Summary and Conclusions of Explosion Research Team

M. Birky (NTSB), J. Kolly (NTSB), J. E. Shepherd (CIT), P. A. Thibault (CDL), M. R. Baer (SNL), K. van Wingerden (CMR), J. E. Woodrow (UNR), J. C. Sagebiel (DRI)

Introduction

A team of researchers contributed to the TWA 800 accident investigation by carrying out a research program on issues connected with the explosion of Jet A (aviation kerosene) vapors. The objectives of this program were: (1) to develop an understanding of the thermal and vapor environment of the center wing tank (CWT) during aircraft operations, (2) to determine the flammability and combustion behavior of Jet A fuel, and (3) to carry out scale-model experiments and develop computer models of the combustion process within the CWT that would aid in the determination of the ignition location.

Fires and explosions do occur in airplane accidents and have always been a potential hazard in aircraft operations. Preceding this investigation, it was known that jet aircraft fuel tanks could be in a flammable condition during some portion of a typical flight. In fact, all commercial jet aircraft are designed under the assumption that fuel tanks are flammable at all times. This design philosophy requires that any potential electrical spark sources inside fuel tanks be limited to energies below a specified minimum ignition energy (200 μJ) typical of hydrocarbon fuel vapors.

Up to the time of the TWA 800 accident, there had been only three published experimental studies (in 1967, 1970, and 1971) on the flammability of Jet A vapor. Consequently, there was very limited data available on the combustion properties and thermochemistry of Jet A; a much greater understanding of these issues was required for this investigation. To this end, the team performed laboratory experiments, scale-model tests, and numerical simulations to examine the explosion of mixtures of Jet A vapors with air under conditions encompassing those experienced by TWA 800's CWT at the time of the accident. Over a period of four years, this group of researchers worked together to determine the chemical and physical properties of Jet A, particularly the flammability limits, combustion behavior, and the propagation of flames through the compartmentalized structure of the CWT.

An initial result of this research was to enable the analysis of the flammability of aircraft fuel tanks under various conditions, including those of TWA 800. This information provides a scientific basis for evaluating proposed methods of reducing fuel tank flammability, including actions recommended by the Safety Board following the accident.

The program continued with a series of scale-model experiments, the development and adaptation of computational models and numerical methods. The numerical tools were used in full-scale simulations of CWT combustion to explore the effects of various parameters and assumptions, especially ignition locations within the tank. A computational rule-based analysis method was then developed to evaluate the simulations against the observed damages from the recovered wreckage. The goal of this computational effort was to narrow down the number of plausible ignition locations within the CWT that were consistent with the physical evidence.

The results of all of these studies were extensively documented in a series of reports that were submitted to the NTSB and will be available through the public docket for this accident investigation.

Activities

This research endeavor involved the use of standardized tests, engineering models, and state-of-the-art scientific techniques; the development of new methods; and the extension of existing ones. Each of these analyses was carried out under experimental conditions encompassing those experienced by TWA 800's CWT at the time of the accident. These specific conditions — temperature, altitude (pressure), mass loading, and weathering — were each considered to have an important effect upon the behavior of the combustion that took place within the CWT of TWA 800.

The fundamental chemical and physical properties of Jet A fuel were explored. This included the analysis of the chemical composition of Jet A liquid and vapor, and the determination of vapor pressure and molecular weight. Ultimately, this information was used to predict fuel vapor concentrations onboard TWA 800; moreover, it is generally applicable to a wide range of situations in aircraft operation.

The flammability of Jet A was investigated to determine the ignition energy required for combustion, the flame speed, and peak explosion pressures. Hundreds of tests were performed over a wide range of conditions. From this work, we were able to determine under what conditions combustion was possible and to quantify the combustion behavior of Jet A vapors.

Temperature and vapor concentrations were measured in airplane fuel tanks under flight and ground conditions. The thermal environment created by the air cycle machines under the CWT was measured and modeled. These tests verified the flammable condition of the CWT of TWA 800 and were used to predict the flammability of fuel tanks in general.

