AFWAL-TR-85-2060

Volume I - Executive Summary

VULNERABILITY METHODOLOGY AND PROTECTIVE MEASURES FOR AIRCRAFT FIRE AND EXPLOSION HAZARDS

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Airplane engine compartment and fuel tank fire safety research conducted under Air Force Contract F33615-78-C-2063 is summarized in this report. The value of ground testing, using the Aircraft Engine Nacelle (AEN) and the Simulated Aircraft Fuel Tank Environment (SAFTE) facilities, was clearly evident as the testing proceeded. Extinguishant tests of simulated nacelle fires indicated that current criteria for extinguishant concentration and duration were more than adqueate for intact nacelles but were just adequate for certain types of simulated combat damage. Test on on-board inert gas generator systems (OBIGGS) revealed that both the permeable membrane and molecular sive adequately inerted the test fuel tank. However, some minor operational difficulties were experienced with both test units which would have to be corrected prior to producing flight hardware.

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VULNERABILITY METHODOLOGY AND PROTECTIVE MEASURES FOR AIRCRAFT FIRE AND EXPLOSION HAZARDS

Volume I Executive Summary

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

Volume I Executive Summary

Volume II Aircraft Engine Nacelle Fire Test Program

- Part 1 Fire Detection, Fire Extinguishment and Hot Surface Ignition Studies
- Part 2 Small Scale Testing of Dry Chemical Fire Extinguishants

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

- Part 1 OBIGGS Ground Performance Tests
- Part 2 Fuel Scrubbing and Oxygen Evolution Tests
- Part 3 Aircraft OBIGGS Designs

PREFACE

Aircraft fire protection research conducted by the Boeing Military Airplane Company under Contract F33615-78-C-2063 is discussed in this report. Most of the research was carried out in newly activated facilities, the Aircraft Engine Nacelle (AEN) simulator, and the Simulated Aircraft Fuel Tank Environment (SAFTE) simulator located at Wright-Patterson Air Force Base and was conducted between February 1981 and October 1984. The contract was sponsored by the Air Force Wright Aeronautical Laboratories (AFWAL) and the Joint Technical Coordinating Committee for Aircraft Survivability (JTCG/AS). Guidance was provided by the Fire Protection Branch of the Aero Propulsion Laboratory (AFWAL/POSH), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 07, and Work Unit 86. Gregory W. Gandee, Terrell D. Allen, and John C. Sparks were the Government project engineers.

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

Volume I <u>Executive Summary</u>

Volume II <u>Aircraft Engine Nacelle Fire Test Program</u>

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

Part 2 Small Scale Testing of Dry Chemical Fire Extinguishants

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

Part 1 OBIGGS Ground Performance Tests

Part 2 Fuel Scrubbing and Oxygen Evolution Tests

Part 3 Aircraft OBIGGS Designs

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

Section | Page

LIST OF FIGURES

1.0 INTRODUCTION

Fire protection for military aircraft has been the focus of continuing research for many years. Engine compartment (nacelle) and fuel tank fire protection have dominated this research because fires in these areas are the most common and potentially the most serious. As aircraft become more sophisticated and costly, protecting these valuable assets becomes even more vital. The current study examined methods for improving both engine compartment and fuel tank fire safety by conducting tests in large scale engine nacelle and fuel tank simulators and other facilities and evaluating the results.

Aircraft engine compartment fires are generally caused by combustibles such as fuels, hydraulic fluid or lubricants coming in contact with ignition sources: hot ducts, hot surfaces or electrical arcs. The combustible fluids may be released by leaking lines or fittings, accidental damage or combat damage. Halon is used almost exclusively as the extinguishing agent for engine compartment fires and is released by crew action in response to fire or overheat warnings. Basic issues addressed in this study included the concentration of Halon required for fire extinguishment and changes in Halon requirements due to combat damage.

Fuel tank fires may be caused by combat damage, lightning, electrostatic discharges, electrical arcing or other factors which create an ignition source for fuel vapors in the vapor space (ullage) of the fuel tank. Several fuel tank fire protection techniques have been implemented on military aircraft. Explosion suppressant foam, which is used in many aircraft, is a filler material which localizes and suppresses flame propagation before damaging overpressures occur. Halon systems are used to provide part-time fire protection when hazardous conditions can be anticipated. Liquid nitrogen (LN_2) systems prevent fuel tank fires by inerting the ullage, i.e., limiting the oxygen concentration to 9% or less. Although these concepts provide effective fire protection, the foam has weight and maintenance disadvantages, and the Halon and LN_2 systems have logistic and cost disadvantages. An attractive alternative is the on-board inert gas generation system (OBIGGS) which processes engine bleed air into a nitrogen rich gas suitable for fuel tank inerting. Since data on the installed performance of an OBIGGS was limited, another thrust of this study was to obtain such data to evaluate OBIGGS performance, identify deficiencies and to provide a basis for developing aircraft OBIGGS preliminary designs.

The results of this program are presented in three volumes. Volume I (this volume) is an executive summary which describes the purpose of each study and highlights important results and conclusions. Volume II details results of engine compartment fire extinguishant and hot surface ignition studies conducted in the Aircraft Engine Nacelle (AEN) simulator at WPAFB and in a small scale test device at Seattle. Volume III describes fuel tank fire protecton studies, primarily conducted using the Simulated Aircraft Fuel Tank Environment (SAFTE) simulator, also at WPAFB. The AEN and SAFTE facilities and the control room are located in I-Bay of Building 71B. The arrangement and installation of these facilities is shown in Figure 1.

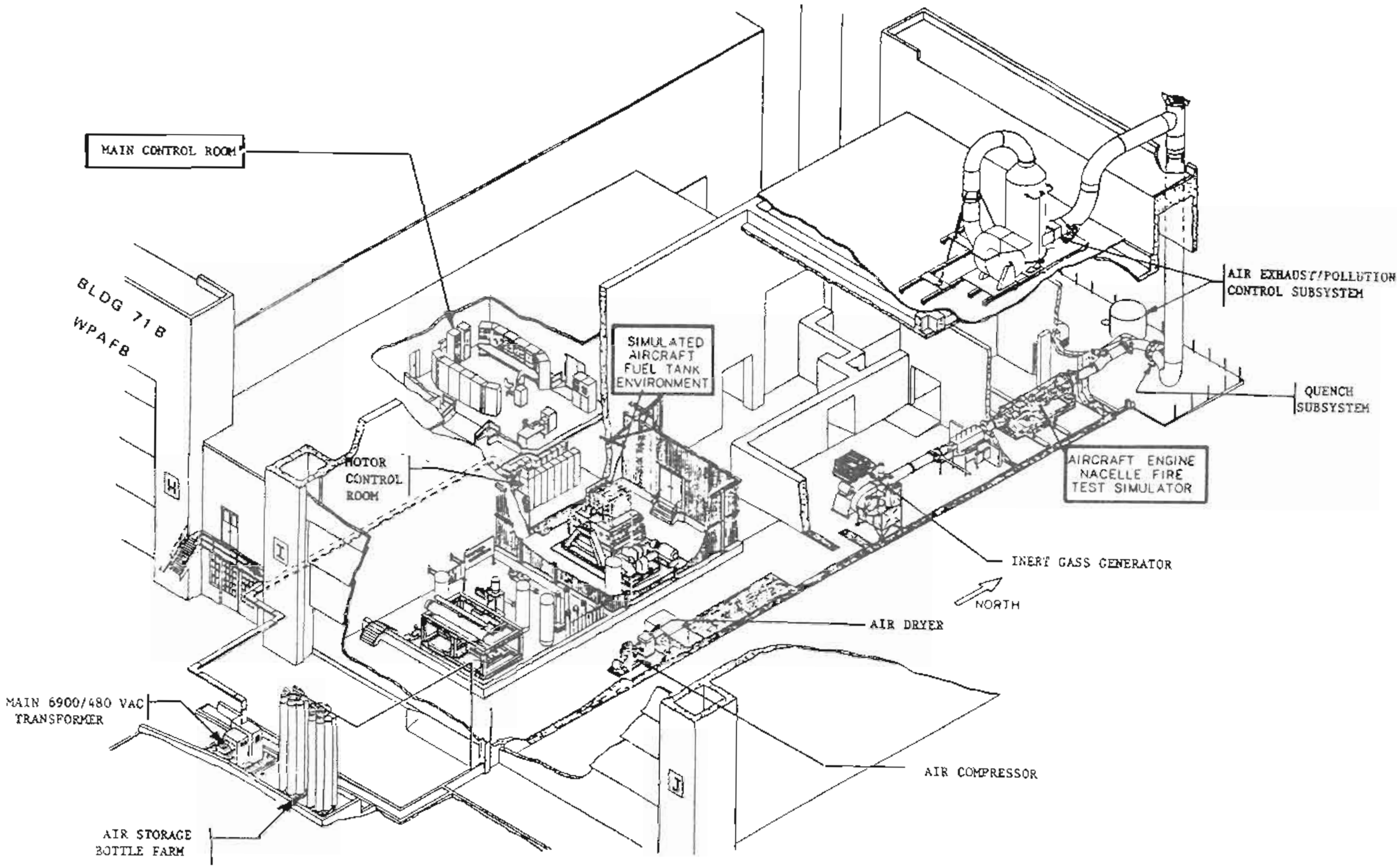


Figure 1. AEN and SAFTE Facilities Complex at WPAFB

2.0 AIRCRAFT ENGINE COMPARTMENT FIRE PROTECTION

The engine compartment fire protection studies presented in Volume II are divided into 2 sections. Results of fire inititation and propagation tests (including the effects of combat damage), conducted under representative dynamic operational environmental conditions, and hot surface ignition tests, are presented in Part 1. Results of dry chemical extinguishant tests conducted in a small scale test rig are discussed in Part 2.

2.1 Simulated Nacelle Fires

The Aircraft Engine Nacelle (AEN) Fire Test Simulator was used to study nacelle fires under simulated flight conditions. The AEN allowed fires to be ignited, to propogate for pre-selected time intervals and then to be extinguished. Specific objectives of these tests were to:

- o verify and/or refine existing design criteria for Halon 1301 and Halon 1202 extinguishants;
- o measure agent concentration in the engine compartment during agent release;
- o determine changes in agent requirements for protection against combat damage; and
- o evaluate the Graviner ultraviolet fire detection system developed for flight testing on the F-111 airplane.

