REALISTIC PROBABILITY ESTIMATES FOR DESTRUCTIVE OVERPRESSURE EVENTS IN HEATED CENTER WING TANKS OF COMMERCIAL JET AIRCRAFT

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ABSTRACT

The Federal Aviation Administration (FAA) identified 17 accidents that may have resulted from fuel tank explosions on commercial aircraft from 1959 to 2001. Seven events involved JP 4 or JP 4/Jet A mixtures that are no longer used for commercial aircraft fuel. The remaining 10 events involved Jet A or Jet A1 fuels that are in current use by the commercial aircraft industry. Four fuel tank explosions occurred in center wing tanks (CWTs) where on-board appliances can potentially transfer heat to the tank. These tanks are designated as "Heated Center Wing Tanks" (HCWT). Since 1996, the FAA has significantly increased the rate at which it has promoted airworthiness directives (ADs) directed at elimination of ignition sources. This effort includes the adoption, in 2001, of Special Federal Aviation Regulation 88 of 14 CFR part 21 (SFAR 88 "Fuel Tank System Fault Tolerance Evaluation Requirements"). This paper addresses SFAR 88 effectiveness in reducing HCWT ignition source probability. Our statistical analysis, relating the occurrence of both on-ground and in-flight HCWT explosions to the cumulative flight hours of commercial passenger aircraft containing HCWT's reveals that the best estimate of HCWT explosion rate is 1 explosion in 1.4×10^8 flight hours. Based on an analysis of SFAR 88 by Sandia National Laboratories and our independent analysis, SFAR 88 reduces current risk of HCWT explosion by at least a factor of 10, thus meeting an FAA risk criteria of 1 accident in billion flight hours. This paper also surveys and analyzes parameters for Jet A fuel ignition in HCWT's. Because of the paucity of in-flight HCWT explosions, we conclude that the intersection of the parameters necessary and sufficient to result in an HCWT explosion with sufficient overpressure to rupture the HCWT is extremely rare.

1.0 Introduction

Four fuel tank explosions occurred in center wing tanks where on-board appliances such as air conditioners that can potentially transfer heat to the tank. These tanks are designated as "Heated Center Wing Tanks" (HCWT). The HCWT is a central fuel tank is located on the underside of the fuselage, directly between the wings, and most modern transport category aircraft are so equipped. (Figure 1, [1]). Ref [1] describes possible causes of the TWA 800 accident; the only HCWT event known to have occurred in flight. One of the four HCWT explosions involved sabotage and is excluded from consideration. The remaining three explosions included the following common factors: hot day, long gate hold, air conditioning packs on and minimal fuel in the HCWT. The TWA 800 explosion occurred in flight on July 1996 while the aircraft was climbing through 13,800 ft. resulting in complete loss of the aircraft with 230 fatalities. The other two HCTW explosions occurred on the ground during refueling.

Since 1996, the FAA has significantly increased the rate at which it has adopted airworthiness directives (ADs) directed at elimination of ignition sources. This effort includes the inauguration, in 2001, of Special Federal Aviation Regulation 88 of 14 CFR part 21 (SFAR 88), ref. [3]. In addition, FAA issued a Notice of Proposed Rule Making (NPRM), in November 2005, ref [4], inviting comments from the all interested parties regarding new requirements mandating flammability reduction means (FRM) such as providing inert atmospheres in HCWT's and/or ignition mitigation means (IMM) to reduce the probability of HCWT explosions. FAA asserts that inerting of the ullage in a fuel tank is the only positive method to insure that fuel tank explosions can be prevented. They contend that there in no absolute procedure to eliminate all ignition sources. Consequently, they propose retrofitting all passenger aircraft with an apparatus that reduces the Oxygen concentration of ullage atmosphere to below the lower explosion limits (LEL) regardless of fuel temperature and flight altitude. They further require that all new aircraft are so equipped from the factory.

