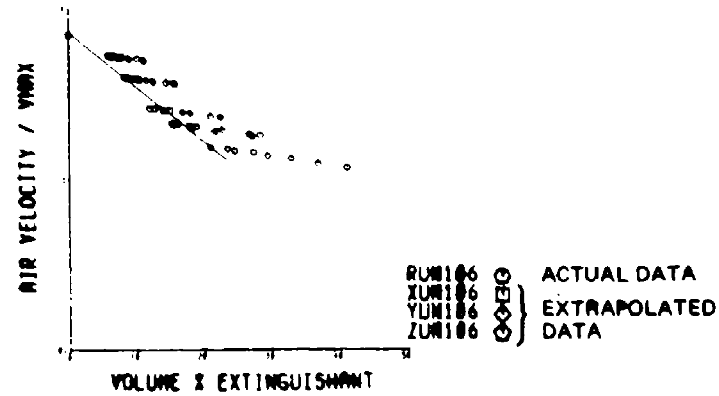



*Figure E - 3. Conversion Calculation Repeated for Each $GN_2$ Data Point, for 3, 6, and 9% Equivalents*

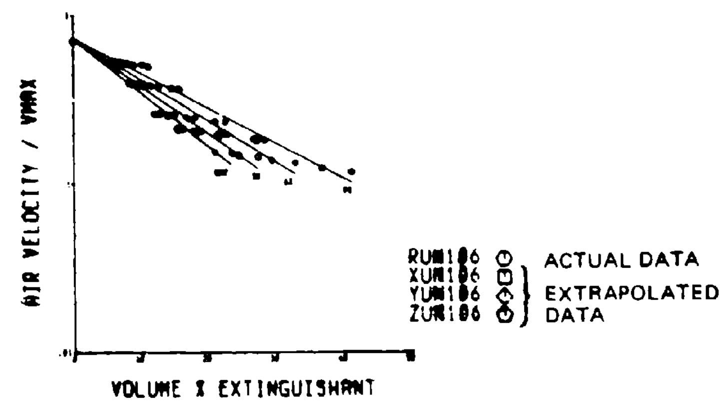



*Figure E - 4. Least - Square Curve Fit for Generated Points*

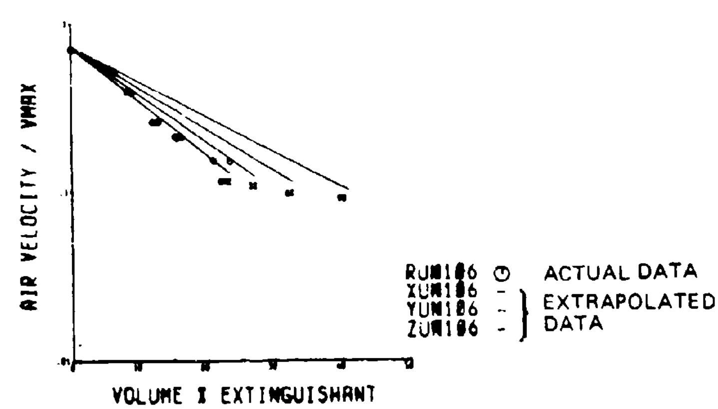



*Figure E - 5. Same Curve with NEA Points Deleted for Clarity*

# APPENDIX F. DATA PLOT RATIONALE

Contemplation of the use of inert gases, such as $GN_2$ or nitrogen enriched air (NEA) for extinguishing aircraft fires has led to the need for modeling of fire extinguishant phenomena. $GN_2$ and NEA act as diluents to the air flow stream, and reduce the maximum temperature in the fire. Usually, the maximum temperature occurs at or near an equivalence ratio of one; adding an inert diluent simply adds more mass to the combustion process, thereby reducing the fire temperature.

It was proposed that fire stability could be studied in terms of the Damkohler number ($D_K$) defined as:

$$D_K = \frac{\tau_r}{\tau_c}, \quad \text{where} \quad \begin{array}{l} \tau_r \simeq \text{combustible mixture residence time, and} \\ \tau_c \simeq \text{combustible mixture reaction time} \end{array}$$

If $D_K$ exceeds the order of one, the fire is predicted to be stable, and if less than one, the fire is predicted to be unstable (extinguished). Residence time ($\tau_r$) is related (see Figure F-1) to stream velocity ($V_2$) near the fire site, and the length (L) of the recirculation zone. Relations between L and $V_2$, the upstream velocity ($V_1$), and flameholder dimensions can be obtained from the literature (Reference 1-1).

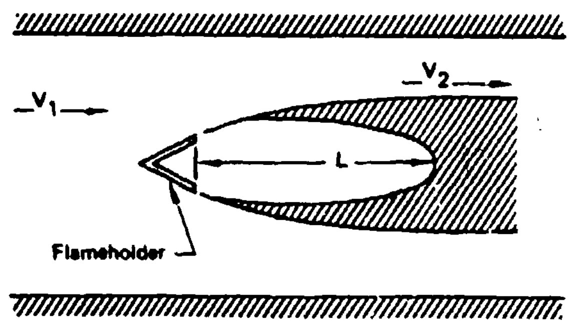



*Figure F-1. Flameholder In a Stream*

The residence time is predicted to be:

$$\tau_r \cong \frac{L}{V_2} = \frac{L}{V_1 A_1}$$ where $A_1$ is a constant depending on channel width and flameholder dimensions.

The combustible mixture reaction time was estimated in Reference 1 from a correlation of flameholder data. The fundamental expression is of the Arrenhius type, with corrections for approach stream temperature and pressure, and the equivalence ratio:

$$\tau_c = \frac{T^{2.5}}{P\,\phi}\, e^{(E/RT_f)}$$ where

$\phi$ = equivalence ratio
p = pressure
T = approach stream temperature
E = activation energy
R = universal gas constant
$T_f$ = flame temperature

At the critical condition ($D_K = 1$),

$$\frac{L}{A_1 V_1} = \frac{T^{2.5}}{P\,\phi}\, e^{(E/RT_f)}$$

Taking logarithms of each side,

$$\ln\left(\frac{L}{A_1}\right) - \ln V_1 = 2.5 \ln T - \ln P - \ln \phi + \frac{E}{RT_f}$$

In the experiments reported in this study, $(L/A_1)$ and p are constants; $\phi$ = 1 is assumed, so that $T_f$ is a (near) maximum calculated from stoichiometry. Combining constants into another constant $A_2$,

$$-\ln V_1 = A_2 + 2.5 \ln T + \frac{E}{RT_f}$$

For non-dimensionalizing reasons, $V_1$ is referenced to $V_{max}$, the maximum velocity, and $T_f$ to $T_{ref}$, a convenient reference temperature (2186K)

$$-\ln \frac{V_1}{V_{max}} = A_3 + 2.5 \ln T + \frac{E}{R} \left(\frac{T_{ref}}{T_f}\right)$$

If T is a constant, this is the equation of a straight line:

$Y = \text{constant} + (E/R)x$, where $y = \ln (V_1/V_{max})$, and $x = (T_{ref}/T_f)$

The use of this expression reduces all data for one fuel and extinguishant at a given air temperature to a straight line.

Further, since flame temperature is inverse to the product of volumetric fraction of extinguishant (v), extinguishant molecular weight (M) and extinguishant specific heat ($C_p$);

$$T_f \propto \frac{1}{vMC_p}$$

it might be expected that the

$$-\ln V_1 = \ln A_3 + E/R\ vMC_p$$

and that this equation would also plot as a straight line, whose slope depends on E/R, M and $C_p$.

When this technique was used, the data could be reasonably well fitted to straight lines. On ($\ln V_2$) vs ($1/T_f$) plots, the slope of the line is E/R, with a generally accepted value for most hydrocarbons of approximately $2\times10^4$ Kcal. Values found from the data plots were within 25 to 30% of this value. In some data sets, approach air temperature was either varied by heating prior to entering the test section, or by a hot surface. These temperature increases contribute to the combustion process by increasing the reaction rate. The $T^{2.5}$ term in the expression for $\tau_c$ would tend to correct for auxiliary heating, although such a correction was not applied in the present data reduction.

The goal of continuing effort along these lines will be to produce a data reduction technique which will reduce all the experimental data on diluent extinguishing agents to one straight line. At this point, different agents plot onto lines of different slopes, and flameholder geometry, degree of atomization of the fuel and equivalence ratio all contribute in ways not easily accounted. Nonetheless, for a given data set, one might expect, and the data appear to confirm, that the approach outlined provides a useful way to correlate and extrapolate data.

The following plot (Figure F-2) shows data in velocity vs extinguishant fraction coordinates; Figure F-3 shows the same data in ln (velocity) vs extinguishant fraction coordinates; Figure F-4 shows ln (velocity) vs ($1/T_f$) coordinates.

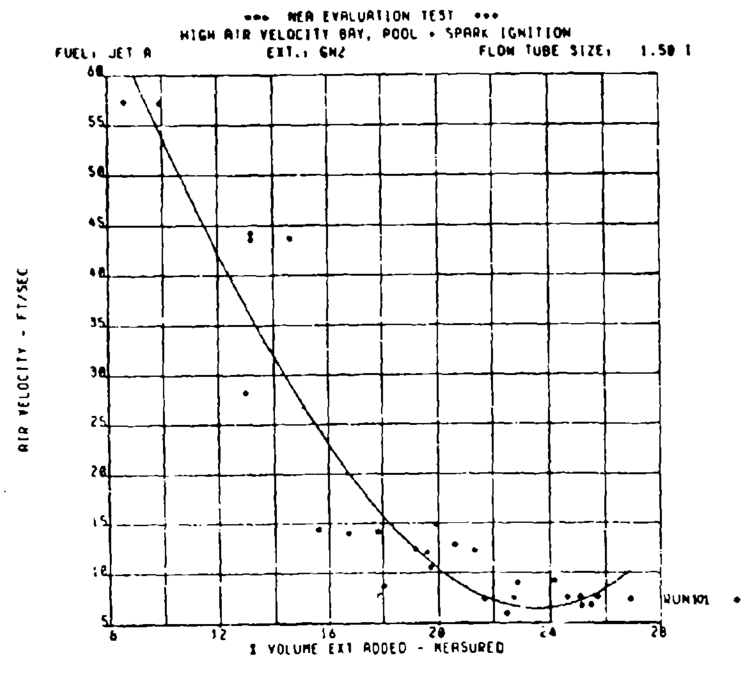



*Figure F - 2. Velocity vs Extinguishant Fraction*

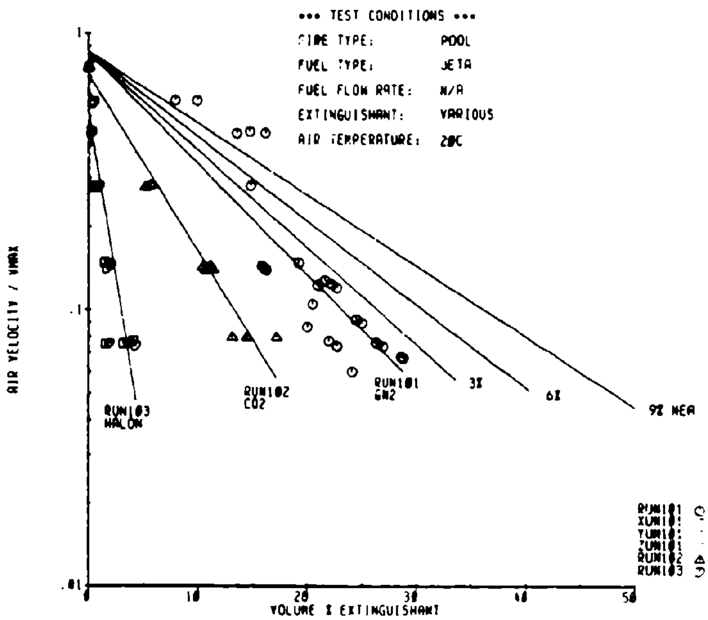
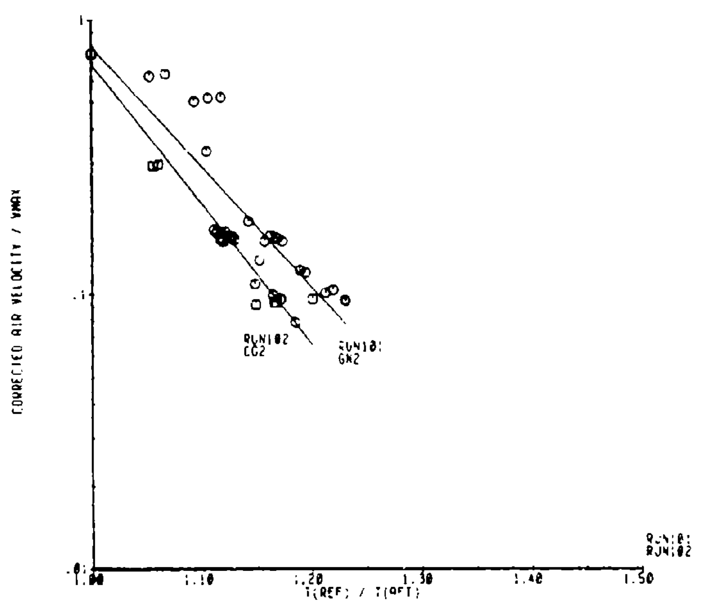


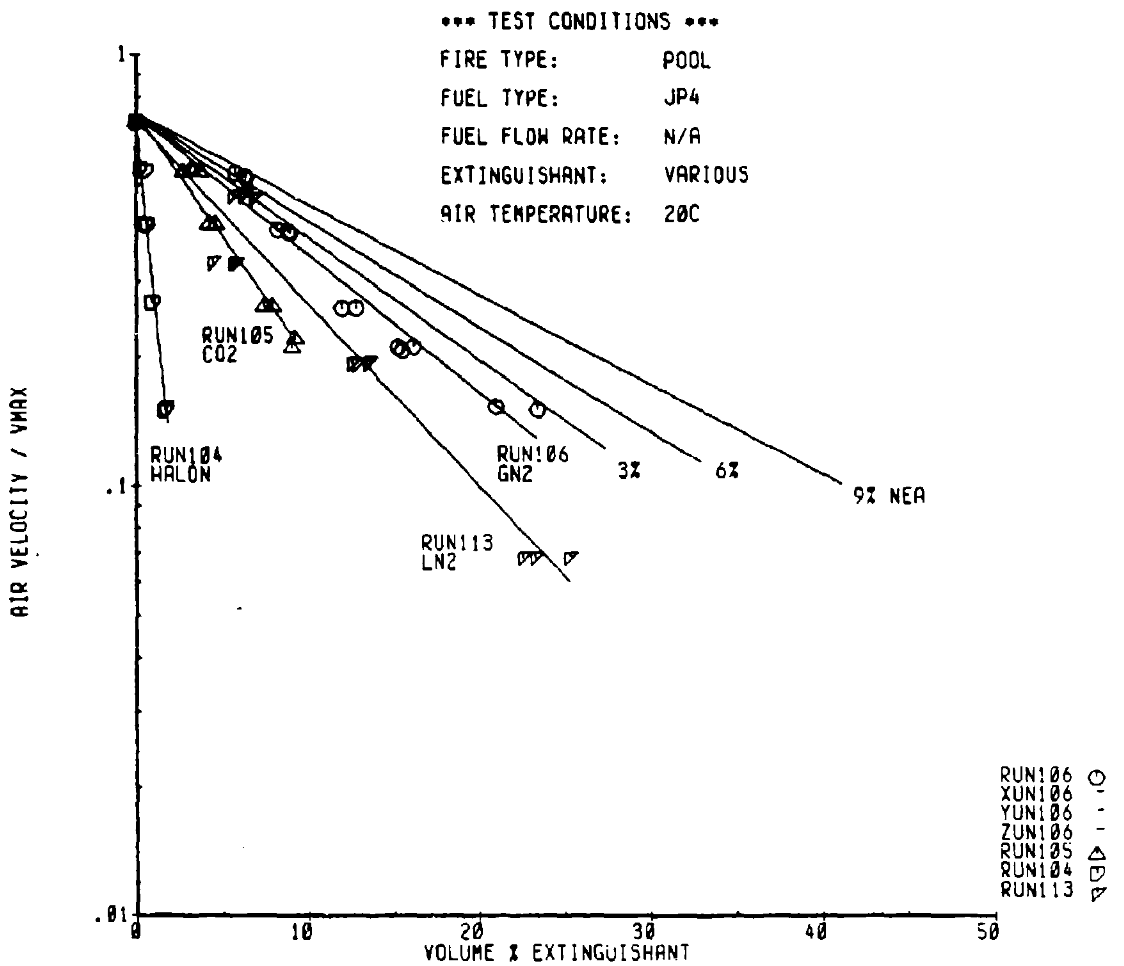

*Figure F - 3. In Velocity vs Extinguishant Fraction*



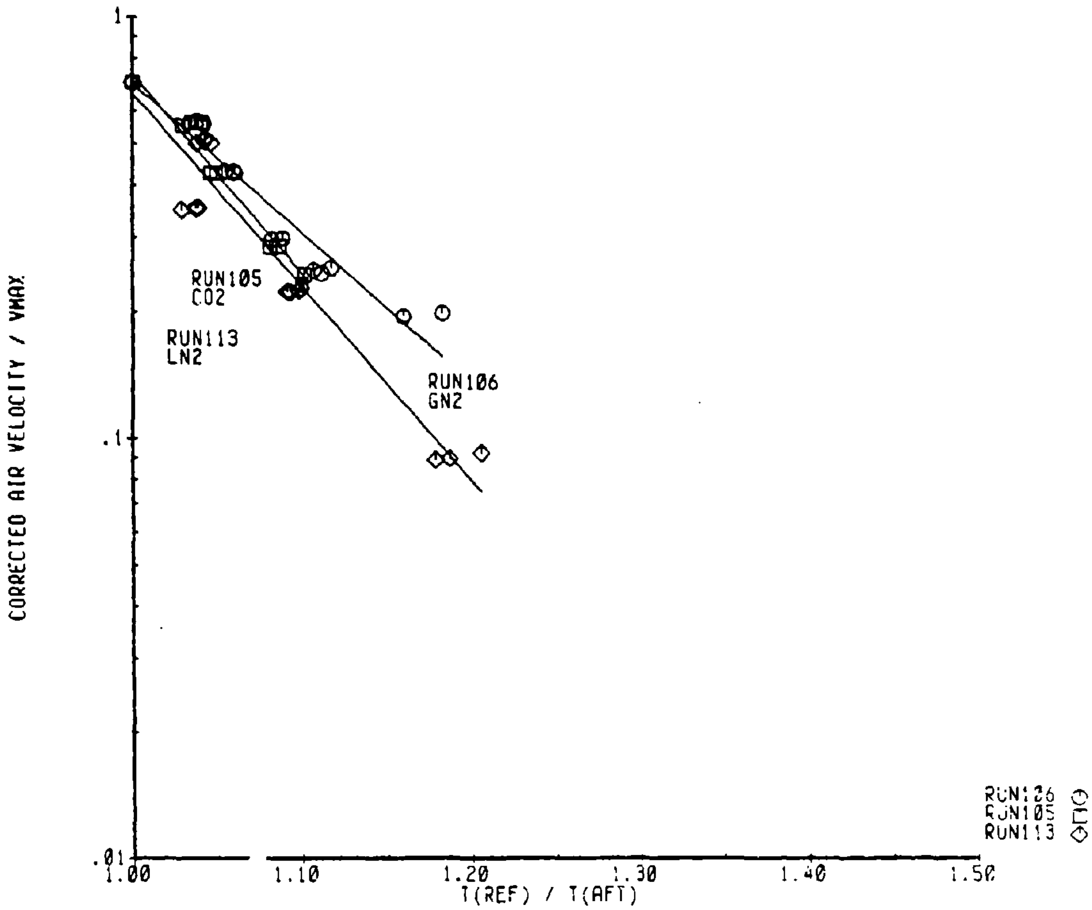

*F - 4. In Velocity vs $(1/T_f)$ Coordinates*

APPENDIX G. DATA PLOTS

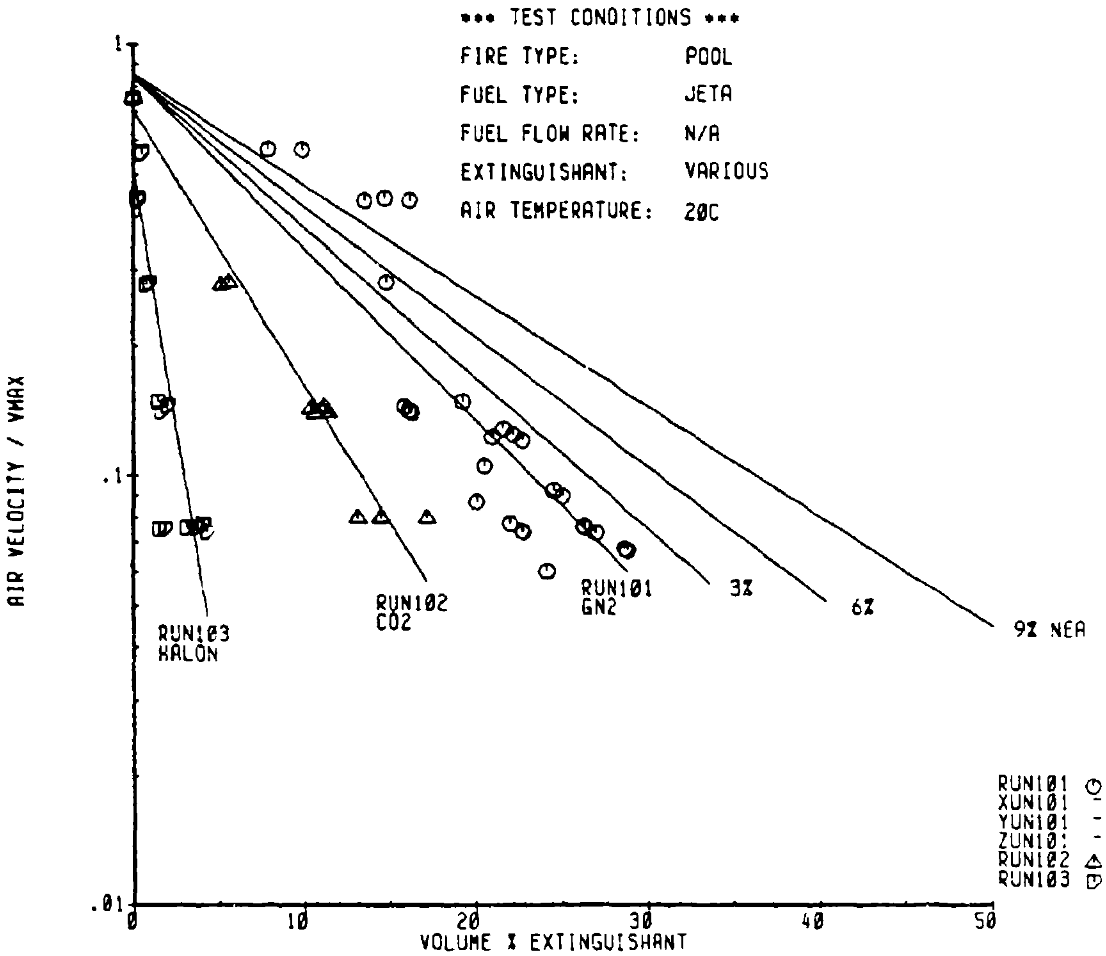
| PLOT TYPES | PLOT NUMBERS | PAGE NUMBERS |
|---|---|---|
| Pool | G-1 through G-9 | 154-170 |
| Spray | G-10 through G-21 | 171-187 |
| Hot Surface | G-22 through G-29 | 188-197 |
| Combat Damage | G-30 through G-35 | 198-204 |
| Bay/Pool | G-36 through G-39 | 205-209 |
| Bay/Spray | G-40 through G-44 | 210-216 |
| Bay/Hot Surface | G-45 through G-48 | 217-221 |
| HRSTD | G-49 through G-54 | 222-227 |



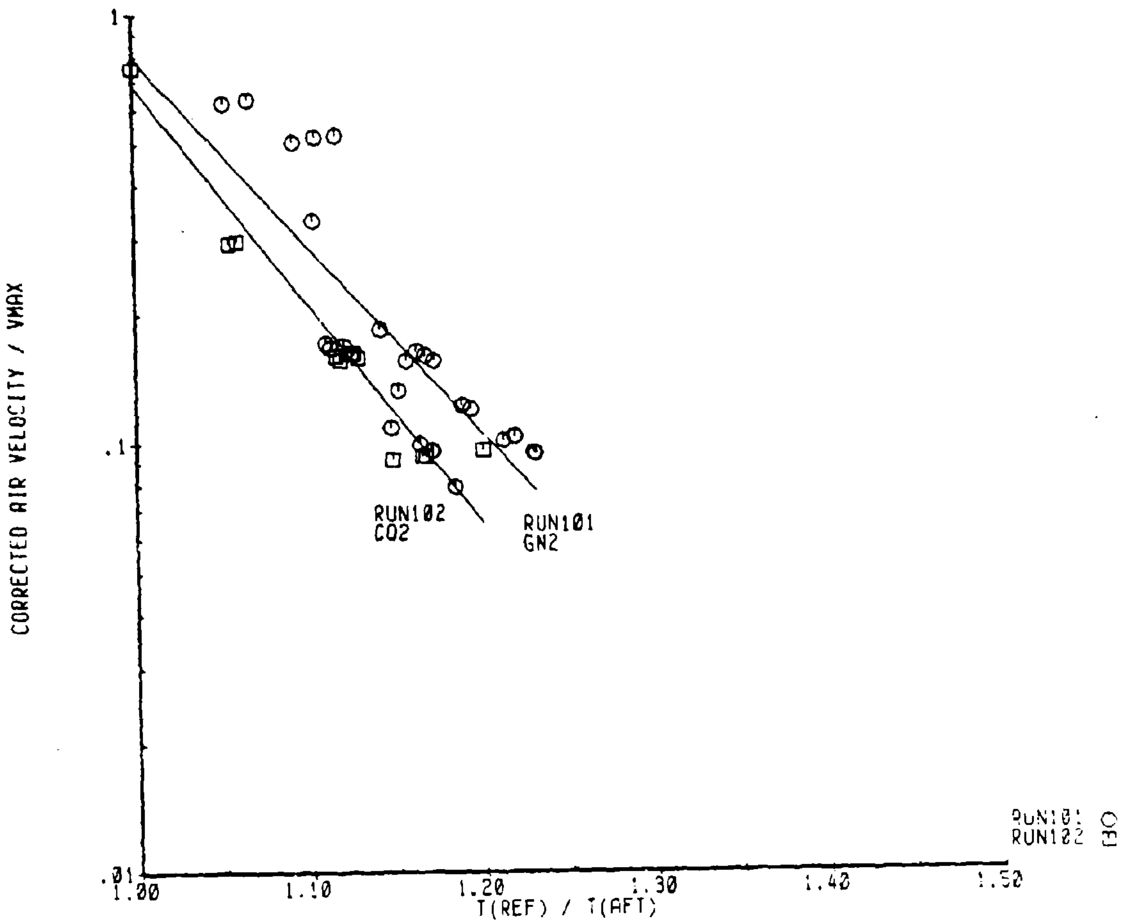

| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION | FIGURE |
| CHECK | | | | | POOL FIRE | G-1A |
| APPD. | | | | | ONE FLUID, VARIOUS EXTINGUISHANTS | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 154 |



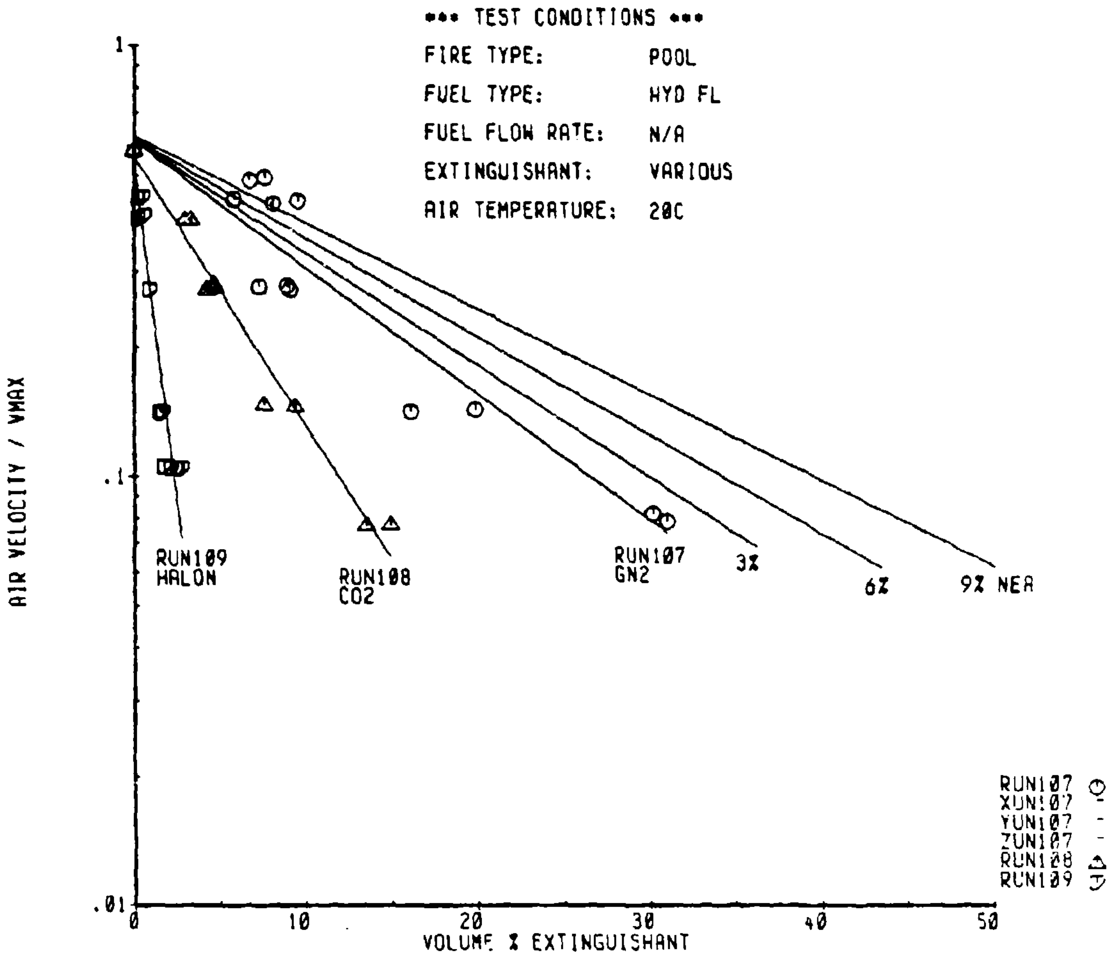

| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 10DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE FLUID, VARIOUS EXTINGUISHANTS | FIGURE |
| CHECK | | | | | | G-18 |
| APPD. | | | | | THE BOEING COMPANY | PAGE 155 |
| APPD. | | | | | | |




| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE FLUID, VARIOUS EXTINGUISHANTS | FIGURE<br>G-2A |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 156 |




| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 10DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE FLUID, VARIOUS EXTINGUISHANTS | FIGURE<br>G-28 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 157 |

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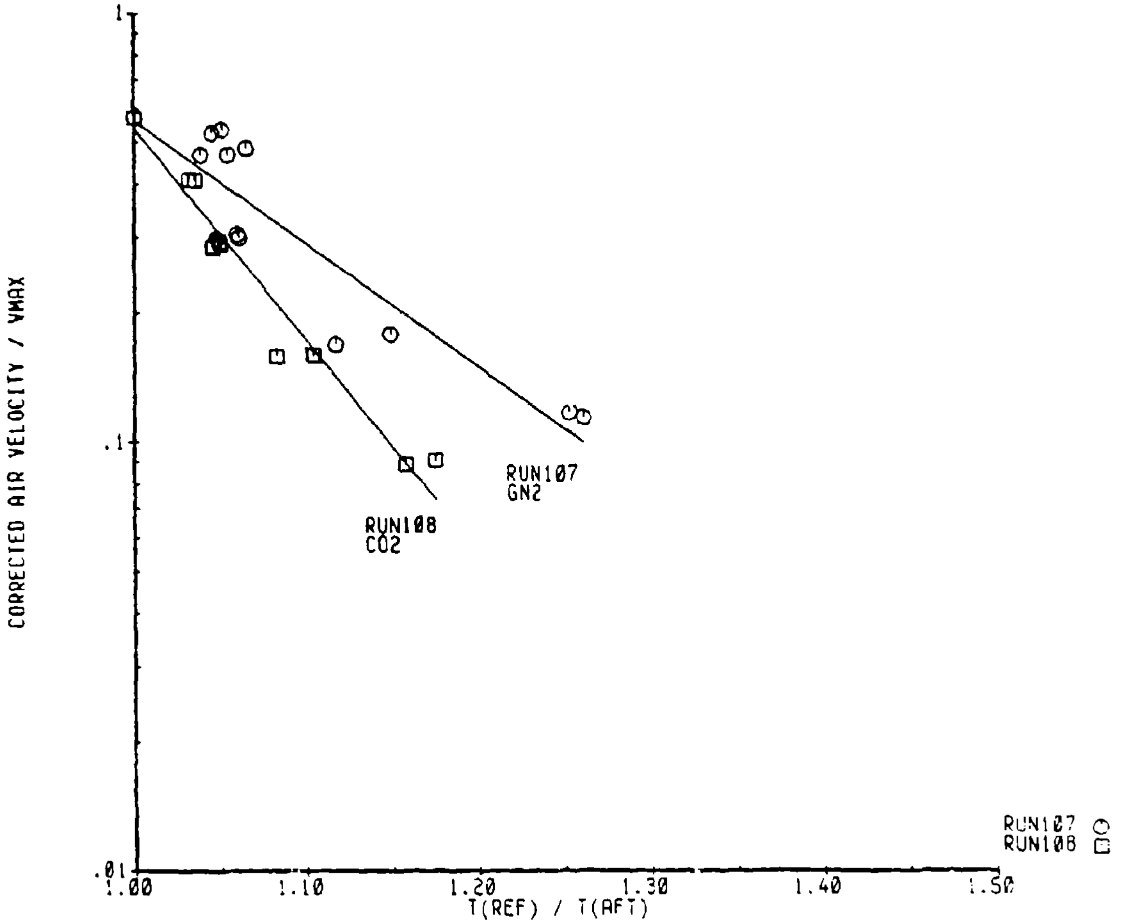
|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE FLUID, VARIOUS EXTINGUISHANTS | FIGURE<br>G-3A |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 158 |

