National Transportation Safety Board

Memorandum

Date: June 5, 2000

To: TWA flight 800 Docket

Through: Dr. Vernon S. Ellingstad, RE-1
Dr. Bernard S. Loeb, AS-1

From: James Wildey II, RE-30, Chief, Materials Laboratory
Joseph Kolly, RE-1, Fire and Explosion Group Chairman

Subject: Boeing Submission

This memorandum serves as a cover page for information provided by Boeing regarding the TWA flight 800 accident investigation. The memorandum contains a discussion of the rationale for the Safety Board request that this information be generated by Boeing, and, where possible, independent concurrence of conclusions and factual information.

In 1997, a team of researchers was assembled by the Fire and Explosion Group Chairman to investigate, in detail, the combustion of fuel vapors and subsequent explosion of the center wing tank (CWT) of the TWA flight 800 airplane. This team of researchers was comprised of experts in the field of explosion research from academia, public and private research facilities. Its members were tasked to develop the basic research and analytic tools necessary to analyze the CWT explosion. A substantial portion of this work was directed toward the development of two independent computer models capable of examining numerous CWT combustion scenarios. The intent was to determine if it was possible to narrow the number of probable ignition locations within the CWT, by examining the consistency between the predicted damages, and the physical evidence observed in the aircraft wreckage.

The analysis required a listing of the observed structural damage that was caused by the initial combustion event. The attached listing of "observable early event damages" was taken from the Metallurgy and Structures Sequencing Group's report on the breakup sequence of the airplane. Associated with each observed damage is a confidence level, as described in the Boeing submission. The Chairman of the Sequencing Group (James Wildey, Chief of the NTSB Materials Laboratory) participated in the development of the list of damages and the associated confidence levels and concurs with the findings as presented in the Boeing submission.

Estimates of the pressure differentials required to initiate failure of the various beams within and at the boundaries of the CWT were needed so that the models could take into account the predicted reaction of the structure to the dynamic buildup of pressure. Further, since the computer model results are descried in terms of pressure differentials, these estimates were used to interpret the pressure differentials in terms of predicted structural damage.

Ultimately, all of the results furnished by the computer model scenarios were then compared to the observable early event damages in an analysis procedure, called a Rules Based Analysis method, to measure the consistency of a particular scenario to the physical damages.

The attachments that follow are the observable early event damages document, and a document listing of the results of the failure pressure analysis.

Ronald J. Hinderberger
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April 26, 2000
B-H200-16937 -ASI

Mr. James Wildey
National Transportation Safety Board
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Subject: Structural Data, TWA 747-100 N93119 Accident off Long Island, NY – 17 July 1996

Reference: Metallurgy/Structures Sequencing Report No 97-38 dated April 8, 1997 in support of TWA Flight 800 accident investigation

Dear Mr. Wildey:

The purpose of this transmittal is to document Boeing's participation in generating the two enclosed data packages produced in support of the TWA Flight 800 accident investigation. This documentation is being provided at the specific request of the NTSB.

Both of the enclosed data packages were generated in direct support of the efforts of Combustion Dynamics Ltd., of Halifax, Nova Scotia, under the leadership of Dr. Paul Thibault. Combustion Dynamics had been contracted by the NTSB during the analysis phase of the investigation to explore the feasibility of modeling a 747-100 center wing tank fuel-air explosion. The effort was aimed at analytically replicating the documented damage from the Flight 800 event, and determining if a probable location of ignition could be identified.

The "Observable Early-Event Damages" table (Enclosure 1) was generated in order to focus on those structural failures identified in the reference report as having been associated with the early sequence of events. These structural failures were presumed to be associated with an explosion of the center wing tank. The format and approach for organizing the data in the subject table was directed by Dr. Thibault. Boeing contributed inputs to the table in the area of structural analysis results, along with an estimated degree of uncertainty accompanying each analysis conclusion. The Boeing analysis was based on the discussion provided in Appendix E of the referenced report. In some cases, for example the maintenance access doors on spanwise beam #1, Boeing performed more detailed additional analysis at the request of Dr. Thibault.

