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SECOND CONFERENCE ON FUEL SYSTEM FIRE SAFETY

Report of Conference

6 & 7 MAY 1970

by

ENGINEERING AND MANUFACTURING DIVISION
FLIGHT STANDARDS SERVICE

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
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Summary

This is a report of the second conference on fuel system fire safety held 6 and 7 May 1970. This conference is a follow-on to the first conference held 11 and 12 December 1967.

This conference was held to report on the activities of the Government-Industry Advisory Committee on Fuel System Fire Safety which was established as a result of the first conference to:

a. Foster and encourage development and testing of means for achieving improved protection against fuel system fire and explosion.

b. Promote trial applications of qualified operational systems on aircraft in regular airline service.

c. Collect and document information on weight, cost, reliability, and maintenance burden of protective systems.

d. Provide specific advice regarding the justification, merit, and feasibility of FAA proposals for amending airworthiness regulations applicable to both new and in-service aircraft.

Technical presentations on ways and means of protecting aircraft fuel systems against fire and explosion were also presented to provide the conference with the presently available information on this subject.

The discussions on the proposal for regulations for fuel system fire safety presented at the conference are not included in this report, but will be part of the preamble to the Notice of Proposal Rule Making when it is published.

INTRODUCTORY REMARKS

Mr. Richard S. Sliff, Deputy Director, Flight Standards Service, opened the conference with statement of purposes and objectives. He welcomed the representatives of the aviation industry, airworthiness authorities, associations and operator's representatives. With these interested groups, he said it is expected there will be many diversified opinions on the subject of fuel system fire safety. He noted that fire safety in a crash is a separate subject from that of the conference. He did not expect that an on-board system in an aircraft would be very effective in controlling an external fire in a crash but believed that an on-board system would be effective in controlling the hazards arising from ignition within the interior of the fuel system. A good many different opinions have been expressed on this subject, and Mr. Sliff stated that all opinions are duly respected. The FAA, having the authority to promulgate safety rules, must look to the expert opinions of the industry itself in developing such rules.

He described the background of the subject hazards in jet aircraft operation, and stated that there is evidence that lives may have been saved if provisions had been made to safeguard the fuel system. A reasonable approach must be taken toward what can and should be done in protecting the public.

As an example of the problems which have occurred, Mr. Sliff reviewed the accident of the DC-8 that went off the runway in Denver, Colorado, struck some construction equipment, caught fire, and some people lost their lives. These people could not escape as the fuel fed fire spread rapidly throughout the airplane. Other examples described were the accident of the Boeing 707 at Elkton, Maryland which was struck by lightning; the aborted takeoff accident at Rome; the disintegration of an engine in flight in San Francisco; a similar accident at London; and the recent one at Rome. In all these cases, fuel system fire safety protection may have changed the results. The aircraft designer strives to protect against sources of ignition but it is questionable that this can be achieved with reasonable assurance. It appears that potential sources of ignition cannot be fully eliminated, so it is necessary to provide an environment which cannot be ignited or can be readily suppressed, if ignited, so that it does not spread or become catastrophic.

He stated that he did not recommend a particular method of providing adequate protection. This is the reason the Advisory Committee was formed. The Committee has been in operation for approximately two years. The purpose of the group is three-fold, (1) to study this whole area, (2) to produce recommendations on methods and means to provide safety in this area and (3) to recommend types of action that should be taken.

He added that if the FAA goes ahead with rule making, it may cost the operators of some types of aircraft a considerable sum of money to provide the protection that such rule making will require. It will be reasonable and sensible to protect existing aircraft, also, so it may be necessary to consider retroactive type of requirements. This is open for discussion. In the case of crashworthiness, retroactive rules were considered necessary. He stated that hand-held slides, inadequate exit warning, inadequate lighting, inadequate exits, and things of this nature would not have been corrected if it was not for the retroactive rules. Some of the arguments that have been presented against rule making in this particular area are that there are better ways of spending the money. This type of an argument is fine and the FAA is more than willing to listen to this type of argument, but would like to hear what the better ways are and who intends to spend the money. Mr. Sliff felt that it may be necessary to adopt requirements in order to produce results. The public must be provided the highest feasible degree of protection.

Mr. Sliff then introduced Herbert H. Slaughter, Chief, Engineering and Manufacturing Division.

Mr. Slaughter joined Mr. Sliff in his welcome to the representatives of the conference. He reviewed past attempts to use CO_2, N_2, and exhaust gases to inert the ullage area in fuel tanks. He felt, however, that the new developments of protective systems now makes protection of the fuel tanks practical. The work being done by the Advisory Committee on Fuel System Fire Safety indicates that inerting the ullage area may be a practical solution to this problem.

Mr. Slaughter pointed out that safety improvements should be given a fair share of the gains in propulsive and aerodynamic efficiency of the modern turbine propulsion system, rather than to channel the entire gains toward aircraft performance and economy. We should be constantly examining those areas in which we can improve safety.

He noted that the government role is to promulgate uniform and objective standards which will provide for needed and feasible improvements in safety. He expects the industry will apply its inventiveness and technical knowledge to provide protection at low cost, high reliability and lowest weight. This protection should be an integral part of the airplane design.

The technical presentations which are scheduled for the conference, he noted, will bring everyone up to date in the area of fuel system fire safety.

Mr. Slaughter then introduced the conference Chairman, Mr. Stephen H. Rolle, Chief, Propulsion Branch, Engineering Division, Flight Standards Service.

Mr. Rolle advised the attendees that the conference proceedings, with a brief summary of the discussions, would be sent to all who filled out the registration forms. He emphasized that the discussions on the proposed rule will not

be published, but would be included in the preamble to the Notice of Proposed Rule Making, if and when, it is published.

ADVISORY COMMITTEE REPORT

In his capacity as Chairman of the Advisory Committee and as conference chairman, Mr. Rolle started the conference proceedings by reporting on the Committee's organization and goals, achievements to date and plans for future actions. The following is a summation of the chairman's report:

In December 1967 the FAA sponsored the 1st conference on Fuel System Fire Safety. Among other things, that conference provided for a review of accident information, the work that had been or was being done on electrostatic generation and control, and the work that had been and was being undertaken to suppress the ignitability of fuel vapors in tanks and in vent systems. Upon conclusion of that conference, the FAA found no disagreement with the goal of eliminating hazards from the existence of ignitable fuel vapors.

It was also clear from that conference that there was a great deal of work being done in various quarters relating to fuel system fire safety. It also became obvious that there existed a need for some sort of a forum to provide for the interchange of information that was being obtained in those various segments of the industry.

In considering the direction in which we should move after that conference, the FAA was also faced with three major problems or tasks which required answers or further exploration. These were:

(a) To determine the most practical and feasible methods of protection.

(b) To obtain information on the economic penalties for such methods of protection.

(c) To obtain useful advice on airworthiness standards.

It was at that point in time that the FAA decided that those problems and tasks could best be undertaken through an Advisory Committee. Steps were then taken to establish and organize the committee. The FAA/Industry Advisory Committee was formed on August 1, 1968. Its membership consists of representation from:

Federal Aviation Administration	Aerospace Industries Association
Flight Engineers International Association	Air Transport Association
Airline Pilots Association	U.S. Air Force

As the need arises, the Committee can call for assistance, on an advisory basis, from other groups such as:

U. S. Army	Flight Safety Foundation
U.S. Navy	National Transportation Safety Board
National Aeronautics and Space Administration	Society of Automotive Engineers
Coordinating Research Council	Manufacturers

The Committee has sought the advice and assistance from some of these groups on several past occasions. The Committee has been meeting four times a year. We have had 8 meetings since the Committee was established. The Committee was set up to function for a 2 year period which ends on August 1 of this year unless steps are taken to continue its functioning.

PURPOSES AND GOALS - FIG. 1

Purposes

As I have mentioned before, there is a great deal of related work being done in various segments of the industry. It is therefore logical that the Committee should act as a coordinating body for the exchange of information regarding the relevant work being done.

Another purpose is to collect information on hazards. This involves the definition of the various modes by which fire or explosion can result.

A third purpose is to examine and evaluate methods of protection. This entails the listing and evaluation of all known methods of protection.

Another purpose is to collect information on hazards. This involves the definition of the various modes by which fire or explosion can result.

Finally, as an advisory body well informed on the various methods of protection, it was felt that the committee members would be in a good position to advise the FAA on rule changes.

Goals

It was recognized during the formulation of the committee that additional testing and trial applications were needed for the more promising protective systems. Therefore, one of the committee goals is to foster and encourage development and test of promising means of protection.

The next goal is to promote trial applications.

Because systems of the magnitude that we have been considering require an assessment of reliability, weight and cost penalties, such assessment has been included as another goal.

The last goal is to advise FAA on Airworthiness rules.

COMMITTEE ACCOMPLISHMENT

In directing your attention now to committee accomplishments, I would like to first point out that there has been a very useful interchange of information and views. We have agreed upon a definition of fire hazard problems. As shown on Fig. 2, those are the situations felt by the Committee to involve fire risks. It will be noted that fire risks associated with refueling, electrical and mechanical failures, engine failures, in-flight fires, lightning strikes and survivable crashes are fairly well itemized and categorized. These represent the agreed upon fire risks. Obviously, some of the risks noted are not directly amenable to the type of protection with which the committee is directly concerned.

CANDIDATE SYSTEMS REVIEW Fig. 3

Inerting of Ullage

The liquid nitrogen system is considered effective and possibly the most effective of the protective systems reviewed by the committee. More will be said about this system later in this conference.

The gas generating systems involve catalytic reactors, passing a certain amount of fuel over a catalyst. This system is in the early stages of development. We will get some further enlightenment on such systems later in the program.

Chemical flame inhibitors entail the delay of ignition by the use of chemicals in the fuel. This concept is now only in the idea stage and work on this method of protection has not yet been undertaken.

Active Suppression

The start of an explosion or a flame front must occur before the operation of this method of protection is activated. While this method is used to protect the fuel tank vent system in a small number of transport aircraft, no trial applications have been made involving a complete tank and vent system. For complete effectiveness for a full scale airplane, this method of protection may entail excessive weight penalties. A multiplicity of sensor units and Freon containers would be required for system effectiveness. With such complexity, the maintenance burden needs to be carefully assessed.

Passive Arresting

The polyurethane foam filler has been proven to be an effective method of protection. More information on this method will be given later in the program.

The use of hollow plastic spheres in fuel tanks has been tried. It was intended that the hollow spheres would act as flame arrestors. Low effectiveness and excessive weight removed this method of protection from further serious consideration by the committee.

Fuel system protection by the use of liquid barriers involves the use of liquid traps in parts of the fuel system to arrest the transfer of flame from one part to another in the fuel system. No work has yet been done on this method of protection.

Modified Fuels

Emulsions and gels created by chemically thickening fuels have been considered by the Committee. Since the thickening of the fuels has no effect on their vapor pressures, such fuels would offer no benefit to the type of protection with which the committee is primarily concerned. These types of fuels will offer some benefits in a crash fire situation because of their slower burning characteristics during spillage following a tank rupture. Much development work needs to be done before these types of fuels can be handled effectively and efficiently in an airplane fuel system.

The use of low vapor pressure fuels as a means for providing fuel system fire protection is now only in the study stages by the U.S. Navy. No test or development work has yet been undertaken.

Some experimental work has been done with the use of non-thickening inertants in the fuel. Inerting has been attempted by saturating the fuel with Freon. Difficulties have been encountered in keeping the fuel saturated.

Fuel Fogging

In another effort to achieve fuel system fire safety, spraying of fuel in the tank ullage in an attempt to keep the fuel vapors in an overrich condition has been tested and evaluated. This means was found to be incapable of keeping the fuel vapors in an overrich condition due to coalescing of fuel particles.

Of all of the candidate systems reviewed, it was the general consensus of the committee that the LN_2 inerting system should be the first protective system to be considered for airline service evaluation. Reasons for this were that

the LN_2 inerting system entailed lesser weight penalties and provided a greater degree of protection than the other systems reviewed.

SERVICE EVALUATION PROGRAM

Fig. 4 outlines the program developed by the committee leading to the service evaluation of a selected candidate system. This is a logical and well conceived program of action. It is the keystone of the committee's activity.

This program has not moved as fast as we would have wished. Nonetheless, a great deal of time consuming work has been done. We are now down to the design phase of the program. More information on the progress being made in this endeavor will be given in one of the presentations scheduled for the conference.

I mentioned earlier that the Committee charter expires on August 1, 1970 unless steps are taken to authorize its renewal. In the meeting yesterday of the advisory committee, it was agreed that the committee should continue to remain active but to hold its meetings down to 2 a year instead of 4 per year.

It is the plan of the committee to continue its work leading to an airline service test of a liquid nitrogen inerting system. The committee also plans to continue to look at other systems of protection, recommend needed research, and foster the service testing of promising systems.

Mr. Rolle opened the floor for discussion, but there were no questions. Mr. Rolle then introduced the next speaker, Mr. Allan Dallas of the Air Transport Association.

ADVISORY COMMITTEE PURPOSES AND GOALS

PURPOSES -

- Provide a Coordinating Body for Exchange
- Collect Information on Hazards
- Examine and Evaluate Methods of Protection
- Submit Recommendations to FAA

GOALS -

- Foster and Encourage Development and Test of Means
- Promote Trial Applications
- Collect and Document Info on Weight, Cost, Reliability and Burden
- Specific Advice to FAA on Airworthiness

FIG. I

SITUATIONS INVOLVING FIRE RISKS

REFUELING
- Electrostatics
- Vented Vapors
- Spillage

ELECTRICAL AND MECHANICAL FAILURES
- Sparking
- Friction

ENGINE FAILURES
- Rotor Failure
- Engine Fires

IN-FLIGHT FIRES
- Powerplant Area
- Fuselage Area
- Tank Leakage

LIGHTNING STRIKES
- Vent Outlet Vapors
- Skin Penetration or Heating
- Inductive Coupling

Survivable Crash
- External Fire
- Ignition of Vented Vapors
- Tank Rupture and Spillage

FIG. 2

CANDIDATE SYSTEM REVIEW

INERTING OF ULLAGE

- Liquid Nitrogen
- Gas Generating Systems
- Chemical Flame Inhibiters

ACTIVE SUPPRESSION

- Freon Explosion Suppressant

PASSIVE ARRESTING

- Foam Filler
- Hollow Spheres
- Liquid Barriers

MODIFIED FUELS

- Emulsions
- Gels
- Low Vapor Pressure Fuels
- Non-thickening inertant

FUEL FOGGING

- Fuel Spray in Ullage

FIG. 3

SERVICE EVALUATION PROGRAM

PRELIMINARY STUDIES

- Analyze Accident Information
- Check Failure Modes and Hazards
- Costs and Savings Studies
- Airline Selection

DESIGN PHASE

- Study of Airline Route Structure
- Firm-up Design and Test Requirements
- Aircraft Selection and System Design

TYPE CERTIFICATION

- Qualification and Fault Analysis
- Install System and Test Instrumentation
- Ground and Flight Testing

SERVICE EVALUATION

- Airline Routine Service on Selected Routes
- Ground Support Equipment
- Maintain Records --

  Performance
  Logistic Problems
  Reliability
  Maintenance Costs

FIG. 4

STATEMENT BY ATA AT THE FAA
CONFERENCE ON FUEL SYSTEM FIRE SAFETY
A.W. DALLAS, VP, ENGINEERING, ATA

This agenda item is listed on the Conference Program as "Airline Activities Leading Toward Installation and Service Test of an LN_2 System." The speakers listed is Mr. B. M. Meador, airline member of the FAA Advisory Committee on Fuel System Fire Safety, and also chairman of the ATA Fuel Safety Sub-committee.

First, Mr. Meador sends his regrets that due to many pressing matters within his airline at this time he is unable to be present today and asked that we extend his apologies. Second, the airline activities concerning "Installation and Service Test of an LN_2 System" as listed on the agenda have not progessed far enough so that a useful and meaningful report can be made at this time. However, the airlines, through the ATA Subcommittee on Fuels Safety, and otherwise, have been investigating ways to improve fuels system safety. The ATA has been represented on the FAA Advisory Committee by Mr. Meador with attendance at all Advisory Committee meetings by other members of the ATA Subcommittee and the ATA staff.

We had hoped that we would be able today to utilize this spot on the agenda to describe the overall activities of the airlines on the subject in some detail, but unfortunately we are unable to do so because of the unfinished status of efforts at this time. Actually the work involved turned out to be greater than we had anticipated. However these brief remarks will cover some general airline thoughts on the subject and will also mention the work underway at this time.

Most of the people at this conference are aware of the extensive study and research which has been underway by government and industry since 1963 in an effort to improve the safety of fuel systems by finding better ways to guard against internal fuel tank fires and explosions. Some of the research involved is included in the agenda of this Conference. This work has been pursued diligently in spite of the high improbability of this type of accident because everyone is interested in improving this aspect of flying safety if it can be shown to be feasible and practical.

Before this morning's coffee break we heard a review of the progress of the FAA Industry Advisory Committee which held its first meeting on August 1, 1968. Seven additional meetings have been held since then and all conceivable aspects of the problem have been discussed by members and others representing the FAA, Air Force, AIA, ATA, ALPA, FEIA and APA. Also the NASA and equipment manufacturers have been involved on appropriate occasions. The airlines have supported this type of activity since it brings together into

one forum all the knowledge of the airline industry, the manufacturing industry and various government agencies including the military.

At the fifth meeting of the FAA Advisory Committee held August 5, 1969 a six-point program planned for investigation of fuel tank fire protection was agreed upon. The six points were as follows (known as Appendix J of the Committee documents):

(1) Collect information from all pertinent accidents where lives were lost or endangered because of fuel tank fire or explosion.

(2) Determine and rate in order of the effectiveness possible solutions which could have reduced or eliminated the loss of life by fuel fire for each accident.

(3) Establish which solutions are most feasible in terms of effectiveness, development status and economic impact.

(4) Conduct failure mode analysis and hazards.

(5) Conduct a "systems engineering" approach to ensure the practicality of any system selected including full economic and logistics considerations including certification, installation, maintenance and logistics costs plus the effects on revenues, insurance and savings in damaged aircraft.

(6) From the above studies, select a system most advantageous from a cost effectiveness point of view, and establish a development program with one of the commercial airlines for a complete evaluation of that system, including design, certification and service evaluation.

The airlines subscribed to this type of practical approach to the problem and began a planned schedule of work following the above outline and employing the help of Boeing for study of various systems that could be applied to the B-747 airplane, this being the first of the large jets in service.

It soon became obvious that a useful study of this magnitude required considerable time and manpower and for this reason, as previously stated, the work is still underway by the airlines with Boeing's help. A comparison of different methods of approach and the facts pertinent to each method requires this in-depth study and analysis. The studies underway evaluate LN_2 and catalytic reactor fuel tank inerting systems plus vent flame arrestors and surge tank suppressors. The costs involved as compared to the safety benefits

gained will be enumerated in detail.

The studies underway are based on the premise that any revision to aircraft fuel systems should make a definable contribution to safety, should not increase operational hazards, or decrease airplane reliability significantly. Also that any new rulemaking should be aimed at eliminating hazards which have been the principal causes of or contributions to loss of life and/or property. The four potential safety improvements mentioned above are being defined to the extent that engineering feasibility can be established. Also preliminary designs and descriptions are being prepared for each of these including failure mode analysis to evaluate safety improvements. Failure mode analysis is very important to be sure that new hazards are not introduced which might make the cure worse than the disease. For example, tank inerting involves positive tank pressurization. Also included in the studies are estimates of ground logistics costs associated with LN_2 systems.

Although the studies underway will include detailed cost-benefit analysis as applied to the systems being considered, we feel that some remarks regarding costs versus benefits may be appropriate at this time because of the fact that the proposed regulation, to be discussed later on this agenda, is worded so that in effect only complete inerting of the ullage space in all tanks would satisfy its requirements. It is well known that complete inerting systems will be very costly and complicated (involving ground logistics in the case of LN_2) and therefore it would appear that the regulatory door should be left open to other simpler means which may already exist or be under development to accomplish an adequate but less costly and perhaps more practical safety improvement.

The source of industry funds for added increments of improved safety are limited as are government funds for the same purpose. In determining a course of action relating to an improved increment of safety, an airline, as with the government, must very carefully determine how such limited funds should be expended. Obviously since the pursuit of the goal of absolute safety is unrealistic from almost any point of view, the airlines must consider where expenditures will do the most good.

As an example of how airline dollars are working toward safety, listed below are some projected capital expenses of one major airline contemplated for the years 1969-1973. Some of the items are in the nature of FAA requirements, either in effect or proposed, and others are being contemplated by the airline because it feels they are necessary.

ATC - Vertical Guidance	$ 4,570,000
All-Weather Display	12,131,000
Altitude Alert	1,359,000
2,500 Alert Radio Altimeters	74,000

ATC Transponder Auto Altitude Reporting	$ 1,866,000
Cabin Materials - Crashworthiness	3,275,000
Area Navigation	67,820,000
Flight Instrument Standardization	1,465,000
CAT	4,050,000
Flight Training Simulators	22,923,000
Visual Aids - Simulators	2,500,000
Fog Dispersal-Research & Development	300,000
SAT Communications	1,562,000
Digital A/G/A Overwater	745,000
CAS	32,485,000
Emergency VHF Communication	57,000
Standby Attitude Indicator	611,000
Aft Evacuation Slide	75,000
VHF Communication Improvements	45,000
Auto Pilot Improvements	45,000
121.5 Monitor	1,683,000
Emergency Evacuation Mockups	378,000

It should be noted the above listing does not include expenditures for such items as reduced smoke burner cans on the JT8D engines or what might eventually be required for noise abatement. The total shown is a lot of the airline's money and of course if expanded to cover what other airlines are doing would amount to a very large sum.

Since the proposed rulemaking excludes solutions other than complete inerting of fuel tanks, it appears to presuppose an acceptable cost-benefit ratio for complete inerting systems. We recommend that rulemaking processes be delayed a while longer until all concerned have had an opportunity to evaluate the industry studies being made since there seems to be little benefit in discussing details of rule wording until we all learn more about possible solutions.

In conclusion we would like to reiterate our continued interest in improving fuel system safety. We have recommended that the FAA Advisory Committee be continued in existence and stand ready to support the flight evaluation of any optimum system or systems that are developed.

USAF EXPERIENCE WITH POLYURETHANE FOAM INERTING MATERIAL

MR. T. O. REED, USAF

INTRODUCTION

The purpose of this paper is to outline the Air Force's experience to date with reticulated polyurethane foam as an inerting material in the fuel tanks of combat aircraft. Included will be background data and experience on the present fully packed concept, as well as an outline of the efforts underway to reduce the weight and range penalties associated with the present foam through the use of low density foams and voiding concepts.

BACKGROUND

The Southeast Asia (SEA) conflict has stimulated renewed interest in the much neglected art of passive defense for combat aircraft. Most of the USAF aircraft originally pressed into service in SEA were designed during the 1950-1960 "Renaissance" period. This period was characterized by a design philosophy which emphasized nuclear store delivery capability and denied the requirement for passive defense considerations other than electronic counter measures for protection against radar detection and attacks by guided missiles. To further justify this de-emphasis in passive defense there was a widely used hypothesis that low flying jet aircraft would be highly invulnerable to small arms ground gunfire because of their relatively high speeds as compared with World War II aircraft. The explosion of this myth in Southeast Asia along with the extensive use of helicopters with their obvious vulnerability has provided the impetus for a critical review of the passive defense stature of combat aircraft. Of all the critical subsystems of aircraft, the fuel system is probably the one most likely to be damaged by any randomly fired projectile. Penetration of the tanks by a projectile may cause loss of an aircraft due to loss of fuel or from fire or explosion.

EXPLOSION HAZARD

The temperatures and pressures at which various hydrocarbon fuels will provide an explosive atmosphere inside a container under stabilized conditions have been determined by numerous experimenters. Although the results of such experiments are seldom in exact agreement from one test to another, Figure 1 shows typical curves for three commonly used fuels. It is important to remember that these classical curves are derived from data generated under stabilized equilibrium conditions. Such conditions seldom, if ever, exist in aircraft tanks during flight. Fuel sloshing with its attendant foams, mists, and sprays will change the temperature-pressure explosive characteristics of the fuel fumes within the ullage space of the tank. Probably the

greatest deviation from the equilibrium curves will be caused by vent system breathing during rapid changes in altitude of the aircraft. More recent ignition tests by the Air Force have shown that under simulated flight conditions and with high intensity ignition sources in the fuel-vapor phase, these lean flammability limits can be extended considerably for JP4 and JP5 type fuels. Another difficulty in determining the explosion hazard in a tank at any given point in a mission is the difference between the fuel temperature and the ambient temperature, which may be considerable at times. Consider, for example, an aircraft that cruises out at some normal cruise altitude and then dives to a low level for a ground support mission. Even though the temperature at the low altitude might indicate an over rich mixture, when referring to the equilibrium curves, the fuel would be closer to the cruise altitude temperature which might fall in the explosive region. When an explosive mixture does exist, an explosion can be triggered by the entry of a small tracer projectile. Figure 2 shows such an explosion occurring in a 200 gallon external tank. The tank before the explosion is also shown in Figure 3. The tank contained approximately 5 gallons of JP-4 at about 60°F. The explosion was triggered by one .30 caliber tracer round. Figure 4 shows the wreckage of the tank and demonstrates the destructiveness of the explosion.

Gunfire is not the only ignition source that has triggered a tank explosion. Malfunctioning or improperly installed electrical equipment, static discharge, and lightning strikes are some of the other potential sources of ignition. Obviously, any provisions for protection against the gunfire hazard would also protect against the others, providing an overall safety improvement for the aircraft.

In early May of 1965, ASD engineers became intrigued with the possibility of using a reticulated foam material for the purpose of preventing explosions inside aircraft fuel tanks. Some of the cars participating in the 1965 Indianapolis 500 Mile Race were being retrofitted with foam filled fuel tanks in conjunction with high strength bladder cells to improve the crash resistance of the tanks. The purpose of the foam was to reduce hydraulic surge resulting from crash impacts and to reduce normal fuel sloshing by virtue of the excellent baffling characteristics of the material.

Considering some of the basic combustion characteristics of hydrocarbon fuels, it was theorized that the material should exhibit the characteristics of a flame suppressor and, when used as a fuel tank filler material, should serve as an effective and simple inerting system.

The Air Force suggested that the Firestone Tire and Rubber Company, who was promoting the race car foam and bladder cell work, conduct certain simple tests to verify the validity of the explosion suppression theories. The impressive results of these tests prompted the initiation of further work to define the problems associated with applying this material to aircraft fuel systems.

APPLICATION PRINCIPLES

The most readily available material having the inerting properties, as well as other required characteristics was a polyurethane reticulated foam with approximately 1/10 inch pore size, produced by the Scott Foam Division, Eddystone, Pennsylvania. This material is reasonably light, is one of the most fuel resistant elastomers known, and has relatively high strength characteristics.

There are two mechanisms by which reticulated foam is believed to suppress the combustion reaction:

a. Removal of energy from the combustion process by absorption of heat.

b. Removal of energy from the combustion process by mechanical interference.

It is a well known fact that a combustible mixture of hydrocarbon vapors and air can exist indefinitely, if maintained below the autogenous ignition temperature and pressure, without evidence of a combustion reaction. However, if a source of energy, such as a spark, is introduced a combustion reaction may occur with explosive suddenness.

When a transient energy source such as a spark (or incendiary bullet) initiates a reaction between a given number of molecules in a fuel-air mixture, the products of combustion of these relatively few molecules are the sole source of energy available for propagating the reaction. If this energy is tranfereed to other molecules in the mixture in such a way as to produce a sufficiently high rate of reactive collisions between fuel and oxygen molecules, the combustion process will be propagated. If, on the other hand, at any point in the reaction, energy in the products of combustion can be absorbed at a sufficiently high rate, the combustion process will be quenched.

Experimenters have found that if the smallest dimension of a container is reduced to 1/10 inch or smaller, the mechanical interference with the transfer of energy will prevent flame propagation in a hydrocarbon air mixture at one atmosphere pressure. It was on

this 1/10 inch quenching distance phenomena that the Air Force engineers based their theory that the open cell foam would function as an explosion suppressing device in aircraft fuel tanks. Actually, it is quite easy to visualize how this material, completely filling the inside of a fuel tank, will drastically reduce the normal turbulence and mixing action that is characteristic of an unrestrained flame front. It is, in fact, reduced to a point where the reactive collisions between the fuel and oxygen molecules occur at too slow a rate to propagate combustion and cause an explosion. The heat of combustion of the relatively few reactions that do occur has sufficient time to be absorbed harmlessly by the air-fuel-foam environment.

Tests with the Scott reticulated foam have shown that 1/10 inch voids are about the largest size that should be used for reliable quenching of fuel-air explosions. This would tend to confirm that the explosion quenching characteristics of the foam are closely related to the 1/10 inch "quenching distance" property of petroleum fuels.

ADVANTAGES AND DISADVANTAGES OF FOAM INERTING

The use of polyurethane foam for fuel tank inerting has certain inherent advantages and disadvantages which might be briefly outlined. On the plus side the foam provides complete or total inerting at all times regardless of ignition source, temperature, altitude, and fuel condition simply because it completely fills the protected tank. Secondly, it has an advantage of being relatively inert to thefuel system both from a compatibility standpoint and from the standpoint of not requiring any servicing or maintenance, such as would be required with a nitrogen inerting system. It also brings with it certain other side benefits which might be important to the designer. These include the benefits of surge or slosh mitigation and with certain types of self sealing tanks provides an added margin of effectiveness in sealing because the foam tends to align the wound and reduce the ram effects. These were demonstrated in early slosh and vibration testing where the foam proved to dampen the sloshing and vibration almost entirely. Improvements to self sealing tanks were noted in gunfire tests of OV-10 fuel cells with the foam.

The disadvantages of the foam include such items as cost, weight and volume penalties, and to some degree it is an added maintenance burden when a fuel tank entry is required. The initial cost of the foam installation is somewhat high at $2-$8 per gallon of tankage, depending on the installation; however, this is a one-time cost with essentially no additional replacement or servicing charges, such as that experienced with a nitrogen inerting system. Weight and volume penalties are somewhat severe at 0.06-0.08 pounds/gallon (gross weight increase) in conjunction with a 4% usable fuel reduction. Attempts are underway to reduce these penalties by voiding techniques and low density

foams, as will be discussed in detail later. If successful, it could result in as much as a 60-70% reduction in the present weight and volume penalties. The other item which appears to be a disadvantage is the added maintenance associated with any required fuel tank repairs. Depending on the tank configuration and complexity, additional time may be required for tank entry, thus making the foam an added cost factor from a fuel system maintenance standpoint. This would be reduced considerably by voiding techniques.

FOAM PENALTIES

The use of the foam material in aircraft fuel tanks imposes certain performance penalties which must be considered. Under the present concept of utilization, a fully packed tank with 10% maximum voiding and 2-5% compression, an overall reduction in usable fuel volume of four (4) percent can be expected. This includes about 2.5% displacement and 1.0 to 1.5% retention. In addition to the tank volume reduction, there is an inherent net weight penalty associated with the foam. Although the dry weight of the foam is approximately 1.86 lbs/ft^3 or 0.24 lbs/gallon, when the 2.5% fuel displacement is taken into consideration, the overall net weight increase to a full tank is about 0.06 to 0.08 lbs/gallon of tankage. Of course this is based on the use of JP-4 and will vary slightly for other fuels and for variations in tank configurations. As an example the use of a heavier JP-5 or commercial kerosene type fuel would tend to reduce the net weight increase; however, this could be offset in some cases where bladder type fuel tanks are used where the foam would actually increase the original tank volume because of a snugger fit in the cell cavity. This phenomena was experienced in the modification of C-119 aircraft tanks where the overall usable fuel was only reduced by 2%. However, for purposes of design it is safe to assume a volume reduction of 3-4% and a gross weight increase of 0.06 to 0.08 pounds per gallon.

COST FACTORS

Estimating the cost of a foam installation is very difficult because of the many influencing factors. Based on Air Force experience with four installations, the range appears to be somewhere between $2.00 and $8.00 per gallon of tankage, including design, fabrication, installation, and testing costs. This range represents what could be considered the simplest installation, that of a 1360 gallon external tank, versus the most complicated, the C-130 integral wing tanks. This data is represented in Figure 5 for four foam installations, and has been represented on a dollar cost per gallon of tankage basis for comparison purposes. The differences in cost can be related to several factors such as the type and complexity of tank configuration, variations in basic material cost, extent of prototype and production testing, and to some extent type of

installation - retrofit or production. In general, for most installations where the system is not extremely complicated the cost can be expected to range from $4 - $6 per gallon of tankage.

The two factors which seem to most influence the overall cost are the tank configuration and the material cost. As an example of this, consider the C-130 which has proven to be the most complicated installation due to its vast network of plumbing, system components, and structural members. Access to the tanks is also limited which presents an added burden to the installer. Because of these complications, the time required for design of the foam pieces, checkout, and installation tend to greatly influence the overall cost and is reflected in the figures shown. It might also be noted that the design of the foam often influences the amount of waste material which results, or in terms of a use factor, the percent of utilization. Experience has shown that the percent utilization can range anywhere from 75 to 90%.

The other important cost factor is the basic material cost which varies anywhere from $0.75 to $1.50 per gallon depending on the quantity purchased. If the number of aircraft modified or the total tankage involved is relatively small, the material cost can be expected to approach the upper limit and thus influence the total cost. This appears to be the case in a comparison of the costs for the B-57 and the A-37 aircraft shown in Figure 5. The difference noted $6.45 versus $3.10 does not appear to relate to the system complexity since both are relatively uncomplicated; however, the number of aircraft involved is significant in that the advantage was on the order of 20:1 favoring the A-37, or on an overall foam requirement basis about 6:1.

The last cost example cited in Figure 5 is for the foam installation in an extremely simple external tank similar to that shown in Figure 3, where the design, fabrication and installation requirements are minimized.

MATERIAL CHARACTERISTICS

The present foam material, designated Scott safety foam because of its application, is basically low density, reticulated polyester polyurethane that is produced by a special process in which all the membranes are eliminated by thermal reticulation from the conventional strand and membrane structure. The resulting structure (Figure 6) is an open pore, three dimensional, skeletal network of strands having a nominal pore size of 10 pores per lineal inch (ppi) and a density of about 1.86 pounds per cubic feet. It is produced by the Scott Foam Division of Chester, Pa., and distributed by Firestone, Goodyear, and US Rubber (UniRoyal) tire and rubber companies. Procurement by the Air Force is to the requirements of Specification MIL-B-83054(USAF) and the Scott Foam designation of SF-2500Z. It is available in standard size buns which are 80X40X8 inches. Some of the more characteristic

physical properties associated with the foam are shown in Figure 7 along with the present MIL-B-83054 specification limits. The more significant properties include porosity (pores per inch), density, tensile strength, solid contamination, flammability, fluid displacement and fluid retention. During production the quality of the material is maintained by control of porosity, density, tensile properties, and solid contamination levels. Experience has shown that with control of these properties the others will remain essentially constant. As can be seen by the comparison in Figure 7, all properties are well within the required specification limits. Production data accumulated over the last three years have also indicated a trend toward a more consistent product with continually improved properties, especially with regard to tensile strength and solid contamination levels. As an example of this trend, solid contamination levels early in the test program ranged from 50 to 400 mg/ft^3; however, with standardized test procedures and improved handling and processing techniques it has been reduced to a present level of 1-5 mg/ft^3. The 2.5 mg/ft^3 value shown represents an average of more than 250 samplings during the first six months of 1969.

The present procurement specification is currently being revised to update the requirements and to include the next generation low density materials now under test. It is anticipated this will be accomplished by the use of two or three classes of materials and several pore sizes to accommodate different voiding applications. A tentative specification release date of October 1970 is planned.

INSTALLATION REQUIREMENTS

The Air Force has through its foam evaluation program and experience in aircraft modifications defined certain minimum criteria for the design, installation, and testing of an aircraft foam installation to insure that the full protection benefits of the foam can be realized and to assure proper fuel system operation. The criteria which have been established for fully packed tanks are outlined in an ASD-TM-69-1, entitled "Foam Installation Criteria", dated 5 January 1968. At the present time this document is being revised to include the latest technology in fully packed applications and will be released as a USAF specification in the near future. Provisions will be included for any future incorporation of design criteria relating to voiding concepts which evolve as a result of current test programs.

Consider now a few of the basic design criteria established for the installation of foam as outlined in Figure 8. From a design standpoint, the material should be slightly oversize (2-6%) in order to fit snugly in the tank thus avoiding any movement, especially at low Temperatures. The foam should be designed for a minimum number of total pieces, and should be designed to be removable through normal access openings without the need to manipulate tank components. Voiding shall be

provided around all internal tank components, vents, and fuel interconnects to eliminate the possibility of interference to normal system component operation. To insure proper inerting under all conditions, the maximum total voiding is currently limited to 10-15% of the total tank volume. The last design item listed is the requirement for a permanent numbering system to identify each foam piece with respect to tank location and orientation. The markings used should be fuel resistant and be of sufficient size to be easily viewed by the installer. In the area of foam processing and installation, certain requirements have been developed to assure minimum contamination to the material while being fabricated. The use of hot wire cutting is suggested for major cutting as a means of reducing this contamination; however, for smaller cuts and voids, the use of electric carving knives is permitted. The use of strict handling and storage procedures is required to minimize contamination to the product. A final cleaning is suggested which involves rubbing each foam piece over a frame mounted mesh screen or hardware cloth to dislodge any frayed or loosened foam particles on the surface. During installation detail inspection procedures are required to assure a proper fit, especially in component and void areas. This is required in order to reduce the probability of any interference to working components and thus system performance. As a final check on the installation, each aircraft is tested to assure proper fuel system operation. This acceptance testing normally involves such items as fuel quantity gauge recalibration, booster pump performance, vent testing, and contamination checks. In addition to these acceptance tests on each aircraft, the first prototype aircraft which is modified should be detail tested to demonstrate the adequacy of the basic foam design for that particular aircraft fuel system. This testing involves the acceptance tests mentioned and other tests including the establishment of new tank capacities, usable fuel quantities and gross weight changes.

