An Assessment of the Safety of Hydrogen-Fueled Aircraft

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Analysis has shown that liquid hydrogen can be significantly safer than liquid methane and synjet, the other alternative fuels for aircraft. With LH_2 there will be less risk of a major spill occurring in the event of a crash in which passengers can survive the impact. If fuel is spilled, and assuming ignition does not occur, LH_2 will not spread as far before it vaporizes, becomes buoyant, and dissipates in the atmosphere. If the spilled fuel is ignited, as will occur more than 80% of the time with any of the fuels, the resulting hydrogen fire will be of such short duration and will be confined to such a small area that the passenger survival rate can be expected to be much higher.

Introduction

THE year is 1996. You are to fly nonstop from London to Los Angeles on a commercial airliner. You have your choice of four aircraft, all equally pleasant insofar as accommodations, service, cost, and schedule are concerned. The only difference is the fuel used. Would you prefer to make the flight on the aircraft fueled with liquid hydrogen, the one fueled with liquid methane, or the ones fueled, respectively, with Jet A or JP-4. Jet A is the conventional kerosene-type fuel currently used in commercial transports. JP-4 is a more volatile fuel generally characterized as wide-cut gasoline.

Chances are, the average airline passenger would opt for the aircraft fueled with Jet A. Very probably, he would consider liquid hydrogen (LH_2) unsafe.

The unsavory reputation of hydrogen as a dangerous fire hazard was spawned largely by the Hindenburg disaster. This event has remained in the public eye far longer and more importantly than is warranted by the facts of the case. First, by modern-day standards the number of fatalities was rather small (35 out of 97 on board, plus 1 member of the ground crew) and the percent of survivors was high (64%); second, the method of containing the hydrogen on board the airship (as a gas in rubberized cloth bags) bears no relation to the manner in which it would be stored in modern applications. For example, in aircraft the hydrogen will be stored as a saturated liquid in insulated aluminum tanks at a nominal pressure of 21 psia.

Fortunately, the scientific community has recognized the potential advantages of hydrogen for various applications and many have realized that the Hindenburg fire is an anomaly that is not representative of the safety of hydrogen in more modern containment situations. As a result, during the past several years the National Aeronautics and Space Administration has sponsored a number of studies to explore the potential of LH_2, liquid methane (LCH_4) and synthetic aviation-grade jet fuel (synjet) as alternatives to petroleum-derived Jet A for use in future transport aircraft.[1-4] The results have shown that liquid hydrogen offers significant advantages. Some of the more important considerations that would influence a decision to pick LH_2 as the fuel for future transport aircraft are the following:

1) Global availability. It can be made from a renewable resource, water, using any source of energy that might be locally available. Fossil resources are not required. LH_2 is therefore free of the constraints implicit in the other alternative fuels.

2) Pollution. Its major product of combustion is water vapor. It emits none of the noxious effluents of carbon-containing fuels, except a minimum amount of NO_x.

3) Noise. Because they are lighter, LH_2-fueled aircraft will require smaller engines and therefore will produce less noise. The aircraft will be about half as objectionable as corresponding, conventionally fueled aircraft to airport neighbors.

4) Energy. As noted above, fossil materials are not required to manufacture hydrogen. However, since coal can be used as an energy source or as a chemical feedstock to manufacture each of the alternative fuels, it provides a convenient basis for comparison of energy requirements. Fewer tons of coal would be required to produce the fuel used by aircraft to fly their design missions if LH_2 is the fuel.

5) Direct operating cost. LH_2-fueled aircraft can be competitive in DOC using current fuel production technology.[5] With advanced processes LH_2 can offer significant advantages.[6]

Crash Hazard Assessment

In 1981 Lockheed-California Company performed a study for NASA Lewis Research Center to assess the relative safety of LH_2-fueled transport aircraft compared with those designed for other fuels.[7] This study, performed in parallel with one by Arthur D. Little, Inc.,[8] also under contract to NASA Lewis, was a very important first step in a comprehensive evaluation of the safety question. One of the objectives of the work was to outline additional analyses and experiments that are needed to provide a satisfactory data base so more complete and valid conclusions can be reached.