2.1.1 AEN Test Facility

The AEN is a ground test facility located at WPAFB, Ohio and designed to simulate the fire hazards in the annular compartment around an aircraft engine. Aircraft engine compartment ventilation air velocity, pressure and temperature, fan case temperature, nacelle geometry, engine bleed air, and the introduction of aircraft flammable fluids can be simulated. Aircraft fire extinguishing agent discharge systems can be simulated using various extinguishants, and their effect on fires in the AEN can be observed and recorded. Principal AEN components are shown in Figure 2.

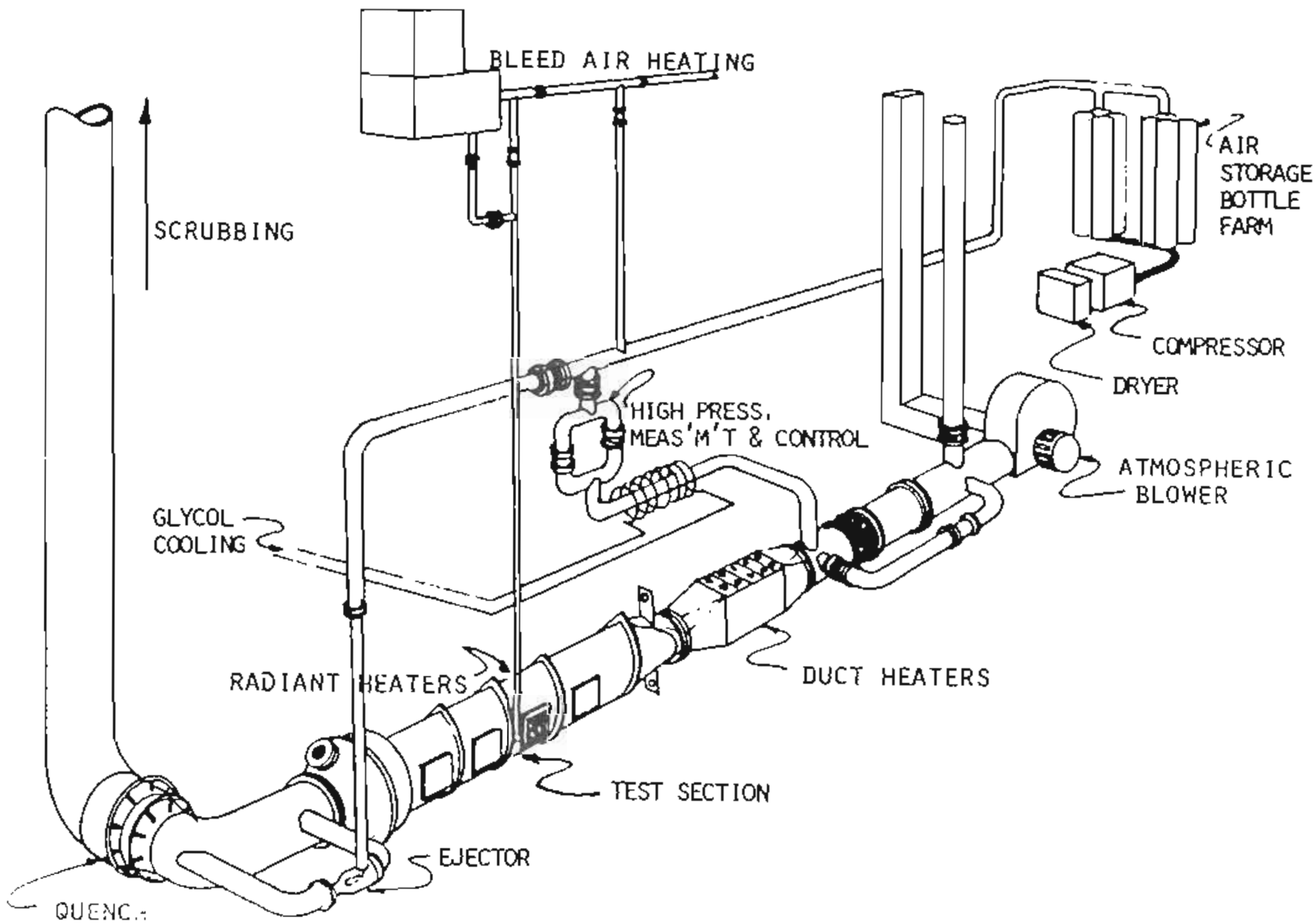


Figure 2. AEN Components

The test section of the AEN (Figure 3) consists of a two radian (114 degrees) segment of the annulus between a 15-inch radius duct, that simulates an engine case, and a 24-inch radius duct, that simulates the engine compartment outer wall. The test section is approximately 14 feet long and is constructed from 1/4-inch stainless steel. Various access ports and viewing windows are provided for access to test equipment and instrumentation and for observation of the fires in the test section. The hardware in an F-16 engine compartment in the vicinity of the engine bleed duct was simulated in the extinguishant tests.

2.1.2 Results and Conclusions

The tests demonstrated the value of the AEN simulator in examining specialized fire safety problems associated with aircraft engine compartments. A Halon 1301 system designed to current criteria had substantially more extinguishant capacity than required for fires in an undamaged engine compartment. The excess capacity was lower for compartments with simulated battle damage that allowed outflow from the compartment. The quantity of agent was adequate for compartments with inflow due to simulated combat damage, but the agent would have to be released at a higher rate to be effective. These conclusions are based on sea level simulations, which are predicted to be the worst case with respect to extinguishant requirements. However, altitude simulation tests should also be conducted to verify this hypothesis. Direct comparisons between Halon 1202 and Halon 1301 revealed that substantially more Halon 1202 was required to extinguish a fire; additional testing would be required before generalized conclusions can be made, especially since other investigations have indicated that Halon 1202 was superior to Halon 1301 in certain applications.

The current design criteria require that a 6% concentration of Halon be maintained for 1/2 second throughout the engine compartment. However, the AEN tests revealed that the quantity of agent required for extiguishment could be reduced if the agent was injected more rapidly (Figure 4). No recommendations for changes to the criteria were warranted without additional test data.