This proposed rule is mandated by the FAA because of the requirement that maximum risk of catastrophic failure for any commercial aircraft system is 10^{-9} per flight hour, and FAA contends that the current risk of HCWT explosions in flight is 1 accident in 60 x 10^{6} flight hours (1.7 x 10^{-8} per flight hour). According to the FAA, this explosion risk level is based on a benefit-cost analysis (BCA) that varied parameters such as SFAR 88 effectiveness, discount rate and the value of a fatal event in their determination of this risk. They assert that this rate is fixed and that the BCA considered no alternate parameters to assess the impact of the variability of the rate. No where in the NPRM is there data or background to reveal how FAA derived the stated explosion risk. Thus, an independent investigation was initiated in an attempt to understand where and how they came to adopt this risk level. The required procedure was to survey the basic data regarding the total flight hours for HCWT equipped aircraft during the time frame of interest (1961-2005) and, using acceptable statistical procedures, independently determine the explosion risk. Moreover, because the NPRM proposal requires all commercial aircraft operators to install ullage inerting equipment, an independent assessment was done to determine the effectiveness of airworthiness directives (AD's) developed and adopted during the SFAR 88 program.

Our statistical analysis, relating the occurrence of both on-ground and in-flight HCWT explosions to the cumulative flight hours of commercial passenger aircraft containing HCWT's reveals that the true probability of HCWT explosions without SFAR 88 implementation is 1 explosion per 1.40 x 10^{8} flight hours. Based on our independent analysis, SFAR 88 reduces current risk of HCWT explosion by a factor of 10, thus meeting the FAA rule.

2.0 Estimated failure rate for HCWT explosions

An important parameter in the benefit cost analysis (BCA) conducted by the NPRM is the estimated HCWT explosion rate. FAA's estimated the HCWT explosion rate to be 1 explosion in 60 x 10^{6} flight hours. FAA projected that nine more airplanes will likely be destroyed due to HCWT explosions in the next 50 years unless remedial action is taken. The (BCA) in the NPRM apparently did not consider alternate parameters to assess the impact of variability in the accident rate, resulting in an unrealistically conservative analysis,

This paper considers only the events that involve aircraft where external appliances heat the center wing tanks that are "normally emptied", meaning that during flight operations, the HCWT often is depleted or is not used. The active timeframe in which HCWTs are involved is from 1967 to 2005, and the accepted total flight-hours in this period are 419 million. Data from the original Aviation Rulemaking Advisory Committee (ARAC-2) data, ref [5], for accumulated flight hours for aircraft with HCWTs was analyzed. The data was applicable through the year 2000. Aircraft that contain only HCWT flight-hours were included in our analysis. Data from the year 2000 through 2005 was also included by assuming a 4% growth rate. Our analysis also included accumulated flight hours for the Airbus A330.

The Federal Aviation Administration (FAA) identified 17 accidents that may have resulted from fuel tank explosions on commercial aircraft from 1959 to 2001. Seven events involved JP 4 or JP 4/Jet A mixtures that are no longer used for commercial aircraft fuel. The remaining 10 events involved Jet A or Jet A1 fuels that are in current use by the commercial aircraft industry. Four fuel tank explosions occurred in center wing tanks (CWTs) where on-board appliances can potentially transfer heat to the tank. These tanks are designated as “Heated Center Wing Tanks” (HCWT). The incident on May 11, 1990 in Bogota Columbia in which an explosion on a Boeing 727-100 occurred while the aircraft was climbing at 10,000 feet is excluded from our analysis because the explosion was caused by a bomb, an act of sabotage. The remaining three HCWT explosions have been confirmed –

1. May 11, 1990, Manila, Philippines, Philippines Airlines Boeing 737 (on-ground)
2. July 17, 1996, New York, TWA Boeing 747-100 (in-flight)
3. March 3, 2001, Bangkok, Thailand, Thai Airlines Boeing 737 (on-ground)

Our estimate of the mean accident rate is --

419 Million flight hours total for aircraft with HCWTs divided by 3 HCWT explosions

= 140 million flight-hours flown.