Liquid hydrogen was shown to pose substantially less hazard to passengers as well as to persons and property in surrounding areas in event of a crash. This conclusion stems from the following considerations: 1) in event of a crash in which passengers can reasonably be expected to survive the impact, LH_2 tanks are less apt to be ruptured, thus minimizing spillage potential; 2) in the event a tank is ruptured and fuel is spilled, LH_2 evaporates almost immediately, the gas becomes buoyant very quickly, and it dissipates into the atmosphere so rapidly the time and the area exposed to flammable mixtures are both quite small compared to the other candidate fuels; 3) if the spilled fuel is ignited, the duration of the hydrogen fire would be so brief that it would not heat the fuselage to the point of collapse, as would be the case with the other fuels, and the heat-affected area would be substantially smaller.

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Tank Vulnerability

Let us examine each of these considerations in turn. First, what is the basis for concluding that LH_2 is less apt to be spilled in event of a survivable crash? The answer is associated with the location, geometry, and design of the tanks.

Both of the cryogenic fuels, LH_2 and LCH_4, must be contained in insulated tanks. It is important to minimize the surface area-to-volume ratios of these tanks in order to minimize not only the weight of the tank and insulation system, but also the opportunity for heat to leak into the cold fuel and cause it to vaporize.

As a result, it has been found preferable to locate the tanks for the cryogenic fuels in the fuselage as illustrated in Fig. 1 for a hydrogen-fueled airplane. Two tanks are shown, one located forward and one aft of the passenger compartment. This arrangement has been shown to provide lowest direct operating cost, a realistic measure of aircraft operating efficiency.[1] In contrast, conventional fuel is tanked in the wing between the front and rear spars as illustrated by the shaded area in Fig. 2 for a Jet A-fueled airplane.

The implications of these two different fuel tanking arrangements on safety are significant. Based on data from National Transportation Safety Board accident reports, tanks located in the fuselage will be less likely to suffer damage in event of a survivable crash, compared to wing tanks. The tank dimension (its width) that is vulnerable in a collision with an obstacle on the ground is significantly less for the fuselage-mounted tanks than for wing tanks. As an example, in the LH_2-fueled aircraft shown in Fig. 1, the fuselage tank has a width of 6.63 m (21.75 ft). The Jet A-fueled aircraft designed for the same mission and illustrated in Fig. 2 has a wing span of 58.5 m (192 ft), most of which contains fuel and is vulnerable to damage from impact which could cause fuel spillage. In both of the cryogenically fueled aircraft, the wings are devoid of fuel except for the supply lines that carry fuel to the engines. These lines are contained between the front and rear spars in the wing structural box and are downstream of shutoff valves controlled from the flight station.

An additional factor in this regard is the consideration that the fuselage-mounted tanks of the cryogenic fuels have a significant amount of structure both ahead of and beneath them to absorb impact loads. Examination of Fig. 1 shows that the entire nose structure of the aircraft would have to be crushed before a frontal collision could impact the forward tank. The underside of the tanks is protected by a minimum of 45.7 cm (18 in.) of space for the forward tank and 35.5 cm (14 in.) for the rear tank, having a specially designed structure to preserve their integrity in event of nose gear collapse, a wheels-up landing, or a tail scrape. The wing tanks for conventional fuel are unprotected.

There are other differences that affect the safety issue. The cryogenic fuel tanks are pressurized to a nominal pressure of 21 psia using gaseous fuel as the pressurant. This nominal internal pressure is maintained regardless of the ambient pressure through which the aircraft may be flying. Thus, at cruise altitude where the ambient pressure may be only 3 psi, the differential pressure that the fuel tank must resist is 18 psi. On the other hand, tanks for the conventional fuels are vented to the atmosphere so that at any altitude there will be only a small differential pressure, thus minimizing the tank weight.

Although this difference in design condition imposes a structural weight penalty on the LH_2- and LCH_4-fueled aircraft, it has two beneficial effects in enhancing the safety of the cryogenic fuels. The first is that since the LH_2 and LCH_4 tanks are each pressurized with their own vapor product, they contain no air or oxygen. Consequently, there is no fire or explosion hazard within the tanks. Since conventional fuel tanks are vented to the atmosphere to minimize differential pressure on the structure, there is always a mix of fuel vapor and air above the surface of the liquid fuel that may be susceptible to ignition. The cryogenic fuels, therefore, present less hazard in this regard.

The second beneficial effect results from the fact that the cryogenic tanks are designed to an ultimate pressure of 208 kPa (30.2 psi). In comparison, regardless of the fuel employed, passenger compartments are designed to an ultimate pressure of only about 124 kPa (18 psi). It is more likely, therefore, that the tanks for the cryogenic fuels would remain intact in the event of a survivable crash because the fuselage would tend to break in its weakest parts.

Considering all these aspects, it seems clear that fuselage-mounted cryogenic fuel tanks would have a better record of crash survival than wing tanks for conventional fuel. This conclusion is supported by statistics from accident reports which show that fuselage damage in impact-survivable accidents is generally far less severe than that sustained by aircraft wings.

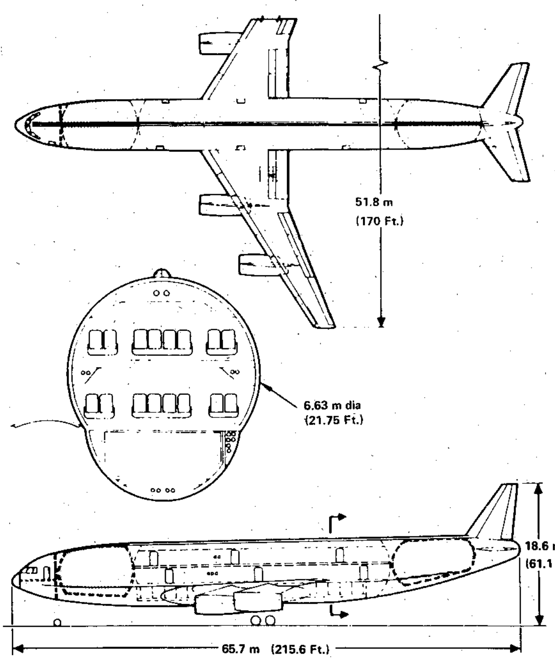

Fig. 1 LH_2-fueled transport aircraft.

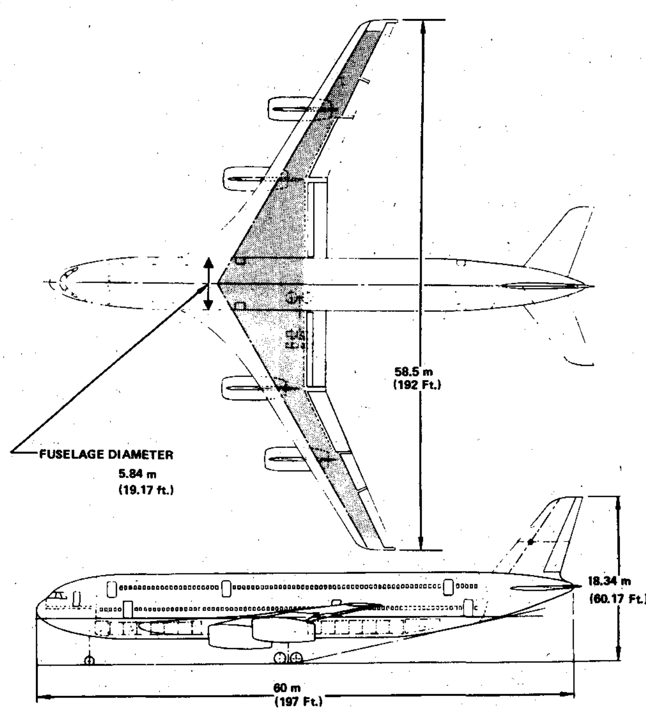

Fig. 2 Jet A-fueled transport aircraft.

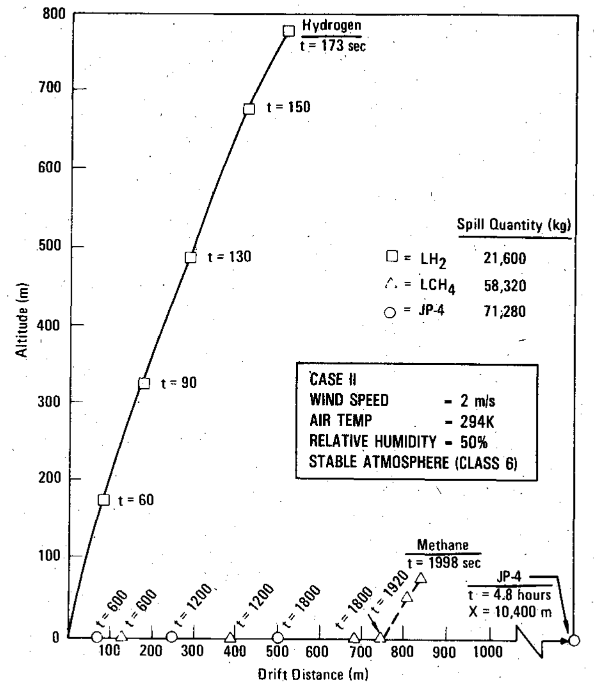

Fig. 3 Altitude vs drift distance for flammable puffs of hydrogen, methane, and JP-4.

Fuel Spreading Characteristics

The next claim is that use of LH_2 results in a smaller area being threatened by a hostile environment in the event a tank is ruptured and ignition does not immediately occur. For comparison, examine the relative sizes of the areas that would be in hazard due to the presence of a cloud of flammable fuel/air mixture as a result of spills of equal percentages of the candidate fuel required by respective aircraft to fly the design mission.

This problem is logically divided into two parts: first, an assessment of the spreading and vaporization of the spilled liquid and, second, the behavior of the fuel vapor cloud after vaporization has occurred.

To assess the spreading and vaporization characteristics of each of the fuels, a mathematical model developed by Fay[9] was used, although a more exact representation designed by Richard Cima of Lockheed Missiles and Space Company, Inc., especially for the subject study was available. Unfortunately, the Cima model displayed computational eccentricities that could not be debugged in time to be of use.

Results from two representative cases which were studied are reported in Table 1. Case I represents an accident in which a fuel tank is ruptured on each airplane such that all the fuel is drained from that tank in 14 s. Case II represents a catastrophic (nonsurvivable) crash where all fuel on board the respective aircraft is spilled instantaneously. The results show that LH_2 spreads the least and evaporates the quickest in all cases.

The second part of this aspect of evaluating the potential hazard posed by the four candidate fuels concerns the behavior of the fuel vapor cloud as it dissipates in the atmosphere.

A mathematical model to predict the position and extent of the flammable fuel vapor cloud at any time after the spilled aircraft fuel begins to evaporate was created by Dr. Eric Walther and associates of the John Muir Institute at the University of Nevada, Las Vegas.† The model was written from the point of view of an observer who travels with a 1 s puff of gaseous fuel that vaporizes from the liquid pool. For purposes of economy only the largest diameter puff was tracked. The mathematical model uses a Lagrangian coordinate system whose origin is the center of the puff volume. Ambient air is turbulently entrained into the puff through the sides and part of the top and bottom. The proportion of puff top and bottom available for entrainment is determined by the ascent angle of the puff. There are other puffs before and after the largest puff tracked by the model. If the ascent is vertical, then no part of the top or bottom is an entrainment surface. If the puff motion is horizontal along the ground, then part of the top but none of the bottom is available for entrainment. As the puff entrains air, a new mass is calculated for the puff for the next time interval.

