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A methodology to determine pre-crash fuel quantity from post-crash fire thermal damage to an aircraft structure

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Abstract
The cause of engine failure that resulted in a catastrophic crash of a twin turbo-jet commuter aircraft is sought. The US National Transportation Safety Board and aircraft manufacturer contend that the engines failed because the aircraft ran out of jet fuel. The aircraft operators are confident that there was adequate fuel and that some other process caused fuel starvation. There was a post-crash fire that caused substantial thermal destruction of aircraft structure. If the majority of fire damage could be attributed to the burning of jet fuel, then it would be likely that the fuel inventory, just prior to impact with the ground, was adequate for continued flight. Thus investigators would have to conclude that some other mechanism caused the fuel starvation. In this work, a methodology is presented to determine the amount of fuel necessary to cause the observed thermal damage on the aircraft structure. The methodology is based on the determination of the heat flux and burning rates from the associated jet fuel pool fire and a heat transfer analysis to obtain the time required to melt structural parts subjected to the resulting heat fluxes. For an Aluminum alloy member, 70 mm thick, the time to reach the melting temperature of the alloy ($\sim$500°C) is almost 4 min. Fully developed jet fuel pool fires burn at a rate of $\sim$0.06 kg/m^{2}s, thus, for a pool fire of 10 m^2, the fuel burned would be $\sim$130 kg, which is equivalent to about 151.4 L (40 US liquid gallons) of fuel. This fuel quantity would have been more than sufficient for the aircraft to reach its destination.

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Moreover, the actual quantity of fuel burnt would have been substantially more because of the conservative assumptions made in the analysis.

Keywords
Aluminum melting, heat balance, jet fuel fire, post crash fire

Introduction

Aircraft crash investigations are structured similarly in most countries. Members of the transportation bureaucracy that specialize in aircraft crashes mobilize a team of interested parties comprised of investigators from the airline operator, the aircraft manufacturer, the power plant manufacturer, air traffic controllers, meteorologists, survival factors specialists, and if the crash involved fire, a specialist in fire investigation. Everything from the crew's performance history and the aircraft's maintenance history to communications between flight crew and operational data recorded on flight data recorders is scrutinized. Communications between flight crew and ground have often provided critical information about the aircraft environmental conditions and flight performance before impact with the surface. In most cases, these communication data do not define the exact nature of the problem but they do provide a starting point for the post-crash investigation and analysis.

Official personnel first to arrive at a crash scene are the police and the fire and rescue units. If there is a fire, it is extinguished and the initial response is to determine if there are survivors. If no one survived, officials secure the site until the investigation team leader gives permission for recovery of the deceased. A good investigation will include dimensional surveys of the site, approach path, and wreckage distribution. In addition, extensive photo and video documentation of the wreckage and terrain is required. Because resources of the departments tasked with this work are limited, the ability to exhaustively pursue crash investigations often depends on current workload or on the visible profile of the accident. If any evidence is discovered at the site that may have bearing on the cause of the accident, the team leader sequesters the item(s) and the remaining wreckage is either stored for future analysis or destroyed.

The accident profiled here is one in which communications by the crew suggested that the percipient cause of the crash was because the aircraft ran out of fuel. The official finding by the US National Transportation Safety Board (NTSB) concluded similarly. The airline operator did not agree with the finding and launched an independent analysis to explore evidence that suggested that the quantity of fuel that caused the post-crash fire was much more than would have been available had the aircraft fully depleted its usable fuel. In this study, an analysis based on relating the quantity of fuel burned to the time required to melt various structural elements of the aircraft is developed using basic heat transfer relationships.

Background

The aircraft that crashed was a twin-engine business turboprop, the Jet Stream model 3101-12. Figure 1 is a drawing showing structural details of the fuselage and wings. Depending on configuration, it can carry up to 19 passengers and 2 crew. The total fuel capacity of both wing tanks is 1718 L (454 US liquid gallons). Due to wing tank design, a very small volume of fuel will be trapped in the tanks and is unavailable to the engines. This is defined as the 'unusable fuel' which for the Jet Stream is 37.85 L (10 gal.) total. Other flammable fluids carried by the aircraft are the hydraulic fluid, where the total capacity of the system is 22.71 L (6 gal.), including a 11.36 L (3 gal.) reservoir tank. The oil inventory of each engine, including the oil reservoir, is 6.81 L (1.8 gal.). The only other flammable materials in the aircraft were cabin materials including seat upholstery, floor covering, and the cabin finishing materials. Tires are also potential fuel contributors.