To obtain confidence intervals for catastrophic HCWT tank explosions, we can assume that the explosion rate is a proportion and use the binomial distribution to obtain confidence intervals for the binomial parameter θ. For large n (in this case accumulated flight-hours) where the binomial distribution can be approximated by the normal distribution; we can obtain confidence levels for estimates of catastrophic HCWT explosion rates:

$$\theta = \frac{x + \frac{1}{2}z^2 + z\sqrt{\frac{x(n - x)}{n} + \frac{1}{4}z^2}}{n + z^2}$$

where x =3 the number of accidents, n is the accumulated flight-hours and z is the standard normal value that corresponds to a certain confidence level for θ.

Confidence levels are presented graphically in Figure 2. Figure 2 shows that the one occurrence in 60 million flight-hour HCWT catastrophic explosion rate appears at the 93% confidence level. A 93% confidence level means that there is only a 7% chance that the true time between explosions is less than 60 million flight-hours. There is a 93% chance that the time between explosions is greater than 60 million flight-hours. The one explosion in 60 million flight-hour rate, therefore, is a statistical outlier and is not representative of the true catastrophic HCWT explosion rate. The best estimate of the mean catastrophic HCWT explosion rate is one explosion in 139.7 per million flight-hours.

3.0 Sandia’s Assessment of SFAR 88 Effectiveness

The FAA commissioned Sandia National Laboratories to determine the effectiveness of airworthiness directives (ADs) under SFAR 88 that have been applied to mitigate ignition sources. This effort ref [6] entailed consideration of: 1) fuel tank explosion history; 2) previous attempts at correcting ignition sources; 3) fuel tank flammability characteristics; 4) industry safety assessments and ADs that were required by SFAR 88 to identify failures and malfunctions that could create ignition sources; 5) fleet statistics and continued increase in exposure; and 6) system safety/defense in-depth concepts. FAA then tasked Sandia with developing a quantitative assessment to (1) evaluate the overall and individual effectiveness of ADs associated with SFAR 88; (2) estimate residual risks after applying these ADs; (3) validate the Aviation Rulemaking Advisory Committee's (ARAC-2) assumed seventy-five percent AD effectiveness in reducing future tank explosions and (4) compare and evaluate independent safety assessment efforts of original equipment manufacturers (OEMs).

The approach of Sandia was to use a top-down fault tree analysis using data provided by Boeing for the 737 Classic airplane center wing tank (CWT) and Airbus for the A320 airplane CWT. Figure 3 shows a generic fault tree structure for HCWT explosion and HCWT rupture that applies to Sandia's fault tree analysis. The Sandia study projected: (1) the probability of an explosion of the heated center wing tank prior to the application of SFAR 88 and associated ADs; (2) the probability of a catastrophic explosion of the heated center wing tank after the application of SFAR 88 and associated ADs, and (3) comparison of these values to the FAA's goal of no more than one explosion in 1 billion flight-hours. Sandia made a compilation of relevant ADs for the Airbus 320. There were a total of thirty-six ADs reviewed related to fuel systems. For the A320, fifteen ADs were deemed relevant to the study, of which nine were issued after the TWA 800 accident. For the Boeing 737, eighty-three ADs were reviewed. Thirty-seven ADs were deemed relevant to the study, of which seventeen were issued after the TWA 800 accident.

Figure 3 represents the top level of the fault tree used by Sandia to estimate explosion risk in HCWT volumes. Event B in figure 3 "Ignition source has sufficient energy to ignite mixture" used six ignition scenarios involving components and conditions that have been identified as probable ignition sources that could cause HCWT explosion. They are: (1) Left fuel pump, (2) Right fuel pump, (3) Fuel quantity indication system (FQIS), (4) Tubing/piping valves (5) Float switch/wires and (6) External threats.

Sandia applied the reliability data provided by Airbus and probability ranges provided by Boeing in their fault tree analysis. According to Sandia, the fuel pumps, fuel quantity indicator systems (FQIS), and fuel level sensing systems (FLSS) have high likelihood rankings for ignition sparks and hot surfaces.

Thirteen ADs pertaining to friction sparks and hot surface development from fuel boost pumps were identified as "driving" failure modes in the analysis. According to Sandia, ADs associated with other failure modes had a relatively small impact on the HCWT explosion rate. Sandia contends that only two or three ADs issued after the TWA 800 accident had a significant effect on ignition or explosion risk.

Sandia further posits that ADs related to the FQIS subsystem may be ineffective for an aging fleet, as wiring degradation over time appeared to be another driving factor. Sandia identified features like boost pump auto-shutoff, current fault interrupters, and transient suppression units helpful in preventing ignition sources in fuel tanks.

The analysis assumed that fuel tank temperatures were optimal for explosion, that fuel vapor at the appropriate fuel/air ratio existed at all times, that external sources had a probability of one and that a surface at the threshold temperature of 450° F (232° C) or a discharge arc of 0.2 mJ existed in the fuel vapor-filled ullage. Sandia recognized that these conditions are extremely conservative (*i.e.*, worst case), and they acknowledged that "fuel vapor combustion events happen very rarely." Sandia states: only "a very minute probability [exists] that the necessary faulted conditions will occur and align, or synergistically combine, with energized circuits to create a potential ignition scenario."

In fact, only three explosion events in HCWT are confirmed, and they all occurred under very similar circumstances. All of the following factors were present in the three explosions: hot day, relatively long gate hold, air conditioning packs on and no useable fuel in HCWT. Two of the three HCWT explosions occurred while the aircraft were in ground operations, and, in both of these cases, HCWT fuel pumps were running dry. The other explosion occurred shortly after takeoff, and the HCWT scavenge pump was never recovered. While the specific ignition sources for these explosion events have never been identified "with certainty," the correspondence of conditions is compelling.

Sandia identified limitations to SFAR 88 ignition source reduction measures as the inability to eliminate all ignition sources, *e.g.* fuel pump running dry in vapor and degraded wires that go undetected. Other limitations cited by Sandia are incidents that may be caused by design, human factors, and aging issues that continue to exist after SFAR 88 implementation. Regardless of all these caveats, Sandia's analysis determined that application of the SFAR 88 AD's would provide a factor of 10 reduction in the ignition risk in HCWT equipped aircraft.

It is difficult to predict HCWT explosion frequency because of problems with identifying all ignition sources. However, this limitation is offset by the conservatism in Sandia's assumptions (spark ignition threshold = 0.2 mJ; hot surface ignition threshold = 450°F (232°C), ullage always at a fuel/air ratio within the lean and rich ignition limits). The paucity of actual HCWT explosions is because the intersection of parameters necessary and sufficient to result in an HCWT explosion is extremely rare.

The fault tree in figure 3 shows the three components necessary for the ullage atmosphere are fuel, oxygen in air, and energy. The fuel, in vapor or gaseous form, (Event E) and air (Event D) must mix in appropriate combination, and the energy source must be of sufficient intensity to initiate their chemical reaction and rupture the HCWT (event A). In order for this reaction to produce an explosion (deflagration or detonation), it must be confined. The limits of flammability for fuel and air mixtures are well known for single component fuels and are defined by the lean (less fuel) and rich (more fuel) limits. The energy requirements for ignition at the limits are generally orders of magnitude greater than at the optimum (stoichiometric) mixture of fuel and air.

Ignition source energy requirements change as a function of fuel temperature (fuel vapor concentration in air) and altitude. Figure 4 ref [7] is a plot of ignition energy as a function of fuel temperature and altitude. These plots are derived from empirical data, which show that the flammable range is from about 100°F (38°C) to about 180°F (82°C) at sea level. As the altitude increases or the fuel temperature deviates from the flash point temperature of 120°F (49°C), which is typical of Jet A fuel, the energy required for ignition increases. **Consequently the range of altitude and fuel temperature for which the Sandia threshold spark energy has potential to ignite a fuel mixture is extremely limited.**

Further, the Sandia report posits that "using an arc channel 1 mm long and roughly 0.5 mm in diameter" that a specifically powered wire could heat an equivalent volume of air to vapor auto ignition temperature. Peer reviewers of the SANDIA report ref [8], point out that Sandia did not consider the physics of ignition when forming their example, especially with regard to the quenching of the combustion reaction in small volumes such as their "arc channel". The quenching distance averages 1.8 mm for paraffin hydrocarbons at sea level, and research done for the FAA in a 1:4 scale B747 fuel tank for 115°F (46°C) flash point Jet A fuel determined that the quenching distance is greater than 1.0 inch (25.4 mm) at an altitude of 14,000. ref [9].