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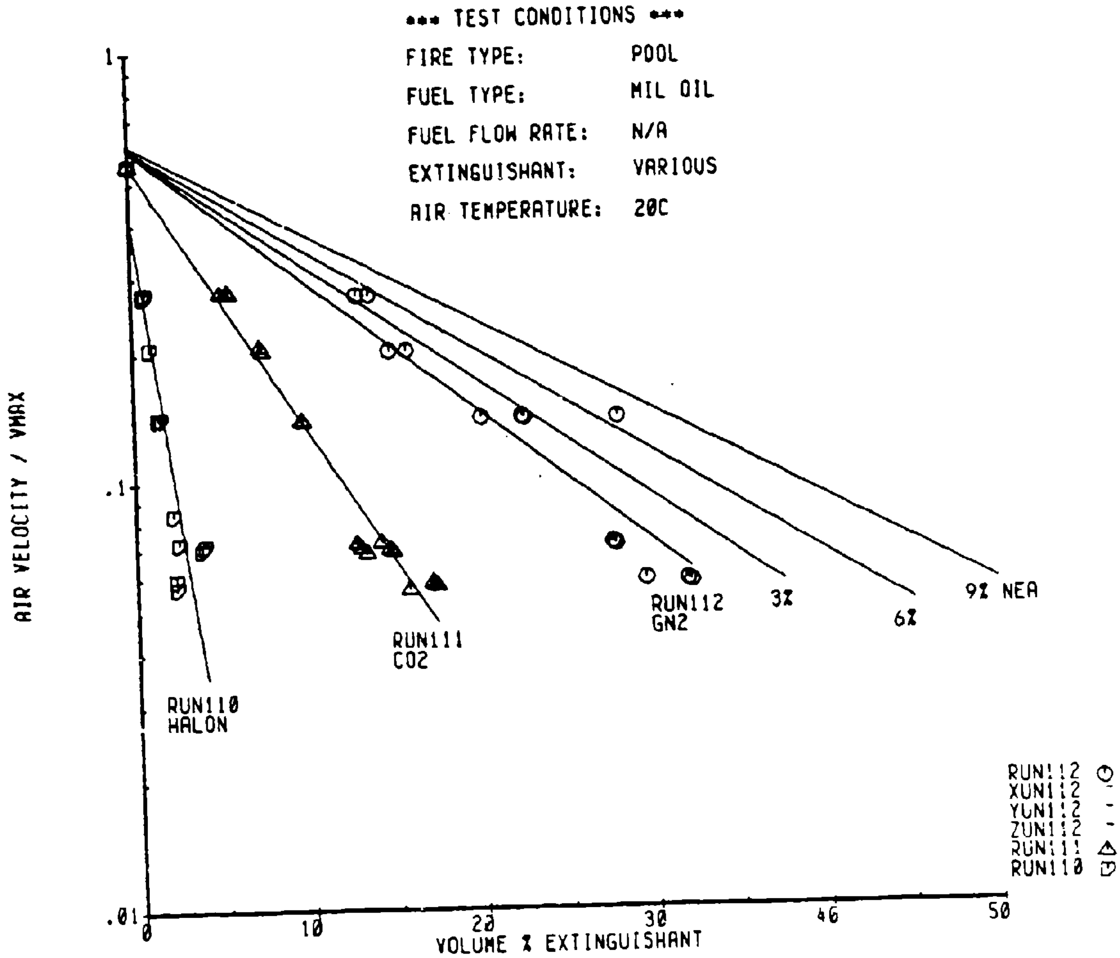
| CALC | | 10DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE FLUID, VARIOUS EXTINGUISHANTS | FIGURE |
| CHECK | | | | | | G-38 |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 159 |




| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE FLUID, VARIOUS EXTINGUISHANTS | FIGURE<br>G-4A |
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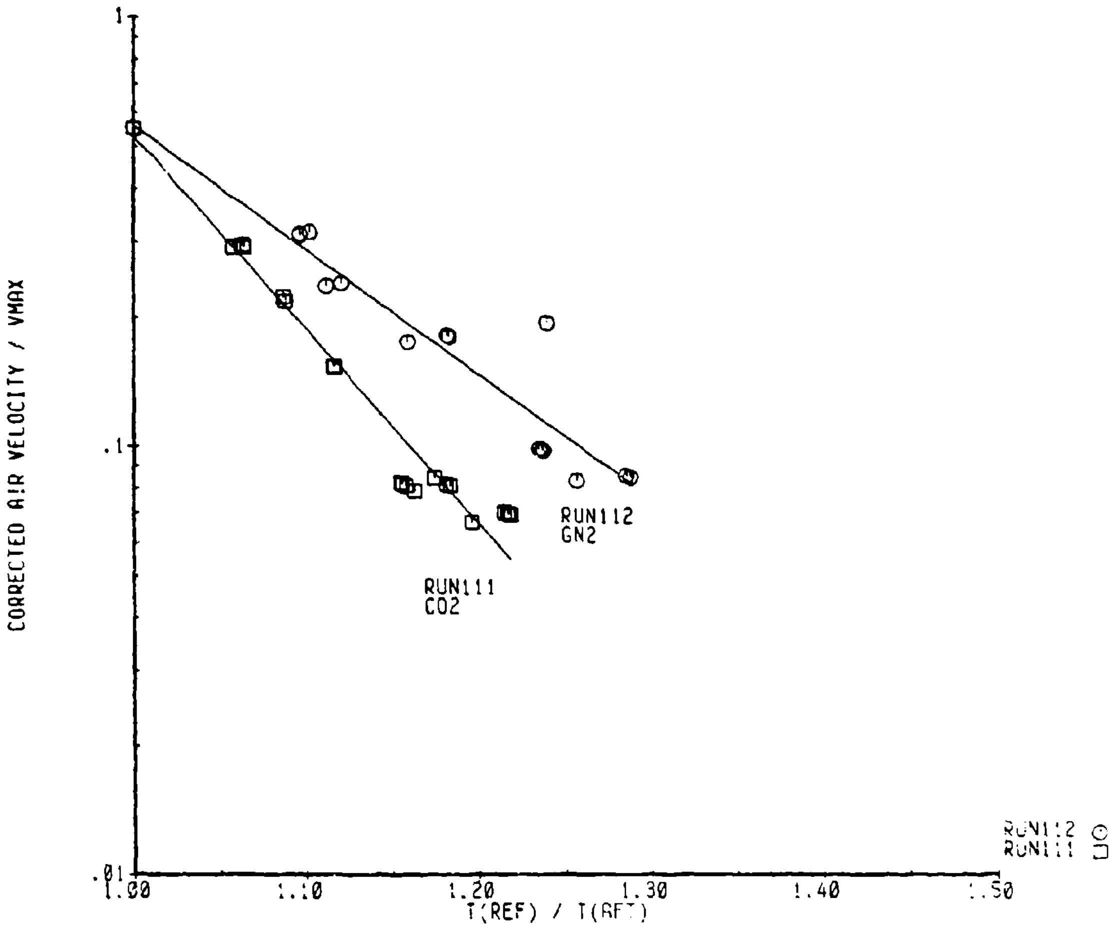
| CHECK | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 160 |
| APPD. | | | | | | |

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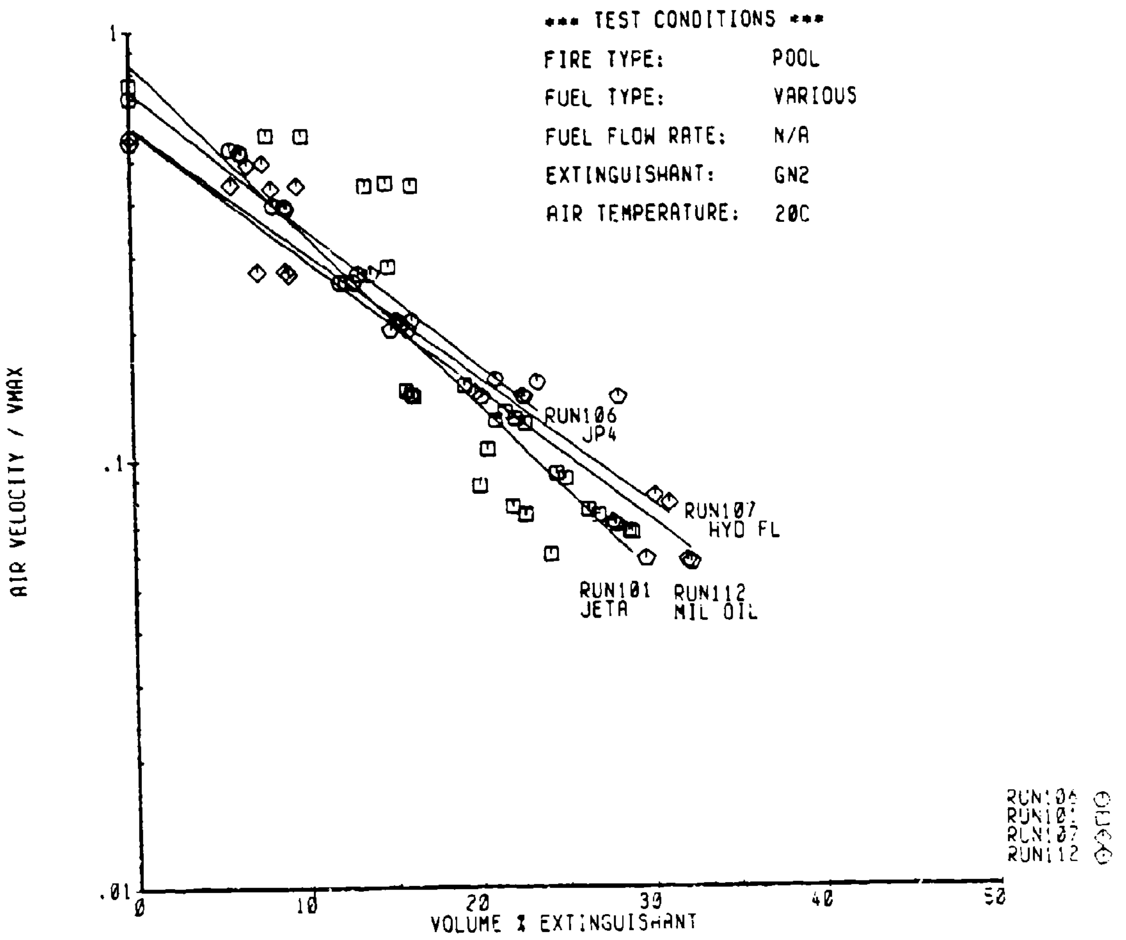
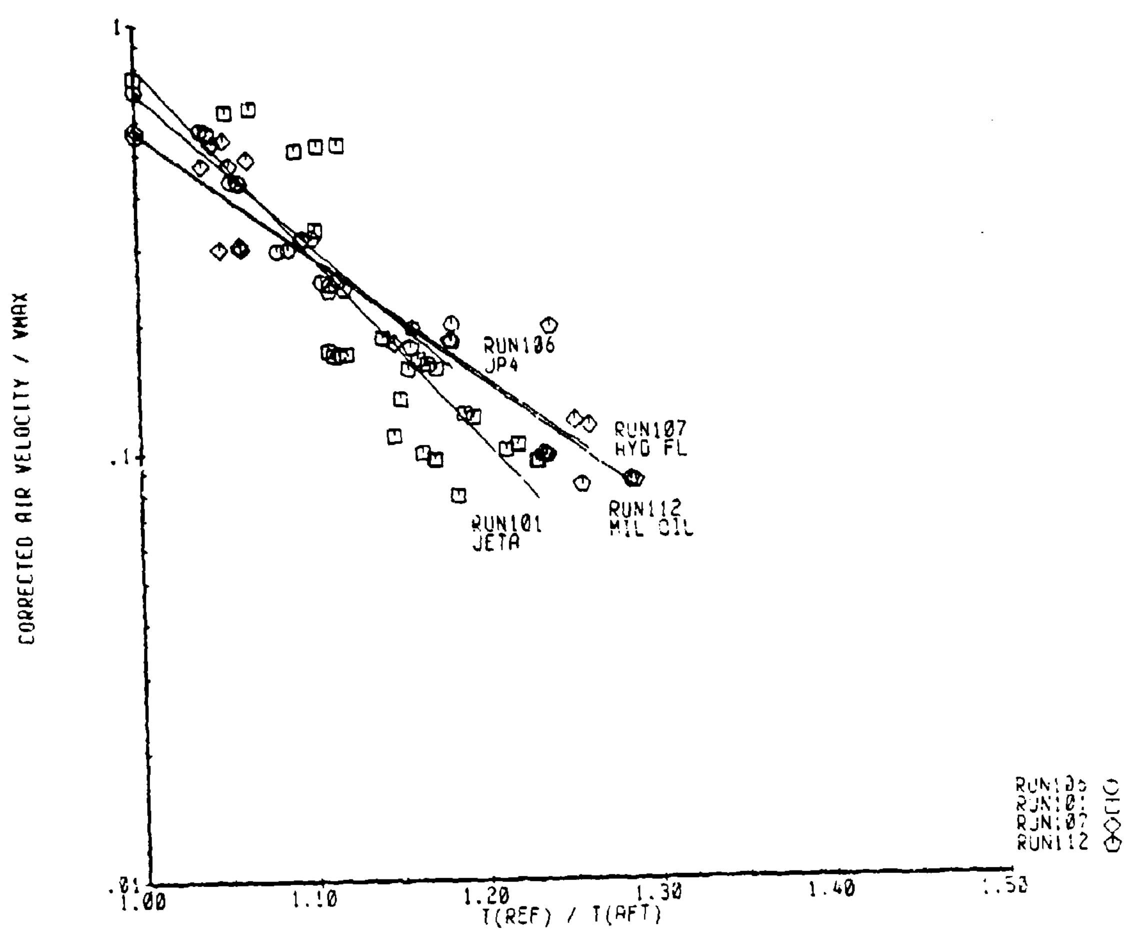
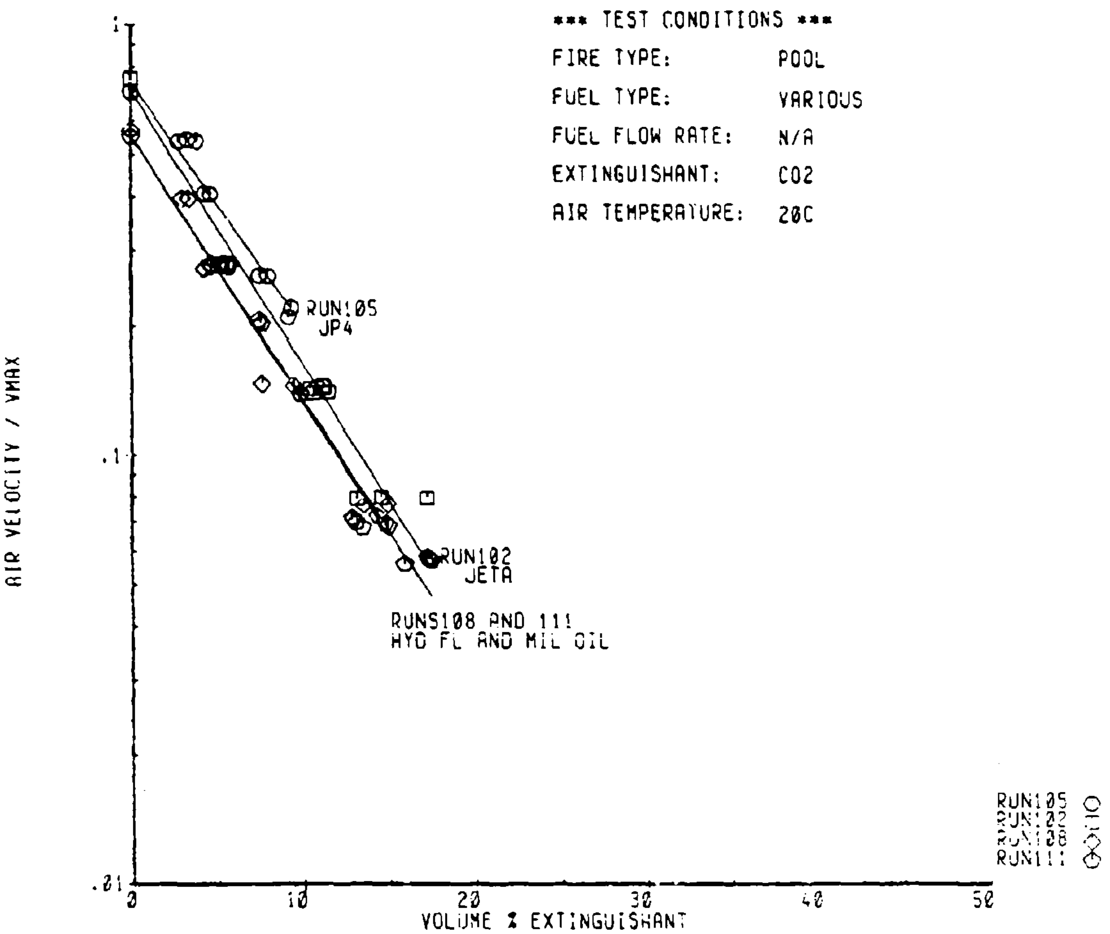
|---|---|---|---|---|---|---|
| CALC | | 10DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION POOL FIRE ONE FLUID, VARIOUS EXTINGUISHANTS | FIGURE G-4B |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 161 |



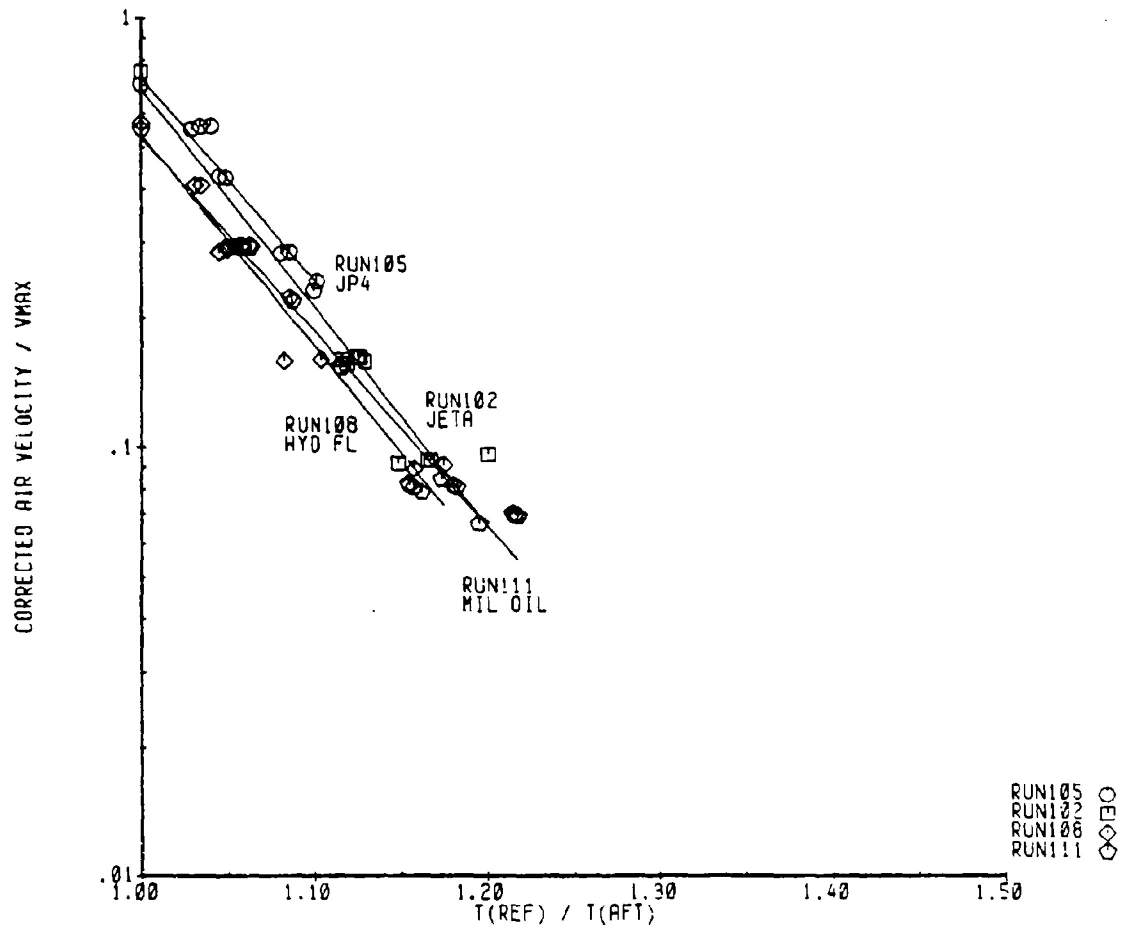

| CALC | ORDEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION POOL FIRE ONE EXTINGUISHANT, VARIOUS FLUIDS | FIGURE G-5A |
|---|---|---|---|---|---|
| CHECK | | | | | |
| APPD. | | | | THE BOEING COMPANY | PAGE 162 |
| APPD. | | | | | |




| CALC | | 10DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE EXTINGUISHANT, VARIOUS FLUIDS | FIGURE<br>G-58 |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 163 |
| APPD. | | | | | | |




| CALC | 28DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE EXTINGUISHANT, VARIOUS FLUIDS | FIGURE<br>G-6A |
|---|---|---|---|---|---|
| CHECK | | | | | |
| APPD. | | | | | |
| APPD. | | | | THE BOEING COMPANY | PAGE 164 |

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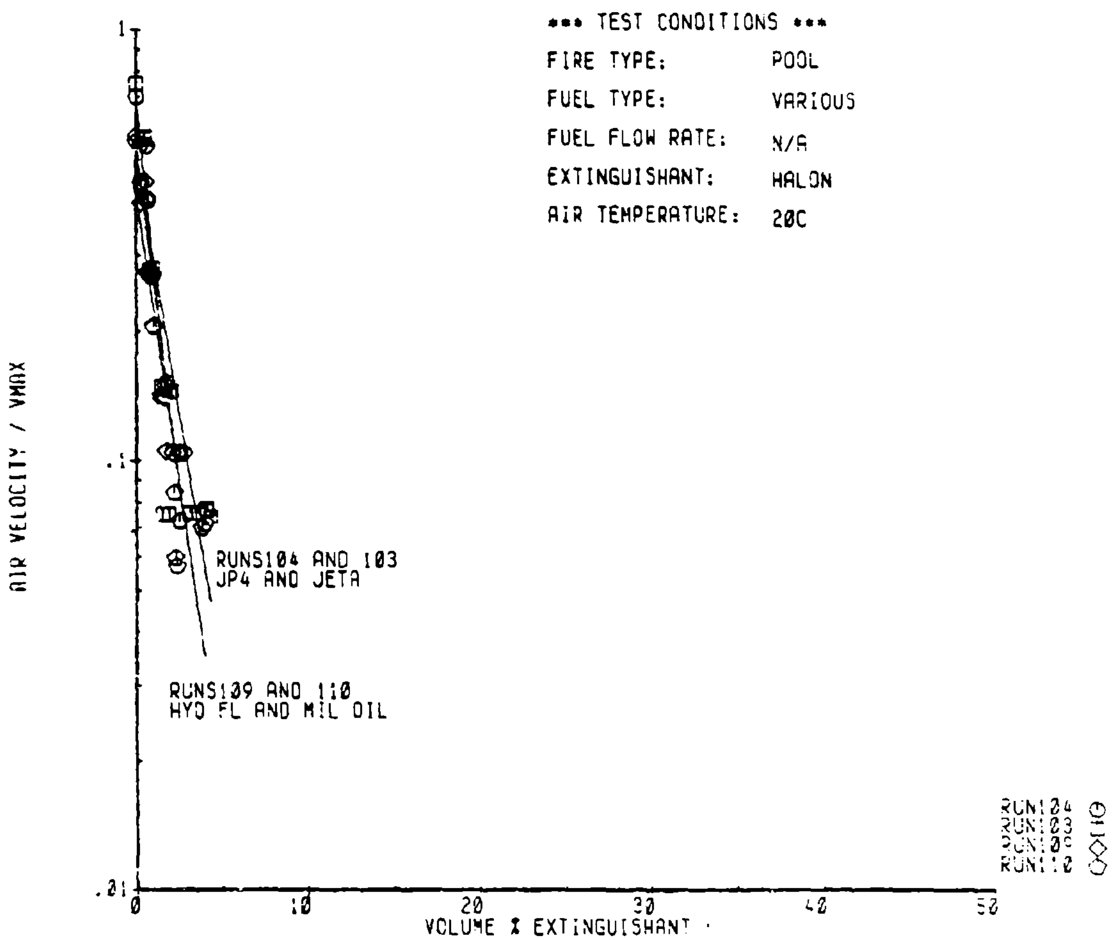
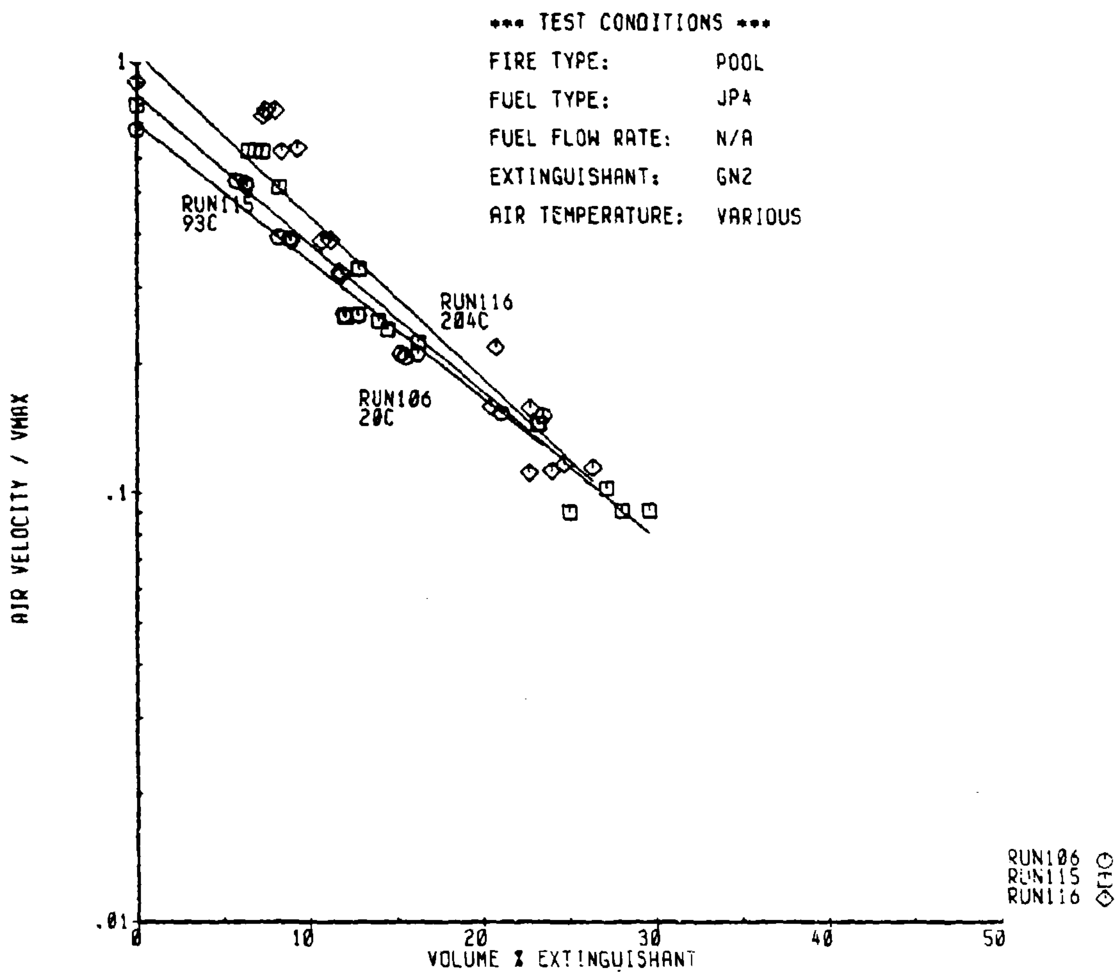
| CALC | | 10DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE EXTINGUISHANT, VARIOUS FLUIDS | FIGURE |
| CHECK | | | | | | G-6B |
| APPD. | | | | | THE BOEING COMPANY | PAGE 165 |
| APPD. | | | | | | |




| CALC | 08DEC90 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE EXTINGUISHANT VARIOUS FLUIDS | FIGURE<br>G-7 |
|---|---|---|---|---|---|
| CHECK | | | | | |
| APPD | | | | THE BOEING COMPANY | PAGE 166 |
| APPD | | | | | |

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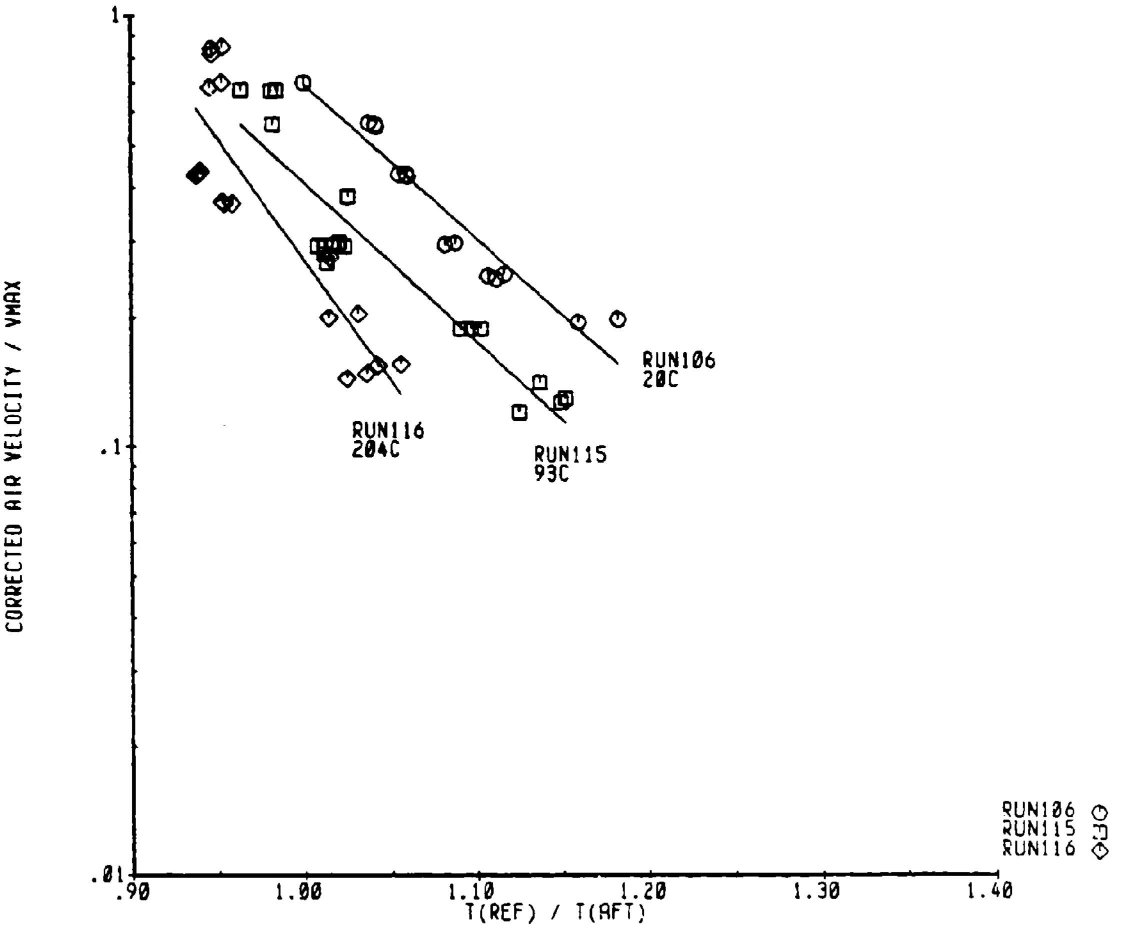
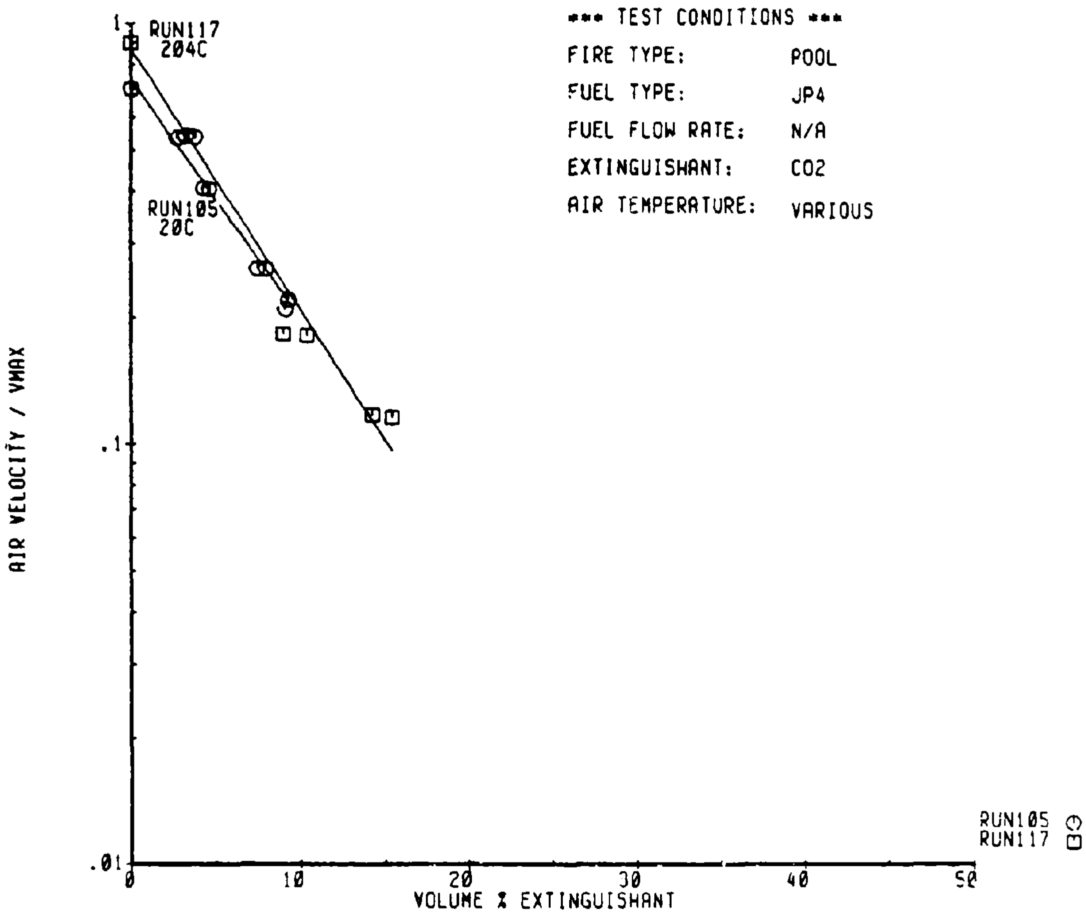
|---|---|---|---|---|---|---|
| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION | FIGURE |
| CHECK | | | | | POOL FIRE | |
| APPD. | | | | | ONE FLUID, ONE EXT, VAR. AIR TEMPS | G-8A |
| APPD. | | | | | THE BOEING COMPANY | PAGE 167 |




| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION | FIGURE |
|---|---|---|---|---|---|---|
| CHECK | | | | | POOL FIRE | G-88 |
| APPD. | | | | | ONE FLUID, ONE EXT, VAR. AIR TEMPS | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 168 |