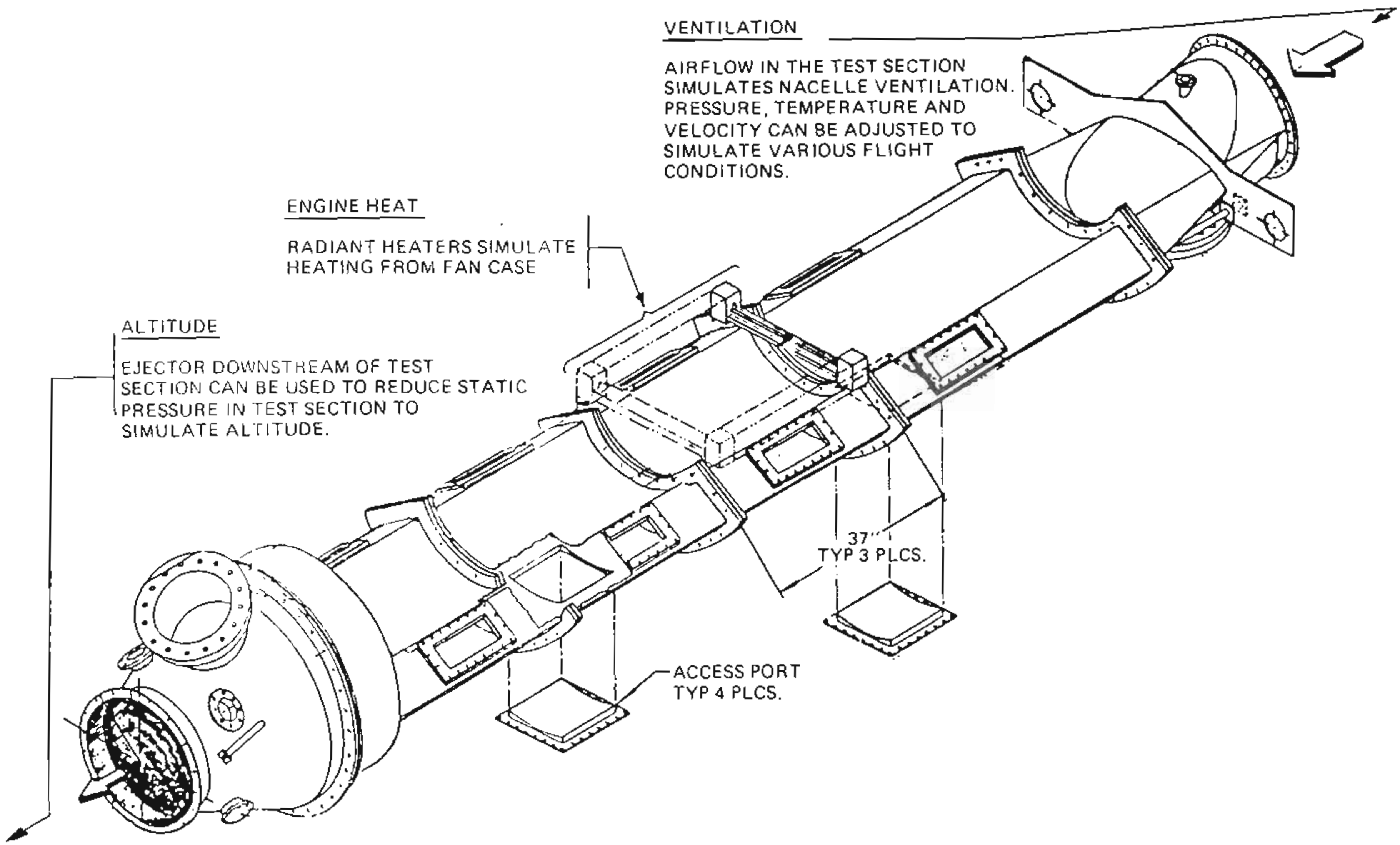


Figure 3. AEN Test Section

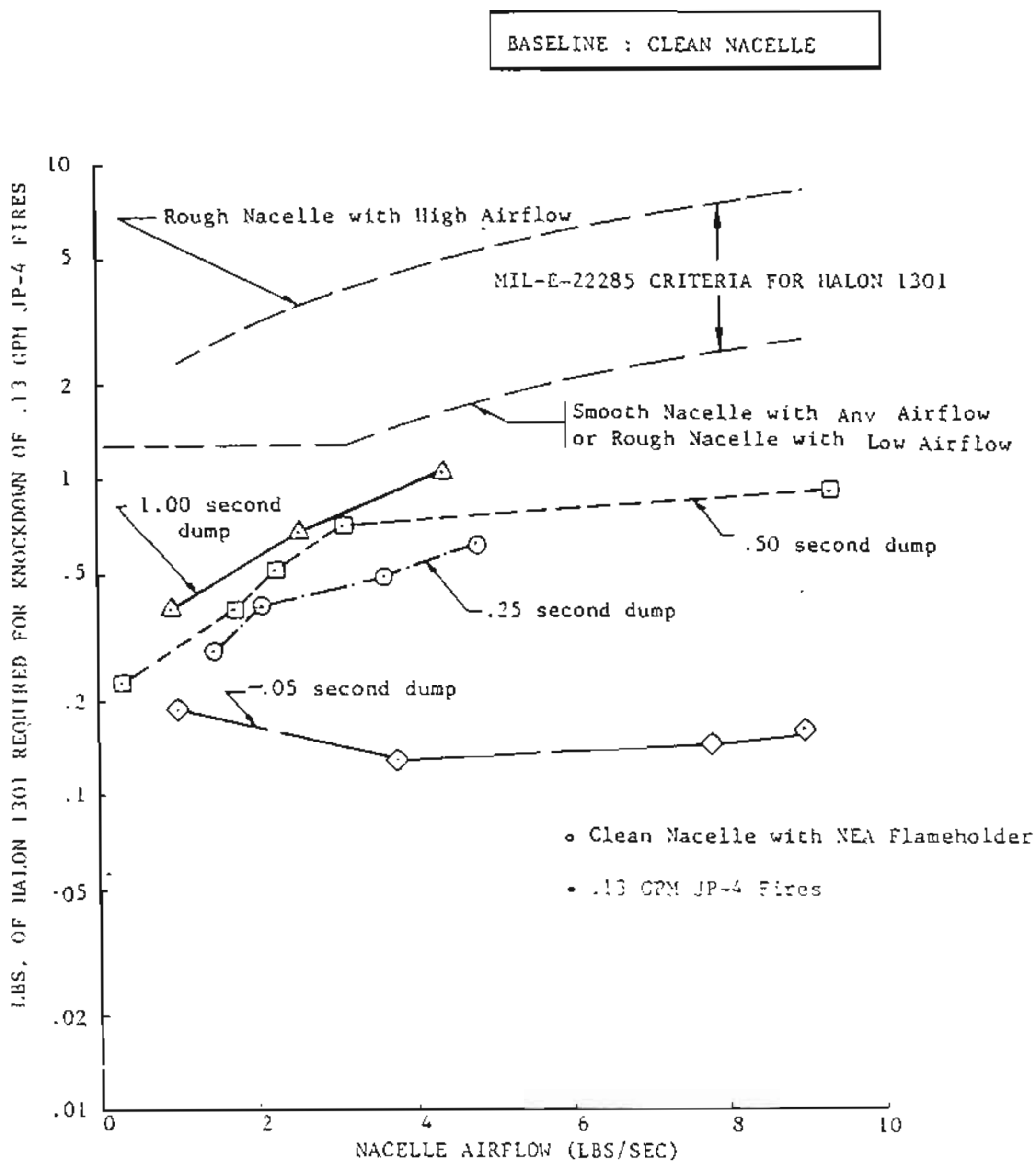


Figure 4. Effect of Dump Duration on Quantity of Halon 1301 Required To Knockdown .13 GPM JP-4 Fires

High combustion temperatures in the engine compartment resulting from airflow due to some types of battle damage could result in major damage before the crew could take appropriate action. It was concluded that a fire detector would have to be monitored by an agent release computer to properly control agent discharge. Such a system would probably be used in addition to, rather than in place of, the conventional fire protection system.

A Graviner fire detector similar to that currently being evaluated on the F-111 airplane was tested in this program to check its response to engine compartment fires. The results indicated that the detector always responded both to a fire and to fire extinguishment.

Hot surface ignition tests were conducted with a simulated F-16 airplane bleed air duct to measure duct temperatures required to ignite JP-4 fuel, lubricating oils and hydraulic fluids used on the F100 engine. The purpose of the tests was to determine if insulation could be deleted from the duct without degrading fire safety. The data were transmitted to the General Dynamics Corp. for risk analysis. The analysis revealed that the increased risk was acceptable and that the insulation was not necessary, thus saving the Air Force about $20 million.

2.2 Small Scale Testing of Dry Chemical Fire Extinguishants

Dry chemical extinguishants offer a potential fire suppression alternative that is superior to other suppressants. Evidence suggests that dry chemicals may prevent hot surface re-ignition of a fire after the initial knockdown of the fire.

Tests were conducted in a small scale test rig using dry chemical extinguishants to:

- obtain performance data about fire knockdown and re-ignition prevention capabilities, and possible material interaction (corrosion) that could impact the AEN facility; and
- gain experience with the techniques of handling dry chemical extinguishants.

Three dry chemicals were evaluated in this study:

- Monnex;
- NaD + Si O_2 (sodium dawsonite plus silicon dioxide); and
- KD + KI + Si O_2 (potassium dawsonite plus potassium iodide plus silicon dioxide).

2.2.1 Test Facility

The test facility used to perform the dry chemical extinguishant tests is shown schematically in Figure 5, and pictorially in Figure 6. Test section fires and ventilation velocities simulated the test conditions in the above AEN tests. The hot surface could be controlled to temperatures up to 1450^{o}F. In addition to evaluating the effectiveness of the dry chemical extinguishants, this facility was used to obtain experience with handling those extinguishants and to identify problems with cleaning up the extinguishants from the facility. This information was considered necessary prior to testing dry chemical agents in the AEN facility.

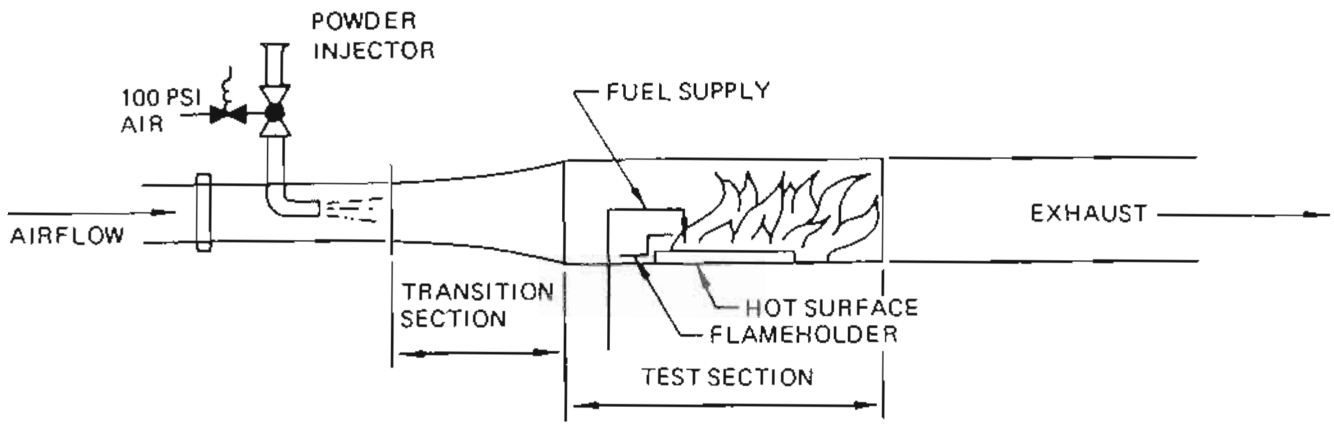


Figure 5. Dry Chemical Test Section Diagram

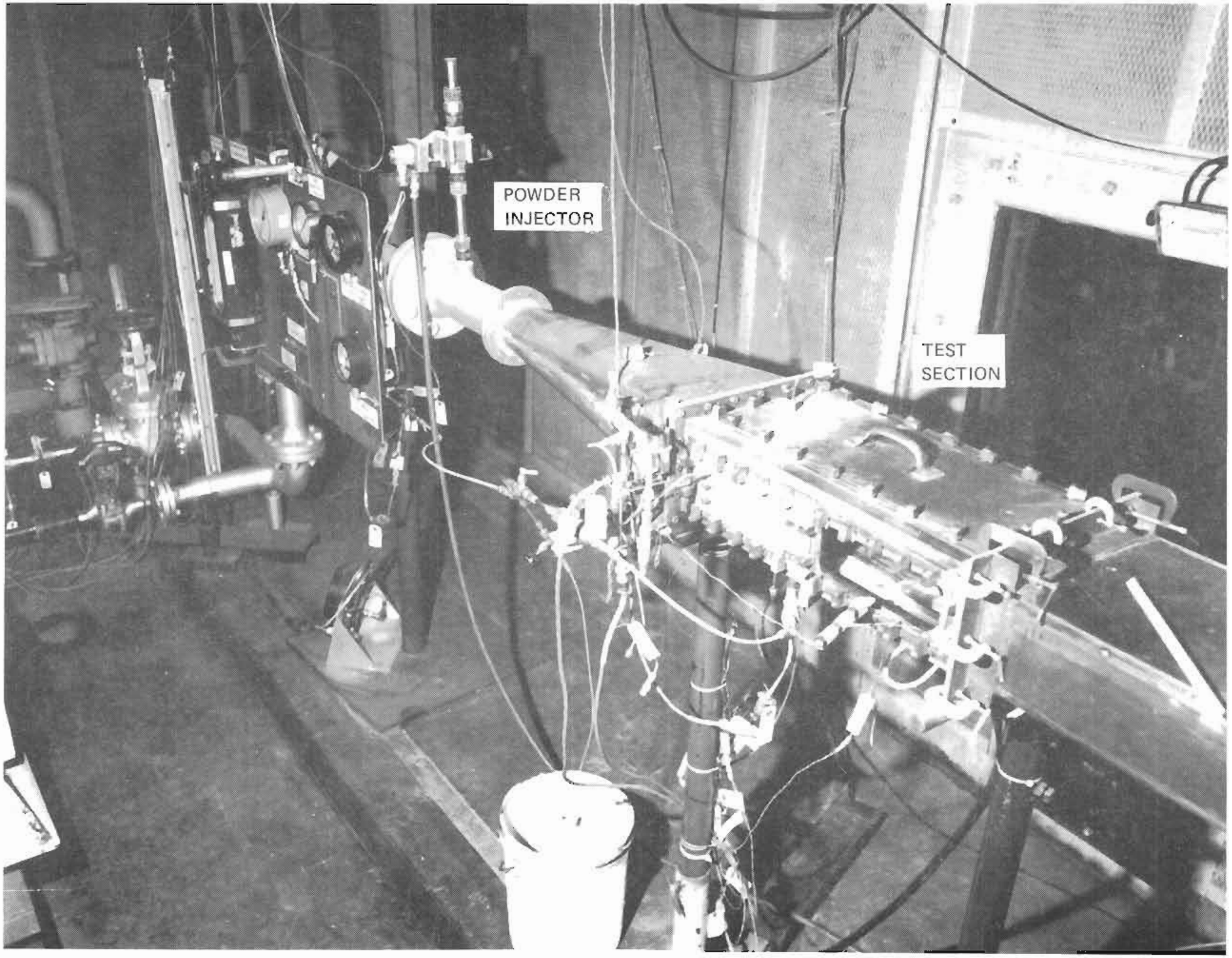


Figure 6. Dry Chemical Extinguishant Test Facility

2.2.2 Results and Conclusions

For fire suppression, Monnex used the least amount of extinguishant to knockdown fires. However, despite the appearance as the most effective fire suppressant, the tests comparing the extinguishants used only one geometry. Therefore, other geometries, as well as conditions, should receive attention in future work.