While these studies provided information beneficial to the investigation at large, the research team also continued to work toward the goal of narrowing down the number of probable ignition locations within the CWT. This process involved a number of steps, including scale-model experiments, numerical simulation, evaluation of the observed damages, and estimation of failure pressures. Ultimately, a limited number of scenarios, i.e., combinations of ignition source location, tank temperature, and structural failure sequences, were evaluated using the numerical simulation and statistical methods.

Scale-model experiments were conducted to demonstrate the propagation of an explosion in a simplified ¼-scale model of the CWT. Most importantly, the scale-model testing was used to validate the numerical analysis. During this testing, quenching or flame extinction was identified as an issue because of the complex nature of the CWT design. This issue was partially addressed through additional experiments and engineering modeling.

Two distinct numerical methods (codes) were used to predict the propagation of an explosion in both a scale-model and a full-scale CWT. The group at CMR adapted the FLACS code to calculate the 3-D flow field and flame propagation with the CWT based on solving the Reynolds-Average

Navier-Stokes (RANS) equations. The group at Sandia developed a method based on flame-front tracking with mass, momentum, and energy balances averaged over each compartment of the tank. The primary output of each code was the time history of the pressure differences across the beams, spars, and doors that divide the CWT into compartments. The two codes complement each other and each was used in evaluating explosion scenarios. Hundreds of simulations were performed in order to develop these methods, compare the results to scale-model experiments, do full-scale simulations, and determine the sensitivity of the results to factors such as fuel concentration, ignition location, numerical mesh size, representation of the connections between compartments, and motion of structural components.

Ultimately, the application of our research findings involved tackling the problem of using the clues that the investigators had gleaned from the wreckage to evaluate the simulations of various explosion scenarios. That effort required addressing how to utilize data and estimates derived from the crash investigation that included varying levels of uncertainty. A quantitative technique based on statistical reasoning was developed especially for this purpose. This technique, called a rule-based analysis method, evaluates the results of our numerical simulations of the explosion process against the observations of damage to the airplane and estimates of structural response.

The rule-based analysis method was used to integrate the results of the numerical simulations with the estimated structural response of the CWT components. The analysis was then used to evaluate the consistency of each of the numerical simulation scenarios to the damage in the CWT wreckage that could be attributed to the initial explosion event.

However, because of the difficulty in identifying damage caused by the initial explosion event, and that caused by the subsequent in-flight break up and impact with the ocean, it was necessary to develop a consensus on the damages caused by the initial explosion event between NTSB investigators and Boeing engineers. The levels of confidence in these observations have been estimated and coded into the rule-based analysis method.

Additionally, estimates of failure pressures of structural members of the CWT were developed and uncertainties assigned to each. This uncertainty exists because a CWT has never been tested to failure pressures and estimates provided by Boeing using traditional analytic methods and numerical computations provide a range of estimated failure pressures. This range was employed in the rule-based analysis method.

The outcome of the rule-based analysis method was a measure of the consistency of the results from each numerical test case scenario compared to the observable damages of the wreckage. This provided the investigators with a method to evaluate each probable ignition location within the CWT.

Summary of Findings

The laboratory and scale-model experiments with Jet A fuel were carried out under conditions simulating the CWT environment at the event altitude: temperatures of 40 to 50 C (104 F to 122 F) and a pressure of 0.585 bar (8.5 psi). These experiments demonstrated that the fuel vapor-air mixture was flammable over the range of temperatures (40 to 50 C; 104 F to 122 F) and fuel loading (50–100 gallons) present in the CWT at the time of the accident. Furthermore, the elevated temperatures inside the tank, caused by heating from the air cycle machines under the tank, increased the explosion hazard over that posed by a cool tank by substantially increasing the amount of fuel vapor and thus decreasing the ignition energy. Flight and ground testing confirmed this finding.

