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Use of FLACS during the TWA-800 Accident Investigation

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Abstract

The TWA flight 800 accident occurred on July 17, 1996 just outside New York City shortly after take-off. The airplane desintegrated as a result of an "explosion" and 230 people were killed. The investigation concentrated on the possibility of a gas explosion in the Centre Wing Fuel Tank (CWT). The hypothesis was that the heating of fuel in the tank by the air conditioning system was the cause of the flammable vapor concentration (temperature above flash-point).
The explosion investigation used laboratory experiments, scale-model tests, and numerical simulations to examine the explosion of Jet-A (aviation kerosene) mixtures with air under conditions simulating the center wing tank environment at the time of the accident. Work was carried out over a period of four years 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 center wing tank. The CFD tool FLACS was adapted and validated against scale-model experiments. The problem of quenching or flame extinction was identified as an issue and addressed through experiments and modeling.
FLACS was then used in full-scale simulations to explore the effects of various parameters and assumptions, especially ignition locations within the tank. All of this information was integrated through a rule-based system to attempt to narrow down the number of plausible ignition locations that would be consistent with the observed damage as deduced from the recovered wreckage.
The paper gives an overview of the various aspects of this part of the accident investigation.

1. Introduction

On July 17, 1996, about 20:31 EDT, Trans World Airlines (TWA) flight 800, a Boeing 747, crashed in the Atlantic Ocean shortly after take-off from John F. Kennedy International Airport (JFK), New York. All 230 people on board were killed, and the airplane was destroyed.

The National Transportation Safety Board led the investigation to determine the cause of the accident. The investigation concluded that the most probable cause was a fuel-air explosion of the center wing fuel tank (CWT). The ignition source could not be determined with certainty, but, of the sources evaluated by the investigation, the most likely was a short circuit outside of the CWT that allowed excessive voltage to enter it through electrical wiring associated with the fuel quantity indication system (National Transportation Safety Board, 2000).

A consortium of explosion experts from several institutions was involved in the explosion investigation with a task to determine the exact location of the ignition source. The explosion investigation team consisted for experts from California Institute of Technology, Combustion Dynamics Limited, Sandia National Laboratory, University of Nevada, Desert Research Institute and Christian Michelsen Research (now Gexcon). The explosion investigation used laboratory experiments, central wing tank scale-model explosion tests, and numerical simulations. The laboratory-scale experiments aimed at determining the chemical and physical properties of Jet A, particularly the flash point, the minimum ignition energy and combustion behaviour. The central wing tank scale-model experiments were used to study the propagation of flames through the compartmentalized structure of the center wing tank. The passageways between the compartments in the partition walls allowed for communication between the compartments. The CFD tool FLACS was adapted and validated against scale-model experiments. Apart from FLACS, a model developed by Sandia National Laboratories was used for modelling exercises (Baer and Gross, 1998).
FLACS was used in full-scale simulations to explore the effects of various parameters and assumptions, especially ignition locations within the tank. All of this information was integrated through a rule-based system to attempt to narrow down the number of plausible ignition locations that would be consistent with the observed damage as deduced from the recovered wreckage.
An important starting point for the investigation was the initial damage that occurred to the central wing tank: on the basis of the analysis of the various parts of the CWT (recovered from the bottom of the ocean) it appeared that only one of the separation walls (in fact the front wall) had failed. This failure led to a progressive failure of the whole fuselage resulting in the plane breaking in two.
The paper gives an overview of the various aspects of this part of the accident investigation as an example of how a CFD-tool such as FLACS can be used to explain the course of events, to understand the mechanisms of accidents, to identify the root causes and to avoid similar events in the future.

2. Brief Description of the CFD tool FLACS

FLACS is a CFD code solving the compressible Navier-Stokes equations on a 3-D Cartesian grid using a finite volume method. The conservation equations for mass, impulse, enthalpy, turbulence and species, closed by the ideal gas law are included. It has been developed in-house since 1980 in order to simulate the dispersion and subsequent ignition in process areas, such as oil platforms. Hjertager (1985, 1986) describes the basic equations used in the FLACS model, and Hjertager et al (1988a,b) present the results of explosion experiments to develop and validate FLACS initially. FLACS uses a standard k-□ model for turbulence (See, e.g. Harlow and Nakayama, 1967) with certain modifications, e.g., a model for generation of turbulence behind sub-grid objects, a model for build-up of proper turbulence behind objects and turbulent wall functions.

The FLACS code uses a “distributed porosity concept” which enables the detailed representation of complex geometries using a Cartesian grid. Large objects and walls are represented on-grid, and smaller objects are represented sub-grid. This enables geometrical details to be characterized while maintaining reasonable simulation times. This is necessary as small details of “obstacles” can have a significant impact on flame acceleration, and hence explosion pressures (Bjerketvedt et al, 1997). The porosity concept models the blockage, drag formulation, sub-grid turbulence generation and flame folding. More details of this concept are given in Hjertager (1985, 1986) and Arntzen (1998).

FLACS contains a combustion model that assumes that the flame in an explosion can be regarded as a collection of flamelets. One-step reaction kinetics is assumed, with the laminar burning velocity being a measure of the reactivity of a given mixture. The model is based on a broad range of experimental data (Abdel-Gayed et al, 1987; Bray, 1990).