Not only were there differences between the extinguishants and the amounts needed for fire knockdown, but there was also a difference in the response of the flame to different amounts of the same extinguishant. For example, Monnex, depending on the amount applied, exhibited three regions of fire suppression: permanent extinguishment, brief extinguishment, and no effect. The difference between permanent extinguishment and brief extinguishment was due to the fuel ignition temperature for the particular air flow. If the surface temperature was near to the ignition temperature when the extinguishant was applied, the momentary extinguishment and cooling by the fuel reduced the surface temperature below the ignition temperature; thus, permanent extinguishment occurred. Conversely, the tests revealed that a maximum temperature existed such that any amount of extinguishant failed to extinguish the flame. These findings are illustrated for Monnex extinguishant in Figure 6. For the conditions and test set-up used for this study, these maximum temperatures were above those normally encountered in typical airplane situations.

Handling the dry extinguishants was comparable to handling the Halons. However, expended extingushants, especially after repeated fire suppression tests, reacted with the test bed. Monnex was the least harmful and easiest to clean up. The sodium dawsonite (NaD) was the most corrosive and most difficult to clean up. Therefore, since repeated extinguishant use in the AEN might prove harmful to the materials in the facility, the facility should be cleaned after each fire suppression test. After reviewing the advantages and disadvantages of using dry powder extinguishants in an engine compartment, it was decided that investigating other extinguishants had a higher priority. However, tests of dry powders in the AEN facility are recommended for future investigation, due to the potential for improved performance offered by these extinguishants.

Injecting the dry chemical agents presented some problems. However, a technique was developed in which the agents were injected into the air stream by differential pressure. In most cases simply opening the agent reservoir to atmospheric pressure was sufficient. However, pressurizing the reservoir was required in some cases to achieve the proper injection rate.

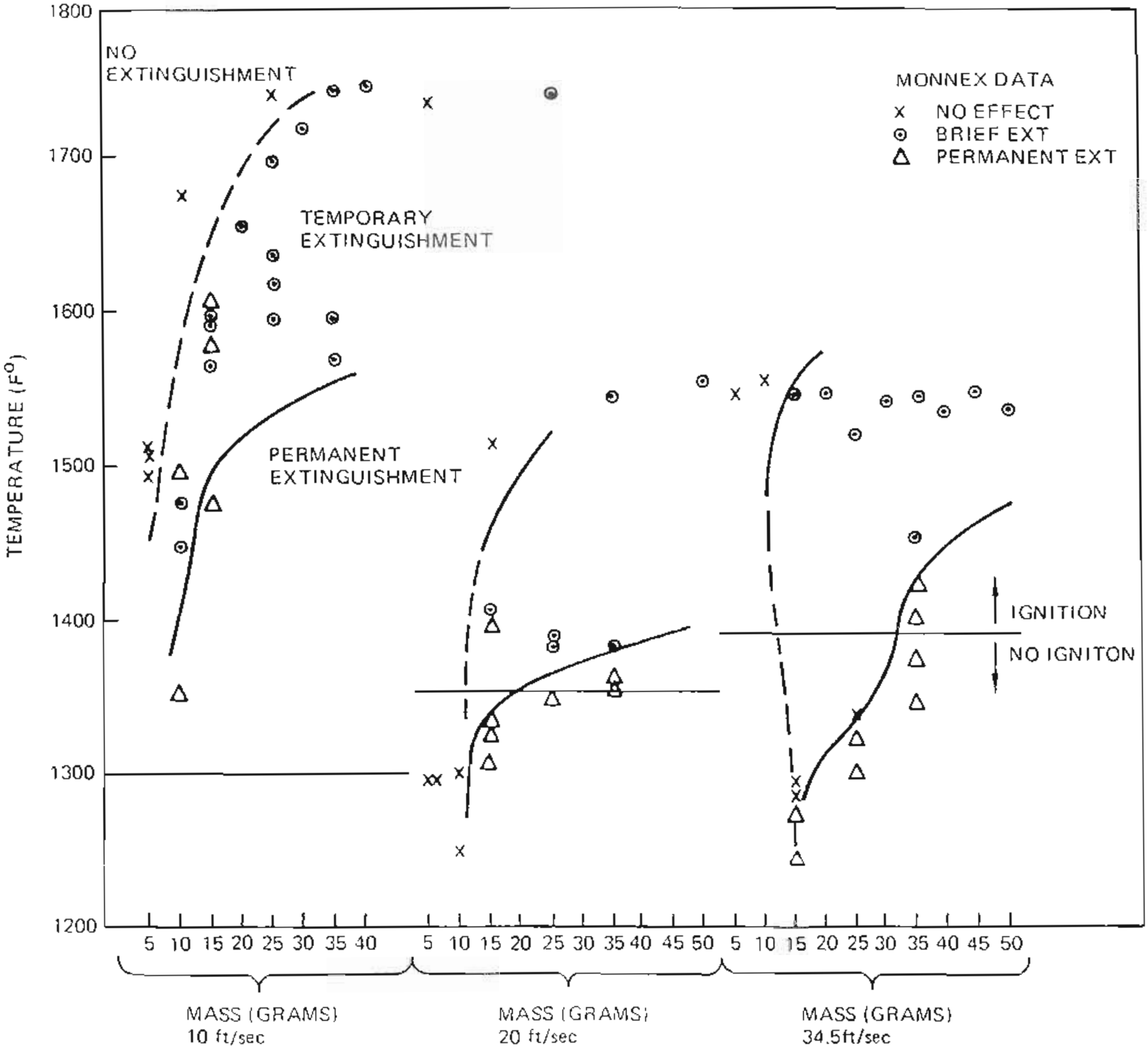


Figure 7. MONNEX Test Data (Grams Versus Surface Temperature)

3.0 INERT GAS GENERATION TEST AND ANALYSIS PROGRAMS

The concept of an aircraft OBIGGS eliminates logistics problems of liquid nitrogen or Halon fuel tank inerting systems and offers considerable weight savings over explosion suppressant foam fuel tank protection systems. The on-board generation concept required ground testing to better understand the performance of inert gas generators under simulated flight conditions, fuel scrubbing phenomena and oxygen evolution from the fuel. The viability of the concept also required study; this was done by developing OBIGGS preliminary designs for the C-5B and advanced fighter airplanes and comparing them with other systems.

Permeable membrane (PM) and molecular sieve (MS) air separation modules were viable candidates to generate the inert gas for the OBIGGS. Both types of modules were included in the performance and feasibility studies conducted under this task.

3.1 OBIGGS Performance Studies

Performance data for PM and MS OBIGGS were obtained using the Simulated Fuel Tank Environment (SAFTE) facility at WPAFB. Data were obtained for both steady state and simulated flight operations. Flight simulations included proper time phasing of bleed air temperature and pressure and altitude pressure as well as simulation of fuel temperatures and usage rates. In addition to the flowrate and oxygen concentration of the nitrogen enriched air (NEA), the OBIGGS performance studies included engine bleed and ram air penalty, immunity to water, durability and reliability, weight penalty and life cycle costs.

3.1.1 SAFTE Test Facility

The SAFTE facility (see Figure 8) consisted of a rectangular tank with a fuel capacity of 582 gallons, and associated instrumentation and controls. The tank skin temperatures and fuel withdrawal rate were computer controlled to simulate a pre-selected KC-135 flight profile. The tank was mounted on a platform which provided slosh and vibration simulation. Five gas sampling

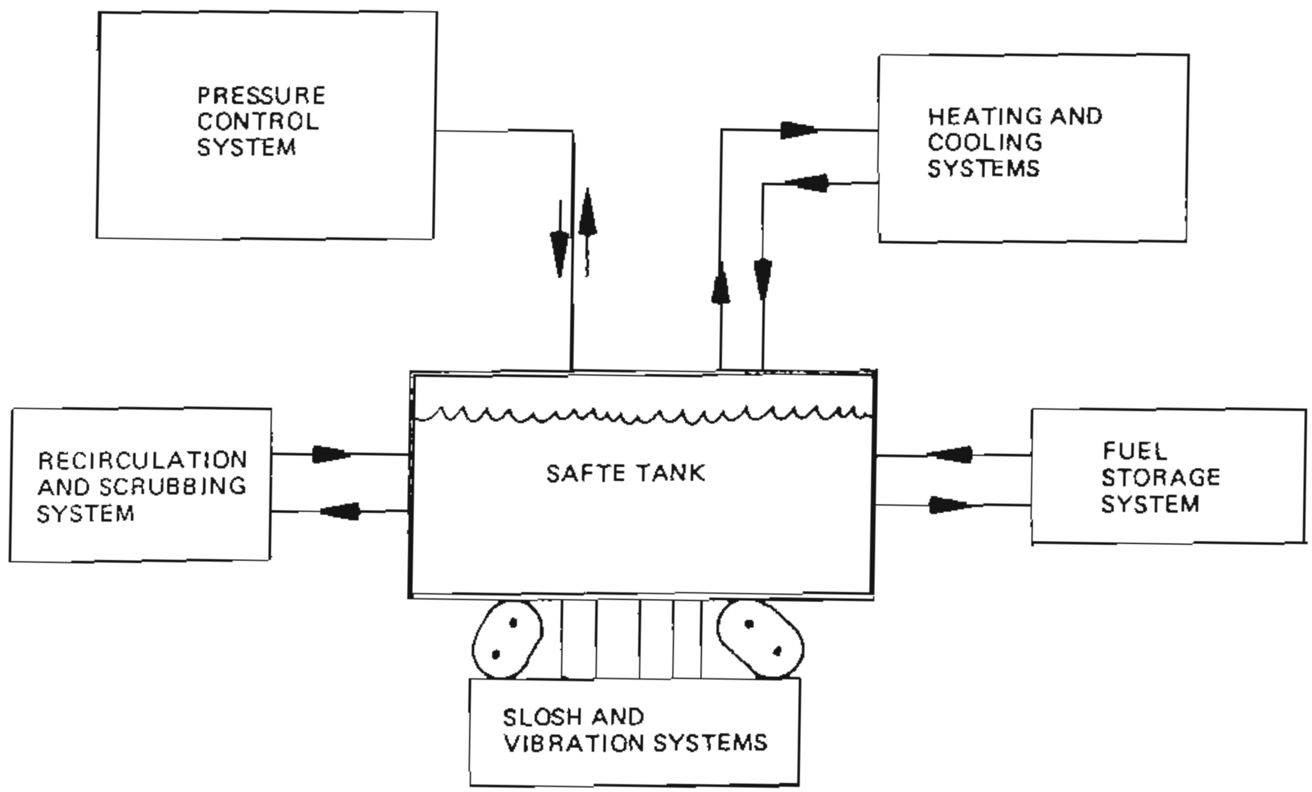


Figure 8. Functional Block Diagram of the Simulated Aircraft Fuel Tank Environment (SAFTE) Facility