FOAM DEVELOPMENT TESTING

During the early phases of the foam program, considerable testing was conducted to not only demonstrate the explosion suppression properties but also the material compatibility with the fuel system environment and its effect on fuel system performance. It was this basic testing which led to the establishment of the design requirements now existing. For purposes of this discussion the testing will be classified into three categories: (a) explosion suppression studies, (b) material compatibility, and (c) fuel system performance. The explosion suppression properties of the material was first confirmed by small scale laboratory tests. Subsequent large-scale tests were condcted with 55 gallon drums and 200 gallon external tanks. These tests were conducted under contract with Firestone Coated Fabrics Co. and the results are summarized in a report entitled "Development and Testing of Cellular Packing Material" (Reference 1). Containers with and without foam were

charged with a JP-4 air mixture. Explosions were triggered by .30 caliber tracer projectiles. An identical tank to that shown in Figure 3, except protected with the reticulated foam, did not explode when penetrated by two separate tracer rounds. The effectiveness of the explosion suppression properties of the material can be appreciated by examination of samples of the material taken from the protected test tank. The tracer bullet was fired from an off loaded cartridge to insure that no exit occurred. After coming to rest inside the foam material, the tracer continued to burn for a short time melting the material and forming a void large enough to have normally supported combustion. Another round disintegrated upon striking the supporting beam of the tank. A piece of this round ignited a void area intentionally cut out of the material at the bellmouth of the fuel discharge tube. The fact that these relatively well developed fires existed for a short time inside a tank containing a combustible fuel-air mixture without a detectable pressure rise in the tank, is dramatic proof of the effectiveness of the foam as an explosion suppression medium. During these tests the tanks were pressurized to 12 psig. This, of course, makes the explosion suppression problem more severe than with a tank at one atmosphere or less.

In addition to the Firestone evaluations, extensive testing was accomplished by the Republic Aviation Division and the Bureau of Mines under contract with the Air Force. The Republic testing included full-scale gunfire tests with and without foam and some limited foam voided configurations, and are summarized in a Fairchild Hiller Corporation Report ETR-67, dated February 1967 (Reference 2). The other program by the Bureau of Mines included detailed flame propagation studies and several voiding configurations with various arrestor materials including the present Scott foam. Results of these tests are outlined in Air Force Aero Propulsion Laboratory reports AFAPL-TR-67-36, March 1967, AFAPL-67-148, February 1968 (Reference 3), and AFAPL-TR-68-11, March 1969 (Reference 4). Within the last year considerable emphasis has been placed on foam voiding configurations as a means of reducing the weight volume penalties. Several voiding configurations have been suggested which provide up to 50% voiding and in some cases limited small-scale testing has been conducted. The Air Force is presently initiating an in-house test program which hopefully will result in defining certain useful voiding configurations, especially for large aircraft type installations such as the C-130. Included in the evaluation will be several new low density foams with pore sizes from 15 to 25 PPI, in addition to the present 10 PPI material. Other preliminary evaluations have been accomplished by the McDonnell Douglas Corporation (Reference 8) which seem to indicate that certain specialized "gross" voiding techniques can be used to provide adequate internal explosion and fire protection with up to 80% voiding. A further discussion on these will be given later under voiding concepts.

MATERIAL COMPATIBILITY STUDIES

During the early phases of the foam qualification program extensive material compatibility studies were conducted on the foam. These compatibility tests along with various fuel system performance evaluations on the foam are outlined in an ASJ Technical Memorandum ASJ-TM-66-1 dated November 1966 (Reference 5). The following represents some of the more significant tests conducted under the Monsanto effort and under the continuing test effort to date:

a. Fluid Exposure Studies. These tests included a standard 28-day immersion at 158°F in JP-4 and standard test fluids TT-S-735 types I and III. Avgas was also tested at 110°F. At the end of the 28 days, the foam was tested for tensile strength, elongation, compression load deflection, color, and the test fluids were analyzed for standard specification tests. No detectable deterioration could be found in either the foam or the fuel properties. An increase in the existent gum levels of the fuels was noted due to extraction of small amounts of foam stabilizers; however, it was found to be within acceptable use limits. To preclude any problems with gum during installation this parameter is monitored as part of the contamination tests on each aircraft.

b. Long Term Fuel Exposures. Foam samples were immersed in JP-4 fuel continuously at 130°F for a period of 10 months without indication of any detectable deterioration. Analysis of the fuel after this expsoure indicated an increase in existent gum content; however, the level was again found to be within use limits. A JP-4 vapor exposure test was also conducted on the foam at 158°F for over 12 months. Results indicated only about a 14% reduction to tensile properties.

c. Cyclic Exposure Tests. This test was designed to simulate an aircraft fuel tank environment in Southeast Asia. Exposure included 20 cycles (or 240 hours) under the following conditions:

70-90% humidity

70° to 135°F over a 3-hour period

135°F continuous for 6 hours

135°F to 70°F for 3 hours

Total Time per Cycle: 12 hours

The test system consisted of 5 gallon vented jars packed with JP-6 Wetted foam and containing 2-1/2 pints of a 25% solution of anti-icing additive and water with an overlay of JP-6 fuel. This level of anti-icing additive

is typical of a fuel tank using JP-4 fuel, where the additive migrates to the water (sump) and builds up to an equilibrium concentration. At the end of the exposure there was essentially no degradation to the foam. Another cyclic type test which is presently included in the foam specification involves a 4-day soak in JP-5 at 200°F and a one-day dry at 250°F. After six (6) cycles or 30 days total exposure an average tensile value of 16.8 psi was obtained which represented a loss of approximately 45% from the original.

d. Contamination Tests. During the early phase of the program a large number of contamination tests were run to establish both a standard procedure and representative limits for the material as received from the manufacturer. Many techniques were tried and contamination values varied widely; as an example, anywhere from 50 to 400 milligrams per cubic foot were measured. Since that original testing, a standard procedure has been developed and is now included in the foam specification for acceptance testing. As a result of standardizing the procedure and the improved handling and processing techniques by the manufacturer, the contamination levels of new foam have been considerably reduced, well below the specification limit of 11 milligrams per cubic foot. To insure that the low levels are maintained throughout the cutting and installation phases, a minimum of two fuel fill and drains are required on the aircraft fuel system after foam installation and the increase in fuel contamination cannot exceed 1 milligram/gallon over the level in the fuel serviced to the aircraft.

e. Low Temperature Tests. A series of tests were conducted to evaluate the low temperature characteristics of foam. Short term static exposure to -65°F in fuel did not affect the foam properties. However, it was found that the foam became very brittle at these temperatures and if allowed to move about within the tank serious abrasion and fragmentation could result. As a result of the data, the requirement was established that the foam be installed 2-6% oversize to preclude any movement at low temperatures.

f. Hydrolytic Stability Tests. The hydrolytic stability of the foam, or its resistance to water and humidity, has always been of concern to the Air Force because of previous experiences with other urethane materials which have failed prematurely under high humidity conditions. Examples of these failures include reversion of electrical polyurethane potting compounds, and isolated cases of delamination of nylon-urethane ground storage tanks. In the case of these failures, especially the potting compounds, the prime environment included high temperature-humidity conditions as opposed to that of the fuel vapor environment in an aircraft fuel system. As a result of the emphasis on the hydrolytic stability, a great number of tests have been conducted

and it has been generally accepted that the foam is somewhat marginal in hydrolytic stability, especially at high temperatures. However, in the presence of fuel vapor, it is essentially unaffected at temperatures below 200°F. Examples of data generated on hydrolytic stability versus fuel compatibility and dry heat exposures are summarized in Figure 9 for reference. It is apparent from this that under a dry heat or fuel vapor environment the foam is infinitely more resistant than under similar temperature-humidity conditions. In other tests where the presence of fuel vapor existed along with water, the foam deterioration was very minor as long as the temperature did not exceed 200°F for extended periods. Provided the foam is continuously exposed to fuel or vapor as in a fuel tank, the presence of small amounts of water will not deteriorate the foam. Based on known characteristics of the material, it is expected that any degradation will be a slow process as indicated by a gradual loss of tensile strength. As a result, the Air Force has developed specific foam inspection techniques for field level personnel to be used whenever tank entry is accomplished. Service experience to date on certain "lead the fleet" and combat aircraft has verified the excellent compatibility of the foam with the fuel system environment. This data will be further discussed under Service Experience.

g. Microbiological Growth Studies. A series of studies were conducted to determine if the material affected the growth rate of typical fuel utilizer bacteria (pseudomonas-aeriginosa) or fungal spores (hormodendrium-clasdosporeum). Two basic conditions were studied including JP-4 fuel with and without the presence of 25% anti-icing additive in the water phase. This additive concentration is representative of the level found in typical aircraft fuel tank water bottoms using JP-4 fuel. The test results essentially showed that the presence of foam neither enhanced nor inhibited the growth of the microorganisms. In the case of the fungal growth it would be possible for the foam to provide a matrix for attachment by the fungus mats. However, in the tests where 25% anti-icing additive was present in the water phase, no growth could be observed with either the bacteria or fungus after a six-hour period. The reason for this is that the anti-icing additive has been shown to be an effective biocide at concentrations above 15% by volume. It appears that as long as JP-4 with anti-icing additive is used, the chance of this type contamination is virtually eliminated. The use of JP-5 or kerosene fuels without anti-icing additive may require stringent maintenance procedures to assure removal of free water from the system and possible periodic inspections. However, in the case where microbiological contamination is not already a problem it is not likely the foam will present any added burden. A detailed microbiological test program on foam has recently been completed by the US Army Natic Labs and the results are scheduled for release in the near future.

h. Foam Life Span Tests. In an attempt to predict the expected life span of the material within a typical fuel system environment, the foam manufacturer conducted a series of accelerated aging tests to determine the effects of kerosene fuels and additives on the foam. Variables included time, temperature, fuel types (JP-4 & JP-5), typical corrosion inhibitors, antioxidants, metal deactivators, anti-icing additive, and soluble water. Effects of the variables on the foam were measured by changes in tensile strength and elongation. A computerized variance analysis was run on the data for eighty (80) experiments; and from the results it was predicted that, under normal use conditions within an aircraft tank, the foam would have a life span of at least ten (10) years. Details of the test results and predictions are summarized in a Scott Foam Division research report #556. (Reference 7.)

FUEL SYSTEM PERFORMANCE

The following represents a summary of the testing conducted in the area of fuel system performance.

a. Corrosion Tests. Two aluminum alloys 7075 and 6061, bare and alodine treated, were exposed for 28 days in contact with foam at 100°F and 100% relative humidity. Comparison of panels with and without foam indicated no corrosion due to the foam contact.

b. Vent Icing Tests. A series of simulated vent icing tests were run to determine the icing characteristics of the foam under extreme conditions. Various parameters affecting vent icing were examined including void area, wet and dry foam, inlet air velocity, foam temperature, and exposure time. The results indicated that even under extreme conditions, far exceeding anything experienced in flight, significant foam icing or pressure drop could not be produced as long as a reasonable size void was provided at the vent inlet. Based on this, the present criteria for voiding around a fuel tank vent was established; that is, a void equal to a cube having sides equal to three times the diameter of the vent opening.

c. Fuel Flow - Pump Down. A series of JP-4 pumping tests were conducted on the foam at room temperature and at -65°F. The test system was designed to simulate a typical fuel tank installation. An aircraft booster pump with a maximum capacity of 41,000 pounds/hour was mounted in a vented tank having the capacity of 117 gallons. Various flow rates from 4,000 to 41,000 pounds per hour were evaluated at ambient and -65°F temperatures. It was determined that, with the normal two-inch clearance around the pump, maximum flow rates could be maintained even at low temperatures. The only differences noted in the data with and without foam was in the total fuel transferred at higher flow rates. Indications were that, if the flow rate from the tank is maintained such that the vertical drop through the foam is 0.44 ft/minute or less, essentially no holdup would occur.

d. Pressure Drop Tests. A series of pressure drop tests were run on the foam at various temperatures and flow rates using a 6 inch diameter pipe 24 inches long, and using JP-4 fuel as the test fluid. Typical relationships between flow rate, temperature, and pressure drop, through the 10 ppi material having a 10% compression were established. A more recent study was conducted on a similar setup with a 3 inch diameter by 24 inches long. Chamber Pressure drop versus flowrate data were established for the 1.86 density foam (10 and 20 ppi), and the 1.35 density black low density foam (15 and 25 ppi). The results shown in Figure 10 indicated, as might be expected, similar pressure drops for the 10 ppi orange and the 15 ppi low density foam, and considerably higher values for the 25 ppi low density material and maximum values for the 20 ppi higher density material. It would appear, based on this data, that the 15 ppi low density material would be an acceptable substitute for the present 10 ppi foam in a fully packed tank configuration; however, the 20 and 25 ppi foams may require additional special installation techniques to eliminate possible flow restrictions. Experience with the 10 ppi material has indicated that it is possible under certain high flow conditions, where tankage involves interconnecting cells, to create abnormal venting conditions or excessive refueling times due to an apparent holdup by the foam. To resolve this it is sometimes necessary to provide additional voiding in component areas.

SERVICE EXPERIENCE.

A total of over three (3) years service experience has been accumulated on the present fuel tank foam by the Air Force on three test aircraft. These include an F-105, C-130A, and B-52 aircraft. In addition, considerable experience has been generated on a number of combat type aircraft in the Southeast Asia environment. As of this date foam installations have been successfully accomplished on over twenty (20) different types of aircraft, boats, and personnel carriers ranging in individual numbers from several hundred to as few as single applications.

In an attempt to follow the condition of the foam in service, a continuous surveillance program has been underway since 1967 which includes periodic material samplings and field level inspections. Foam samples have been obtained from a total of ten (10) aircraft, including the three test aircraft mentioned. A summary of the significant data accumulated on these samples, including tensile strength, elongation, and solid contamination, is presented in Figure 11. As can readily be seen, the values for tensile strength and elongation are all well above the 15 psi and 250% levels which are the acceptable specification minimums for new material. The range of values 18 to 31 psi and 265-505% are considered to be typical of an open cell foam material and can probably be attributed to the basic characteristics of the product and variations

in test techniques. The other data shown for solid contamination are a measure of the dirt and debris level of the foam as a result of exposure to the fuel system environment. Again it is apparent that a considerable scatter in the results exists even within the same aircraft. For comparison the solid contamination of new foam averages around 2.4 mg/ft^3. The increase during service is to be expected and the values will tend to vary considerably due to many factors such as location in the tank, time in service, aircraft location, etc. With exception of the high values for the F-105 at one and two years and the C-130 at 21 months, the data tends to suggest a pattern below 100 mg/ft^3. The reason for the high values on the F-105 is not readily apparent; however, it is possible the basic material at production may have been high, since at that time standards were not as yet established for acceptable solid contamination levels. The real significance of this contamination data is yet to be established; however, it does serve as a guideline for possible foam life criteria if the levels tend to increase indefinitely, or if a correlation between contamination and foam life emerges. The present contamination levels have not presented any known problems to a fuel system or engine operation.

The overall data so far is promising from the standpoint of foam compatibility. It appears at this point in time that provided established guidelines are followed and periodic inspections are conducted, the foam material will provide satisfactory operation for many more years to come. It is too soon, however, to make any firm predictions relative to the manufacturer's estimate of a 10 year minimum life span for the foam. It is anticipated that the present surveillance program will continue in an effort to establish any limitations to the predicted foam life span.

DRY BAY APPLICATIONS

In addition to the foam applications already mentioned, a program was undertaken to provide inerting to certain C-130 wing dry bay areas, that is areas directly adjacent to and between wing fuel tanks which contain many fuel and hydraulic lines. (Figure 12.) This area is of considerable volume and therefore vulnerable to fire and explosion due to the presence of unprotected fuel lines and other potential fuel leakage areas. The Air Force, recognizing this potential hazard adopted a dry bay foam inerting system to supplement the fuel tank protection. This concept is identical to the fuel system inerting system except it employs a white 10 ppi foam containing a Fire Retardant Additive for improved flammability. The color of the material is white and the Scott designation is SF-2502 ZR. The improved flammability was suggested based on the knowledge that a possible fire hazard existed in the dry bay area and because the complicated installation required that the foam be installed with large voided areas adjacent to vents where considerable airflow could be expected.

Application of this technique was accomplished in a number of C-130 aircraft. Within a period of approximately 6 months after deployment, reports were received that the white foam in the dry bay areas was degrading severely. Investigations revealed that the foam was being severely degraded as by excessive temperatures and humidity conditions resulting from the direct impingement of engine exhaust gases into the dry bay area. Further investigations also revealed that this phenomena was only occurring on the "A" Model aircraft, whereas the late "E" Model was experiencing no problems with the foam, due apparently to the difference in airflow conditions. As a result of this problem use of the white FR foam in the C-130A dry bays has been discontinued. Subsequent inspections on the E Model aircraft after one year of service have revealed no evidence of deterioration to the white foam.

Additional laboratory testing conducted on the white FR foam revealed that its resistance to humidity and temperature was considerably less than the orange foam due to the presence of the FR additive. As a result the use of the white FR has been discontinued for dry bay applications.

PRESENT AND FUTURE CONSIDERATIONS

Experience with the foam inerting concept has brought to the spotlight a certain emphasis on its penalties, especially the weight considerations. Although this concept appears to be ideal from an inerting standpoint, it suffers from inherent weight and volume penalties which must be reduced if it is to be successfully applied to very large aircraft or for commercial airliners. Analysis tells us that there are basically two ways to reduce the foam penalties: (a) by reducing the basic foam weight by lower density materials, and (b) by reducing the amount of required material through voiding techniques.

LOW DENSITY FOAMS

A program has been initiated by the Air Force and Scott Foam Division to develop, test, and if possible qualify a low density next generation foam for use in combat aircraft. Limited samples of a 1.36 lb/ft^3 density material as well as an experimental 1.15 lb/ft^3 material have been produced and are now being tested. The experience gained from this initial effort leads us to believe that a 25-30% reduction in density can be achieved within the present "state of the art" without appreciable sacrifices to material properties. Any further reductions, say to the 1.0 lb/ft^3 density level, will inevitably require significant changes to the present techniques and cannot be expected to be successfully developed for some time to come. Nevertheless, a successful reduction in density is considered to be within reach at this time and a concerted effort is underway to establish the merits of this 1.35 density foam as compared to the present 1.86 density material. It is estimated that,

provided the 1.36 density material is shown to be acceptable, qualification to MIL-B-83054 can be realized within the next 6-8 months. The primary questions at this time are whether the material compares sufficiently to the 1.86/10 ppi orange foam in environmental performance and whether it can be mass produced to the quality standards now existing. The flame arrestor characteristics of the 15 and 25 ppi material have been demonstrated to be considerably better than the present 10 ppi foam.

For a comparison of the physical properties of the low density foams versus the present 10 ppi orange, see Figure 12. As a means of identification the new materials have been color coded black for the 1.36 density, 15 and 25 pore, and red for the experimental 1.18 density material. Pore sizes on each have been expressed as a visual porosity and as a corresponding pressure drop porosity based on the present standards for the orange foam. The only significance of the pressure drop reference is to show the comparison of the low density materials to the orange foam under the same airflow conditions, that is at 575 FPM. In all cases the lower density foams are essentially equal to or better than the present orange foam from an airflow pressure drop standpoint.

The tensile and elongation data on the foams seem to correlate rather well; however, it is obvious that the lower density materials tend to be slightly lower than the averages for the present orange foam. At this time the differences don't appear to be significant based on only one sampling; however, this will be better defined when humidity and fuel exposure testing are completed. It seems logical to expect some differences in compatibility with the lower density foams since in theory there is less basic polymer present to resist degradation by fuel and water. Of the other properties shown, the trend again is toward slightly lower results, and again the significance is not known at this time. From the standpoint of fuel retention and displacement, the results are quite impressive in that the trend is toward improvement. These basic improvements along with possible voiding techniques could prove to be very appealing.

The only property shown which might be of concern is the flammability. It appears, from the limited results, that the tendency is toward a more flammable material. Ideally, an improved flammability would be desirable; especially since one of the planned end uses is for gross voiding installations where the question of internal fire is yet unanswered. Again we just don't know what ultimate effect this property may have on its end use, if any.

The only compatibility data available at this time is under 250°F dry heat conditions, where the low density foams have been as compatible as the orange material after approximately two (2) months' continuous exposure.

Future plans for testing include an extensive evaluation on both low density materials from an environmental and a system performance standpoint. Many tests will be run which are similar to those previously mentioned for the present orange foam; however, emphasis in many cases will be on extending the time intervals so that basic differences between materials can be established. As an example, the normal tests outlined in MIL-B-83054 will be accomplished, along with a humidity exposure at 200°F, and fuel and fuel vapor exposures up to 200°F for extended periods. Fuel system performance tests will also be conducted; especially pump down, pressure drops, and venting, and possibly a limited number of icing tests, especially on the 20 and 25 pore materials. Based on limited fuel flow tests already conducted (Reference Figure 7), it appears that a 15-20 pore, 1.36 density material can be successfully used in the fuel system under full tank applications without sacrificing fuel flow or performance; however, additional data should be obtained at higher flows before any firm commitments are made. On the other hand, the fuel flow data does indicate the 25 pore foam has a significant effect on pressure drops, even at low flow rates, and may require additional detailed testing to establish suitable design criteria for its application.

Plans have also been initiated for a long term service evaluation on the two low density materials in an F-105 aircraft similar to that now in existence on the orange foam. Present scheduling calls for installation of the test foam kit sometime in late May or early June of this year. This will serve as the Air Force's "lead the fleet" type installation and serve to provide advance information on the foam compatibility prior to any future implementation.

FOAM VOIDING CONCEPTS

The possibility of reducing foam weight and volume penalties by voiding was recognized early in the program; however, because of a lack of knowledge of the many complex factors associated with this technique, little has been accomplished toward any full-scale implementation.

Before discussing some of the voiding concepts under consideration, it might be appropriate to define the meaning of voiding and some of the terminology associated with its use. Voiding has reference to systematically cutting preplanned patterns of voids (holes) into the foam, thus reducing the overall amount of material required to pack a fuel tank. The objective is to preplan these voids so that an effective inerting system results under all use conditions. To a limited degree the use of voiding is applied in the current fully packed foam concept. This is required in order to prevent interference of the foam with the successful operation of the fuel system. The present voiding limit is set at 10-15% of the fuel tanks' vapor space under all fuel level conditions. Limits are also placed on the size and location of these individual voids.

The technique of voiding is often further categorized as "coring" and "gross voiding". The basic difference between the two categories is in the size of the individual voids employed. As an example, "coring", as it is known, can refer to either cubical type voids or cylindrical with strict limitations on the void size, say 4-6 inch cubes and 2-3 inch diameter, by 8 inch long cylinders. The thickness of foam separating these voids is also critical and depends on the porosity of the material. In a large tankage application each of these voids would be a relatively small percentage of the total system, usually less than 1 percent. The basic limitations to coring seems to be its application drawbacks and the amount of total voiding which can be accomplished, usually in the range of 40% by volume.

"Gross Voiding" techniques as we know them refer to the use of larger individual voids which generally range from 3% to as high as 17% of the total tankage. A further subdivision of this gross voiding, which has been developed by the McDonnell Douglas Corporation, is called "Compartmenting", where a large tank is divided into interconnected compartments and the "key" is to limit the size of openings between compartments to around 10-30% of the total area. The basic advantage of this technique is that overall voiding percentages of up to 80% can be theoretically accomplished with the use of 25 ppi foams. The basic drawback is that it requires special hardware for compartmenting the tank unless this can be designed into the system at its inception, and it also requires special techniques for attaching the foam to the tank interior. As we now see it, this technique will probably be limited to future aircraft applications because of these installation drawbacks. The use of uncomplicated "gross voiding" appears to be the most promising technique for reducing weight; however, this approach will be limited to around the 50% voiding category because of tank configurations.

Before any attempt is made to discuss specific voiding configurations now under evaluation, consider a few of the basic principles applying to the design of a voiding system.

As previously discussed, the idea of foam inerting is based on the principle that if an ignition source enters a tank and ignites the explosive mixture therein, the foam by its physical make up prevents the flame from propagating throughout the tank, thus preventing excessive pressure and temperature buildups. In the case where voiding techniques are applied, the same flame arresting characteristics are applied; however, the idea is that if ignition occurs in a voided area, combustion is permitted to occur. Consequently, as a pressure and temperature rise occurs it is relieved through the surrounding foam and into the entire tank volume, thus maintaining an overall pressure within the capability of the system. Of course the principle is to restrict the combustion to a specific voided area by means of the foam. The surrounding tankage volume is used as a heat/pressure sink. The primary considerations when

designing a voided system are how to successfully control the combustion when it occurs and what is the maximum rise to be anticipated. Other factors that also need to be considered when voiding include: internal fire, multiple ignitions, optimum porosity of the foam for quenching, initial tank pressure, etc. Of course, not all of these variables (parameters) are defined for various void configurations and it becomes necessary to develop these relationships for each configuration and ultimately prove a design by full-scale testing.

From a theoretical approach, the relationship of pressure rise to void ignition for a stochiometric mixture of fuel and air at one atmosphere can be expressed as:

$$\frac{V_T}{V_C} = \frac{P_T}{P_C} \quad \text{or} \quad P_C = \frac{V_C}{V_T} 125$$

where V_T = Total Tank Volume

V_C = Combustible Volume ignited

P_T = Maximum pressure that could result if a stoichiometric mixture is ignited in an unprotected tank. P_T is approximately 125 psig for hydrocarbon fuels at one atmosphere.

P_C = Maximum pressure resulting from the combustible volume V_C.

A plot of this relationship is shown in Figure 14 where percent void or V_T/V_C versus pressure rise is given. Examination of this relationship indicates one basic assumption: that the entire combustible volume represented by the specific voided area is ignited. This of course has been shown by many experimenters to be untrue due to certain mechanics of the system such as turbulence, combustion interference by foam, etc. The actual Pressure-Volume relationship for this type of ignition is somewhere below the theoretical curve. However, it is yet undefined for most voiding configurations. In certain specific voiding configurations, such as that developed by McDonnell Douglas Corporation (Reference 6) for a compartmented system, the Pressure-Volume relationship has been shown to be minimal as demonstrated by the Pressure-Curve on the left. Here the tankage was compartmented and the relief area of each compartment was limited by use of foam and tank structure. In other experiments by the Bureau of Mines (Reference 3 & 4), external tanks were tested with various coring and gross voiding configurations. In all cases, including some small-scale tube tests, values for pressure rises were well below the theoretical values and didn't appear to follow any trend. This leads one to believe that the exact pressure relationship may be dependent on several factors including configuration, ignition sources and location, venting capability, and to some degree

the foam porosity. Although the effect of initial pressure has not been considered, it too has a great influence on combustion pressures. This will not be discussed in detail because the use of voiding for tank pressures above atmospheric will probably be limited due to the obvious problems with increased pressure rise and the added burden to the foam from a flame quenching standpoint.

One other factor which became apparent from the available data is the need for large-scale testing as a final proof of a voiding concept.

As an example of some of the work which is underway in this area, the Air Force is looking toward possible voiding concepts for not only present aircraft but for future aircraft. One such aircraft which appears to be ideal for voiding is the C-130 where the wing tanks contain numerous bay areas and structural members between which the foam could be installed. Examples of a few of the various voiding configurations being considered are shown in Figures 12, 15, 16, and 17. Figure 12 represents the layout of the wing tanks and dry bay areas containing foam in the fully packed configuration. Total foam weights in this configuration for the 1.86 density orange foam is 1428 pounds and 930 pounds for the 15 ppi 1.36 density material. This represents a considerable improvement in weight even without voiding. Figure 15 is a 30% gross voiding configuration which is being considered for use with 10 ppi orange or 15 ppi low density. Again, the weights are shown and represent another 30% savings at 998 lbs. The feasibility of this configuration with 10 ppi material is questionable, based on the Bureau of Mines' gross voiding testing with external tank configurations. It must be shown by large-scale testing that pressures resulting from individual bay ignitions do not exceed the tank limit. The question here is not so much of the size of the voids involved, but of possible propagation or hot gas ignition through the foam to adjacent voids, resulting in secondary ignitions. A more logical consideration in this case would be a 15 or possibly a 20 ppi low density foam because of their improved flame arresting characteristics.

Figure 16 represents a similar C-130 voiding configuration but extended to the 50% level. Here again, the voided bays represent void volumes which could produce pressures in excess of the wing tank limit of 5 psi; especially if propagation or ignition extends through the foam into an adjacent bay. Considering the 10 ppi for this appears unfeasible; however, use of the 25 ppi low density could be successful. Again, however, large-scale testing would be required to prove the concept.

The final configuration shown in Figure 17 is also for a C-130 but using an 80% voiding concept proposed by the McDonnell Douglas Corporation (Reference 7). It is similar to that used in the establishment of Figure 14. Here the use of about 4-6 inches of 25 ppi low density material would be required on each side of the bay structure and possibly

limit the openings between bays (relief area) to 10-20% of the present opening which approaches 90%. The only drawback to this would be in the attachment of the foam to the tank structure. The use of attachment plates or screens could be utilized; however, this would add weight to the system. With this configuration, the concept becomes considerably more complicated from an installation standpoint. Considering these increased installation drawbacks, one would probably revert back to the 50% voiding concept mentioned, where essentially no changes to the system would be required.

As an example of the weight and volume savings that could be realized with various combinations of voiding and low density foams, Figure 18 lists the volume and weight penalties on a percent volume and a per gallon of tankage basis for three density materials and for various voiding percentages up to 80%. The purpose in this comparison is not to suggest that all of these concepts are feasible but only to suggest that significant improvements could be realized if the proper techniques of application are made available.

It might be appropriate to end up the subject of voiding by summarizing some of the points which have evolved as a result of the work done to date:

a. Voiding in general appears to be a feasible approach to possible weight and volume reductions of the present foam inerting system; however, tests to date have been limited in most cases to small-scale configurations with only selected concepts in mind. The use of voiding in systems where tank operating pressures are above atmospheric may not be feasible because of the increased combustion pressures and added burden to the foam from a flame quenching standpoint.

b. When designing a voiding concept, many parameters must be considered and not all of these are yet well defined: relationship of pressure to combustion volume, foam porosity versus thickness requirements, tank configurations, fuel system limitations - including weight and pressure capabilities, venting characteristics, relief areas, initial pressures, the number and type of ignition sources, and possible internal fire problems.

c. From the standpoint of explosion protection, the coring techniques appear to be most effective; especially for use with the larger pore foams such as the 10 and 15 ppi. However, this technique has certain inherent limitations, including those associated with installation and fabrication and from a maximum voiding consideration to 30-40%.

d. Gross voiding techniques appear to be better suited for use with 20-25 ppi foams and provide a better potential for voiding up to the 50% and possibly even the 80% levels. These techniques also appear to be more suited for certain aircraft configurations where the structure can be utilized for maintaining the foam. However, until more detailed large-scale testing is accomplished, it is doubtful that a full understanding of this technique can be realized. One specific gross voiding technique under evaluation by the McDonnell Douglas Corporation involving the use of compartmented tanks appears to be very promising, based on the limited testing to date.

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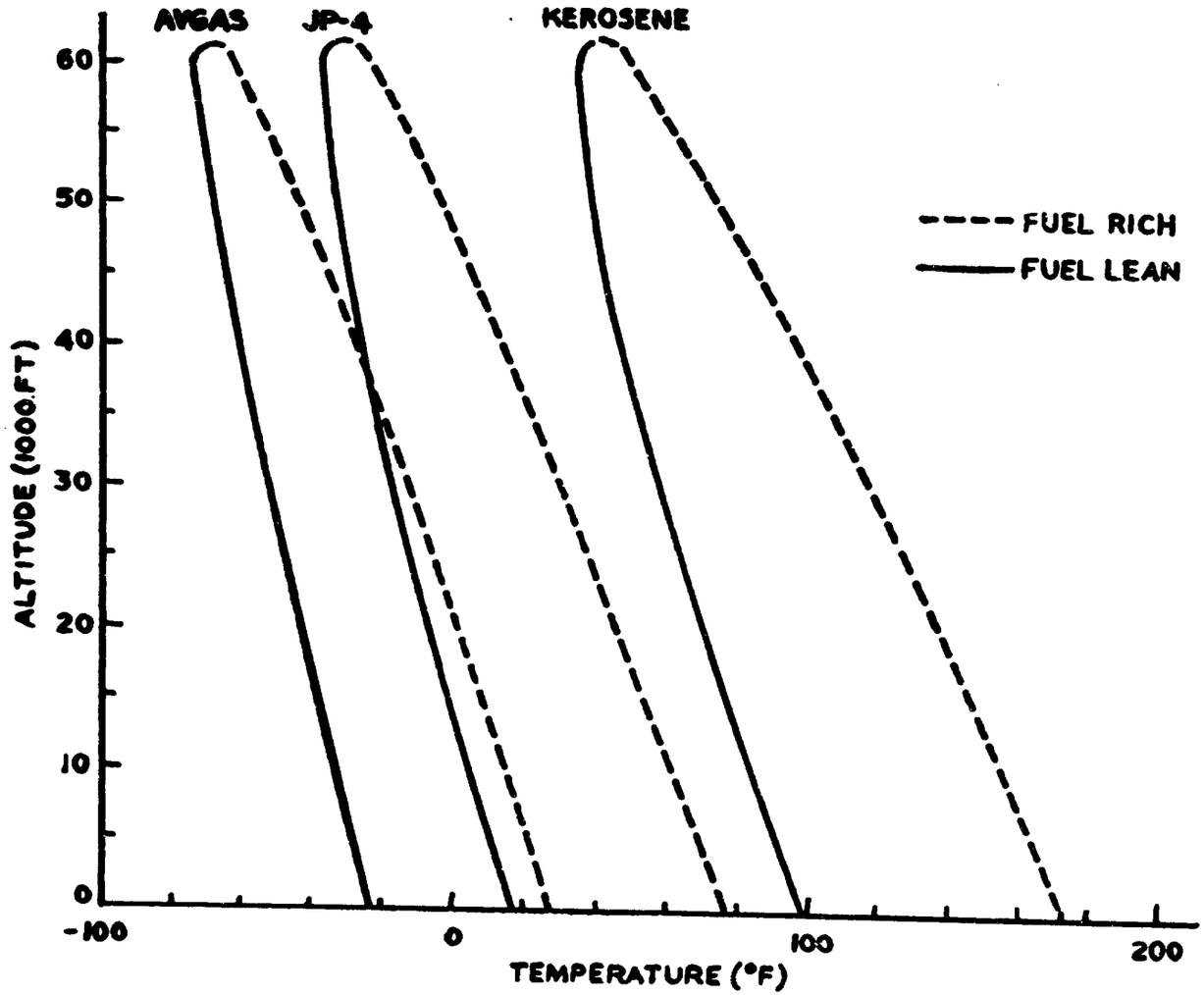


FLAMMABILITY LIMITS IN AIR

FIGURE 1

FIGURE 2

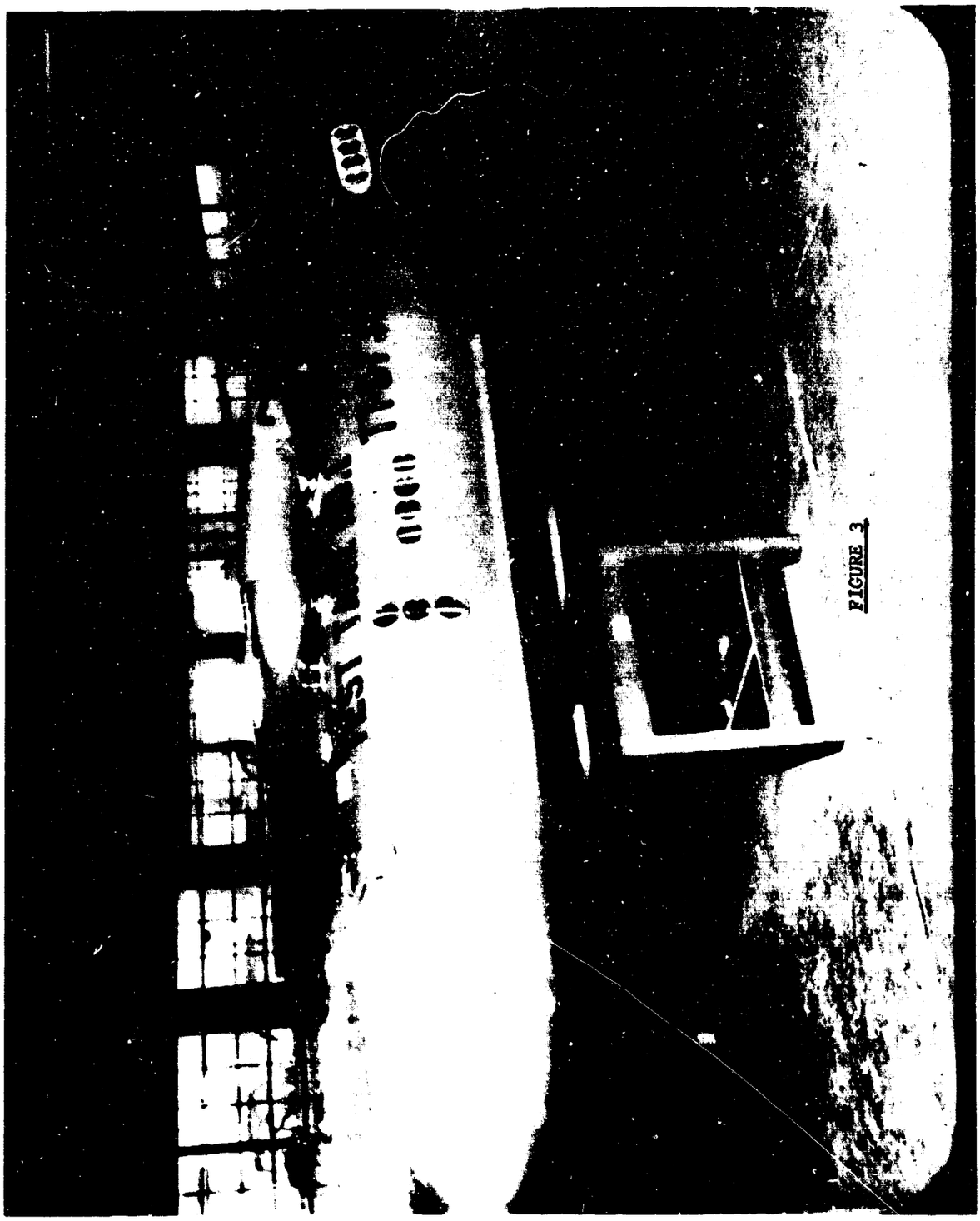


FIGURE 3

FIGURE 4

Typical Foam Installations Costs

A/C	Tankage	Foam Weight	Total Cost	Type Installation, Tank
C-130E	9680 gal.	2420	$7.90	Production, Integral Wing Tank Very Complicated Design
B-57G	2862 gal.	706 lbs.	$6.45	Retrofit, Rubber Wing-Fuselage External - Uncomplicated
A-37	890 gal.	220 lbs.	$3.10	Production - Self-Sealing Wing-Fuselage, External, Uncomplicated
C-130E	1360 gal.	390	$1.96	Production - External Only Extremely Simple

Basic Material Cost -$0.75 - $1.50/gallon ($75 - $1.30 per bun)