3. Experimental investigations performed

The starting point of the investigation by the explosion investigation team was the assumption of an explosion in the central wing tank. The central wing tank is located in between the wings of the aircraft. Figure 1 shows a schematic view of the Central Wing Section. It was divided laterally into compartments by six beams, including (from farthest aft to forward) the rear spar, spanwise beam SWB-1, the mid spar, SWB-2, SWB-3, and the front spar. The compartments are referred to as dry bay, bay 1, bay 2, left mid bay, right mid bay, left aft bay and right aft bay (see Figure 1). The various compartments are connected via passageways allowing the fuel to flow from one compartment to the other.

The hypothesis was that the heating of fuel in the tank by the air conditioning system was the cause of the flammable vapor concentration (temperature above flash-point). The air conditioning system was positioned directly underneath the central wing tank of the aircraft. The conditions (operating temperatures, pressures, and accelerations) prevailing in the central wing tank at the moment of the explosion were obtained from a series of flight tests. Also the conditions prevailing before and during the flight (fueling, taxiing, switching on and off of air-conditioning system, etc.) were reproduced as detailed as possible. Examination of the temperature data collected during the flight test indicated that the highest ullage temperature measured at 13,700 feet was 127° F (53 °C) and that it occurred in the left mid bay. The tank is open to atmosphere and the pressure prevailing in the tank at the moment of the explosion was 8.6 psi (0.59 bar). This temperature is above the flashpoint of Jet-A and definitely at the pressure prevailing at 13,700 feet (Shepherd, et al, 2000a), implying the possibility of the presence of a flammable mixture in the CWT.

Minimum ignition energy measurements performed under conditions prevailing in the CWT and deviating from these confirm the presence of a flammable mixture, which is easy to ignite (energies between 1 and 10 mJ) (Shepherd et al, 2000b). Closed vessel overpressures in the order of 3.5 bar (50.8 psi) are seen.

The propagation of an explosion in a scale model (1/4-scale) multi-compartment center wing tank (see Figure 3) was investigated using both a simulant fuel (16.7% C_3H_8, 83.3% H_2) and Jet-A. The simulant fuel was chosen to mimic the properties of Jet A and approximate the environmental conditions in the CWT at the moment of the explosion. The experiments performed with the simulant fuel showed that the flame propagated from the bay in which ignition occurred to the other bays causing turbulence generated at the passageways. The turbulence enhanced the combustion rate in the ensuing bays sometimes causing considerable pressure piling. The strong sudden pressure increase could cause flows through passageways to turn around causing additional turbulence in the bays the flame propagated from initially. The different pressure profiles in the various bays caused differential pressures across the various partition walls. An example of a test results in shown in Figures 4 and 5.

Additional tests were carried out with Jet A vapor and a thin liquid layer at temperatures of 40 and 50 °C and a pressure of 0.59 bar (conditions simulating those in the TWA accident). To this end the ¼ scale facility was placed into an insulated enclosure (see figure 6). The Jet A used in these tests had a 115 °F (46 °C) flash point. A 3 kg/m^3 mass loading of liquid simulated the situation in the CWT at the time of the explosion. The effects of temperature and ignition location was investigated. These tests demonstrated that flame propagation and pressure traces similar to those obtained with the simulant fuel could also be obtained in certain cases with Jet A as the fuel. An interesting feature however was that the flame was not always able to reach all bays: in several scenarios quenching of the flame occurred downstream of the passageways. The strong turbulence generated there caused flame stretch sufficient to stop flame propagation. The extent of quenching was dependent on both ignition location and mixture composition (temperature in the facility).

The problem of quenching or flame extinction was identified as an issue and further addressed through modeling.