The smoke plume from the crash guided rescue personnel to the crash site, which was near the top of a mountain. The aircraft hit the ground at a steep angle in an extreme left bank. At impact, the aircraft rotated such that the wreckage was found facing in the approach direction. All airplane parts except for the tail section were found in relatively normal configuration and location. The tail section was upside down but still connected to the main fuselage by control cables. Figure 2 is the NTSB sketch of the wreckage distribution and Figures 3 and 4 are photographs of the wreckage looking from rear and forward directions, respectively. Note that wreckage is resting on a pile of boulders.

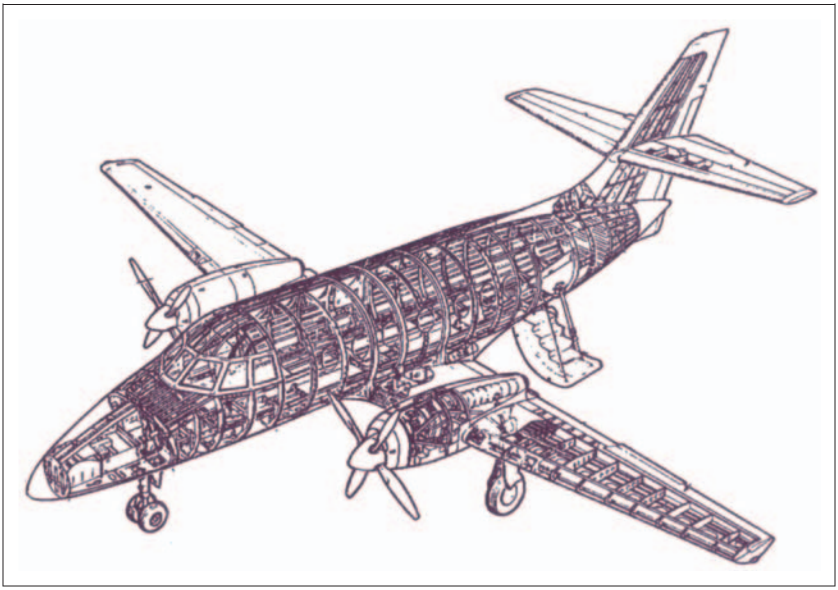

Figure 1. Structural schematic of Jet Stream Series 3100 Aircraft.