The measured peak pressure rises recorded during our experiments were between 1.5 and 4 bar (20 to 60 psi), sufficient to cause failure of structural components inside the CWT of a B-747 aircraft. Scale-model experiments, using both Jet A and a simulant fuel, and numerical simulations reveal that the flame front can propagate rapidly between the compartments of the tank once the flame reaches the passageways and vent stringers connecting the compartments. In some cases, the flame will be quenched as it passes through these openings or connections. The motion of the flame through the tank follows a complex path that results in pressure differences between compartments. Scale (¼) model experiments and numerical simulations have confirmed that the flame path, and consequently, the pressure differentials generated across the fuel tank structures, are dependent upon ignition location.

Our experimental measurements and numerical calculations have shown that combustion-induced pressure differences produce forces on CWT internal structures (span-wise beams and spars) that can cause deformation and failure of these components. The magnitude and direction of these forces determine which components fail, in what direction, and the sequence of failure. The location of the ignition source is reflected in, but not obvious from the examination of, the damage to the various internal structures, since the forces created during the explosion depend on that location, among other factors.

Numerical models, validated against laboratory and scale-model experiments, simulated combustion within a full-scale CWT. Ultimately, 32 full-scale scenarios were calculated. These scenarios were created by parametrically varying the ignition location (8 points corresponding to fuel quantity instrumentation system (FQIS) components), fuel vapor concentration (2 temperature levels), and time delay (0–24 ms) between failure of the front spar (FS) and the manufacturing door in span-wise beam 2 (SWB2). Each of these scenarios was analyzed using the rule-based analysis method to quantify its consistency with the observable damages.

The rule-based analysis employs a set of rules derived both from the physical damage of the wreckage and structural failure estimates. Key elements in the establishment of these rules were that the wreckage indicated a particular sequence of events involving the failure of the two forward structural components (FS and SWB3), while the rear components (SWB2, MS, SWB1, and RS) probably remained essentially intact during the early explosion event. A total of 15 key observations were considered in the rule-based analysis method as probabilistic constraints or rules. In order for an ignition location to be considered plausible, the associated scenario must show a high degree of consistency between the observed and predicted damages.

The rule-based system evaluation of these numerical simulations found several ignition locations that would produce propagating flame fronts within the tank volume and pressure differences on the structural components that were consistent with the observed damages. Although the evaluation considered a limited number of specified points as the ignition locations, the uncertainties associated with this analysis preclude making a determination of ignition location with a high degree of certainty. In particular, substantial uncertainty exists in extrapolating the combustion behavior from ¼-scale to the full-scale (actual) CWT. As a result, a unique and most probable ignition location could not be identified.

The conclusions from this research are that the Jet A vapor-air mixture present in the center wing tank of TWA 800 was flammable at the time of the accident, and that a propagating flame resulting from a localized ignition of this mixture can generate overpressures which are consistent with the observed damages in the wreckage of TWA 800.

Uncertainties and Limitations

The limitations and sources of uncertainty in this evaluation fall into two broad areas: combustion modeling and structural response.

Combustion modeling

1. <u>Quenching criteria.</u> One of the sources of uncertainty is associated with the quenching (extinction of combustion) of Jet A flames when passing through the small openings in the tank internal structures. Quenching was observed in some ¼-scale experiments. We do not have a universal quenching criteria that applies to any fuel. An empirical criterion was developed based on extensive propane tests and limited numbers of Jet A tests. This criterion was applied to the results of the numerical simulations which assumed no quenching in order to estimate pressure differentials that would have been created had quenching occurred. Since no full-scale experiments were carried out, there is a significant uncertainty associated with the quenching estimates. Quenching does play an important role in the evaluation of the ignition locations since the pressure differences between compartments are significantly altered when quenching occurs, as observed in the ¼-scale experiments with Jet A. We believe that quenching is an important effect that must be simulated correctly in order to reproduce the observed damages. The method we have used to treat quenching is *ad hoc*, but we judge that it is far outside the scope of this crash investigation to be able to substantially improve this model.

   Our quenching criteria are based on a Karlovitz number (ratio of chemical to flow time scales relevant to quenching) that uses flame speed and thickness to determine the chemical time scale. Although this is the traditional approach, it is known from contemporary research that other factors, such as Lewis number (ratio of thermal diffusivity to species diffusivity) and Zeldovich number (nondimensional activation energy), play an important role. It is also known that the characteristic extinction strain rate provides an alternative chemical time scale. Considerations of these factors provide plausible explanations of the very pronounced quenching behavior observed in Jet A tests as compared to the simulant fuel, which exhibited no quenching. Quenching and extinction of flames by turbulence and flame stretching is an area of active research. A reliable engineering correlation appropriate for our studies is not yet available. Resolution of quenching issues awaits substantial advances in basic combustion research.

2. Sensitivity of results to ignition location. Computations indicate that the outcomes of simulations are extremely sensitive to the exact location of ignition and, to some degree, to the method of numerical solution and spatial discretization. In particular, a detailed study of ignition location in the ¼-scale geometry indicated variations in pressure differentials of 100% are possible for slight displacements of the ignition source in the vicinity of location 5 (near the compensator in compartment 2). This problem is exacerbated by the fact that a flow passageway not modeled in the ¼-scale experiment but present in the actual tank is located very close to this ignition location. The sensitivity of the predicted pressure histories to these factors indicates that one must be extremely cautious about assigning special significance to any locations that display a higher level of consistency with observed damages. Quantitative prediction will require substantial advancements in many areas of simulation and combustion science.

3. Distribution of Jet A vapor in the tank. Flight and ground tests with 747-100 airplanes revealed a range of temperatures existing within the center fuel tank due to the localized nature of the heating by the components of the air-cycle machines under the tank. Temperatures varied throughout the tank volume and across the hot lower surface. The construction of the tank and the small amount of residual fuel causes the liquid fuel layer to be non-uniform. The actual amount and distribution of liquid in the accident airplane is unknown. All of these factors indicate that actual distribution of fuel vapor and thermodynamic conditions were non-uniform within the center fuel tank. The experiments and numerical simulations were idealized and these nonuniformities were not modeled, although two levels of fuel concentration, corresponding to tank temperatures of 40 and 50 C (104 F to 122 F), were considered.

4. Role of liquid Jet A. A layer or pool of liquid fuel was present on the bottom of the CWT at the time of the explosion. Observations were made of liquid lofting and combusting in the experiments, but this was not included in the numerical simulations. Suspended liquid in the form of droplets can both contribute to the combustion energy release and also absorb energy from the surrounding hot gases. Scale-model experiments with Jet A indicated that the vapor combustion appeared to dominate the explosion event inside the tank, but substantial external combustion of dispersed liquid Jet A was observed in some cases. However, the dispersion process was also observed to be sensitive to the presence of obstacles on the tank floor and no full-scale tests were carried out. Treating the combustion of suspended liquids would introduce an entirely new level of complexity in the simulations that did not seem appropriate given the other uncertainties in the problem.

5. Anomalous combustion behavior in Jet A. Experiments with simulated fuel and Jet A had very different outcomes in many cases. In some tests, this was clearly due to the difference in the quenching behavior of Jet A. There were other phenomena in the experiments, such as partial flame extinction in the ignition bay prior to reaching an orifice, that could not be readily explained using standard engineering models of flame propagation. A related phenomenon was the delayed re-ignition of partially reacted mixtures created when quenching occurred just downstream of a passageway. These observations may be related to low-temperature combustion chemistry associated with higher molecular weight hydrocarbons. At present, engineering explosion models do not account for such complex chemical effects and attempting to include these was judged to be outside the scope of this project.

6. <u>Simplification of tank geometry.</u> Numerous simplifications were made in the geometric models of the CWT that were used for the numerical simulations and the ¼-scale model. Small features such as stiffeners, stringers, and longerons were not reproduced. The access and maintenance panels were not simulated, except for the panel in SWB2, and the exact shape of openings or vent stringers was not reproduced. Although these features are small, it is not obvious how omitting them affected the outcome of the simulation.

7. <u>Ignition type.</u> To simulate the ignition source, a point was used in the simulations, an electric spark was used in the laboratory tests, and a filament in the scale-model. However, the actual ignition source was unknown and we have observed that the type of ignition source can significantly affect the initial development of the flame in the ignition bay.

8. <u>Combustion model.</u> Although state-of-the-art combustion models were used for our engineering explosion computations, they are very simplistic and there is little experience in applying these models to multi-component fuels. In particular, the development of instabilities on the flame front and the associated increase in flame surface area during the initial phase of flame propagation is treated in an empirical fashion. The effect of scale and fuel type on the initial phase of flame propagation is not well understood.

Structural Response

1. <u>Structural failure modeling.</u> The CWT is a typical modern airplane structure and consists of a large number of individual components such as stringers, stiffeners, and panels held together with rivets and removable fasteners. The structural loads produced by an internal explosion are very different than the standard loads considered in the process of airplane design. It is very challenging to evaluate the failure mechanism and thresholds for this type of construction subjected to an internal explosion. Despite the very substantial amount of work carried out by Boeing on the structural response, the resulting failure criteria remained approximate. No experimental structural failure tests were carried out and the explosion investigation team did not carry out independent failure analyses of the structure. As a consequence, the evaluation of the failure pressures was based exclusively on computations carried out by Boeing. Although sophisticated finite-element simulations were carried out in some cases, the results were still not definitive since the initiation of cracks in a complex jointed structure is highly unpredictable. The analyses were also limited by the constraints of available computing resources so that only a limited portion of the structure could be considered at one time. We were not able to quantify how the failure of one portion of the structure affects the residual strength of the other portions of the structure (see the subsequent discussion of progressive failure).

2. <u>Failure pressure values.</u> Boeing provided a range of failure pressures. We chose to use the upper end of this range, which was based on finite-element calculations. Using the lower set of values resulted in significantly larger internal damage to the fuel tank. The lower set of numbers is based on “minimum initial failure strength” computations whereas the upper range of numbers is “estimated maximum initial failure strength.” *Minimum initial failure strength* is typically determined by conventional stress analysis methods used in commercial airplane design for ensuring that minimum strength will always exceed regulatory requirements.

Estimated maximum initial failure strength is typically determined from large finite-element models capable of load redistribution in the plastic range. Initial failure is determined by input % strain at failure.

3. Progressive failure. The failure pressures used in the evaluation are based on the failure of a single panel. Once a panel has failed, the failure pressure of adjacent panels will be lower, leading to the possibility of sequential or progressive failure of multiple panels within the tank. This was not considered in the present evaluation.

4. Uncertainty in CFD codes. In the rule-based system calculations, a value of 10% uncertainty was used for the peak differential pressure computed by the numerical simulations. Simulations of the ¼-scale experiment without quenching indicate that differences of up to 100% are possible. Further, replicate ¼-scale tests show an inherent variation in peak differential loadings of 50%. Due to the large pressure differentials that can be produced by quenching, uncertainties in the quenching model could result in even larger percent uncertainties in the predicted pressure differentials for the full-scale geometry. A sensitivity analysis on the rule-based calculations indicates that a higher CFD prediction uncertainty results in less distinction between the levels of consistency for the various ignition locations

5. ¼-scale model. The ¼-scale model was not intended to model the structural response of the actual tank. Five of the six sides of the structure were rigid. In most tests, rigid beams and spars were used in order to facilitate numerical simulation of the combustion process. A limited number of tests were performed to examine the effect of failure of the spanwise beams and spars on the combustion process. The influence of structural failure on combustion was also examined only in a limited fashion in the computations. The computations considered only the influence of the failure of FS, SWB3, and the panel in SWB2.

6. Simplification of rule-based system. The rules expressing the constraints determined from the observed damage were limited to a subset of the observations. Some observations, such as the deformation caused by the impact of the manufacturing door on the upper skin, or collision of SWB3 with the front spar were not included in the analysis. This was due to the difficulty of trying to associate quantitative criteria to these deformations. Finally, the probabilistic approach used in the rule-based analysis was based mostly on uncertainties estimated by the team members and crash investigators rather than on actual statistical data.

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