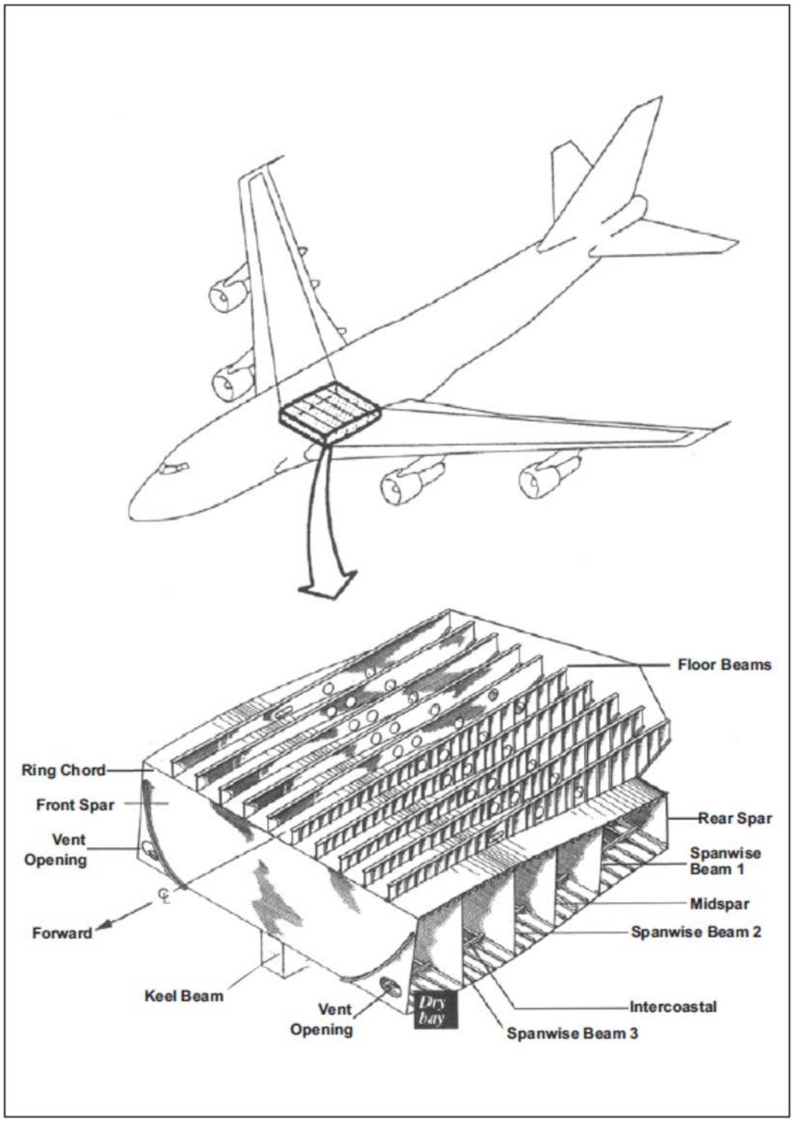

Figure 1a. Position and schematic of the Centre Wing Tank showing the separation walls.

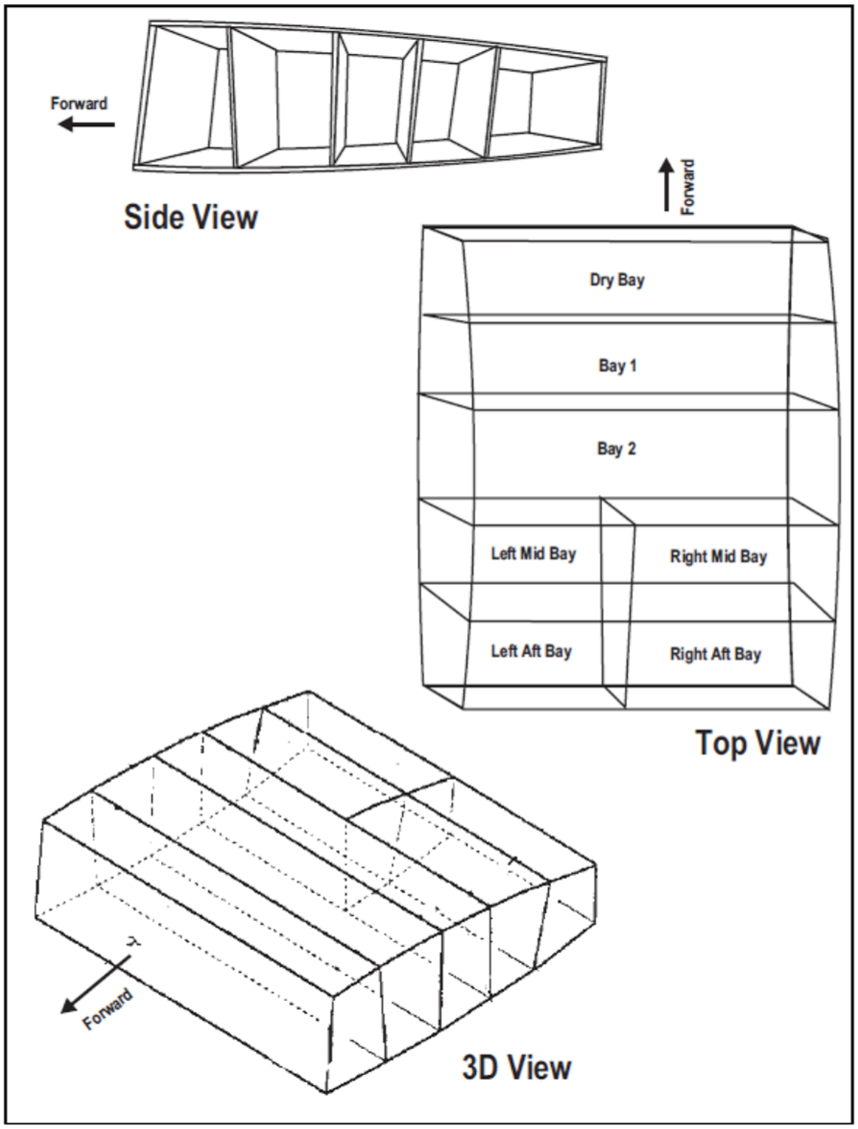

Figure 1b. A schematic of the Centre Wing Tank showing the compartments inside.