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Dr. Thibault also requested that Boeing provide an updated summary of calculated failure strengths predicted for selected main components of the 747-100 wing center section (which includes the center wing tank). This data was provided in the form of the "747-100 Wing Center Section Beam Overpressure Capability" summary (Enclosure 2). Because of the inherent degree of uncertainty of an entirely analytical prediction of respective failure strengths, the summary reflects a "minimum initial failure strength" as a lower bound, and an "estimated maximum initial failure strength" as an upper bound. This assessment therefore supercedes similar failure strength summaries provided by Boeing at various points earlier in the investigation process.

If you have any questions, please do not hesitate to call.

Very truly yours,

for

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Encl.: 1) Observable Early-Event Damages" table, 9 pages
2) 747-100 Wing Center Section Beam Overpressure Capability Summary, 1 page

cc: Mr. Al Dickinson, IIC

Observable Early-Event Damages

- The following tables document the inspection and calculation confidence for certain early event damages.
- Early event damages are as a direct result of overpressure resulting from assumed fuel-air explosion.
- Observations and confidence based on:
  - Structures Group and Sequence Teams direct observations and inspection of wreckage.
  - Analysis based on hand calculations accomplished on site.
  - Finite element computer structural modeling at Boeing to validate Sequence Team observations and stress calculations.
- Confidence level based on inspection and/or calculations assigned to individual observations.
- Combined confidence level typically less than or equal to inspection confidence level

Definitions of Relative Levels of Confidence

Inspection		Calculation
Hardware either not recovered or sufficiently damaged to obscure inspection of critical features.	---	No analysis accomplished (deemed impossible or impractical to accurately model)
Inspection of wreckage provides no evidence or substantiation (i.e. initial event vs. later event)	***	Analysis provides no substantiation (analytical replication unsuccessful or inconclusive)
Almost Certainly Did Not Happen	0%	Almost Certainly Did Not Happen
Low Probability of Happening	25%	Low Probability of Happening
Equal Probability of Happening	50%	Equal Probability of Happening
Likely Happened	75%	Likely Happened
Most Likely Happened	90%	Most Likely Happened
Almost Certainly Happened	100%	Almost Certainly Happened

- Action column to note further proposed action required.

Observable Early-Event Damages

Location	Observation	Confidence: Inspection	Confidence: Calculation	Combined Confidence	Comments	Action
Front Spar	Failure in vertical leg of upper chord at fillet radius.	100%	---	100%	• Examination of fracture surface along upper chord fillet radius indicates bending fracture with multiple initiation sites coincident with floor beam locations. • No finite element model run to validate conclusion that failure would necessarily occur in upper chord fillet radius. Hand calculations would indicate that bending failure in vertical leg at fillet radius would be consistent with overpressurization.	
	Sine wave deformation of spar (wrapping around water bottles)	100%	100%	100%	• Upper vertical flange of spar chord had residual curvature deformation. • Finite element model validated observation. Analysis assumed upper chord separation from upper panel, 25psi uniform overpressure, and full water bottles supported at attach points.	
	Symmetric failure pattern	100%	---	100%	• Examples of symmetry included upper chord failure initiations at floor beam locations, bowing of front spar around water bottles, and tension failure of vertical flange portion of upper chord at LBL and RBL 66. • Symmetric failures, while not validated by analysis, are consistent with the symmetry of the structure and assumed uniform loading for analysis purposes.	
	Failure due to impact	***	50%	50%	• Front spar stiffener free flange damage and buckling / crippling of stiffeners associated with impact damage from SWB#3 is well documented but direct observation alone does not provide confidence of overall front spar failure being caused by impact vs. pressure differential. • Combustion Dynamics Ltd. dynamic analysis looked at front spar failure due to SWB#3 dynamic failure vs. pressure differential. Results of modeling indicated that it would take 16.5ms for SWB#3 to impact the front spar at 120 m/sec vs. 12.2 ms to develop 7 psi pressure differential on front spar which was used as failure pressure. These two time scales are comparable and differ by less than 4 ms. Without more detailed CFD calculations and dynamic CSM calculations, both mechanisms appear to be equally probable at this time.	