After all the conservation equations are solved, the resulting acceleration and velocity determine the vertical and horizontal displacement of the puff center in a set of Eulerian (fixed) coordinates with the origin at the center of the top surface of the liquid spill pool.

The thermodynamic processes that are handled in the model are: 1) the heating of the gaseous fuel by the warmer entrained air, 2) the condensation of water vapor in the entrained air as it is cooled by the gaseous fuel, 3) the freezing of the water droplets upon further cooling, 4) the melting of these same frozen hydrometeors later in the life of the puff, and 5) the evaporation of the water droplets still later.

A complete description and explanation of the basis for the gaseous diffusion model is provided in Ref. 7. The results reported therein show that hydrogen rises rapidly in every case and therefore poses minimum risk to areas surrounding a spill. The other fuels are nonbuoyant for extended periods and flammable clouds are blown along the ground. Figure 3 is a plot of altitude vs drift distance, with time indications shown on the path of each fuel. The hydrogen puff leaves the ground within 20 s after the spill has spread to a radius of 54.2 m. It rises to an altitude of 782 m in 173 s before being diluted to less than the lower combustible limit. In comparison, methane is negatively buoyant for more than ½ h and travels along the ground, covering 851 m in the 2 m/s wind before it begins to rise and is dissipated. In like manner, the JP-4 gas puff could theoretically move 10.4 km downwind in the 2 m/s wind speed of the example. For almost 5 h it would pose a threat of conflagration to anything in its path as it moved along the ground. Jet A is not reported because at the ambient temperature used in this analysis (294 K), it does not vaporize sufficiently to form a flammable concentration.

Hazard from Fuel Fires

The third claim was that if spilled fuel is ignited during or immediately following a crash, passengers as well as persons and property in the immediate vicinity would be considerably safer if the crashed airplane used LH_2 fuel.

It is of interest to note that analysis of pertinent National Transportation Safety Board records showed that fire did result more than 80% of the time when fuel was spilled in aircraft accidents. Thus, the question of relative hazard in event of a fuel fire is particularly pertinent.

To answer this question an analysis was made of the heat-transfer problem. It was assumed the passenger cabin was intact and that fuel was spilled such that the aircraft fuselage is imbedded in large-scale flames from the pool of burning fuel.

A thermal model of the fuselage sidewall of a modern commercial transport aircraft was created, accounting for the aluminum skin, stringers, and frames of the outer fuselage; the conventional layer of fiberglass insulation; and the interior liner panel of composite honeycomb.

The heat absorbed by the fuselage will be due to both radiation and convection. A summary of the heat fluxes calculated for each of the fuels is shown in Table 2.

The absorbed radiant heat flux q_R'' was calculated on the basis that emissivity of the fuselage skin is 0.9, which is characteristic of a painted skin or one subject to corrosive

†Dr. Walther is currently with Lockheed Engineering and Management Services Company, Las Vegas.

Table 1 Spreading and vaporization from radial fuel spills[a]

Fuel	m, kg	$\dot{m}$, kg/s	Q_0, m^3	$\dot{Q}_0$ m^3/s	r_m, m	t_m, s
			Case I (without burning)			
LH_2	12,600	900	117.8	12.70	35	32
LCH_4	34,398	2457	81.13	5.795	61	117
JP-4	42,210	3015	54.12	3.865	143	785
Jet A	42,210	3015	54.12	3.865	331	4180
			Case I (with burning)			
LH_2	12,600	900	117.8	12.70	26	15
LCH_4	34,398	2457	81.13	5.795	35	38
			Case II (without burning)			
LH_2	21,600	∞	304.74	∞	49	39
LCH_4	58,968	∞	139.08	∞	77	140
JP-4	72,360	∞	92.77	∞	175	895
Jet A	72,360	∞	92.77	∞	406	4790
			Case II (with burning)			
LH_2	21,600	∞	304.74	∞	37	22
LCH_4	58,968	∞	139.08	∞	43	43

[a]Nomenclature: m = mass of fuel spilled, $\dot{m}$ = spill rate, Q_0 = volume of fuel spilled, $\dot{Q}_0$ = volume rate of spill, r_m = maximum radius of spilled liquid, t_m = time to maximum spill radius.