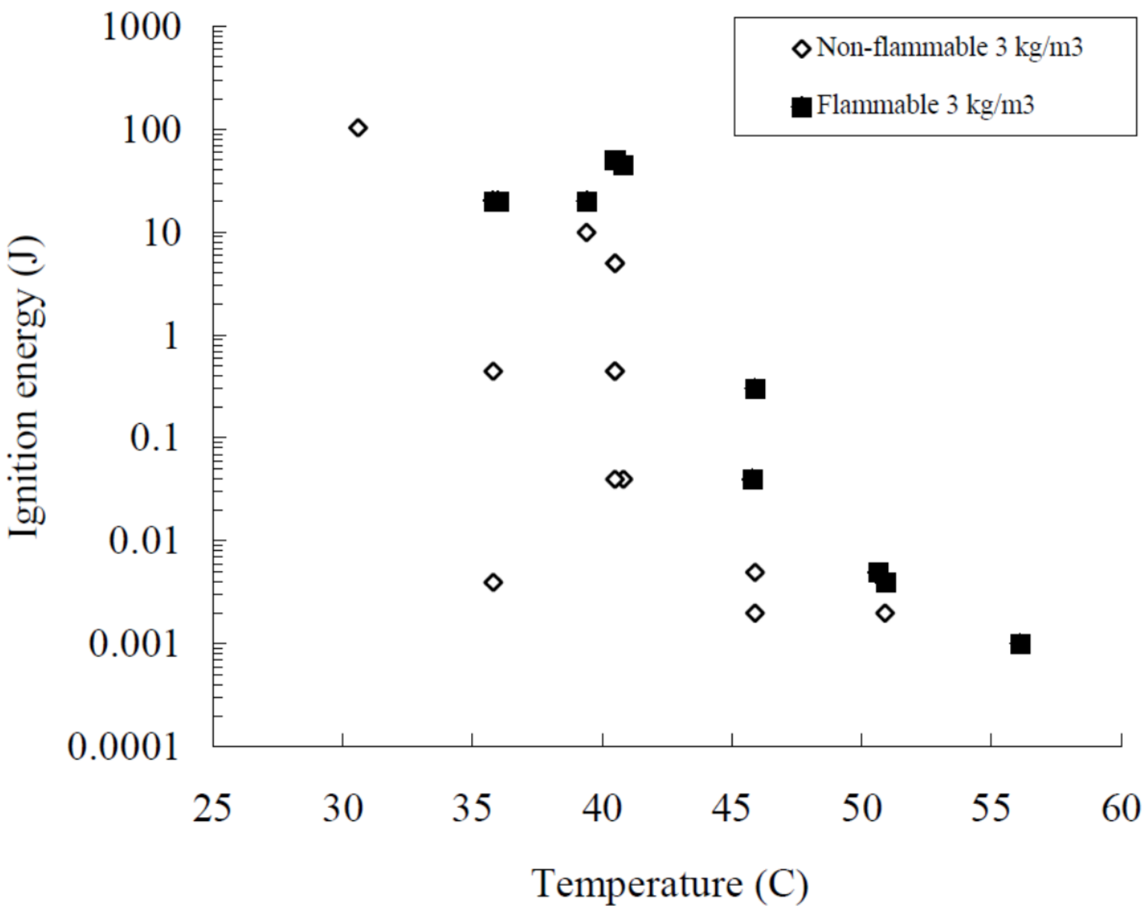

Figure 2Minimum ignition energy of Jet-A – air mixtures as a function of temperature (there is liquid Jet-A in the test vessel; mass loading similar to conditions prevailing in CWT of TWA-800). Initial pressure 0.59 bar (Shepherd et al, 2000b)

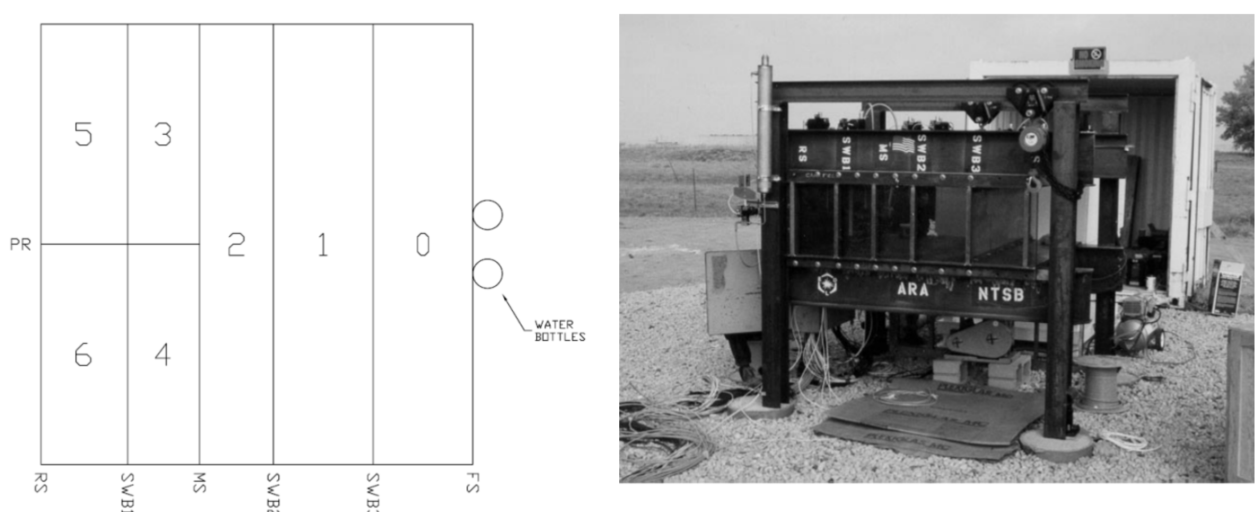

Figure 3Schematic and picture of ¼-scale facility (Shepherd et al, 2000c).