Location	Observation	Confidence: Inspection	Confidence: Calculation	Combined Confidence	Comments	Action
	Failure due to pressure differential	***	50%	50%	• Combustion Dynamics Ltd. dynamic analysis looked at front spar failure due to SWB#3 dynamic failure vs. pressure differential. Results of modeling indicated that it would take 16.5ms for SWB#3 to impact the front spar at 120 m/sec vs. 12.2 ms to develop 7 psi pressure differential on front spar which was used as failure pressure. These two time scales are comparable and differ by less than 4 ms. Without more detailed CFD calculations and dynamic CSM calculations, both mechanisms appear to be equally probable at this time.	
	2 Symmetric cracks at BL66	100%	---	100%	• Examination of front spar indicates early failures in the upper chord near LBL 66 and RBL 66. These failures propagated down through the front spar web and ended at the lower edge of the web once again near LBL and RBL 66. The cracks also propagated down through the lower pressure bulkhead at symmetric stiffener locations near LBL and RBL 66 and into lower fuselage skin panel at stringer locations S-40R and S-39L. • Symmetric failures, while not validated by analysis, are consistent with the symmetry of the structure and assumed uniform loading for analysis purposes. • Finite element modeling accomplished to validate Sequence Team findings indicated stress concentrations in the lower fuselage skin panel near LBL and RBL 66 with the front spar web failed at those locations.	
SWB#3	Failed and rotated down to impact the front spar	100%	---	100%	• Impact marks on the aft side of the front spar stiffeners predominately in a zone approx. 12" below the upper skin IML at the front spar is consistent with SWB#3 rotating forward to impact the front spar. • Continued forward rotation and downward movement of SWB#3 resulted in tearing fractures in the front spar web.	
	Non-symmetric failure sequence (left went earlier)	50%	---	50%	• Web shearing fractures indicate relative movement of Spanwise beam sections but unable to conclusively determine by inspection if relative movement occurred during early event or as a result of later break-up of Spanwise Beam.	

Location	Observation	Confidence: Inspection	Confidence: Calculation	Combined Confidence	Comments	Action
	Fully attached access door deformed 1/10" forward	50%	---	50%	• Measurements of the recovered wreckage indicates .10" forward bowing of the SWB#3 access door . • Overall residual vertical and horizontal curvature of the remainder of the spanwise beam reduces overall confidence that deformation of access door is as a result of initial overpressure but that overpressure effects may be masked as a result of damage incurred during subsequent impact and break-up.	
SWB#2	Beam did not experience general or significant partial failure due to an overpressure gradient (i.e. typical failure mode involving failed upper shear ties, stiffener free flanges, and vertical leg of upper SWB chord.) Consequently, no significant increase in venting area through the beam would have occurred.	75%	75%	75%	• Extensive failure of SWB#2 would reduce the confidence that the remainder of the Wing Center Section would be capable of sustaining the wing loading to subsequently fail the wingtips prior to the complete failure of the Wing Center Section. • Differential pressures required to subsequently separate the manufacturing access door would have required that the SWB had not experienced an extensive failure that would have compromised the pressure carrying capability of the beam from a venting or structural integrity standpoint. • The majority of the left side of SWB#2 was not recovered or identified and some portions recovered were heavily burned which reduces confidence that general or significant partial failure could not have occurred on the left side. Portion of right side of SWB#2 remains attached to the upper panel with upper chord attached.	
	Manufacturing Access Door Failed	100%	---	100%	• The manufacturing access door was recovered from the red zone and the remainder of SWB#2 was recovered from the green zone. • Failure of the manufacturing access door and subsequent departure of door is prior to fire damage supported by examination of overall soot accumulation on door vs. remainder of spanwise beam and examination of sooted vs. clean fracture surfaces. • Inboard/lower rivets on access door sheared as a result of in-plane overload. Outboard/upper rivets failed in tension due to out-of-plane overload.	

Location	Observation	Confidence: Inspection	Confidence: Calculation	Combined Confidence	Comments	Action
	Maintenance Access Door Failed	---	---	---	• No comment can be made in regards to the effects or levels of early event damages due to overall fire damage and low level of recovered structure adjacent to the access door.	
	Manufacturing Access Door failure due to keel beam loading	75%	75%	75%	• Keel beam downward motion and separation resulted in failure of bolts at tension fitting at RBL9.0 and LBL9.0. Stiffener common to inboard edge of manufacturing access door is common to RBL9.0 keel beam tension fitting and would have seen high tension loads during keel beam separation. • