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Analysis of a Boeing 747 Aircraft Fuel Tank Vent System

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This monograph presents an analysis of a 747 aircraft fuel vent system. The system is comprised of several fuel tanks feeding into a single vent tube. The analysis consisted of formulating equations that govern the venting and heating of the center tank. Flow losses along each section of the vent system were applied to correct the ideal flow from the center fuel tank. These equations were programmed for solution on a digital computer. Results were computed for a flight from Athens, Greece, to New York with a 5-hour delay on the ground before taking off again from New York. The heating caused by air conditioning and bleed air from the engines on the ground during the long delay caused vaporization of fuel and increased the density of the air-fuel vapor. The result was very sluggish venting and "choked" flow producing a significant overpressure, at 13,000 ft altitude, sufficient to fail some component of the center tank. This was a precursor event leading to serious consequences. The analysis supports a hypothesis of overpressure as the cause of the Trans World Airlines Flight 800 accident and shows that heating caused by air conditioning contributed to the sequence of events.

Nomenclature

A	=	area, in.^{2}
Cf	=	discharge coefficient, nondimensional
Cp, v	=	specific heats at contant volume or pressure, ft^2/s^2/°R
chf	=	heat-transfer factor, Btu/in./°F
H	=	enthalpy, Btu/lb
h	=	altitude, ft
m	=	mass, slugs or (lb-s)^2/ft
P	=	pressure, lb/in.^{2}
q	=	heating rate, Btu/s
R	=	gas constant, ft^2/s^2/°F or °R
$\mathcal{R}$	=	Reynolds number
T	=	temperature, °F or °R
t	=	time, s, min, or h
u	=	stream velocity, ft/s
V	=	volume, ft^3
$\Delta(\ )$	=	difference between values
$\partial(\ )$	=	partial of ( )
μ	=	kinematic viscosity, Stokes
ρ	=	density, slugs/ft^3
$\sum$	=	summation

Subscripts

A	=	ambient, atmosphere
L	=	losses
O	=	initial value
T	=	tank

Introduction

A HYPOTHESIS for the TWA Flight 800 accident is that the tank ruptured prior to the explosion of burning fuel. The rupture allowed fuel vapor to leak outside the tank where it was then readily ignited by an ignition source outside the tank. Once ignited, the fuel vapor burned back into the tank where the bulk of the fuel vapor was ignited with catastrophic results. This sequence would occur so rapidly that it would be indistinguishable from an event in which the fuel was ignited within the tank. This monograph presents an analysis of a Boeing 747 aircraft fuel tank vent system that explains how and why this would happen.

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Discussion

By way of illustrating the power of excess overpressure, it was such an event that caused a serious accident during SKYLAB launch. Sea-level atmospheric pressure was trapped behind one of the solar panels. At altitude the differential pressure between the trapped air pressure and the reduced atmospheric pressure on the outside of the panel caused the panel to prematurely deploy and subsequently fail. The falling panel struck the side of the Saturn SII rocket booster, damaging the explosive prima-chord, which was and supposed to sever the interstage at separation. Consequently, the interstage was only partially severed and was carried into orbit. The potential for a similar kind of occurrence is manifest for Trans World Airlines (TWA) Flight 800 or any high-performance aircraft that takes off with nominally sea-level atmospheric pressure within the fuel system and then ascends to 13,000 ft (3962 m) altitude within 6–12 minutes. The difference in pressure between sea level and 13,000 ft is over 800 lb/ft^2 (38,304 n/m^2) without pressure relief. Of course aircraft routinely fly to even greater altitudes where the pressure differential is even greater, but fuel tanks are fitted with venting sytems to provide pressure relief. Were the circumstances for the TWA Flight 800 such that significant differential pressure existed sufficient to cause a rupture? The answer appears to be in the affirmative.

There are two items that could contribute to significant differential pressure at altitude. Of first consideration was the tank venting system. A second item considered was the prolonged delay on the ground prior to departure on a hot summer day with the air-conditioning system operating. It was hypothesized the two items combined to cause the aircraft to depart with greater than atmospheric pressure in the fuel system. The tank pressure and the differential pressure at altitude are amenable to analysis. An analysis is presented further on, but the tank venting system and the effect of the air-conditioning system are discussed first.

Venting System and Center Fuel Tank

The center tank vent system is redundant because the tank is connected to two venting manifolds leading to the plenum chambers in either wing. These plenum chambers or surge tanks are freely vented to the atmosphere. A schematic of the starboard side of the fuel tanks and venting system are shown in Fig. 1. The figure is based on information contained in Ref. 1 and 2. The arrangement of the center fuel tank and venting system are shown in Fig. 2, which follows. This figure shows the partitioning of the fuel tank into compartments or bays and indicates the approximate volume of each compartment. Also shown is the arrangement of the venting system within the tank showing four tank inlets to the vent lines. The primary vent line is a rectangular duct 2.75 × 4.75 in. (6.99 × 12.06 cm) or a vent area of

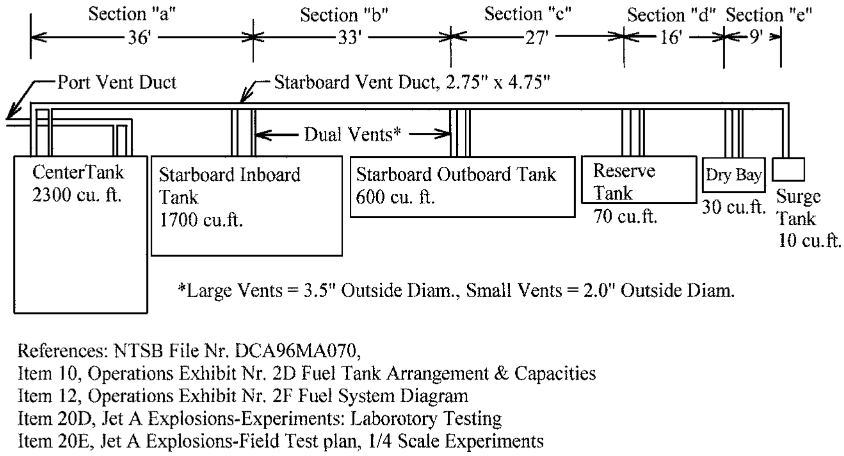

Fig. 1 Schematic layout of a 747 aircraft fuel tank vent system.

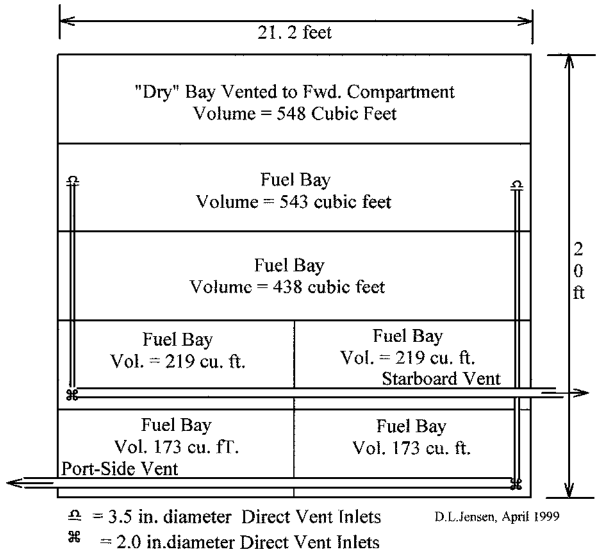

Fig. 2 Plan view, center fuel tank, Boeing 747 aircraft.

13.06 in.^{2} (84.26 cm^2). The size of primary vent inlets and the size of the secondary vent lines connecting to the primary vent line are 3.5 in. (8.9 cm) and 2.0 in. (5.1 cm) outside diameter. The size of the vent exit from the surge tanks at the wing tips is estimated to be 3.75 in. (9.52 cm). Also, indicated on the figure are bays, which are directly vented and those which are vented through compartment openings. These openings vary in size from 0.74 in.^{2} (4.72 cm^2) to 108 in.^{2} (697 cm^2), but no attempt was made to estimate flow between compartments. Because there are five tanks venting through each wing vent, the nominal flow coefficient for each tank is one fifth. However, the outboard tanks, with progressively shorter vent distances and lesser flow losses, necessarily use proportionally more of the vent capacity, further reducing the effective flow coefficient for the center tank. Based on a flow loss analysis for each tank, the center tank has only a 13% share of the vent capacity, i.e., the flow coefficient for the center approaches one eighth, which would restrict flow even more.

Air-Conditioning System and Fuel Tank Heat Transfer

The air-conditioning system was operating for a period of about 5 hours on the ground prior to flight. This was necessary because it was a hot day—90–95°F (32–35°C) in New York. This would probably be accompanied by high relative humidity, but water vapor effects were not included in the analysis although this could have an effect as a result of the increased density of highly humidified air. The system operated on ground power for about three of those hours before it began to operate from onboard power during the remainder of time on the ground and subsequent flight. There are three air-conditioning system modules in a compartment underneath the center fuel tank and in close proximity to the tank so the tank could be expected to absorb heat from the air-conditioning units. A schematic of the air-conditioning system and its arrangement is shown in Ref. 3. A significant feature of the air conditioning is the "bleed" air at 300–350°F (149–177°C) from the jet engines, which is routed to the air-conditioning modules under the tank. Information in Refs. 4 and 5 indicates the temperature in the air-conditioning compartment under the tank would be about 140°F (60°C) as a result of the jet engine bleed air and operation of the air-conditioning units. Reference 4 indicates a corresponding temperature of 115°F (46°C) for fuel in the center tank, a difference of 25°F (14°C). Also, there is no insulation on the bottom of the tank, and heat transfer is very efficient because of conductivity of aluminum. A consequence of heating caused by operation of the air-conditioning unit would be a pressure increase in the tank. The change in pressure caused by heating exceeds the change in pressure caused by change in volume through venting by a factor of 4.6. The pressure increase would be caused by two effects. One is the heating of the air-fuel-vapor mixture, and the other would be caused by vaporization of liquid residual fuel in the tank. As more fuel is vaporized, the density of vapor in the tank increases because fuel vapor is heavier than air by a factor of 2.7. This in turn effectively reduces the amount of venting because venting is proportional to the inverse of density to the half power, i.e., venting proportional to $1/(\text{density})^{1/2}$.

It was hypothesized that these considerations could contribute to an overpressure condition, which could have serious consequences to the flight. Consequently, an estimate was made of the amount of heating that the air-conditioning system could generate for inclusion in the analysis. The estimated air conditioning and other parameters are included in an Appendices A–F. Another feature is the inclusion of heat balance for the air-conditioning machinery (ACM) compartment underneath the center fuel tank and for the center tank itself. These heat balances are shown in Appendices F. From these the heat transfer between the ACM compartment and the center fuel tank was estimated giving the evaporation rate of Jet A fuel based on 187 Btu per unit mass as given in Ref. 6.

Analysis

The analysis consisted of formulating equations that govern the physics of venting and heating of the center tank. These include the effect on tank pressure of heating and venting through the fuel tank vent system. The fundamental equation relating fuel tank pressure and temperature is the equation of state for gases. Pressure times volume divided by temperature is equal to a constant or

$$PV = nRT \tag{1}$$

Differentiating this relationship,

$$\frac{\partial P}{\partial V} = \frac{-nRT}{V^2} \tag{2}$$

change in pressure caused by venting, and

$$\frac{\partial P}{\partial T} = \frac{nR}{V} \tag{3}$$

change in pressure caused by heating.

It is worthwhile to note the change in pressure from temperature change is greater than change caused by venting by the factor of the affected volume, i.e., $\partial P/\partial T = V \partial P/\partial V$.

Also, using Torricellis' equation for fluid discharge from a nozzle

$$\frac{dV}{dt} = CfA(\text{vent})\left[\frac{2(P_T - P_A - P_L)}{\rho}\right]^{\frac{1}{2}} \tag{4}$$

defines vent flow, where P_L represents flow losses. A flow loss analysis for the center tank is presented in Appendix E. References 8 and 9 were the sources for the flow analysis. The results of this analysis show that the nominal losses (at one p.s.i. pressure differential) for flow from the center tank amount to 70% for "unchoked" flow. Consequently, pressure "head" loss,

$$P_L = 0.7(P_T - P_A) \qquad \text{or} \qquad (P_T - P_A - P_L) = 0.3(P_T - P_A) \tag{5}$$

was applied to correct the ideal (no loss) flow velocity from the center fuel tank. In addition the flow velocity was limited to sonic velocity, i.e., velocity less than or equal to the speed of sound, $(gp/\rho)^{1/2}$ because the vent configuration precludes supersonic flow. Such limited flow is referred to as "choked" flow.

Continuing, the change in tank temperature was calculated based on the heat flow in or out of the tank;

$$\frac{dT}{dt} = \frac{778q}{mC_v} \tag{6}$$

change in temperature with heating. Heat transfer to and from the tank was based on the difference in temperature between tank temperature, air temperature, cabin temperature, and temperature in the air-conditioning compartment under the tank;

$$q = k(0.24Ta + 0.54Tacm + 15.5 - Tt)$$

where

$$k = \sum chfAf/d \tag{7}$$

Heat flow was based on a heat balance between the center fuel tank and the air-conditioning machinery compartment located underneath the center fuel tank as presented in Appendix F. Combining Eqs. (1–5),

$$\frac{dP}{dt} = \frac{\partial P}{\partial V}\frac{dV}{dt} + \frac{\partial P}{\partial T}\frac{dT}{dt} \tag{8}$$

change in pressure with time.

Integrating

$$\text{pressure, } P = Po + \text{integral}\left(\frac{dP}{dt}\,dt\right), \qquad 0 < \text{time} < 15 \text{ h} \tag{9}$$

$$\text{temperature, } T = To + \text{integral}\left(\frac{dT}{dt}\,dt\right), \qquad 0 < \text{time} < 15 \text{ h} \tag{10}$$

The center tank differential pressure is just the difference between tank pressure and ambient atmospheric pressure, i.e.,

$$\Delta P = P_T - P_A \tag{11}$$

Thus, the basic equations for the tank pressure and venting dynamics are readily established. These equations, along with some adjunct functions as presented in Appendices A–F, were programmed for solution on a digital computer. The results of these computations follow.