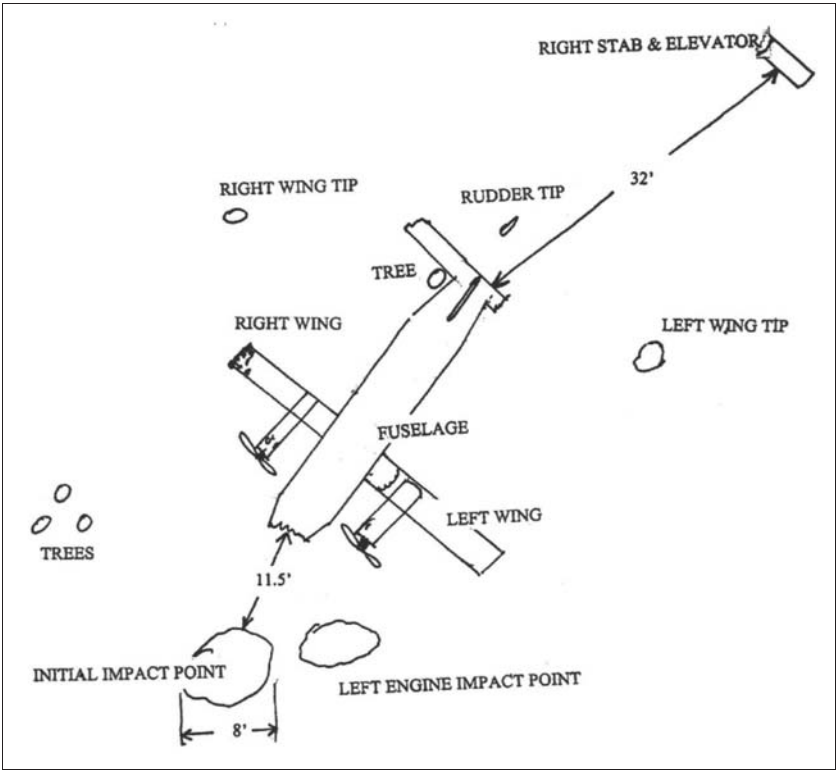

Figure 2. NTSB Structure Group Chairman's factual report wreckage distribution diagram. Reproduced from the NTSB [1].

The Survival Factors Specialist's Factual Report [1] contains data about the post-crash condition of the aircraft as it pertains to the potential for survival of passengers and crew. In this report are surveys of impact and fire damage to aircraft structure. The fire damage descriptions indicate that the post-crash fire was substantial. Specifically, in the section describing damage to the fuselage it was stated that; 'Portions of the airplane fuselage and some wing root material was found in the form of molten metal pools, shredded sheet metal, and airplane hardware. The fuselage was consumed from the cockpit area throughout the cabin area. Cables and electrical wires were heavily fire damaged and were found lying on the ground with their support structure missing.' In the section describing damage to the airframe, the left wing, outboard of the engine nacelle, was described as being 'heavily fire damaged' and the left inboard wing between engine nacelle and fuselage 'was consumed by fire.' Similarly, the right inboard wing section between the engine nacelle and fuselage 'was consumed by fire.' Internet search of all commercial airline crashes from 1970 to the present identified only three crashes where fuel depletion was established as the probable cause of the accident [2]. No post-crash fires were reported for these three accidents. This result is similar for

Figure 3. Wreckage site photograph, aft view. Reproduced from the NTSB [1].

Figure 4. Wreckage site photograph, forward view. Reproduced from the NTSB [1].

accidents in the private aviation sector. Thus, given the data reported in the Survival Factors Specialist's Report and the statistics that show the low frequency of post-crash fires reported for fuel starvation accidents, it is not surprising that the airline operators disputed the NTSB findings for this event.

Wreckage inspection

The preserved evidence was stored in two truck trailers after the NTSB released the wreckage to the airline. The procedure of inspection was to collect and identify items that were part of specific aircraft structure and place them in proximity to their location prior to the accident. Through this procedure, the extent of both mechanical and thermal damage sustained by the aircraft could be surveyed and these observations could then be related to the findings in the Survival Factors Specialist's Report.

The areas of the aircraft destroyed by fire include but are not limited to:

1. The area between the junction of the left wing and the fuselage and the inboard side of the aft right engine nacelle.
2. The right engine mount and forward nacelle.
3. A substantial area of the left wing between the left aft engine nacelle and the fuselage, behind the main spar.
4. The left flaps and middle portion of the left outboard wing.
5. The aft cabin and fuselage behind the wings.

The extent of thermal destruction to the aircraft structure is outlined on the plan view of the Jet Stream 3101 in Figure 5. Because so much of the structure was destroyed by the impact and fire and the inspection facility was limited in area, documentation photographs of the evidence show only limited elements of the damage. Figure 8(a) shows the bottom of the portion of the right wing that survived the fire. There were no recognizable components of structure that survived the accident between the engine station of the right wing and inboard connection between the left wing and cabin. Figure 8(b) is a photograph of the reconstructed left wing that was assembled from recovered elements of the wreckage. The mid-span void in the reconstruction is surrounded by incipiently melted Aluminum caused by the post-crash fire that surrounded the wing. Radiant heat effect (incipient melting of aluminum skin and paint degradation not associated with direct flame contact) to the outboard surface of the forward portion of the engine nacelle is an indication of the thermal intensity of the fire plume.

Analysis

The only fuel to initiate this fire and to cause the major structural damage observed and documented was the jet fuel inventory released during the crash kinematics. Some of the damage to upper fuselage areas probably resulted from burning of cabin upholstery during the fire. However, this damage would be limited to materials above floor level. The heavy forgings and castings that support the wings through the fuselage, the wing spars and the landing gear are below the elevation of the fuselage floor. The only fire that could engage these structural members would be from fuel released by the fuel reservoirs. Ignition sources for the released fuel were most likely electric arcs resulting from disrupted electrical circuits.