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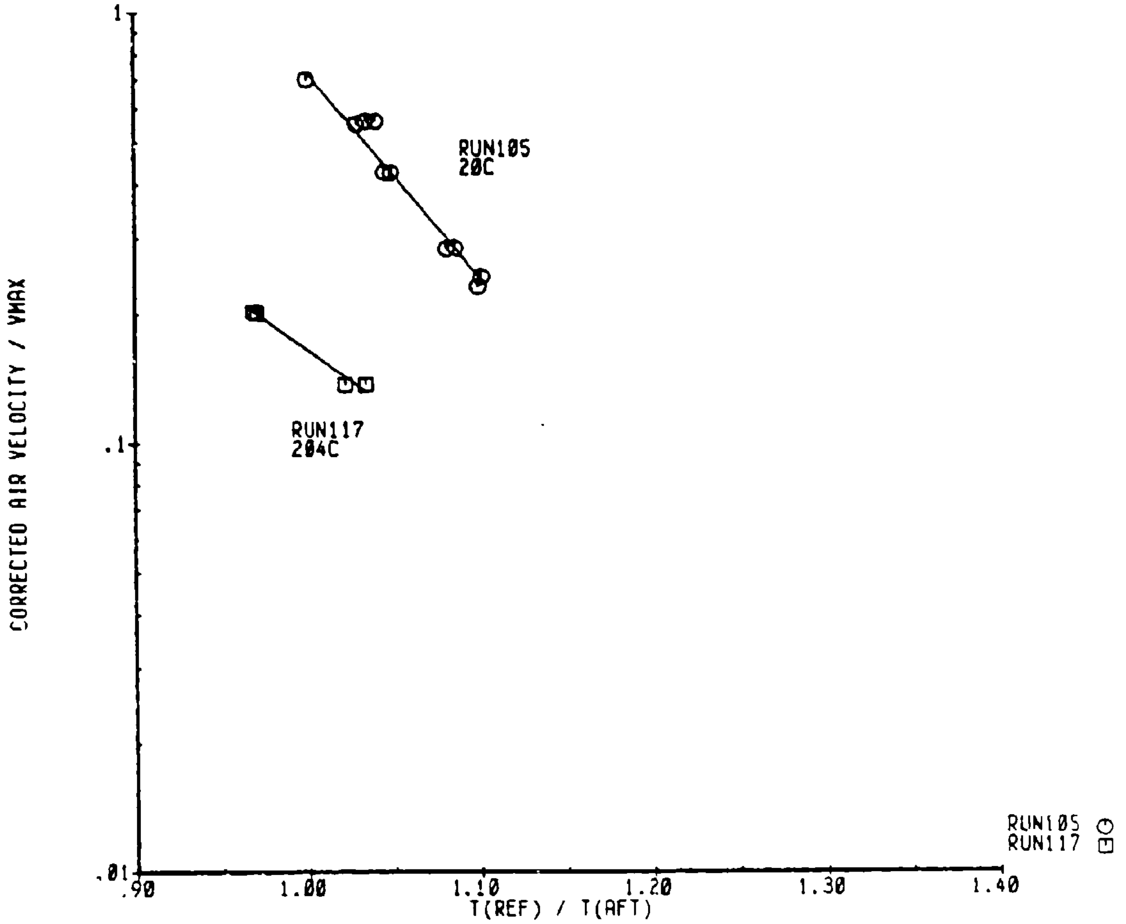
|---|---|---|---|---|---|---|
| CALC | | 08DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE FLUID, ONE EXT., VAR. AIR TEMPS. | FIGURE<br>G-9A |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 169 |

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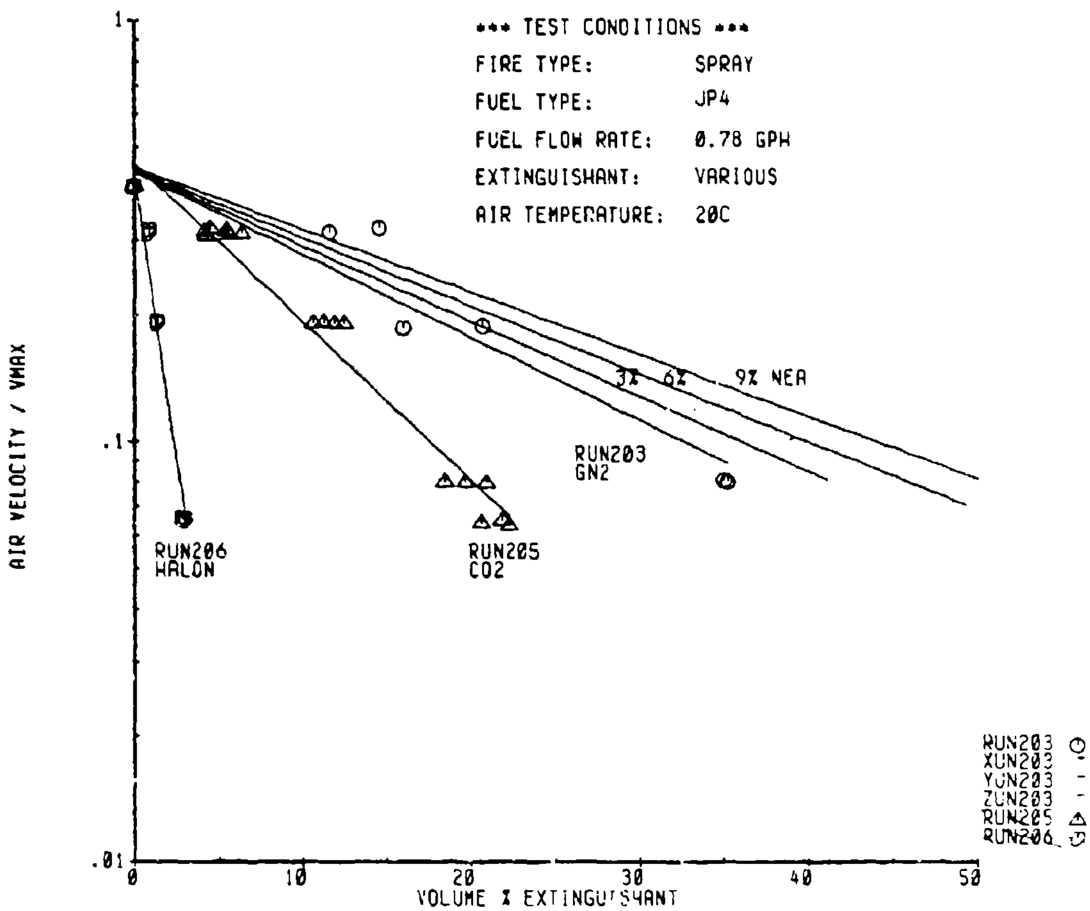
|---|---|---|---|---|---|
| CALC | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>POOL FIRE<br>ONE FLUID, ONE EXT, VAR, AIR TEMPS | FIGURE<br>G-98 |
| CHECK | | | | | |
| APPD. | | | | | |
| APPD. | | | | THE BOEING COMPANY | PAGE 170 |

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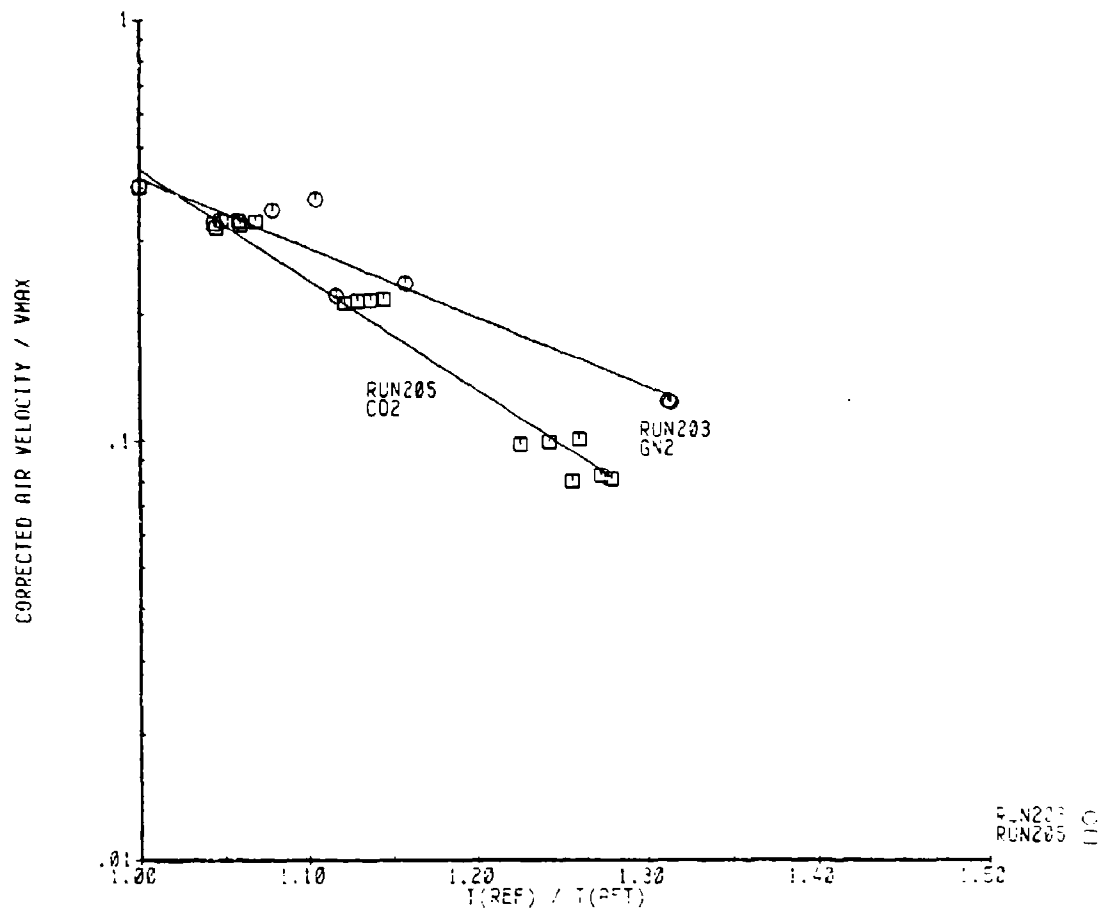
|---|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE<br>ONE FLUID, VARIOUS EXTINGUISHANTS | FIGURE<br>G-10. |
| CHECK | | | | | | |
| APPD | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 171 |

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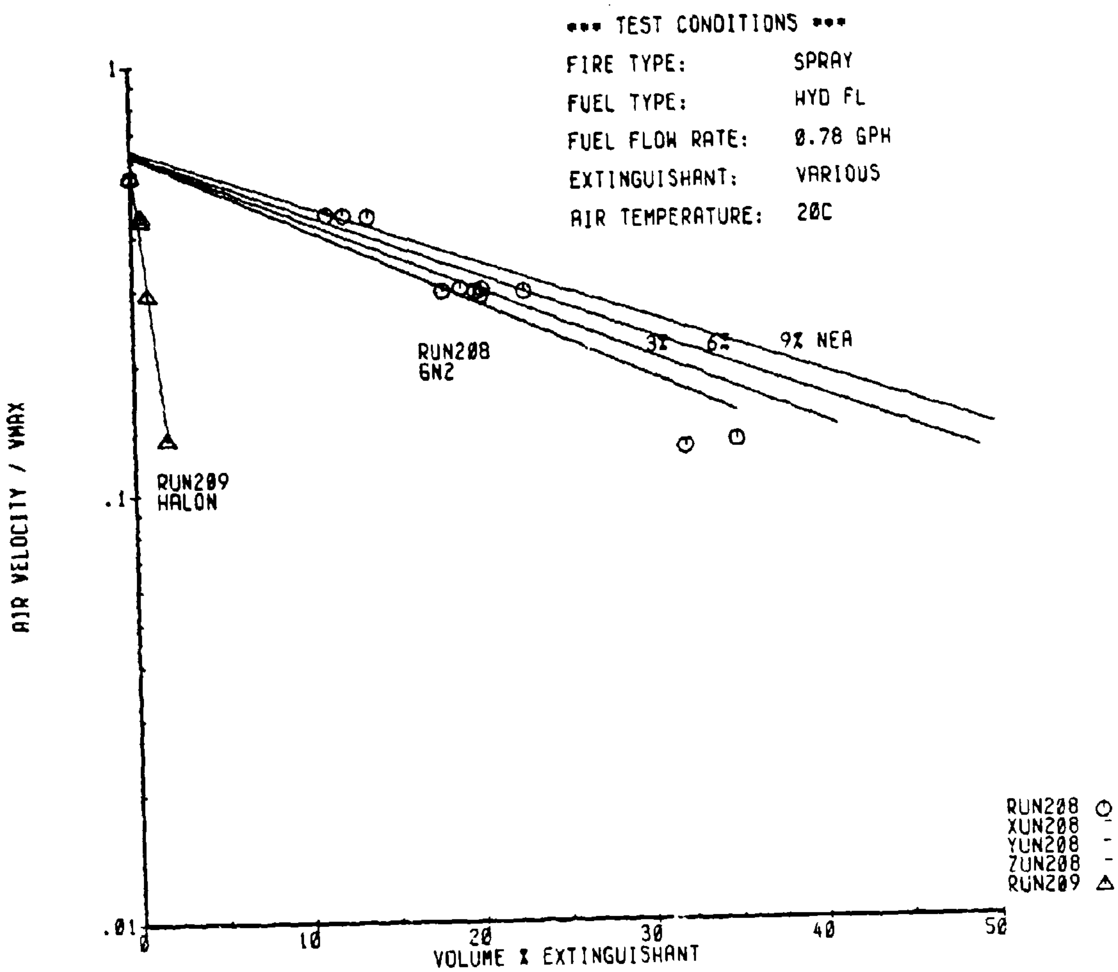
|---|---|---|---|---|
| CALC | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE<br>ONE FLUID, VARIOUS EXTINGUISHANTS |
| CHECK | | | | |
| APPD. | | | | |
| APPD. | | | | THE BOEING COMPANY |

FIGURE G-10B

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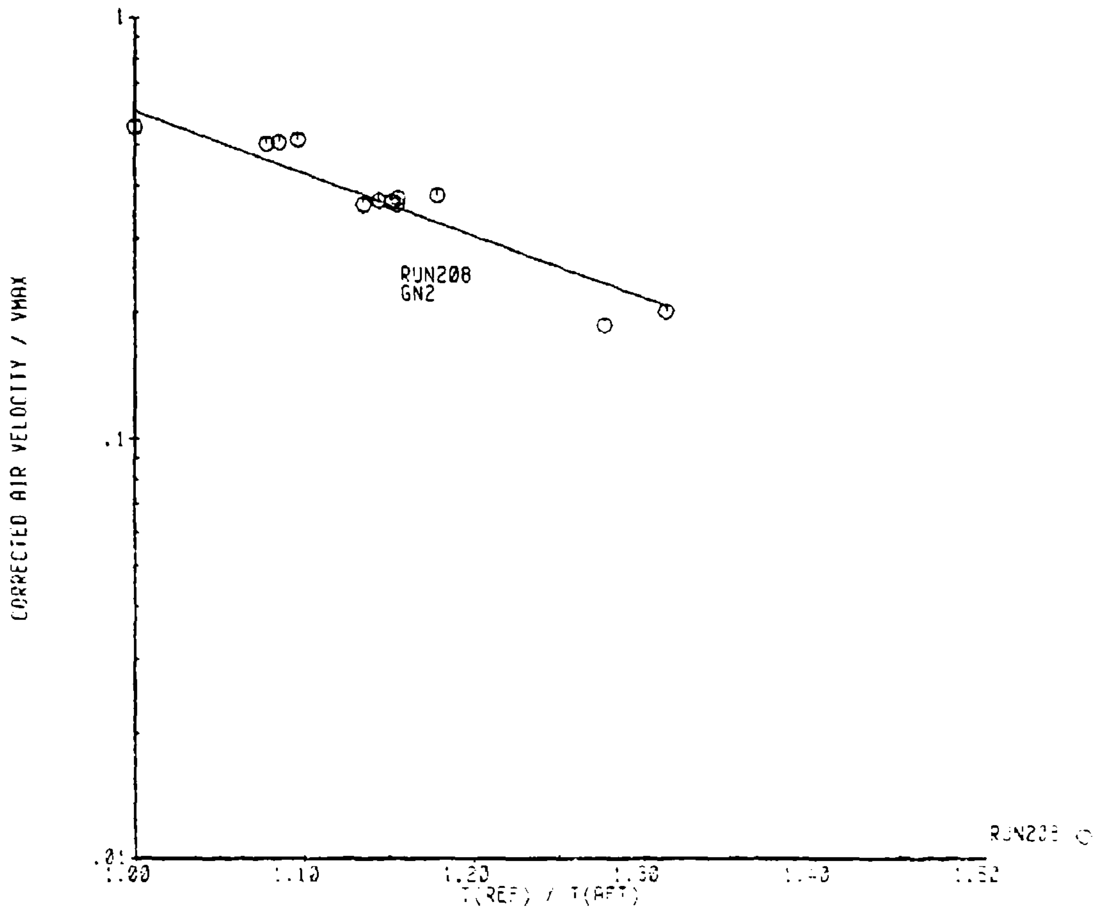
|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE<br>ONE FLUID, VARIOUS EXTINGUISHANTS |
| CHECK | | | | | |
| APPD. | | | | | |
| APPD. | | | | | THE BOEING COMPANY |

FIGURE G-11A



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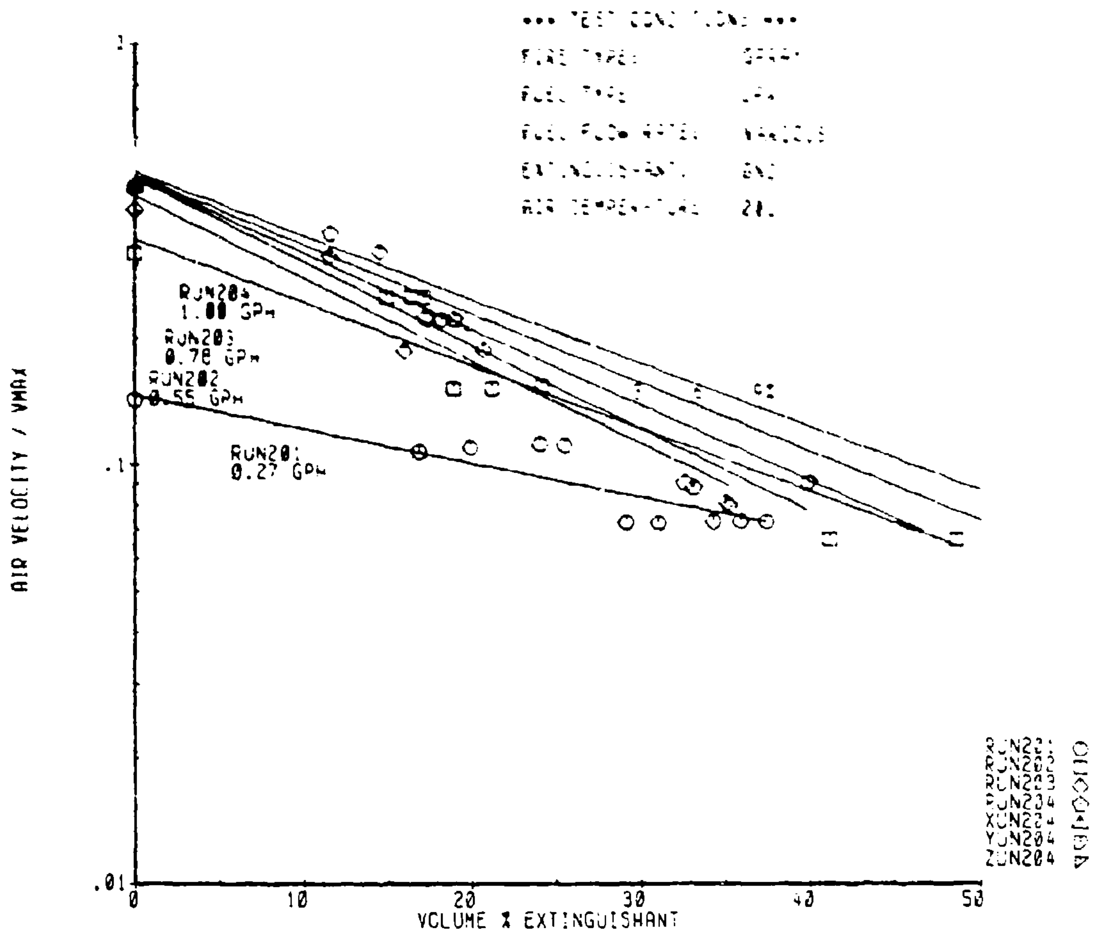
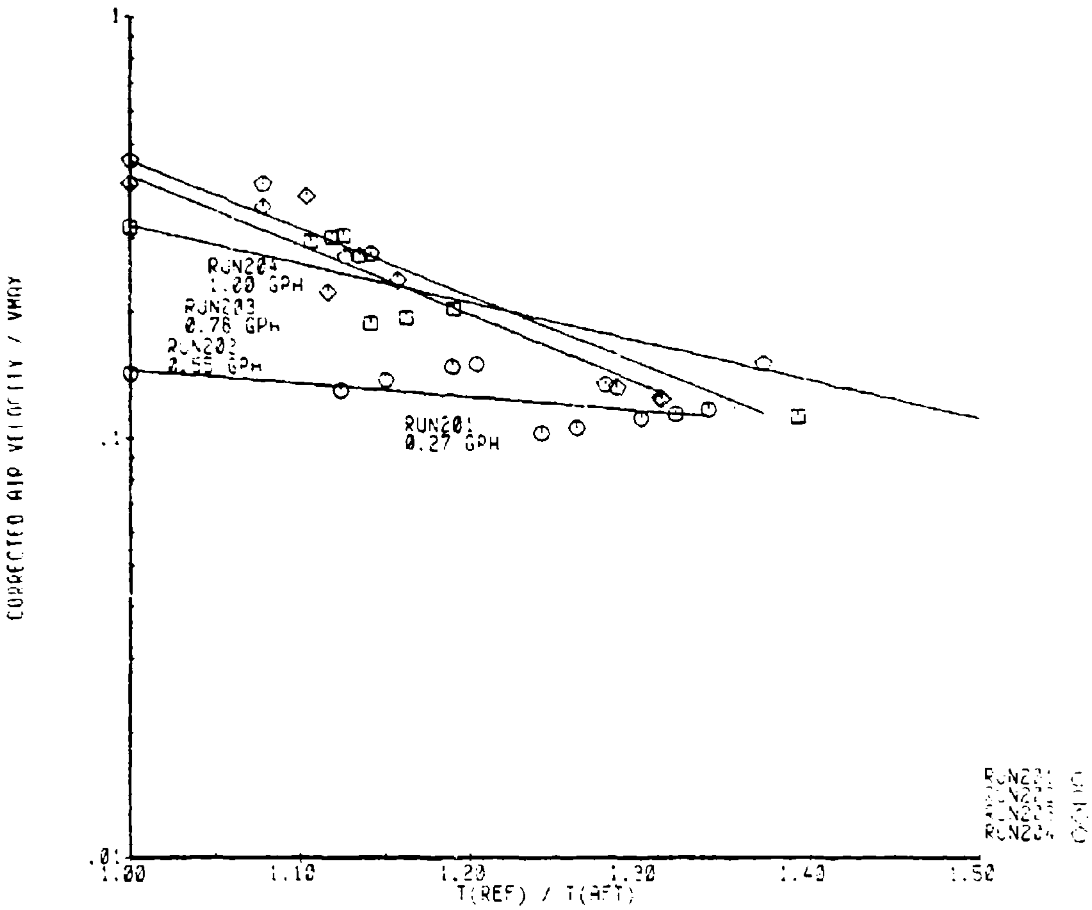
.1
CORRECTED AIR VELOCITY / VMAX
RUN208
GN2
1.00
1.10
1.20
1.30
T(REF) / T(AFT)

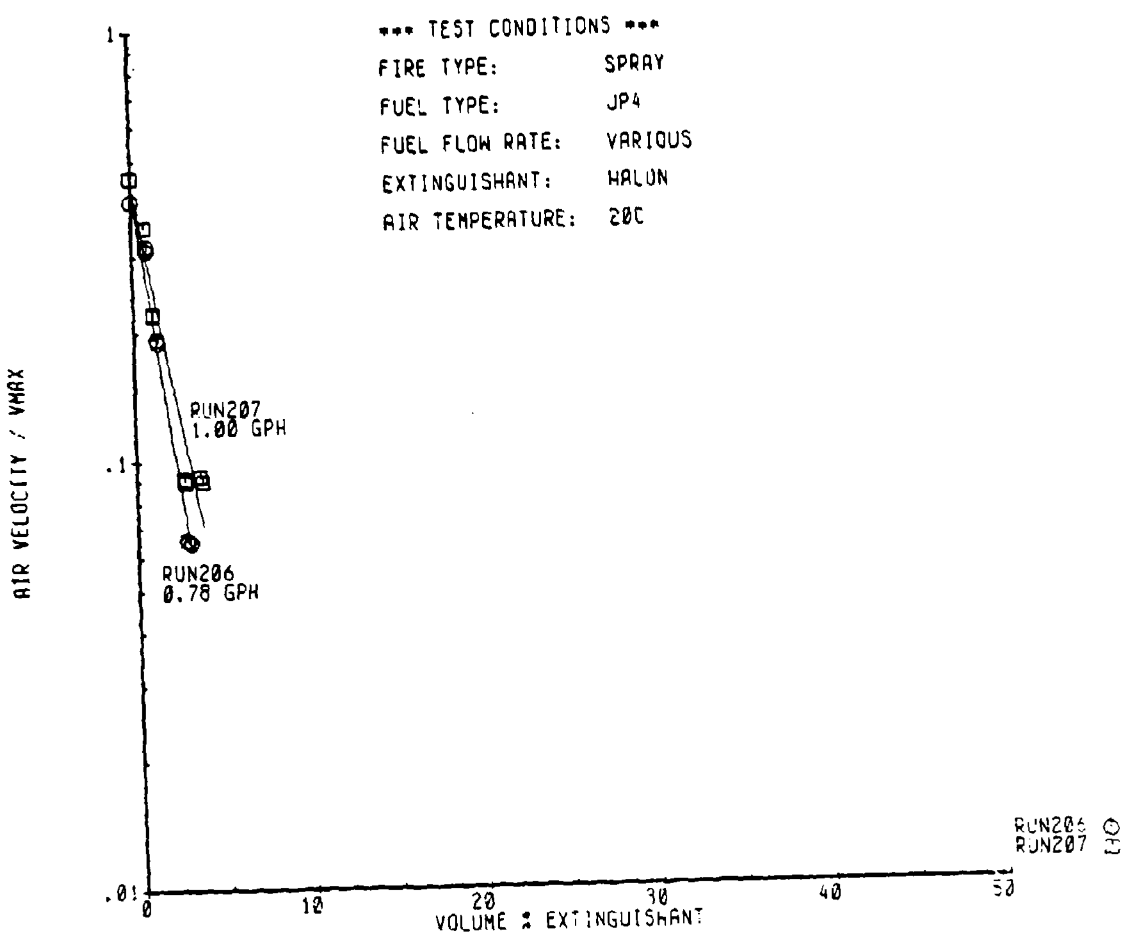

FIGURE G-11B



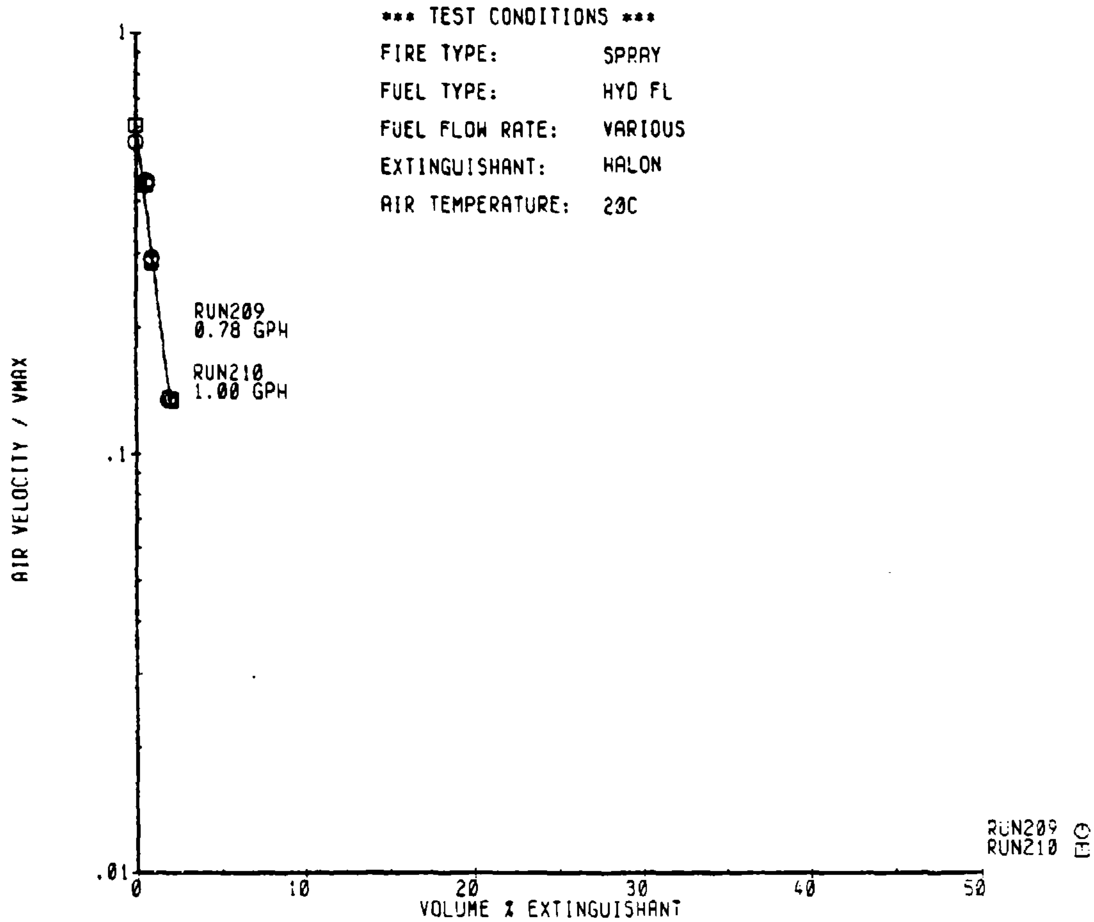

| CALC | 10DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE | FIGURE<br>G-12A |
|---|---|---|---|---|---|
| CHECK | | | | | |
| APPD. | | | | | |
| APPD. | | | | THE BOEING COMPANY | PAGE 175 |




| DRAWN | CHECKED | REVISED | DATE | ENGINE COMPARTMENT SIMULATION SPRAY FIRE ONE EXT., ONE FLUID, VAR. FUEL FLOW | FIGURE G-12B |
|---|---|---|---|---|---|
| CHECK | | | | | |
| APPD. | | | | | |
| APPD. | | | | THE BOEING COMPANY | PAGE 176 |




| CALC | | 10DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE<br>ONE EXT., ONE FLUID, VAR. FUEL FLOW | FIGURE<br>G-13 |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 177 |
| APPD. | | | | | | |

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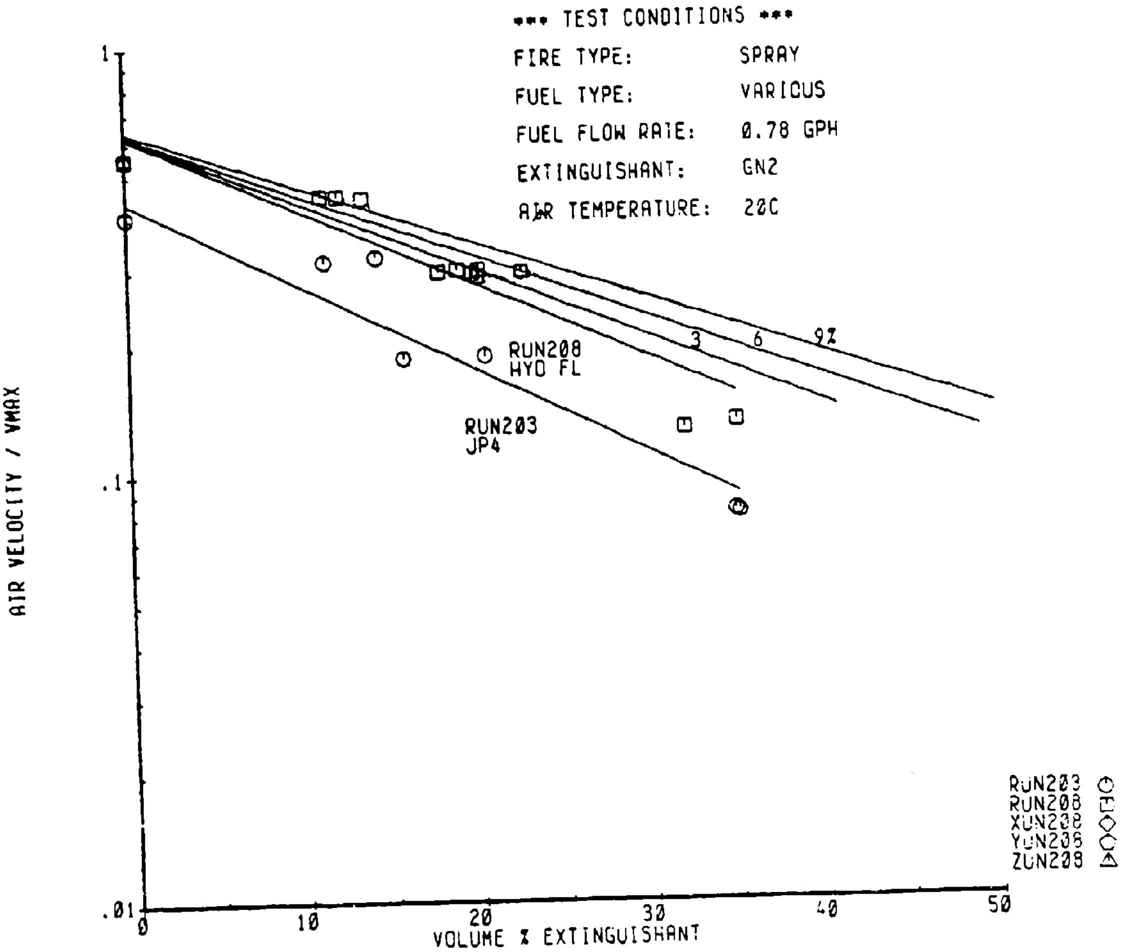
| CALC | | 10DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE<br>ONE EXT., ONE FLUID, VAR. FUEL FLOW | FIGURE<br>G-14 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 178 |