Results

Figure 3 is a plot of an altitude history representative of a flight from Athens, Greece, to New York, with a 5-hour delay on the ground before takingoff again from New York. Temperature on the ground at Athens was assumed to be 59°F (15°C). Temperature on the ground at New York was in the range of 90–95°F (32–35°C). The cruising altitude from Athens to New York was about 34,000 ft (10,363 m). Heat caused by air conditioning was included during the 5-hour ground delay at New York. Three of the hours on the ground used ground power for air conditioning, but the final two hours used onboard power so the effect of high-temperature bleed air from the engines caused an incremental increase in center tank temperature. Temperature and pressure at altitude were consistent with a standard day atmosphere with temperature linerarly adjusted in transit for a hot day at New York. The figure terminates at 13,000 ft (3962 m), just under the 13,500-ft (4115 m) elevation of the TWA explosion. Figure 4 shows the comparable differential center tank pressure during the representative flight. Reference 4 indicates that TWA aircraft departed Athens with the center tank full. However, for purposes of this analysis the tank was assumed empty at Athens. In this way a comparison could be made between a more normal takeoff and climb to altitude compared with circumstances (long delay and hot day) at New York. The data show no overpressure occurred after takeoff from Athens and during climb to cruising altitude. Conversely an underpressure of about 1.5 lb/in.^{2} is attained during descent and landing at New York. After takeoff and during climb to cruise altitude, the figure shows an overpressure of about 3.3 lb/in.^{2} (22,800 n/m^2) occurring at an altitude of about 13,000 ft. It is hypothesized that this is indicative of a pressure occuring sufficient to fail some component of the tank, such as a sump pump seal, exceeding its fatigue stress life cycle at that particular time. The aircraft had reportedly been in service long enough to accumulate the order of 18,000 cycles of stress

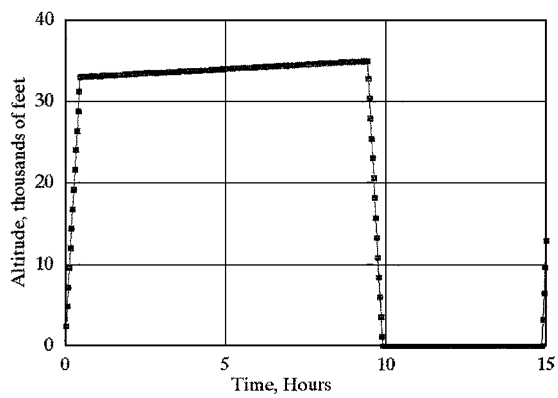

Fig. 3 Flight profile, TWA flight 800, Athens to New York.

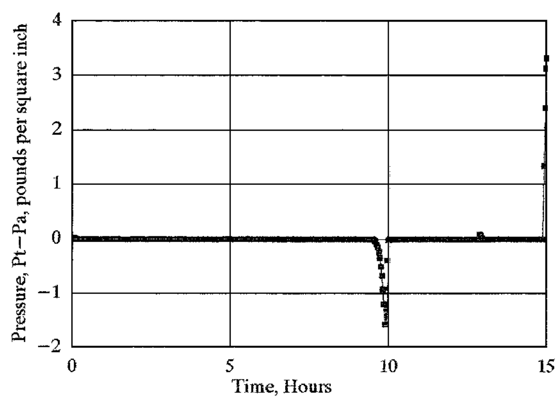

Fig. 4 Center tank differential pressure.

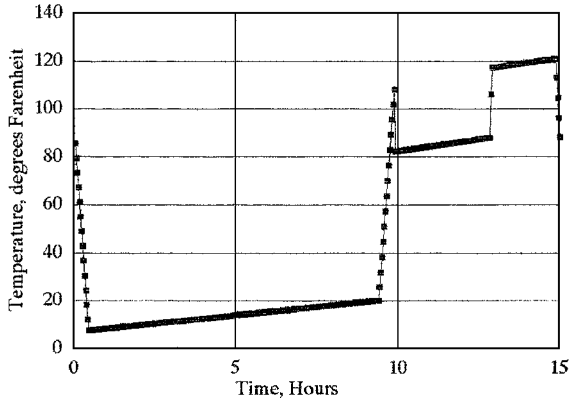

Fig. 5 Center tank temperature.

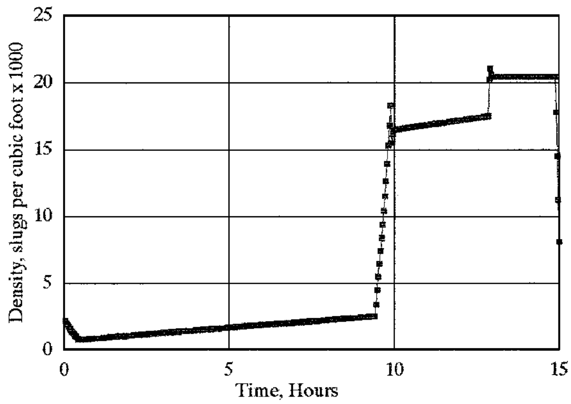

Fig. 6 Center tank fuel vapor density.