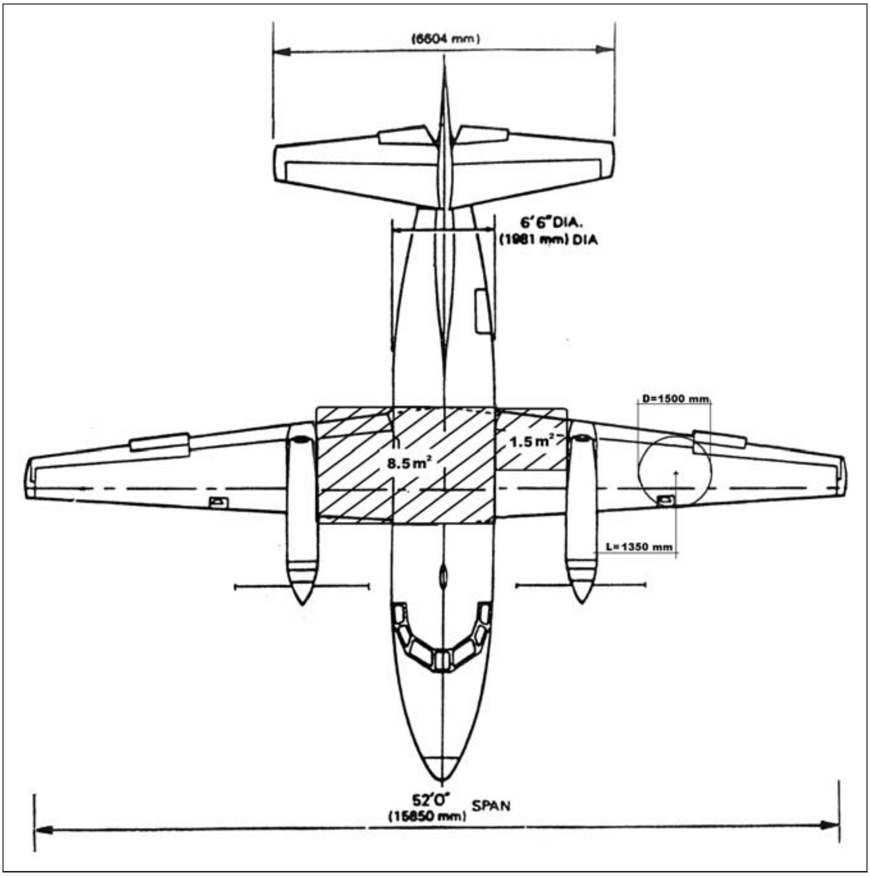

Figure 5. Major fire destroyed areas outlined on plan view of Jet Stream Aircraft.

Other possible ignition sources could be friction sparks produced when steel surfaces scraped across rocks or hot engine parts. A conservative estimate of the thermally destroyed portions of the fuselage and inboard wing areas shown in Figure 5 is $10\,m^2$ ($108\,ft^2$) Similarly, the thermally destroyed area in the middle section of the outboard left wing is greater than $1\,m^2$ ($11\,ft^2$).

Heat flux from a fire on a burning layer of jet fuel varies with the size of the fire plume, where flux intensity increases proportionate to plume height and fuel base area. At maximum intensity when the fire becomes optically dense, flame emissivity approaches unity. This maximum intensity has been measured to be in the range of $100\,kW/m^2$ ($8.7\,Btu/ft^2s$) [3]. At this intensity, the fuel consumption rate per unit area of burning jet fuel has been measured to range between 0.05 and $0.07\,kg/m^2s$ (0.01–$0.014\,lb/ft^2s$) [4]. The threshold melting temperature of 2024 T-6 Aluminum alloy, the alloy used in aircraft structure that has the lowest melting temperature, is approximately 500°C (932°F) [5]. Using standard heat transfer relations, it is possible to calculate the time necessary for different fuselage structure to reach their melting temperature. By correlating these times to the burning rate (fuel consumption rate) of the fuel and to the area of thermal destruction, the quantity of the spilled fuel that burned to cause the damage can be estimated.