Sandia's contention that a small element heated to 450°F (232°C) is a valid threshold limit for initiation of explosion in the HCWT ullage is too low because it is based on standard laboratory tests to determine the auto ignition temperature of fuels. These tests are conducted in an isothermal reactor, which does not correspond to hot surface ignition from an isolated heated surface. The most recent data available comes from tests where a uniformly heated semi-infinite plate is employed as the defined hot surface, ref.[10]. In the hot surface test, single drops of fuel contact the surface, and the surface's temperature is sequentially increased until ignition occurs. Figure 5 ref. [10] shows the ignition probability of aviation fuels as a function of surface temperature. For Jet A, the probability of ignition is 0 (zero) at ~970°F (507°C). Moreover, tests to measure the ignition of JP 8 vapor were conducted in a 9 cubic foot test article, where the fuel vapor was produced in a heated metal pan. The hot ignition element was a heated metal block (1" thick, 3" wide, and 6" long). Ignition of a near stoichiometric atmosphere of JP 8 did not occur until the block attained a surface temperature of 1350°F (732°C) ref. [11]. Higher temperatures will be required to produce ignition as the altitude or the fuel/air mixture ratio deviates from the stoichiometric ratio. Note that the properties of Jet A, Jet A1 and JP 8 are essentially the same as shown in the HandBook of Aviation Fuel Properties ref [12].

The Sandia analysis appears to not have addressed the extremely limited set of conditions that need to intersect for an explosion to occur in HCWT environments. Even with that omission, Sandia's analysis, resulting in a "factor of 10" improvement in inherent risk of transport aircraft fuel tank explosions, is as conservative as the parameters they adopted for the analysis. Consequently, we believe that the "factor of 10" improvement understates the true improvements that are currently in place as a result of SFAR 88 AD's applications.

3.0 Conclusions

Examination of the relevant ADs and Sandia's analysis provides ample evidence that a factor of ten for SFAR 88 effectiveness in reducing the HCWT explosion rate is reasonable. Sandia states a factor of ten reduction based on a conservative analysis. The reduction could be less than a factor of ten since, as discussed earlier in this report, all ignition sources may not be identified. However, further analysis shows that that the reduction factor is greater than ten because Sandia's assumptions regarding ignition source requirements for HCWT explosions are extremely conservative. As discussed earlier, stoichiometric mixtures do not exist at all times in HCWTs. In addition, Sandia understated the ignition temperatures and electrical energy required for ignition of the HCWT ullage atmosphere. Thus, the opposing factors described above offset each other and a factor of ten is a reasonable estimate for SFAR 88 effectiveness. In addition, there is strong evidence to show that a major source of ignition is a dry running pump when the fuel temperature is high and existing ADs address this problem.

Statistical analysis, relating the occurrence of both on-ground and in-flight HCWT explosions to the cumulative flight hours of commercial passenger aircraft containing HCWT's reveals that the best estimate of the mean HCWT explosion rate is 1 explosion in 1.40×10^8 flight hours, not 6.0×10^7 flight hours as stated in the NPRM. Based on Sandia's conservative analysis, SFAR 88 reduces current risk of HCWT explosion by at least a factor of 10, thus meeting an FAA risk criteria of 1 explosion in a billion flight hours and negating the need, expense and potential unknown risk factors for retrofitting fuel inerting devices in operating commercial aircraft.