caused by takeoffs and landings (see Ref. 6). The results show a significant difference between the tank pressure history after takeoff from Athens and takeoff from New York. So it appears the heating on the ground during the long delay at New York had a significant effect on the events that subsequently transpired. There was a very slight overpressure existing, just sufficient to vent the excess air-fuel vapor as the heating vaporized residual fuel in the tank. The estimated fuel tank temperature variation is shown in Fig. 5. The significance of the temperature variation is shown by the reflection of variation in the fuel vapor density shown in Fig. 6. The vaporization increased the density of the air-fuel vapor because vaporized fuel could have a density of about 0.3–0.4 lb/ft^3 (4.8–6.4 kg/m^3), whereas dry air has a density of 0.07–0.08 lb/ft^3 (1.2–2.3 kg/m^3). This increase in density by itself would reduce venting by as much as 53–54% if no other factors were involved. However, there is the additional consideration of choked vent flow. The vent geometry precludes supersonic flow so that flow is limited to sonic velocity in the extreme case, i.e., choked flow. The analysis showed that choked flow occurred during descent and during ascent from New York for the last 4–6 minutes of flight.

The results of the analysis are considered a representative approximation to what occurred in flight. In the extreme case, if there were no venting the differential pressure at 13,000 ft (3982 m) would be 5.7 lb/in.^{2} (38,000 n/m^2). The calculation of the results presented herein are precise within the limits of the assumptions used and the formulation of the problem. There are reasons to think the calculated result may be less than what actually occurred. First, the choked flow condition would necessarily mean greater flow losses, which in turn would produce a greater overpressure at altitude. Second, the assumption that the center tank shared equally in the venting is too optimistic because, as already stated, a flow loss analysis for the other tanks shows they take up a larger share of vent capacity. Reduction of the center tank share of the vent from 20% used for this analysis to 13% based on a flow loss analysis for all tanks would produce substantially greater overpressure at altitude, i.e., an increase to about 4.5 lb/in.^{2} Consequently it seems likely the actual overpressure was somewhere between 3–5 lb/in.^{2}

Conclusions

It is concluded that a significant overpressure existed in the TWA Flight 800 center fuel tank after takeoff from New York and during climb to 13,000–14,000 ft (3982–4267 m) altitude. This was apparently a consequence of several factors that combined to produce an unusually great density of fuel vapor in the center tank. The duration of the flight from Athens to New York allowed a great amount of fuel to be vaporized in transit. Similarly, during the descent to New York and the long delay on the ground, fuel evaporation continued resulting in exceptionally great density of vapor at takeoff from New York. The result was sluggish venting and choked flow producing a significant overpressure at 13,000 ft (3982 m) altitude. This overpressure would have been sufficient to cause a failure or rupture of the tank prior to the explosion. This would vent fuel vapor external to the tank where it could be ignited by a source external to the tank. The burning vapor would then act like a fuse, carrying the flame back into the tank where it would ignite the bulk of the fuel, creating the catastrophic explosion that subsequently occurred. The effect of heating on the ground contributed significantly to the events that occurred. Temperature increase caused by heating required continuous venting, and heating continuously vaporized heavy vapor fractions to replace lighter vapor fractions being vented. The resulting increased vapor density reduced venting sufficient to cause a significant overpressure at altitude. The analysis supports the hypothesis of overpressure as the cause of the accident and the hypothesis that heating caused by air conditioning contributed to the sequence of events in a substantial way.

It is concluded that several factors contributed to an overpressure condition of TWA Flight 800 on departure from New York. These factors are 1) the long duration flight and long delay on the ground, 2) the heating caused by use of the air conditioning, 3) the hot day, 4) the rapid rate of climb (see Ref. 7), 5) venting system losses and choked flow limited to sonic velocity, and 6) great density of fuel tank vapor from vaporization. Finally, for reasons stated, it appears likely the analysis underestimates the pressure that may actually have occurred. The analysis shows overpressure could have been the cause of the TWA flight 800 accident.

Recommendation

Additional work is necessary to advance the hypothesis of overpressure as a cause of the TWA flight 800 accident. The amount of overpressure that will cause failure is unknown. A center tank pressure test is recommended as a way to obtain data that could support or refute the hypothesis. Such a test can be accomplished in a relatively simple and inexpensive way. A 747 aircraft used center fuel tank could be obtained, and a graduated stand pipe attached about 15 ft (4.6 m) in height as shown in Fig. 7. The tank can then be filled through the stand pipe with dye marked water, in 2.76-in. (7.01 cm) increments (2.76 in. of water is equivalent to a tenth of a pressure). At each increment the tank would be inspected for signs of leakage. In this way the pressure at which the tank leaks and location of the leaks could be determined. A 15-ft high stand pipe would permit pressure testing to 6.5 lb/in.^{2} (44,900 n/m^2).