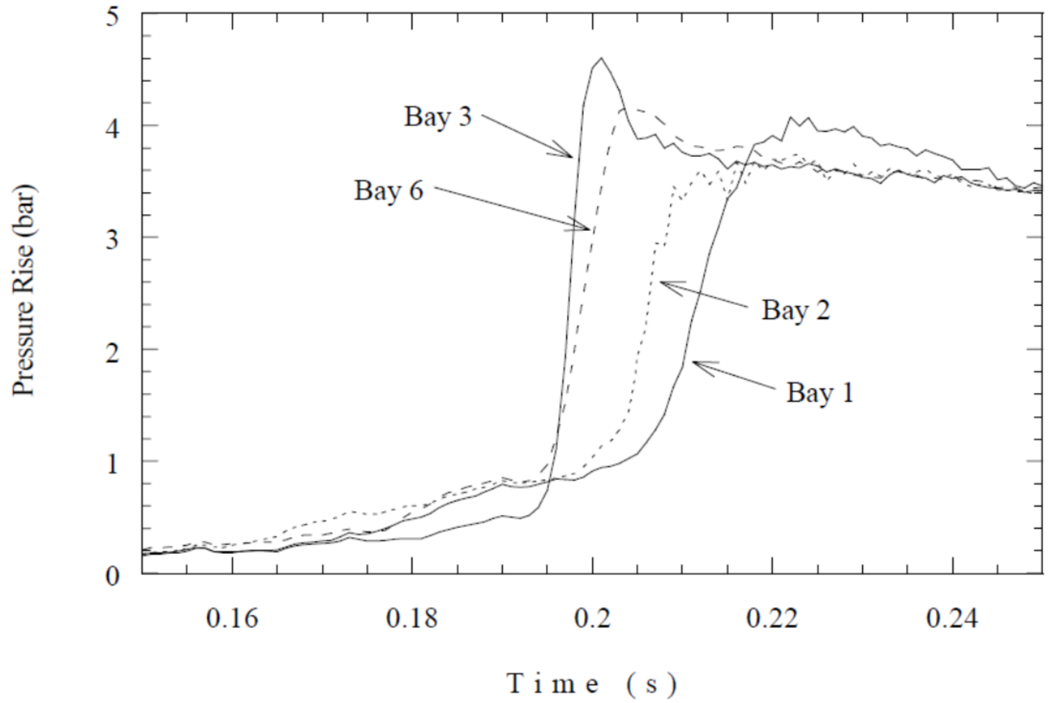

Figure 3Examples of pressure-time histories measured in the various compartments of the CWT (1/4 scale experiment performed with simulant fuel (16.7% C_3H_8, 83.3% H_2)). Ignition occurred in bay 1 (Shepherd et al, 2000c).

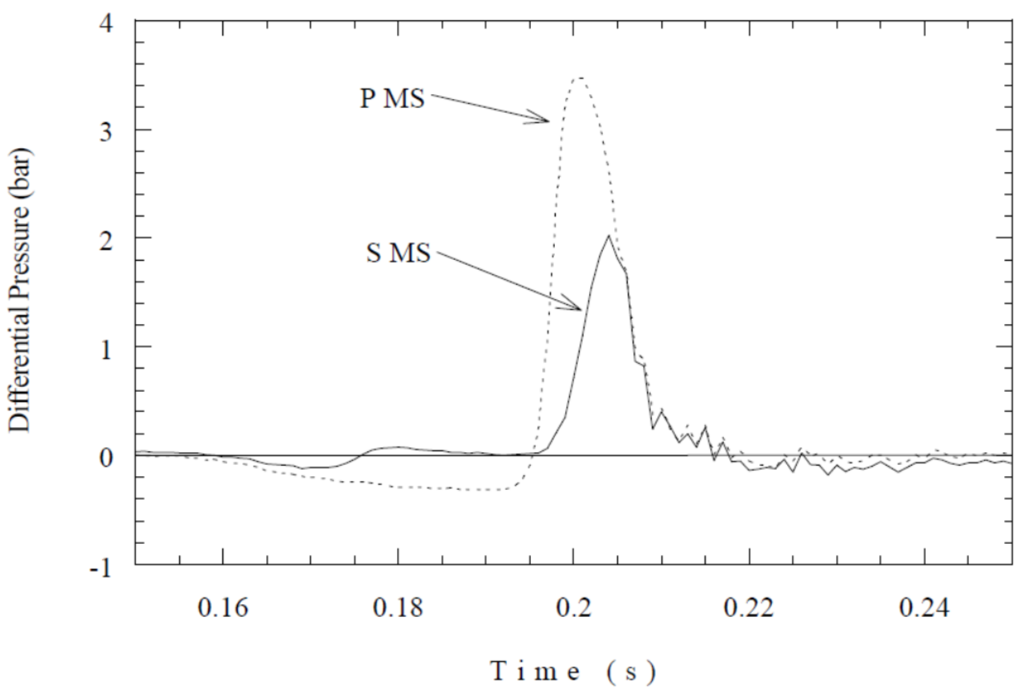

Figure 4Examples of pressure differential time histories measured across the midspar of the CWT (1/4 scale experiment performed with simulant fuel (16.7% C_3H_8, 83.3% H_2)). Ignition occurred in bay 1 (Shepherd et al, 2000c).

Figure 6Heater enclosure for the 1/4-scale set-up (Brown et al, 1999).

4. Modelling

Two distinct numerical methods were used during the TWA-investigation to predict the propagation of an explosion in both the ¼ scale-model and the full-scale CWT. Baer et al (1998) developed a method based on flame-front tracking with mass, momentum, and energy balances averaged over each compartment of the tank. Van Wingerden et al (2000) applied FLACS.
The two codes complement each other and each was used in evaluating explosion scenarios.

Both tools were validated against the ¼ scale explosion experiments (assessing the sensitivity of the results to factors such as fuel concentration and ignition location and considering factors such as numerical mesh size and representation of the connections between compartments).
Upon validation both tools were used to predict pressure loadings on partition walls for a large number of scenarios. The model developed by Baer et al (1998) was especially used to predict the effect of ignition location in the ¼ scale geometry. FLACS was used for prediction of scenarios in the full-scale central wing tank,

For FLACS it was found on the basis of the validation exercise that a butane-air mixture with an equivalence ratio (ER) of 0.79 at an initial temperature of 50 °C was able to represent the Jet-A fuel (that is a complex mixture of over a 100 hydrocarbons) reasonably well (at the correct operating conditions). The burning velocity of this mixture is 43 cm/s at the prevailing conditions. Similarly, it was found that a Jet-A mixture at 40 °C could be represented by an ER = 0.62 butane-air mixture. This mixture has a laminar burning velocity of 21.6 cm/s.

To represent flame quenching at the passage ways a criterion was developed and inserted into FLACS (these were independent from the Jet-A experiments performed in the ¼-scale CWT facility). The development was based on experiments reported by Larsen (1998). Larsen performed experiments varying the distance between the ignition source and an opening investigating the ability of the flame passing the opening depending on the size of the opening. A typical result is shown in Figure 7. The experiments were aiming at determining the critical opening size at which the flame just about managed to propagate through the opening.

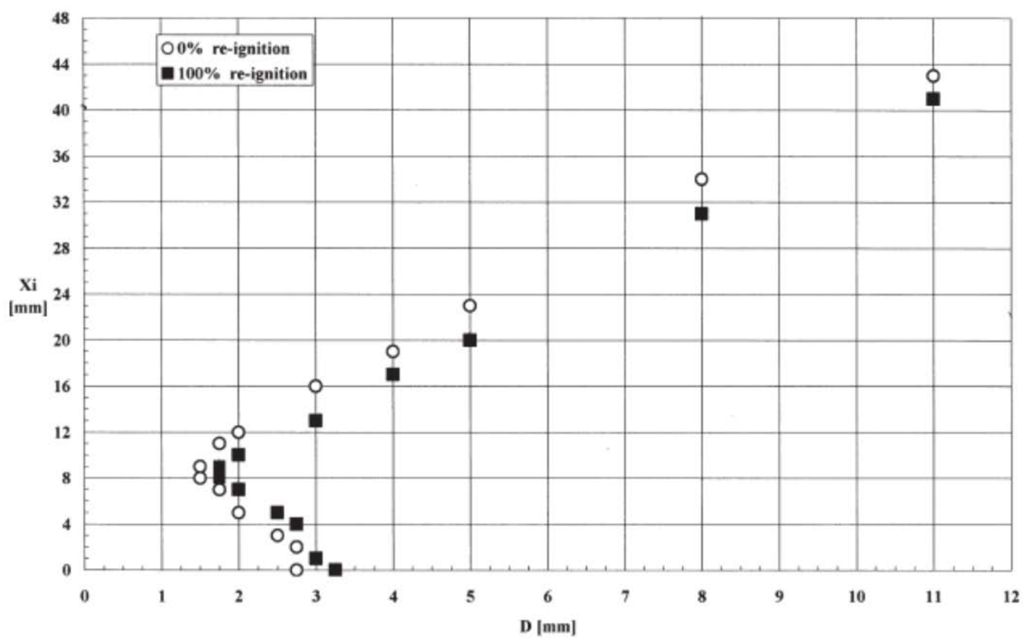

Figure 7Effect of distance between ignition source and opening on the critical transmission opening size (length opening 12.5 mm; fuel: 4.2 % propane-air) (Larsen, 1998).

In general the critical opening size initially decreased when the location of the ignition source was moved further from the opening. When the ignition occurs further away from the opening higher pressures prevail in the explosion vessel at the moment the flame enters the opening. The higher pressure results in higher flow/flame speeds through the opening shortening the contact time and thereby heat loss. At a certain opening size turbulence generated on the other side of the opening becomes that intense that flames are quenched due to flame stretch. Moving the ignition source further away the turbulence becomes more intense and quenching starts occurring at larger openings explaining the shape of the curve.

The criterion developed is based on the Karlovitz number K. The Karlovitz number is a ratio of the combustion time scale (δ / S_L) to the turbulence time scale (u' / λ). This has been used by Abdel-Gayad et al. (1987) to express conditions at which quenching due to flame stretch would occur. From the calculated velocities and observed flame transmission phenomena, a critical

Karlovitz number was established as a function of the opening diameter. For opening diameters larger than 7 mm (the minimum size in the full scale CWT), the critical Karlovitz number was found to be K = 140−150. This criterion was further consolidated by comparing to the results of ¼-scale experiments. On the basis of these results, the criterion derived from the experiments performed by Larsen (1998) was revised into a criterion representing a likelihood of transmission as a function of Karlovitz number. This indicated e.g. a quenching probability of 20 % for K = 100−200 and a quenching probability of 100 % for K > 300.

Figure 8 shows several moments of flame propagation of an explosion ignited in bay 3. The simulations revealed reasonable agreement with experimentally observed overpressures. It can be seen from Figure 8 how the flame shoots from bay to bay via the connecting holes after a relatively slow initial phase causing turbulence and considerably faster explosions in these other bays. For some bays (especially bays 3, 4, 5 and 6) flames can enter a bay from more than one direction due to the presence of several surrounding bays. This could for some scenarios lead to a very big sensitivity of change of ignition position.