The framework structure shown in Figure 1 illustrates the typical frame and stringer matrix to which aircraft skin is attached. Insulation blankets generally fit between the frames, especially in the passenger sections. When a large fire plume envelops the fuselage of an aircraft, the heat is transferred from the skin to the stingers and frames – substantially, prolonging temperature rise time and melting of the skin. The only time that thin Aluminum reaches melting temperature rapidly is when the exposure fire is very large and the support structure is wide spaced. Any structure shielded by the skin and its support matrix or insulation does not suffer intense heat exposure until after these components degrade. Thus, the heat transferred from fires to aircraft structure is a sequential process that affects progressively more materials as shielding components are eroded away. Moreover, heavy Aluminum forgings and castings such as wing spars and the spar carry through beams are supported by other massive Aluminum structure, providing efficient thermal conduction sinks that, because of the high thermal conductivity of the Aluminum, reduce the heating rate of these components.

The only recognizable components from the inboard wing and fuselage region of the aircraft that was recovered and preserved at the wreckage storage site were portions of the main spar carry through beams that were part of the fuselage structure of the aircraft. Figure 6(a) shows a portion of the spar caps for these beams. Figure 6(b) is the melted element of one of the beams where the un-melted dimensions are approximately 72 mm (3 in.) per side. The temperature response of these Aluminum beams exposed to a fire of the size consistent with the destroyed area in the center of the aircraft can be calculated using a standard lumped capacitance heat transfer equation and the thermal properties of 2024 Aluminum. This relationship is shown in Equation (1):

$$\rho c L A \frac{\mathrm{d}T}{\mathrm{d}t} = q_f'' A - q_{\mathrm{loss}} \tag{1}$$

The first term of the equation shows that the temperature history of the solid is controlled by its volume (LA), its density (ρ) and its specific heat (c). The second term defines the total energy ($q_f''A$) deposited at the surface of the solid and the third term (q_{loss}) collects the thermal losses of the element that result from conduction, re-radiation, and convection processes. In essence, these losses slow down the temperature rise of the element. Note that this relationship only calculates the temperature increase of the element. Once the element reaches the melting temperature, additional energy is required for the melting to occur. Thus, another term that includes the density, volume, and latent heat of fusion, should be added to the

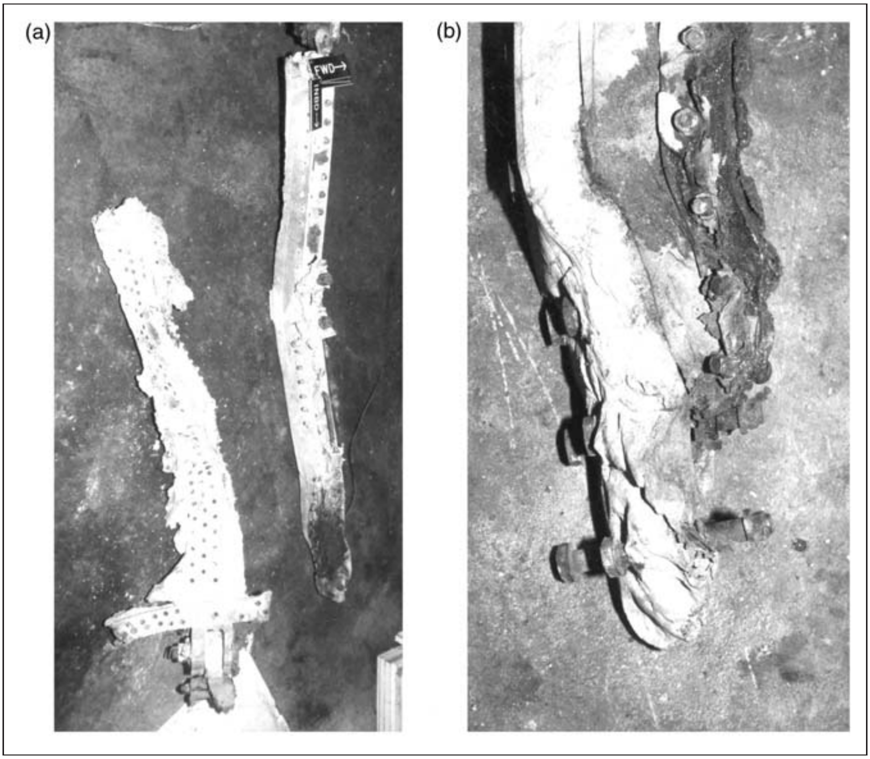

Figure 6. (a) Wing spar carry through segments; portions of the spar caps. (b) Melted end of one of the spar cap segments shown in Figure 6(a).

equation to have a more complete accounting of the temperature accumulation of the element.