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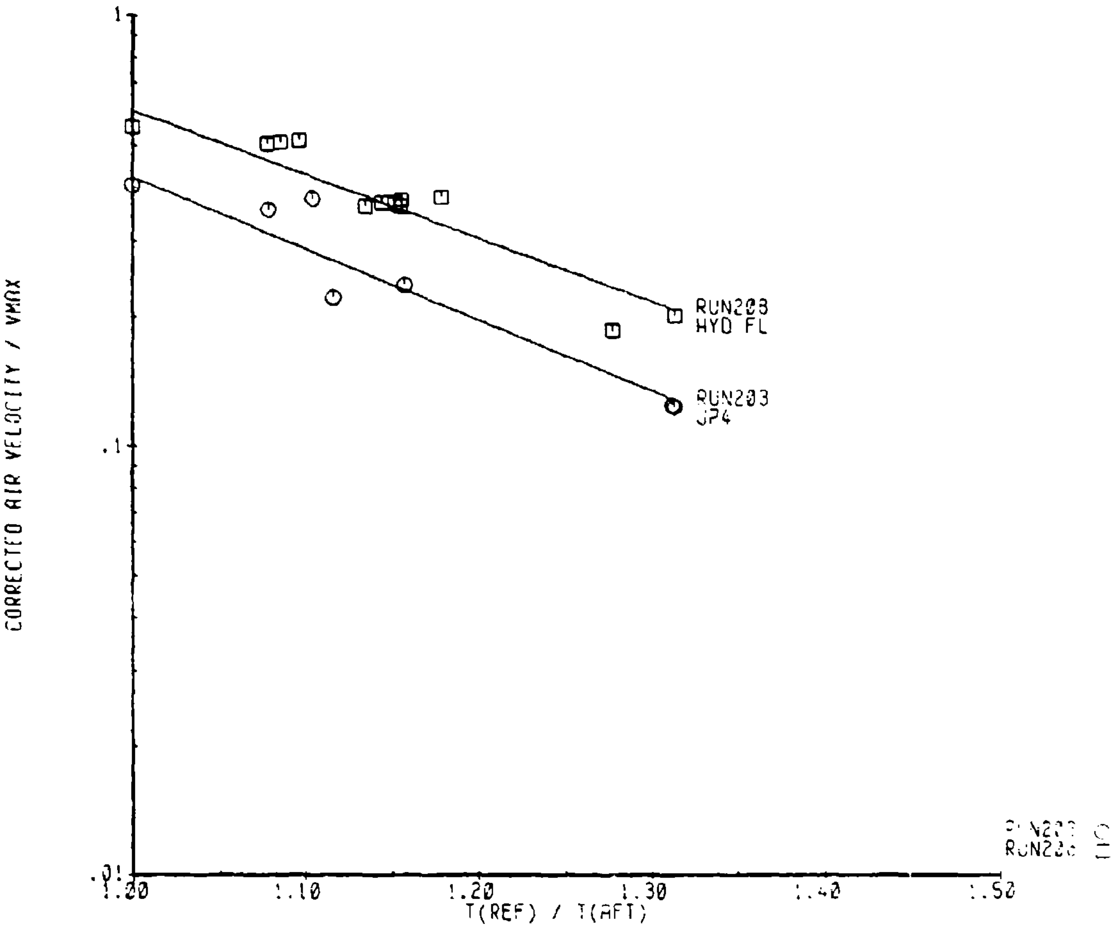
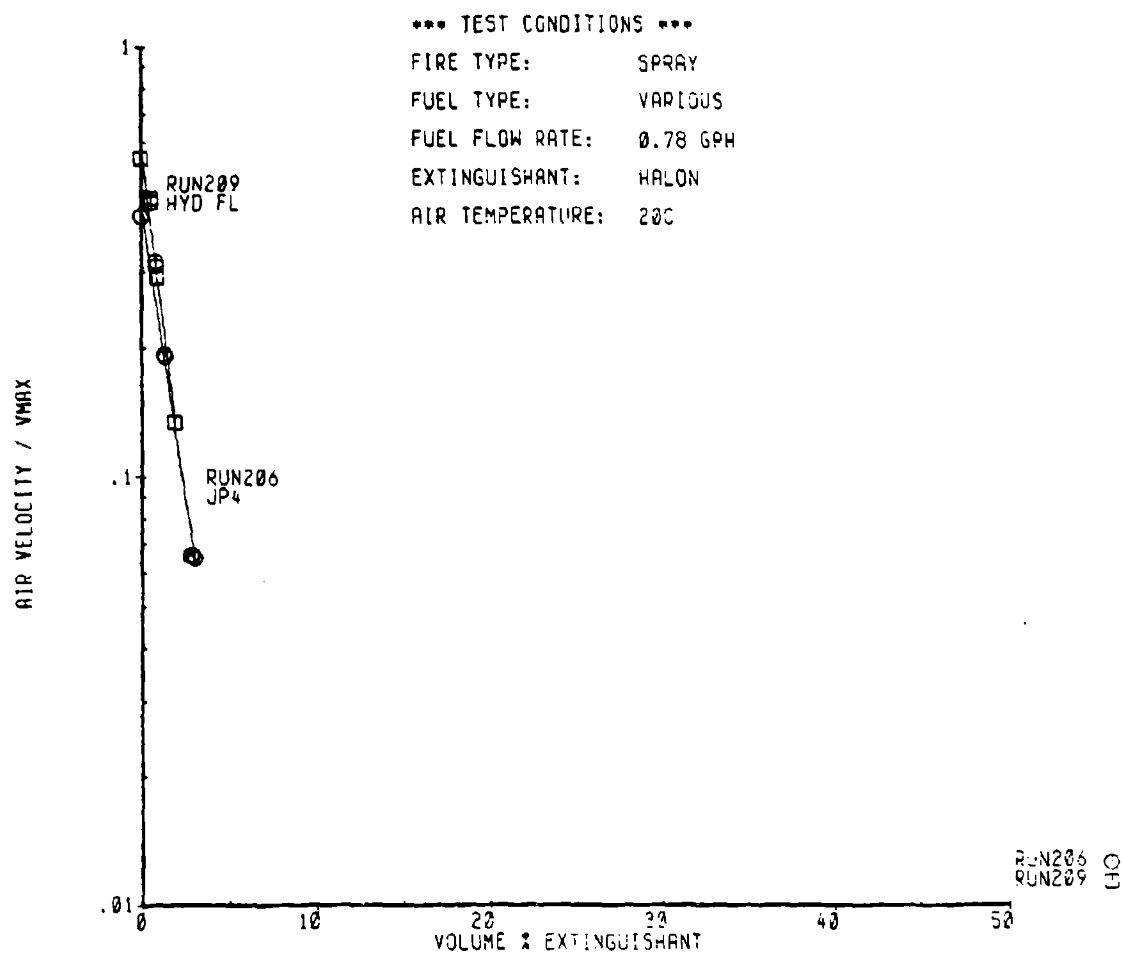
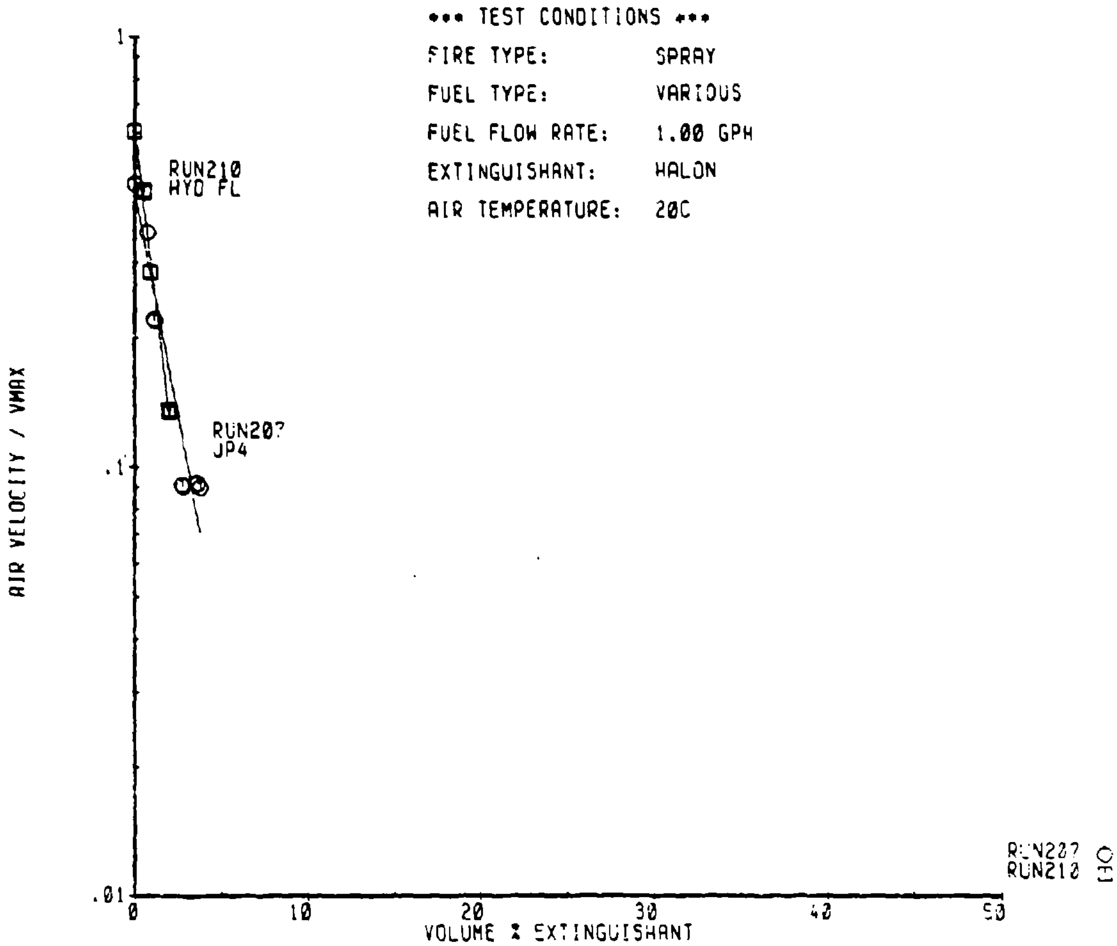
|---|---|---|---|---|---|
| CALC | | 10DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE<br>ONE EXTINGUISHANT, VAR. FLUIDS |
| CHECK | | | | | FIGURE G-15A |
| APPD. | | | | | THE BOEING COMPANY |
| APPD. | | | | | PAGE 179 |




| CALC | 110380 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION | FIGURE |
|---|---|---|---|---|---|
| CHECK | | | | SPRAY FIRE | |
| APPD. | | | | ONE EXTINGUISHANT, VAR. FLUIDS | G-158 |
| APPD. | | | | THE BOEING COMPANY | PAGE 180 |




| CALC | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION SPRAY FIRE ONE EXTINGUISHANT, VAR. FLUIDS | FIGURE G-16 |
|---|---|---|---|---|---|
| CHECK | | | | | |
| APPD. | | | | | |
| APPD. | | | | THE BOEING COMPANY | PAGE 181 |

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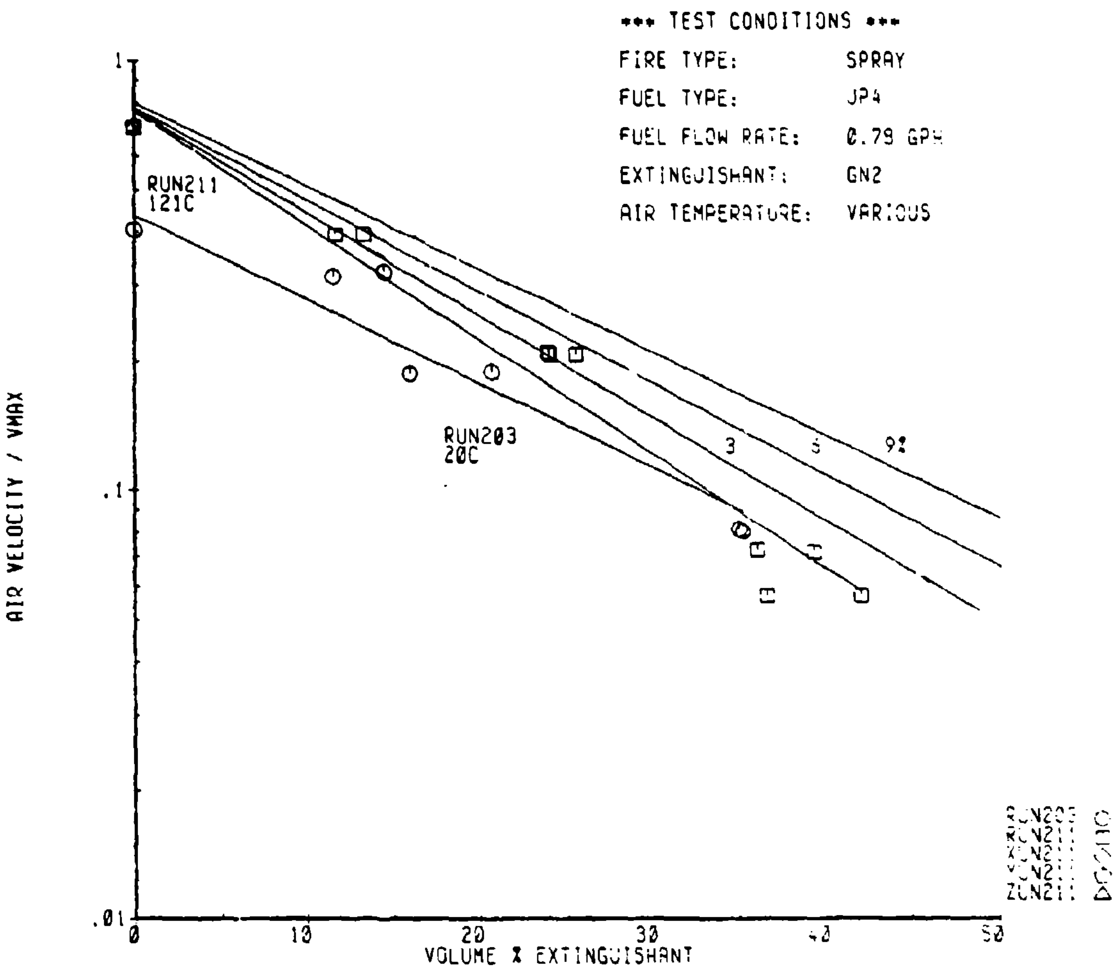
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE<br>ONE EXTINGUISHANT, VAR. FLUIDS |
| CHECK | | | | | FIGURE G-17 |
| APPD. | | | | | |
| APPD. | | | | | THE BOEING COMPANY |
| | | | | | PAGE 182 |

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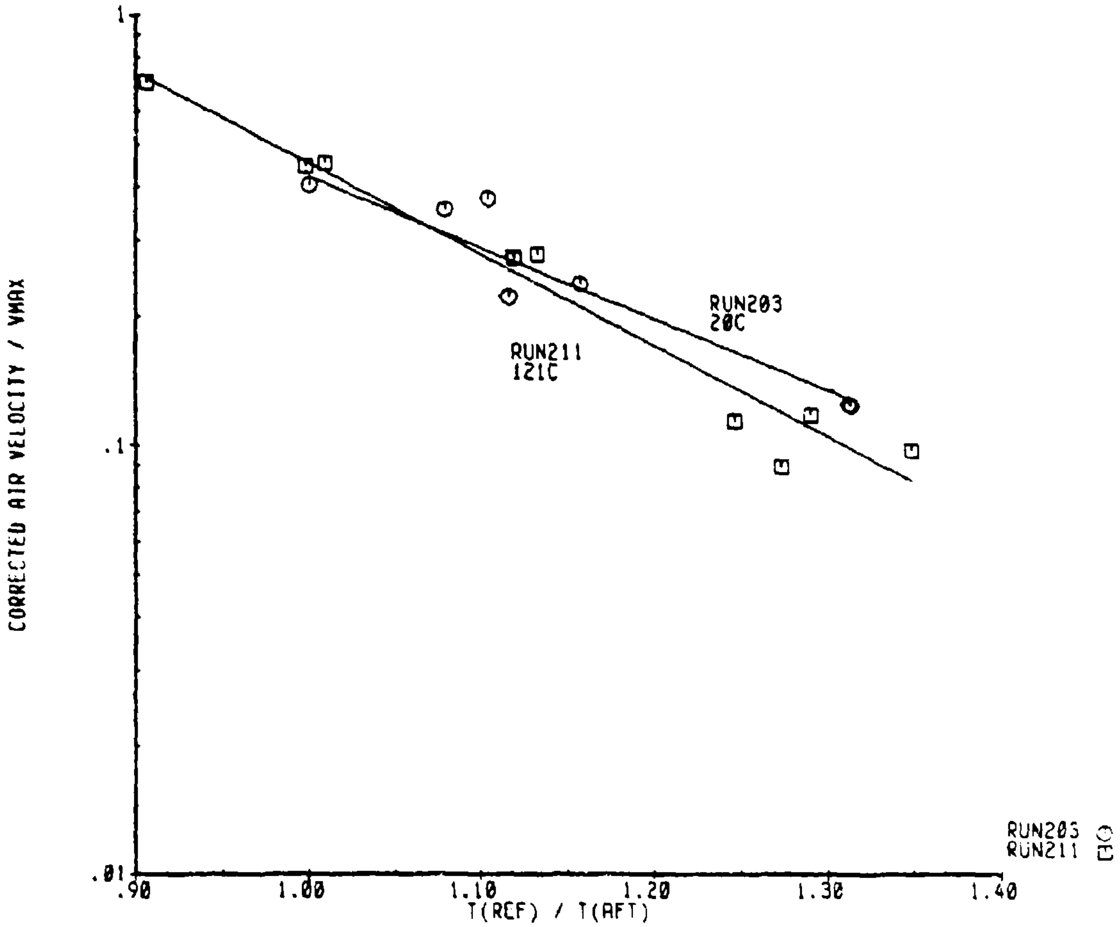
| CALC. | 11DEC80 | REVISED | DATE |
| CHECK | | | |
| APPD. | | | |
| APPD. | | | |

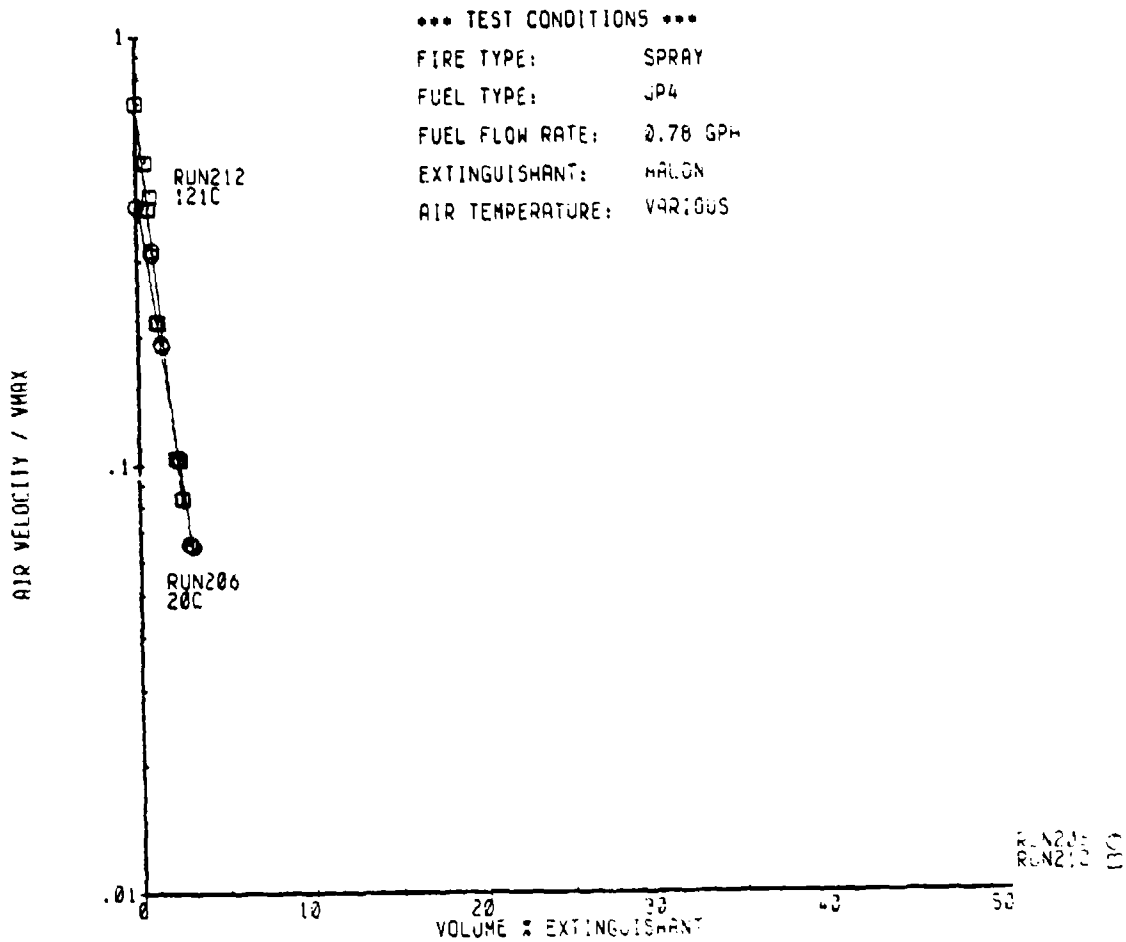
ENGINE COMPARTMENT SIMULATION
SPRAY FIRE
ONE EXT., ONE FLUID, VAR. AIR TEMP.

THE BOEING COMPANY

FIGURE G-18A




| CALC | | 14DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE<br>ONE EXT. ONE FLUID. VAR. AIR TEMP. | FIGURE<br>G-188 |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 184 |

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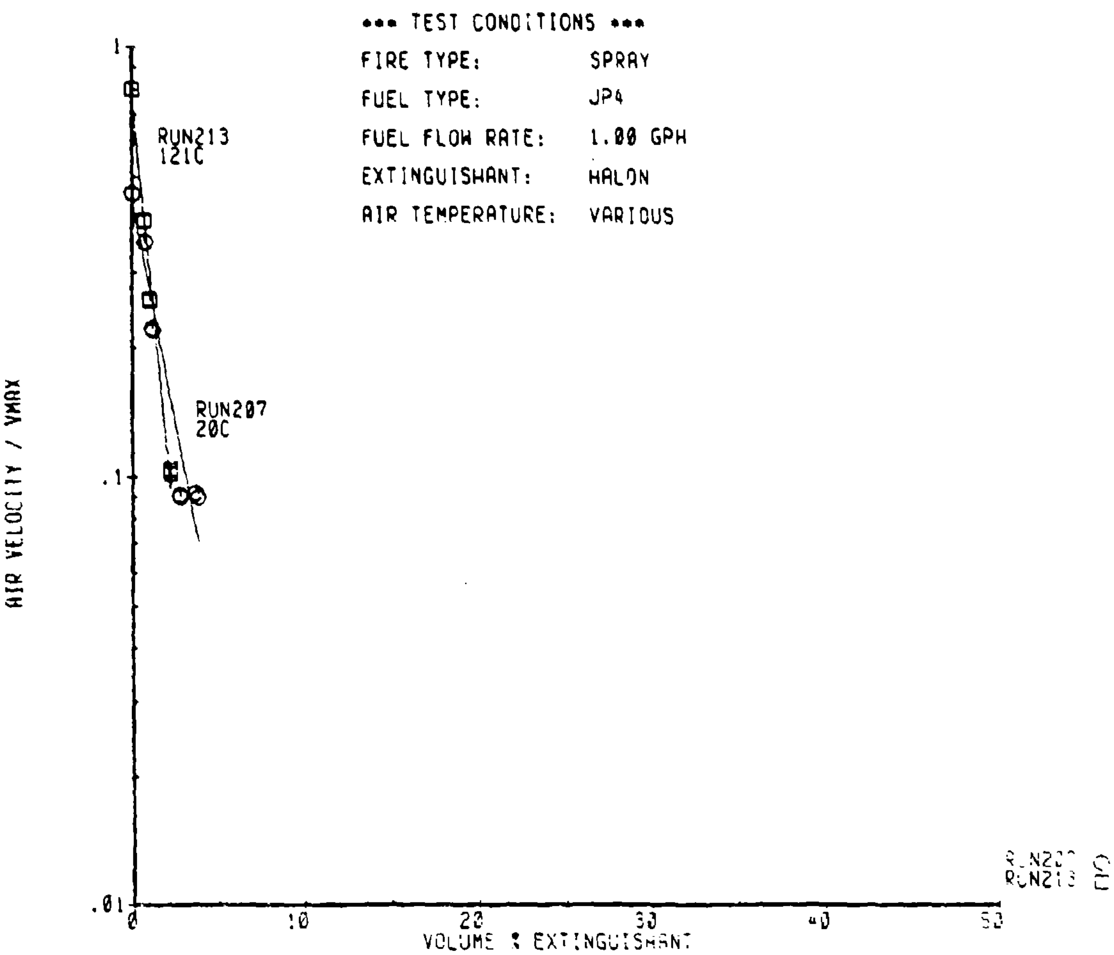
|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE<br>ONE EXT., ONE FLUID, VAR. AIR TEMP. | FIGURE G-19 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 185 |

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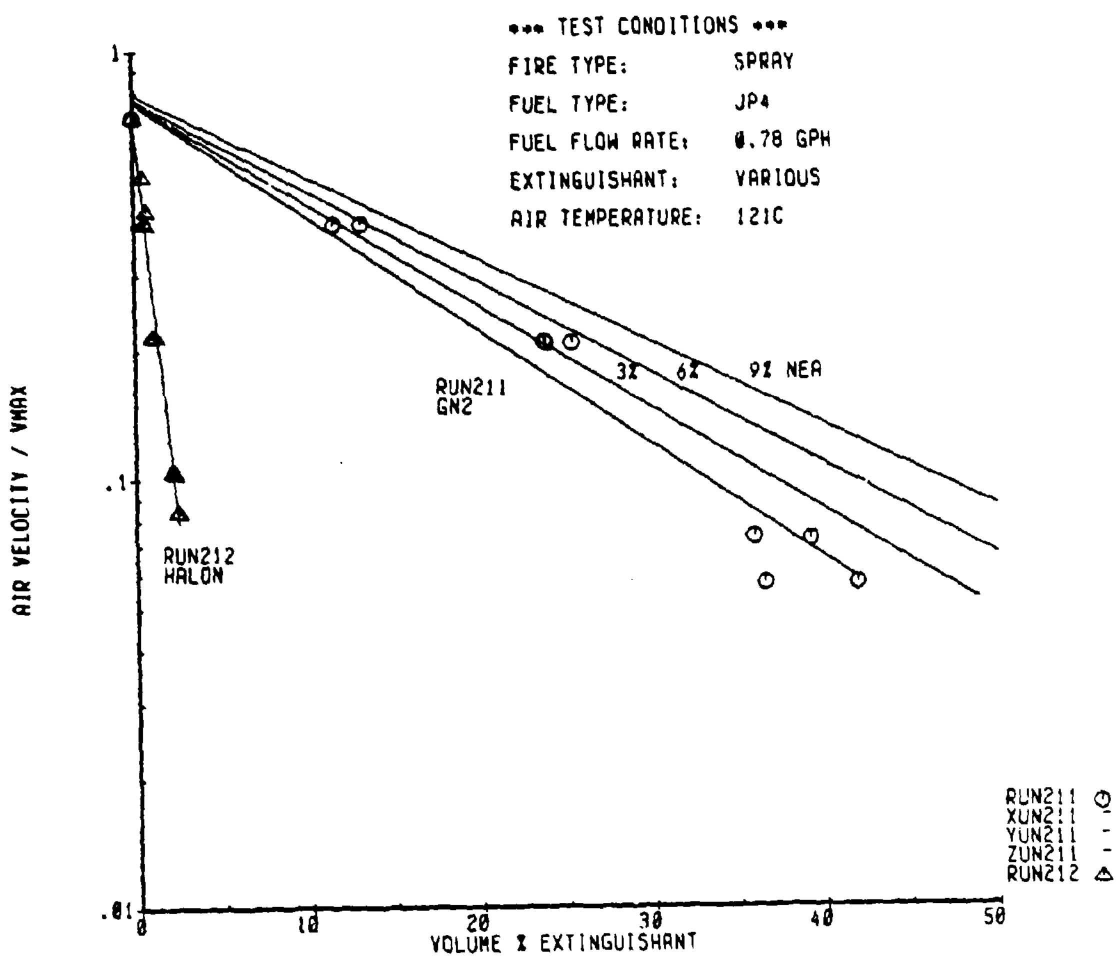
| CALC | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE<br>ONE EXT., ONE FLUID, VAR. AIR TEMP. | FIGURE<br>G-20 |
| CHECK | | | | | |
| APPD. | | | | | |
| APPD. | | | | THE BOEING COMPANY | PAGE 186 |

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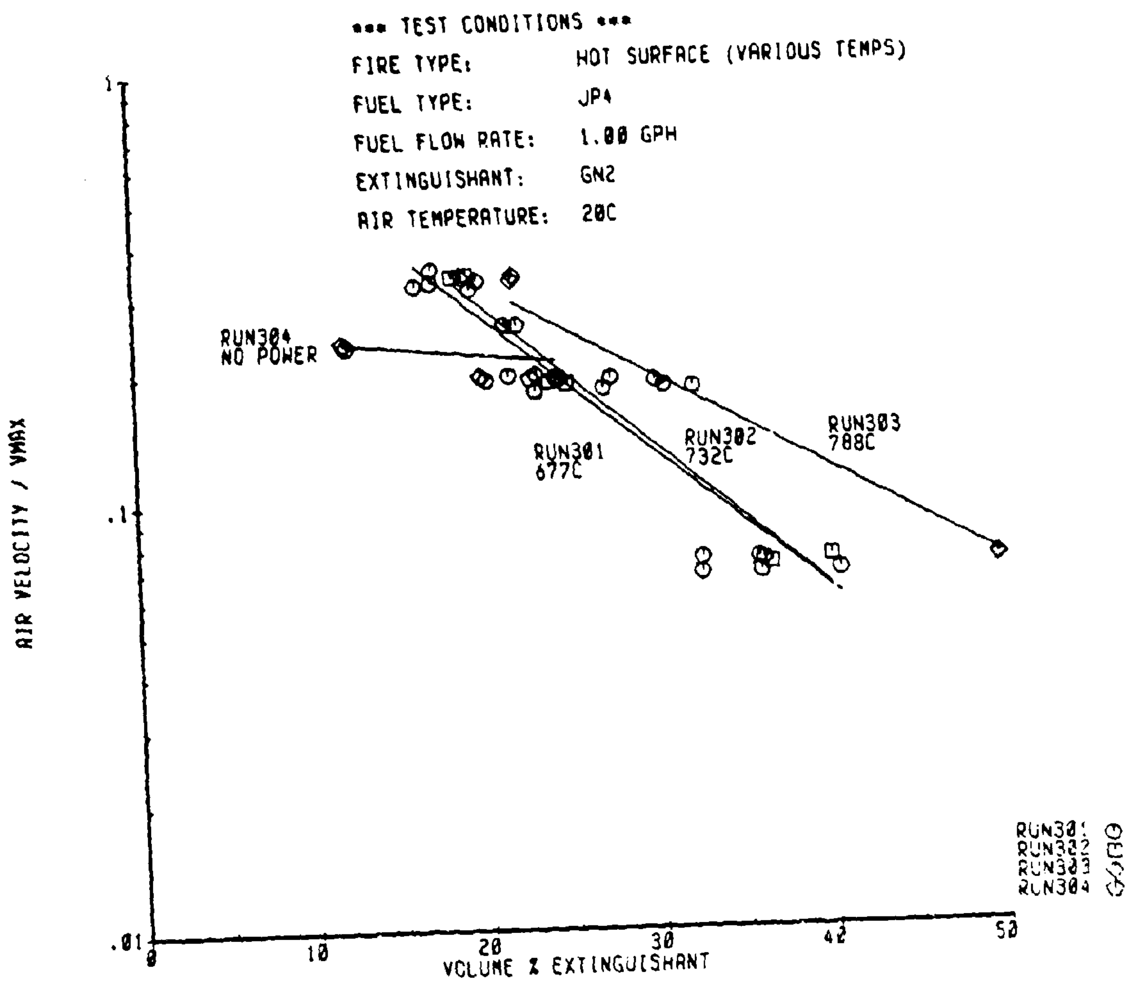
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>SPRAY FIRE<br>ONE FLUID, VAR.EXT., HI TEMP AIR | FIGURE<br>G-21 |
| CHECK | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 187 |
| APPD. | | | | | | |