probes, which moved vertically within the tank gas space, provided three-dimensional mapping of the gas composition. The gas samples collected were routed to a mass spectrometer for analysis. A vacuum system was used to simulate in-flight pressure. Standard pressure, temperature and flow rate instrumentation was provided, and the data were computer recorded.

Flight simulations were computer controlled to automatically position valves and to set pressures and temperatures corresponding to in-flight boundary conditions on both the air separation modules and the simulated airplane fuel tank. Data acquisition, reduction and presentation were automatically produced by the same computer. Progress of the simulated mission was monitored in the control room and provisions were made to revert to manual control if the need arose. The OBIGGS ground simulation facility is shown schematically in Figure 9.

As mentioned above, both PM and MS inert gas generators were tested. The inert gas generation process for the PM and MS units is illustrated in Figures 10 and 11 respectively. Since the PM and MS units were designed for the KC-135 airplane but the fuel capacity of the SAFTE simulator was only about 3% of the KC-135 tankage, a flow proportioning scheme was developed in which 30.3 pounds of the NEA product flow was discharged to the atmosphere for each pound of product flow supplied to the SAFTE tank.

3.1.2 Results and Conclusions

Both the PM and MS OBIGGS satisfactorily inerted the test fuel tank. However, the value and wisdom of ground testing became increasingly evident as the tests proceeded. OBIGGS sizing was based on the inert gas flow rate required for a fuel tank repressurization during a high speed descent, assuming the recompression process was adiabatic. However, test data (Figure 12) showed that the recompression process was more nearly isothermal, revealing that the air separation modules were undersized for the intended mission. Ground testing also revealed that trimming of the control systems was required to achieve satisfactory performance and that design deficiencies existed in both the PM and MS air separation test modules. The primary deficiency with the PM OBIGGS was fiber breakage due to rapid pressurization of the modules which resulted in a performance degradation with time. The problem could be solved