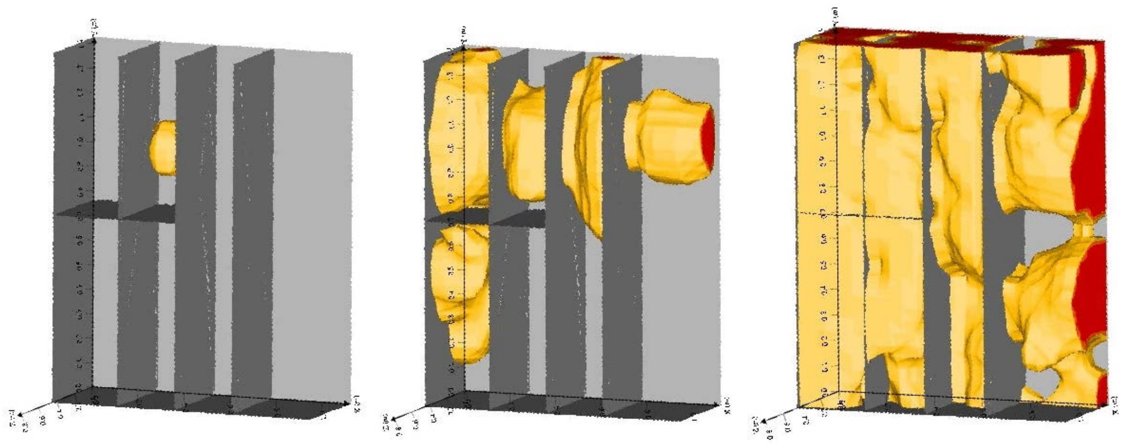

Figure 8. Moments of flame propagation in the ¼-scale rig as described by FLACS.

After the completion of the validation against ¼-scale experiments, simulations for the real CWT were carried out. The ignition position was limited to the seven fuel probe positions and the position of the compensator, thus giving a total of 8 ignition locations (large tanks had 2 ignition positions, and smaller tanks had 1) (see Figure 9). The different scenarios were created by parametrically varying the ignition location (8 points) and fuel vapor concentration (2 levels).
Failures occurred in the CWT: the partitioning wall SWB3 is known to have failed during the explosion. This failure also caused the subsequent failure of the Front Spar either through impact, and/or indirectly due to the resulting pressurization of the dry compartment. This again must have created a sudden pressure differential across SWB2. The manufacturing door in SWB2 also failed and the time of failure had an impact again on the loading of the SWB2. According to analysis performed by Thibault (2000) this failure occurred approximately 16-40 ms after failure of SWB3. Hence all scenarios described above were carried for a failure of the manufacturing door in SWB2 occurring at both a delay time of 16 and 40 ms after failure of SWB3.