In this treatment of the problem, the loss factors are ignored to simplify the solution. Integrating for time assuming a constant heat flux results in:

$$t = \frac{\rho c L}{q''_f}(T_m - T_a) \tag{2}$$

Note that by neglecting the loss factors, the time for the element to reach melting temperature is decreased. This correspondingly decreases the time of fire exposure and the amount of fuel consumed. Equation (2) is evaluated using the following properties of 2024 Aluminum alloy, its threshold melting temperature, the assumed surface heat flux and environmental values: ρ is the density (2770 kg/m^3), c the specific heat (875 J/kg°C), L the thickness (mm), T_m the melting temperature, 502°C (~900°F), T_a the ambient temperature, 20°C (~77°F), and q''_f the surface heat flux (100 kW/m^2).

With the preceding values, the time for the element to reach melting temperature for different thicknesses of the alloy is calculated to be:

$$t = 11.5L_e \quad (3)$$

where t is time (s) and L_e the element thickness (mm).

Using Equation (3), the time required for an element that is the thickness of the spar cap (76 mm) of the spar carry through beam to reach melting temperature can be calculated to be 874 s (14.5 min).

Geyer [6] describes tests done to determine fire penetration time for fuselage structure exposed to intense fuel spill fires. In these tests, the fire exposure was from a 232 m^2 (2500 ft^2) pool of JP 4 located on the up-wind side of a simulated fuselage. The geometry of this exposure was for one surface to be exposed to the fire source while all other surfaces were insulated. Figure 7 (Figure 21 from [6]) plots the two specific temperature end-points reached by different thicknesses of aircraft Aluminum panels as a function of fire exposure time. The equation for the 900°F (502°C $= T_m$) curve is:

$$t = 11.7L_e \quad (4)$$

These tests results thus provide an independent check that confirms the validity of Equation (3).

The melted end of this beam was located near the center of the most heavily burned-out (10 m^2) area of the aircraft. The average fuel-burning rate for large fuel pool fires is 0.06 kg/m^2s. With these data, the amount of fuel required to cause this

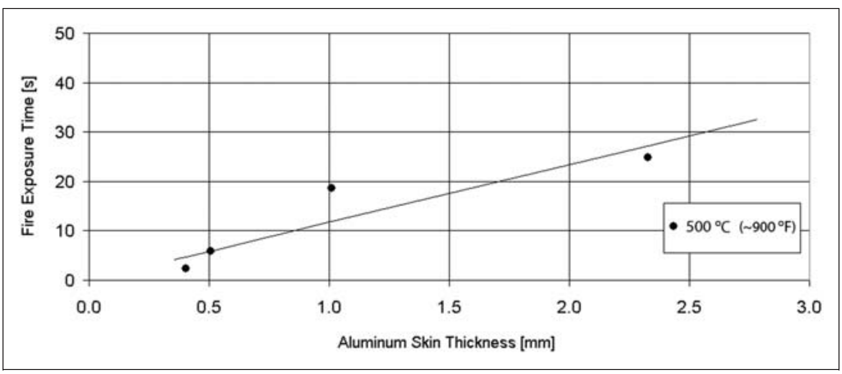

Figure 7. Melting time for different thicknesses of aircraft Aluminum as a function of fire exposure time. (6).

temperature to reach the melting range of the alloy can be calculated as follows:

$$0.06\frac{\text{kg}}{\text{m}^2\text{s}} \cdot 874s \cdot 10\,\text{m}^2 = 524\,\text{kg} \quad \text{(about 1156 lb)}$$

Jet fuel is about 802.66 kg/m^3 (6.7 lb/gal.). Therefore, the volume of fuel burned in the 10 m^2 area was 651 L (172 gal.) (assuming that the beam was exposed to radiant flux on one side only).