FIGURE 5

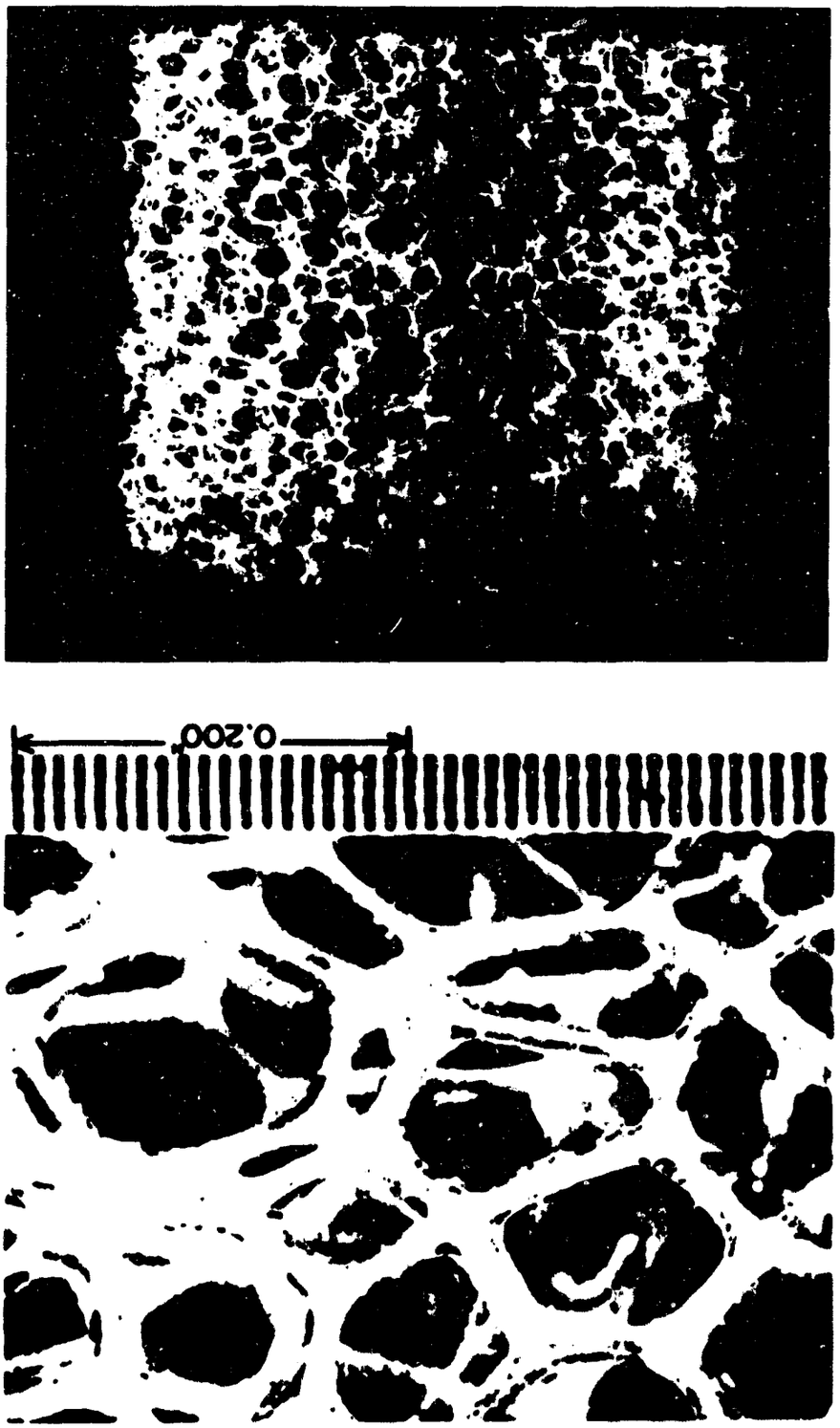


FIGURE 6

BASIC ORANGE FOAM PROPERTIES

Property	Specification Limit	Production Values
Density (lb/ft^3)	2.1 Max.	1.79 average
Tensile (PSI)	15 Min.	31.0 average
Elongation (%)	250 Min.	388 average
Pores Per Inch	7-15	12 average
Solid Contamination ($mg./ft^3$)	11 Max.	2.5 average
CLD at 25% (PSI)	0.5 Min.	0.5 - 0.6
Flammability (in./min.)	10 Max.	4-6
Tear Resistance (lb./inch)	5 Min.	6-8
Fuel Retention (% Vol.)	2 Max.	1.0-1.5
Fuel Displacement (% Vol.)	3 Max.	2.5
Extractables (% Wt.)	3 Max.	1.6-2.3

FIGURE 7

FOAM INSTALLATION REQUIREMENTS

DESIGN

Oversize Fit 2 - 6%
Maximum Total Voiding 10% of Tank
Proper clearances around components, vents, interconnects
Minimum Number Pieces - Removable
Permanent Numbering System

CUTTING AND INSTALLATION

Hot Wire Cutting
Proper Handling and Storage
Final Cleaning
Assure Fit in Component Areas

TESTING

Quantity Gage Recalibration
Demonstrate System Operation - Pump, Vent, Transfer
Contamination Analysis
Determine Usable Fuel, Weights

FIGURE 8

Hydrolytic Stability Data
(Orange Foam - 1.86 Density)

Temperature	Humidity Condition	Failure Mode
100°F	100% R. H.(1)	< 5 PSI After 1 Year
100°F	Water Immersion(1)	9.9 PSI After 1 Year
135°F	95% R. H.	No Change in 30 Days
140°F	Water Immersion	Failed at 4 Months
160°F	100% R. H.	13.9 PSI at 30 Days (-42%)
160°F	Water Immersion	8.3 PSI at 30 Days
160°F	25% AIA +Water	19.7 PSI at 14 Days
200°F	20% R. H.	7.3 PSI at 85 Days
160°F	Dry Heat	17.2 PSI at 10 Months
250°F	Dry Heat	No Change at 53 Days
135°F	JP-4 Immersion	29.5 PSI (-6%) at 10 Months
160°F (1)	JP-4 Vapor	16.9 PSI (-14%) at 1 Year
160°F	Jet Reference Fluid	35.4 PSI (13%) After 30 Days

Note: AIA = Anti-Icing Additive (MIL-I-27686)

(1) Reference MAA Report 69-45 dated 2 July 1969 (See Reference 6)

FIGURE 9

PRESSURE DROP DATA FOR VARIOUS FOAMS

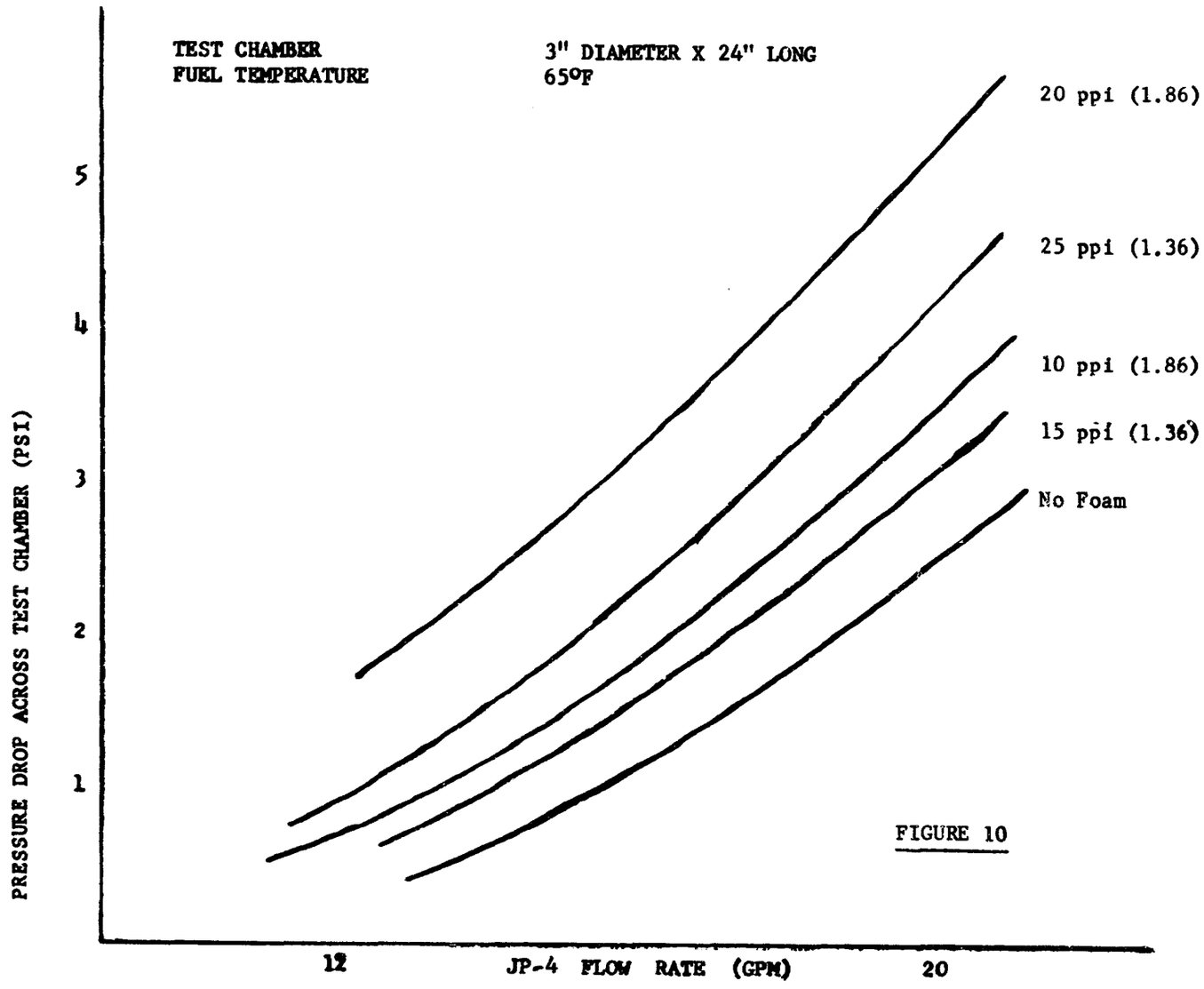
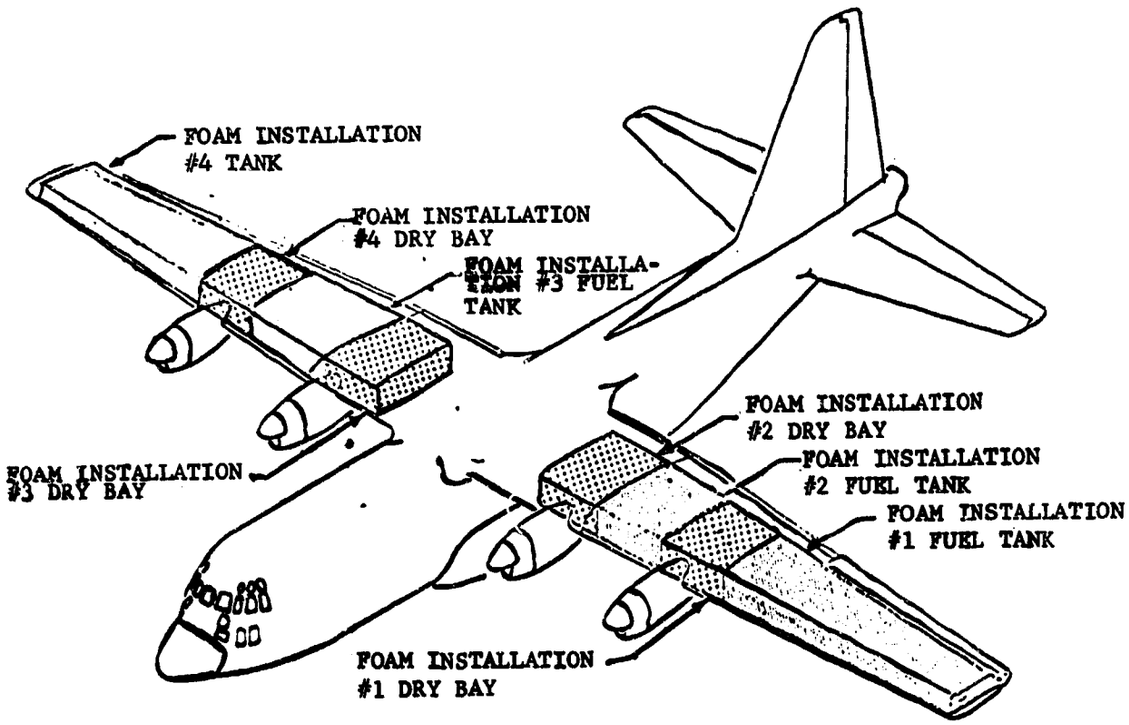


FIGURE 10

Foam Service Data

Aircraft	Time	Location	Tensile	Elongation	Contamination
F-105 Test Aircraft					
	12 Mo.	USA	28.9 PSI	505%	283 mg/ft^3
	21 Mo.	USA	19.4	377	261;150
	24 Mo.	USA	25.7	387	58
	36 Mo.	USA	26.4	445	59
C-130A Test Aircraft					
	8 Mo.	SEA	25.5	286	-------
	21 Mo.	USA	20.6	360	195
	30 Mo.	USA	20.9	375	19
B-52 Test Aircraft					
	12 Mo.	USA	30.8	355	16
Service Aircraft					
A	6 Mo.	SEA	18.5	275	44
B	7 Mo.	SEA	22.3	362	60
C	12 Mo.	SEA	20.9	285	174;11
D	13 Mo.	SEA(AVGAS)	22.7	390	----
E	13 Mo.	USA(AVGAS)	25.9	275	21
F	21 Mo.	SEA	28.3	377	59
G	24 Mo.	SEA(AVGAS)	25.1	388	73
New Foam			15 Min.	250 Min.	11 Max.

FIGURE 11



Fuel Tank Foam Weight (Orange) - 1428 lbs (5500 gal.)(15 PPI-1.36 = 940 lbs.)
Dry Bay Foam Weight (White) - 400 lbs.

C-130A FOAM INSTALLATION

FULLY PACKED

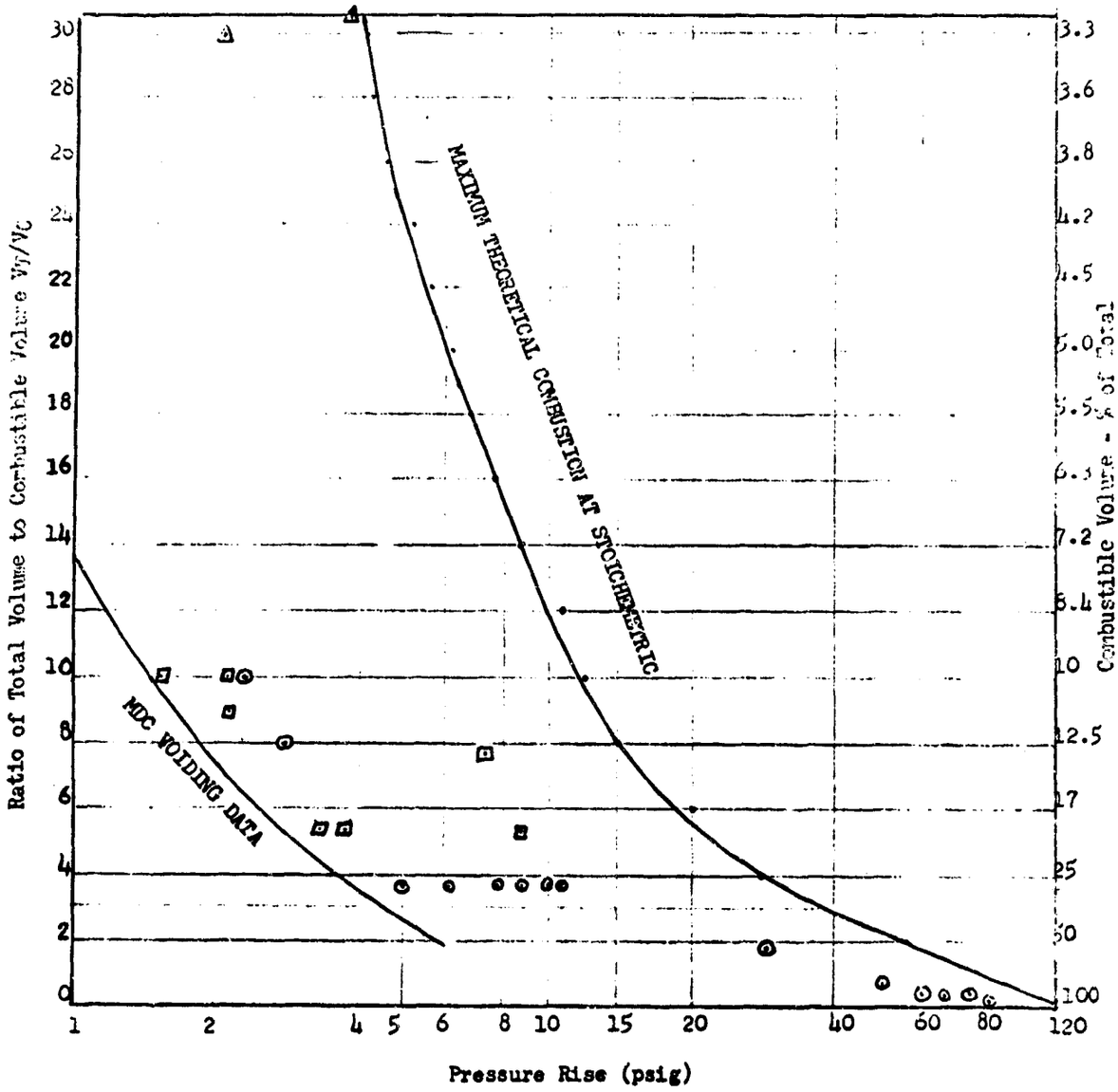
FIGURE 12

PROPERTIES OF LOW DENSITY FOAMS

Property	Orange	Black	Black	Red
Density(lb/ft^3)	1.86	1.36	1.36	1.15
PPI Visual)	10	15	25	15
(Pres. Drop)	10	6	9.5	5
Tensile (PSI	31.0	26.8	22.5	19.4
Elongation (%)	388	365	305	305
CLD at 25% (PSI)	0.5-0.6	0.42	0.52	0.42
Flammability (in/min)	4-6	8.9	10.0	13.0
Tear Resistance (lb/min)	6-8	5.8	5.8	5.3
Fuel Retention (%)	1.1	1.1	1.8	1.0
Fuel Displacement (%)	2.5	1.8	1.8	1.5

FIGURE 13

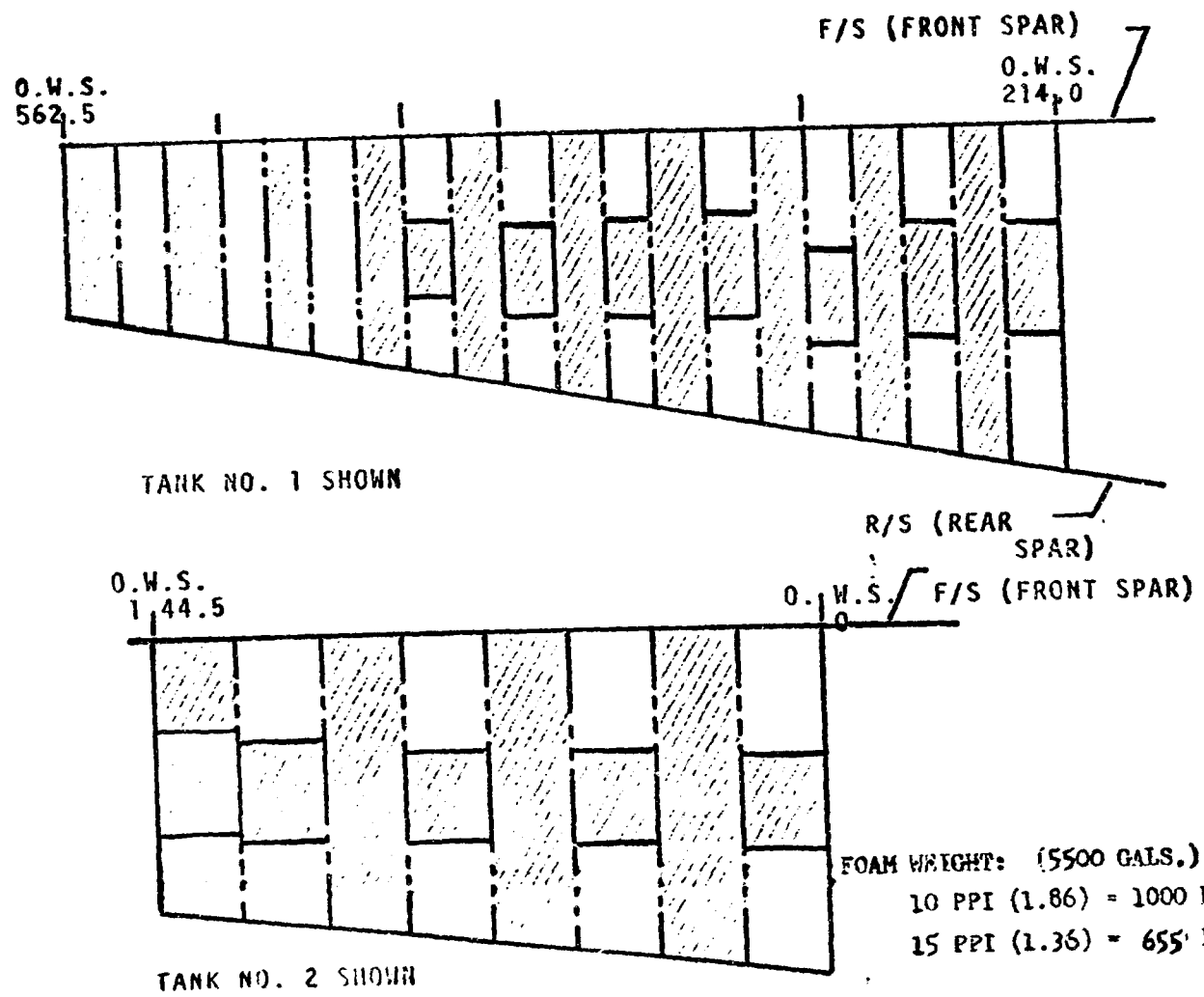
RELATIONSHIP OF COMBUSTIBLE VOLUME V_C AND
TOTAL RELIEF VOLUME V_T TO PRESSURE RISE
(ATMOSPHERIC PRESSURE)



TUBE TESTS
450 GALLON EXTERNAL TANKS
CORED EXTERNALS

FIGURE 14

C130A WING TANKS
30% VOID CONCEPT



FOAM WEIGHT: (5500 GALS.)
10 PPI (1.86) = 1000 LBS.
15 PPI (1.36) = 655 LBS.

FIGURE 15

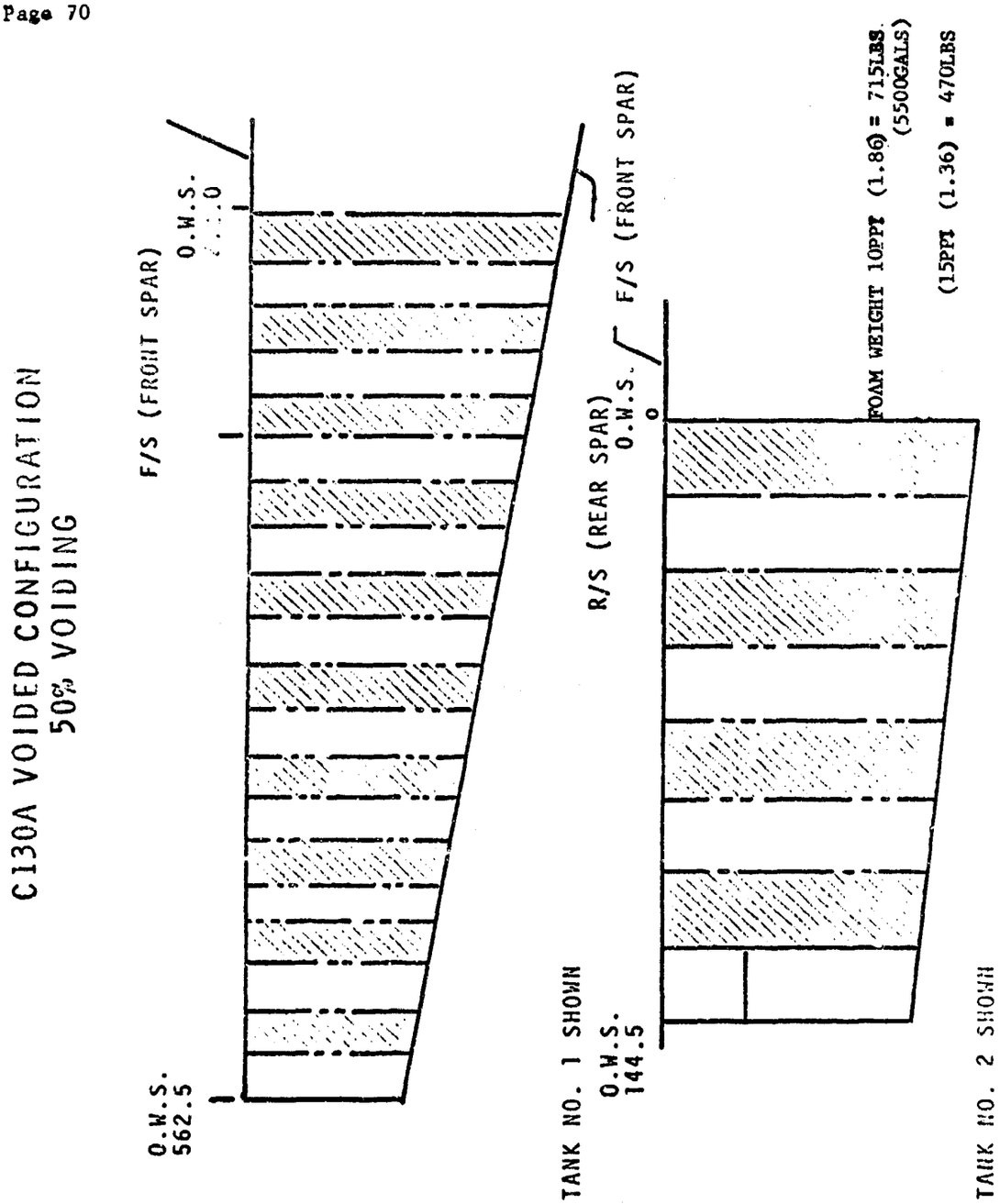
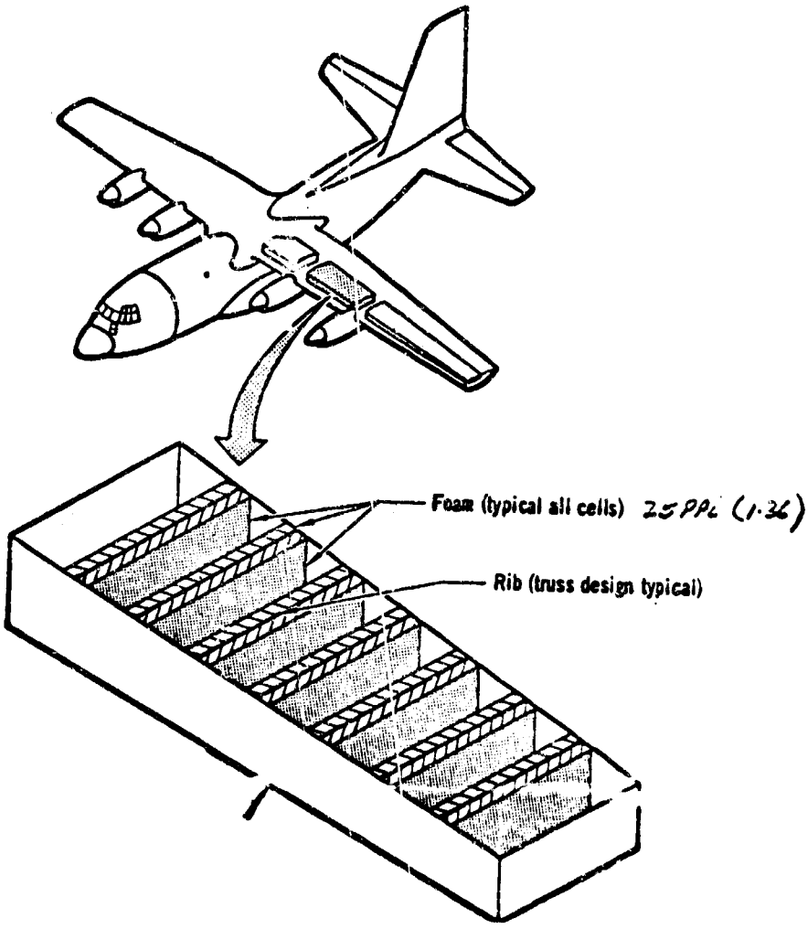

C130A VOIDED CONFIGURATION
50% VOIDING
F/S (FRONT SPAR)
O.W.S.
0
O.W.S.
562.5
TANK NO. 1 SHOWN
R/S (REAR SPAR)
O.W.S.
0
F/S (FRONT SPAR)
O.W.S.
144.5
FOAM WEIGHT 10PPI (1.86) = 715LBS
(5500GALS)
(15PPI (1.36) = 470LBS
TANK NO. 2 SHOWN

FIGURE 16

C-130A WING TANKS

(80% VOID CONCEPT)



FOAM WEIGHT:

25 PPI (1.36) = 190 LBS (5500 GALS)

FIGURE 17

REFERENCE MCDONNELL AIRCRAFT CO. REPORT MDC-A-0044

COMPARISON OF PENALTIES FOR VARIOUS FOAMS

Weights are in Pounds Per Gallon of Tankage

Orange 1.86	% Retention	% Displacement	Dry Wt.	Net Wt.
Fully Packed	1.0	2.5	0.24	0.06-0.08
30% Void	0.7	1.7	0.16	0.05
50% Void	0.5	1.2	0.12	0.04
Low Density 1.36				
Fully Packed	1.0	1.8	0.17	0.05
30% Void	0.7	1.3	0.12	0.04
50% Void	0.5	0.9	0.08	0.02
80% Void	0.2	0.4	0.04	0.014
Low Density (1.0)				
Fully Packed	1.0	1.3	0.13	0.04
30% Void	0.7	0.9	0.09	0.03
50% Void	0.5	0.7	0.07	0.02
80% Void	0.2	0.3	0.03	0.01

FIGURE 18

Resume of Discussion Following Mr. Reed's Presentation

1. In reply to a question, Mr. Reed advised that B-52 test tank held approximately 4,000 gallons.

2. As for refueling, over the wing type refueling of a foam filled tank has not been a problem. For pressure refueling, the refueling rate will be affected by the design of the voided areas in the vicinity of the inlet.

3. Mr. Reed advised that it does not appear that internal fuel tank structural inspection can be made with the foam in place. The USAF has not tried to make an inspection with the foam in place.

4. The design, fabrication and installation of foam in the first C-130 required 2900 manhours and 6 weeks. (corrected data).

5. With foam in the tanks, it was necessary to recalibrate the gaging system since the tanks hold three to four percent less fuel. The foam also cuts down sloshing.

6. The USAF has run considerable testing with foam. There has been no noticeable effect on microbia growth with foam filled tanks.

7. As for foam fouling of the fuel booster pumps in the tanks, this has not been a problem as it is installed with about 2 inch clearance around the pump inlet.

8. There is no data on fueling time. Fueling rate will depend on system design, interconnections and clear area around the interconnections. Refueling has not been a significant problem.

9. FAA tests of a ruptured tank showed that with small pieces of foam, the foam could come out. With large sections of foam, it is expected the spillage rate would be reduced.

USAF, C141 and C-135 FUEL TANK NITROGEN INERTING TESTS

MR. W. Q. BROOKLEY, USAF

Polyurethane foam has had and will continue to have applications in many Air Force aircraft. Some aircraft, however, because of size or tank configuration make the use of foam impractical due to weight or installation penalties. For this reason other methods of fire and explosion suppression have been explored. The most promising of these suppression systems has been nitrogen inerting. The inerting principle is not new. Experimental systems have been tried on a B-50, a B-36 and a B-52. The B-57, SR-71 and B-70 all used nitrogen inerting systems. Early in 1968 Parker-Hannifin Corporation of Los Angeles, California was contracted to furnish an inerting system for a C-135 and one wing of a C-141. The system had new design features to eliminate problems encountered in the past. Both installations originally were to be made in Aeronautical Systems Division aircraft. Later a higher priority project made the C-141 unavailable. Military Airlift Command (MAC) was requested to fly a service test of a system installed on one of their C-141s. MAC granted the request providing a complete system be installed. This was done. The C-135 was to complete flight test before the start of the service test and was much more thoroughly instrumented than the C-141. Ground testing of components and systems for both aircraft have been completed. The service test of the C-141 has also been completed, but due to a series of delays the flight test of the C-135 is yet to be started.

This discussion provides a summary of the C-141 and C-135 fuel tank nitrogen inerting tests and, test results obtained to this time. Testing yet to be conducted and an explanation of instrumentation installation and operation will be presented.

Formal qualification tests were not required for the two flight test inerting systems. Tests were established to show proper operation of the components and systems and to prove that in no way could safety of flight of the aircraft be jeopardized by the inerting systems. This included normal operations, any type of failure or by affecting aircraft components or structure.

Emphasis was placed on the testing of the vent valve since it was the most critical component in the system and was a newly designed component. Failure of the climb or dive valves to open due to ice was considered the most serious problem. Several severe icing tests were performed to verify that the design was sufficient to prevent failure from icing. In the first test the valve assembly was mounted in an environmental chamber and cooled to +10°F. A fine water mist was sprayed on both sides of the valve. The force to open the unit was measured using a spring gage. The valve was then warmed to ambient, chilled to -65°F, warmed to ambient, and cooled to +32°F. The cracking force was measured at each of the above temperatures. The force required to open the climb valve did not change for any condition. The maximum change in the dive opening pressure was an increase of 0.2 pound from ambient to iced condition. A modification of this test was repeated on the final design vent valves which incorporated auxiliary climb valves. The water mist was sprayed on at 18°F. The valve was warmed to 24°-28°F and cooled back to 18°F where it was held one hour. Ice thickness was approximately 1/16 inch with localized

areas up to 1/8 inch thick. The cracking pressure increased 0.21 psi for the auxiliary climb valve, 0.11 psi for the climb valve, and 0.10 psi for the dive valve.

A second icing test consisted of chilling the valve assembly to -40°F and spraying water onto the surface, forming about 1/32 inch of ice. Again the climb valve cracking force did not change while the dive valve varied 0.1 pound from ambient to iced condition.

A moisture condensate test was performed by placing the valve assembly on a pressure container with lengths of 0.010 inch diameter wire placed across the seats at three equally spaced locations. The assembly was cooled in air to 0°F for one hour, then placed in a humidity chamber and warmed above freezing. The chill-warm procedure was repeated three times. The assembly with condensate was placed in a 25°F air environment for one and one-half hours, then pressure checked. The cracking pressure for both climb and dive valves increased 0.02 psi from ambient to iced condition.

A water soak test was conducted on a valve assembly mounted on a pressure container. The unit was placed in 70°F water for one hour. All parts of the valve were exposed to the water. The assembly was removed from the water and placed in a 25°F air environment for two hours, then pressure checked. Both the climb and dive valves' cracking pressures were 0.06 psi higher in the iced condition than they were at ambient.

Endurance of the vent valve was tested by cycling it up to one hundred thousand cycles with no deterioration of the hinges, springs, or seats.

No testing was required to determine if the climb or dive valves could be failed in the open position because this type of failure would not effect safety of flight. Nitrogen consumption would merely increase should either valve remain open.

The remainder of the components in the inerting system, such as solenoid valves, pressure regulators, etc., were not subjected to any testing to assure safety of flight, since they are state-of-the-art items and because failure mode operation was to be demonstrated during the system tests. All components, including the climb-dive valves, were required to successfully pass individual, calibration and functional testing as specified in applicable military specifications and in the system specification. These tests are shown on the table.

In order to assure the compatibility of an inerting system operation with the aircraft fuel system, performance tests were run on a fuel booster pump and a level control valve during fuel scrubbing. The booster pump performance was improved as shown on graph, and the change in level control performance was negligible.

System operation testing was accomplished on a boiler plate Boeing 707 #2 main fuel tank. The test stand was capable of simulating such phases of

flight as altitude change, fuel consumption, and booster pump operation. Gas samples were taken from 12 locations in the ullage space. Oxygen content of the gas was determined by a Beckman Analyzer with readouts on Sanborn Recorder strip charts. The altitude of the tank and the differential pressure across the vent valve were also recorded.

Many simulated flights were made with the test tank. Flights were made with normal operation of the inerting system, with the scrubbing system inoperative, and while simulating failure modes of all components. A typical flight was: A 36 minute climb to 40,000 feet with 2-minute level offs at 10,000 feet increments; a 30-minute cruise; and a 40-minute descent to sea level. The graph shows the oxygen contents during the flight and shows that there is very little difference in O_2 content in the various locations in the ullage space. The data also indicates the large increase in O_2 concentration without scrubbing.

The limits set for the differential pressure across the vent valve during failure mode operation were set at a positive 1.5 psid and a negative 1.0 psid. These values were well within the tank pressure limits of both the C-135 and C-141. With a pressure regulator failed full open, the ΔP was 0.62 psid. A ΔP of 0.73 psid resulted when the scrub solenoid valve was failed full open and again when the pressurization solenoid valve was failed full open. When the pressurization valve was failed closed and a rapid descent from 40,000 feet was made, the maximum ΔP was a negative 0.8 psid.

Flight tests of the C-141 nitrogen inerting system began on 18 March 1969. The aircraft had basic instrumentation on it. This included ullage space pressure from #1 main, #1 auxiliary, left hand extended range, #2 main, and #2 auxiliary fuel tanks, differential pressure of the left hand vent valve, ambient pressure and dewar quantity and pressure. Lights were used to indicate when the scrub and pressurization solenoids were energized and when the dive valve opened. Aircraft instrument readings were also recorded at the various data points. When it was found that the C-135 flight test was to be greatly delayed, a decision was made to incorporate at least one ullage space sampling capability on the C-141. The location chosen to remove samples which gave the simplest installation, plus representative samples, was the vent line in the center wing dry bay. Accurate sampling could be made during all phases of flight except during descent when GN_2 was introduced into the vent boxes. This location was felt to be especially good during climbs because samples from every section of every tank have to pass through the vents and overboard during climb and because removing samples during a flow condition does not effect the composition of the sample.

A summary of the C-141 test results will be presented. A complete test report is available in ASD Evaluation Report No. ASNJI-20-69-1, dated 24 April 1970. During the service test 53 operating hours and 112 takeoffs and landings were accumulated for inerted flights. Sixty-five (65) flying hours and 170 takeoffs and landings were made uninerted. Total time on the system was 112 hours and 282 takeoffs and landings. No maintenance problems were

encountered with the inerting system during the flight test and only a minor malfunction. The malfunction was the pressure switch on the vent valve being effected by high vibration just before landing and cycling the pressurization solenoid. This has been corrected on a design change by using a pressure regulator and locating it in the fuselage. Fuel tank pressures were maintained within the inerting system design pressures during ground and normal flight conditions. During extreme maneuvers the pressures did not exceed those pressures expected in a C-141 without a nitrogen inerting system installation. Several emergency descents were made, ranging from 8000 to 13,000 feet/min. On one occasion with a large ullage space the dive light came on momentarily.