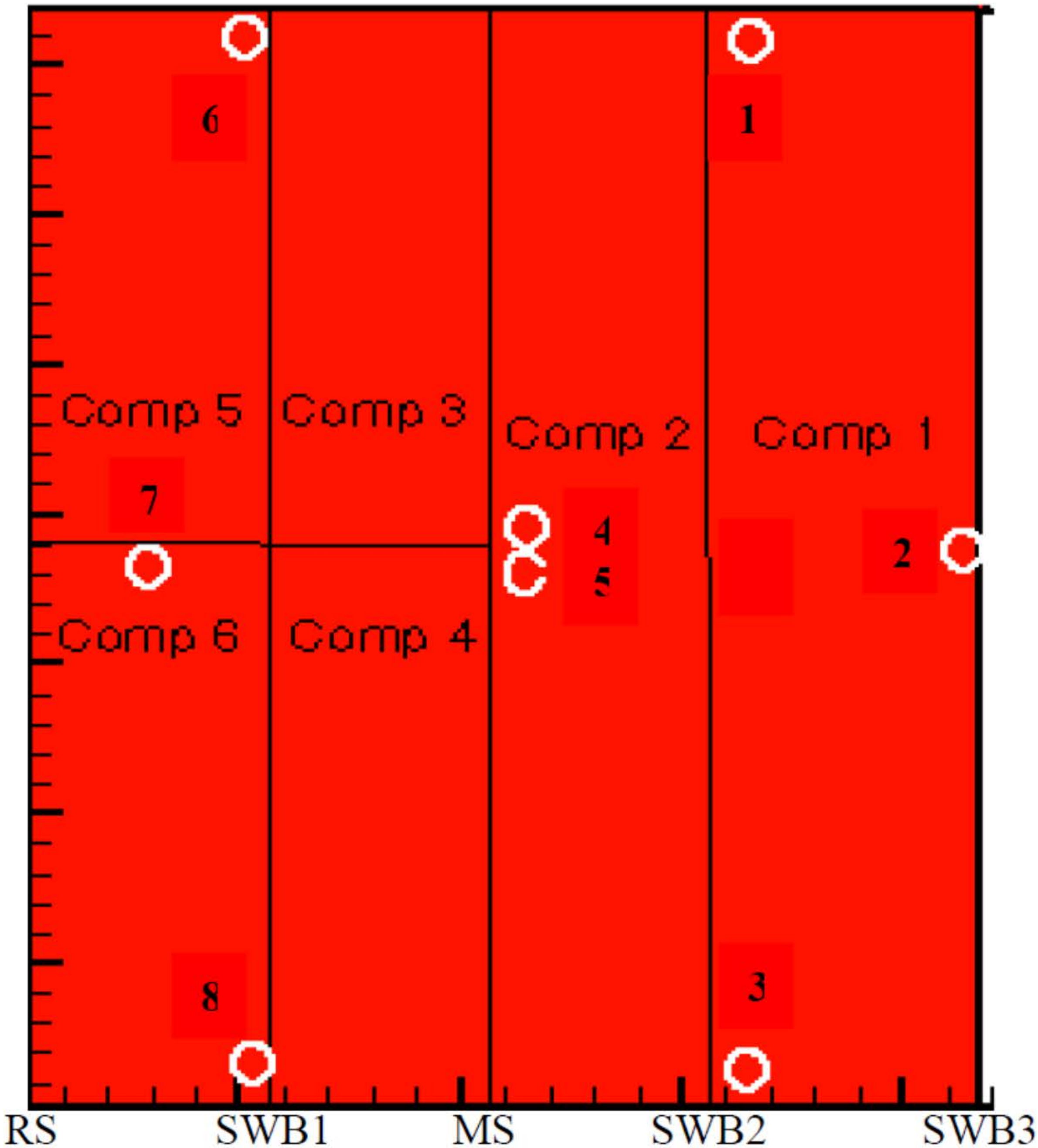

Figure 9Ignition positions used in the full-scale CWT FLACS simulations.

The results of the simulations considered the loading of each partition as a function of time and the possibility of flame quenching in the various orifices upon flame arrival. The question of probable ignition location was addressed by combining the results of numerical explosion simulations with structural failure estimates to predict damage caused by the pressure differences within the wing tank structure.

Thibault (2000) developed in collaboration with Boeing and the National Transportation Safety Board minimum and maximum failure pressures for each of the partitioning walls. These failure pressures are reproduced in Table 1.

Table 1 Estimate of failure pressure of each of the partitioning walls of the CWT (Thibault, 2000)

Partitioning wall	Minimum failure pressure (psi)	Maximum failure pressure (psi)
Front Spar	20	25-30
SWB3	20	25
SWB2	20	30-35
Mid Spar	20	35-40
SWB1	25	45-50
Rear Spar	30	45-50

The predicted and observed damages were folded into a rule-based system to evaluate the consistency between internal explosion scenarios and the observed damages associated with the early events. This system was developed by Thibault (2000) in order to evaluate the explosion scenarios as a function of various parameters. The agreement with observed damage was expressed by a consistency factor. An example of results is shown in Figure 10.

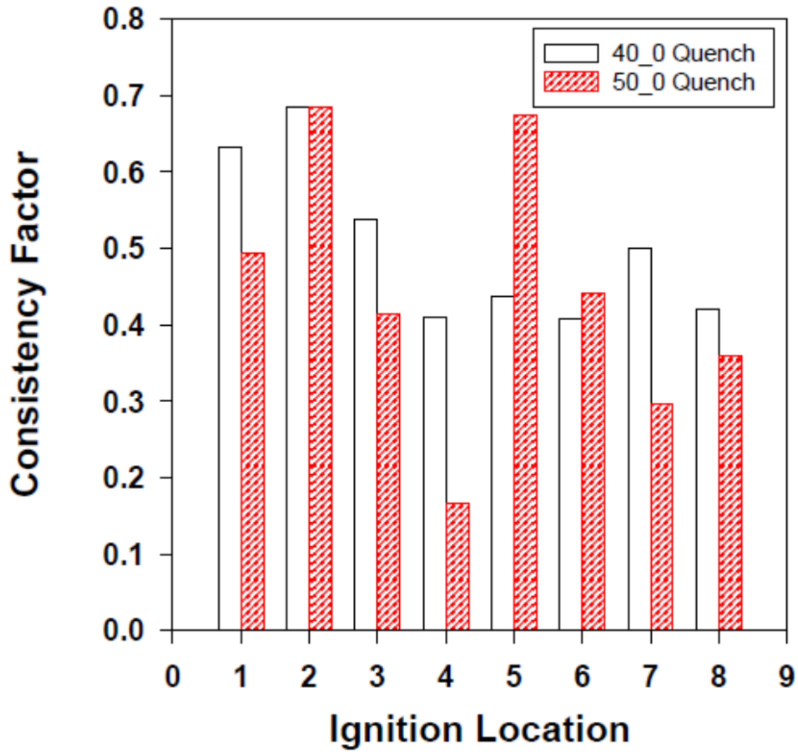

Figure 10 Comparison of consistency factors for 8 ignition locations for CWT temperatures of 40 and 50 °C and assuming quenching occurs according to the developed criterion (Thibault, 2000).

The rule-based system evaluation of these numerical simulations found 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. The results of Figure 10 show that the most consistent ignition source locations are 2 and 5 assuming a 50 °C in the CWT and 1 and 2 assuming a 40 °C in the CWT. A single ignition location could not be established but the results were such that one could conclude that a single ignition source could have ignited the fuel and the resulting gas explosion could have caused the damage seen and the accident as it occurred.

4. Conclusions

The FLACS simulations performed indicate that the pressure differentials produced by an internal fuel-air explosion are consistent with the overall level of damage observed in the CWT. Hence the investigation showed that the TWA-800 explosion most likely is due to a gas explosion in the CWT.

On the other hand none of the ignition locations considered in the FLACS simulations were consistent with all of the observed damages.

The most probable ignition location depends strongly on the initial temperature and on the quenching phenomena which play an important role for Jet-A/air flames. Differences in consistency factors between ignition locations are much more evident when quenching is present due to the large pressure differentials created at a partitioning wall when quenching occurs.

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