A square beam of Aluminum, 76 mm per side, immersed in an optically dense fire would be exposed to the same flux on four surfaces (assuming that the length of the beam exposed to fire is long enough so that conduction losses to the ends extending out of the fire is negligible). For this condition, the time for the beam to reach melting temperature is 0.25 of the time for the single surface exposure. Thus, the amount of fuel consumed would be 0.25 times 651 L, which equals 162.75 L (43 gal.). Because the rate of heating of these spar elements will be influenced by the loss factors that have been ignored in this treatment and by unknown shielding processes, it is believed that the fuel required to cause element melting would be substantially higher than these calculated values.

Fire damage to the outboard left wing, shown in Figure 8 appears to have been caused from fuel that spilled independently from outboard left wing fuel cells.

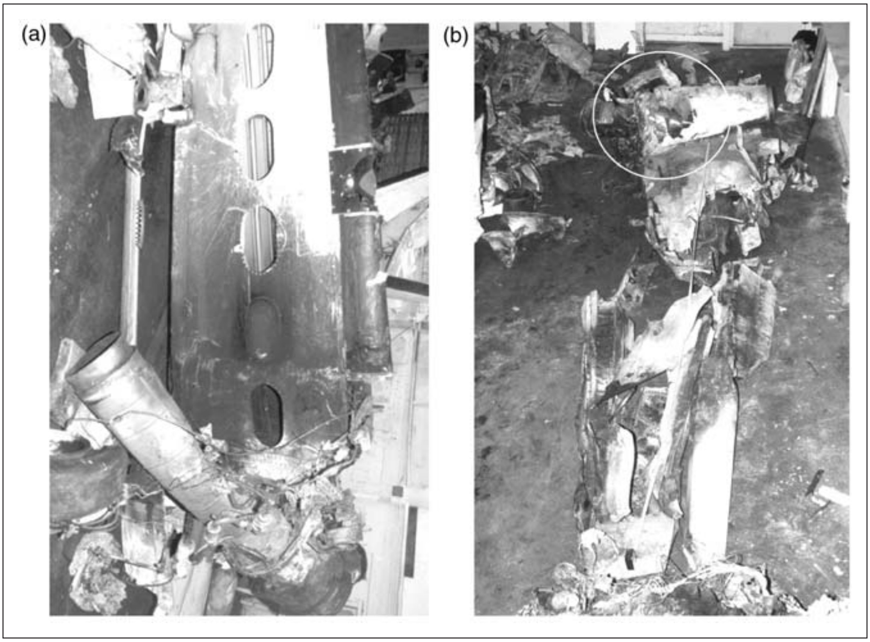

Figure 8. (a) Section of bottom right wing from engine station to outboard. Leading edge to right side of photograph. (b) Photograph of top left wing from tip to engine nacelle. Leading edge to left side of photograph.

An interesting area of thermal damage was sustained on the outboard vertical surface of the aft engine nacelle. This area (circled in Figure 8(b)) was degraded by thermal radiation since spared surfaces and structures around the degraded area show no evidence of flame exposure. To estimate the quantity of fuel that caused this damage to the outboard surface of nacelle, experimentally derived equations from reference [7] were used to estimate the radiant heat flux from a range of potentially possible fire plumes to the surface of the nacelle. The time required for radiant flux to raise the temperature of the nacelle to melting temperature was then determined, using Equation (2). The fire plume size was estimated by assuming a base diameter of 1.5 m, which is consistent with the most thermally eroded area of the outboard wing, defined during the wreckage inspection. Finally, the quantity of fuel consumed was calculated.

The radiant flux absorbed by the nacelle is given by:

$$q''_d = \alpha F_{12} q''_f \tag{5}$$

where q''_d is the absorbed radiant flux, α the surface absorptance (0.8 for white paint), F_{12} the view factor between the plume and the nacelle surface (0.55, from reference [5]), and q''_f the radiant heat flux to the nacelle (derived from reference [5]).

$$q''_f = 15.4\left(\frac{L_s}{D}\right)^{-1.59} \tag{6}$$

where L_s is the distance from the center of the fire plume to the surface of the nacelle (1.35 m) and D the fire plume base diameter (1.5 m).