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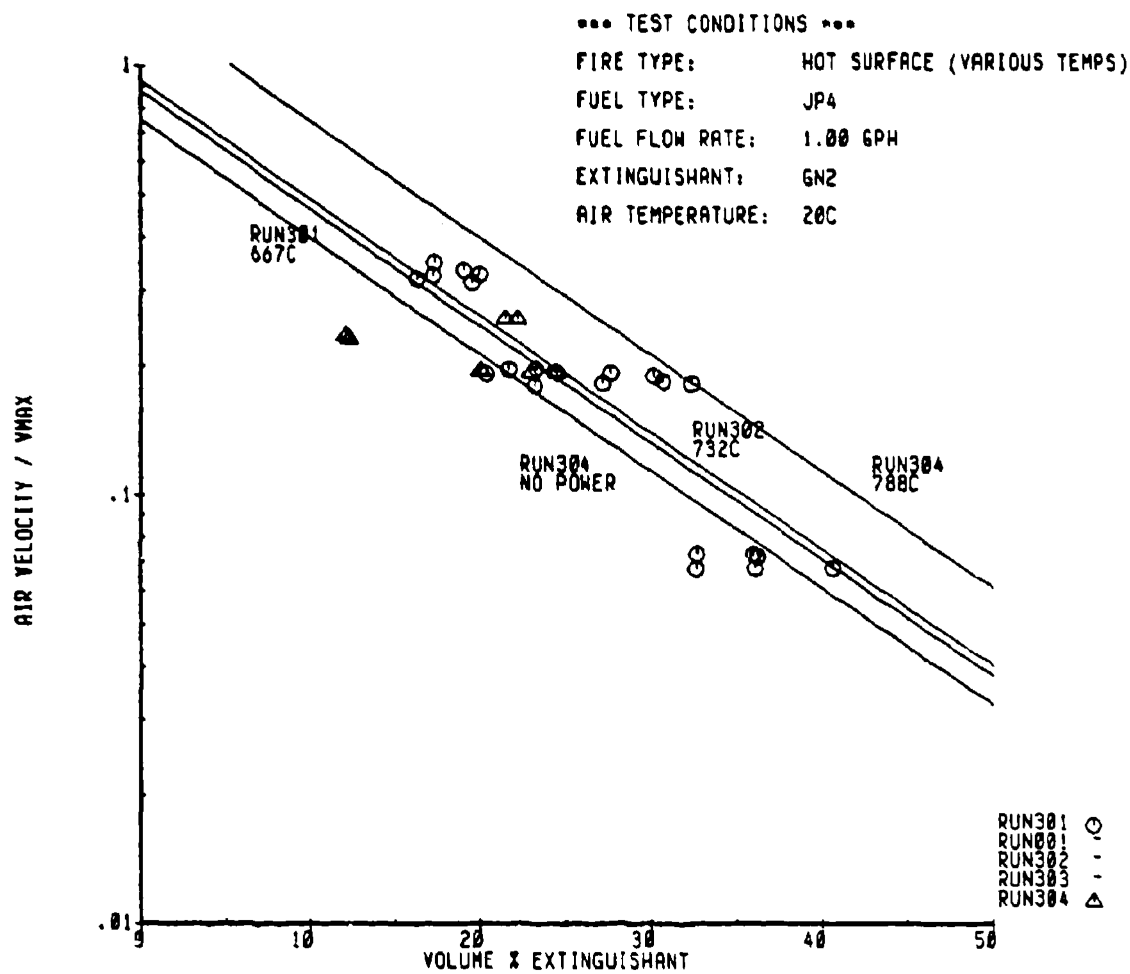
|---|---|---|---|---|---|---|
| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>HOT SURFACE<br>ONE EXTINGUISHANT, VAR. SURFACE TEMP | FIGURE |
| CHECK | | | | | | G-22A |
| APPD. | | | | | THE BOEING COMPANY | PAGE 188 |
| APPD. | | | | | | |

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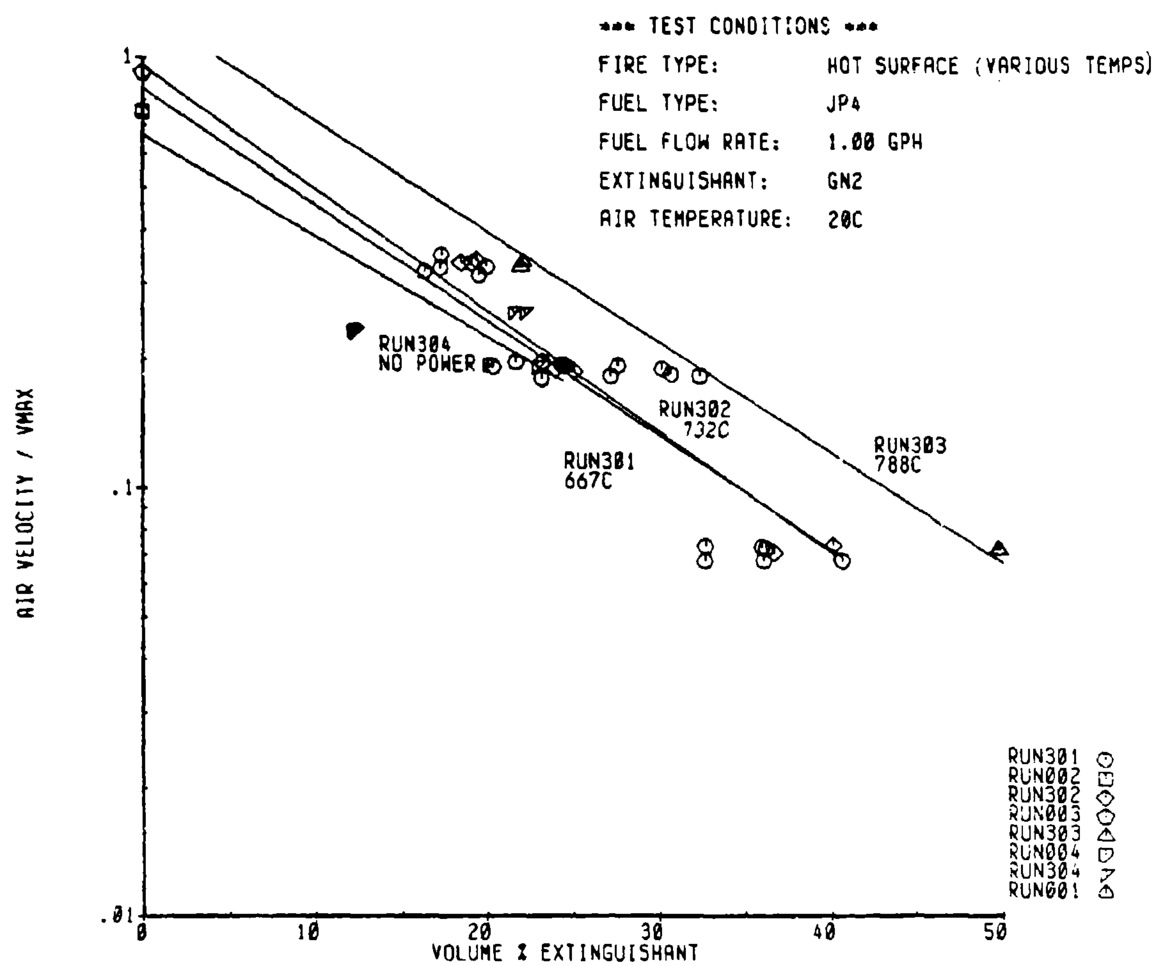
|---|---|---|---|---|---|---|
| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>HOT SURFACE<br>ONE EXTINGUISHANT, VAR. SURFACE TEMP | FIGURE<br>G-228 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 189 |




| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>HOT SURFACE<br>ONE EXTINGUISHANT, VAR. SURFACE TEMP | FIGURE<br>G-22C |
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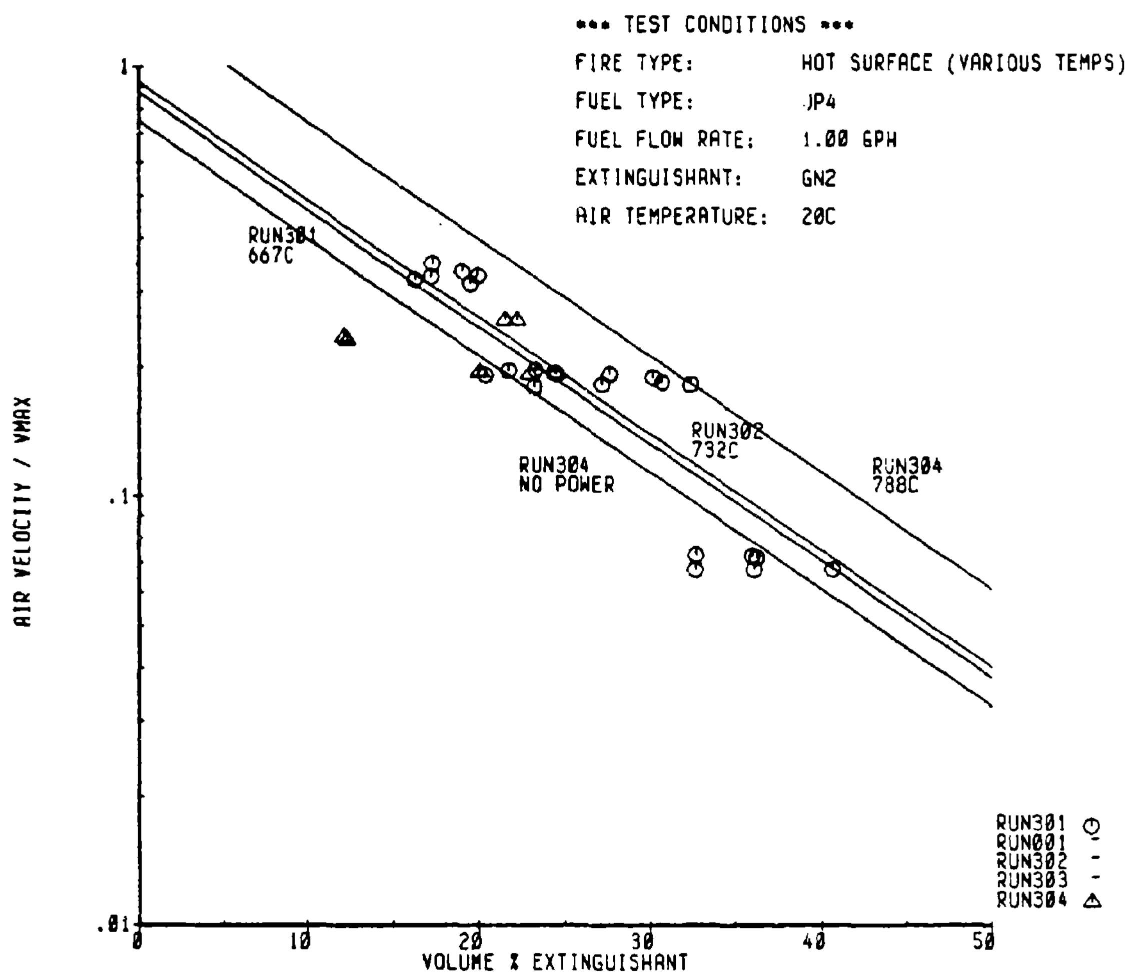
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 190 |

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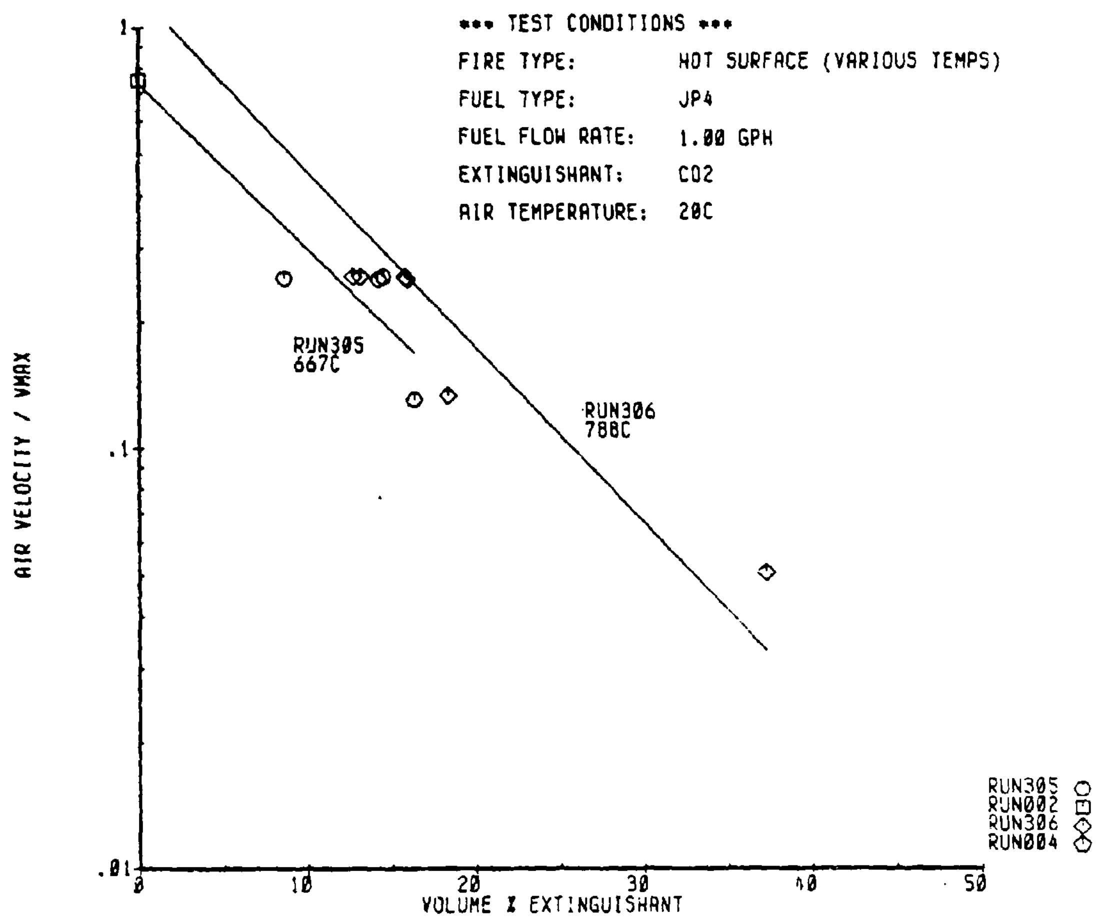
| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>HOT SURFACE<br>ONE EXTINGUISHANT, VAR. SURFACE TEMP | FIGURE<br>G-22B |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 189 |

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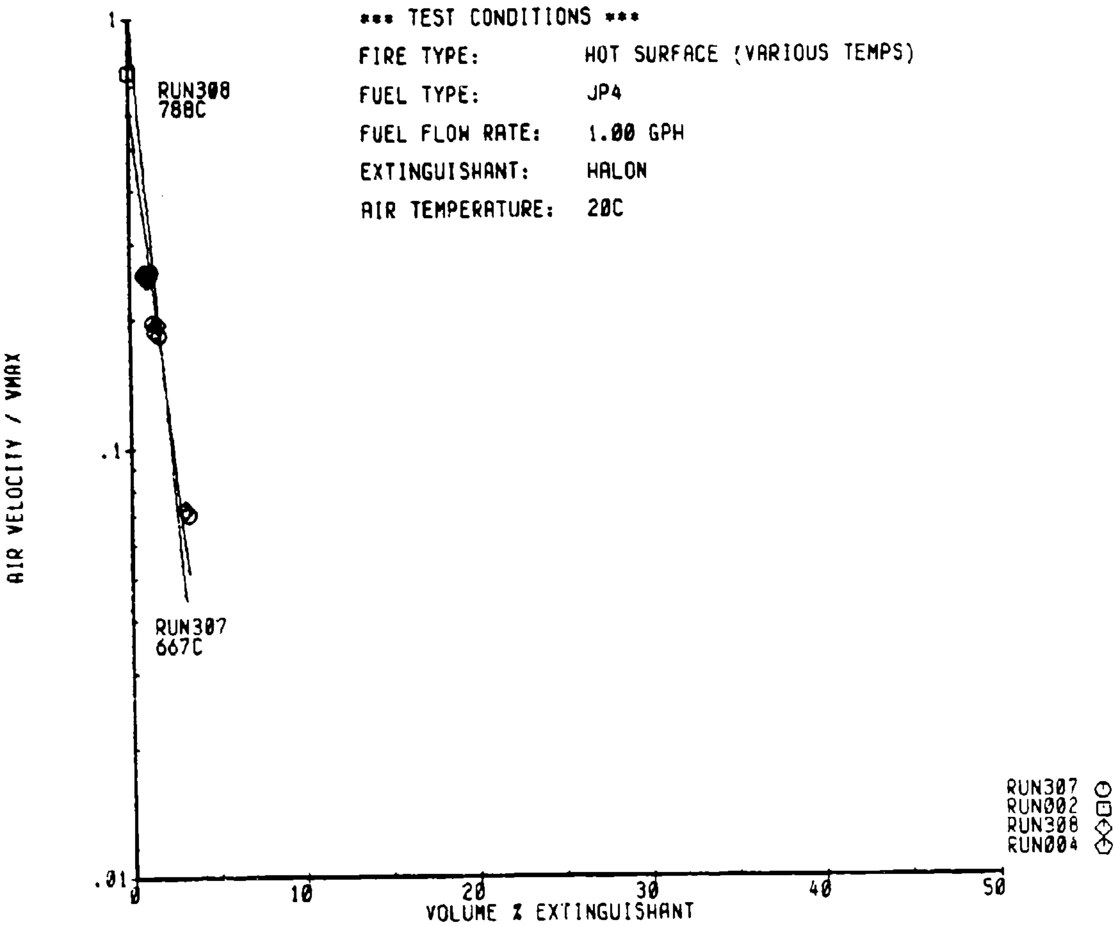
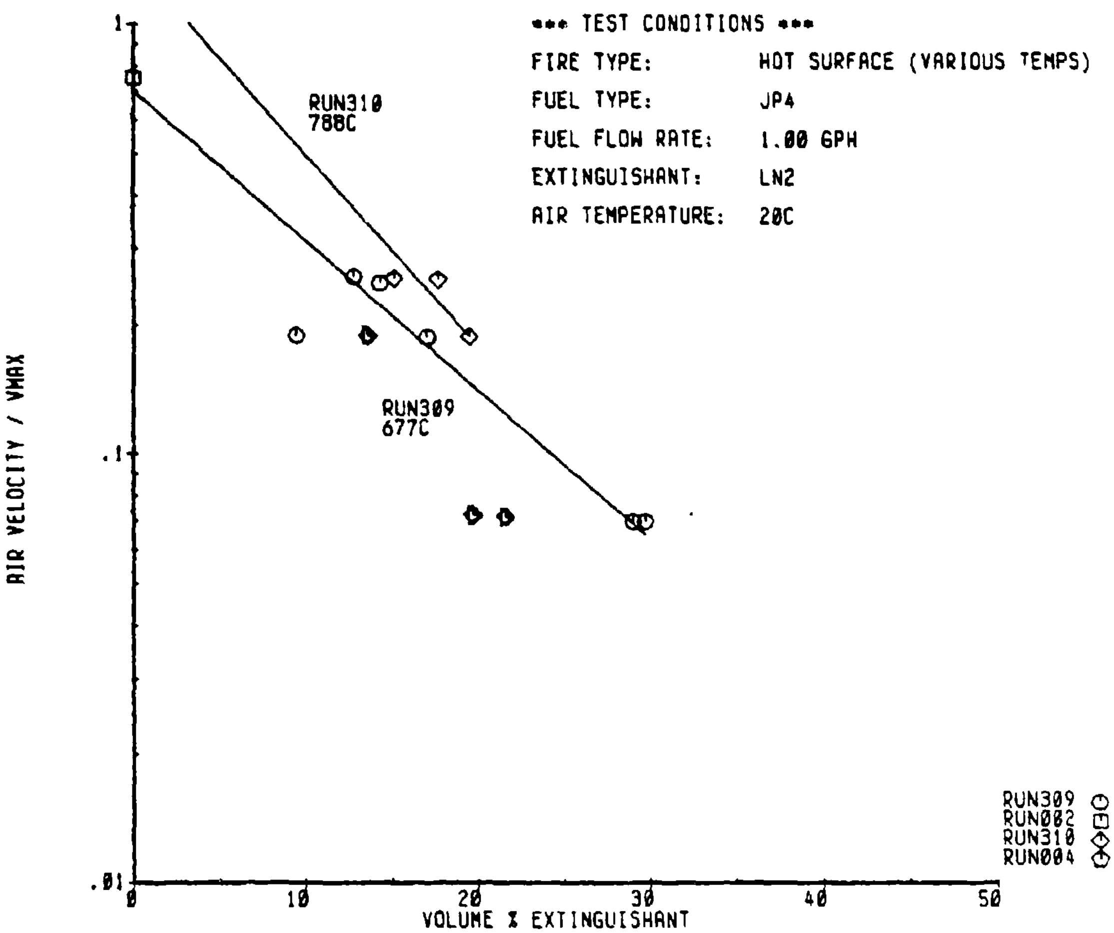
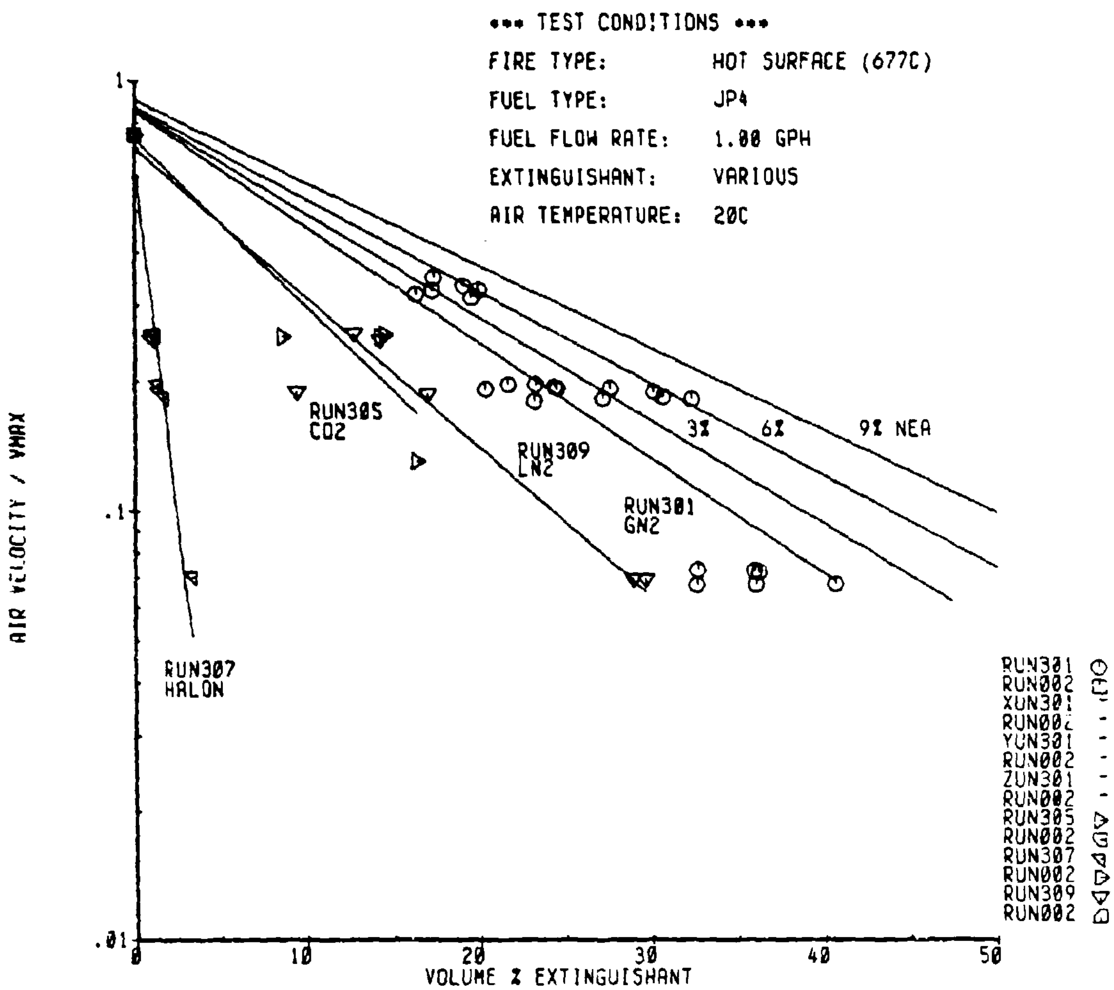
| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>HOT SURFACE<br>ONE EXTINGUISHANT, VAR.SURFACE TEMP | FIGURE<br>G-23 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 191 |




| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>HOT SURFACE<br>ONE EXTINGUISHANT, VAR. SURFACE TEMP | FIGURE<br>G-24 |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 192 |




| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>HOT SURFACE<br>ONE EXTINGUISHANT, VAR. SURFACE TEMP | FIGURE<br>G-25 |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 193 |

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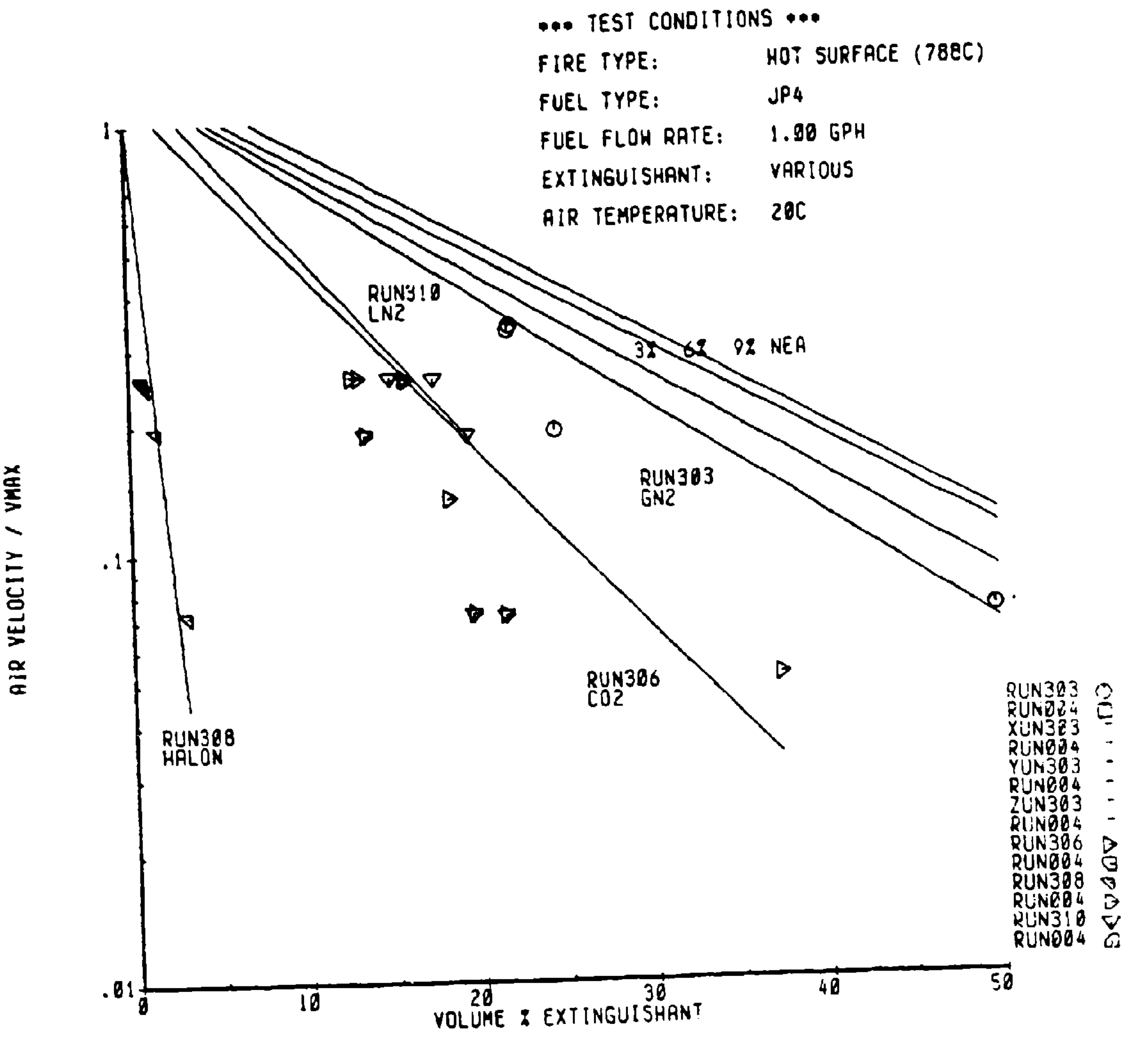
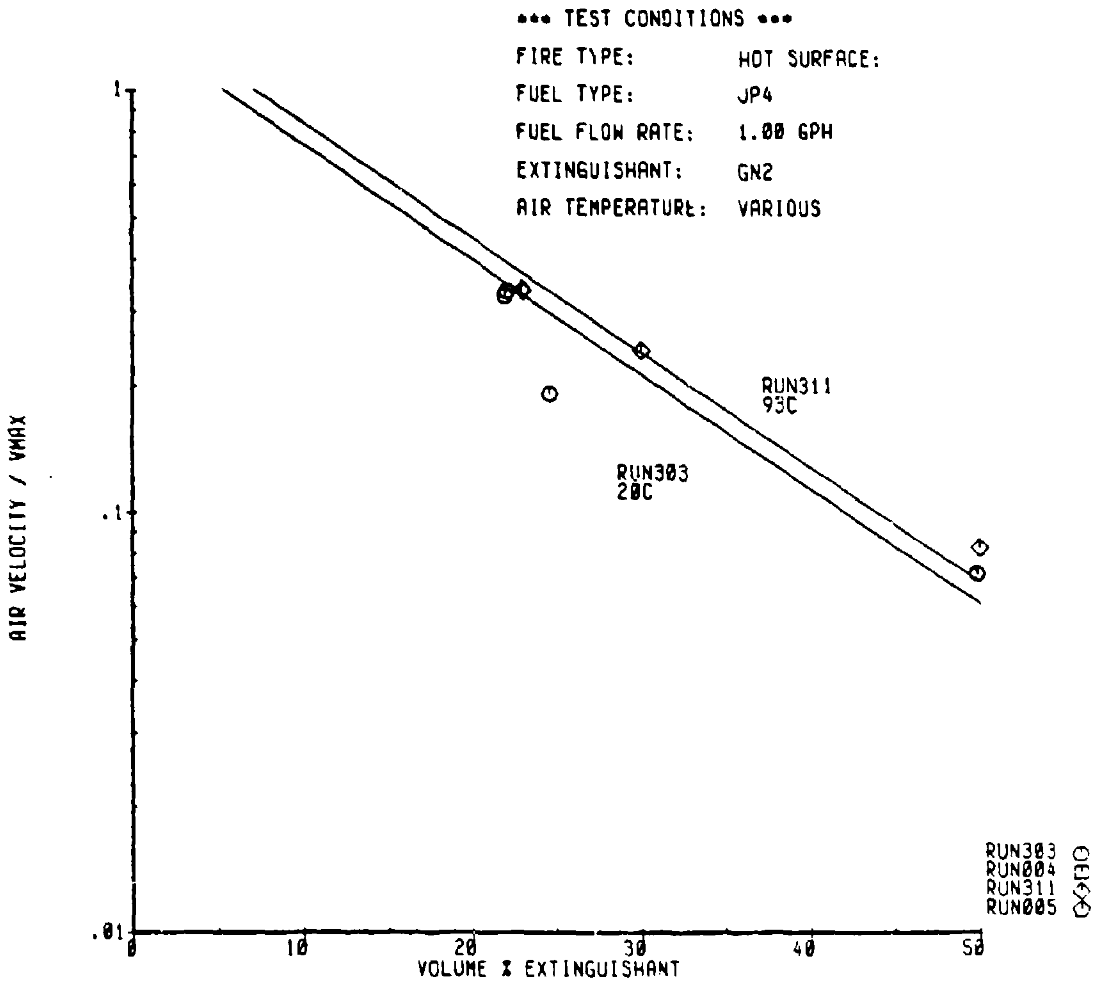
|---|---|---|---|---|---|---|
| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>HOT SURFACE<br>ONE SURFACE TEMP, VAR, EXTINGUISHANT | FIGURE |
| CHECK | | | | | | G-26 |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 194 |




| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>HOT SURFACE<br>ONE SURFACE TEMP. VAR. EXTINGUISHANT | FIGURE<br>G-27 |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 195 |
| APPD. | | | | | | |