Table 2 Absorbed fuselage skin heat flux in the various flames[a]

Fuel	q''_F, kW/m^2	q''_R, kW/m^2	q''_c, kW/m^2	q'', kW/m^2
LH_2	189.4	85.2	31.8	117.0
LCH_4	229.6	103.3	27.2	130.5
JP-4	74.7	33.6	18.2	51.8
Jet A	74.7	33.6	18.2	51.8

[a]Nomenclature: q''_F = incident radiation heat flux from flames, q''_R = absorbed radiation heat flux from flames, q''_c = convective heat flux from flames, q'' = heat rate per unit area to the solid surface.

flames. If the aluminum skin is bare, the emissivity could be reduced to about 0.1. The radiation view factor from the curved fuselage skin to the flames was taken as 0.5.

The transient thermal model of the fuselage cabin wall was run over a range of absorbed heat fluxes q'' to determine fuselage wall temperature as a function of time for flames from each of the fuels. The hazard to passengers inside the cabin is that the aluminum skin and stringers will reach a temperature of 430-480°C (805-896°F). At these temperatures the structure will collapse due to its own weight.

Based upon the maximum expected absorbed heat fluxes from the various flames, the fuselage should collapse after ~40 s in a methane flame, after ~50 s in hydrogen flame, and after ~120 s in a JP-4 or Jet A flame. When these fuselage collapse times are compared with the calculated burning times of the fuel spills from case I, the worst survivable case from Table 1, it is seen that LH_2 will pose no problem. The pool fire would last only 15 s. LCH_4 is marginal, the pool fire would last 38 s, uncomfortably close to the ~40 s calculated for fuselage collapse. Although the pool burning times were not calculated for JP-4 and Jet A, it is obvious from accident experience that fuselage collapse would occur in event those fuels were used.

Passenger Exposure to Cryogenic Fuel

A unique potential problem posed by the location of the tanks for the cryogenic fuels in the fuselage is the question that surviving passengers and crew could be faced with the hazard of exposure to the fuel itself. Very brief contact with LH_2 produces the effect of a burn on human skin. Exposure of large areas of the body to cryogenic temperatures for even brief periods would be fatal.

It is always possible to postulate circumstances in which large quantities of fuel are spilled and some of it drains into the passenger compartment. However, in view of the design of the tank and its installation, it is considered unlikely that there would be a survivable crash where this would happen. The pressure bulkhead that forms the end of the passenger compartment, as well as the adjacent end of the fuel tank, would both have to rupture. Alternatively, the sidewalls of the fuel tank and the passenger compartment would both have to be punctured.

The probability of this happening is difficult to assess realistically. To provide some potentially useful information relative to the situation, an experimental program has been suggested that would involve carefully instrumented crashes of suitably modified surplus aircraft.

Caveat

The results of the analysis performed in this study for NASA have shown that LH_2 has definite advantages in the safety aspects considered. However, it must be realized that there are many other situations that have not yet been analyzed. A great deal more study, coupled with well-planned experiments, is required before final conclusions can be reached. Among the situations urgently needing to be considered are the following, some of which do not lend themselves to analysis but would require experimental research or testing:

1) Effect of fuel tank pressure on dispersion of the cryogenic fuels if tanks are ruptured. Analysis supported by confirmatory tests is required.

2) Hazard of detonation of the cryogenic fuels due to partial confinement in a postcrash fire. For example, it is recognized that a hydrogen fire has a propensity to progress from conflagration to detonation if it is confined on at least three sides. Very little information of a scientific nature exists that can be used to substantiate a credible theory concerning why, how, and under what circumstances such a progression might occur. Fundamental research is needed.