From Equation (6) it follows that the heat flux to the nacelle is proportional to the size of the fire plume. Replacing q''_f in Equation (2) by q''_d from Equation (5) allows the calculation of the time for the Aluminum skin of the outboard nacelle surface to reach its melting temperature. The thickness of the nacelle skin is assumed to be 1.1 mm (0.04 in.). This thickness is consistent with average skin thickness listed in the structural repair manual. For these conditions, the calculated time to melting temperature is 158 s. The corresponding fuel consumed was calculated to be 21.2 L (5.6 gal.) Note that this calculation is for radiant exposure only, since the thermal damage to the outboard nacelle surface shows minimal evidence of flame contact patterns.

Discussion and conclusions

Site photographs and inspection of retained wreckage show that the Jet Stream aircraft was severely damaged by the post-crash fire. Two specific areas of the surviving structure contained evidence that indicated that independent fuel sources were responsible for the fires that caused their thermal damage. The amount of fuel required to produce the damage sustained by these two areas was calculated by determining how long the fires had to burn to raise specific structural elements to their melting temperature. The analysis was conservative because the heat loss terms and the latent heat of melting were not considered in the calculations. Moreover, no effort was made to include the effects of attached and adjacent structure that would directly modify and increase the temperature rise time. Consequently, the times to melting temperature calculated in this analysis are substantially shorter than times that would be determined if all heat loss parameters had been included.

Based on this analysis, the quantity of fuel that caused the thermal damage to the mid-fuselage and the wings, inboard of the engine nacelle ranges between a minimum of 155.2 L (41 gal.) to a maximum of 617 L (163 gal.). The quantity of fuel to cause the damage to the outboard left wing was calculated to be of the order of 21.2 L (5.6 gal.). Thus, the minimum total inventory of fuel on board at the time of impact would be 176.4 L (46.6 gal.), over four times the volume of unusable fuel for the aircraft from the two wing tanks, the valves to both of which were in the 'open' position according to the NTSB. The contribution of hydraulic fluid to the fire would be trivial since the content of the hydraulic reservoir is less than a 10th of the minimum calculated burned fuel. Similarly, the engine oil reservoirs were located away from the analyzed areas of thermal damage. Note that this analysis does not include estimates of quantity of fuel that cause thermal damage to other areas of the aircraft e.g., the aft fuselage and the right engine mount. No account has been made of fuel lost during the crash kinematics or of how much fuel could be absorbed by the crash site terrain. For these reasons, it is likely that the amount of fuel released from the fuel cells during the crash would be substantially more than the quantities calculated by this analysis. Thus, this aircraft did not crash because there was not enough fuel on board.

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References

1. National Transportation Safety Board. Survival factors specialist's factual report. Washington (DC): National Transportation Safety Board; 2000 August 8 Docket No.: DCCA00MA052.
2. Major Airline Disasters. Involving commercial passenger airlines 1920-2002. http://www.airdisasters.co.uk/.
3. Gregory J, Mata R and Keltner N. Thermal measurements in a series of large pool fires. Albuquerque (NM): Sandia National Laboratories; 1987 August SAND85-0196-TTC-0659, UC-71, Section 3, pages 197–240 .

4. Mudan KS. and Croce PA. Fire hazard calculations for large open hydrocarbon fires. In: *The SFPE handbook of fire protection engineering*, 2 ed. Quincy, MA, USA: National Fire Protection Association, 1995, Section 3/Chapter 11.
5. Incropera FP. and DeWitt DP. *Fundamentals of heat and mass transfer*, 4th ed. New York: John Wiley & Sons, 1996.
6. Geyer GB. *Effect of ground crash fire on aircraft fuselage integrity*. Atlantic City Airport (NJ): US Department of Transportation – Federal Aviation Administration, National Aviation Facilities Experimental Center; 1969 December Report No.: NA-69-37 (RD-69-46).
7. SFPE Engineering Task Group on Engineering Practices. *Engineering guide for assessing flame radiation to external targets from fire sources*. Bethesda, MD: Society of Fire Protection Engineers, 1999.