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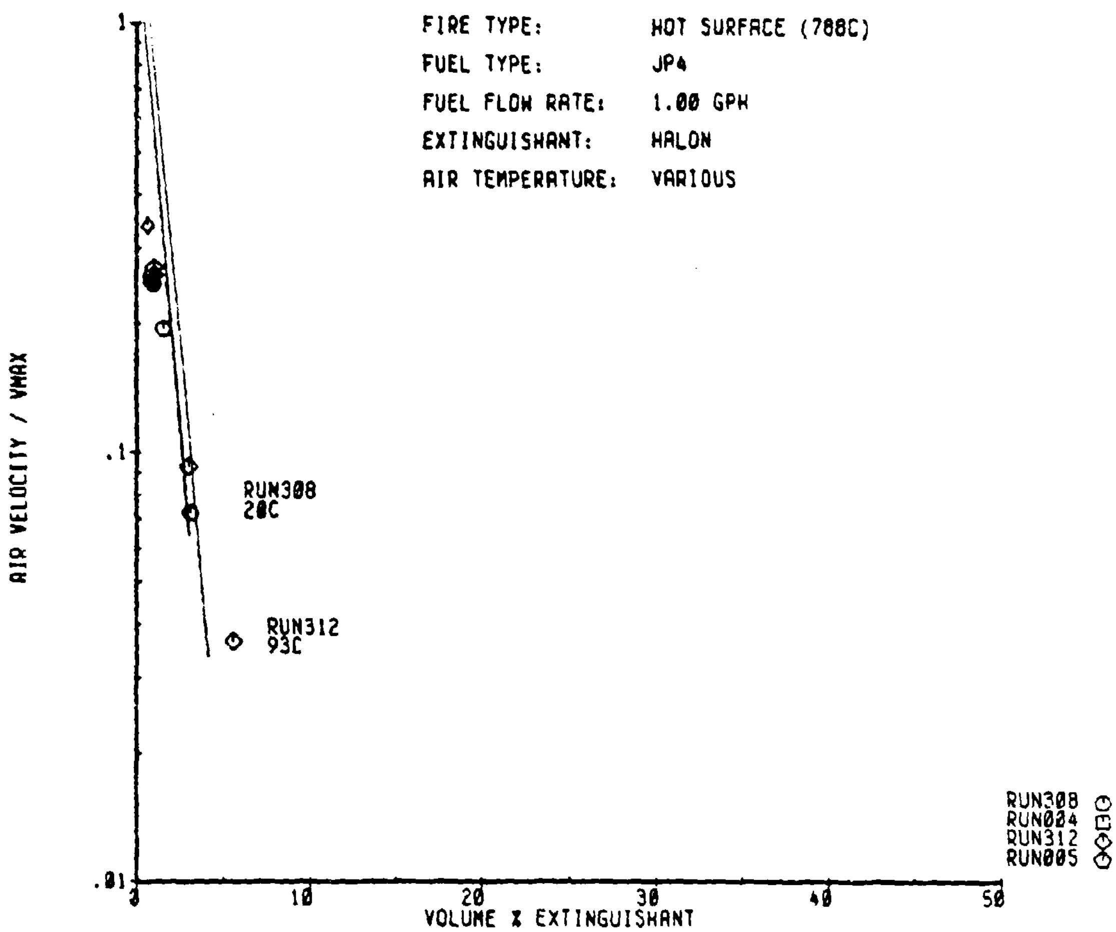
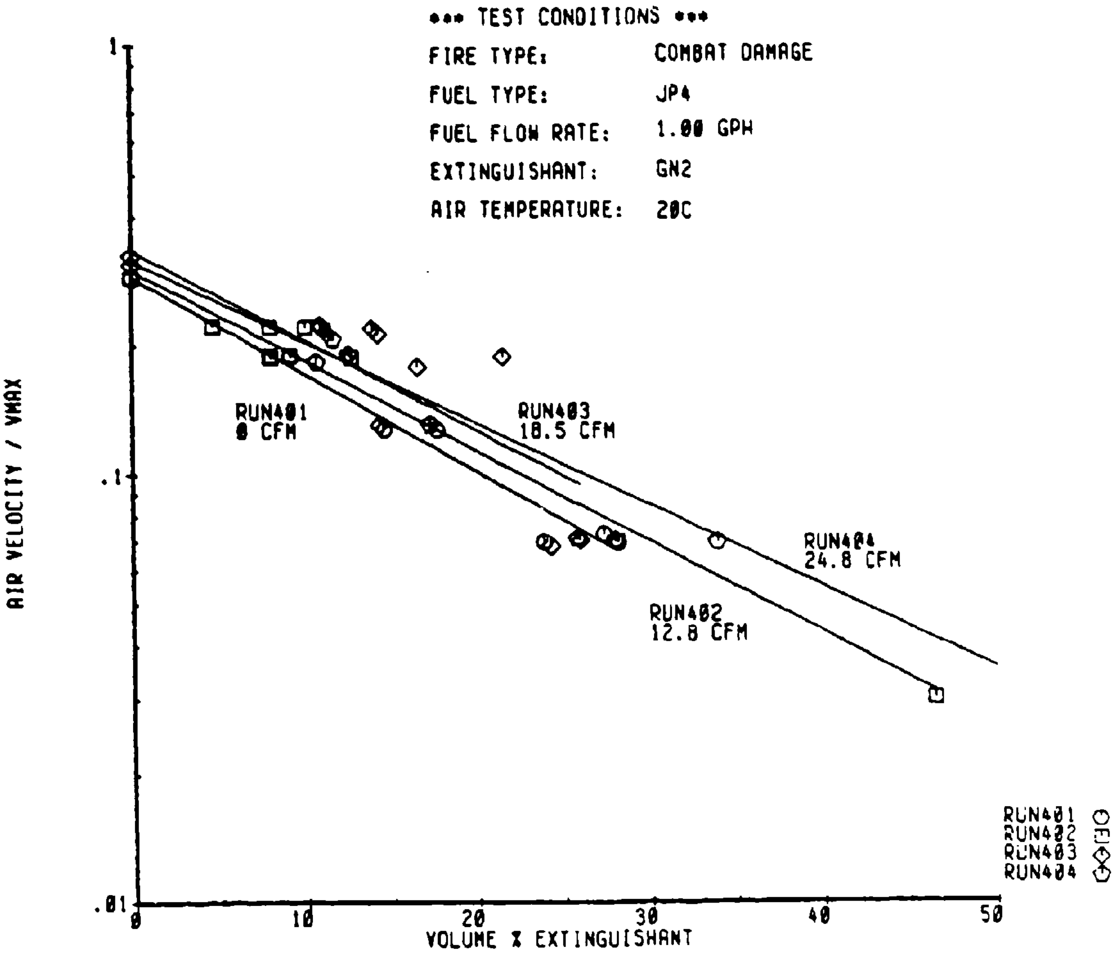
|---|---|---|---|---|---|---|
| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>HOT SURFACE<br>ONE SRFC TEMP, ONE EXT, VAR AIR TEMP | FIGURE<br>G-28 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 196 |
| | | | | | | |

*** TEST CONDITIONS ***

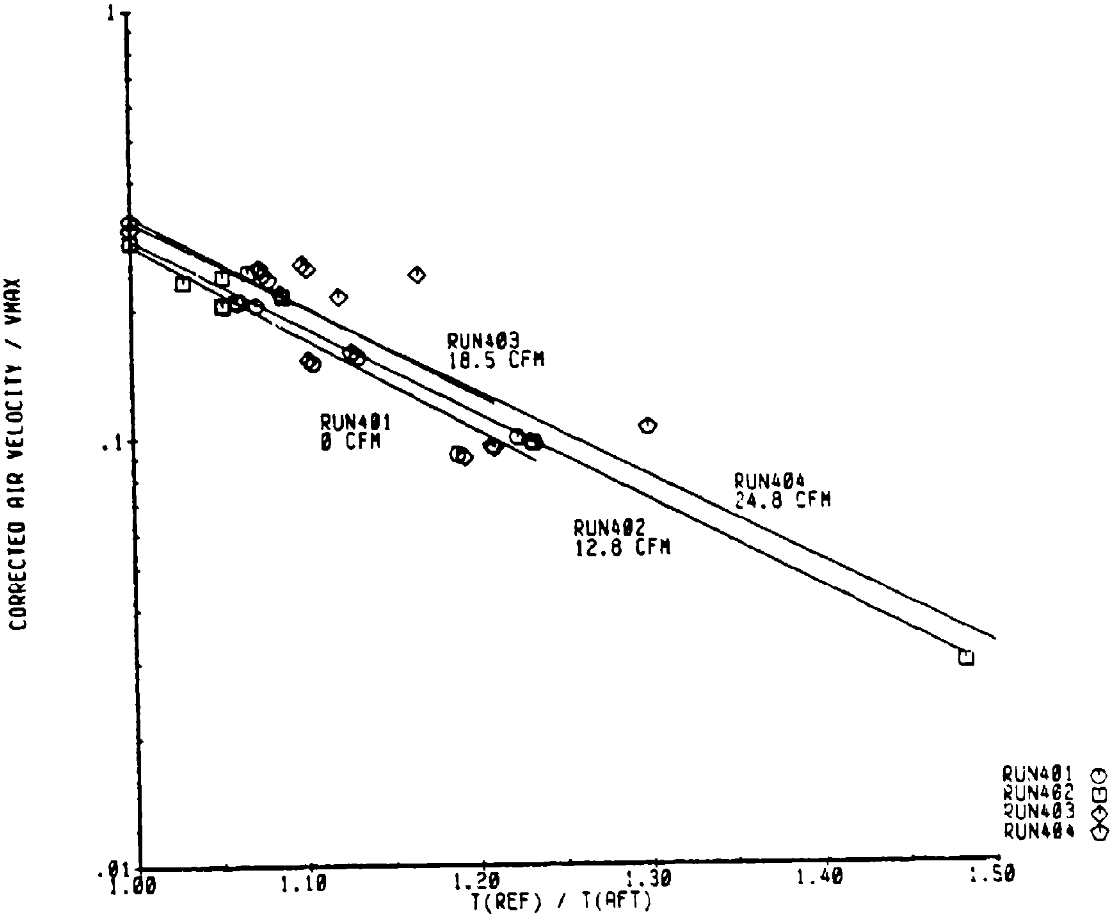
FIRE TYPE: HOT SURFACE (788C)
FUEL TYPE: JP4
FUEL FLOW RATE: 1.00 GPH
EXTINGUISHANT: HALON
AIR TEMPERATURE: VARIOUS



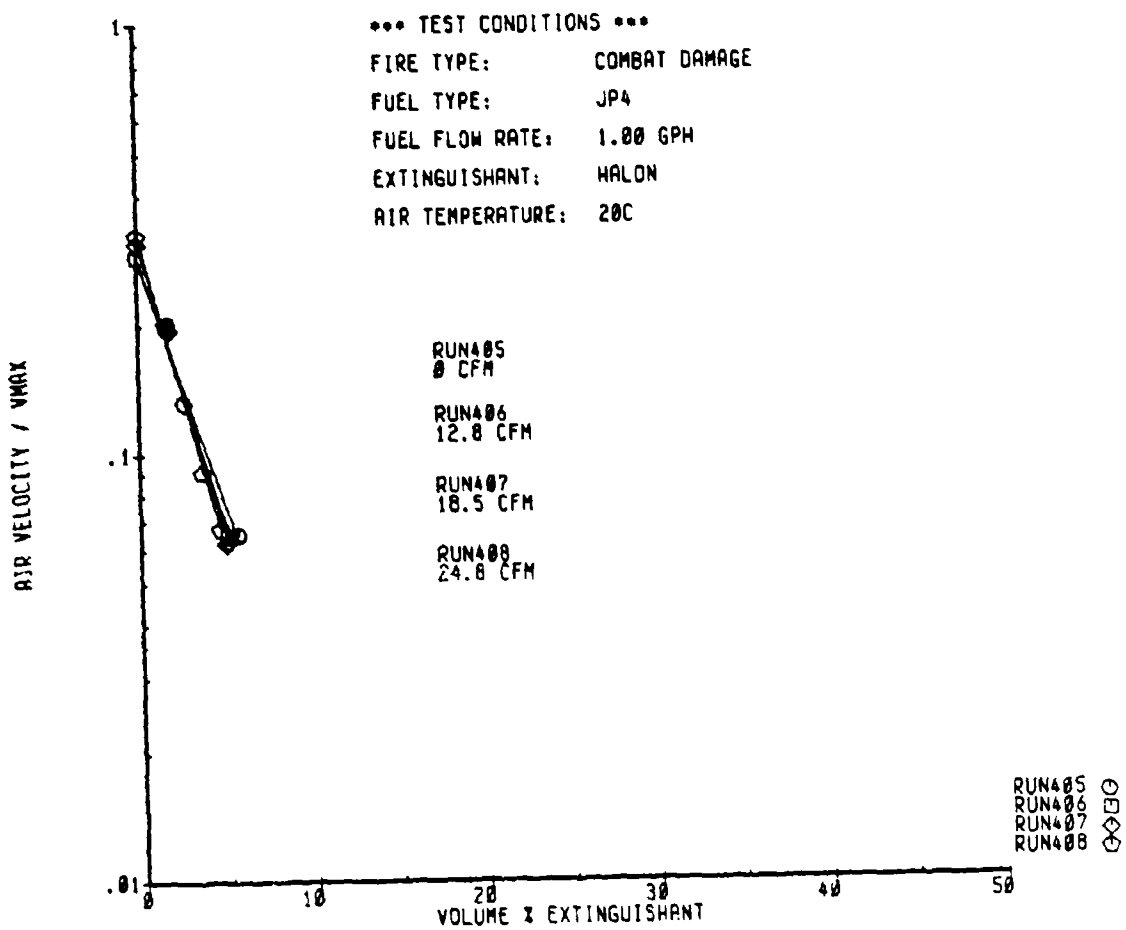

| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 13DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>HOT SURFACE<br>ONE SRFC TEMP, ONE EXT, VAR AIR TEMP | FIGURE<br>G-29 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 197 |



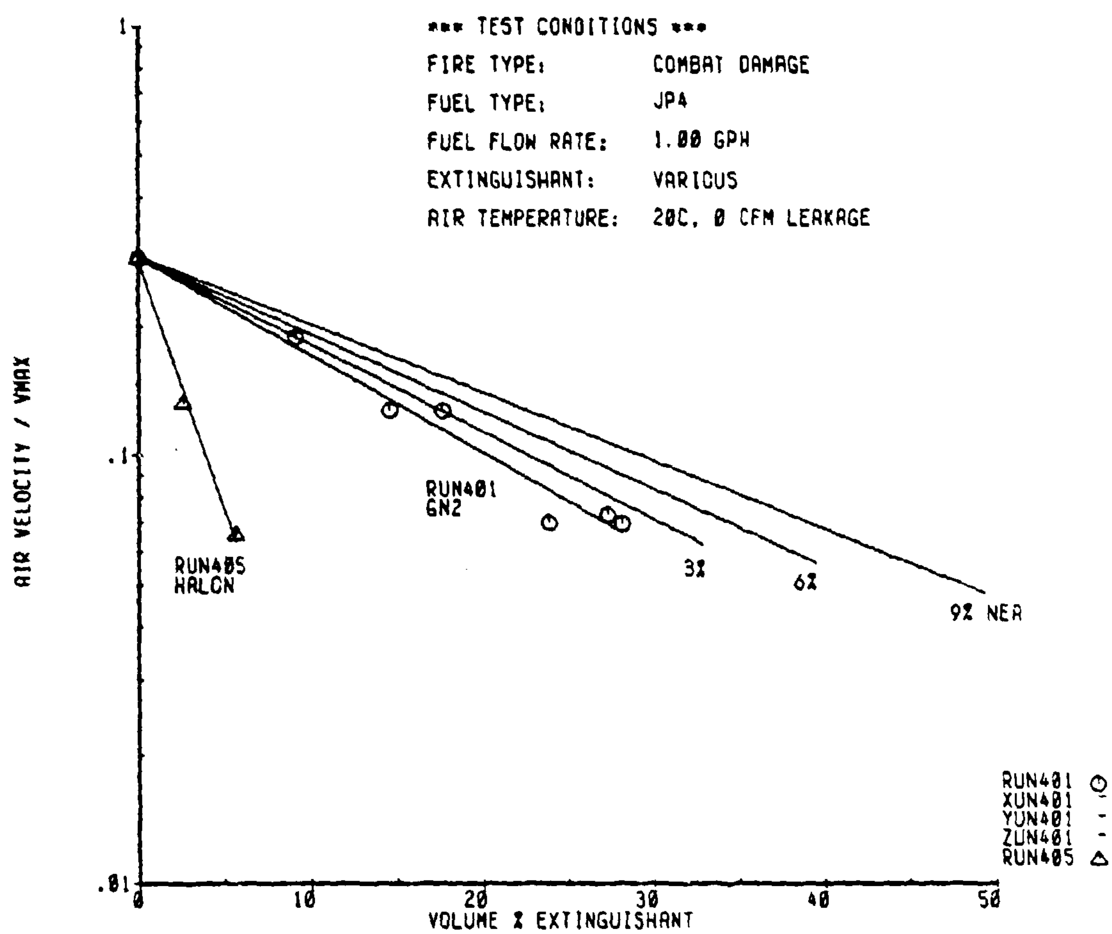

| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>COMBAT DAMAGE<br>ONE EXT. VARIOUS LEAKAGE RATES | FIGURE<br>G-30A |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 198 |



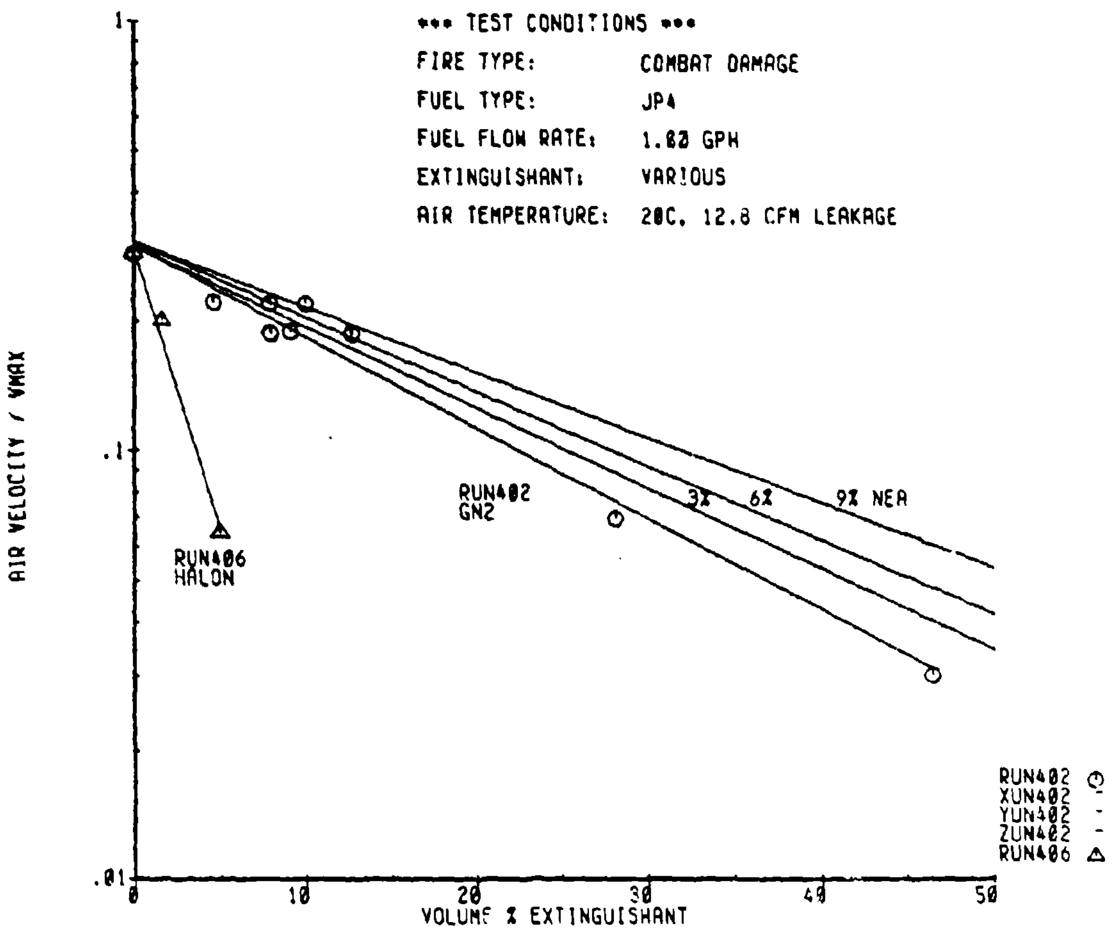

| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>COMBAT DAMAGE<br>ONE EXT., VARIOUS LEAKAGE RATES | FIGURE |
| CHECK | | | | | | G-30B |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 199 |
| | | | | | | |




| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>COMBAT DAMAGE<br>ONE EXT., VARIOUS LEAKAGE RATES | FIGURE |
| CHECK | | | | | | G-31 |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 200 |




| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION | FIGURE |
|---|---|---|---|---|---|---|
| CHECK | | | | | COMBAT DAMAGE | |
| APPD. | | | | | ONE FLUID, VAR EXT, ONE LEAK RATE | G-32 |
| APPD. | | | | | THE BOEING COMPANY | PAGE 201 |

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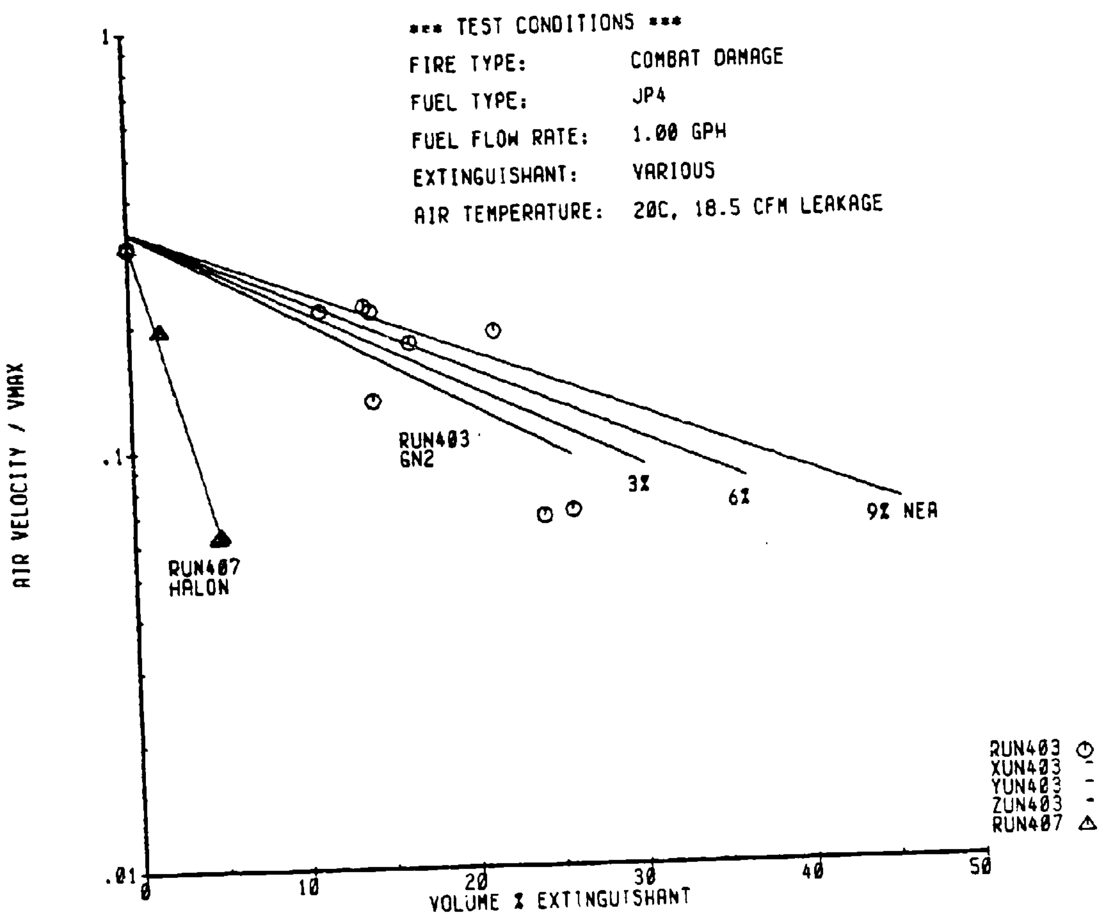
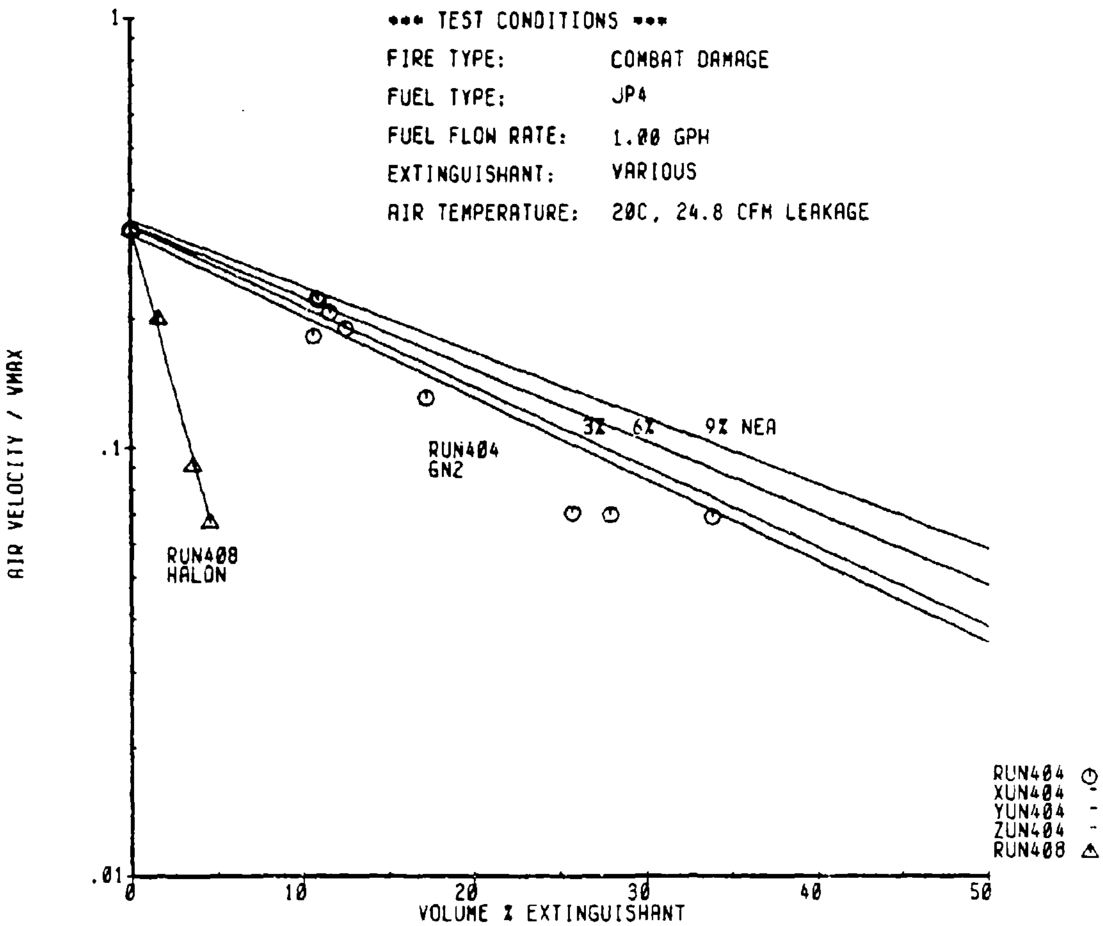
|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>COMBAT DAMAGE<br>ONE FLUID, VAR EXT, ONE LEAK RATE | FIGURE |
| CHECK | | | | | | G-33 |
| APPD. | | | | | THE BOEING COMPANY | PAGE 202 |
| APPD. | | | | | | |




| | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>COMBAT DAMAGE<br>ONE FLUID, VAR EXT, ONE LEAK RATE | FIGURE<br>G-34 |
|---|---|---|---|---|---|---|
| CALC | | | | | | |
| CHECK | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 203 |
| APPD. | | | | | | |

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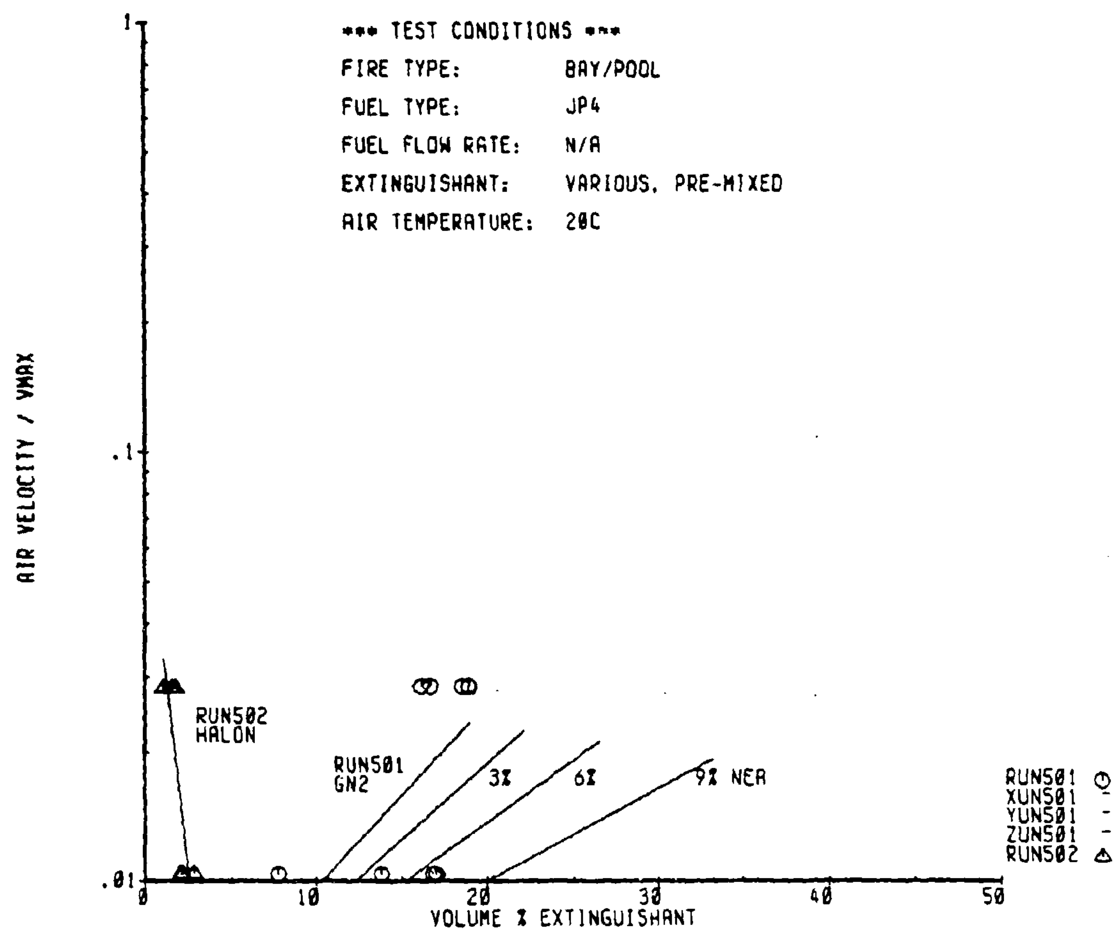
|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION<br>COMBAT DAMAGE<br>ONE FLUID, VAR EXT, ONE LEAK RATE | FIGURE<br>G-35 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 204 |

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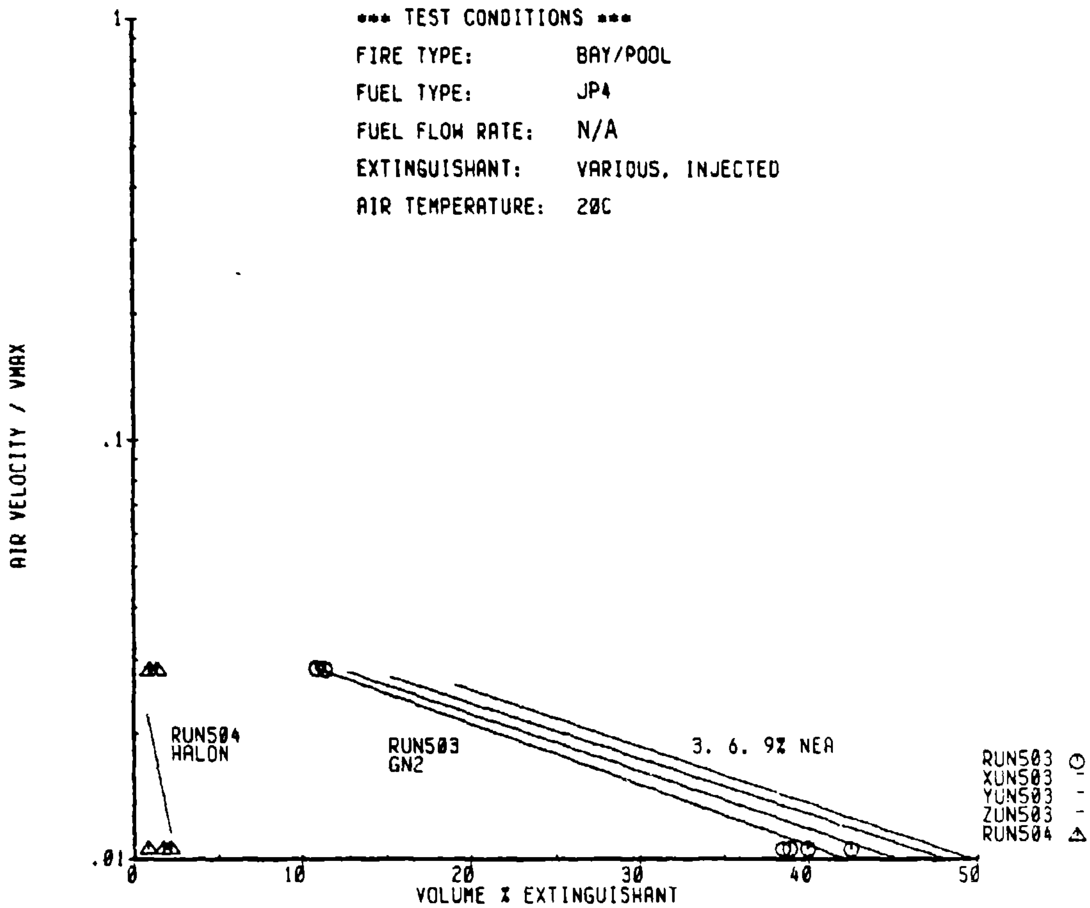
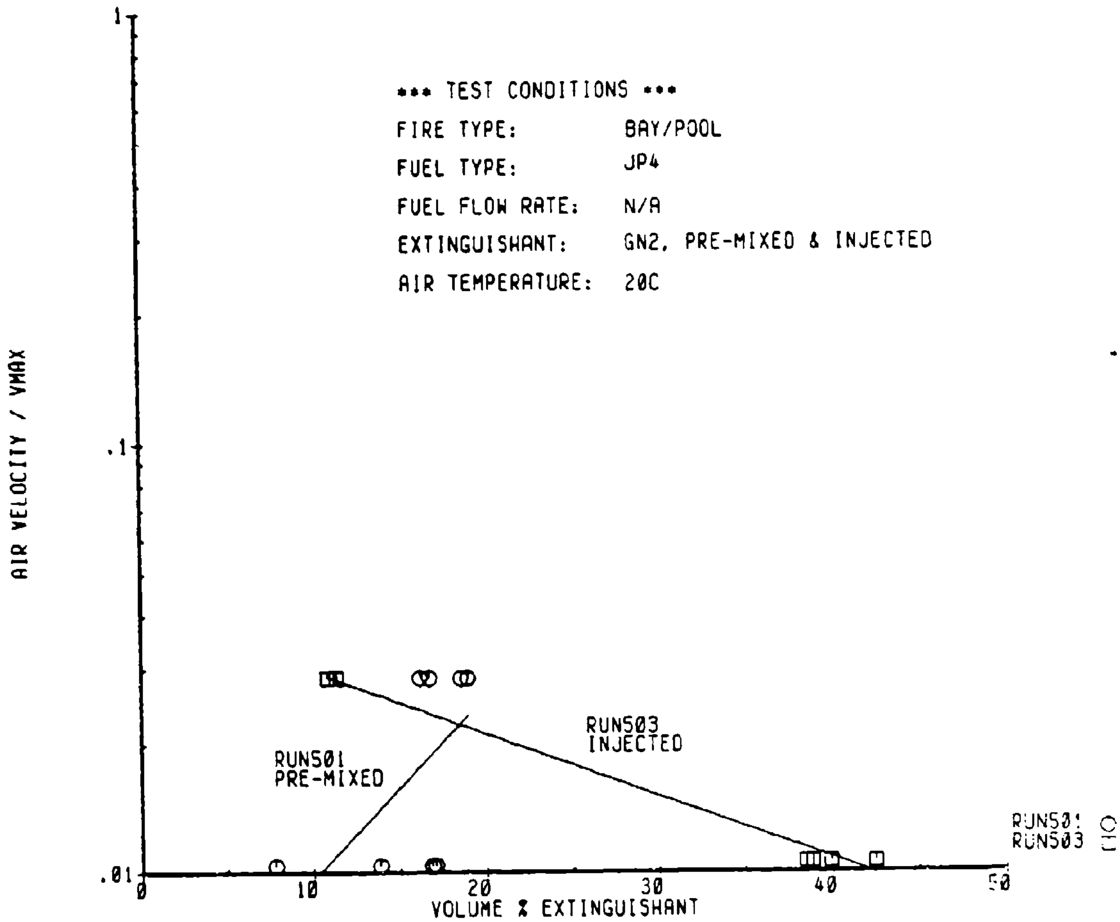
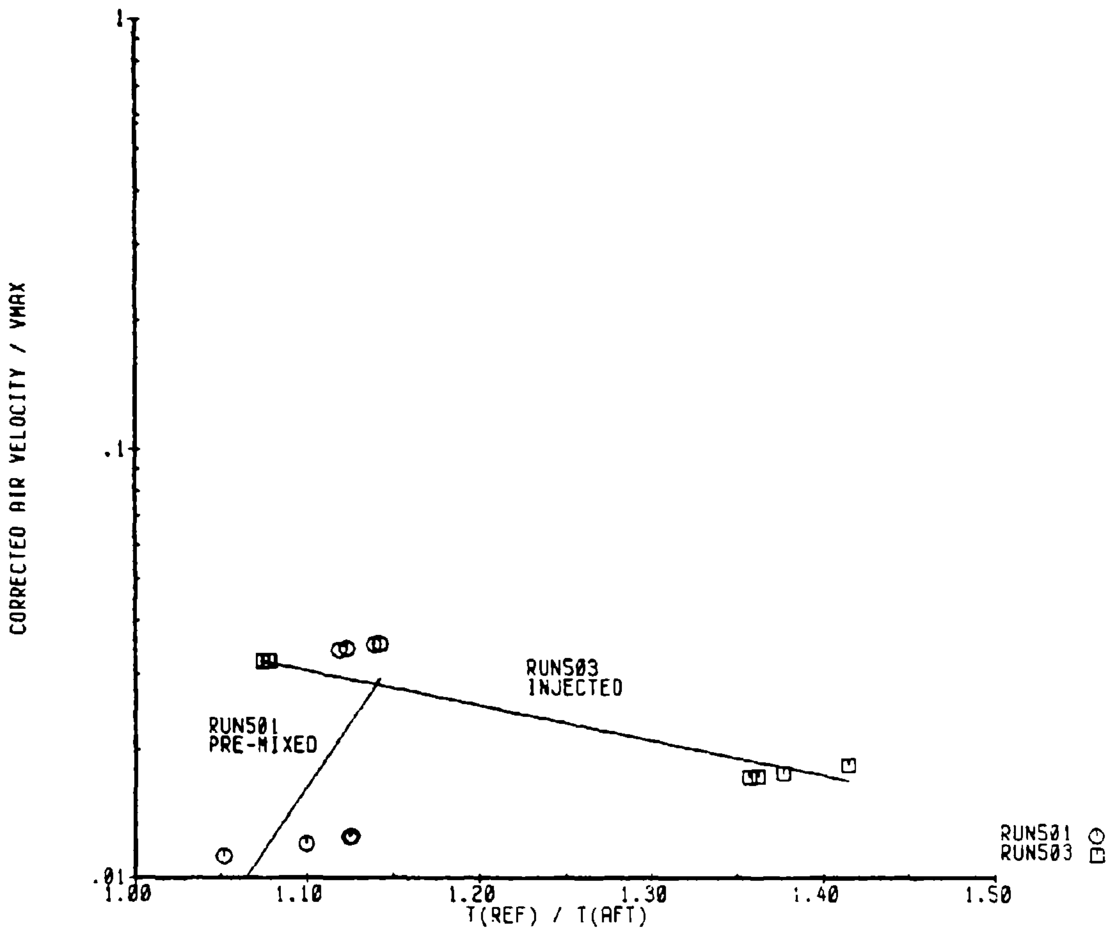
|---|---|---|---|---|---|---|---|
| CALC | | 11DEC88 | REVISED | DATE | ENGINE COMPARTMENT SIMULATION | FIGURE | |
| CHECK | | | | | POOL FIRE | | |
| APPD. | | | | | VARIOUS EXTINGUISHANTS, PRE-MIXED | G-36 | |
| APPD. | | | | | THE BOEING COMPANY | PAGE | 205 |




| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>POOL FIRE<br>VARIOUS EXTINGUISHANTS, INJECTED | FIGURE<br>G-37 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 206 |




| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 10DEC80 | REVISED | DATE | DRY BAY SIMULATION | FIGURE |
| CHECK | | | | | POOL FIRE | |
| APPD. | | | | | ONE EXTINGUISHANT, DIFERENT MIXING | G-38A |
| APPD. | | | | | THE BOEING COMPANY | PAGE 207 |