Oxygen concentration samples taken after several flights using a Beckman Analyzer, showed that the oxygen content varied between 1% and 3% depending on the starting and flight conditions. An analysis of the vapor space was taken directly from two fuel tanks through the over-wing filler neck and the results corresponded reasonably with the vent sampling. Two flights were made with continuous vent sampling. During the first climb of each flight the O_2 concentration went above 11%; for very short periods the first to 15.45%, for approximately 2 minutes, the second to 11.82% for approximately 1 minute. An explanation was found when it was discovered that the aircraft had been fueled into almost empty tanks after long periods of uninerted flight. All testing in the simulated tank had been done after servicing into an inerted tank. The reason for the difference in readings between the two flights is that before the flight with the 11.82% O_2 concentration, the aircraft had had 12 hours ground time after the inerting system had been serviced and the pressurization system had been cycled prior to flight thus diluting some oxygen. On the other hand the flight with the 15.45% O_2 concentration had been serviced with nitrogen just before takeoff and had not had the pressurization system cycled. Because the squadron to which the C-141 was assigned was moving to another base, further flight testing could not be run. To verify the reasoning simulated flights were made on a test stand, however, and the conditions were duplicated. Either servicing into a nitrogen filled fuel tank or extended purging is necessary to maintain an oxygen concentration in the nonflammable region although the short period of time above 11% was considered insignificant. Servicing into inerted tanks requires the least nitrogen and time. If the tanks are uninerted the LN_2 servicing should be accomplished before fueling to fill the tanks with nitrogen.

The much delayed C-135 flight test is now scheduled to begin on 1 August 1970. The progress of the work thus far indicates that this is the most promising date in two years. The instrumentation that will be onboard the C-135 when it flies is as follows:

Vapor space pressure in right hand center wing, #3 main, #4 main and #4 reserve tanks. Taps at highest point of forward wing spar.

Vapor space temperature in right hand center wing, #3 main, #4 main and #4 reserve tanks. Thermocouples are at highest point in tanks near the vent hat beam.

Differential pressure across the climb-dive valves.

Vent ram scoop pressure.

Skin temperature near fog nozzle of #3 main tank.

Fuel temperature in #2 main tank.

Distribution manifold pressure.

Vibration of left hand climb-dive valve - 3 axis.

Booster pump bleed pressure for scrubbing from #3 and #4 main tank cwt aft pumps.

Scrub manifold pressure #3 and #4 main, #4 reserve tanks and center main tank right side.

Internal dewar pressure.

Aircraft static pressure.

Free air temperature.

Gravity.

Voltage signals from pressurization and scrub solenoid and both dive valves.

Event marker.

Tank oxygen content from left-hand center wing, #1 main, #2 main and #1 reserve tanks.

All standard engine instruments.

Engine fuel pressure direct reading.

Vapor sampling lines temperature and pressure direct reading.

The samples to determine oxygen concentration will be taken from the outboard section of each tank next to the vent "hat" section as shown on the drawing. This location keeps the sampling tubes in the ullage space the majority of the time and takes a sample that is least affected by vent flows, fog nozzle injection, baffles, etc. The sampling lines are quarter inch tubing which run from each tank to the instrumentation table in the cargo compartment. Here each line has a shutoff valve. Down stream of the shutoff valves, the lines are manifolded together. The gas for analysis will be taken from this manifold from one tank at a time. The manifold is vented overboard.

This method of sampling is considered good because readings are available immediately and conditions which may cause any variances in readings can be assessed at the time. The chance of getting an erroneous reading because of leakage is eliminated because the pressure in the sample line is higher than the outside pressure so that any leakage will only result in loss of some gas but will not change the mixture. The use of vacuum bottles was considered, but because of the complicated installation and the chance of leakage into the bottle on descent to sea level, they were rejected. The inlet conditions of the sampling line in the tanks are the same regardless of what method is used since the gas is caused to flow by introducing a lower pressure. An attempt is being made to incorporate a traversing probe in the right-hand center wing tank.

The oxygen concentration of the sample gas will be determined using a mass spectrometer gas analyzer. The spectrometer to be used is a modified Aero Vac Model 370 which has a mass range of 2 to 300 AMU. This analyzing technique has the capability of providing precise data regardless of tank pressure. The modification to the 370 was the installation of an ion pump in place of an oil diffusion pump. This was done to adapt the unit for flight. The schematic shows the mass spectrometer installation. The inlet is a small Hone Vernier needle valve. The mechanical pump maintains a flow of the sample past the gas analyzer inlet at a pressure of approximately 200 microns. This flow is controlled by the needle valve. A portion of the flow is diverted through the spectrometer for analysis by the ion pump operating at a pressure of 10 -6 torrs. The flow through the gas analyzer is controlled by the main throttle valve. As the gas enters the analyzer it passes through a filament which is emitting electrons under control of an emission regulator. The electrons ionize the gas molecules present by bombardment. Ions of each specie are produced in quantities directly proportional to the total amount of each molecular species present. The ions are then focused and accelerated as a beam through a magnetic field. The magnetic field deflects each ion according to its mass. This causes ions of different masses to follow curved paths of different radii. The effect is much the same as passing light through a prism to separate the colors of the spectrum. The molecules in each path are focused on the collector at the end of the spectrometer tube where they are counted and converted to a signal for readout either on a strip chart or an oscilloscope. A slow scan can be set to read out all or part of the elements within the sensitivity of the unit on the strip chart. A fast scan can be used to view several elements at one time on the oscilloscope. If desired, one element can be selected for continuous readout. The chart shows a typical spectrum strip chart recording. The size of the peaks are not directly related to the percent of the elements in the mixture, but the ratios of the size of the peaks will always be the same for a given composition. It has been necessary to perform calibration tests for a range of O_2, N_2, and hydrocarbon vapor combinations. The other elements will be insignificant and are not being included in the calibration tests.

The C-135 flight test program is scheduled for ten flights of four hours each. More testing can be done concurrently with another project which is

installed on the aircraft if necessary. Fuel samples will be taken before and after each flight. The first flights will be to obtain baseline data. The inerting system will not be serviced or activated. All parameters will be recorded for the following conditions:

a. Static aircraft - engines off.

b. Engines running from idle to max. power.

c. Normal takeoff and climb to 35,000 feet with a level off at 10,000 feet increments for stabilized readings.

d. Normal descent.

e. Maximum climb until readings stabilize.

f. Emergency descent until readings stabilize.

g. Standard flight maneuvers - turns, slips, slow flight, etc.

h. Extreme flight maneuvers - approach to stalls, steep turns, unusual positions, etc.

i. Normal approach and landing.

j. Maximum performance takeoff.

k. Emergency return to field.

The next flights will be performed with the inerting system serviced and activated but the scrub system disconnected. The procedures of (a) through (e) of the baseline flights will be repeated. The next flights will be with normal operation of the inerting system. All the procedures of the baseline flights will be repeated. All tests will be run two or more times to establish repeatability. Each flight will be started with essentially unscrubbed fuel. At least two takeoff and climbs will be made after servicing into uninerted fuel tanks. Preflight and postflight inspections will be made of the system for each flight. An attempt will also be made to take readings during refueling.

While the C-135 flight tests will provide invaluable information on fuel tank inerting, the Air Force considers that the data obtained to date is sufficient to warrant the incorporation of systems in its aircraft. Testing has proved that an oxygen concentration well below the flammability limit of 11% can be maintained during all phases of flight and ground operation following prescribed methods. The flammability and spontaneous ignition limits have been well established by such organizations as the Bureau of Mines, USAF Laboratories, Royal Aircraft Establishment, Boeing Aircraft Company and many more. The Air Force has lost many aircraft and lives due to fires both in flight and on the ground. A study of several of these fire losses showed

that the savings that would have been realized with an inerting system would have paid a large percentage of cost to retrofit the entire fleet of similar aircraft with systems. The saving of lives by preventing secondary explosions after crash is also a big consideration in favor of nitrogen inerting.

The use of nitrogen for inerting appears to be a favorable method for the Air Force since liquid nitrogen can be made readily available wherever its aircraft go and handling of LN_2 has progressed to the point where it is comparable to servicing jet fuels. The many uses of nitrogen besides inerting makes it desirable to have on board aircraft. Liquid nitrogen can be used for refrigeration, fire extinguishing and avionics or be converted to gas to inflate landing gear struts, tires and accumulators.

The Air Force has also had a great deal of trouble with water in the fuel tanks. The water affects fuel quantity probes and causes microorganic growth and corrosion. Nitrogen inerting will prevent most if not all of this.

Another factor the maintenance people look at is the ability to put an inerted aircraft into a hangar without long purging cycles. Maintenance can even be performed in the tanks with the use of breathing apparatus without draining, drying and airing the tanks.

MAC has submitted a Required Operational Capability (ROC) to have the entire C-141 fleet nitrogen inerted. The ROC has been cleared through all commands and the Pentagon. A Requirements Action Directive (RAD) is to be prepared and when this is completed it will go for funding. MAC will submit ROCs for the C-5 and the C-9 if funding for the C-141 is provided.

Resume of Discussion Following Mr. Brookley's Presentation

1. Reference was made to the cost of installing a liquid nitrogen system versus the cost of the loss of a single aircraft. Mr. Brookley advised he could give examples for US Air Force aircraft and that the cost per aircraft would reduce with a greater number of aircraft installations. Also it would be difficult to evaluate cost of installation versus cost of life.

2. The oxygen content necessary for combustion decreases with increase in temperature to about 2½% at 800° F. However, at this condition, the force of the reaction is reduced 50 times.

3. For a normally vented C-141 aircraft in maximum climb or descent, the pressure went no higher than 0.7 to 0.8 psi.

4. Fueling into an inerted tank is safest and is not difficult to do as the tanks can be serviced with LN_2 before fueling. As fuel level goes up, the nitrogen is forced out but the tank would be inerted.

5. Inerting is a simpler system than cabin pressurization.

6. As for an oxygen analyzer, from the USAF viewpoint, this would only be needed in setting up the system. Once the system has been checked out, it will not be necessary to monitor the oxygen content.

OXYGEN DILUTION REQUIREMENTS FOR INERTING AIRCRAFT FUEL TANKS

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INTRODUCTION

Various inerting methods have been proposed to protect against explosions in aircraft fuel tanks. One of the earliest methods proposed was the use of bottled inert gases,[8/] such as nitrogen (N_2) or carbon dioxide (CO_2), to render fuel vapor-air mixtures in the tank nonflammable. Recently, liquid N_2 systems have received the most attention and have been reported to perform satisfactorily under flight conditions.[11/] Other inerting methods suggested for this application include the use of the exhaust gases from an aircraft engine,[8,9/] vaporizable flame inhibitors that are added to the liquid,[10/] and inert gas generators that consume the available oxygen in the fuel tank.[8,13/] An important quantity in defining the inerting or dilution requirements is the minimum oxygen concentration (Min O_2) below which flame propagation will not be sustained. Such information is available for aircraft fuels[12/] and for various hydrocarbons and other fuels.[2,15/] This paper briefly reviews the effectiveness of various inerting agents to prevent ignition and flame propagation in hydrocarbon fuel-air systems. In this connection, data are presented on the variation of limits of flammability, minimum ignition energies, and minimum autoignition temperatures (AIT's) with oxidant or diluent concentration. The potential explosion hazard that may be

encountered over a range of flight temperatures and pressures is discussed, and guidelines are given for specifying safe oxygen concentrations for aircraft fuel tanks.

1. Inerting Requirements to Prevent Flame Propagation

To provide effective inerting, it is necessary to prevent the formation of fuel vapor-oxidant-diluent mixtures which can sustain flame propagation when they are ignited. In atmospheric air under equilibrium conditions, a typical Jet B fuel like JP-4 can form flammable vapor-air mixtures at temperatures between about -10° and 60°F, compared to values of about 110° and 180°F or higher for a Jet A type kerosine. The concentration limits of flammability which correspond to such temperature limits are narrowed by the addition of an inert gas, particularly by the lowering of the fuel-rich limit. In this connection, flammability diagrams such as that shown in figure 1 for JP-4 are useful in predicting the complete range of possible flammable mixture compositions. According to the Bureau of Mines data[15/] in figure 1, the minimum amount of inert gas to prevent the formation of flammable JP-4 vapor-air mixtures at 80°F (1 atm) is approximately 29 percent with CO_2 and 43 percent with N_2; the corresponding minimum O_2 values below which flammable mixtures will not form are 14.3 percent with CO_2 and 11.5 percent with N_2. These inerting requirements are typical of those expected in normal flame propagations with most hydrocarbon fuels. As noted in figure 2, the minimum O_2 values for several paraffin hydrocarbons, a 100/135 octane gasoline, and a JP-3 jet fuel are between 14 and 15 percent with CO_2 inerting and between 11 and 12 percent with N_2 inerting.[4/] Ignitions of near-limit mixtures under confinement can easily produce damaging

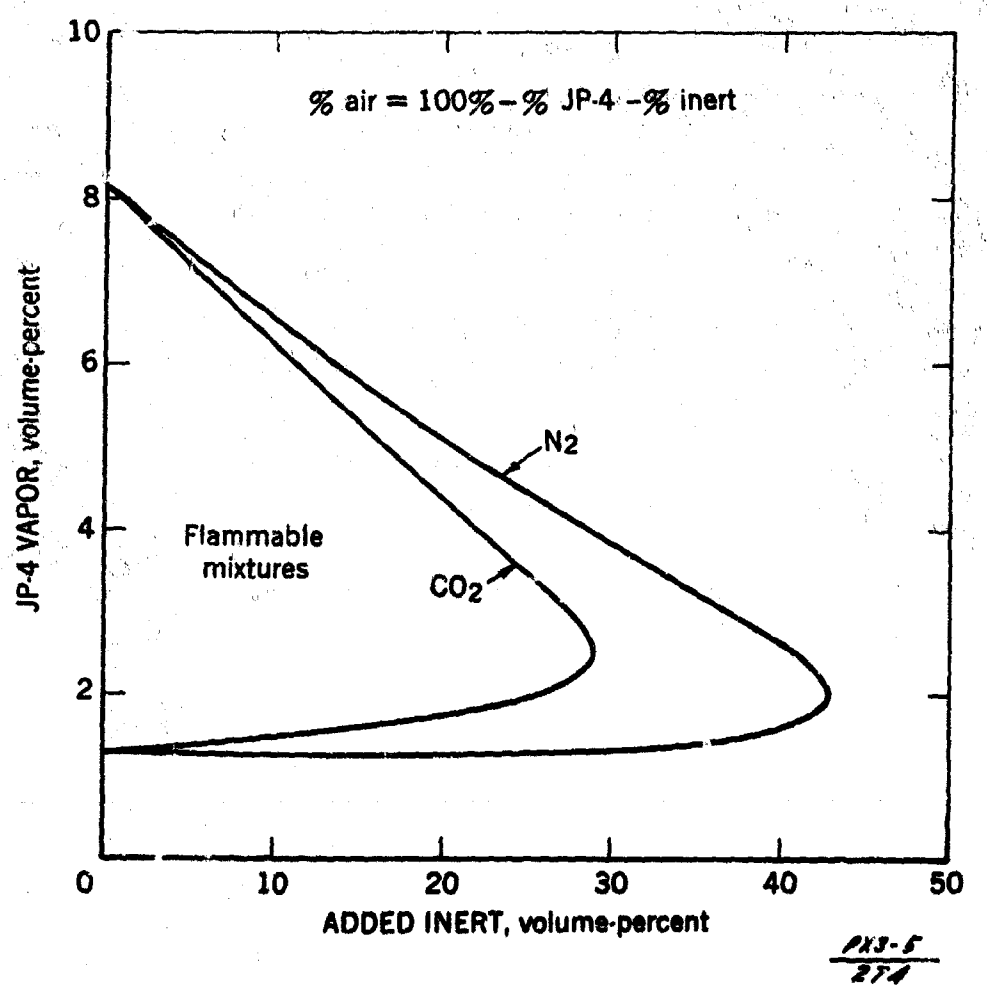

Figure 1. - Limits of Flammability of JP-4 Vapor-Nitrogen-Air Mixtures at 80° F and Atmospheric Pressure.

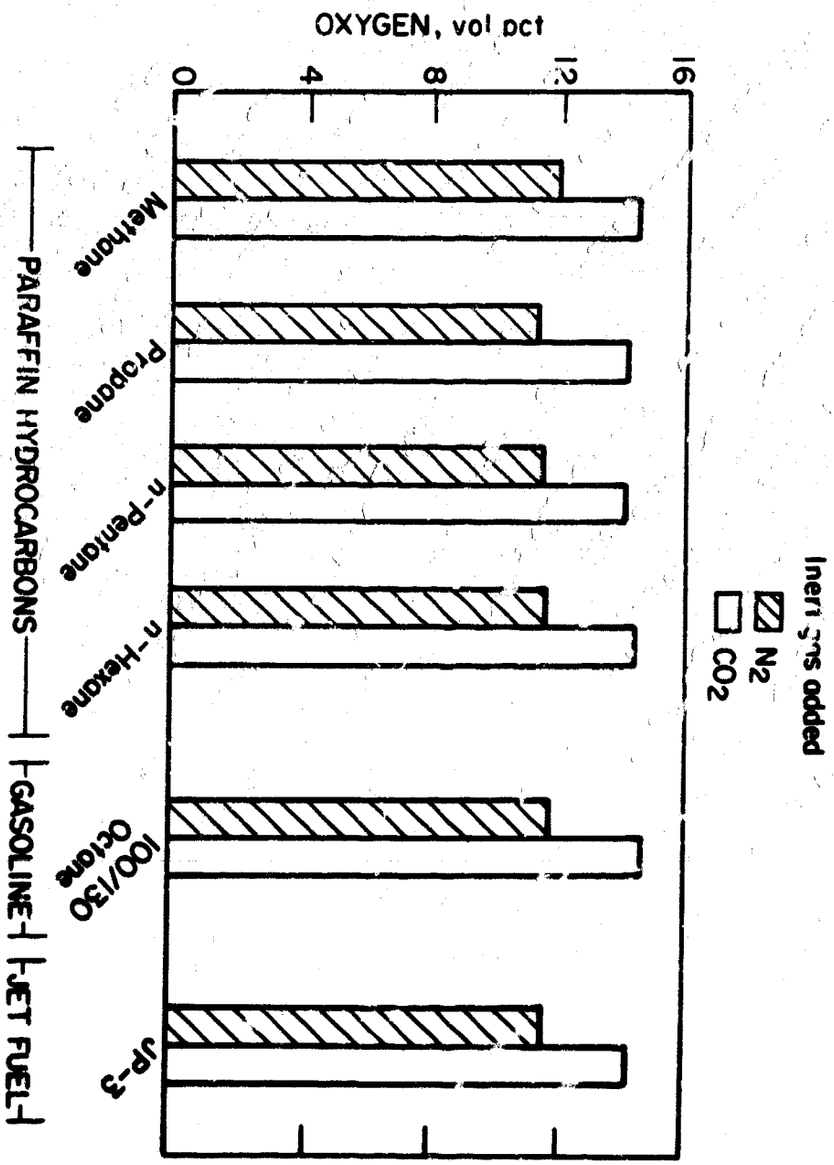

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Figure 2. - A Comparison of Minimum Oxygen Concentrations Required for Flame Propagation in Various Combustible Vapor-Air Inert Gas Mixtures at 80°F and Atmospheric Pressure (constant pressure apparatus).

pressures since the minimum temperature at which many hydrocarbon flames can be sustained is of the order of 2400°F, depending upon the diluent.

The limits of flammability of hydrocarbon fuel-air mixtures do not vary greatly with decreasing pressure, providing the vapor pressure of the fuel and ignition energy are not limiting factors. Thus, their inerting requirements also should not be greatly sensitive to a reduction in pressure. Table 1 summarizes minimum O_2 data that have been reported for several hydrocarbon fuels at various pressures.[4,12] The variations between the two sets of data listed for JP-4 with N_2 or CO_2 inerting can be attributed to differences in ignition source energy, test vessel size, and the flammability criteria. The lower minimum O_2 values reported by Stewart and Starkman were obtained in a 12-1/2 ft^3 tank using several 3-joule spark sources, as compared to a 2- or 4-inch-diameter vessel with a single spark source that was used in the Bureau work. With the more severe ignition source, it appears that the oxygen content of JP-4 vapor-air mixtures must be reduced to below about 10 percent at atmospheric pressure and below about 13 percent at a pressure of 2.13 inches of mercury, or an altitude of 60,000 feet, to inert the mixtures with N_2; the critical O_2 values with CO_2 as the inert were significantly higher, as expected. In this latter work, the appearance of any flame was taken as evidence of a flammable mixture and the pressure rises may have been only a few pounds per square inch. Thus, the reported limits are expected to be lower than normal flammability limits which define the mixture concentrations that can sustain flame propagation beyond the ignition source.

TABLE 1. - Minimum Oxygen Requirements for Flame Propagation With Various Fuels in Air-CO_2 and Air-N_2 Atmospheres.

Fuel	Press. in Hg	Press. Altitude ft	Temp. °F	Minimum O_2 Values, Vol. Percent CO_2 Inert	N_2 Inert
JP-1 1/	29.3	0	300	13.9	10.5
JP-1 2/	3.44	50,000	140	14.8	12.7
JP-3 1/	29.3	0	75	14.3	11.8
JP-4 1/	29.3	0	75	14.3	11.5
	15.0	18,000	75	14.5	11.4
	8.0	32,000	75	14.6	11.7
	4.0	47,000	75	14.9	12.4
JP-4 2/	29.3	0	70	12.5	9.8
	13.75	20,000	70	13.2	10.4
	5.54	40,000	70	14.1	11.3
	2.13	60,000	70	15.7	13.3
Av Gas 100/130 3/	29.3	0	80	14.8	11.9
Motor Gas 3/	29.3	0	80	14.7	11.5
Kerosine 3/	29.3	0	300	13.0	9.9
Benzene 3/	29.3	0	300	13.1	10.0

1/ Data from reference 4, single spark source.
2/ Data from reference 12, multiple spark source.
3/ BuMines unpublished data.

Where the fuel is in the form of a spray or mist, the minimum O_2 values are greater than with fuel vapor mixtures. Data that were obtained for JP-4 and Avgas (115/145) sprays in air-N_2 and air-CO_2 atmospheres are compared in figure 3. These data show that the minimum O_2 values for sprays of such fuels tend to increase greatly when the pressure is reduced below some critical value ($\sim$7.5 in Hg). Similar results would be expected with low volatility fuels like Jet A, although the minimum ignition energies of their sprays at a given temperature would be higher than those for high volatility fuels.

Since high flash point fuels like JP-1 and Jet A do not form flammable vapor-air mixtures at room temperature, their inerting requirements can be evaluated only at elevated temperatures or reduced pressures. Available data indicate that the amount of oxygen dilution required to inert JP-1 vapors in air-N_2 or air-CO_2 mixtures is comparable to that needed for JP-4 vapor-air mixtures; table 1 includes minimum O_2 data for JP-1 at atmospheric pressure (300°F) and at a reduced pressure of 3.44 inches of mercury (140°F). Considering that the lower limits of flammability of hydrocarbon vapor-air mixtures and their limit flame temperatures ($\sim$ 2400°F) vary only slightly with N_2 or CO_2 dilution, the effect of temperature on minimum O_2 values should be predictable from that observed on lower flammability limits. Accordingly, the expression suggested by Zabetakis[15/] for lower limits may be applied for predicting the minimum O_2 values at various temperatures (T):

$$\frac{(\text{Min } O_2)_T}{(\text{Min } O_2)_{77°}} = 1 - 0.00040\ (T-77) \qquad (1)$$

where T is in °F.

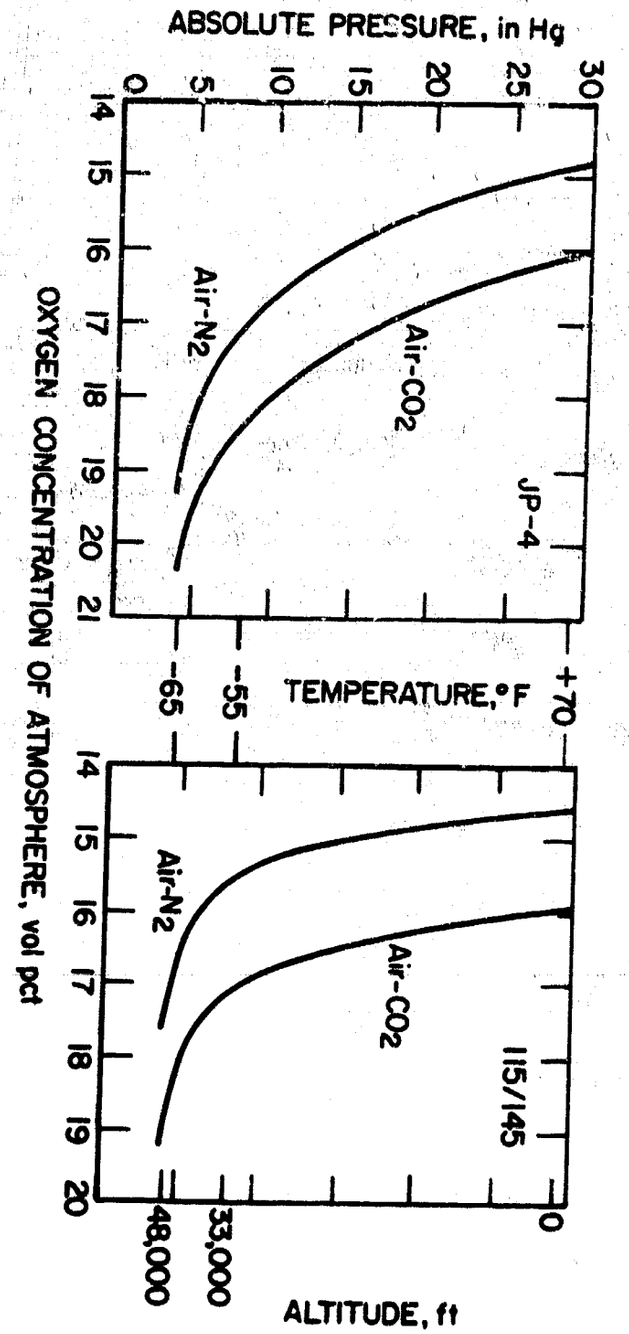

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Figure 3. - Minimum Oxygen Concentrations Required for Flame Propagation of JP-4 and Avgas 115/145 Sprays in CO_2 and N_2 Vitiated Atmospheres.

The effects of other inerting gases such as helium or argon are generally less than that of N_2, whereas that of water vapor or engine exhaust gases tends to be between N_2 and CO_2. Differences in heat capacity or thermal conductivity can account for the observed variations in their inerting ability. In comparison, certain halogenated hydrocarbons are substantially more effective than the above inerting agents. This is illustrated in figure 4, which shows the range of flammable mixtures for gasoline (73-100 octane) in atmospheric air with various inert gases and halogenated hydrocarbons.[2/] As noted, approximately 42.5 percent N_2 (11.6% min O_2) must be added to the air to eliminate flammable mixtures, compared with only 11 percent with an inhibitor such as fluorotrichloromethane (17.2% min O_2). One of the most effective flame inhibitors is bromotrifluoromethane (Halon 1301); a 6.6 percent concentration is reported to be adequate for inerting JP-4 vapor-air mixtures.[7/] The greater effectiveness of chemical flame inhibitors is attributed to their ability to form free radicals that inhibit the chain branching reactions in a flame. It is also believed that the chemical inhibitors increase the temperature required to sustain a flame of a hydrocarbon vapor-air mixture, whereas the inert gases have a small effect on the limit flame temperature. This is supported by ignition temperature data obtained with jets of hot gases. For example, the minimum ignition temperature of a stoichiometric ethane-air mixture is about 1550°F with a hot nitrogen jet and increases to over 2000°F when a few percent of Halon 1301 are added to the nitrogen jet.

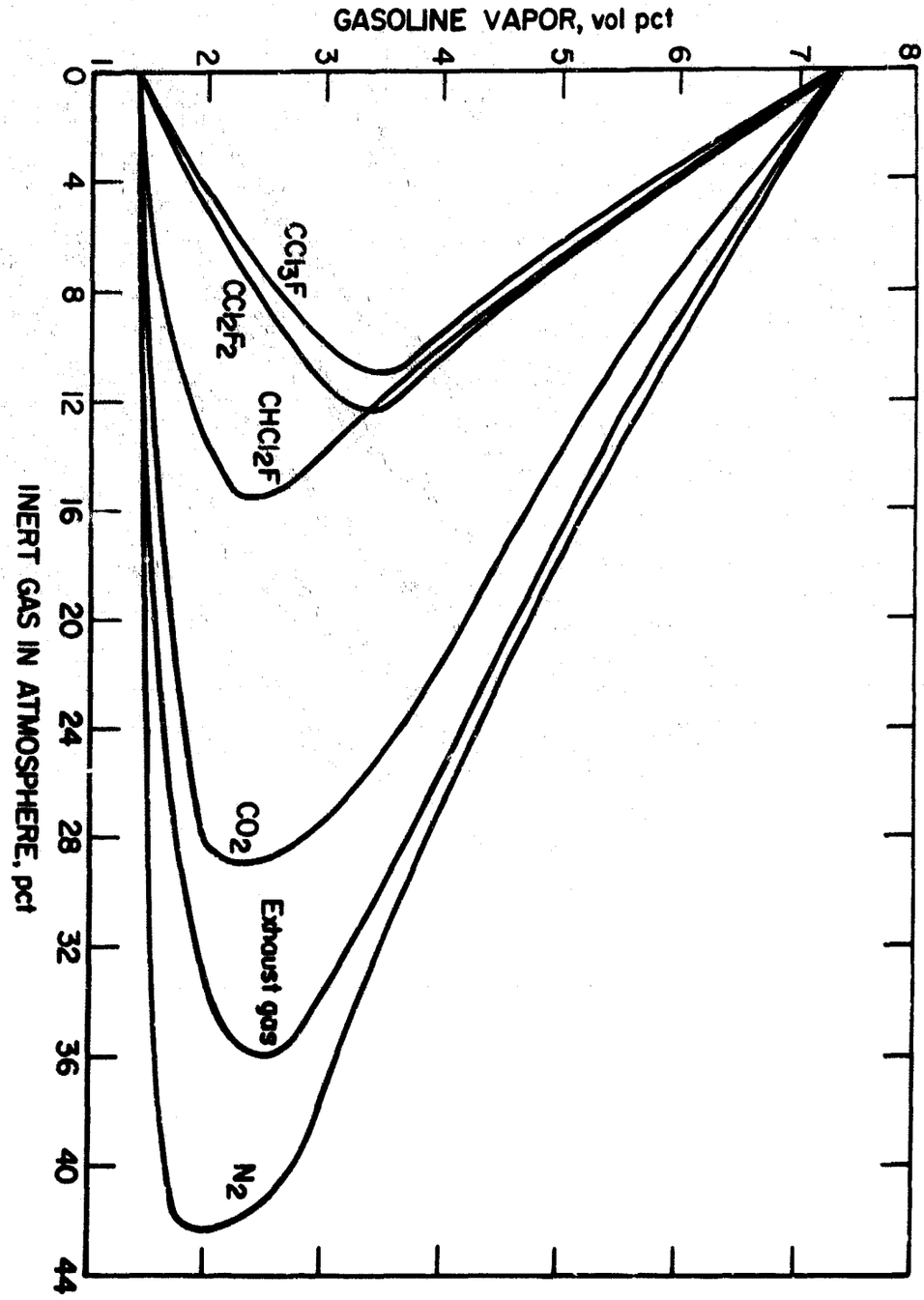

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Figure 4. - Limits of Flammability of Gasoline Vapor in Air With Various Inert Gases and Halogenated Hydrocarbons at 80°F and Atmospheric Pressure.

2. Effect of O_2 Concentration on Spark Ignition Energies

Since flammability limits can vary with the ignition source energy, it is of interest to examine the minimum spark energies required for the ignition of flammable fuel vapor-oxidant-diluent mixtures. The minimum spark ignition energy for the optimum fuel vapor-air mixtures of most hydrocarbon fuels is about 0.25 millijoule at atmospheric pressure. It can be assumed that the energy discharge ($\leq$ 15 mj) which can occur from accumulation of static electricity on a human being would be sufficient to ignite such mixtures, as well as many other mixtures at less optimum fuel-oxidant ratios.[14/] Ignition energies ordinarily increase with decreasing ambient pressure and oxygen concentration, as shown for propane in figure 5. These data are taken from reference 6 and are typical of those found for other hydrocarbons, although their optimum fuel-oxidant ratios for ignition are not the same. For example, minimum ignition energies in air at atmospheric pressure occur at equivalence ratios ($\emptyset$) of 0.9 for methane, 1.3 for propane, and 1.8 for n-heptane, where $\emptyset$ is equal to 1.0 for a stoichiometric mixture.

Because of the diluent effect, ignition energies are higher in O_2-N_2 mixtures than in O_2 even when the oxygen partial pressure is the same. Also, they are maximum at the minimum O_2 concentration required for flame propagation, although the data are meager at such conditions. Data reported for methane-O_2-N_2 mixtures at 1/3 atmosphere pressure show about a 4-fold increase in the minimum ignition energy when the O_2 concentration is decreased from 21 to 17 volume percent.[6/] The flammability

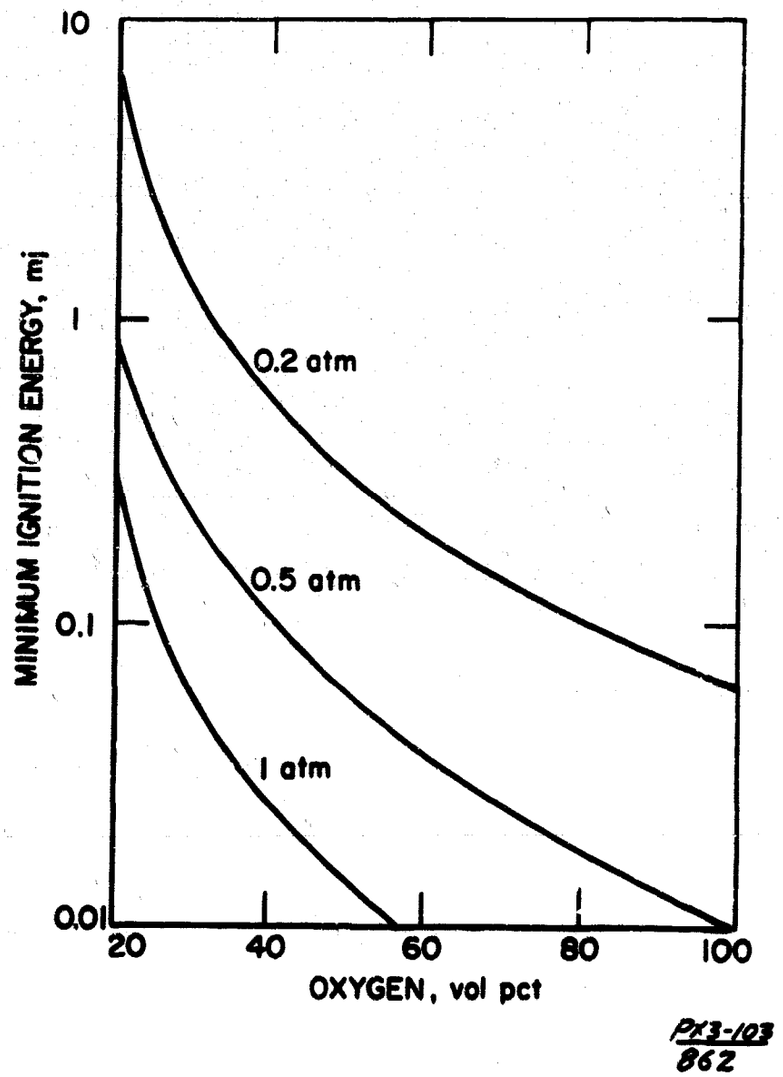

Figure 5. - Variation of Minimum Spark Ignition Energies With Oxygen Concentration for Propane-Oxygen-Nitrogen Mixtures at 0.2, 0.5, and 1 Atmosphere Pressures.

experiments of Stewart and Starkman with JP-4 vapor-O_2-N_2 mixtures (1 atm) also provide an indication of the magnitude of ignition energy required at low O_2 concentrations. For example, although at least partial flame propagations were observed at an O_2 concentration of 9.8 percent using fourteen 3-joule spark sources, no ignitions were possible below this O_2 value using 6-joule sources or a total of 84 joules. In the event fuel-air sprays or foams were present at such critical O_2 values, the possibility of ignition would be even more remote because of the much higher energies that would be required.

3. Effect of O_2 Concentration on Autoignition Temperatures

The autoignition temperature (AIT) hazard associated with fuels in a heated tank is also influenced by the O_2 content of the tank atmosphere, although varied results are frequently reported because of apparatus effects. Variations in mixture composition are not expected to produce the same effect in autoignition as in spark ignition, largely because of the much shorter heating times (μ seconds) in spark ignition and its dependence upon the magnitude of energy input instead of temperature. The minimum AIT's of most jet fuels are about 450° ± 25°F in air at atmospheric pressure, when the appearance of flame is taken as evidence of ignition. At reduced pressures or O_2 concentrations, the AIT values can vary noticeably with the vessel dimensions and ignition criteria.