3) The phenomenon of "flameless detonations." Large spills of liquid methane (LCH_4) and liquid natural gas (LNG) have, on occasion, produced a series of violent pressure pulses that have continued for several seconds, without ignition having occurred.[10] Again, the causes and circumstances leading to their occurrence, as well as their potential for

catastrophic results, are virtually unknown. A research study should be made of this phenomenon for LH_2 as well as for LCH_4 and LNG.

4) Greater ignitability of hydrogen relative to jet fuel—is this an asset or a liability? It is recognized that hydrogen is combustible over very wide limits of mixture ratio and that extremely low spark energy levels will provide ignition. However, it can be argued that the best way to prevent large-scale damage is to ignite a hydrogen leak or spill as soon as possible in order to avoid accumulation of a quantity that, upon ignition, would be apt to detonate. There are many nuances to this question. Thoughtful study, analysis of various circumstances, and carefully designed experiments are required to provide acceptable answers.

5) Safety of fuselage occupants in a situation where hydrogen gas can accumulate in the cabin via openings resulting from a crash. The probability of such a situation occurring in an impact survivable crash can be studied based on results of crash tests of surplus aircraft equipped with representative LH_2 tanks and fuel systems (see Recommendations of Ref. 7).

6) Radiation hazard through cabin windows from fuel flames outside the fuselage. Effective flame temperatures and lateral emissivities from LH_2 fuel flames need to be determined as a function of size of the fire and atmospheric conditions. An analytical model to predict the transmitted radiant heat flux and the transient temperatures of the cabin window panes should be developed. The design of window coverings necessary to eliminate the radiation hazard to fuselage occupants can then be established.

7) Hazard due to hydrogen leaks from aircraft fuel system components. Minute flaws in any part of the LH_2 fuel system can cause leaks of gaseous hydrogen inside the aircraft structure. The probability of such leaks developing at any time during the life of the aircraft needs to be recognized, and a comprehensive system for detecting the presence and source of the leaks must be developed, as well as a means of safely purging the leaked hydrogen from the aircraft.

Summary

On the basis of the analyses performed, LH_2 was found to be a safer fuel than any of the other candidates. The passengers on board, and people and property in the immediate surroundings, would be exposed to less hazard if a crashed aircraft were fueled with LH_2. This results from three fundamental considerations.

1) LH_2 tanks are less susceptible to damage:

a) They are mounted in the fuselage where they present a far smaller dimension to frontal impact.

b) They are protected by a significant amount of structure, both ahead of and beneath, which must be crushed or penetrated before the tanks are exposed.

c) They are designed for higher pressure than the rest of the fuselage and therefore are less apt to be the point of failure in an impact survivable crash.

2) In the event a tank is ruptured and there is a large spill of fuel, LH_2 does not spread as far as other fuels, it evaporates in much shorter time, becomes buoyant almost immediately, and rises and dissipates into the atmosphere so rapidly that very little hazard is presented to surroundings outside the immediate area of the crash.

3) If the spilled fuel is ignited, the duration of the LH_2 fire would be so brief that it would not heat the fuselage to the point of collapse, as would be the case with the other fuels. The passengers could be advised to simply stay in their seats until the fuel-fed fire is burned out. In addition, the area affected by the fuel-fed fire would be substantially smaller.

The subject study was a preliminary investigation. The findings are very favorable for hydrogen. However, it must be recognized that there are many other cases and circumstances to be analyzed, the tools for analysis need to be improved, and experimental testing must be performed to establish a more complete basis for validation of the computer model results and to determine the effect of other potentially hazardous aspects of crashes, before complete and final conclusions can be reached.

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Because of the recent move of AIAA Headquarters to 1633 Broadway, New York, N.Y. 10019, journal issues have unavoidably fallen behind schedule. The Production Department at the new address was still under construction at the time of the move, and typesetting had to be suspended temporarily. It will be several months before schedules return to normal. In the meanwhile, the Publications Staff requests your patience if your issues arrive three to four weeks late.