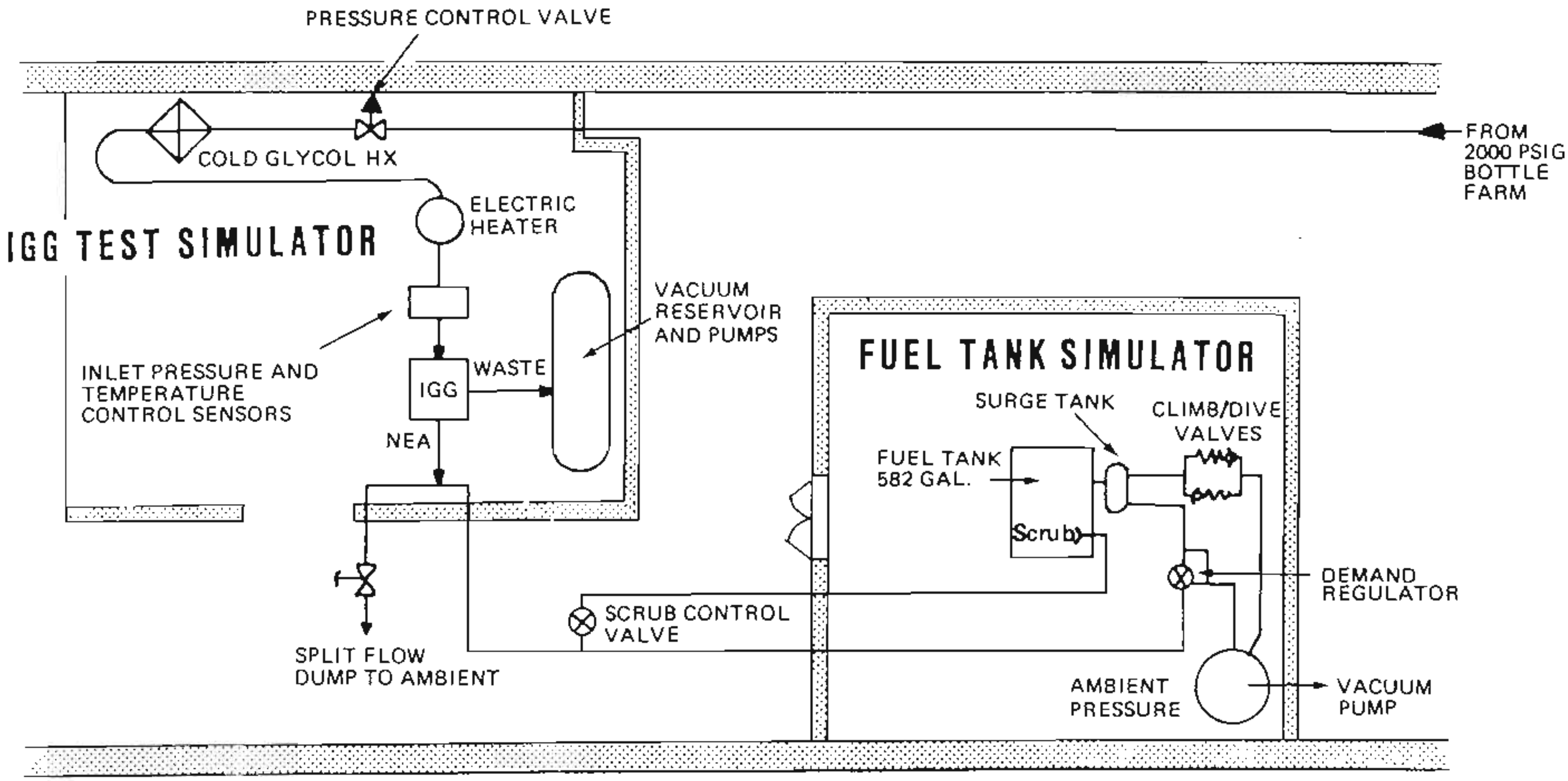


Figure 9. OBIGGS Ground Simulation Test Facility

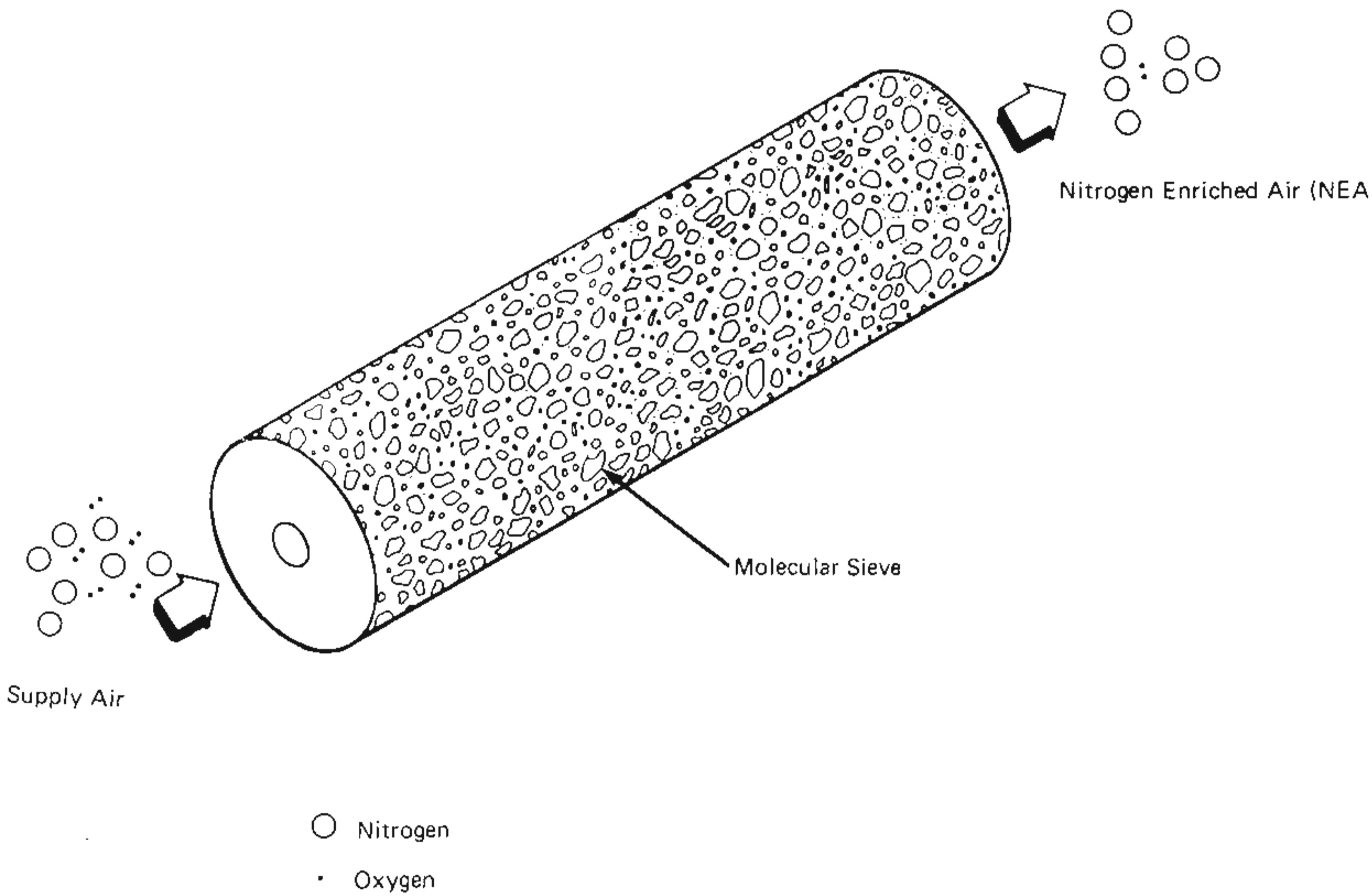


Figure 10. Molecular Sieve Air Separation Module

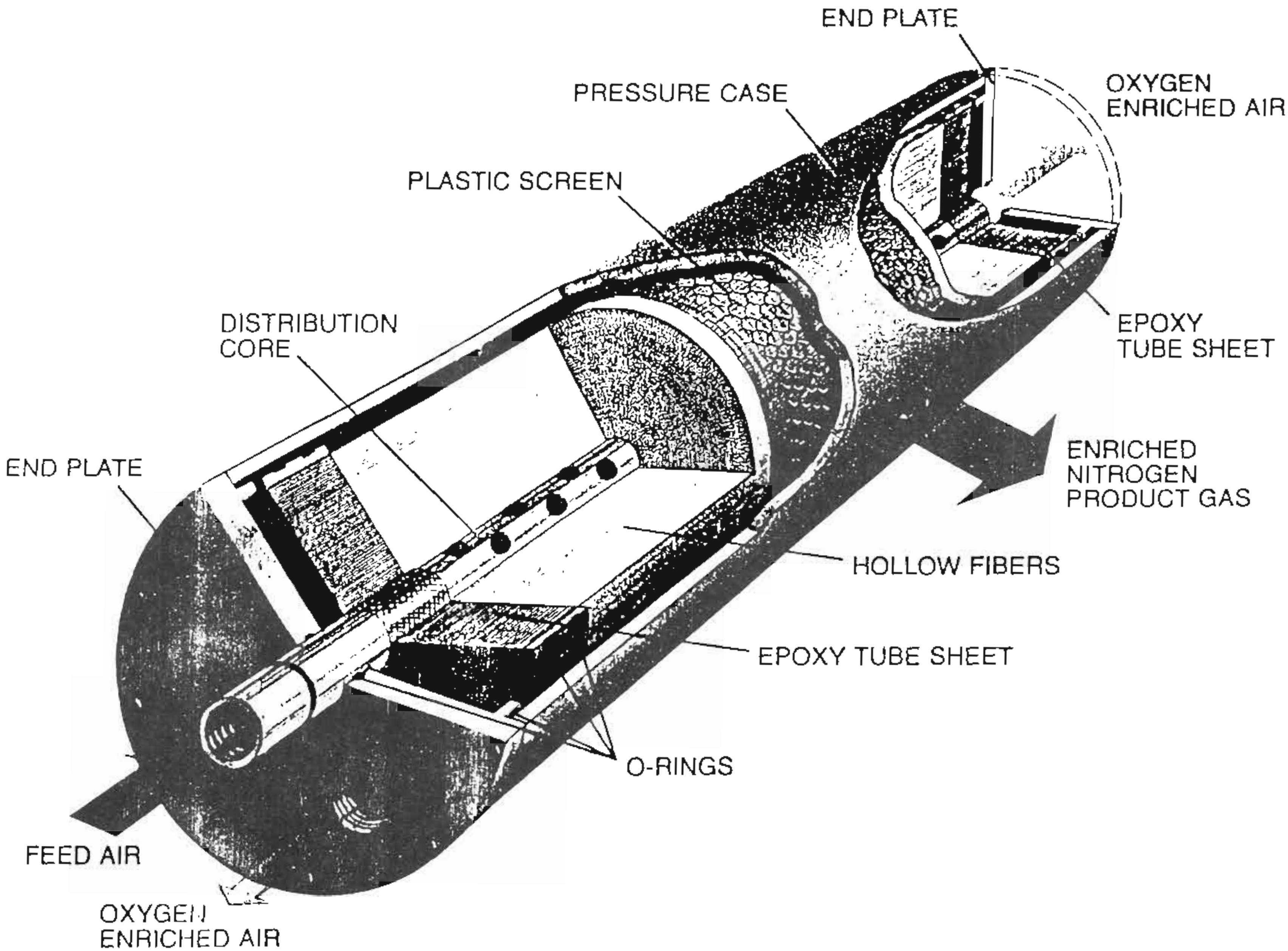


Figure 11. Permeable Membrane Air Separation Module

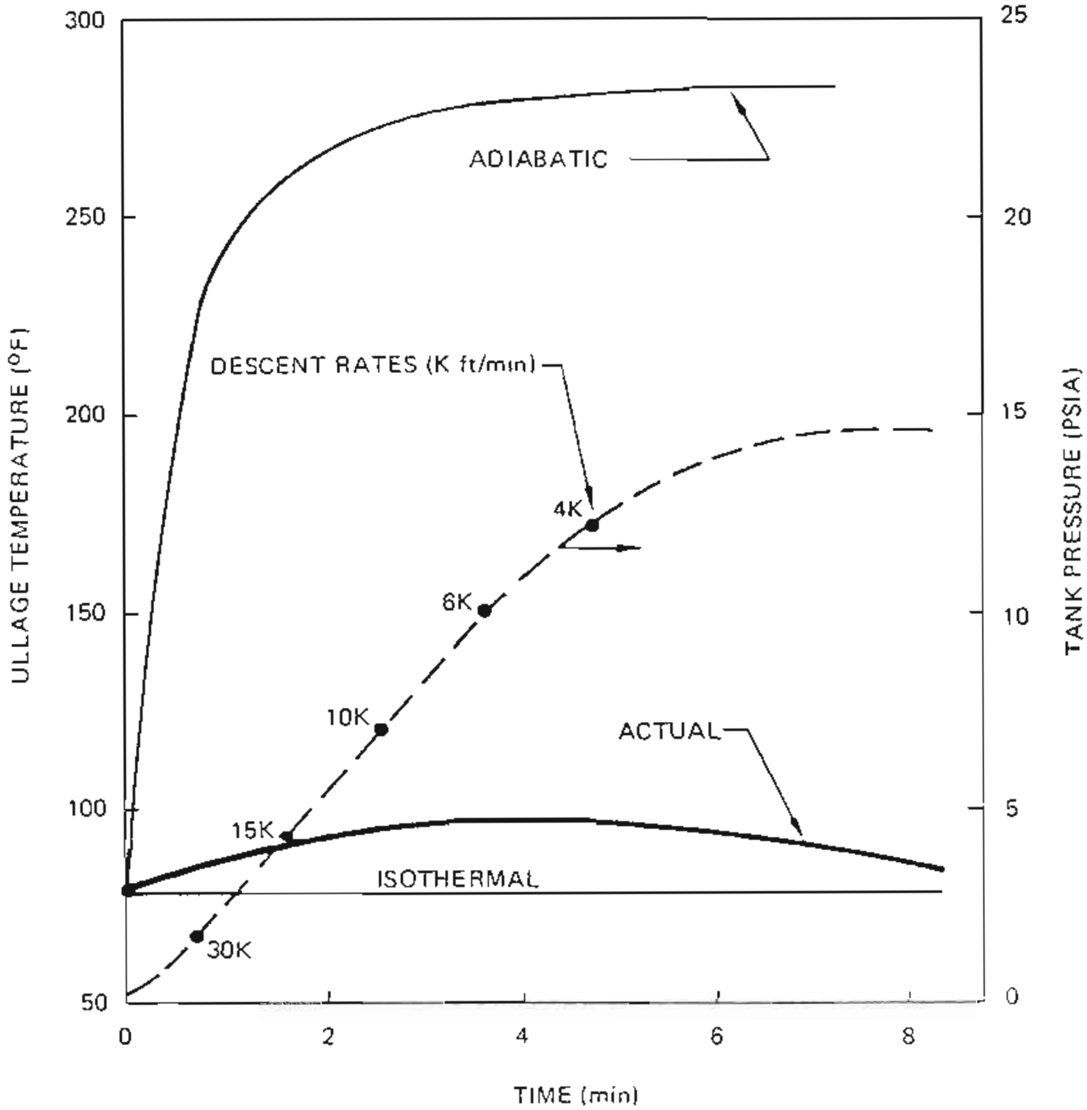


Figure 12. Ullage Repressurization, Adiabatic Analysis Comparison with Experimental Data

by simply controlling the repressurization rate but the limiting rate was not established in this program. The primary deficiency with the MS OBIGGS was valve reliability for the prototype units tested. Developing a valve with suitable reliability is predicted to be a tractable design problem.

Comparing the units, the MS OBIGGS required almost twice the supply air flow as the PM OBIGGS for a specified inert gas flow rate and oxygen concentration. However, since a higher supply air pressure was required for the PM OBIGGS and its maximum operating temperature was lower, additional engine bleed air was required to provide additional air conditioning. Therefore, the total bleed air requirements of the PM OBIGGS installation were almost twice that of the MS OBIGGS.

Preliminary designs for the two systems revealed that the total weight for a KC-135 installation was 712 pounds for the PM OBIGGS and 787 pounds for the MS OBIGGS. However, the total fuel penalty for a 5.1 hour mission was 522 pounds for the PM OBIGGS versus 410 pounds for the MS OBIGGS, due to the higher bleed air requirements for the PM OBIGGS. The overall range penalties for a 5.1 hour mission were comparable; 22 nautical miles for the PM OBIGGS and 17 nautical miles for the MS OBIGGS.

The MS OBIGGS generally showed less performance degradation than PM OBIGGS but the constant cycling of the valves in alternating the supply air flow from one set of molecular sieve beds to the other led to premature valve failures. The PM OBIGGS was especially sensitive to rapid start-up (pressurization) as indicated by performance degradation with time.

There was no clear choice between the PM and MS OBIGGS based strictly on performance. The decision would rest on other factors such as reliability, maintenance requirements and life cycle costs. Since these factors had to be estimated due to lack of in-service experience, these results were also inconclusive.