For jet fuels like JP-6, the variation of AIT with O_2 content and total pressure of the O_2-N_2 atmosphere correlates reasonably well with the oxygen partial pressure, whereas minimum ignition energies for hydrocarbon fuels do not give such a correlation. Figure 6 shows the JP-6 AIT data which were obtained in 2000 cc vessels with optimum fuel-oxidant

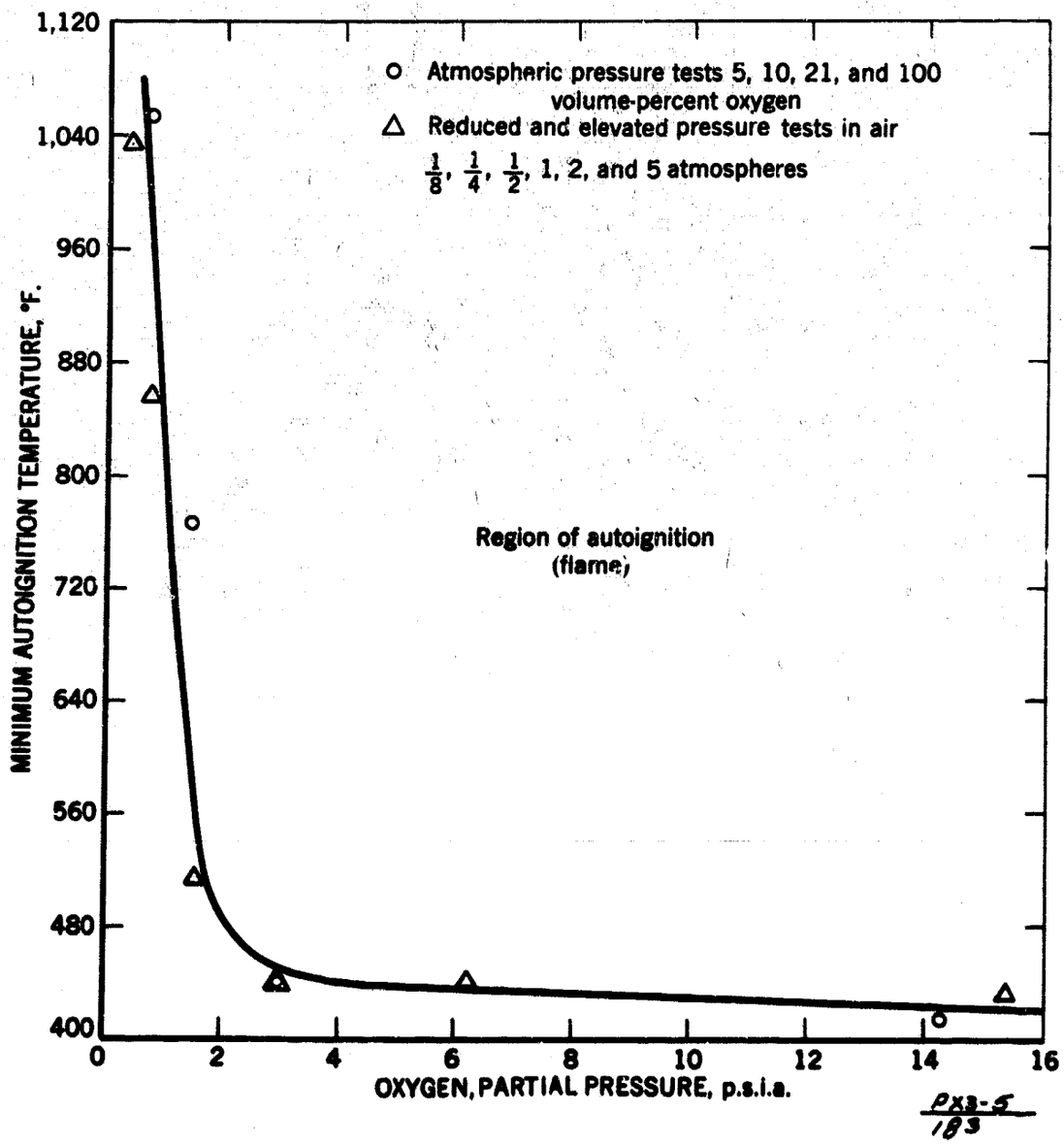

Figure 6. - Effect of Oxygen Partial Pressure on the Minimum Autoignition Temperature of JP-6 Fuel-Vapor-Oxygen-Nitrogen Mixtures at Various Initial Pressures.

concentrations and visible flame as the ignition criterion.[5/] The pressure rise ratios (P_2/P_1) observed at each minimum AIT were above 1.3 in the experiments made in air at various pressures and in an O_2-N_2 atmosphere with 10 percent O_2 (1 atm); with 5 percent O_2 at atmospheric pressure, the P_2/P_1 was about 1.2 at a temperature of 1055°F and flame was barely visible to the naked eye. Other experiments performed in a much larger vessel (572 cubic inches) but at a temperature of only 500°F also indicated that little reaction can be expected in heating JP-4 in highly oxygen deficient air;[5/] maximum temperature rises of less than 50°F occurred in atmospheres with less than 10 percent O_2. Similar results have been obtained by other investigators[3/] with JP-4 and JP-6 vapor-O_2-N_2 mixtures at temperatures up to 550°F; as noted in table 2, 4 percent fuel mixtures with between 4 and 16 percent O_2 reacted at 500 mm Hg to give very low pressure rises.

TABLE 2. - Pressure Rise Data from Autoignition Experiments With 4 Percent JP-4 and JP-6 Fuel Vapor-Air-Nitrogen Mixtures at 500 mm Hg Pressure (P_1) and Temperatures Between 400° and 550°F.[1/]

Total Nitrogen Vol.%	Total Oxygen[2/] Vol.%	P_2/P_1 JP-4	P_2/P_1 JP-6
76	20	3.6	>2.2
80	16	1.06	1.10
88	8	1.04	1.01
92	4	1.01	None

1/ Data from reference 3.
2/ Approximate values.

Considering the minimum O_2 data from flammability experiments with JP-4, it is not surprising that such low pressure rises occurred in the above experiments with highly O_2 deficient air. Since the minimum O_2 value would not be less than about 9.3 percent at a mixture temperature of 550°F, mixtures with a lower O_2 content at this temperature would not be capable of normal flame propagation and insignificant pressure rises would result, as was observed above; the 9.3 percent value is calculated by the use of equation (1) using the Bureau's value of 11.5 percent for JP-4 at 75°F.

4. Flight Considerations

During a flight of an aircraft, the hazard of forming flammable fuel vapor-air mixtures in a fuel tank will vary with temperature, pressure, vent conditions, and the vapor pressure of the fuel. In a typical flight to a cruise altitude of 30,000 feet,[1/] a Jet A fuel (110°F Flash Point) initially at 100°F could form flammable vapor-air mixtures under equilibrium conditions during the climb or early stage of the flight; also, it would be capable of forming flammable mists during the entire flight. A Jet B fuel (-10°F Flash Point) under the same temperature conditions would normally form vapor-air mixtures too fuel rich to be flammable, except during the descent stage; however, such mixtures could fall into the flammable range as a result of air enrichment due to tank "breathing" or oxygen enrichment due to the release of oxygen dissolved in the fuel. If the fuels were initially at a lower temperature such as 0°F, Jet B would be able to form flammable vapor-air mixtures during the entire flight, whereas Jet A would be below its flash point. Nevertheless, equilibrium conditions cannot be relied upon in predicting whether flammable

vapor-air mixtures exist in the fuel tank, because of the dynamic conditions encountered in flight.

Since flight conditions can vary greatly, the inerting requirements must provide protection over a wide range of temperatures and pressure altitudes. According to the available flammability data, aircraft fuel tanks initially at 100°F can be protected against explosions by maintaining the O_2 concentration below 10 percent with N_2 or below 12.5 percent with CO_2. These values are applicable to both Jet A and Jet B type fuels and are based on data obtained with a severe ignition energy source. At significantly higher temperatures than 100°F, the values would be lower as approximated by equation 1 in this paper. To provide some margin of safety, the minimum O_2 values should be reduced by a factor of 20 percent. The added safety factor is needed particularly to guard against cool flames or weak ignitions.

Although CO_2 is more effective than N_2 as an inert on a volume basis, it is less attractive on a weight basis. CO_2 is also more soluble in hydrocarbon fuels than N_2. For example, the absorption coefficients of these gases indicate that CO_2 is 10 to 40 times more soluble than N_2 in 100 octane fuel, depending upon temperature.[8/] Another disadvantage of CO_2 is that freezing problems can occur when the demand is great and high flow rates are required. Because of the greater effectiveness of chemical flame inhibitors, methods should be explored to determine the feasibility of using a nitrogen-chemical inhibitor system; Halon 1301 is one possibility although its solubility in a jet fuel at flight temperatures may be a great limitation.

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Resume of Discussion Following Mr. Kutchta's Presentation

A question was raised concerning the significance of small pockets of flammable vapor in an otherwise inerted tank. Mr. Kutchta advised that designers should try to prevent such pockets, however, if the pocket is less than 10% of the volume of the ullage space, it is considered small and would not likely be detrimental.

IN-FLIGHT CONTROL OF POWERPLANT FIRES WITH LIQUID NITROGEN

MR. EUGENE P. KLUEG

INTRODUCTION

The availability of large quantities of cryogenic nitrogen aboard commercial aircraft for inerting fuel tanks may make other application of the nitrogen feasible. One such application is the use of liquid nitrogen (LN_2) for extinguishing powerplant fires. At the request of Flight Standards and Aircraft Development Services of the FAA, a project was initiated in August 1968 to investigate the extinguishing properties of cryogenic nitrogen and to determine the best method of using it in an installed fire extinguishing system. The first phase of testing under this project was initiated in September 1968 and completed in November 1968. The results of the first test phase are contained in Propulsion Section, NA-542, Data Report No. 54 dated April 1969. The results generally indicate that (1) LN_2 is effective in extinguishing fires in aircraft powerplant compartments, (2) the quantity of LN_2 expected to be available from an LN_2 fuel tank inerting system would be sufficient to extinguish the fires, and (3) on aircraft where a large quantity of LN_2 is available, an LN_2 fire extinguisher system could provide greater in-flight powerplant fire protection than the limited quantity of agent available in a conventional high rate of discharge extinguisher system.

A second phase of testing was initiated in September 1969 and is expected to be completed by July 1970. This phase is intended to develop design and evaluate criteria by experimentally establishing the requirements for an effective extinguishing system as influenced by nacelle ventilation and free volume and in terms of agent quantity, discharge rate, discharge conditions and distribution provisions. The effects of an inadvertent discharge, damaged cowling, and the cooling of potential reignition sources are also being investigated under this phase. The work described here summarizes the findings to date resulting from these efforts and discusses current areas of investigation.

Like carbon dioxide, the effectiveness of LN_2 in extinguishing fires is dependent upon (1) cooling to reduce the temperature of the combustible below its ignition temperature or the point at which it vaporizes and (2) oxygen dilution to the level that will no longer support combustion. A comparison of the physical properties of LN_2 carbon dioxide and the two most common halogenated fire extinguishing agents (CBr_2F_2 and $CBrF_3$) currently in use on U. S. Military and commercial aircraft is made in Table 1. Since nitrogen at atmospheric pressure has a lower boiling point than the other three agents and a higher heat of vaporization than the two halogenated agents, the amount

of cooling during an LN_2 discharge can be expected to be significantly greater when compared on a weight basis. Likewise, since the expansion ratio of nitrogen when converted from a liquid to a gas is considerably higher than the other three agents, nitrogen produces the greatest amount of oxygen dilution. The overall effectiveness of LN_2 as a fire extinguishing agent cannot be expected to be as great as the highly effective halogenated agents, however. These agents do not depend primarily on cooling and oxygen dilution, but on a chemical interference with the combustion process. The lower effectiveness of nitrogen does not eliminate it from consideration as a fire extinguishing agent on aircraft where large quantities can be made available from the reserve supply of LN_2 stored for inerting fuel tanks and other purposes.

DISCUSSION

The effectiveness of LN_2 as a fire extinguishing agent is being investigated at the FAA's test facilities near Atlantic City, New Jersey. Tests are being conducted in two wind-tunnel-type facilities. One facility (Figure 1) simulates the subsonic low altitude flight conditions around an instrumented Number 2 Jet Star powerplant installation (Figure 2). Liquid nitrogen extinguisher systems were developed and used in this facility to extinguish test fires in the compressor and accessory compartment of the Jet Star's JT-12 turbojet powerplant nacelle. An LN_2 storage container and distribution system are illustrated in Figure 3. LN_2 was routed from the cryogenic container by operating a control valve, through one-inch tubing; and discharged into the nacelle through either four fog nozzles or open-end tube systems.

The second facility shown in Figure 4 is a boiler plate mockup of an engine nacelle. Outside air is drawn into the tunnel circuit by an axial-flow fan and fed through a perforated plate into the test section. The air flows through the annular passage formed by an elliptically-domed cylinder positioned within a larger cylinder to simulate a cowled engine. The airflow through this annulus is broken up by ribs installed alternately on the outer and inner cylinders. The air exits the test section through a perforated ring into the exhaust section of the tunnel. The volume of the test section can be varied by positioning the perforated ring fore or aft on the inner cylinder. The LN_2 extinguisher systems used in both facilities were similar. LN_2 was discharged into the second facility through either open-end tube systems or a perforated tube system. In both facilities, no attempt was made to optimize the type of discharge and the distribution within the test compartments.

The nitrogen was stored under pressure as a saturated liquid. All of the test fires to date resulted from spray releasing and spark igniting JP-4 jet fuel. The test fires were located in a remote area relative to the discharge location to prevent localized high concentration of nitrogen in the area of the fire.

Typical minimum nitrogen requirements for extinguishment are shown in Table 2 for low and high airflows. The effectiveness of LN_2 appeared to be primarily a function of the rate at which it was applied to the fire, not the discharge time or total quantity utilized. The type of discharge was not critical from the standpoint of effectiveness. The open-end tube type of discharge was as effective as the fog discharge.

The LN_2 discharge rate requirements for the perforated tube system were 10 to 40 percent less than the open-end tube system. As the free volume was reduced from 53 to 40 cubic feet, the LN_2 discharge rate required for extinguishment decreased by 30 to 45 percent.

A cooling effect was apparent during the nitrogen discharges. For example, ambient temperatures in the Jet Star installation at a location remote from the fire and not in line with the LN_2 discharge were initially approaching 600°F (Figure 5). After releasing nitrogen for 7 seconds at a rate of 1 lb/sec. the temperatures were lowered to 150°F. Likewise, small metal components were cooled by the nitrogen. For example as shown in Figure 6, 41-gage twisted safety wires remotely located relative to the LN_2 outlet in the Jet Star installation were heated to temperatures of 1400°F by test fires. The wire cooled to 500°F in 5 1/2 seconds during a 2.8 lb/sec discharge of nitrogen. The time required for the wire to reach this temperature under conditions of normal cooling following a fire was 13.0 seconds. This cooling is considered to be beneficial in decreasing the rate at which remaining fuel is vaporized and in eliminating potential reignition sources. An item of possibly more significance than the cooling effect shown here, is the fact that the systems in use on current aircraft may dissipate the agent in a half second after reaching the concentration required to extinguish a fire. With normal cooling, the temperature of the safety wires a half second after the fire, cooled 50°F to 1350°F. In the case of the nitrogen extinguishing system, it is possible with the availability of large quantities of nitrogen, the discharge could be prolonged for 30 to 60 seconds or longer to allow for cooling of potential reignition sources and dissipation of fuel.

Two comparative tests were conducted to determine the relative effectiveness of liquid nitrogen to the fire extinguishing agent currently being used on the majority of U. S. commercial transport aircraft ($CBrF_3$). As shown in Table 3, one test involved a 1.0-lb discharge of $CBrF_3$ under 500 psig pressure through the standard Jet Star perforated tube fire extinguishing distribution system. During the second test, 1.0 lb of $CBrF_3$ was discharged from the standard pressurized container through the liquid nitrogen fog nozzle distribution system. In both cases, the fires were extinguished. Under the same test conditions, a 1.1 lb/sec discharge of LN_2 for 3.9 sec was required, expending an effective quantity of 4.1 lb of LN_2. Although no attempt was made to determine the minimum required quantity of $CBrF_3$, it is estimated on the basis of prior experience with extinguishing fires

in the Jet Star installation that, on the basis of weight, approximately four times more LN_2 is required as compared to $CBrF_3$.

Tests have also been conducted to determine the effects of pressure losses in the distribution system and flashing of LN_2 to gas on the quantity requirements for extinguishing fires. The pressure losses and amount of flashing was controlled by varying the size of an orifice plate at the container outlet. The results are summarized in Table 4. Nitrogen was saturated at 100 psig and plumbed through 21 feet of 1-inch tubing and discharged through open-end tubes into the Jet Star installation. A comparison of the nitrogen discharge rates shows that the pressure losses and flashing of LN_2 did not substantially affect the quantity requirements for extinguishing the fire. The state of the nitrogen was not critical as long as the distribution system was sized to provide at least the minimum discharge rate.

A series of tests was conducted on the Jet Star installation to determine the effects of fire size on the LN_2 quantity requirements for extinguishing fires. The results of these tests are summarized in Table 5. The size of the simulated fuel leak is seen to have affected the quantity requirements of nitrogen for extinguishing fires. As the fuel leak size was increased, the discharge rate of nitrogen required increased until there was evidence of unburned fuel within the compartment. At this point burning started to occur outside of the compartment and the required nitrogen discharge rate no longer increased. This point occurred at approximately 0.3 gpm fuel flow.

Items presently under investigation include determining the effectiveness of an LN_2 extinguishing system when used to extinguish fires in a nacelle with damaged cowling. Under this item, the capabilities of an extinguishing system containing a large quantity of LN_2 are being determined as a function of the amount of air leakage and the size of openings in the cowling.

Other items under investigation include (1) the cooling effects of an inadvertent LN_2 discharge on engine and installation components, (2) the effects of long line lengths, with the shutoff valve near the outlet, on LN_2 extinguishing requirements, (3) the effects of container pressure, line size, line length, nitrogen flashing, type discharge, and fittings on the flow rate of nitrogen through distribution systems. A search is also being made for equipment suitable for measuring the concentration and distribution of nitrogen or oxygen in a nacelle during an LN_2 fire extinguisher system discharge. The response rates of

most oxygen analyzers currently available are too slow for this application. However, a commercially available analyzer which measures oxygen pressure using a high temperature calcium-stabilized zirconium oxide cell, has been located and at the present time, offers the best possibility of meeting the requirements for measuring the oxygen concentrations. If this analyzer is available prior to the completion of testing, concentration and distribution measurements will be made under conditions identified as having sufficient LN_2 for extinguishing fires in the Jet Star installation.

TABLE 1. PHYSICAL PROPERTIES OF SEVERAL EXTINGUISHANTS.

CHEMICAL FORMULA	LN_2	CO_2	$CBrF_3$	CBr_2F_2
BOILING POINT at 1 atm, °F.	-320	-109	-72	76
HEAT OF VAPORIZATION at boiling point, Btu/lb.	85	113	48	53
VOLUME of 1 lb of gas at 70 °F & 1 atm, cu ft.	14	9	3	3
GAS TO LIQUID VOLUME RATIO gas at 70 °F & 1 atm, liquid at:	696:1 Boiling Point	403:1 70°F	254:1 70°F	356:1 76°F

TABLE 2. INSTALLATION EFFECTS ON NITROGEN FIRE EXTINGUISHING REQUIREMENTS.

ENGINE INSTALLATION	LN_2 SYSTEM	LN_2 DISCHARGE RATE LOW AIRFLOW	HIGH AIRFLOW
JET STAR:	FOG NOZZLE	0.8 lb/sec	-----
	OPEN-END TUBE	0.8 lb/sec	-----
SIMULATED ENGINE (53 cu ft Volume):	OPEN-END TUBE	0.6 lb/sec	2.5 lb/sec
	PERFORATED TUBE	-----	1.6 lb/sec
SIMULATED ENGINE (40 cu ft Volume):	OPEN-END TUBE	0.5 lb/sec	1.4 lb/sec

TABLE 3. EFFECT OF AGENT TYPE ON FIRE EXTINGUISHING REQUIREMENTS.

EXTINGUISHANT	TYPE DISCHARGE	DISCHARGE RATE	EFFECTIVE QUANTITY
LN_2	FOG NOZZLES	1.1 lb/sec	4.1 lb
$CBrF_3$	PERFORATED TUBE	6.5 lb/sec	< 1.0 lb
$CBrF_3$	FOG NOZZLES	11.1 lb/sec	< 1.0 lb

TABLE 4. PRESSURE AND FLASHING EFFECTS ON NITROGEN FIRE EXTINGUISHING REQUIREMENTS.

FLASHING	LINE PRESSURE LOSS	LN_2 DISCHARGE RATE
LOW (2%)	3 psi	> 1.02 lb/sec, < 1.26 lb/sec
MODERATE (7%)	42 psi	> 0.91 lb/sec, < 1.06 lb/sec
HIGH (22%)	83-psi	> 0.91 lb/sec, < 1.16 lb/sec

TABLE 5. EFFECT OF FIRE SIZE ON NITROGEN FIRE EXTINGUISHING REQUIREMENTS.

FUEL FLOW RATE	LN_2 DISCHARGE RATE
0.1 gpm	> 0.91 lb/sec, < 1.22 lb/sec
0.3 gpm	> 1.33 lb/sec, < 1.38 lb/sec
0.5 gpm	----- < 1.33 lb/sec
0.7 gpm	----- < 1.42 lb/sec

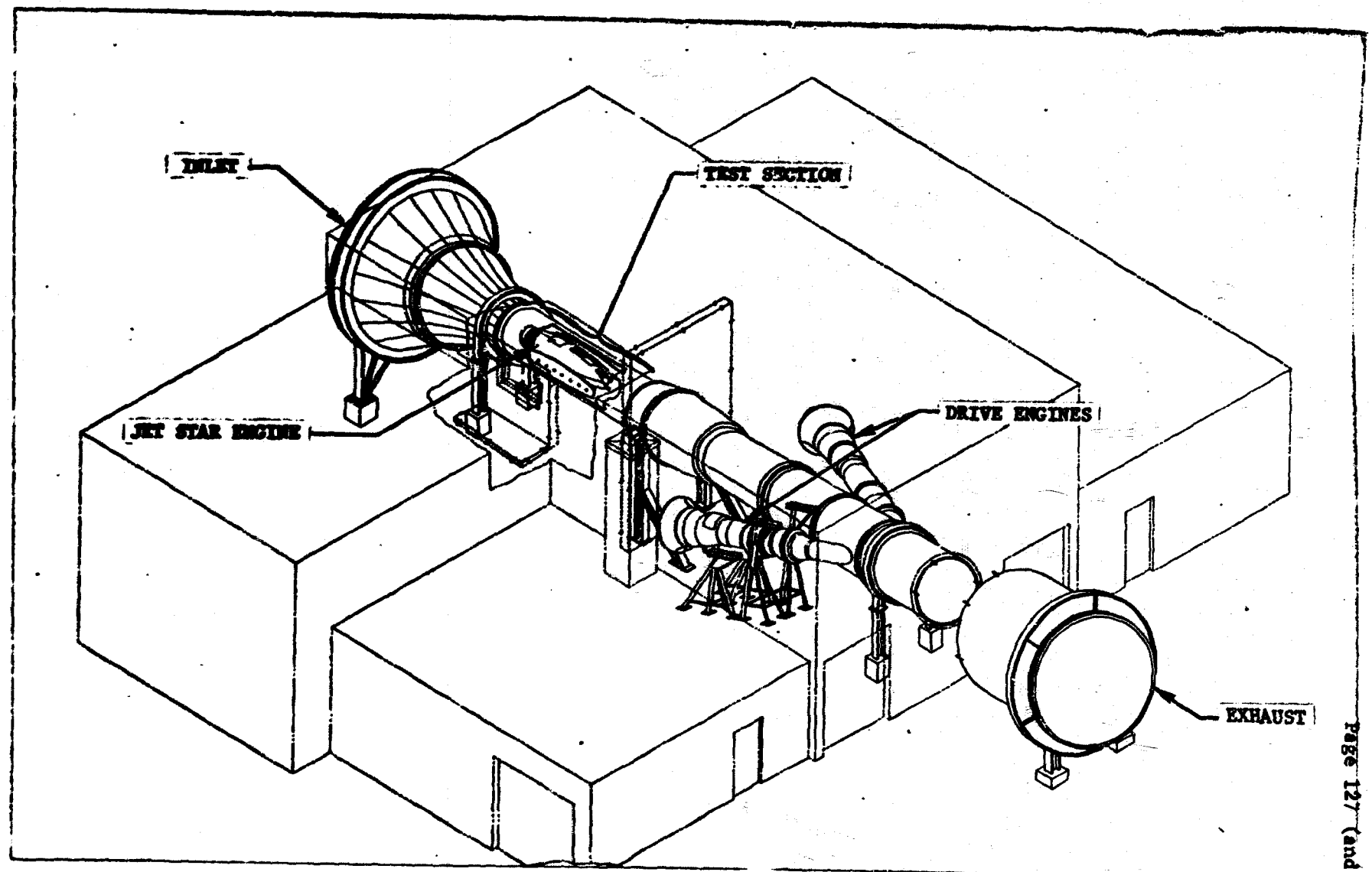


FIGURE 1. WIND TUNNEL FACILITY.

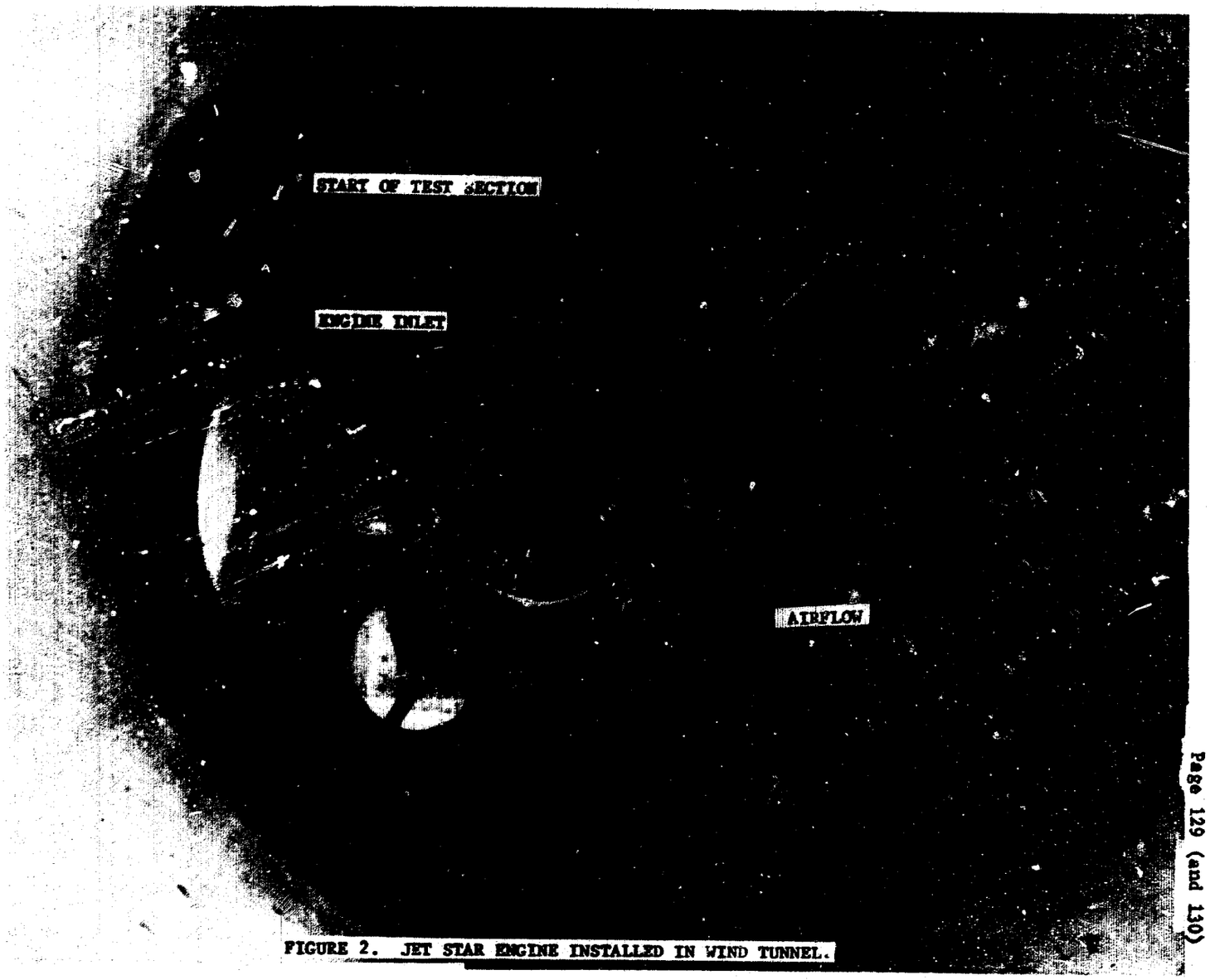


FIGURE 2. JET STAR ENGINE INSTALLED IN WIND TUNNEL.

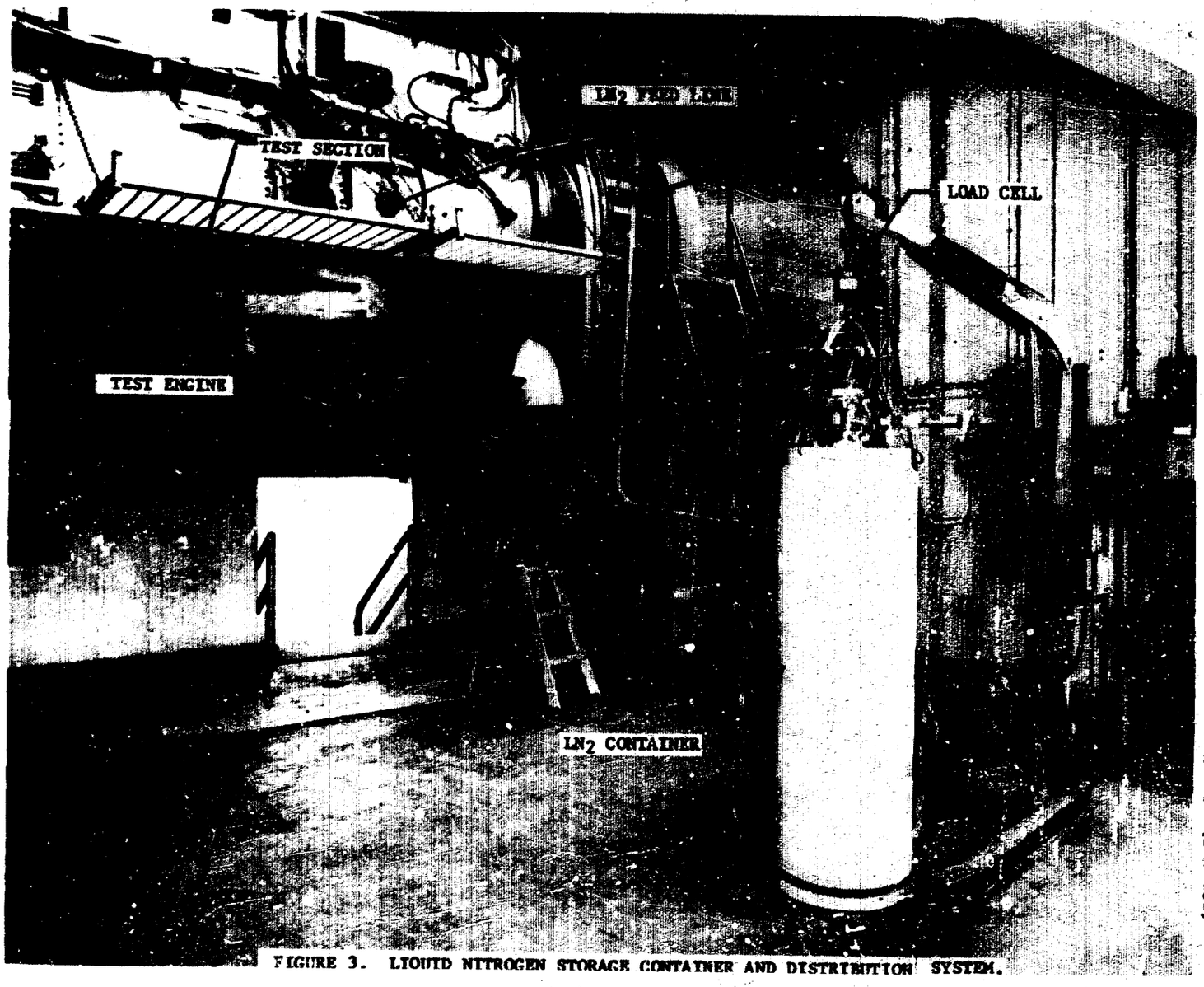


FIGURE 3. LIQUID NITROGEN STORAGE CONTAINER AND DISTRIBUTION SYSTEM.

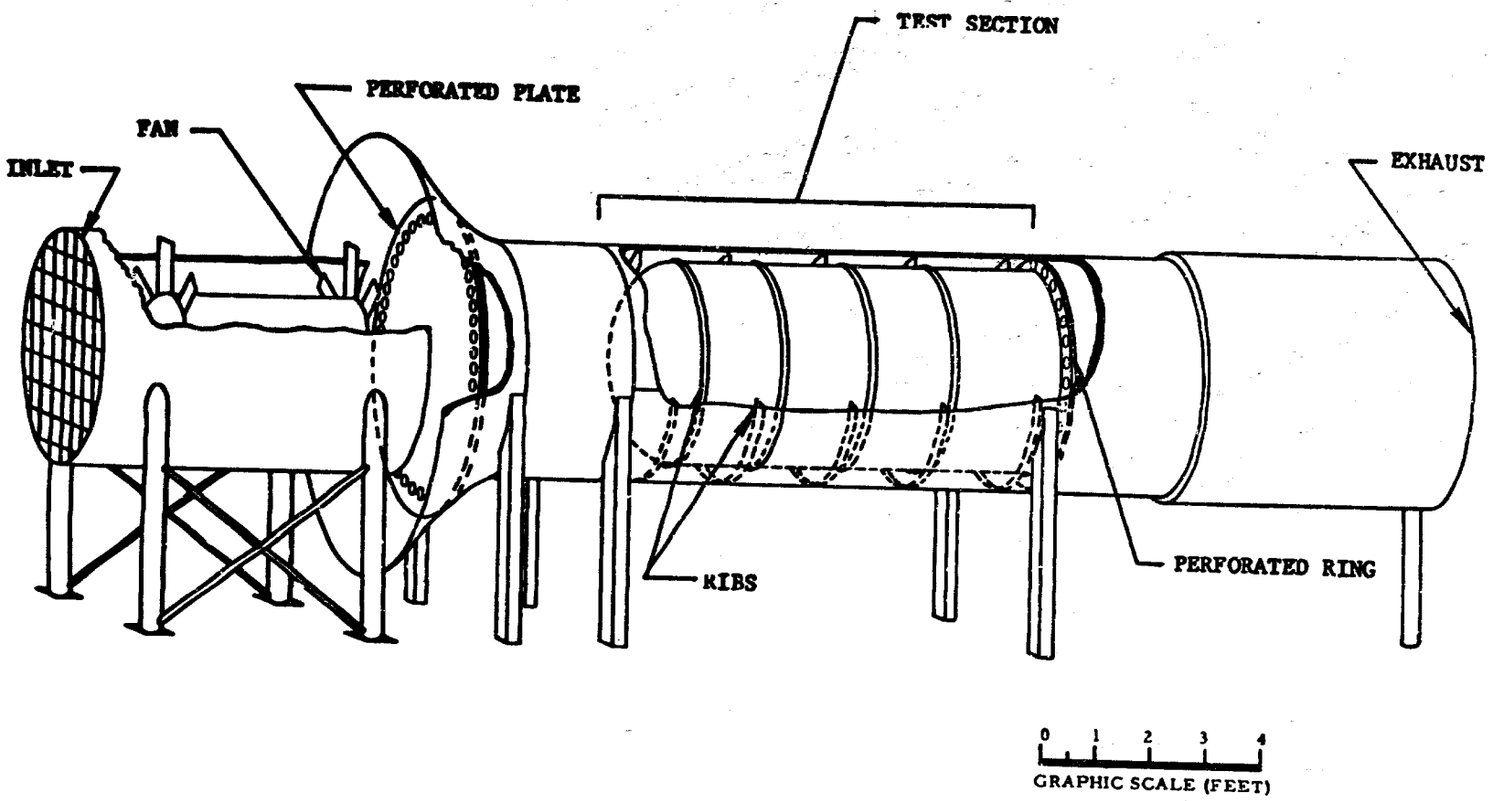


FIGURE 4. SIMULATED ENGINE FACILITY.