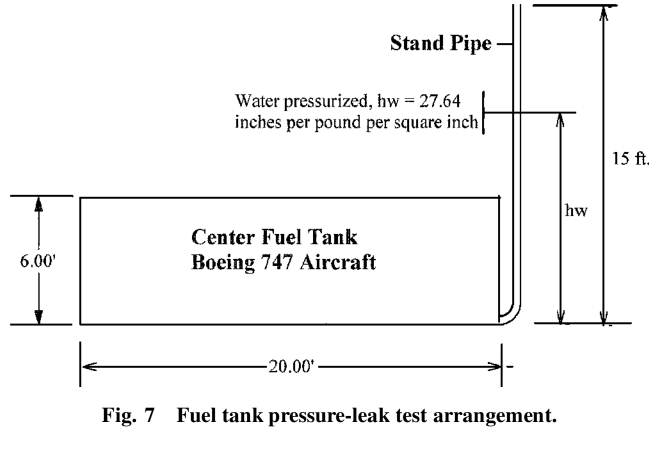

Fig. 7 Fuel tank pressure-leak test arrangement.

Appendix A: Auxiliary Functions

The air density and temperature were made functions of altitude according to a standard atmosphere; 59°F, 14.7 lb/in.^{2}, 0.002378 slugs/ft^3 on the ground.

Temperature of air:

$$T(h) = T(\text{ground}) - 0.00358 \times h \tag{A1}$$

standard lapse rate.

Temperature on the ground was increased linearly from 59 deg in Rome to 95 deg at takeoff from New York.

Air pressure:

$$P(h) = 14.7 - ah + bh^2 \tag{A2}$$

Air density:

$$\rho(h) = \rho(\text{ground}) - ch + dh^2 \tag{A3}$$

fitted to the standard atmosphere at 15,000 and 30,000 ft altitude.

$$a = 5.1/104, \qquad b = 0.556/108$$

$$c = 6.79/108, \qquad d = 0.609/1012$$

Appendix B: Cabin Air Volume for Air Conditioning

It was assumed that the air-conditioning unit changed the air in the cabin once every hour. So the weight of air conditioned by the air conditioning unit was

$$\text{weight/s} = V(\text{cabin vol.}) \times \rho(\text{air density})/3600\text{ s} \tag{B1}$$

V (cabin volume) = 49,009 ft^3; ρ (air density) = 0.076 lb/ft^3; weight of air conditioned per second = 1.03 lb/s.

Appendix C: Air-Conditioning Heat Rejection

An air-conditioning coefficient of performance is

$$C.P. = T(\text{cabin}) + 460/[T(\text{exhaust}) - T(\text{cabin})] \tag{C1}$$

Assuming the cabin is maintained at 72°F and exhausting to a temperature of 95°F, the estimated coefficient of performance would be 23.

Also, the coefficient of performance is

$$C.P. = H(\text{air}) - \text{work per lb/work per lb} \tag{C2}$$

or solving for the work done;

$$\text{work per lb} = H(\text{air})/(C.P. + 1) \tag{C3}$$

For H (air) = 51 Btu/lb and $C.P.$ = 23, work per lb = 2.125 Btu/lb estimated heat exhausted by the air-conditioning unit per pound of air processed. Heating caused by air conditioning, q = 2.125 × 1.03 = 2.2 Btu/s.

Appendix D: Estimates Thermal Parameter

The gas constants for use in the eqaution of state were calculated as follows:

$$R = 144 \times \text{molecular weight} \times \text{pressure}$$
$$\times \text{ unit volume/(weight/unit vol.} \times \text{temp.)} \tag{D1}$$

For air,

$$R = 144 \times 29 \times 14.7 \times 1/(0.0765 \times 519) = 1546\ \text{ft}^2/\text{s}^2/\text{deg}$$

for a representative hydrocarbon fuel,

$$R = 144 \times 80 \times 14.7 \times 1/(0.211 \times 519) = 1546\ \text{ft}^2/\text{s}^2/\text{deg}$$

Using

$$Cp - Cv = R, \qquad Cp/Cv = 1.4 \tag{D2}$$

The specific heat at constant volume is

$$Cv = R/0.4 = 3865$$

Number of moles of gas in tank is

$$n = \text{weight of air/molecular weight}$$
$$+ \text{weight of fuel vapor/molecular weight}$$

$$n = (91/29) + (252/80) = 6.3$$

or 183/29 for dry air or 504/80 for fuel vapor if tank is filled with all one constituent or the other.

Appendix E: Vent System Flow Losses

The system is comprised of several tank flow sources feeding into a single branch, the vent. The procedure was to calculate entry, expansion, turning, and viscous losses along each section of the vent system. Many of these losses are dependent on the Reynolds number associated with the flow at a particular section of the vent system. The flow characteristics and losses were estimated for the Boeing 747 vent system as shown in Figs. 1 and 2. The computation was an iterative process starting with an assumed 50% loss of pressure "head" and iterating until the initial loss and the final value were in agreement. The results generally converged within 10 iterations. The losses were as follows:

Entry loss:

$$\rho u^2/576 \tag{E1}$$

Expansion loss:

$$\rho(u_k - u_{k+1})^2/2 \tag{E2}$$

Turning loss:

$$\rho f(1/r)u^2/288 \tag{E3}$$

$1/r$ equivalent ratio, length of bend to radius, (Ref. 8, p. 115).

Tube and flow loss:

$$\rho f(1/c)u^2/288 \tag{E4}$$

($1/c$ ratio, length to wetted perimeter).

Flow factor:

$$f = 0.074/R^{0.2} \tag{E5}$$

(Ref. 9, p. 7–119).

Reynolds' number:

$$\mathcal{R} = \rho' cu/m \tag{E6}$$

where ρ' is an average estimate of density downstream of a tank station for merged flow upstream of a particular tank and flow from the tank. These losses were computed for each tank connected to the vent system: the center tank, the inboard tank, the outboard tank, the reserve tank, and the dry bay tank. The losses through the plenum chamber (surge tank) were included primarily as expansion losses. The results of these computations are shown in Table E1.

Appendix F: Heat Balance

Heat balance for the air conditioning machinery (ACM) compartment and the center fuel tank formed the basis for the heat transfer and the heating, which caused evaporation of the residual fuel in the center tank.

Table E1 Iterative vent flow analysis for center fuel tank, Boeing 747 aircraft

Differential pressure	0.5	0.2	0.36	0.26	0.32	0.28	0.31	0.29	0.30	0.29	0.30
Tube flow-velocity	157	98	133	112	126	118	123	120	122	120	121
Duct flow-velocity											
a	141	88	119	101	113	105	110	107	109	108	109
b	282	176	239	201	226	211	220	214	218	216	217
c	423	265	358	302	339	316	330	321	327	323	326
d	564	344	465	392	440	410	429	417	425	420	423
e	705	502	679	573	642	599	627	609	620	613	618
Reynolds number											
3.5-in. tube	87,055	54,500	73,775	62,181	69,726	65,039	68,040	66,154	67,354	66,596	67,077
2.0-in. tube	41,787	26,160	35,412	29,847	33,468	31,219	32,659	31,754	32,330	31,966	321,97
Reynolds number											
a	348,222	218,000	295,098	248,725	278,902	260,155	272,161	264,615	269,415	266,384	268,307
b	527,949	330,516	447,407	377,100	422,852	394,428	412,631	401,190	408,468	403,873	406,788
c	1,423,166	890,956	1,206,053	1,016,530	1,139,861	1,063,241	1,112,310	1,081,469	1,101,088	1,088,701	1,096,559
d	2,584,170	1,617,789	2,189,939	1,845,805	2,069,748	1,930,621	2,019,720	1,963,720	1,999,344	1,976,852	1,991,121
e	4,642,954	2,831,092	3,832,342	3,230,115	3,622,010	3,378,542	3,534,463	3,436,463	3,498,804	3,459,445	3,484,415
Flow factors											
3.5-in. tube	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
2.0-in. tube	0.009	0.010	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Flow factor											
a	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
b	0.005	0.006	0.005	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
c	0.004	0.005	0.004	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
d	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
e	0.003	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Entry-loss	0.450	0.176	0.323	0.230	0.289	0.251	0.275	0.260	0.269	0.263	0.267
Expansion loss	0.100	0.039	0.072	0.051	0.064	0.056	0.061	0.058	0.060	0.059	0.059
3.5 in. Tube loss	0.164	0.070	0.121	0.089	0.110	0.097	0.105	0.100	0.103	0.101	0.102
2.0 in. Tube loss	0.016	0.007	0.012	0.009	0.011	0.009	0.010	0.010	0.010	0.010	0.010
Turning loss	0.092	0.040	0.068	0.050	0.062	0.055	0.059	0.056	0.058	0.057	0.058
Duct loss											
a	0.066	0.028	0.049	0.036	0.044	0.039	0.042	0.040	0.042	0.041	0.041
b	0.080	0.035	0.060	0.044	0.054	0.047	0.051	0.049	0.051	0.049	0.050
c	0.062	0.026	0.045	0.033	0.041	0.036	0.039	0.037	0.038	0.038	0.038
d	0.035	0.034	0.059	0.043	0.053	0.047	0.051	0.048	0.050	0.049	0.049
e	0.014	0.007	0.012	0.009	0.011	0.010	0.011	0.010	0.011	0.010	0.011
Exit losses	0.029	0.015	0.027	0.019	0.024	0.021	0.023	0.022	0.023	0.022	0.023
Total loss	1.11	0.48	0.85	0.61	0.76	0.67	0.73	0.69	0.71	0.70	0.71

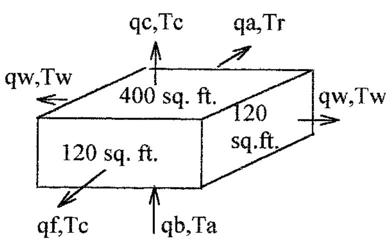

Fig. F1 Center tank heat balance.

Heat Balance for Center Fuel Tank

A schematic for the center tank heat balance is shown in Fig. F1. Equating the sum of the heat flows to null,

$$qa + qb + qc + qf + 2qw = 0 \tag{F1}$$

where the individual heat flows are

$$q = chf\,Af\,\Delta T/\mathrm{d} \tag{F2}$$

where *chf* is 0.42 for aluminum and d is distance for heat transfer, material thickness. Substituting representative values,

$$qa = 403(Tt - Tr), \qquad \text{assume } Tr = (Tt + Ta)/2 \tag{F3}$$

$$qb = 1344(Tt - Tacm) \tag{F4}$$

$$qc = 134(Tt - Tc), \qquad \text{assume } Tc = 72^{\circ}\mathrm{F} \tag{F5}$$

$$qf = 403(Tt - Tc) \tag{F6}$$

$$qw = 806(Tt - Tw), \qquad \text{assume } Tw = (Tt + Ta)/2 \tag{F7}$$

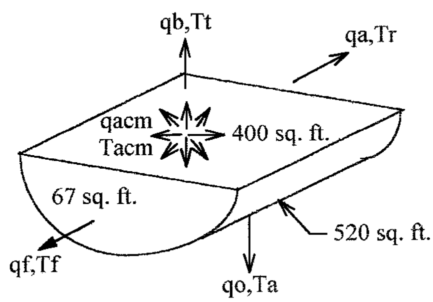

Fig. F2 ACM compartment heat balance.

Solving for *Tt*,

$$Tt = 0.24Ta + 0.54Tacm + 15.5 \tag{F8}$$

Heat Balance for ACM Compartment

A schematic for the center tank heat balance is shown in Fig. F2. Equating the sum of the heat flows to null,

$$qa + qacm + qb + qf + qo = 0 \tag{F9}$$

where the individual heat flows are

$$q = chf\,Af\,\Delta T/\mathrm{d} \tag{F10}$$

Substituting representative values,

$$qa = 900(Tacm - Tr), \qquad \text{assume } Tr = (Tacm + Ta)/2 \tag{F11}$$

$$qb = 1344(Tacm - Tt) \tag{F12}$$

$$qf = 225(Tacm - Tf), \qquad \text{assume } Tf = (Tacm + Ta)/2 \tag{F13}$$

$$qo = 900(Tacm - Ta) \tag{F14}$$

$$qacm = 900(Tacm - Tb), \qquad \text{engine bleed air, } Tb = 350^\circ\mathrm{F} \tag{F15}$$

Solving for *Tacm*,

$$Tacm = 0.65Ta + 0.225Tb + 8.9 \tag{F16}$$

Acknowledgment

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References

[1]Item 12, Operations Exhibit Nr. 2F, Fuel System Diagram, National Transportation Safety Board File Nr. DCA96MA070, Note 2.

[2]Item 10, Operations Exhibit Nr. 2D, Fuel Tank Arrangement and Capacities, National Transportation Safety Board File Nr. DCA96MA070.

[3]Item 22, Operations Exhibit Nr. 2P, Air Conditioning System Diagram.

[4]Shepherd, J., Krok, J., and Lee, J., National Transportation Safety Board Exhibit 20D, "Jet 'A' Explosions-Experiments: Laboratory Testing," June 1997 (corrected Nov. 1997).

[5]Shepherd, J., Krok, J., and Lee, J., National Transportation Safety Board Exhibit 20E, "Jet 'A' Explosions-Field Test Plan, $\frac{1}{4}$ Scale Experiments," June 1997 (revised Nov. 1997).

[6]"Interview with James, Hall, Chairman NTSB," *Aerospace America*, Feb. 1998.

[7]Cash, J. R., NTSB Exhibit No. 12-A, Group Chairman's Factual Report of Investigation, Cockpit Voice Recorder (see excerpt below), Oct. 1997.
2019:35 "Vee R" # (rotation speed)
2021:48 "climb thrust"
2025:34.5 "- - -about 2000 ft a minute- - -"
(33.3 feet per second))
2027:47 (sound of altitude alert tone)
(arrival at 13,000 feet in 8.12 minutes is an average climb rate of 26.7 feet per second)
2028:25.7 "- - -fuel one seven nine decimal zero,- - -"
(179,000 pounds of fuel)
2030:18 "climb thrust"
2030: 25 "climb thrust"
2030:35 "powers' set"
2030:42 (sound similar to mechanical movement in cockpit)
2031:03 * #(unintelligible word)
(#-editorial notes added by author).

[8]Powell, R. W., *Hydraulics and Fluid Mechanics*, Macmillan, New York, 1951, p. 115.

[9]Eschbach, O. W., *Handbook of Engineering Fundamentals*, Wiley, New York, 1952, pp. 7–119.