3.2 Fuel Scrubbing and Oxygen Evolution Tests

Oxygen evolution from the fuel during climb can be a major problem in mantaining an inert ullage. To prevent excessive oxygen accumulation, the fuel is scrubbed with inert gas either during refueling or during climb. Climb scrubbing, which was studied in this program, involves bubbling inert gas through the fuel to displace dissolved oxygen and subsequently cause the oxygen rich gases to be vented overboard.

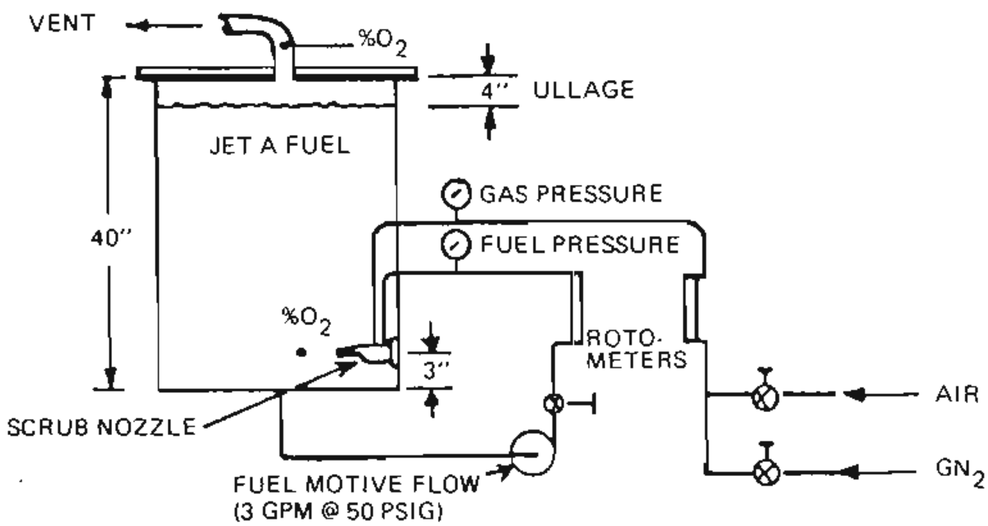
3.2.1 Test Facilities

A test program was conducted at the Boeing Fuels Laboratory in Seattle, with two main objectives: (1) to evaluate the performance of a production C-5A fuel scrub nozzle for use in the 582-gallon fuel tank in the SAFTE facility at WPAFB and (2) to validate a computer model for predicting fuel scrubbing performance for a typical airplane mission.

The scrub nozzle, submerged in a 156-gallon rectangular tank containing 140 gallons of Jet A fuel, was operated over a range of inert gas flow rates and motive fuel flow rates representative of airplane installations (see Figure 13). Continuous measurements were made of oxygen concentration in both the ullage and fuel sample using a polarographic membrane-type oxygen probe. Both pure gaseous nitrogen (GN_2) and nitrogen enriched air (NEA) with a 9% oxygen concentration were used in the scrubbing system.

Based on the good agreement between measured and predicted values of oxygen concentration in both the ullage and fuel, the C-5A scrub nozzle was judged to be acceptable for use in the WPAFB SAFTE tank. Also, scrubbing with NEA was a viable technique, although longer scrubbing periods are required than for GN_2 to achieve a specific ullage oxygen concentration, as would be expected.

Accurate analytical modeling of the ullage gas composition depends on knowing the rate of oxygen evolution from the fuel under various conditions. Tests were conducted in the SAFTE facility to help develop the required data base for predicting evolution rates. Oxygen sensors were used both in the fuel and the ullage to measure oxygen concentration.



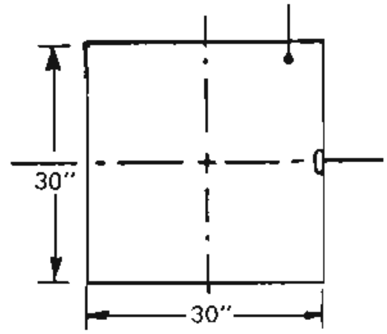


Figure 13. Test Set-up for the Scrub Nozzle Evaluation

As stated above, other tests revealed that the C-5A scrub nozzle would be compatible with the SAFTE facility. Therefore, the nozzle was installed in the SAFTE facility and scrubbing tests performed.

3.2.2 Results and Conclusions

Oxygen evolution tests were conducted in the SAFTE facility during simulated airplane climbs with and without fuel scrubbing. Without scrubbing, the data showed that the oxygen concentration in the ullage could be predicted fairly well from gas solubility relationships (Figure 14). When the fuel was scrubbed using the C-5 scrub nozzle and design NEA and motive flowrates, scrubbing effectively reduced the ullage oxygen concentration to 9% or less during the simulated climb, except for a short period early in the climb (see Figure 15). The slight variations in hydrocarbon composition are probably due to small variations in temperature (about $\pm 2^{o}$F) during the run.

The data revealed that stratification of ullage gases occurred with natural gas evolution (no scrubbing) and was more pronounced with larger ullage volumes. Whether localized zones of oxygen concentrations above 9% constitute a problem will await results of detailed ullage flammability studies. Scrubbing was found to be beneficial in reducing ullage gas stratification.

3.3 Airplane OBIGGS Installations

3.3.1 C-5B OBIGGS Studies

The C-5A and C-5B airplanes are equipped with a liquid nitrogen (LN_2) storage system which enhances airplane fire safety and survivability by inerting the fuel tanks and providing fire protection for a number of airplane bays or compartments. Although the liquid nitrogen system is well suited to fuel tank inerting and fire protection, the logistics problem of providing a supply of liquid nitrogen at the time of airplane refueling is a continuing concern. The development of OBIGGS, which produce NEA by processing engine bleed air, offers a solution to the logistics problems. The feasibility of using NEA for fuel tank inerting and compartment fire fighting on the C-5B airplane was the objective of this study.

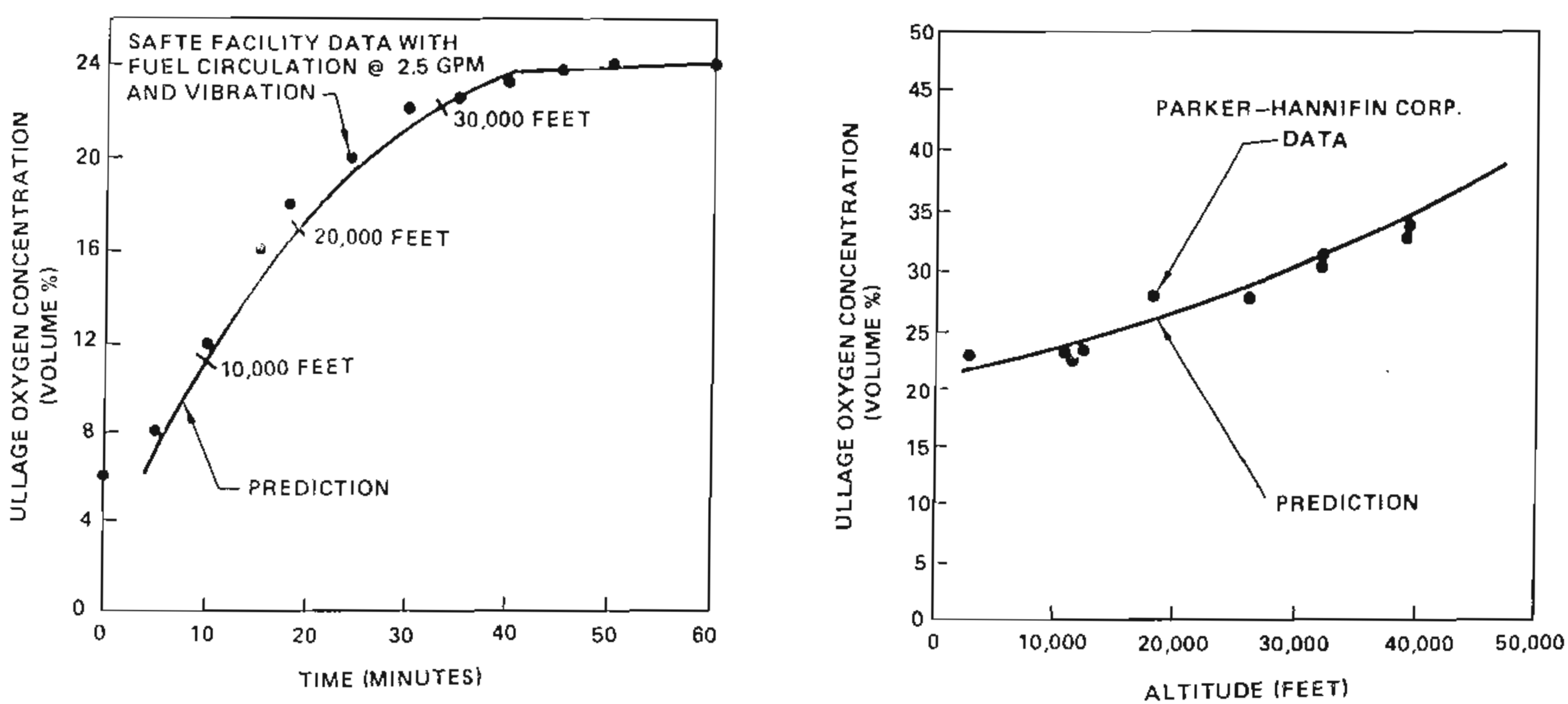


Figure 14. Measured and Predicted Ullage Oxygen Concentration for a Simulated Climb Without Scrubbing