FIGURE 5. AMBIENT TEMPERATURE DURING NITROGEN DISCHARGE

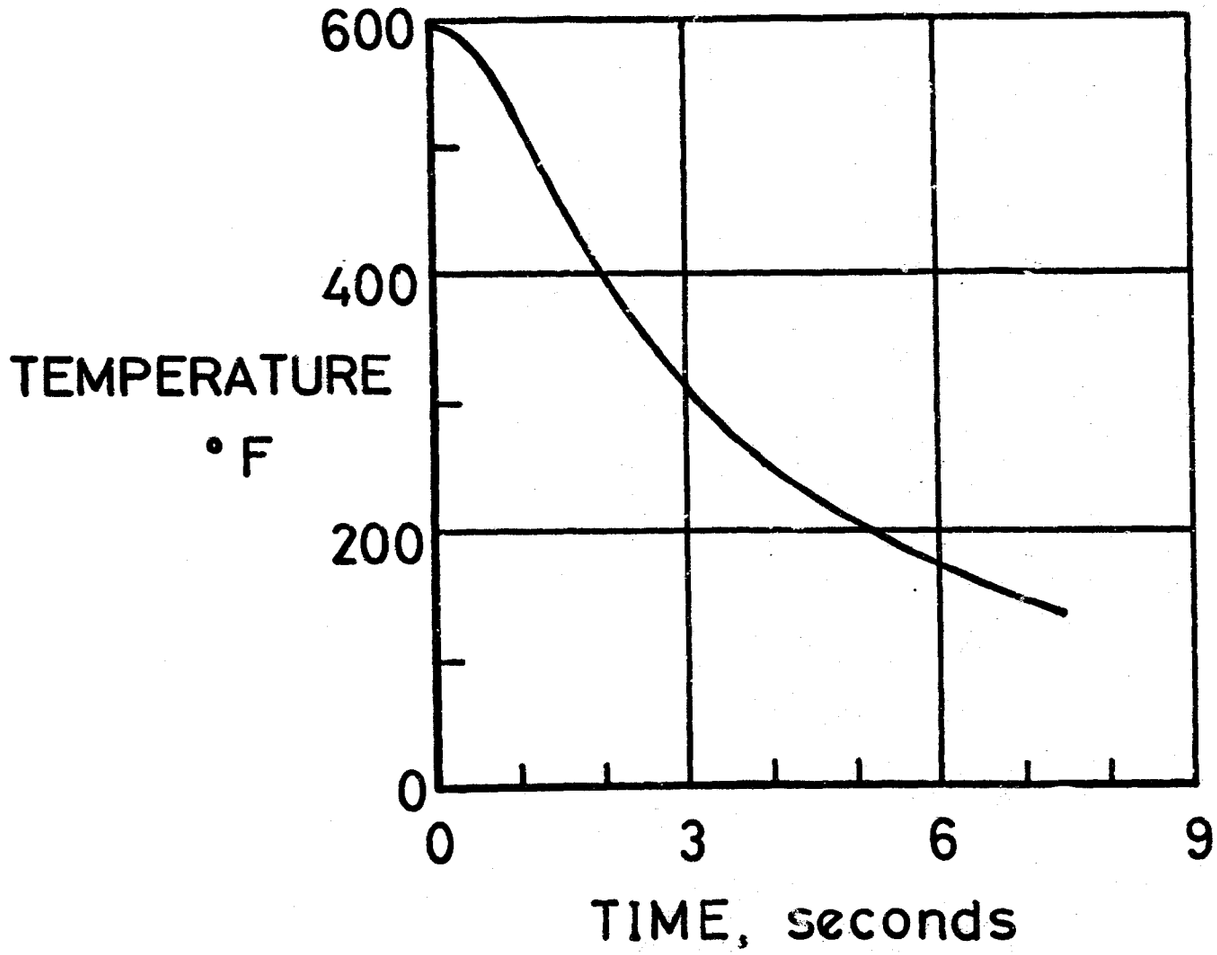
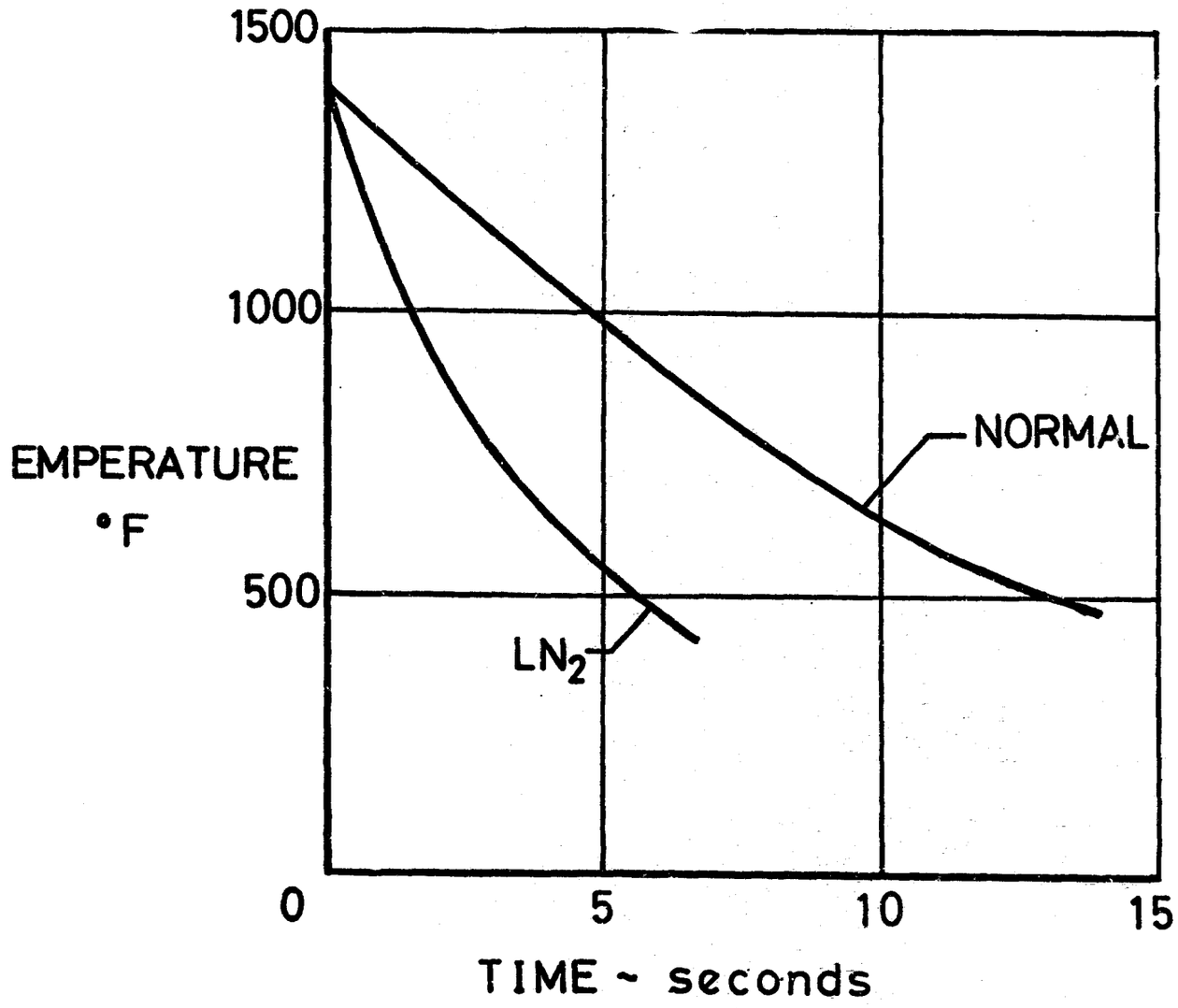


FIGURE 6. POST-FIRE COOLING OF WIRE



Resume of Discussion Following Mr. Klueg's Presentation

1. Mr. Klueg advised that fires were extinguished in a period of two to six seconds after initiation of discharge of liquid nitrogen. The discharge rate is established within the first two seconds.

2. The nitrogen line from the tank was one inch in diameter and this size is sufficient for low airflow nacelles.

3. In reply to a question on availability of test data, the report is expected to be released in early fall, 1970, giving the data accumulated during this testing.

FUEL TANK INERTING USING CATALYTIC COMBUSTION TECHNIQUES

MR. ROBERT G. CLODFELTER

INTRODUCTION: There has been several past efforts devoted to the utilization of the products of combustion for inerting of fuel tanks. In the old days when the Air Force was concerned with reciprocating engines, the exhaust products due to the low oxygen content could be used directly from the engine. Flame arresters and water separators were required and the corrosive atmosphere of the ballast gases was of concern. With the introduction of the gas turbine, a different approach was required due to the high average percentage of oxygen in the exhaust products of the gas turbine. Separate combustion units were studied as well as selective abstraction of low oxygen content exhaust products from the gas turbine. Inherent in any inert gas generator are the companion problems of reliability and control. This was one reason that a Purge Gas Generator for the B-52 floundered. Dry ice was used operationally in the B-47 and B-36 aircraft for fuel tank inerting. Both GN_2 and LN_2 have been used on past Air Force aircraft with the LN_2 inerting system under serious consideration for near future Air Force aircraft. A detail presentation on the history of inerting systems may be found in reference 1.

This paper discusses the catalytic combustion technique for inerting of aircraft fuel systems. The catalytic combustion approach offers potential advantages over other combustion concepts by providing efficient oxygen conversion over a wide range of operating condition with the generation of only a small amount of corrosive reaction products. The qualitative advantage of lower operating temperature and no combustion flame must also be considered.

For the future, the catalytic inerting concept offers the potential of lower system weight and lower operational cost over currently available inerting systems. Since the system is essentially self-contained the logistics problems associated with military operations are minimized. The prospects of the catalytic reactor inerting system appear particularly good for military aircraft requiring multiple mission capability without servicing, or prolonged inerting in the presence of a battle damaged fuel system.

CATALYTIC INERTING PROGRAM: The current Air Force effort to develop the catalytic combustion technique into an effective system for generating inerting gases for aircraft fuel tanks is divided into three phases. The first phase was performed by American Cyanamid during the period of April 1968 through June 1969 under Contract F33615-68-C-1500. This phase dealt primarily with defining the catalytic combustion reactor with some attempt at conceptual design. The second phase started April 1970 and will last eight months. The specific objective of this exploratory development effort is the preliminary design of a catalytic reactor inerting concept which offers both system advantages over existing inerting techniques and has a high potential of satisfying future Air Force requirements. For this phase there are two contractors,

AiResearch Manufacturing Company under Contract F33615-70-C-1492 and Hamilton Standard under Contract F33615-70-C-1616. The basic approach in these two programs are similar yet different from a hardware standpoint. Assuming successful completion of Phase II a third phase will be initiated. By successful completion I mean that the catalytic reactor approach should have been shown to offer sufficient advantages over the LN_2 approach in satisfying at least some of the Air Force's future aircraft requirements. For the purpose of this program the LN_2 system of inerting is considered baseline and state-of-the-art. The third phase will deal with the development of prototype/breadboard hardware for design evaluation including both ground test and flight test. As currently planned, this phase should be completed about mid 1972. At this point in time the technology will be transitioned from the Air Force Aero Propulsion Laboratory to the Deputy for Engineering (ASN) for further development or operational deployment.

PHASE I - CATALYTIC REACTOR: A simplified combustion-type inerting system is shown on Figure 1. Aircraft fuel and engine bleed air are supplied to the combustor at a controlled rate. With a catalytic reactor, the combustion temperature may be controlled to a level far below those existing in non-catalytic combustors. The heat of combustion (780 BTU/# of inert gas) is essentially the same for both types of reactions and therefore it is necessary to remove heat from the combustor to prevent overheating of the catalyst. This may be accomplished with fuel, ram air or with steam as the heat sink. The moist ballast gas exiting the combustor will have typical temperatures around 1200°F. At this point it is appropriate to mention the selection of the catalytic combustion approach over the flame combustion approach. The lower operating temperature is one reason but the main reason is the wide range of flow rate control. After leaving the combustor the ballast gas may be cooled in several stages even to the point of condensing out water generated by the fuel-air reaction. In the American Cyanamid program we had a design goal on water removal of below 5 PPM in the ballast gas. The approach taken in Phase I to achieve this goal was the use of chemical drying agents such as calcium carbide. The dry ballast gas may be routed to the fuel system in a similar way as the LN_2 inerting system including a similar fuel scrubbing process. The scrubbing process removes dissolved oxygen from the fuel.

What was accomplished during Phase I will now be briefly discussed. First of all I would like to review the goals given the contractor. As may be seen on Figure 2 the goals are quite demanding upon any inerting concept, particularly the goals B and F which require less than 5 PPM water in the ballast gas and the capability of supplying

ballast gas during a dive rate equivalent to a pressure change of 14.7 psi/minute.

The main effort of Phase I was the investigation of the catalytic reactor or combustor. A catalytic combustion test unit shown schematically on Figure 3 was assembled. Twelve different catalysts were selected for test following an initial analytical screening process. The tests were designed to determine the activity of the candidate catalysts under various temperature, pressure and composition conditions. Typical results are as shown on Figure 4 for code A catalyst. As we can see on this Figure the higher the conversion temperature the lower the oxygen concentration in the ballast gas for a given amount of catalysts. Here we have our first trade-off, catalysts weight vs. temperature which is equivalent to pre-heat requirements for start-up and heat exchanger weight for cooling the combustor exit gases.

Code A catalyst is actually Aero-Ban manufactured by American Cyanamid and was the recommended catalyst for the catalytic reactor. The catalyst is a production material initially developed for the State of California for use in automobile mufflers to oxidize hydrocarbons. It satisfactorily met the life requirements of that application including 12,000 miles without servicing. It has been shake tested without measurable attrition, and has shown no performance loss or leaching after soaking in either fuel or water and evaporating.

The effect of Space Velocity (SV) on the reaction rate is given on Figure 5. Space Velocity is equivalent to a flow rate for the purpose of this paper. This figure illustrates the wide operational range which is possible with the catalytic reactor concept.

EFFECT OF FUEL COMPOSITION: Various test runs were made using both JP-7 and JP-4 (MIL-T-5161G) to investigate the following factors:

a. Space Velocity and temperature effects

b. Effect of Sulfur

c. Coke Deposition

d. Conversion to CO_2

The experimental findings indicate that JP-4 and JP-7 fuels offer no serious problems insofar as catalyst performance is concerned. The JP-4 tests are of special significance because the properties of the MIL-T-5161G samples used represent about the most deleterious that

could be expected in field use, and because the tests were carried out over a period exceeding 60 hours.

CATALYST LIFETIME TEST: A run of 60 hours duration was made to define the performance of Catalyst A while operating with an excess of JP-4 fuel typical of the MIL-T-5161G specifications. During most of the run, a mixture containing approximately 100% excess of JP-4 was used but, there were periods during the first half of the run when the excess of fuel ranged from 45% to 400%. A plot showing the principal performance trends is given in Figure 6. Figure 6 shows that the fraction of oxygen converted to CO_2 may have declined about 10% over the course of the entire run, but was stabilized at the 70% level during the last 25 hours.

A sample of catalyst taken at the conclusion of the 60 hour JP-4 run contained 10.6% carbon, indicating a considerable deposition of coke. The specific surface of this sample was 139 m^2/g, as compared to 191 m^2/g for fresh Catalyst A. It is not known if the level of coke had reached an equilibrium value, or if it was continuing to increase as the test progressed. The fact that the sulfur content of the catalyst was reduced from 0.47 to 0.20% during regeneration indicates that at least a large part of the sulfur was associated chemically with the coke deposit, rather than with the catalyst itself.

REGENERATION: The charge of catalyst contained in an operational catalytic reactor can most readily be regenerated without removing it from the reactor. Conceptually, either the reactor itself could be removed from the aircraft as a cartridge unit, or the regeneration could be performed in place (on the aircraft) by making connections to a service truck. In either event, the regeneration would involve passing a flow of oxygen-containing gases through the bed at a temperature sufficient to support combustion. The gas mixture should not be too rich in oxygen, otherwise the catalyst might become overheated.

A regeneration experiment was carried out using the charge of Code A catalyst that had received a propane activity check following the 60 hour run with JP-4 fuel.

The effect of this regeneration treatment on catalyst activity was checked using propane fuel, and a comparison is given in Figure 7. It can be seen that there was no substantial effect, and it cannot be said that there are any benefits to be gained by regeneration after 60 hours on stream with a 100% excess of JP-4 fuel.

Further work is needed over longer periods, to determine just how long the catalyst can be used without regeneration. It would be desirable to carry this work through at least two complete regeneration cycles, or 500 hours of reaction time, whichever comes first, and to operate at mixtures more representative of anticipated operations, i.e. approximately 10% excess fuel.

WATER REMOVAL: At this point in Phase I we started to penalize the catalytic concept with a water removal goal that was unrealistic (i.e. less than 5 PPM water in Ballast Gas). To achieve the goal, a chemical drying agent approach was taken. The 5 PPM requirement and the 50 hour without regeneration resulted in a dryer system which weighed up to 61% of the total catalytic system depending on the mission and type of aircraft.

The 5 PPM goal came from the requirement of not more than 5 PPM water in the fuel as delivered to the aircraft. Late in the Phase I effort information as shown on Figure 8 was obtained from the USAF Environmental Technical Applications Center concerning the atmospheric water content for Southeast Asia. The 5 PPM is equivalent to 3×10^{-6} # H_2O/# dry air. With this information and knowledge of the air density-altitude relationship it was determined that even during clear weather the average atmospheric water content was about 4.8×10^{-3} #H_2O/# dry air. During a cloudy or rainy day the water content will be much higher. This information was generated too late to impact the Phase I results however. The goal established for Phase II was reduced to 1×10^{-3} #H_2O/# dry air which still provides for a dry fuel tank yet being three orders of magnitude less demanding then the goal established for Phase I. 1×10^{-3} #H_2O/# dry air corresponds to a dew point temperature of $5^{\circ}F$.

CONCEPTUAL DESIGN: During Phase I conceptual designs of the catalytic inerting system were made which met the target performance goals at all times (including powered dives) during missions typical of a tactical aircraft, a military transport, and the SST. Based on these unoptimized, preliminary designs, it was determined that complete inerting protection and control over the water admitted to the fuel tanks could be provided at a penalty of from 1.8% (transport) to 6.4% (tactical) of the initial fuel weight. These figures reflected industrial plant equipment weights, and substantial reductions have since been illustrated through the use of flightweight equipment of optimized design. Even though substantial reductions in these weights have been illustrated since the completion of Phase I, the catalytic

inerting system as defined in Phase I was competitive from a weight standpoint with the fully packed polyurethane foam approach. Some of the advantages and disadvantages of the catalytic inerting system are given of Figure 9 when compared to the LN_2 approach which is considered state-of-the-art. The detail results of Phase I are given in Reference 2.

In summary the results of Phase I were sufficiently encouraging for the Air Force Aero Propulsion Laboratory to initiate a Phase II effort. The following technical items remain to be investigated in detail during Phase II.

a. Water Removal at an acceptable weight penalty.

b. Heat Removal at an acceptable weight penalty

c. Contaminant Generation

   1. Unconverted Oxygen

   2. Flammable Gases

   3. Acid Forming Compounds

d. Automatic Control

   1. Range of acceptable performance

   2. Performance Monitoring

   3. Fail Safe

PHASE II - CATALYTIC INERTING SYSTEM: The objective of the Phase II effort is to establish that the catalytic inerting concept offers both system advantages over existing techniques and has a high potential of satisfying future Air Force requirements. In addition, the concept must be proven technically to such a degree that the development of prototype/breadboard hardware may be pursued in a later phase with a high confidence level. The initial task of Phase II is the establishment of realistic fuel system inerting requirements and goals. The following two basic types of aircraft will be considered: (a) Long Range Bomber and (b) High Performance Fighter.

With the preliminary inerting system specifications established the physical and functional characteristic of several catalytic

inerting concepts will be defined. Problem areas will be identified, solutions projected, technical risk established and comparisons made with the LN_2 inerting concept. Following selection of a particular catalytic inerting concept, the necessary detail analysis and experimentation will be performed to translate the selected concept into a worthy preliminary design.

The typical catalytic inerting concept being considered during Phase II is shown on Figure 10. The main difference between this concept and the concept of Phase I is the approach to water removal. With the air-cycle refrigeration concept of water removal large system weight reductions are possible. As noted previously, the water removal approach of Phase I weighed up to 61% of the total system weight.

The balance of Phase II will be devoted to the development of a Test and Evaluation Program Plan for Phase III. Ground testing, flight testing and critical environmental testing will be performed during Phase III. The objective being to prove the catalytic inerting concept to such a degree that engineering development of operational hardware may be pursued as required in later programs.

PERMISSIBLE OXYGEN FOR INERTING: One of the big problems of operational utilization of any inerting system is to understand the conditions required for fire protection of the fuel tank. Detector information on the oxygen concentration at several locations in each fuel tank of the aircraft is a desired control feature but is impracticable from the system standpoint. To attempt to reduce the oxygen concentration under all flight conditions to zero is also an unacceptable approach. It is therefore necessary to have detail basic knowledge of the factors effecting the fuel tank environment so that protection can be insured within acceptable design constraints.

Using Reference 3 as a departure point the Air Force Aero Propulsion Laboratory plans to conduct several in-house efforts devoted to the determination of what is required for fuel tank protection by inerting. A summary of the results from Reference 3 are given by Figure 11. This 15 year old study shows that as a minimum the oxygen concentration must be below 10% for both the natural environmental threat (sparks, etc.) and the hostile threat (Gunfire). The protection of aircraft fuel tanks from gunfire activated reactions is one of the main reasons the Air Force is considering aircraft inerting. Other reasons deal with the natural environmental threat which is the main subject of this conference.

Additional factors being considered by the Air Force relates to lowering the water build-up in fuel tanks and the improvement in fuel stability at elevated temperature when a large percentage of the oxygen has been removed.

There are several reasons the Air Force feels additional testing is required. They are stratification of the gaseous components which form the fuel tank ullage and the apparent extension of the conventional rich and lean limits when a projectile travels from the liquid phase to the vapor phase creating a mist. Under these conditions we have observed JP-5 reaction 140°F below the flash point and we have noted JP-4 reactions 60°F above the rich limit. Under dynamic conditions of slosh and vibration and spark ignition we have observed a 60°F lowering of the lean limit for JP-4. Similar results are being obtained with JP-8 which is the Air Force equivalent to Jet A.

In summary fuel tank inerting is being seriously considered by the Air Force as an acceptable approach to fuel system fire protection and the Catalytic Inerting Concept offers long term advantages over existing inerting concepts.

REFERENCES

REFERENCE 1: "Air Force History and Experience with Inerting, Suppression, and Purging Systems", F. A. Wright, Conference of Fire Safety Measures for Aircraft Fuel Systems: Report of Conference, AD 672036, December 11-12, 1967, FAA (Washington, DC).

REFERENCE 2: "Generation of Inerting Gases for Aircraft Fuel Tanks by Catalytic Combustion Techniques", AFAPL-TR-69-68 Volume 1 and Volume II, August 1969.

REFERENCE 3: "Inerting Conditions for Aircraft Fuel Tanks", WADC-TR-55-418, September 1955.

COMBUSTION-TYPE INERTING SYSTEM

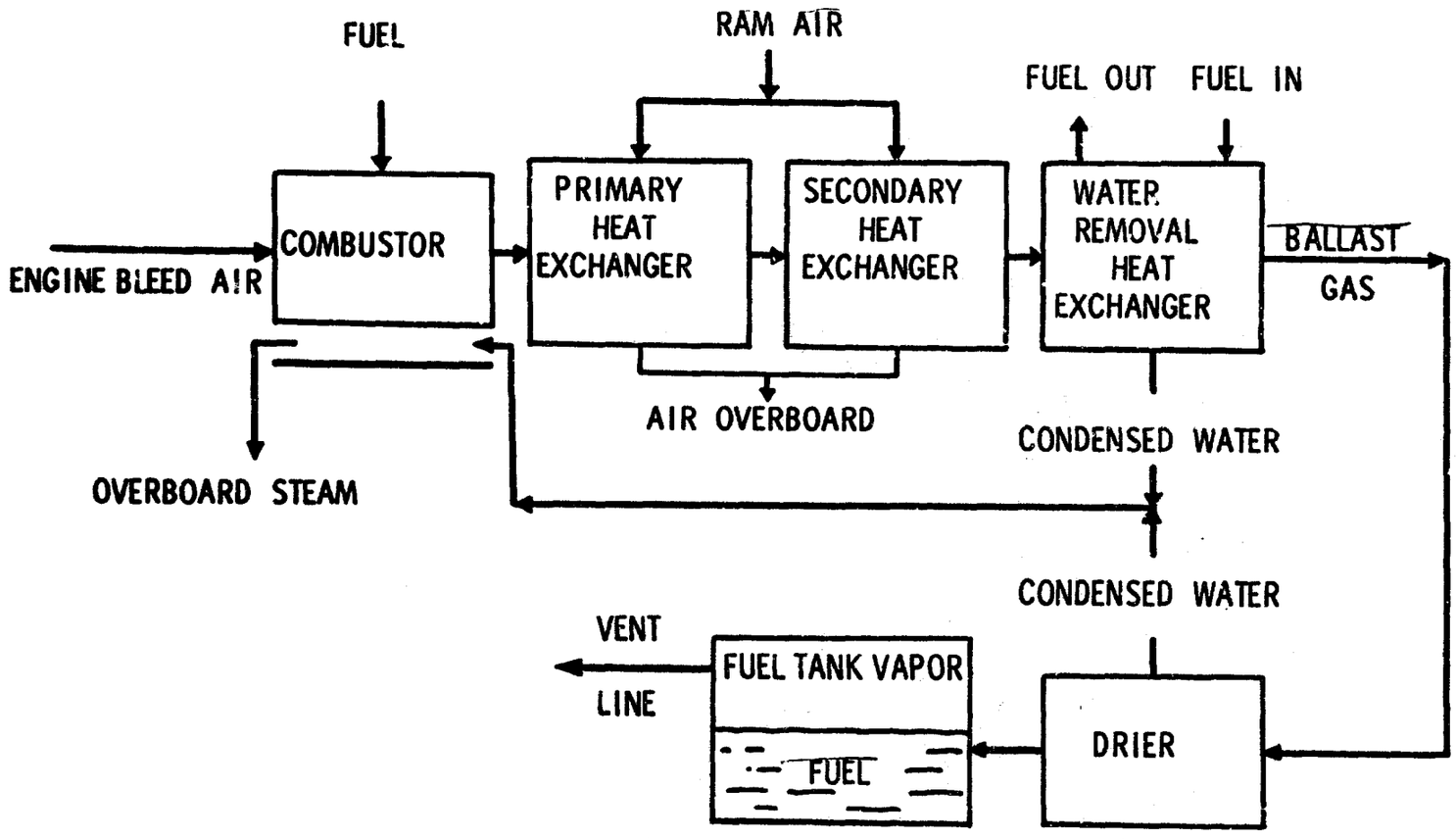


FIGURE I - SIMPLIFIED COMBUSTION-TYPE INERTING SYSTEM

A. Oxygen concentration of 2 to 9% (volume) in the ballast gas.

B. Maximum water concentration of 5 ppm in the ballast gas.

C. Minimum catalyst life of 50 flight hours without regeneration.

D. Regeneration capability by a technique which does not require unusual or highly intricate equipment, enabling the catalyst life to reach a minimum of 500 flight hours.

E. Inerting subsystem weight not to exceed 0.4% of the original fuel weight.

F. Capability to supply ballast gas during a dive in which the ambient pressure change reaches 14.7 psi/minute.

G. Capability to function with JP-4, JP-5, or JP-7 fuel.

H. Capability to provide the desired inerting protection for both subsonic and supersonic aircraft at altitudes of 0 to 80,000 feet.