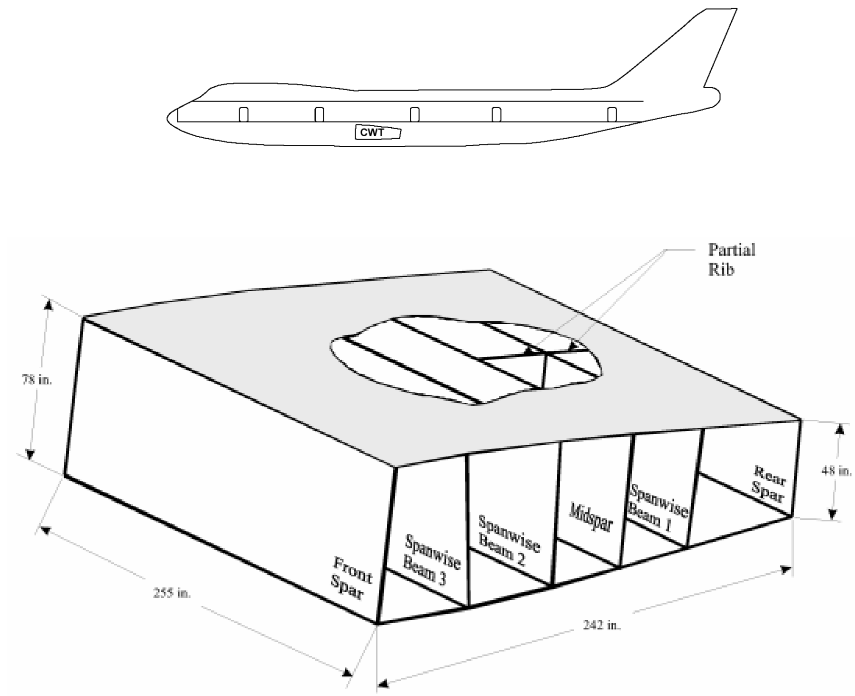

Figure 1. --Schematic of a Central Fuel Tank, Including Dimensions and Partitions, and its Relative Position in a Boeing 747 From a Side View. The Central Fuel Tank, which is also commonly called the Center Wing Tank, is Labeled as "CWT" from Ref. [1] (Modified From NTSB D, 1997 Ref.[2]).

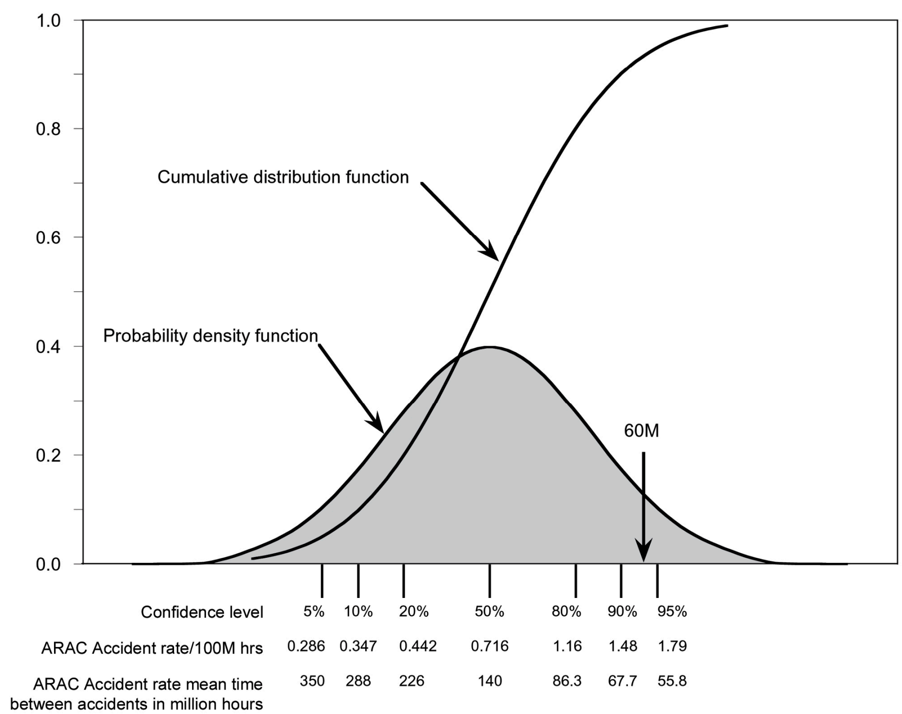

Figure 2 -- Confidence Levels for Catastrophic Heated Center Wing Tank (HCWT) Explosion Rate without SFAR 88 implementation

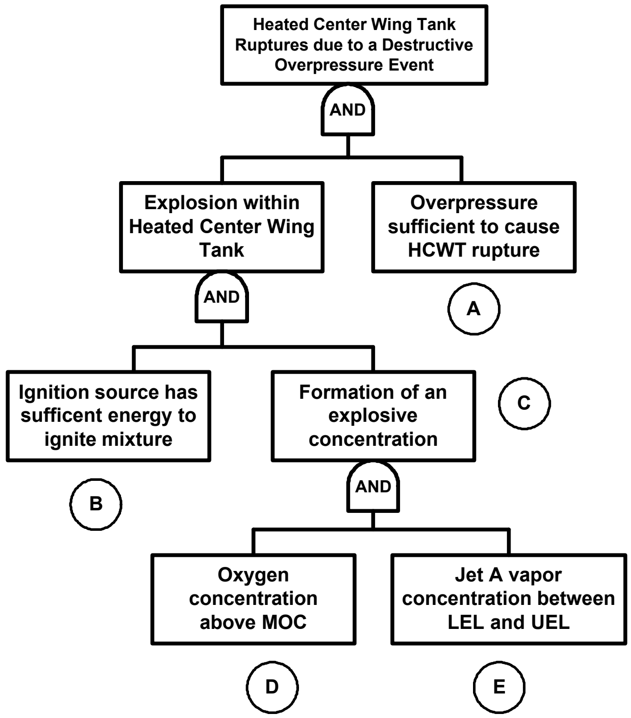

Figure 3 – Generic Fault Tree for HWCT explosion and Rupture

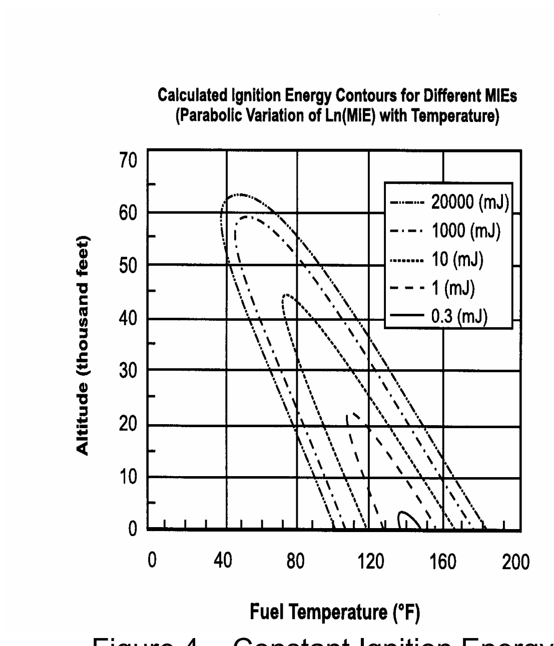

Figure 4 – Constant Ignition Energy Contours Predicted by the Recommended Correlation for a Fuel with a Flash Point of 120°F (49°C) ref (7)

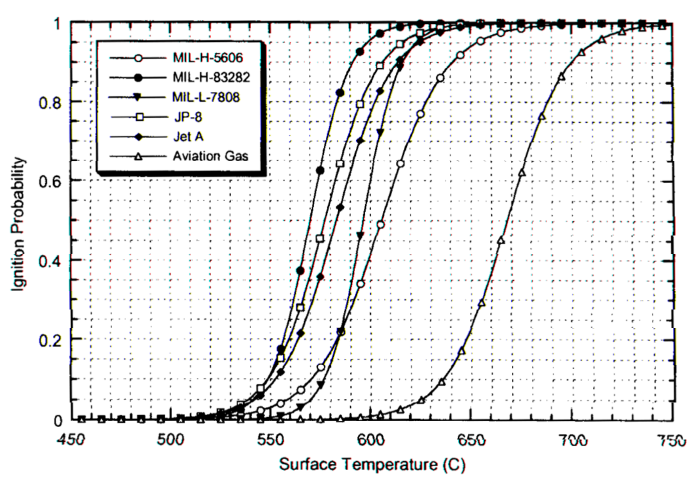

Figure 5 – Ignition Probability as a Function of Surface Temperature for Aviation Fluids, ref (10).

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