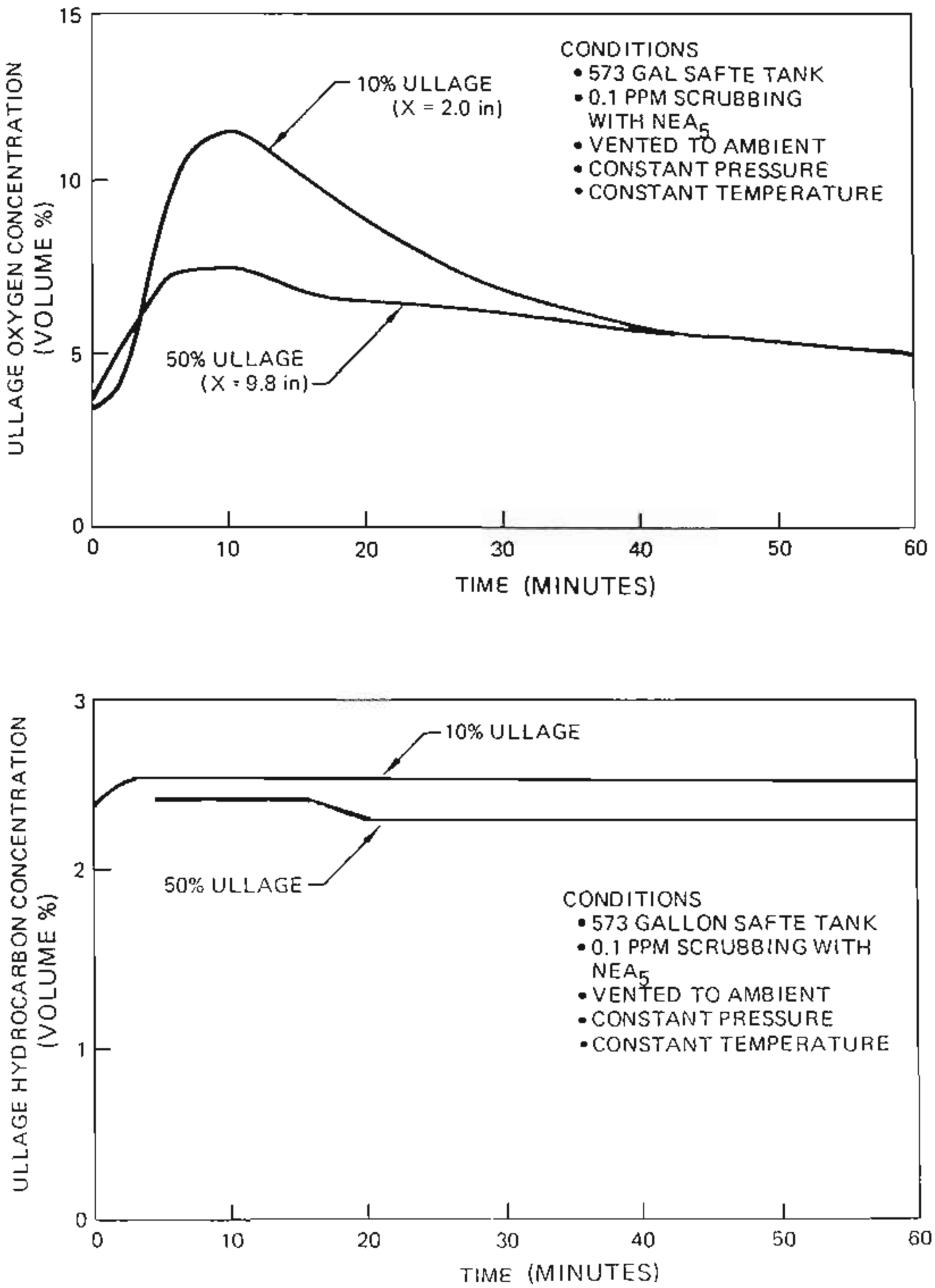


Figure 15. Mid-Ullage Oxygen and Fuel Vapor Concentrations for Constant Volume/Constant Pressure Scrubbing at 10% and 50% Ullage Volume

3.3.1.1 Ground Rules

Among the study ground rules were:

- the OBBIGS design was required to provide full time fuel tank inerting except that the dive valve could open during an emergency descent if the maximum ullage oxygen concentration did not exceed 12% by volume.

- the OBIGGS design was optimized for fuel tank inerting. However, once the design was established, the use of the OBIGGS to provide NEA for compartment fire protection was evaluated.

- the OBIGGS design was developed for a stored gas system rather than a demand system (a system which must have the capacity to produce the highest inert gas flow rate required). The stored gas system has the advantage of requiring smaller air separation modules since NEA is compressed and stored during the mission to provide a reservoir of inert gas for high flow rate requirements.

3.3.1.2 Results and Conclusions

A preliminary design and economic analysis was completed of an OBIGGS installation to provide fuel tank inerting on the C-5B airplane. A similar study was performed for the C-5A airplane and the results were reported in AFWAL-TR-83-2021, Volume I. However, the C-5B study had some significant differences:

- The OBIGGS was required to provide full time inerting for normal operations, but the dive valve was allowed to open during an emergency descent, provided the oxygen concentration did not exceed 12% by volume.

- The OBIGGS was optimized for fuel tank inerting rather than for both inerting and compartment fire protection as specified for the C-5A study.

Based on the ground rules for the C-5B study, the optimized OBIGGS was a unit which produced 3 lb/min of NEA with a 5% oxygen concentration and had a minimum of 167 pounds of stored inert gas. Trade-off studies of Halon versus NEA for providing fire protection to various zones of the airplane revealed that little weight savings would result if the OBIGGS was used for fire suppression. Thus, NEA should be restricted to fuel tank inerting and Halon should be used for compartment fire suppression on the C-5B airplane.

Economic analyses considered acquisition costs, operating costs and life cycle costs. Since in-service costs of OBIGGS are unknown, those costs were estimated. The results indicated that the costs to install an OBIGGS would be comparable to a LN_2 system but the operating costs of the LN_2 system would be significantly higher due to the cost of liquid nitrogen. Therefore, the OBIGGS was found to offer significant economic as well as logistics advantages when used for fuel tank inerting on the C-5B airplane.

Both the PMIGG and MSIGG were included throughout the study. Neither system emerged as being clearly superior for C-5B application.

3.3.2 Fighter OBIGGS Study

Fuel tank fire protection is a key requirement for the Advanced Tactical Fighter (ATF) airplane under development by the Air Force. The primary objective of this study was to investigate the feasibility of using OBIGGS for ATF fuel tank fire protection. The potential extension of the OBIGGS for dry bay protection was considered in the selection of the NEA quality used for the OBIGGS sizing studies.

3.3.2.1 GROUND RULES

Unclassified but representative ATF configurations and missions were selected for this study. The primary study ground rules were to:

- o provide full time inerting including an emergency descent at any time in the mission;
- o design for standard day operation;
- o design for JP-4 fuel; and

- consider the potential use for dry bay fire protection in determining nitrogen enriched air (NEA) quality requirements.

Full time inerting implies limiting the oxygen concentration in the fuel tank vapor space (ullage) to less than 9% at all times. While this requirement was satisfied for most of the mission, a temporary relaxation of this requirement during taxi was required to prevent the OBIGGS from becoming excessively large. The candidate missions were analyzed in terms of flight segments with high inert gas demand. From these analyses, the mission with the highest demand was used to size the OBIGGS.

3.3.2.2 Results and Conclusions

An OBIGGS fuel tank fire protection system was developed for an ATF airplane based on representative but unclassified configurations and missions. The key to sizing the OBIGGS for sufficient inert gas flow was the number of descents during the mission. A subsonic air-to-ground mission was the OBIGGS sizing mission, primarily because that mission included two planned descents as well as a possible emergency descent. The air-to-air missions studied had less demanding inert gas requirements, although penetration was at supersonic speeds, because the mission has only one planned descent.

The ATF OBIGGS was based on a stored inert gas system; an OBIGGS sized to provide the required inert gas flow rates without gas storage (a demand system) was prohibitively large for an ATF application. Since stored gas systems produce NEA at a constant flow rate and oxygen concentration, a decision on oxygen concentration was required. A trade-off study revealed that nitrogen enriched air with oxygen concentration of 5% was the appropriate choice.

A detailed study was made of the inert gas requirements for fuel scrubbing. Relaxing the goal of full time inerting during the taxi phase of the mission, to prevent excessive OBIGGS weight and volume penalties, was considered an acceptable compromise, since the airplanes would be located at friendly air bases during that phase of operations.

As was true for the C-5B, the overall performance and penalties of the PM OBIGGS and MS OBIGGS for ATF application were similar. The PM OBIGGS was chosen for a technical and economic comparison with foam, and full time Halon and liquid nitrogen systems somewhat arbitrarily, based on the supposition that the PM OBIGGS would have higher reliabilty. The comparison assumed that a foam could be developed for the high temperature ATF environment which was similar in weight and cost to existing foams. Using these assumptions, the OBIGGS weight was only about one-third of the foam weight but was roughly twice as heavy as the Halon system. Protection against a single combat threat is expected to be similar for all systems considered. A Halon concentration of 30% was assumed to be necessary for protection against a 23 mm HEI threat (in some applications 20% has been considered adequate). The foam system is considered superior to the others for multiple hit protection. Volume comparisons with foam were not meaningful, but the OBIGGS required greater volume than the Halon and liquid nitrogen systems. Life cycle cost analysis, based on best available data and projections, revealed that the OBIGGS costs would be about seven times higher than foam, would be comparable to liquid nitrogen systems, and would be one-third the cost of the Halon system. The high cost of the Halon system is primarily due to the cost of the Halon itself. The life cycle costs did not include costs of providing liquid nitrogen and Halon resupply facilities at additional airports. Nor did the costs include any factor for unscheduled maintenance and replacement of foam blocks; this has been a problem with previous explosion suppressant foam installations.

Since the solubility of Halon in fuel is relatively high, significant amounts of Halon could be dissolved in the fuel when the ullage Halon concentration is in the 20 to 30 percent range. Halon solubility not only affects the amount of Halon required for fire protection, but also could adversely affect engine components. Although limited engine testing has not revealed any negative effects of using fuel with dissolved Halon, the effect of long term engine component exposure to Halon associated with full time inerting or frequent use of a part-time inerting system should be examined.

4.0 OVERALL SUMMARY AND CONCLUSIONS

Significant advancements were made toward improving aircraft engine compartment and fuel tank fire safety as a result of this program. The AEN and SAFTE facilities were brought on line and important test data were obtained. The value of such test facilites was proven not only in predicting aircraft installed performance but also in identifying potential design weaknesses in candidate fire protection systems.

Among the noteworthy technical advancements were:

- o The performance, endurance and airplane compatibility of full sized PM and MS OBIGGS units were examined in detail.

- o an analytic model, that predicts ullage oxygen concentrations during all phases of flight with NEA inerting, was developed and validated by test data.

- o Simulated nacelle fire testing revealed that current agent requirements for Halon 1301 may be excessive, that Halon 1301 is more effective than Halon 1202 and that more effective use of the agent is obtained by if the agent is released more rapidly.

- o Preliminary OBIGGS designs were developed for the C-5B and ATF airplanes and compared with other fire protection systems.

A follow-on effort currently in progress will continue engine compartment and fuel tank fire protection research. More extensive studies will be made of nacelle fire protection including other extinguishants and nacelle materials. Fuel tank fire safety studies will include the performance of new technology inert gas generators and detailed studies of ullage gas stratification and flammability.

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