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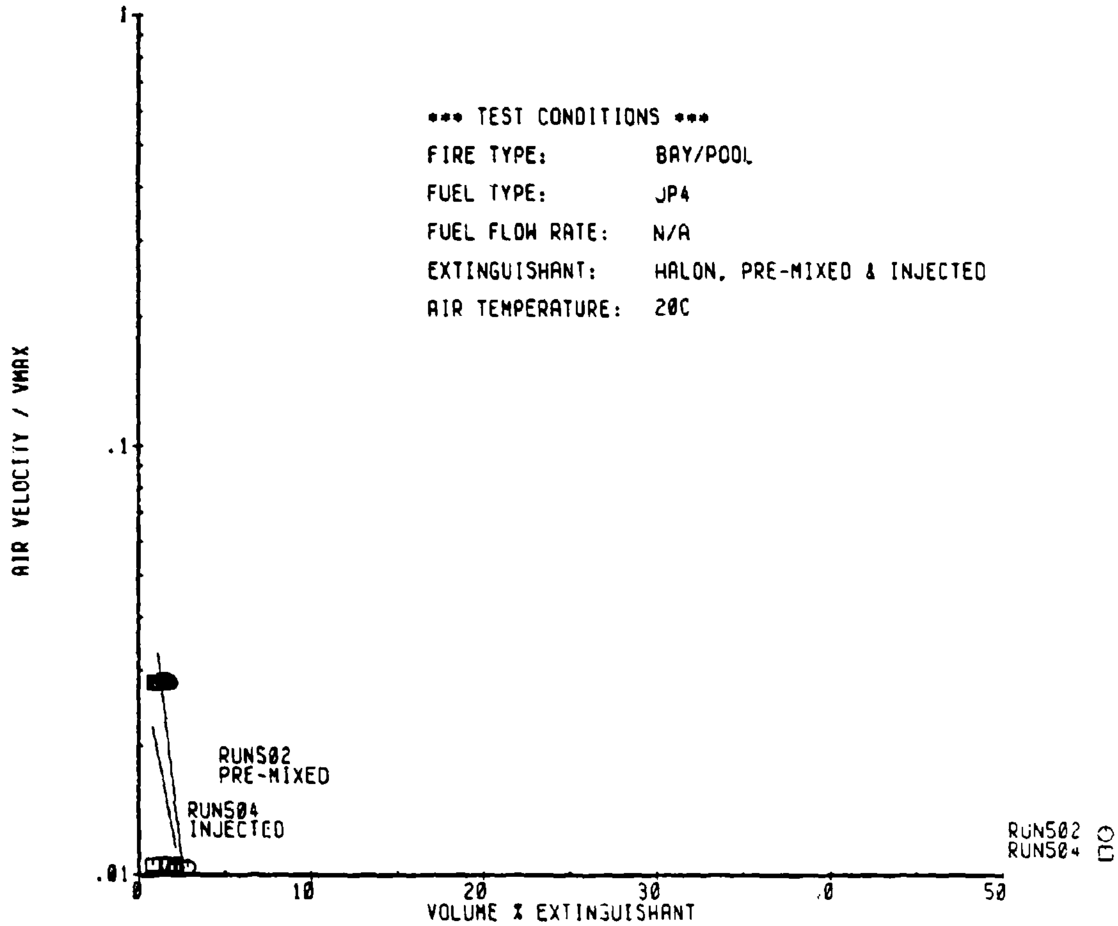
|---|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>POOL FIRE<br>ONE EXTINGUISHANT, DIFFERENT MIXING | FIGURE | G-388 |
| CHECK | | | | | | | |
| APPD. | | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE | 208 |

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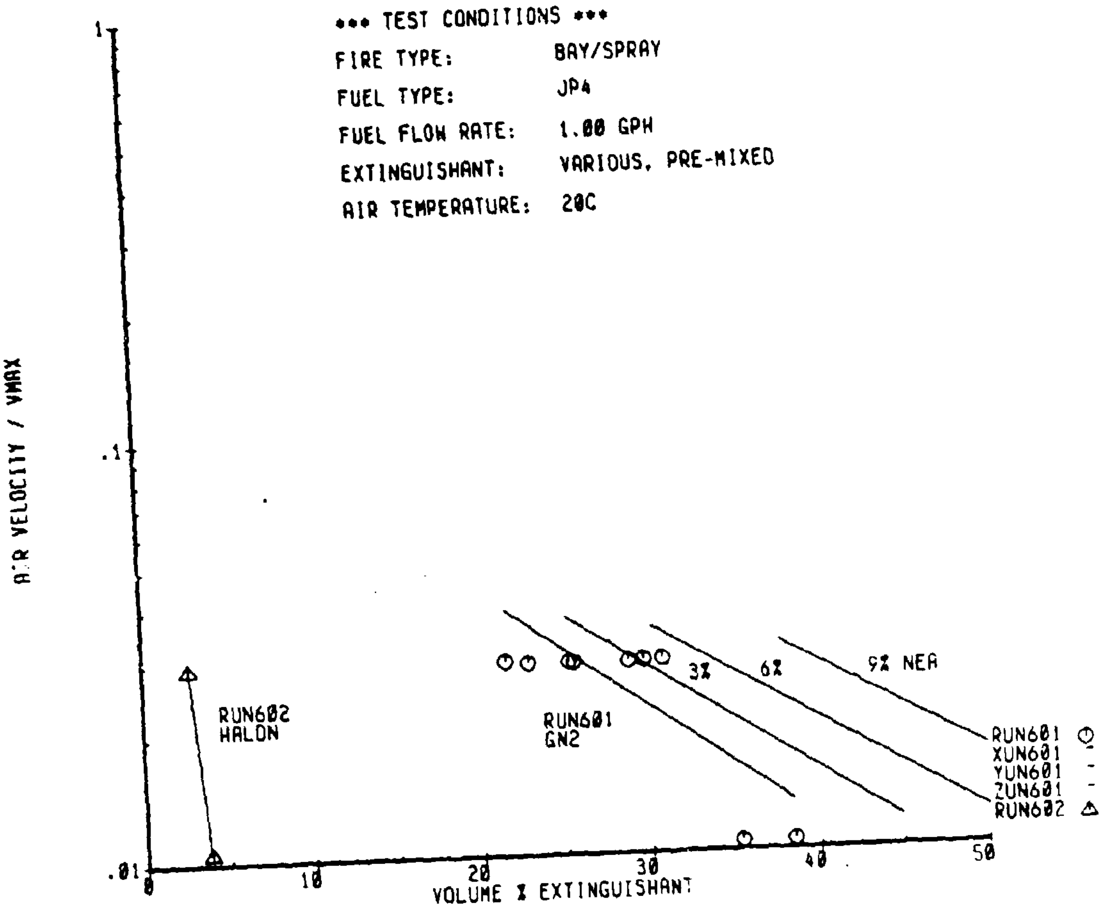
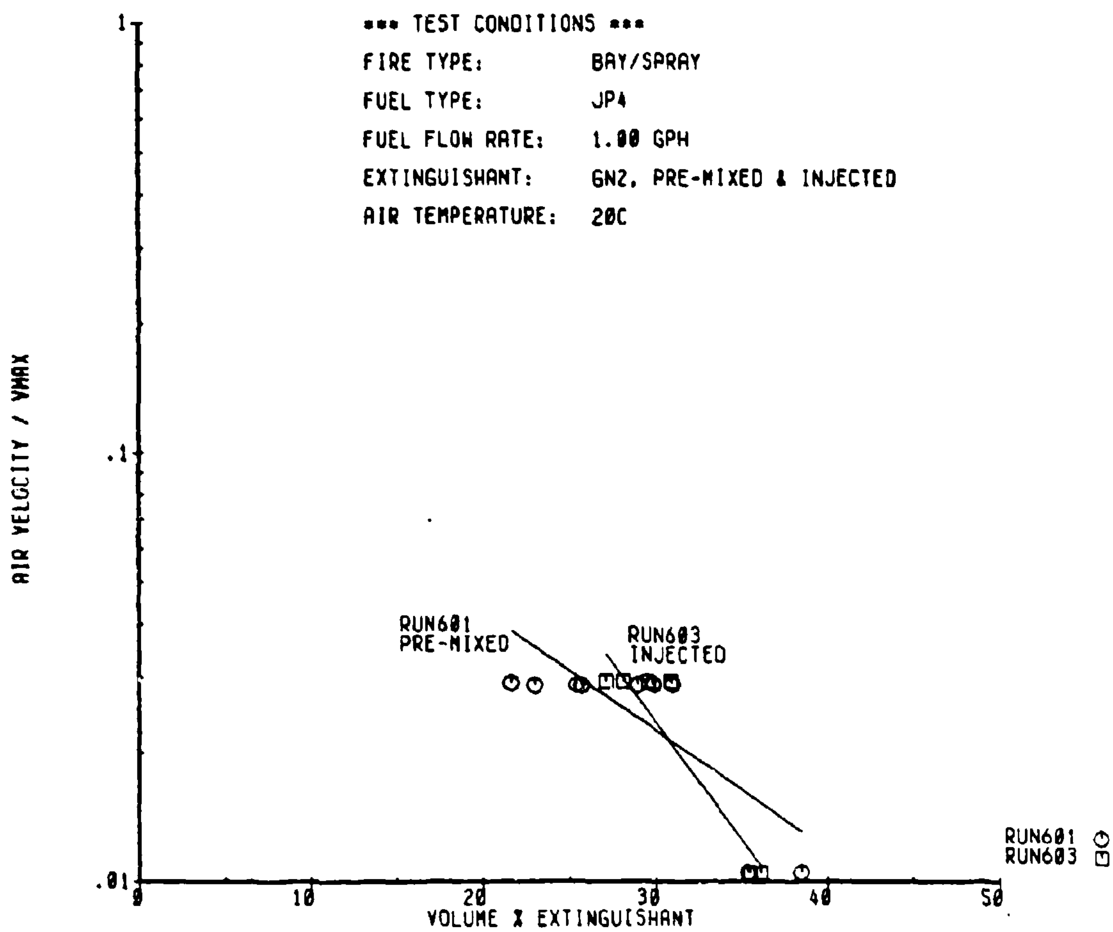
|---|---|---|---|---|---|
| CALC | | 10DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>POOL FIRE<br>ONE EXTINGUISHANT, DIFERENT MIXING | FIGURE |
| CHECK | | | | | | G-39 |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 209 |




| CALC | | 11DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>SPRAY<br>ONE FLUID, VARIOUS EXTINGUISHANTS | FIGURE<br>G-40 |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 210 |
| APPD. | | | | | | |

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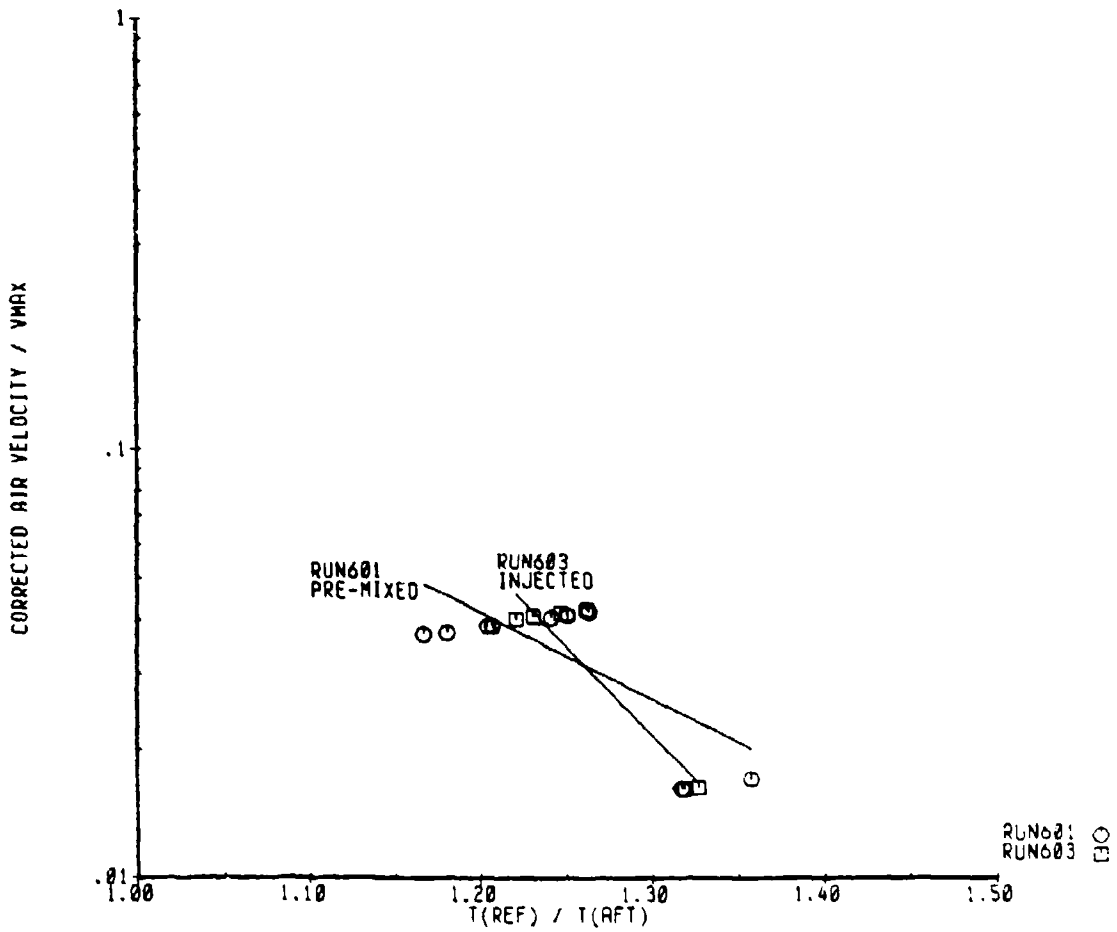
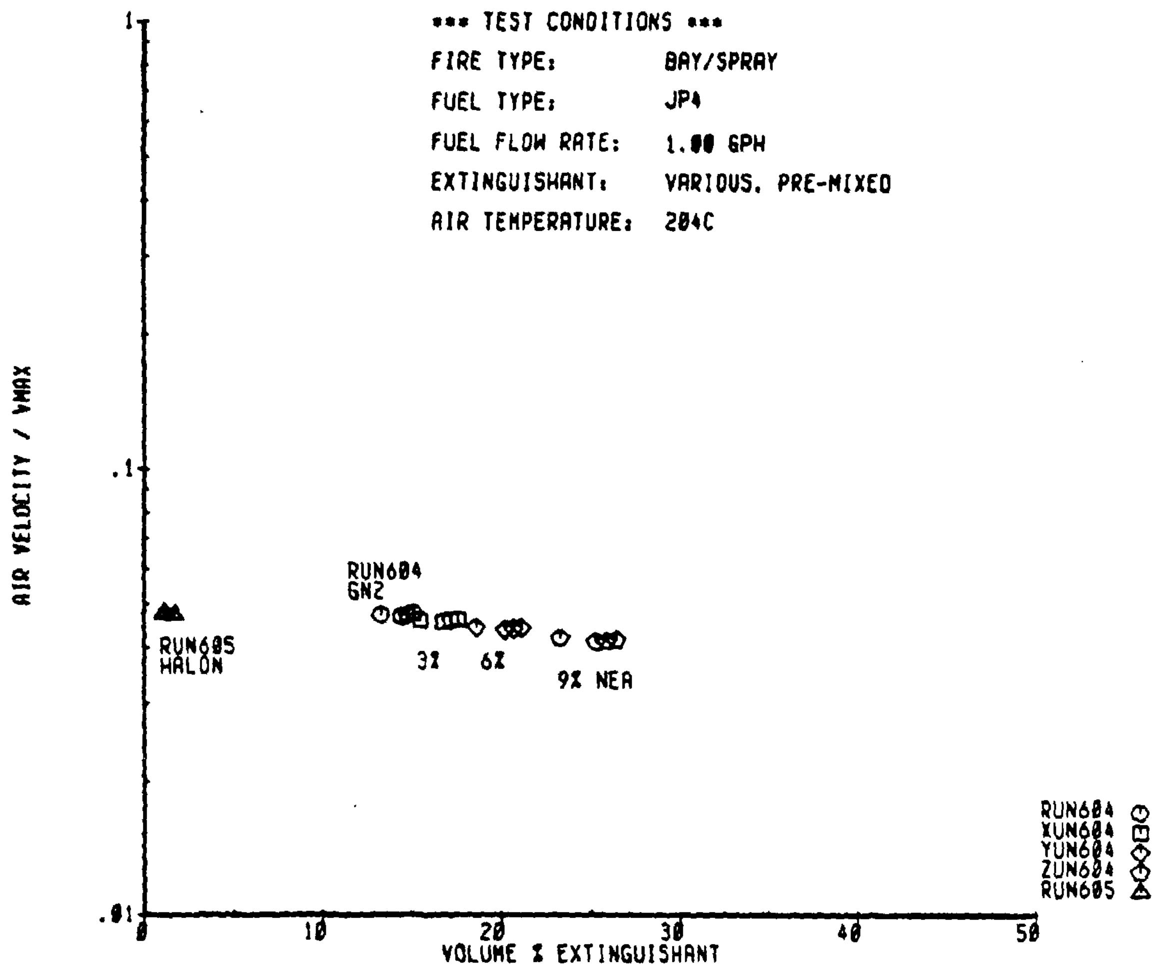
|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>SPRAY FIRE<br>ONE EXTINGUISHANT, DIFFERENT MIXING | FIGURE |
| CHECK | | | | | | G-41A |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 211 |




| CALC | | 11DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>SPRAY FIRE<br>ONE EXTINGUISHANT, DIFFERENT MIXING | FIGURE<br>G-416 |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 212 |

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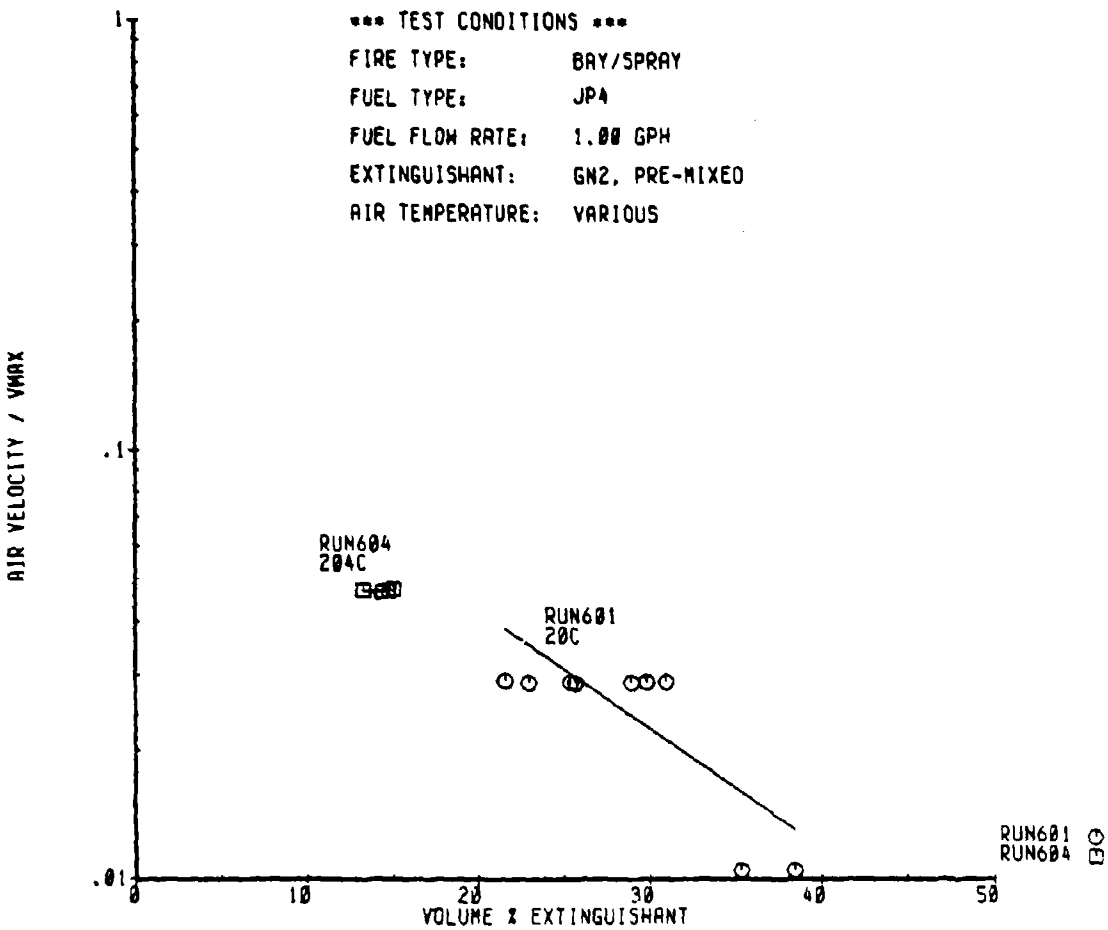
|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>SPRAY FIRE<br>ONE FLUID, VARIOUS EXT, HI TEMP AIR | FIGURE |
| CHECK | | | | | | G-42 |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 213 |

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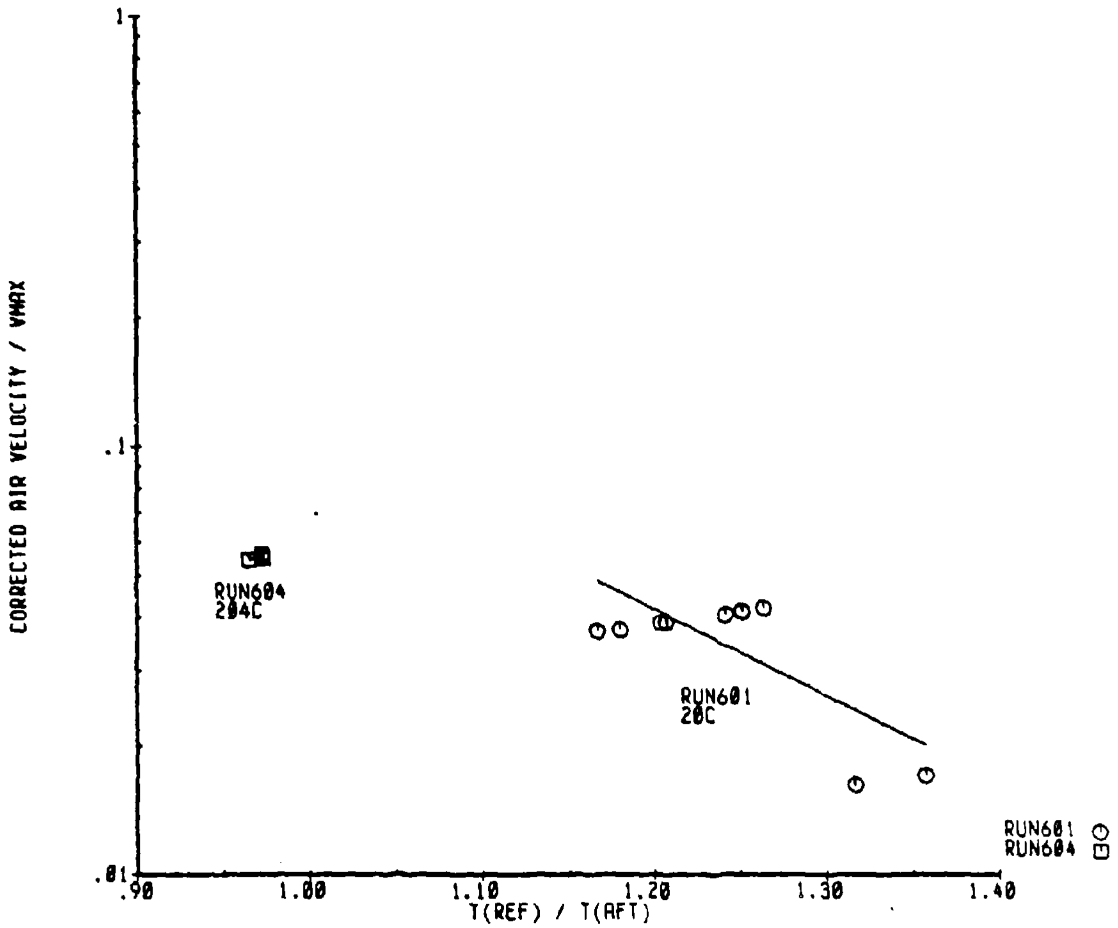
|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>SPRAY FIRE<br>ONE EXTINGUISHANT, DIFF. AIR TEMPS. | FIGURE |
| CHECK | | | | | | G-43A |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 214 |

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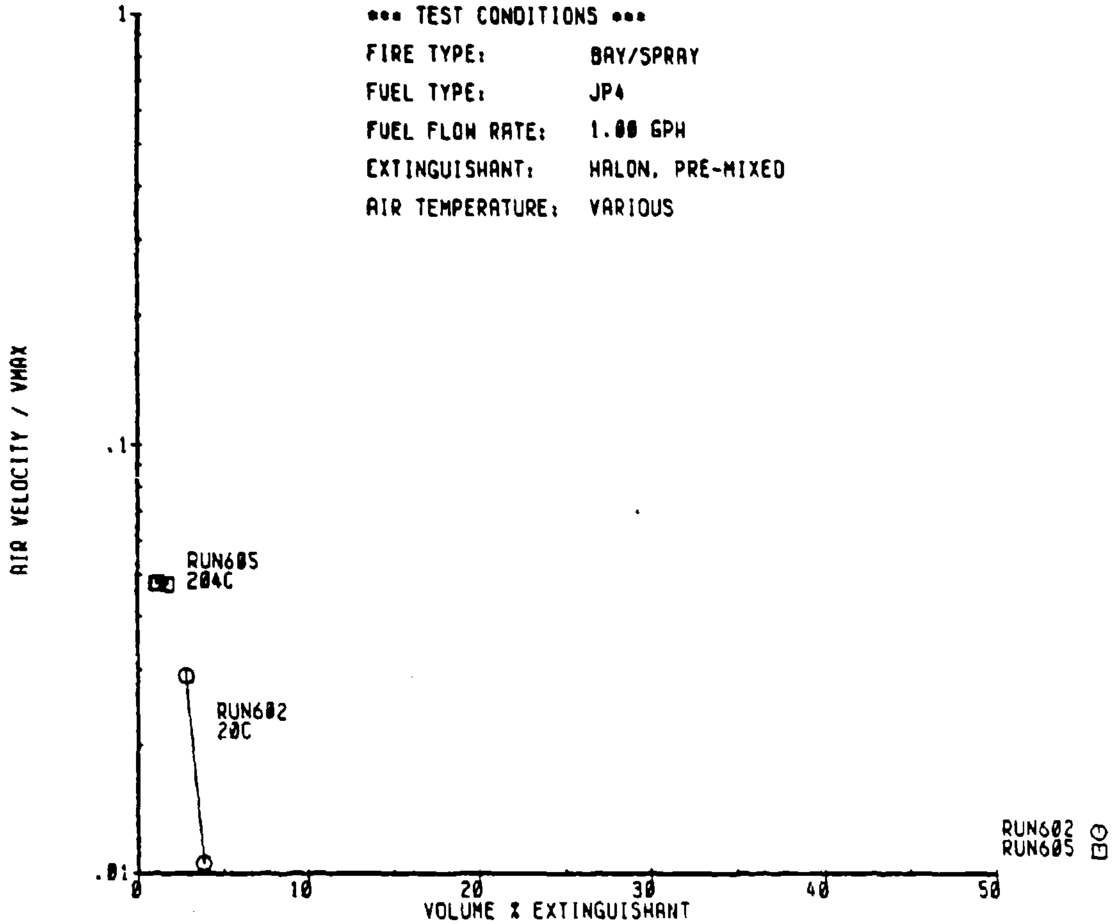
|---|---|---|---|---|---|---|
| CALC | | 14DEC88 | REVISED | DATE | DRY BAY SIMULATION<br>SPRAY FIRE<br>ONE EXTINGUISHANT, DIFF. AIR TEMPS | FIGURE<br>G-438 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 215 |