FIGURE 2 - CATALYTIC INERTING PERFORMANCE GOALS FOR PHASE I

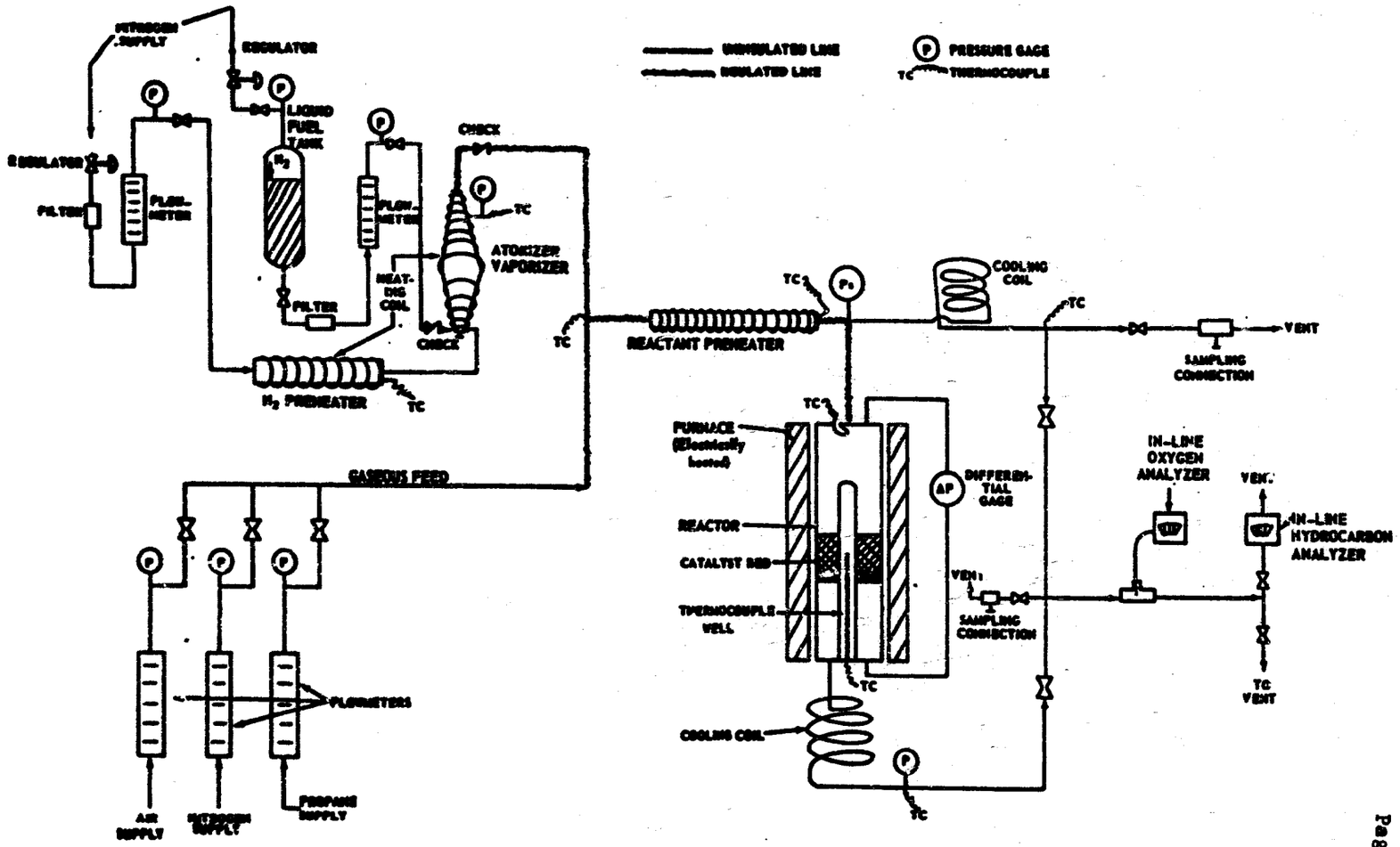


FIGURE 3 SCHEMATIC DIAGRAM OF CATALYTIC COMBUSTION TEST UNIT

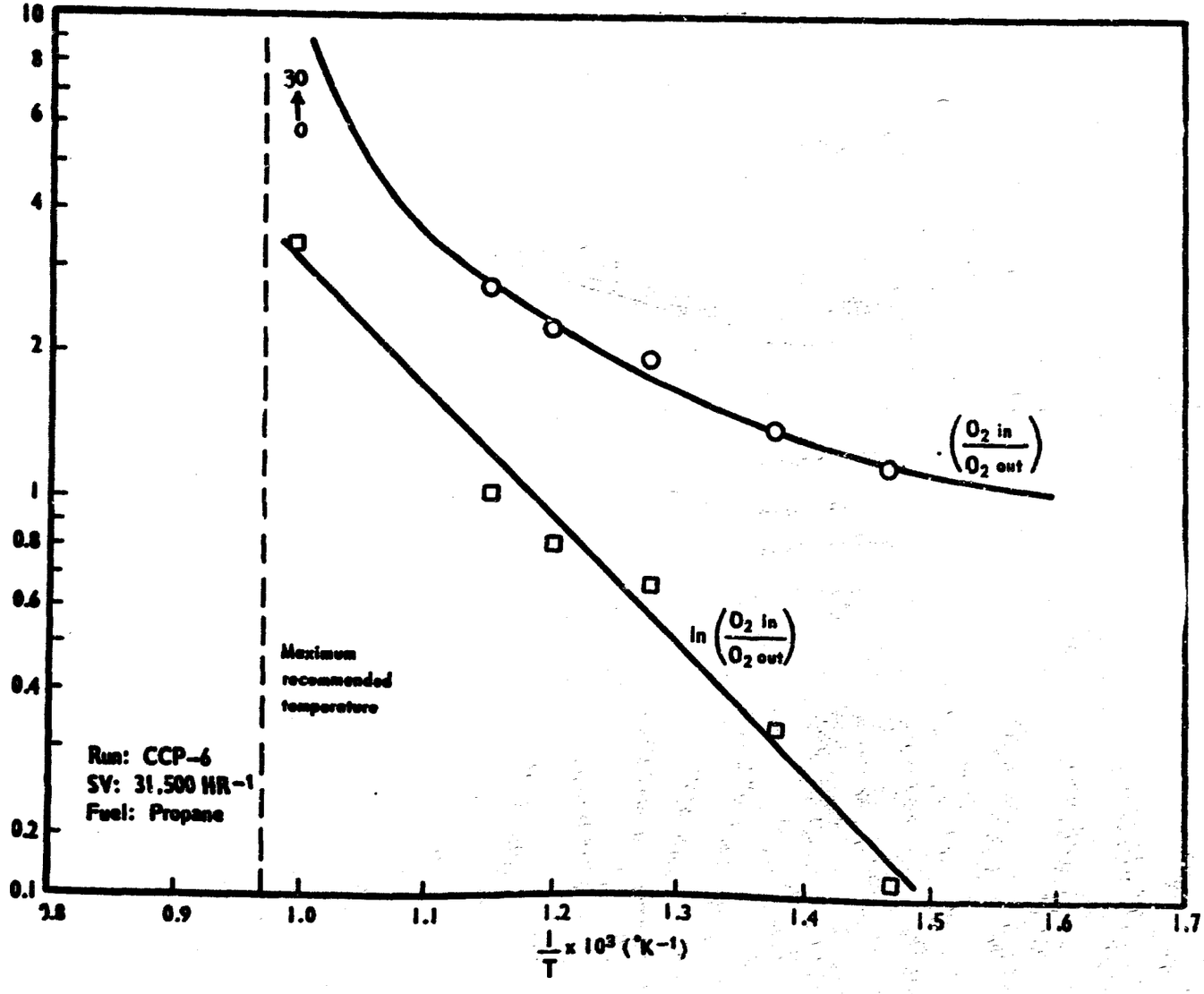


FIGURE 4 EFFECT OF TEMPERATURE ON OXYGEN CONVERSION, CODE A CATALYST

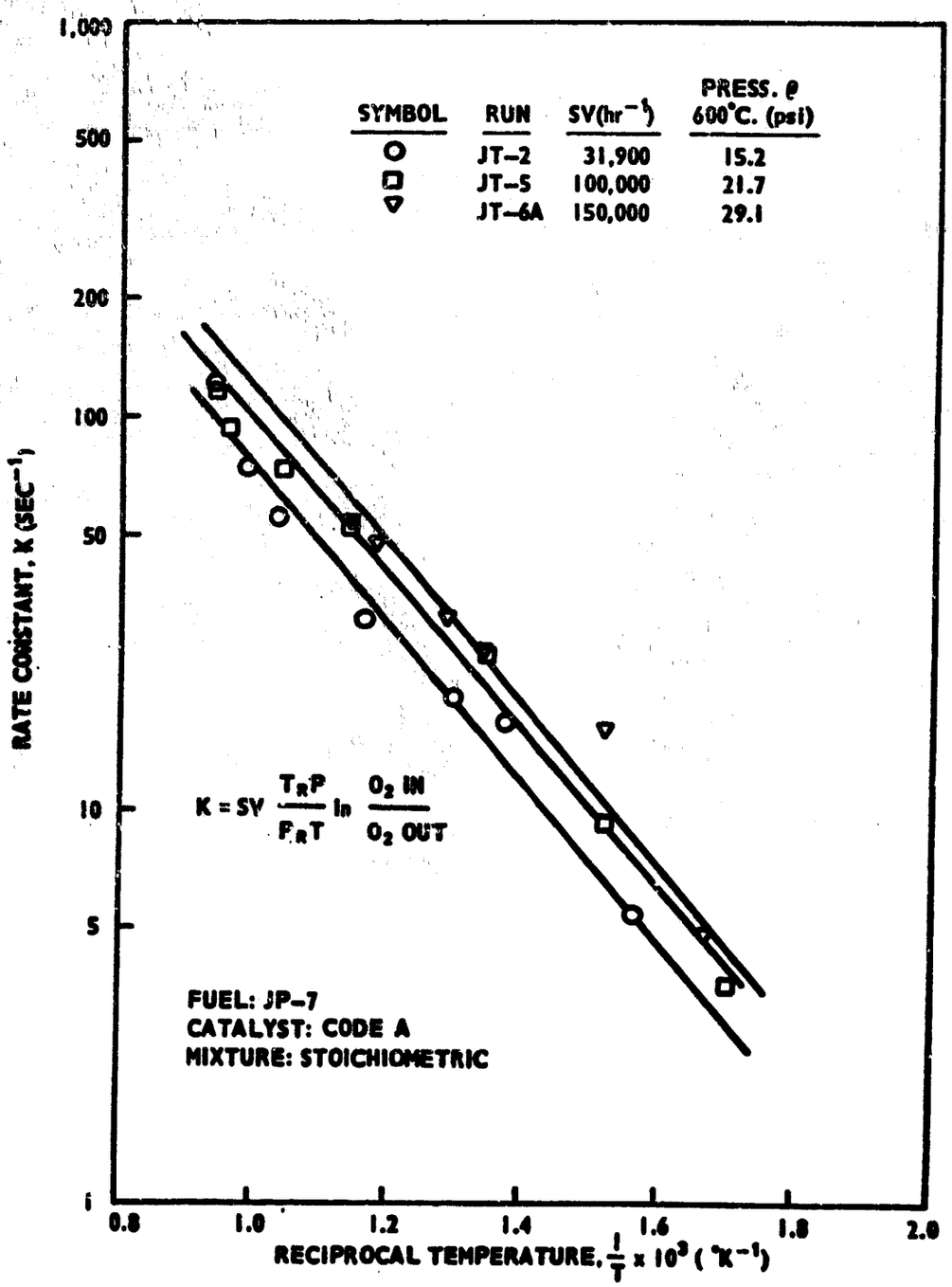


FIGURE 5 EFFECT OF RUN CONDITIONS ON REACTION RATE CONSTANT

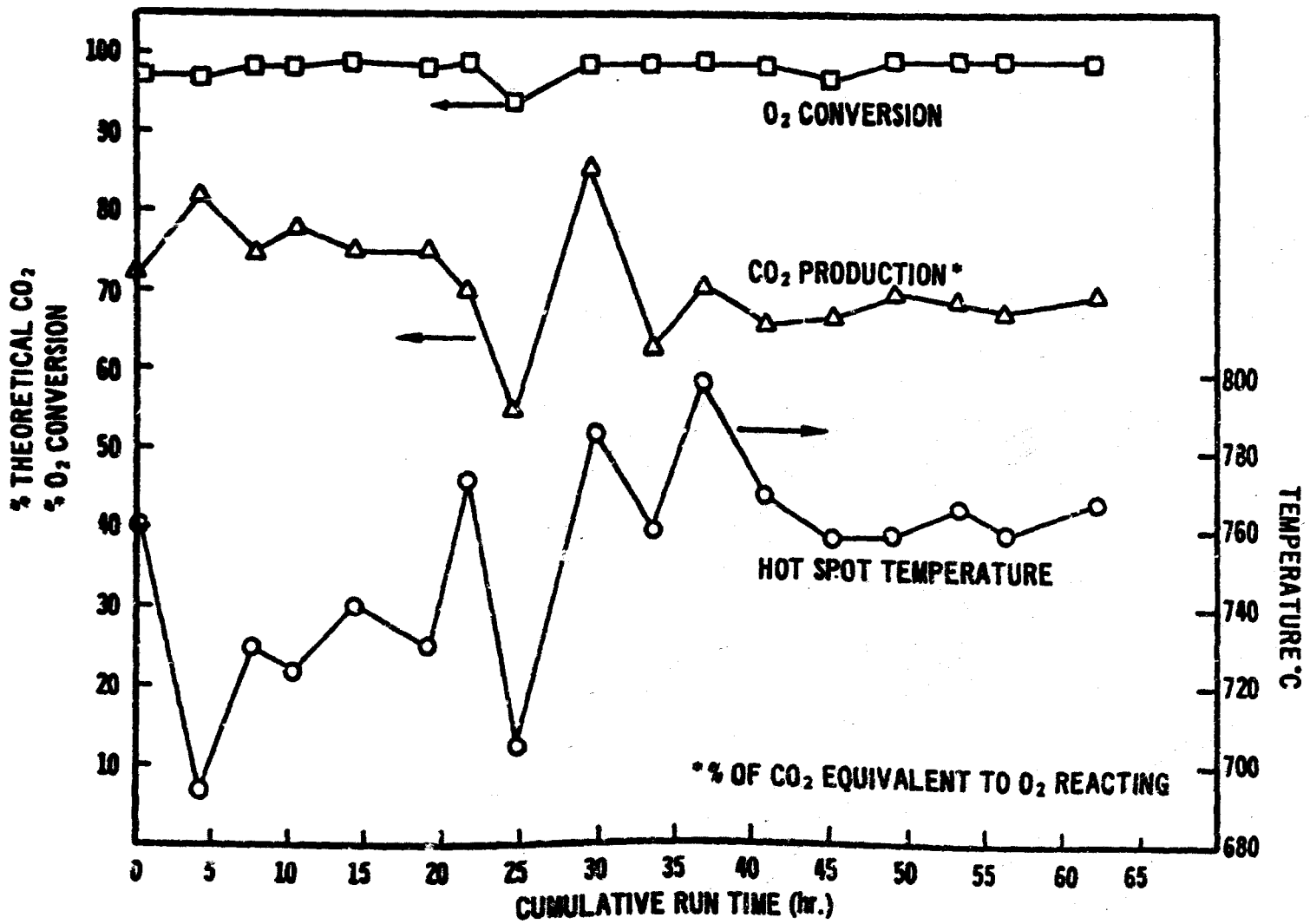


FIGURE 6 CODE A CATALYST PERFORMANCE DURING 60-HOUR TEST WITH MIL-T-5161G FUEL

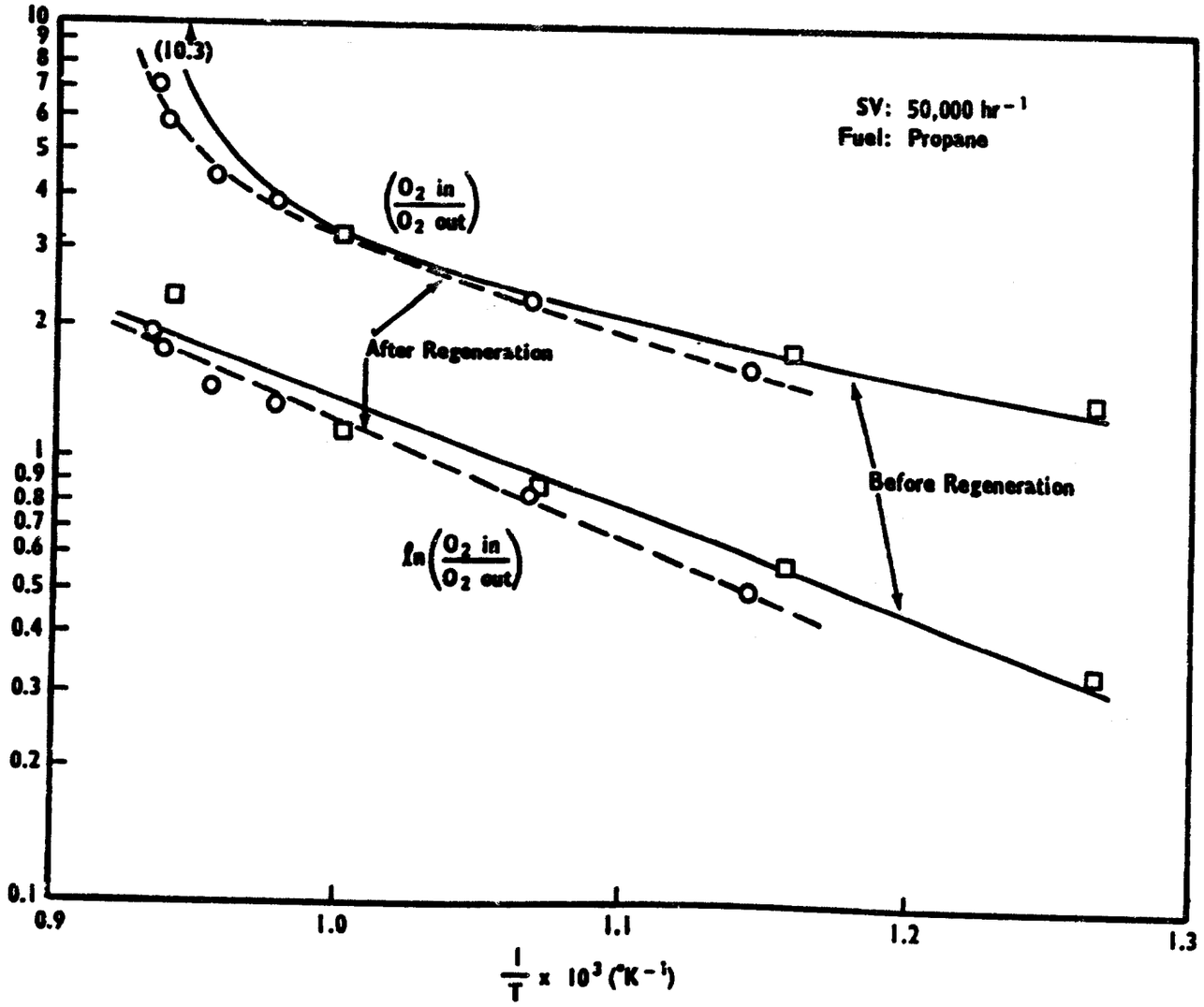


FIGURE 7 EFFECT OF REGENERATION ON PERFORMANCE OF CODE A CATALYST AFTER 60-HOUR TEST RUN

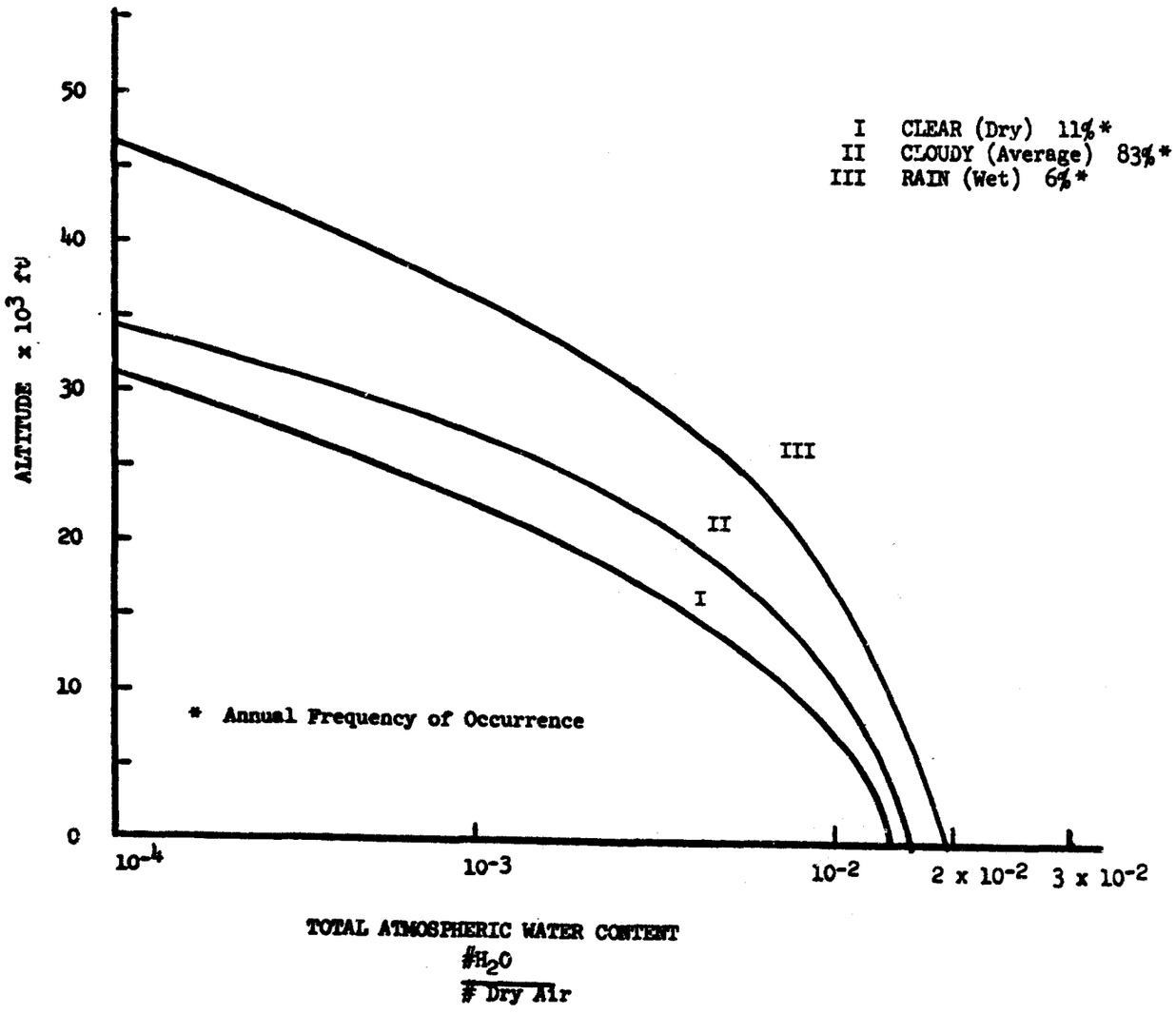


FIGURE 8 - SELECTED PROFILES OF TOTAL ATMOSPHERIC WATER CONTENT (BY WEIGHT) FOR SOUTHEAST ASIA

ADVANTAGES	DISADVANTAGES
Lower Recurring Cost	High Non-Recurring Cost
Lower Weight	Complex
Meets Bare Base Concept	Not Currently Available
Unlimited Gas Supply	Gas High In Moisture
Dry Bay Inerting Potential	Bleed and Ram Air Required
	Fuel Required

FIGURE 9 - ADVANTAGES/DISADVANTAGES OF CATALYTIC INERTING SYSTEM (BASELINE LN_2 SYSTEM)

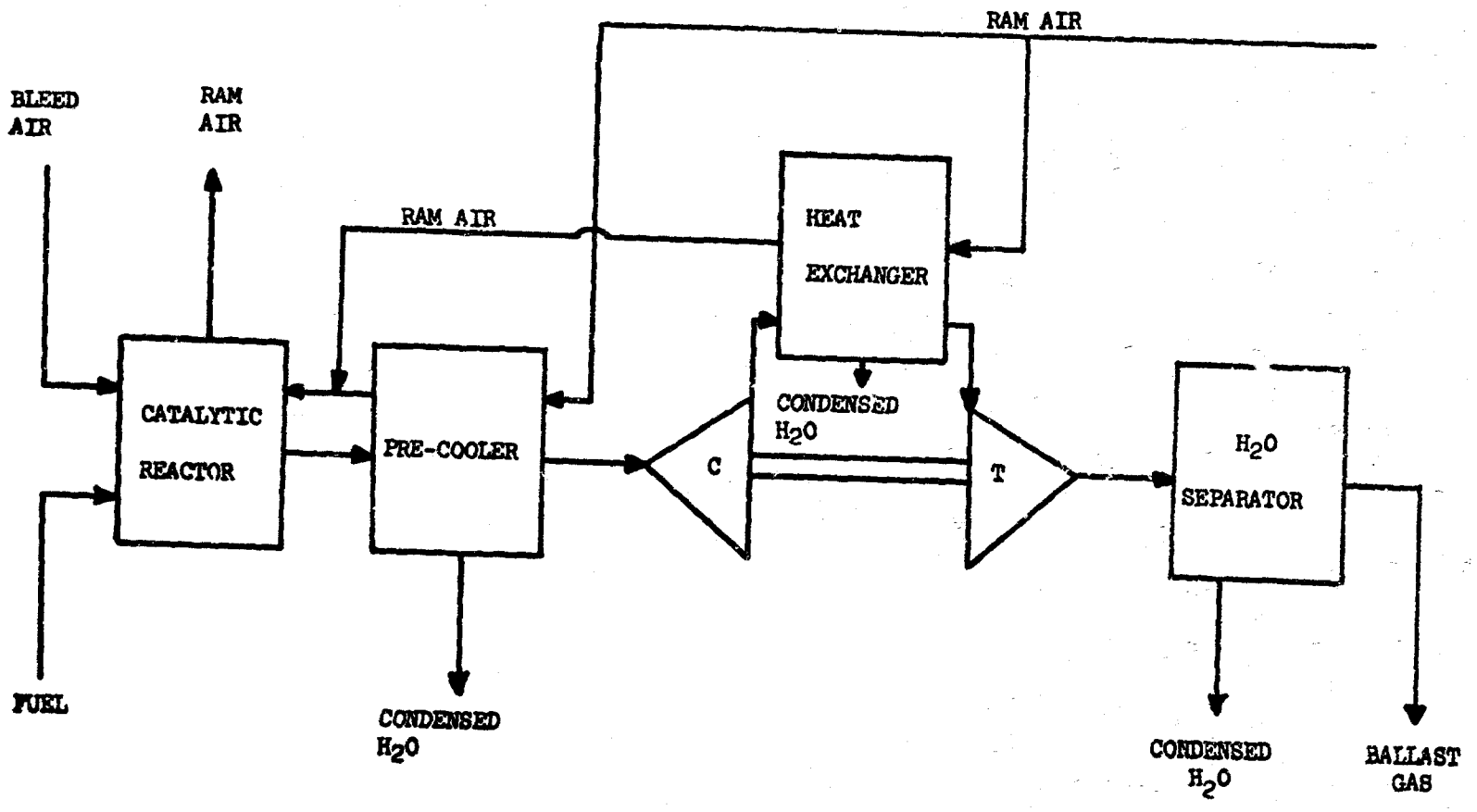


FIGURE 10 - TYPICAL CATALYTIC REACTOR-AIR CYCLE REFRIGERATION INERTING CONCEPT

GUN FIRE TESTS SUMMARY

WADC-TR-55-418

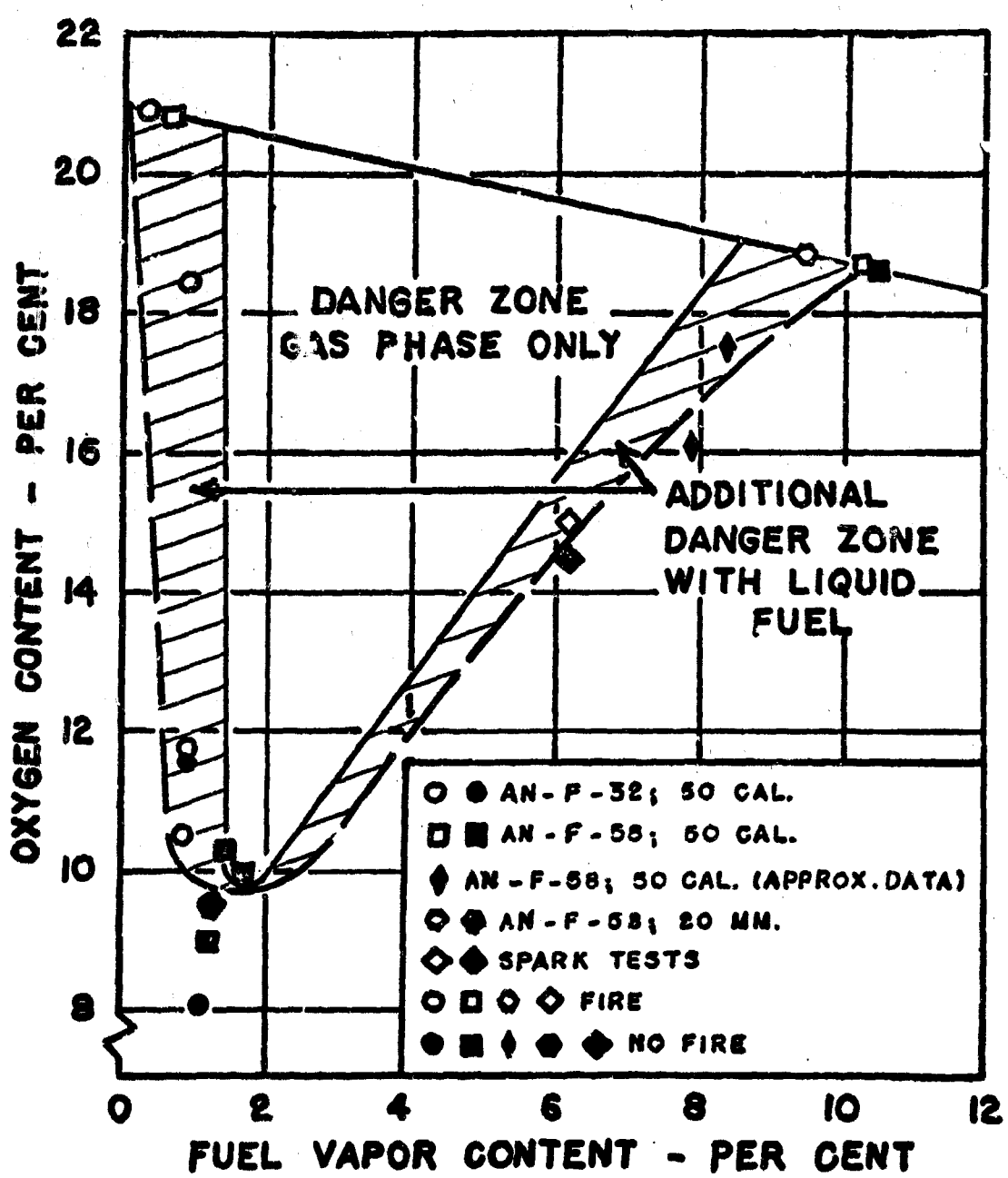


FIG. 11

LIGHTNING INDUCED VOLTAGES IN ELECTRICAL CIRCUITS ASSOCIATED WITH AIRCRAFT FUEL SYSTEMS

By

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Introduction

The possible effects of lightning upon aircraft fuel systems have been the subject of extended investigations carried out by the aircraft industry, governmental agencies, and a number of research laboratories. Much of this investigation has centered about definition of the direct lightning stroke effects; namely, the possibility of fuel vapor ignition via hot spot or hole formation, ignition at the vent outlet, or sparking associated with fuel system access doors, filler caps and probes.

Electrical circuits associated with aircraft fuel systems have also been regarded as a possible source of ignition, and considerable design effort has been expended to assure that electrical circuits or devices may not permit sparks to occur within fuel tank areas. Probably, as a result, comparatively little additional research has been accomplished to evaluate the effects of lightning upon these systems. With continually changing designs, however, the possibility of increasing vulnerability to lightning is always of concern.

One of the first questions to be answered in evaluating the vulnerability of fuel system electrical circuits to lightning is the extent to which lightning may induce voltages in them. It has been recognized that magnetic fields created by the lightning currents flowing through metallic aircraft skin and structure can link aircraft electrical circuits within and create induced voltages. Similarly, lightning currents may also cause resistive voltage rises along the skin of an aircraft, which may be part of an electrical circuit if the skin is used as a return path for such circuits. The possible magnitude of these voltages will determine whether or not they may be a hazard to the fuel system, or any other component to which the circuits may be connected.

As part of a research program, sponsored by NASA, to evaluate the characteristics of induced voltages in representative types of aircraft electrical circuits, the General Electric High Voltage Laboratory made a series of measurements of lightning-induced voltages in the fuel system electrical circuits within the wing of an aircraft. From these measurements, mathematical expressions for these voltages were derived, relating them to the causative lightning current parameters.

With this information at hand, further analysis was undertaken to consider the possible effects of these induced voltages upon the fuel system. This paper briefly describes the experimental procedures and results, as well as the analysis of possible effects on the fuel system.

Experimental Procedures

Test Object

The right-hand wing of an F89-J (Scorpion) fighter aircraft was utilized as the test object for this investigation. A wing was chosen because it is among the locations most frequently struck by lightning, and lightning currents must flow along the length of the wing to reach the other extremities of the aircraft from which the stroke would leave. Much of the fuel system and associated electrical components of interest are present in a wing. The F89-J wing, shown in Figure 1, is also equipped with a 600-gallon tip fuel tank and an underwing pylon. The tip fuel tank is mounted on the wing by two bolts and a pin, and flexible fuel hose and electrical cables provide necessary connections between the wing and tip tank.

The wing is of full cantilever, multispar construction using heavy, tapered alclad skin. This skin, tapered in the lengthwise direction, is generally of substantial thickness, as required by the mission of the aircraft. Skin thicknesses ranged between 0.051 inch for the trailing edge sections to 0.291 inch for several of the inboard main panels. Panels covering the fuel cells ranged in thickness between 0.154 inch and 0.230 inch. These thicknesses are greater than some of those found in more recent commercial or military aircraft. As a result, the electromagnetic shielding effectiveness of this wing is likely to be greater than that of a wing plated with thinner skins. The outer wing panels are reinforced with aluminum honeycomb. A more complete description of the wing is given in References 1 and 2.

There are a total of twenty-nine functional electrical circuits within this wing, consisting of from one to twenty or more conductors each. The circuits generally run from connectors within the root end of the wing to various electrical components in the wing. Electrical return paths may be through the airframe or through a separate conductor. Of these circuits, three are directly associated with the fuel system. These include the fuel quantity indication, fuel vent valve and wing tank booster pump circuits. A general description of these circuits is given in the following table.

Fuel System Electrical Circuits

Circuit Code	Name (Function)	General Location	Return Path	Shielding	Comments
E.0710	Fuel Quantity Indication	Leading and trailing edges, fuel cells and tip tank	Isolated conductors	Individual coaxial shielded	Connects fuel measurement probes to capacitance bridge
Q.0401	Fuel Vent Valves	Fuel cells and wing tip	Airframe	Conduit in fuel cells	Operates fuel vent valve
Q.060	Wing Tank Booster Pumps	Center and fuel cells	Airframe	Conduit in fuel cells	Operates fuel tank booster pumps

In this program, measurements were made of voltages induced in each of these circuits as a result of simulated lightning currents flowing through the wing.

Test Setup

To permit passage of simulated lightning currents through the wing, the wing was positioned in a test bay of the High Voltage Laboratory with its tip above the lightning current generator as shown in Figure 1. In this manner, current from the generator could be readily delivered, via a movable electrode, to selected stroke locations on the wing. The root end of the wing was joined to a double-screened instrument enclosure, into which the simulated lightning currents passed from the wing. An aluminum foil return path along the floor connected the screened enclosure with the current generator, completing the circuit. In order to remove current from the wing as naturally as possible, the wing was attached to the instrument enclosure utilizing all of the attachment bolts located at the root end of the wing, in the same manner as the wing would actually be attached to the fuselage.

The induced voltages appearing at the open-circuit terminals of the wing circuits were measured with oscilloscopes located within the instrument enclosure. This enclosure provided a magnetic shielding of the oscilloscopes and measurement leads, into which extraneous voltages could otherwise be induced by the strong magnetic field presented by the lightning currents.

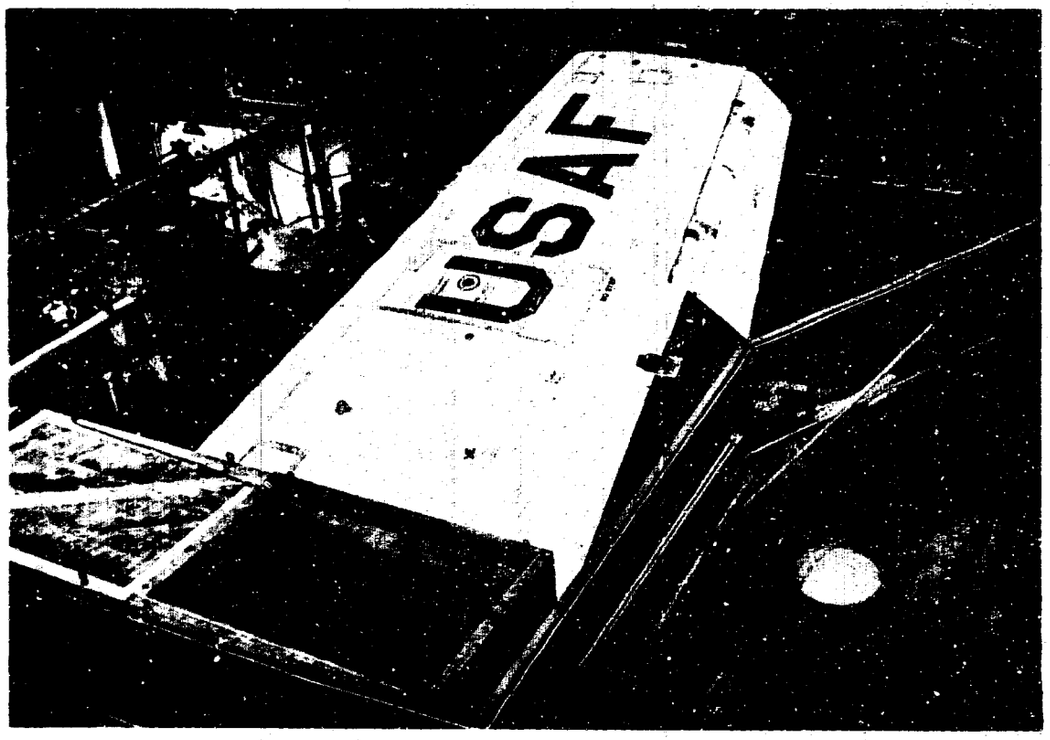


FIGURE 1. - F89J RIGHT WING SHOWN POSITIONED FOR TEST IN HIGH VOLTAGE LABORATORY TEST BAY. LIGHTNING CURRENT GENERATOR IS BENEATH TIP TANK. SCREENED INSTRUMENT ENCLOSURE IS SHOWN AT ROOT OF WING.

Lightning Simulation

The lightning currents which pass through an aircraft when it is struck by lightning are believed to be a combination (ref. 3, 4) of high-amplitude, short-duration "strokes" and low-amplitude, long-duration "continuing currents". The continuing currents are known to produce thermal erosion and resultant damage to aircraft skins (ref. 5, 6). However, these currents create comparatively little magnetic flux, and that which is created does not change rapidly. Accordingly, these currents cannot produce significant induced voltages in internal circuitry. For this reason, continuing currents were not simulated in this program.

The high-amplitude, short-duration strokes, however, may have very high rates of rise, and the resultant rapidly-changing magnetic flux (ϕ) can induce large voltages in magnetically coupled circuits, since

$$E_{induced} = \frac{d\phi}{dt}$$

Therefore, the high-amplitude, short-duration strokes were simulated for all of the tests in this program.

The simulated lightning currents were delivered to the wing by means of an arc approximately 8 inches long from an electrode positioned adjacent to desired stroke locations on the wing or tip tank. Since natural lightning strokes may vary in wave shape, amplitude, polarity and attachment location, it was desired to evaluate, insofar as possible, the effect of each of these variables upon the voltages induced in the wing circuits. Initially, a series of preliminary tests were run to establish whether the amplitude of induced voltage was directly proportional to the amplitude of simulated lightning current. Results of these tests showed this to be the case, and henceforth all tests were made at a single amplitude of 40 kiloamperes. This level was chosen as it is near the center of the range of measured natural lightning current amplitudes.

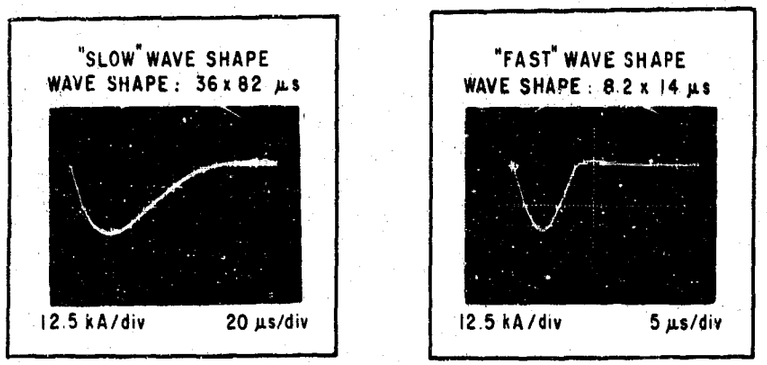
Because magnetically-induced voltages are proportional to the rate of change of magnetic flux linking a circuit, the effect of variations in lightning current wave shape (rate of rise and decay of current) are of considerable interest. Accordingly, measurements were made on each circuit of the voltages induced by currents with the following two wave shapes:

"Slow" Wave Shape = 36 x 82 μs

"Fast" Wave Shape = 8.2 x 14 μs

Each of these wave shapes is within the range of wave shapes measured from natural lightning strokes (ref. 7). Figure 2 shows oscillograms of each of these wave shapes. In the above notation, the first number defines the time from zero to the wave "crest", while the second number defines the time from zero to 50% amplitude on the wave "tail". The 8.2 x 14 μs stroke provided a rate of change of current with respect to time (di/dt) of 8 kiloamperes per microsecond which is four times as fast as that characteristic

of the 36 x 82 μs stroke (2 kA/μs).



SIMULATED LIGHTNING CURRENT WAVE SHAPES

FIGURE 2

To enable evaluation of the relationship between stroke attachment location and induced effects, identical strokes were applied to each of 5 locations on the wing. These included the forward end of the tip fuel tank, outboard and inboard ends of leading edge, outboard trailing edge of aileron, and the bottom center of the wing. Induced voltage measurements were made in each circuit for strokes delivered to each of these locations.

Experimental Results

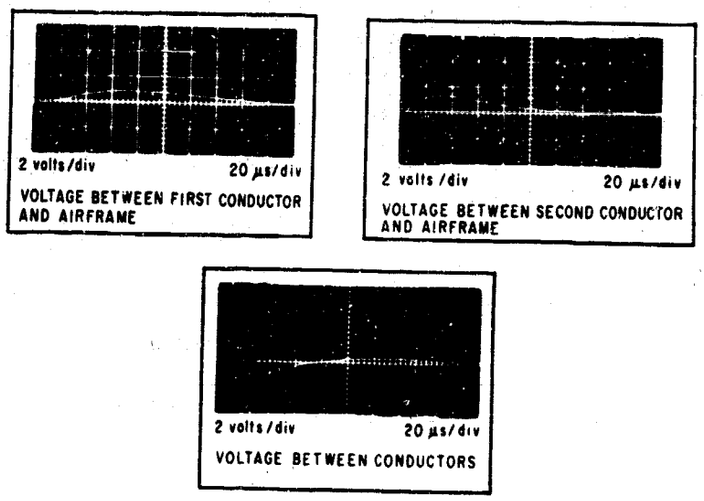
The maximum amplitudes of all induced voltage measurements made at each of the fuel system circuits are tabulated in Reference 1. However, the following paragraphs summarize the voltages measured, and discuss other interesting results.

Circuit E.0711 Fuel Quantity Indication

This circuit connects the fuel quantity probes located in the wing and wing tip fuel tanks to the capacitance bridge fuel quantity indication system within the fuselage. The fuel quantity probes are of the concentric cylinder type, with a dry capacitance of 15 picofarads. Variations in the height of the fuel between the cylinders result in changes in probe capacitance, the value of which is continuously measured by the bridge system and translated

into an indication of fuel quantity. The circuit operates at very low voltage and is entirely isolated from the airframe. Two shielded conductors connect each probe, and some probes are connected in parallel. There are three pairs of shielded conductors in the circuit. The shields are connected to the airframe via the probe frames, and also incidentally as they pass through bulkheads in the wing. Since the circuit employs isolated return paths, induced voltage measurements were made between each conductor pair and between each conductor of a pair and the airframe. The measured open-circuit voltages in all cases ranged between ±3 volts under all test conditions. Little variation was evident in the amplitude of induced voltages as a result of stroke location or wave shape variations. This result is attributable to the extensive shielding provided these circuits, and to the use of isolated (and shielded) return paths.

Figure 3 shows an example of the measurements made on one conductor pair, illustrating the voltage measured between the pair, and between each conductor and the airframe. By definition, the difference between each of the conductor voltages to ground must equal the voltage between conductors. This relationship is apparent from the oscillograms of Figure 3.



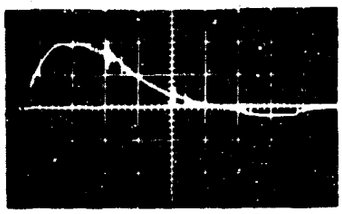
CONDUCTOR-TO-AIRFRAME AND CONDUCTOR-TO-CONDUCTOR INDUCED VOLTAGES IN INBOARD FUEL PROBE CIRCUIT RESULTING FROM 40 kA 36 x 82 µs STROKE TO INBOARD LEADING EDGE OF WING

FIGURE 3

The voltage wave shape of Figure 3 is nearly identical to that of the lightning current itself (36 x 82 μs), indicating a capacitance coupling between this conductor and the resistive voltage rise occurring in the airframe. The other conductor shows a delayed and sloped-off wave shape as compared with the lightning wave. This appears to represent a delayed capacitive coupling with the wing resistive voltage rise, possibly because this connector is connected to the inner concentric cylinder of the probe.

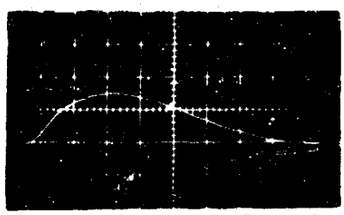
The (short circuit) currents flowing through the conductor shields to the airframe at the wing root were also measured, as was the voltage between the shields and the airframe when the shields were disconnected from the airframe at the wing root. Figure 4 shows an example of these measurements. It is interesting to note that, even though the shields are grounded to the airframe at several locations, a short-circuit current of approximately 15 amperes was measured. The wave shape of the current oscillogram (Figure 4) is nearly identical to that of the applied lightning current, indicating that this current is directly conducted into the shield and not magnetically coupled.

Due to the very high impedance of the fuel probe circuits it was not possible to measure any short-circuit currents associated with the circuit conductors.



1 volt/DIV 20 μs/DIV

OPEN CIRCUIT INDUCED VOLTAGE
(SHIELD TO AIRFRAME)



10 amps/DIV 20 μs/DIV

SHORT CIRCUIT CURRENT
(SHIELD TO AIRFRAME)

INDUCED VOLTAGE AND CURRENT IN A SHIELD OF TIP TANK FUEL PROBE CIRCUIT, RESULTING FROM 40 kA 36 x 82 μs STROKE TO FORWARD END OF TIP TANK

FIGURE 4

Circuit Q.0401 Fuel Vent Valves

This circuit conducts power to the solenoid-operated fuel vent valve located on the lower surface of the outer wing. It passes along a circuitous route through conduits extending through the forward and aft fuel cells, and between, as shown in Figure 9. The circuit applies power through a single conductor to close the normally open solenoid fuel vent valve prior to firing of rockets from the pylon. It uses the airframe as its return path. The conductor is not exposed and, due to its passage through conduits within the fuel cells, it receives some shielding not afforded some other wing circuits.

The voltages induced in this circuit showed greater apparent relationship to test condition variations than did those measured in the fuel probe circuit. This is probably due to the greater magnetic flux coupling that is permitted by the use of the airframe path, as compared with the fuel-gauge circuits which have parallel return conductors. For this same reason, the voltage amplitudes were somewhat greater. Voltage amplitudes arising from the "slow" lightning wave ranged from 1.8 to 2.8 volts, while fast wave created induced voltages of between 1.9 and 6.5 volts. Due to the large inductance of the valve solenoid coil, very little short-circuit current was measured.

As in other circuits employing the wing as the return path, the induced voltages consisted of a resistive as well as an inductive component. The inductive component was predominant in voltages induced by the fast lightning current wave form.

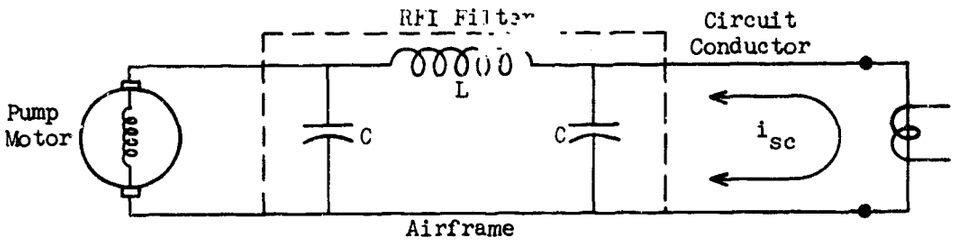
Circuit Q.060 Wing Tank Booster Pumps

This circuit, shown in Figure 10, conducts power via two individual conductors to two respective fuel pump motors. The 28 volt d-c motors are equipped with radio frequency interference (RFI) noise filters to eliminate motor noise from interfering with other aircraft circuits and communication systems. The electrical description of these filters was not obtainable; however, it is assumed that they were a standard pi-type filter employing a series inductance together with a pair of shunt capacitors.

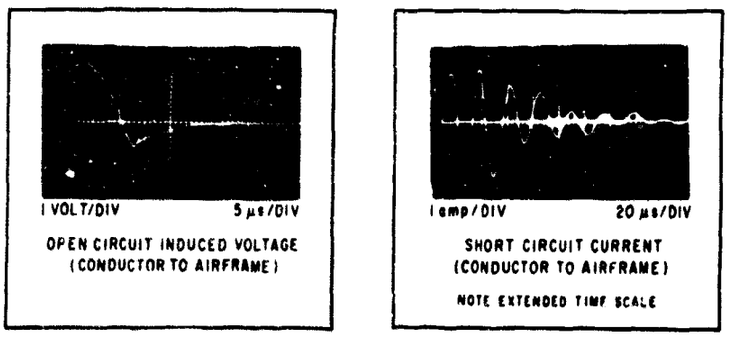
Open-circuit induced voltage measurements showed relationships between induced voltages and test conditions similar to those found in other circuits employing the airframe as a return path. Since both of these pump motor circuits extended only a short way out into the wing, variations in stroke locations farther out on the wing did not significantly change the magnitude or wave shape of voltages induced in these circuits. Strokes to the locations nearest the circuits resulted in the highest induced voltages, as might be expected.

The induced voltage wave forms exhibited the same combination of resistive and inductive components which had been evidenced in other circuits using the airframe as the return path. The inductive component was predominant in voltages induced by the fast lightning wave forms. An example of such a voltage is shown in Figure 5. Also shown is the corresponding short-

circuit current measurement. This current oscillates for an extended time, far exceeding the duration of the induced voltage itself. The short-circuit current oscillation is probably flowing between the inductive and capacitive elements in the circuit, as shown below:



It is believed that the RFI filter is located next to the pump motor, so that voltage is primarily being induced in the circuit conductor between the filter and the terminals at the wing root, where the voltage was measured. When these circuits are shorted together, the major portion of this voltage is impressed across the filter. This voltage stores energy in the filter capacitances, exciting an oscillation between the L and C elements of the circuit which persists long after the exciting (induced) voltage has vanished. This phenomena was observed only in circuits such as this one, which has both inductive and capacitive elements. This is an example of where the addition of a filter to eliminate one type of interference (motor noise) may aggravate the effect of interference created by another source (lightning).



INDUCED VOLTAGE AND CURRENT IN BOOSTER PUMP CIRCUIT RESULTING FROM 40 kA 8.2 x 14 μs STROKE TO INBOARD LEADING EDGE OF WING

FIGURE 5

Since these tests were made with the motor inoperative, it was decided to perform a comparison test with the motor operating, to see if this condition had any effect upon the level of induced voltages. For this purpose, a 24-volt battery was attached to the circuit terminals, and the motor was operated. Measurements were made of the induced voltage and current across the battery. Since the resistance of the battery was very low, ($\approx$ .05 ohm), the induced current measured thus constituted very nearly the short-circuit current. The current measured through the battery compared closely in amplitude and wave shape with the short-circuit current previously measured. Hence, the operating condition of the pump motor does not affect the voltages induced in the circuit.

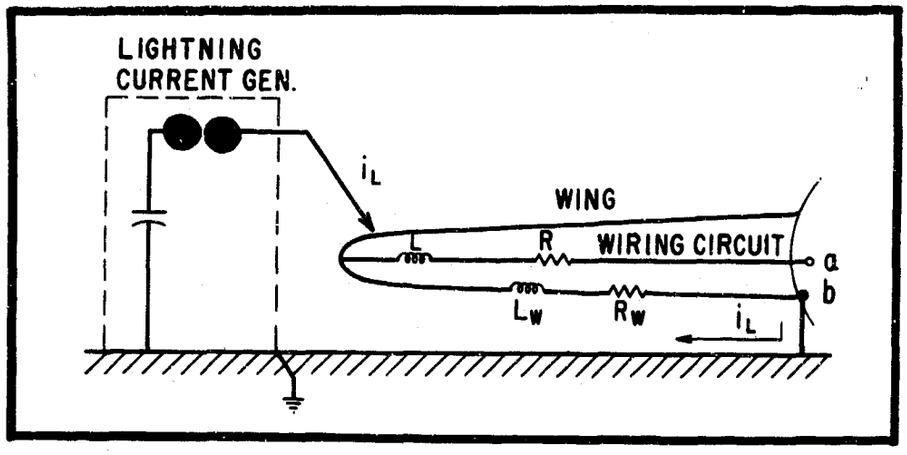
Analysis of Induced Voltages

In order to determine quantitative relationships between the induced voltages and various wing or lightning current parameters, it is necessary to describe these voltages mathematically, preferably by means of an expression itself a function of significant lightning current or wing parameters.

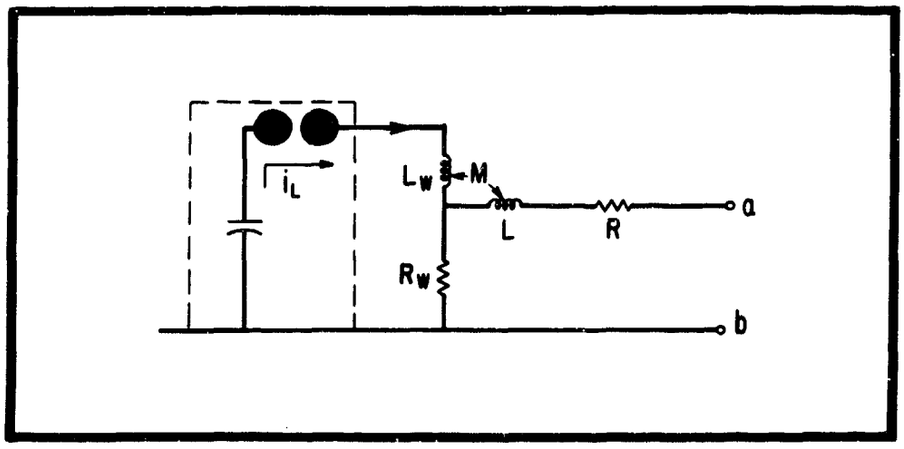
To determine such an expression, consider Figure 6 in which the wing and a hypothetical circuit within are represented electrically by lumped impedances. The components R_w and L_w are the equivalent resistance and inductance, respectively, of the wing structure and skin, while the components R and L are representative of the electrical circuit within the wing. The circuit shown employs the airframe as its return path. These elements are rearranged more clearly in the equivalent circuit representation also shown in Figure 6. In this figure the magnetic coupling effect between the wing inductance and that of the electrical circuit within the wing is represented by the mutual inductance M. Also shown is the path of the lightning current, i_L, and the resultant induced voltage, e_{oc}, measured at the open wing circuit terminals. From this representation it can be seen that the induced voltage, e_{oc}, can be expressed as:

$$e_{oc} = R_w i_L + M \frac{di_L}{dt} \qquad (1)$$

as shown in Figure 6.



TEST CONFIGURATION



SIMPLIFIED CIRCUIT REPRESENTATION

FIGURE 6

This is an expression for e_{oc} in terms of the lightning current and its derivative (both are time-varying functions) and two other parameters, R_w and M, dependent presumably only upon characteristics of the wing and the particular electrical circuit. Since the simulated lightning current i_L is known and can be described mathematically, it is only necessary to obtain values for the parameters R_w and M before an expression for e_{oc} is completely defined. From the experimental results, it is obvious that e_{oc} is not identical for all wing circuits or test conditions, even if the applied lightning stroke is unchanged. Therefore, the parameters R_w and M cannot be the same for all conditions, but must be dependent upon such factors as stroke location and circuit characteristics.

If i_L is known and values of e_{oc} for all discrete times are obtainable from the experimental measurement e_{oc}, then equation (1) is an equation in two unknowns, R_w and M. Since e_{oc} and i_L are time-varying functions, but R_w and M are presumably not, equation (1) can be written at two discrete times, resulting in a set of simultaneous equations which can be solved for R_w and M. Selection of appropriate discrete times is facilitated by reference to Figure 7, which shows a typical lightning current and resulting open-circuit induced voltage wave forms. If equation (1) is assumed to be valid for e_{oc}, then:

$$e_{oc} = R_w i_L + M \frac{di_L}{dt} \tag{1}$$

At $t = T_1$, the lightning current is unchanging; therefore,

$$\frac{di_L}{dt} = 0 \tag{2}$$

and

$$e_{oc} = R_w i_L \Big|_{t = T_1} \tag{3}$$

from which

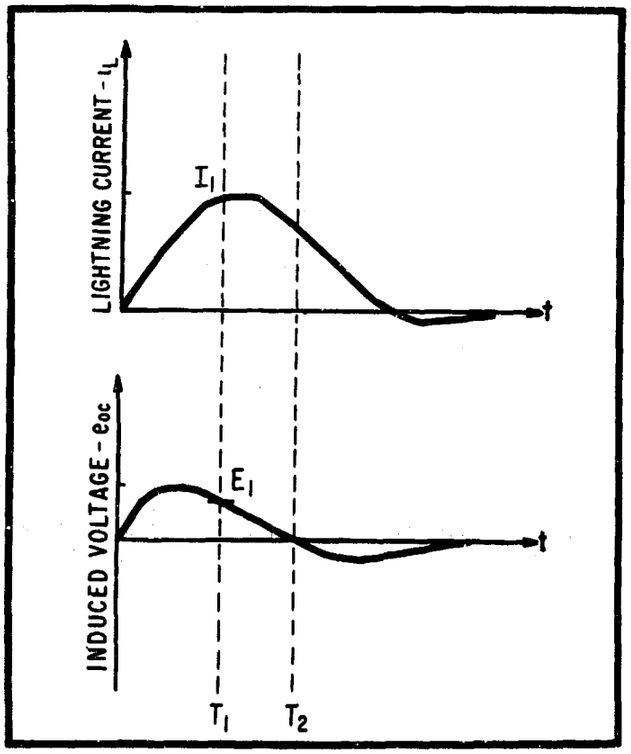
$$R_w = \frac{e_{oc}}{i_L}\Big|_{t = T_1} \tag{4}$$

which gives the solution for R_w. At $t = T_2$, the induced voltage is zero; therefore,

$$e_{oc} = 0 \tag{5}$$

and

$$0 = R_w i_L + M \frac{di_L}{dt}\Big|_{t = T_2} \tag{6}$$



$$e_{oc} = R_W i_L + M \frac{d}{dt}(i_L)$$

AT T_1: $\frac{d}{dt}(I_L) = 0$ $\quad R_W = \frac{E_1}{I_1}$

AT T_2: $e_{oc} = 0$ $\quad M = -R_W i_L / \frac{d}{dt}(i_L)$

DETERMINATION OF EFFECTIVE WING RESISTANCE (R_W) AND MUTUAL INDUCTANCE (M) FROM EXPERIMENTAL DATA

FIGURE 7

from which

$$M = -R_w \left. \frac{di_L}{dt} \right|_{t = T_2} \qquad (7)$$

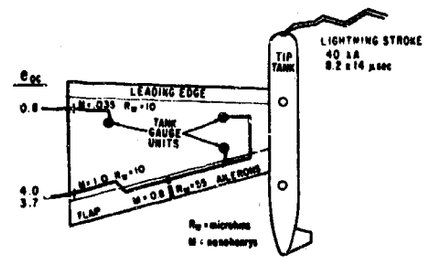
where R_w has been obtained from equation (3).

Thus, from an expression for the lightning current and two discrete voltage values from the measured open-circuit voltage oscillogram, a mathematical expression for the complete induced voltage wave form is obtained, in the form of equation (1). This expression was then used to calculate e_T for all values of time, and the resulting calculated wave form, e_T, was then compared with the actual measured wave form, e_{oc}, for verification. Close agreement between the calculated and measured wave forms in nearly all cases proved that this is a valid technique for generating an expression for the induced voltage e_{oc}.

In order to calculate R_w and M for each circuit and set of test conditions applied, a computer program entitled "ETCAL" was written for use on the General Electric time-sharing computer system. From the simple input values of $e_{oc}(T_1)$ and $i_L(T_2)$ obtained from the measured oscillograms, ETCAL produces R_w and M and thus an expression for e_{oc} in the form of equation (1).

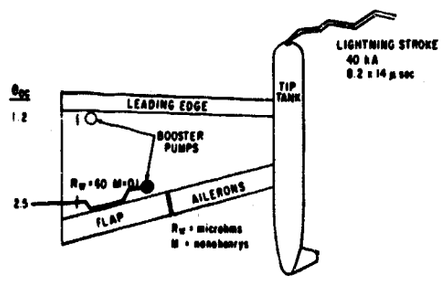
Equation (1) illustrates that the wave form of the complete "induced" voltage is really a combination of two component voltage wave forms. One is a resistive voltage rise proportional to and in phase with the lightning current wave form. The other is a magnetically-induced voltage proportional to the time derivative (rate of change) of the lightning current. The proportionality constants are the effective wing electrical parameters R_w and M, which represent effectively a wing resistance and mutual inductance with the electrical circuit in question. As would be expected, these latter quantities are not the same for all test conditions (even for the same wing circuit).

There is, in fact, considerable variation among values of R_w and M for each circuit, and also for different stroke locations when measurements were made upon the same circuit. Since both R_w and M must be functions of the effective lightning current path through the wing and its relation to the particular wing electrical circuit, these variations seem natural. For example, some interesting relationships exist between values of R_w and M and the wing circuits or test conditions. The first of these is the tendency for both R_w and M to increase as the length of the aircraft electrical circuit increases. This is logical since the circuit parallels a greater resistive voltage drop along the wing, and links a greater amount of magnetic flux generated by the lightning current. Examples of these relationships are apparent in Figures 8, 9 and 10 which show the values of R_w and M derived for each of the three circuits associated with the fuel system. These figures also show the peak values of the induced voltages generated by the 8.2 x 14 μs simulated lightning current when delivered to the tip tank.



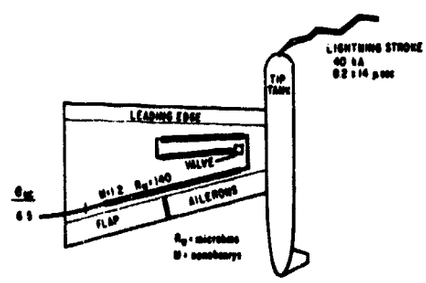
FUEL QUANTITY INDICATION CIRCUITS
- MUTUAL INDUCTANCES WITH RESPECT TO LIGHTNING CURRENT FLOW
- INDUCED VOLTAGES AT OPEN CIRCUIT TERMINALS

FIGURE 8



FUEL BOOSTER PUMP CIRCUITS
- MUTUAL INDUCTANCES WITH RESPECT TO LIGHTNING CURRENT FLOW
- INDUCED VOLTAGES AT OPEN CIRCUIT TERMINALS

FIGURE 9



FUEL VENT VALVE CIRCUIT
- MUTUAL INDUCTANCES WITH RESPECT TO LIGHTNING CURRENT FLOW
- INDUCED VOLTAGES AT OPEN CIRCUIT TERMINALS

FIGURE 10

It can be seen from these figures that even the faster of the two test strokes applied during this program did not generate appreciable voltages in any of the fuel system circuits. As compared with voltages induced in some other electrical circuits within this wing, the voltages induced in these circuits were among the lowest. Several factors probably account for this. In each case, the circuits are afforded greater electromagnetic shielding than is present for many other circuits. The conductors leading to the fuel gauge probe units, for example, are individually shielded. In addition, the circuit is entirely isolated from the airframe. Both the fuel vent valve and booster pump circuits do utilize the airframe as return path, thereby permitting direct coupling of the wing resistive voltage rise; however, in the case of the fuel vent valve, the circuit conductor is well shielded by virtue of its passage through conduits within the fuel cells, as shown in Figure 9. The booster pump circuits, while not as completely shielded as the others, are shorter in length and thus are less susceptible to induced or resistive voltages.

Discussion of Results

In determining if induced voltages may present a hazard to the fuel system, there are two basic areas of concern. First, and most important, is the possibility of electrical sparking within a fuel vapor area. Second, is the possibility of damage or interference with avionics or other electronic equipment to which the circuits might be connected elsewhere in the aircraft. The sparking possibility is of more serious concern, since ignition of fuel vapors may be catastrophic.

From the measurements made in this program it is evident that no voltages were induced of great enough magnitude to cause insulation breakdown, arcing across air gaps or any other phenomena creating sparking. Even the "fast" wave form created no voltage greater than 6.5 volts in any of the three circuits. This wave form, however, with a maximum rate of rise of 8 kiloamperes per microsecond is not nearly as fast as some naturally occurring lightning strokes. For example, Figure 11 shows probability distributions of lightning current rates of rise and amplitudes, based on

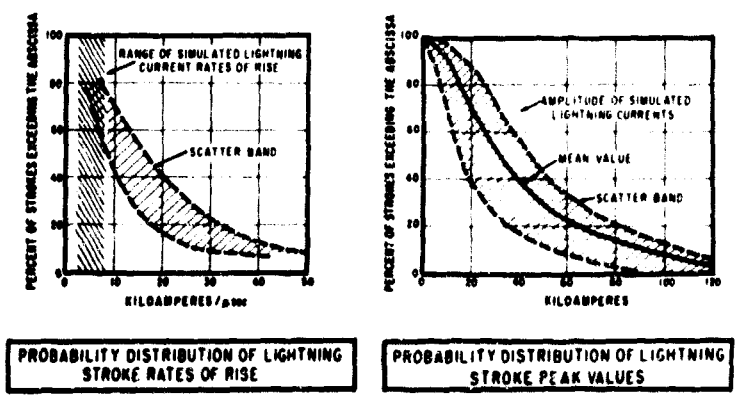
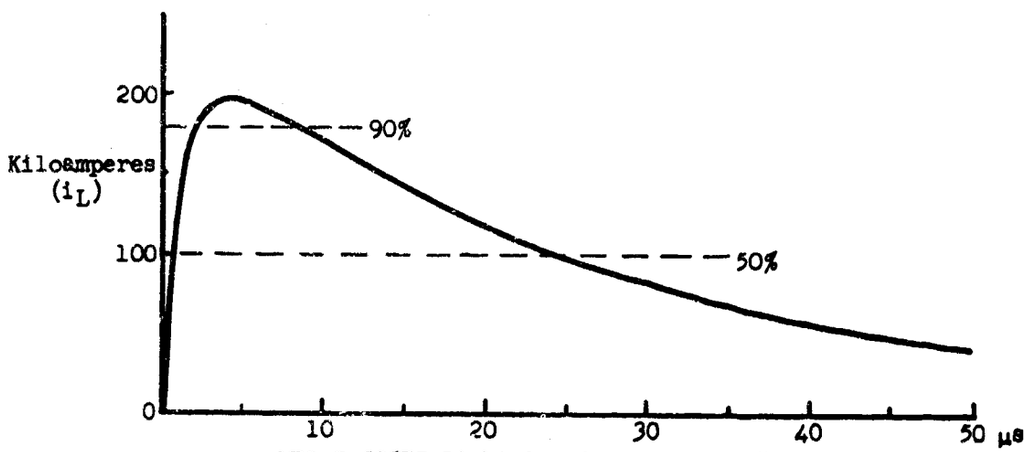


FIGURE 11

measured characteristics of natural strokes. From this figure it is apparent that natural lightning strokes considerably greater in amplitude and rate of rise than those simulated in these tests may exist. To determine the magnitude of induced voltages a very severe lightning stroke might cause, the parameters of a severe stroke were used as inputs to the ETCAL program, together with the R_W and M values determined, as previously described, from voltages induced by the test wave forms. As an example of a severe lightning stroke, the test wave form specified in MIL-B-5087B, Para. 3.3.4.5, was utilized. MIL-B-5087B, which is the military specification for electrical bonding and lightning protection for aerospace systems, specifies in Para. 3.3.4.5 that:

> "Laboratory tests of lightning protection provisions for external sections, such as radomes and canopies, shall be performed to demonstrate adequate protection. The test wave form shall have a peak value of 200,000 amperes, a width of 5 to 10 microseconds at the 90-percent point, and not less than 20 microseconds width at the 50-percent point at the rate of rise of 100,000 amperes per microsecond."

Such a wave shape would look like:



MIL-B-5087B Lightning Current Test Wave Form

The equation for the wave shown above is:

$$i_L = 241\left(e^{-.035t} - e^{-.805t}\right) \quad \text{(kiloamperes)}$$

where t is expressed in microseconds.

If this wave were applied to the forward end of the tip tank, and it is assumed that R_W and M remain the same as determined from the measured data, the maximum induced voltages in the circuits, calculated by the ETCAL program, would be as shown in Table I.

TABLE I

COMPARISON OF VOLTAGES INDUCED BY MODERATE AND SEVERE LIGHTNING STROKES

Circuit Description	Effective Wing Impedance[1]		Open Circuit Induced Voltages	
	R_W Microhms	M Nanohenrys	Test Wave Form[2]	MIL-B-5087B Wave Form
Fuel Gauges				
• Inboard Units	10	0.071	0.8	13.2
• Outboard Units	75	1.0	4.0	185.6
• Tip Tank Units	55	0.8	3.7	148.5
Booster Pumps				
• Leading Edge	--	--	1.2	--
• Trailing Edge	60	0.1	2.5	18.6
Vent Solenoid Valve	140	-1.2	6.5	223.0

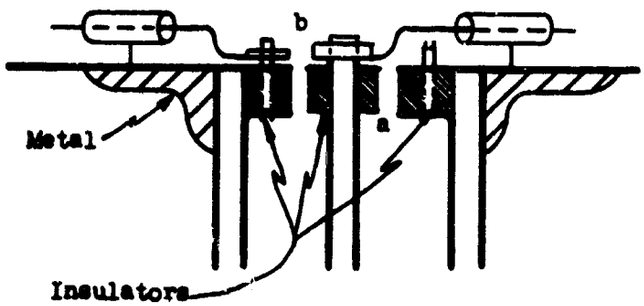
1. Measured from voltage induced by test wave. Some variations occurred for other wave shapes.

2. 8.2 x 14 μs

From these calculations it is apparent that the severe lightning current wave shape of MIL-B-5087B will be expected to induce voltages many times greater than those caused by the moderate 40-kiloampere strokes applied in these tests. Even these voltages, however, apparently do not exceed several hundred volts. Voltages of this level may be a hazard to sensitive avionics equipments making use of solid-state devices or microcircuitry; however, these voltages are still unlikely to cause insulation failure or sparking across air gaps, unless such gaps are very small (i.e. loose connections and bonds, etc.).

In the three circuits under consideration, the components most likely to permit any sparking appear to be the fuel gauge tank units. These capacitance-type probes have electrodes separated at varying distances from each other, as shown in the following sketch.

Tank Gauge Unit



To determine the voltage level at which sparking may occur in such a unit, one of the units from the F89-J wing was removed and subjected to transient voltage withstand and sparkover tests. Transient voltages were applied between each electrode and between electrodes and the airframe, corresponding to the manner in which induced voltages might also be applied in service, as shown on Figure 8. Voltages rising to crest in one microsecond were applied, corresponding to the rise time of the induced voltages calculated (Table I) for the MIL-B-5087B lightning current wave form. No sparking occurred until a voltage of 12 kilovolts was reached, at which level sparking occurred inside the probe, at location "a" between the center electrode and inner cylinder, and also on "outside" of the unit, at location "b", between the connecting lugs for the center electrode and the inner cylinder. No flammable fuel-air vapor was present for this test, so it is not known whether a flame, if ignited inside the unit, could propagate outside to the surrounding fuel tank area. In any event, the 12,000 volts required to create sparking is much greater than the voltages induced even by the severe MIL-B-5087B wave form; hence, the possibility of any sparking occurring in the tank units within this aircraft must be considered as very remote.

Conclusions

From the measurements made in this program, there is no reason to conclude that lightning may induce voltages sufficient to cause sparking in the fuel system electrical circuits or components within the F89-J. The circuits are sufficiently shielded and safely routed so that they are not susceptible to severe induced voltages. If similar techniques are utilized in other aircraft, a similar situation is likely to exist, although variations in the characteristics of different aircraft can cause greater or lower voltages to be induced in the circuits thereof. In particular, greater voltages are likely to appear in circuits of aircraft larger than the F89-J, or which utilize metallic skins thinner than those of the F89-J.

The more likely hazard to be expected from voltages induced in fuel system electrical circuits of aircraft such as the F89-J may be interference or damage to avionics equipments. In the particular case of the F89-J and aircraft of a similar vintage, extensive use of vacuum tube circuitry in avionics makes this equipment inherently able to withstand larger transient overvoltages. The increasing use of solid-state devices and microcircuitry in present-day avionics makes this equipment much more susceptible to transient overvoltages, particularly of magnitudes of several hundred volts or more, which are possible in these circuits, as shown in Table I .

Accordingly, it is strongly recommended that aircraft designers continually be aware of the possibility of lightning-induced voltages and undertake measures to control them and assure that they will create no hazardous effects. Continually changing aircraft designs can result in unsuspected hazards where none previously existed, unless the designer is continually aware of this possibility.

Since this paper has intended to present only the phenomena of lightning-induced voltages in electrical circuits, the possible hazards created by resistive and inductive voltage rises resulting from lightning current flow through or between structural members have not been discussed. These possibilities are of equal or greater concern, as are the possibilities of fuel vapor

ignition via hot-spot formation on the tank skin or vent efflux ignition. Any complete lightning protection program must consider all of these possible hazards.

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Acknowledgments

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FAA DC-9 Liquid Nitrogen Fuel Tank Inerting Program

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Engineering and Safety Division
Aircraft Development Service

Presentation at the FAA Conference on Fuel System Fire Safety, 6 and 7 May 1970, Washington, D.C.

The Aircraft Development Service of the FAA recently awarded a contract to the Systems Division of Parker Hannifin Corporation for a nitrogen fuel tank inerting system to be installed in the FAA DC-9-15 (Series 10) airplane which is used for air carrier inspector training at the Aeronautical Center in Oklahoma City. This system will consist of qualified components and will be demonstrated to comply with all applicable airworthiness standards of Part 25 of the Federal Aviation Regulations for transport category airplanes. Following supplemental type certification of the inerting system in the DC-9, the airplane shall continue to be used in its normal missions with the inerting system in operation in order to evaluate its functional characteristics and determine whether it is feasible and viable for commercial air carrier service.

A schematic of the proposed system which will be installed in the DC-9 and subjected to subsequent evaluation by personnel from the FAA Los Angeles Office is shown in Figure 1. Every attempt was made in developing the contractual work statement and in the initial system design to provide for a system that can be certificated, but it is possible that some changes may have to be made to the configuration shown in Figure 1 following detailed evaluation and testing.

The inerting system will replace oxygen in the fuel tank vapor spaces and vent lines with nitrogen so that the oxygen concentration will normally be 8 percent by volume or less under all flight and ground conditions. This design concentration was selected with a degree of conservatism to assure that the 9 percent maximum concentration contractual requirement is met. This 9 percent requirement in itself was conservative since an 11 percent concentration is nonflammable at 80°F. Based upon conservative extrapolation of the lower safe flammability limits from available data, 8 percent is the oxygen lean limit at sea level to obtain a nonflammable vapor space at a vapor temperature of 300°F, while 9 percent is the limit at 200°F. Some investigators have suggested that 9 percent may be a safe limit even at 300°F and about 10 percent at 200°F. The 8 percent system concentration will provide for protection in the event flames enter the vent outlet after the vapor temperature has been increased as a result of a ground fire.

The functions of the DC-9 inerting system are the same as the system previously tested in a C-141 airplane and serve to reduce the oxygen concentration in the vapor spaces and vent lines which is normally caused by the entrance of air into the tanks as fuel is consumed or when the airplane descends and by the oxygen dissolved in the fuel prior to fueling the airplane. The system discharges liquid nitrogen into the main tanks

through fog nozzles during level flight, descent, and taxiing as fuel is consumed to keep the tanks and vent lines pressurized with nitrogen to about 0.1 psig which enables vent valves at the vent outlets to close and prevents air from entering the tanks. The fog nozzles discharge a small amount of nitrogen during cruise and the major amount during descent to maintain this positive pressure as atmospheric pressure increases. It removes dissolved oxygen from the fuel through the use of a proprietary refueling process and scrub nozzles located in each baffled section of the fuel tanks and in the center tank. The scrubbing system discharges nitrogen through the fuel during climb to reduce the oxygen released from the fuel during climb to a safe level. The vent valves open at 0.2 psig to vent the gases overboard. Nitrogen will not be discharged into the tanks by the scrub nozzles and the fog nozzles simultaneously.

The discharge of nitrogen into the fuel tanks is controlled by a single stage pressure regulator. This regulator senses pressure on both sides of the vent valves and introduces vaporized nitrogen through the fog nozzles as required to maintain a positive internal tank pressure of 0.1 psig. In case this regulator should fail open, a second identical regulator called the pressure limiter is mounted in series upstream of the first. This second regulator or pressure limiter senses the discharge pressure of the first regulator. As long as the discharge pressure is below 1.5 psig, the pressure limiter remains wide open. Should the pressure rise above 1.5 psig, the pressure limiter will start to close and will stop all liquid nitrogen flow at 1.9 psig. In case both regulators should fail open, an overboard relief valve is installed in the discharge line from the regulators. This relief valve will vent nitrogen to atmosphere to prevent tank pressure from exceeding 2.3 psig.

There are a total of four vent valves, two at each vent outlet. Each valve is capable of flow both inward and outward and is sized to handle the total maximum demand of the system. If fuel tank pressure ever exceeds 0.2 psig, a vent valve will open and allow the gases to pass overboard whether the outflow is a result of climb or pressurization system failure.

To create a pressure of sufficient magnitude within the fuel tanks which could cause structural damage would require:

(a) The failure of two vent valves during climb or descent, or

(b) The failure of two vent valves, two regulators, and a relief valve during steady flight or while on the ground.

It is considered that the probability of either two or five simultaneous failures of these simple mechanical components is highly remote.

Figure 2 shows the inerting system installation in the DC-9. The left and right main tanks each have separate pressure regulators, limiters, and

relief valves since the DC-9 does not have any interconnection between the left and right vent boxes. A fog nozzle is not provided in the center tank which is pressurized by nitrogen through the vent system from the right main tank.

The dewar contains 350 lbs. of liquid nitrogen as shown in Figure 3, which is estimated to be sufficient for an all-day airline operation consisting of six takeoffs and landings. This capacity was offered and accepted as an option to the proposal requirement for a round-robin 3.5 hour cross-country and three landing training mission capability which would have required about 140 pounds of liquid nitrogen and a total system weight of about 350 lbs. The greater optional capacity of liquid nitrogen together with the hardware weight of 241 lbs. results in a total DC-9 installed and serviced system weight of 591 lbs.

All system components will be subjected to appropriate qualification testing according to Specifications MIL-STD-810B and MIL-F-8615C. The endurance and icing tests conducted on the vent valve will exceed these specifications in view of the important function of this component. The endurance test will consist of one million complete cycles of operation instead of the specified one hundred thousand cycles. The performance of the complete system will be demonstrated in a ground test rig under simulated flight and ground conditions and all possible component failures shall be simulated to satisfy the fail-safe requirements of the system.

The inerting system is scheduled to be installed in the DC-9 during January 1971 with issuance of the Supplemental Type Certificate and final acceptance of the system scheduled in May 1971. The contractor will provide engineering support during the system installation and nitrogen servicing assistance and specialized field service support during the flight test program leading to system certification. Operation, service, and maintenance data will be provided for continued operation of the inerting system following certification.

It is planned to obtain additional data beyond that required for certification during the resumed training missions of the DC-9. The liquid nitrogen servicing operations will continue to be monitored and actual consumption will be checked against predicted values. Maintenance requirements will be evaluated and any added benefits, such as removal of dissolved water and reduction of microbiological growth, will be determined. It is intended to "wring out" the system in the FAA DC-9 in a manner similar to an airline service test.

While this effort is related to the DC-9, the program is intended to generate data on nitrogen inerting systems which will be applicable to all turbine-powered aircraft. This program should enable the safety advantages and functional characteristics of an approved production fuel tank nitrogen inerting system to be evaluated and the costs associated with use of the system to be determined.

DC-9 SYSTEM PICTORIAL SCHEMATIC

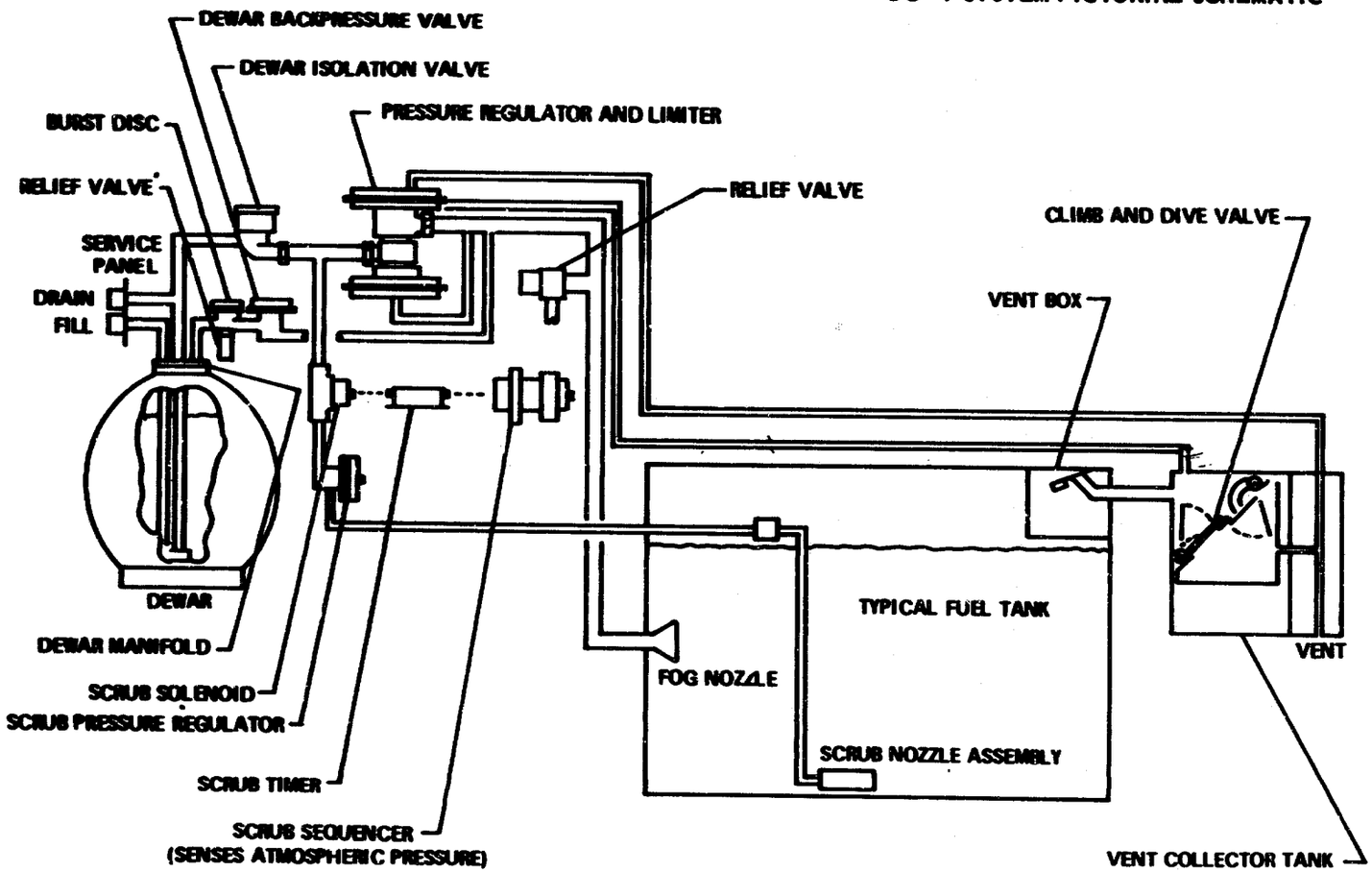

FIGURE 1

DC-9 [illegible] INSTALLATION

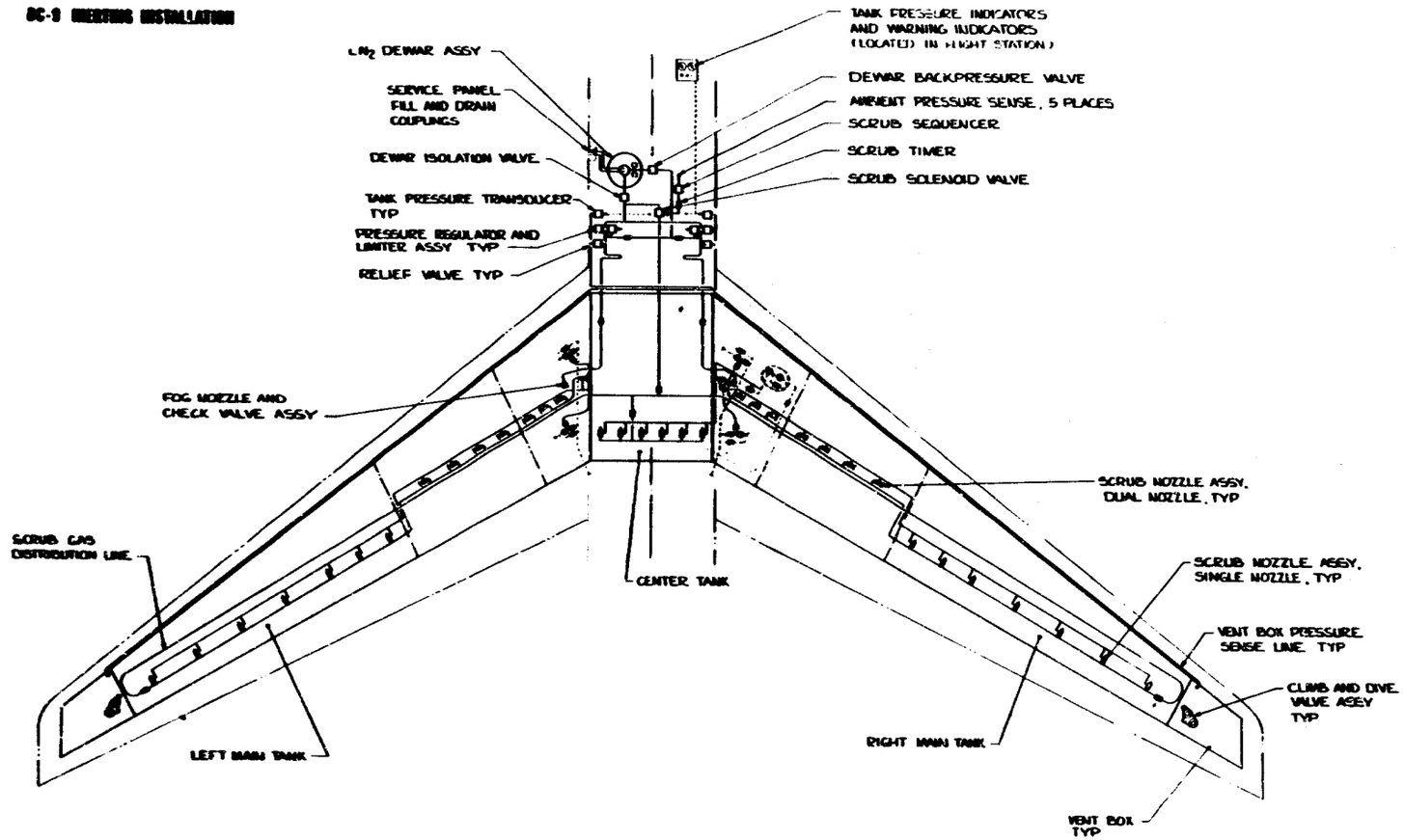

FIGURE 2

DC-9 INERTING SYSTEM WEIGHT

1. SCRUB SYSTEM:	
COMPONENTS	13.8 LB
PLUMBING	38.3 LB
2. PRESSURIZATION SYSTEM:	
COMPONENTS	25.7 LB
PLUMBING	36.5 LB
3. DEWAR, CONTROLS, SERVICING PANEL AND DISPLAYS	107.5 LB
4. DEWAR AND COMPONENTS PLUMBING	19.4 LB
TOTAL DRY WEIGHT	241.2 LB
5. LIQUID NITROGEN	350 0 LB
TOTAL SYSTEM WEIGHT (INSTALLED AND SERVICED)	591.2 LB

FIGURE 3

Resume of Discussion Following Mr. Horeff's Presentation

1. The contract to install an inerting system in the FAA DC-9 had just been awarded with installation due to be completed by February 1971.

2. Preflight checking of the inerting system will be possible. There is to be a preflight checkout display in the cockpit with warning lights for vent valve operation.

3. The estimated weight of an inerting system for the Boeing 747 will be in the ATA report which will be available about June 1970.

4. The DC-9 was reported to carry 1393 gallons of fuel in each main tank and 507 gallons in the center tank.

5. The 350 pounds of LN_2 for the DC-9 installation is in excess of that required by the FAA request for proposal. The 3½ hours round robin mission for the DC-9 used in training by the FAA will require about 140 pounds of LN_2.

6. In reply to a question on how long it will take to get meaningful maintenance data, it was stated that it is expected data would be obtained for a year or two.

7. The Dewar tank will not be made to ICC regulations but will be designed to assure its safe operation under the conditions expected to be experienced in the aircraft.

8. The installation of the nitrogen inerting system will be made either by the FAA at Oklahoma City or by contract to an outside firm. This has not been firmed.

9. The system for the FAA DC-9 will not be operated on a go-no-go basis since it is not required equipment. It was suggested that the system should be operated in such a manner in order to obtain meaningful operating cost data.

10. In a typical FAA training mission, it is expected the airplane will be refueled after each three to three and a half hour flight.

11. In reply to a question on operation of the inerting system with the aircraft on the ground, it was stated that the system will keep the fuel system inerted for at least 24 hours with the airplane unattended.

LIST OF ATTENDEES

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