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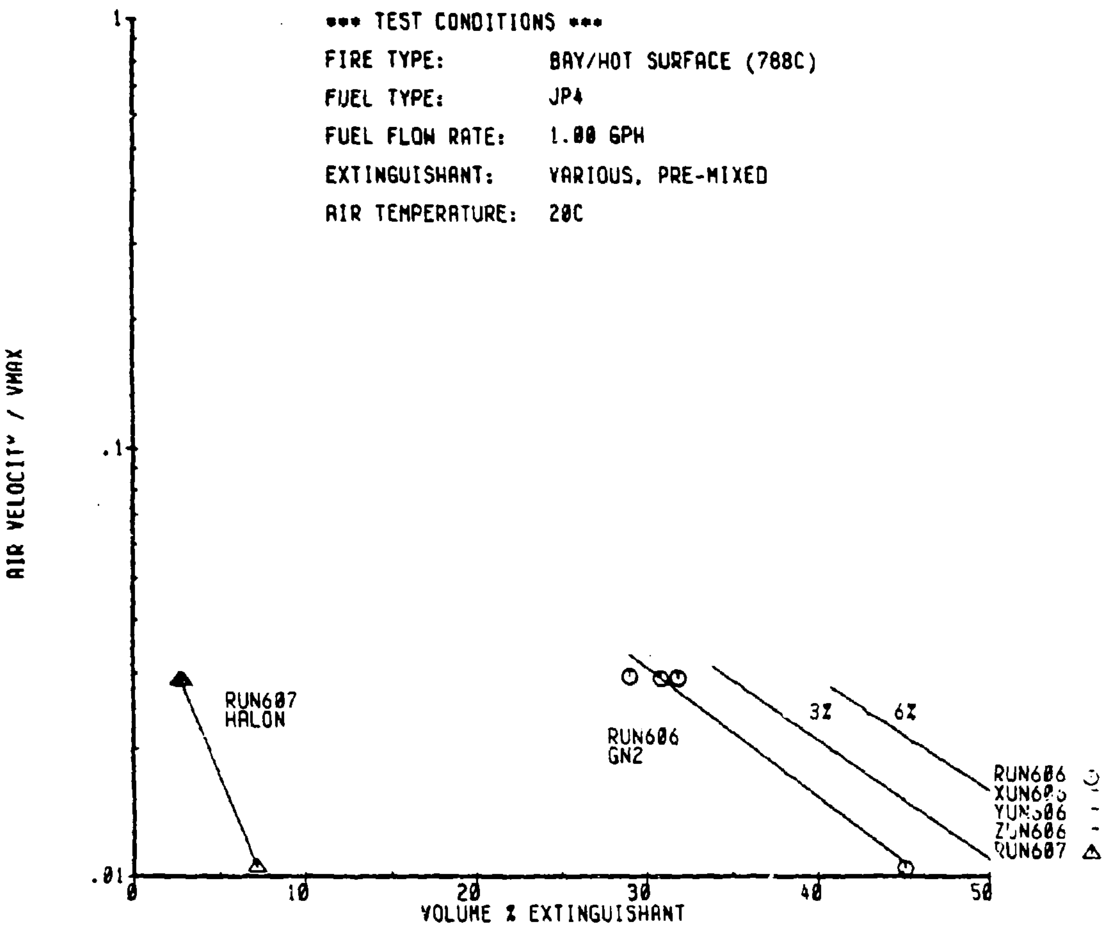
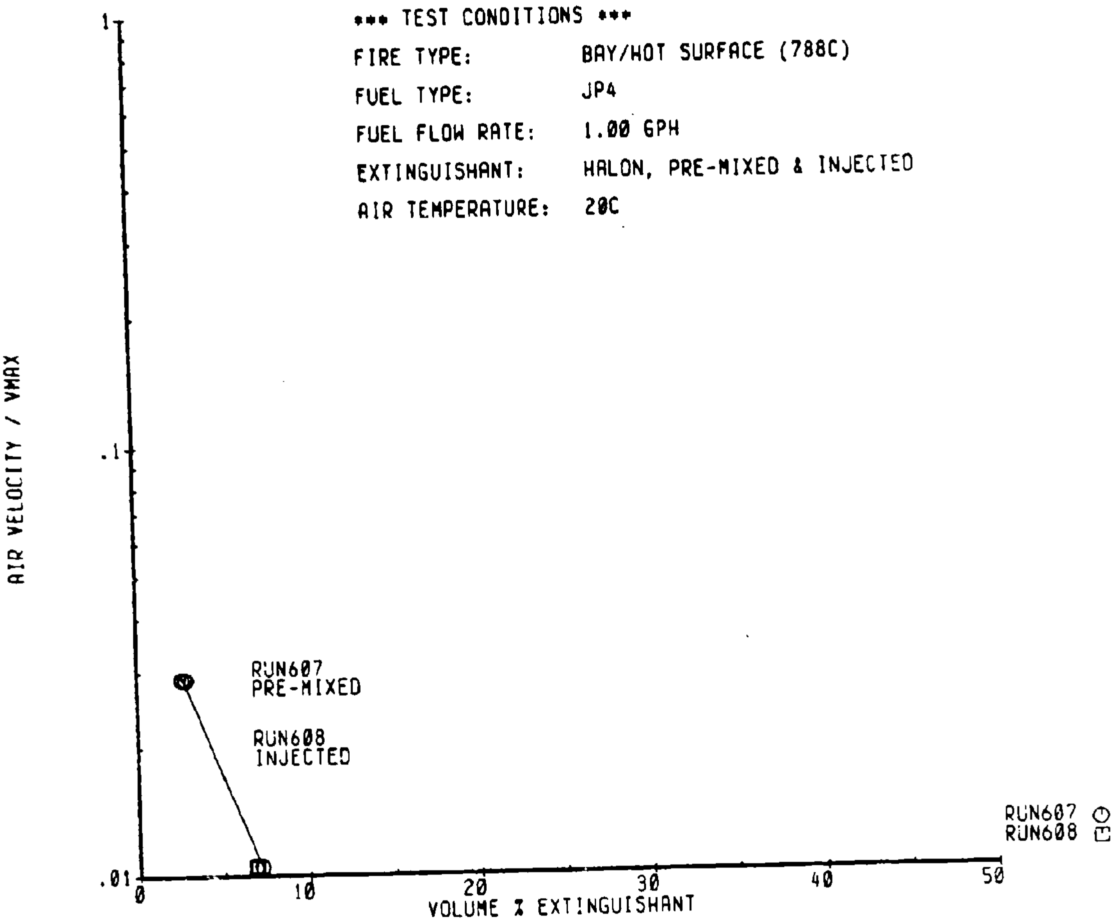
|---|---|---|---|---|---|---|
| CALC | | 11DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>SPRAY FIRE<br>ONE EXTINGUISHANT, DIFF. AIR TEMPS. | FIGURE<br>G-44 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 216 |




| CALC | | 11DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>HOT SURFACE<br>ONE FLUID, VARIOUS EXTINGUISHANTS | FIGURE<br>G-45 |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 217 |

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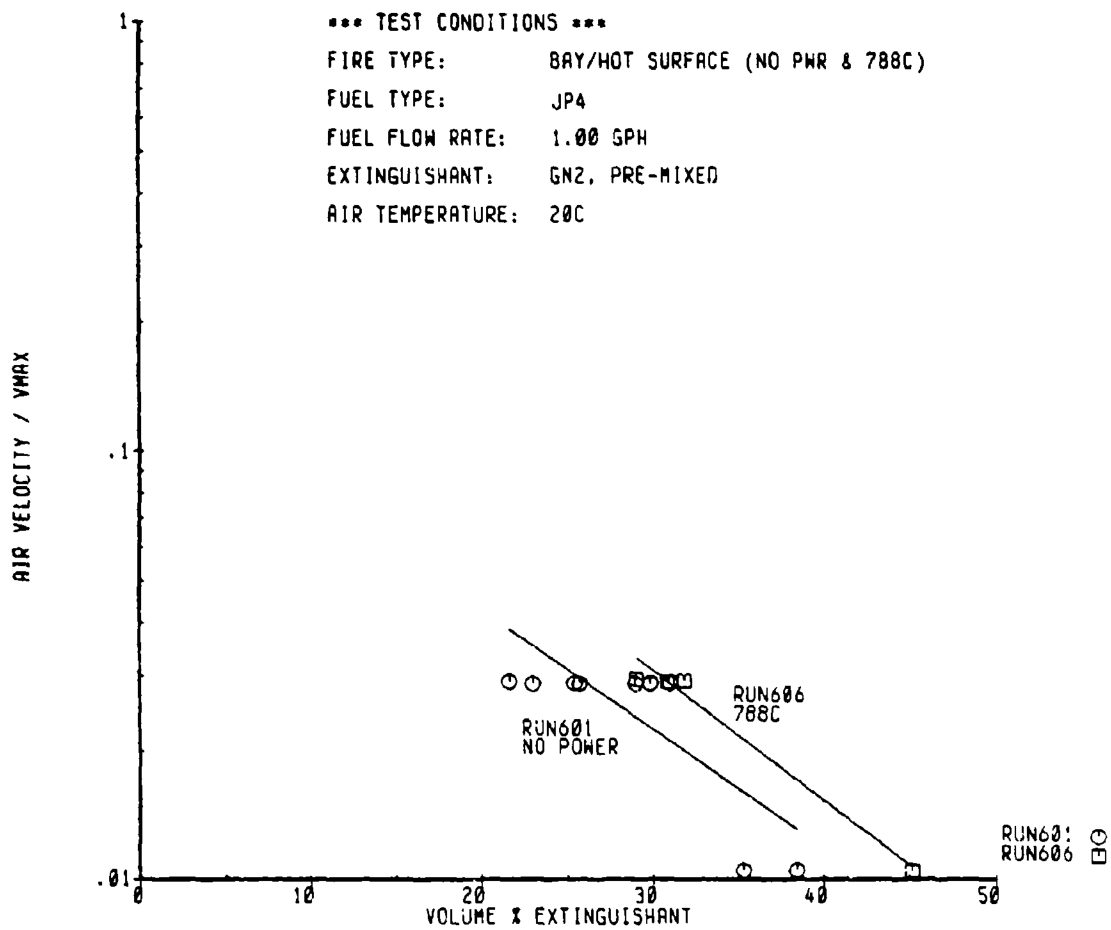
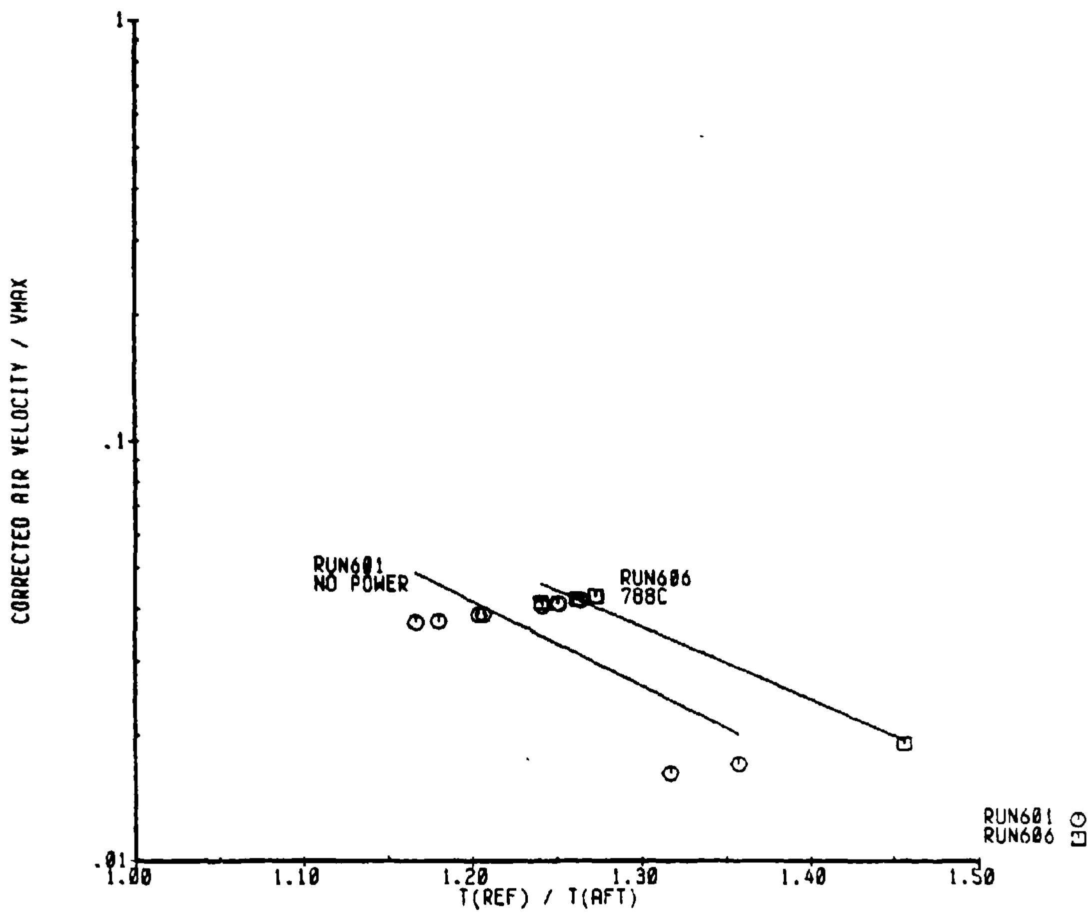
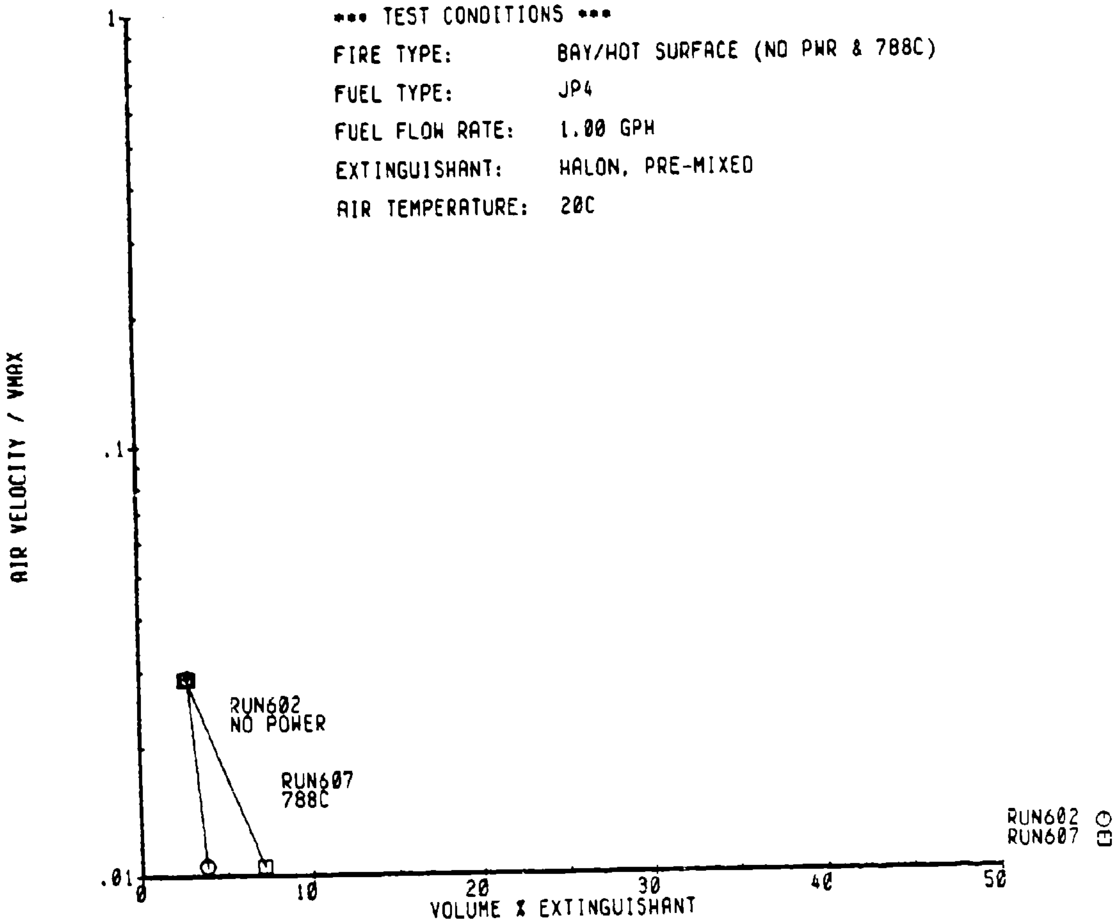
|---|---|---|---|---|---|---|
| CALC | | 10DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>HOT SURFACE<br>ONE EXTINGUISHANT DIFFERENT MIXING | FIGURE<br>G-46 |
| CHECK | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 218 |
| APPD. | | | | | | |



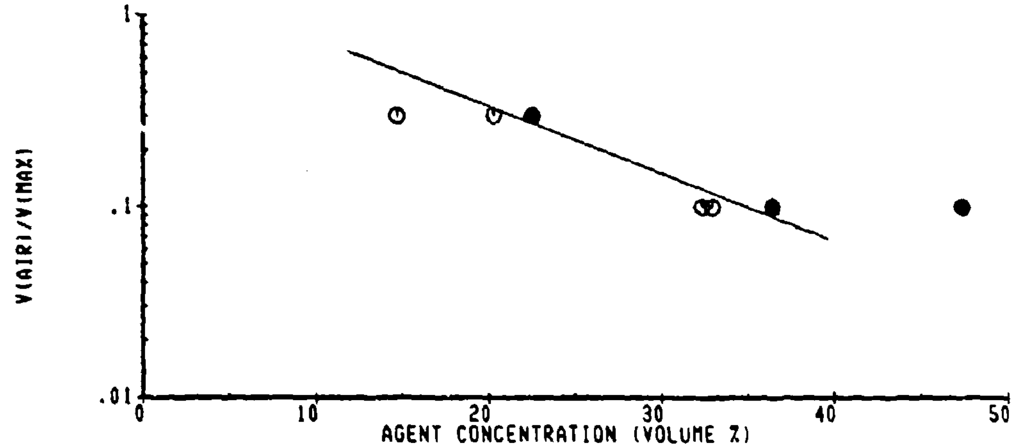

| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 10DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>HOT SURFACE<br>ONE EXT., DIFFERENT SRFC TEMPS | FIGURE |
| CHECK | | | | | | G-47A |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 219 |



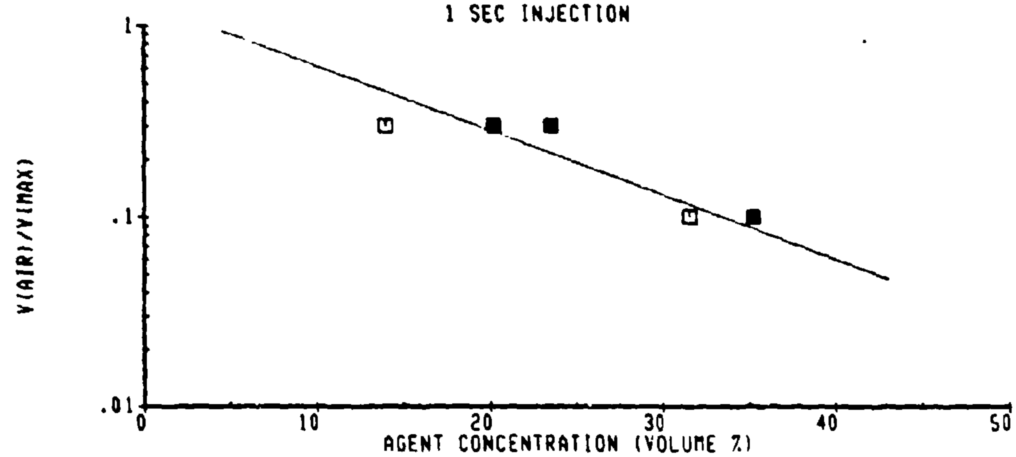

| CALC | | 11DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>HOT SURFACE<br>ONE EXT., DIFFERENT SRFC TEMPS | FIGURE<br>G-47B |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 220 |
| | | | | | | |




| CALC | | 10DEC80 | REVISED | DATE | DRY BAY SIMULATION<br>HOT SURFACE<br>ONE EXT., DIFFERENT SREC TEMPS | FIGURE<br>G-48 |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 221 |

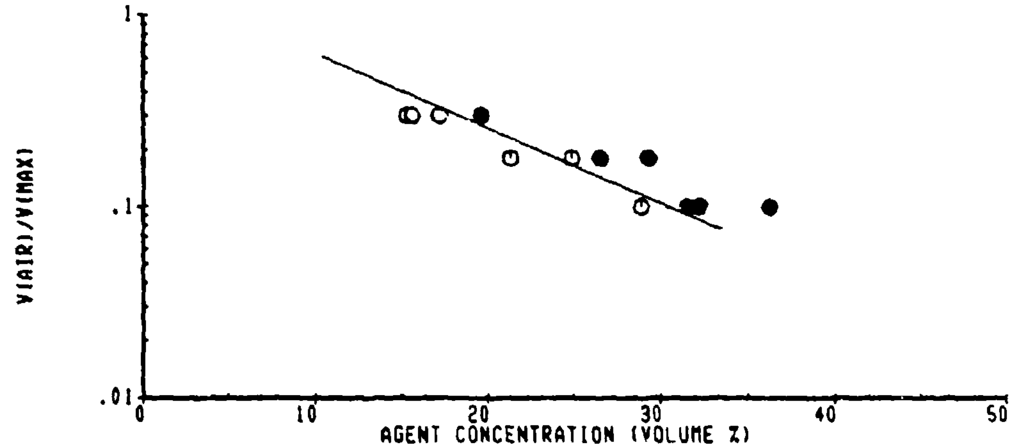



1 SEC INJECTION

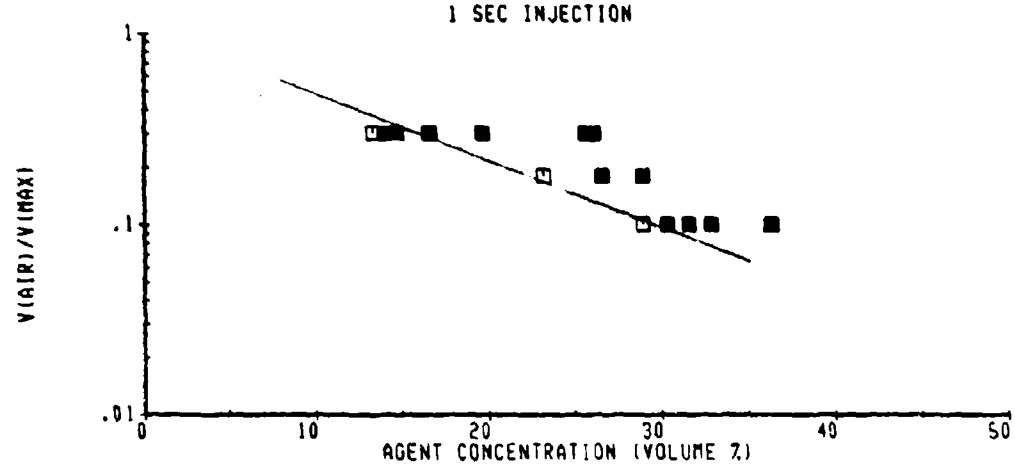



4 SEC INJECTION

| CALC | | 13OCT81 | REVISED | DATE | ADD-ON TEST DATA<br>1450F HOT SURFACE<br>INJECTION TIME COMPARISON, GN2 | FIGURE<br>G-49 |
|---|---|---|---|---|---|---|
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 222 |

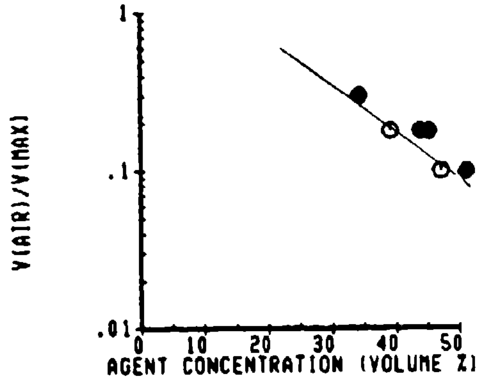



1 SEC INJECTION

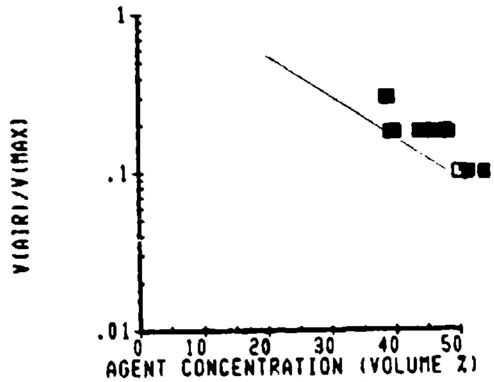



4 SEC INJECTION

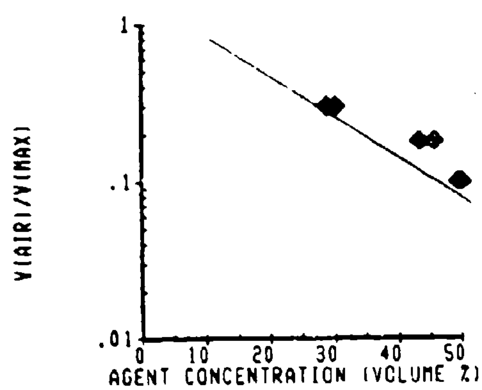
| | | | | | |
|---|---|---|---|---|---|
| CALC | | 13OCT81 | REVISED | DATE | ADD-ON TEST DATA<br>700F HOT SURFACE<br>INJECTION TIME COMPARISON, GN2 | FIGURE G-50 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 223 |



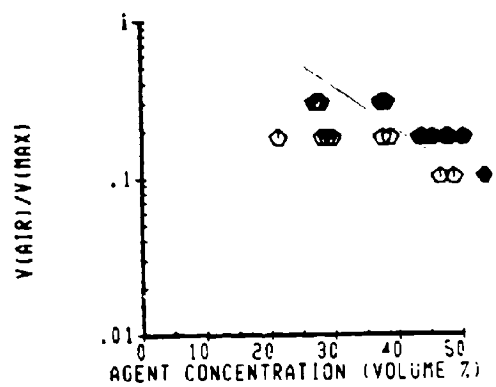

1 SEC INJECTION




2 SEC INJECTION

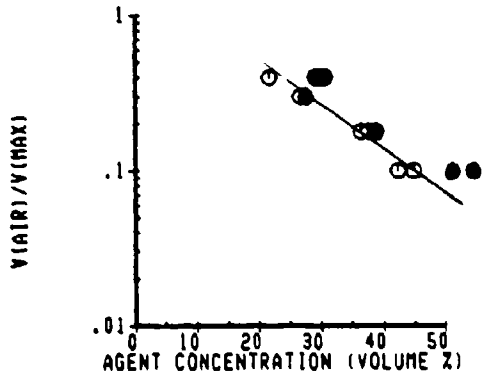



3 SEC INJECTION

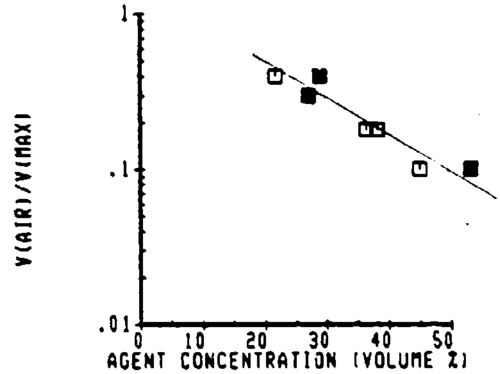



4 SEC INJECTION

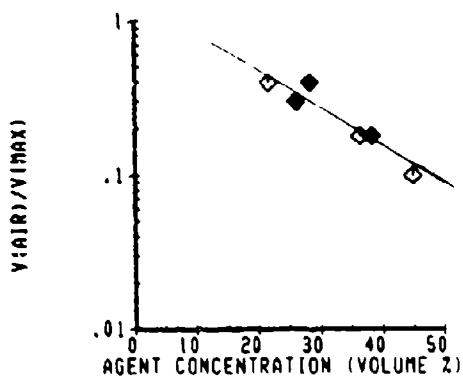
| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 09OCT81 | REVISED | DATE | ADD-ON TEST DATA<br>1450F HOT SURFACE<br>INJECTION TIME COMPARISON, NEA9 | FIGURE<br>G-51 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 224 |



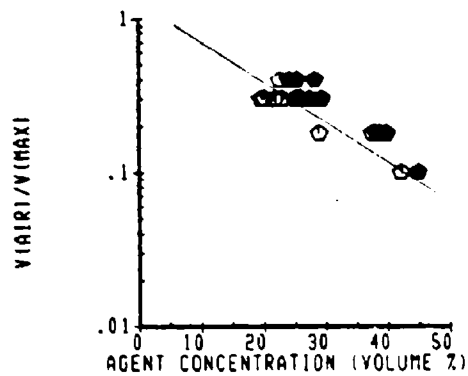

1 SEC INJECTION




2 SEC INJECTION

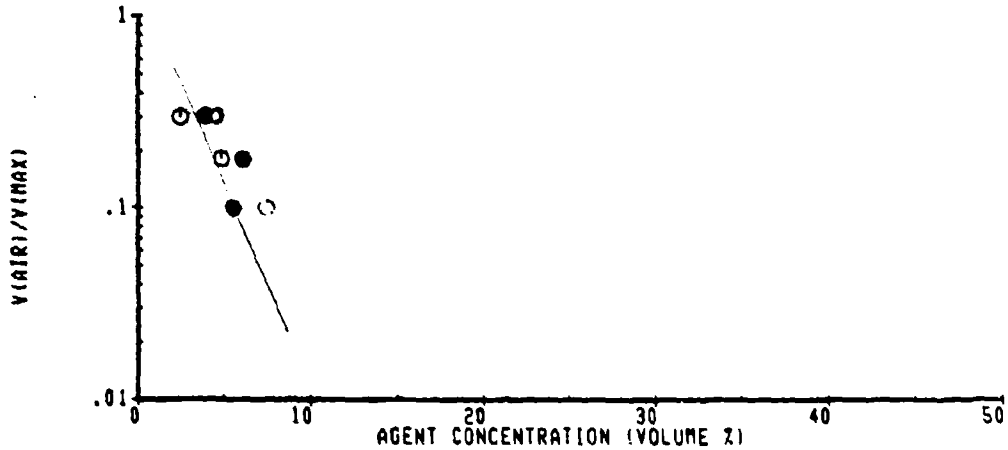



3 SEC INJECTION

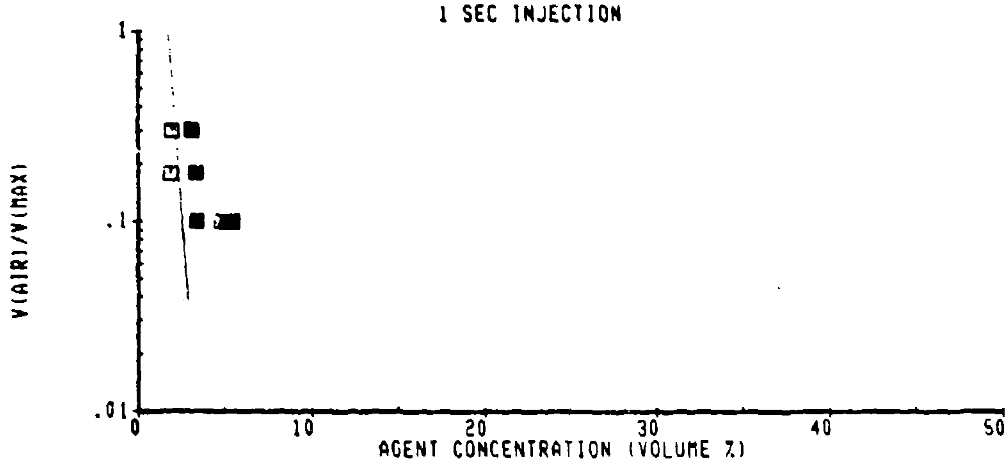



4 SEC INJECTION

| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 13OCT81 | REVISED | DATE | ADD-ON TEST DATA<br>700F HOT SURFACE<br>INJECTION TIME COMPARISON, NEA9 | FIGURE<br>G-52 |
| CHECK | | | | | | |
| APPD. | | | | | | |
| APPD. | | | | | THE BOEING COMPANY | PAGE 225 |




1 SEC INJECTION




4 SEC INJECTION

| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 13OCT81 | REVISED | DATE | ADD-ON TEST DATA<br>1450F HOT SURFACE<br>INJECTION TIME COMPARISON, HALON 1301 | FIGURE<br>G-53 |
| CHECK | | | | | | |
| APPD. | | | | | | |
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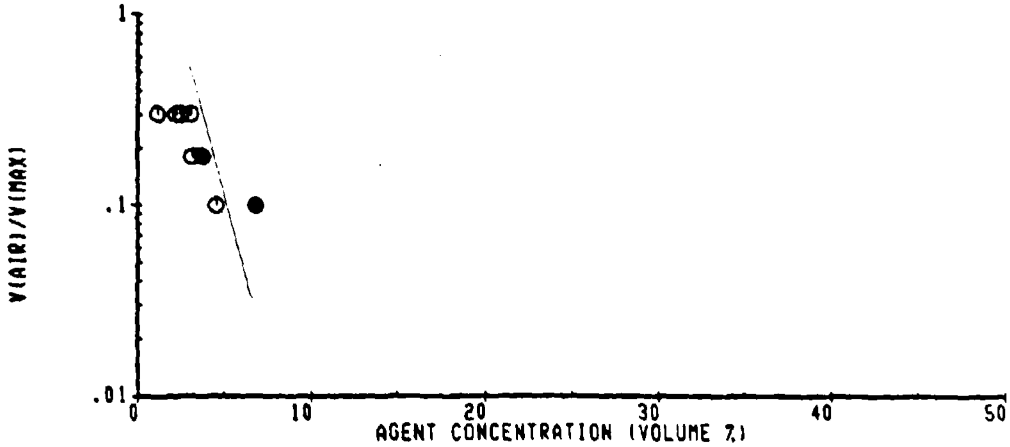
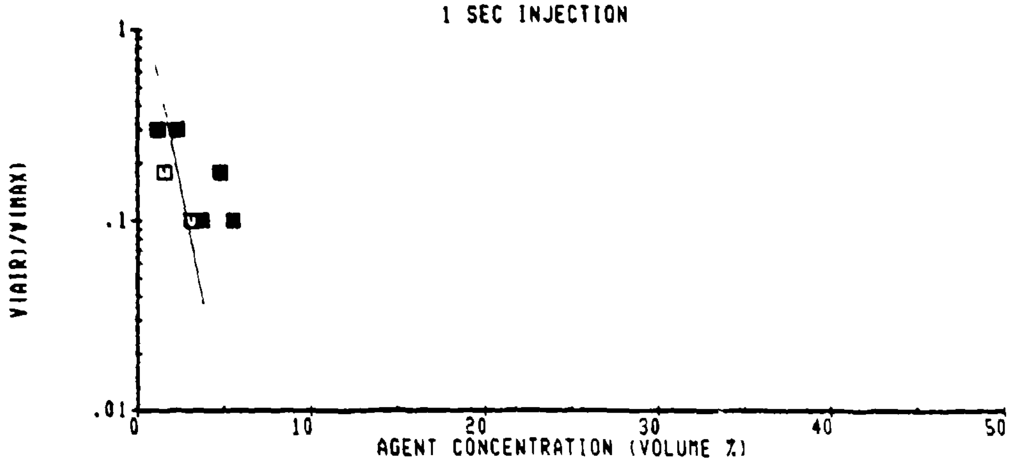



1 SEC INJECTION




4 SEC INJECTION

| | | | | | | |
|---|---|---|---|---|---|---|
| CALC | | 13OCT81 | REVISED | DATE | ADD-ON TEST DATA<br>700F HOT SURFACE<br>INJECTION TIME COMPARISON, HALON 1301 | FIGURE |
| CHECK | | | | | | G-54 |
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| | | | | | | |

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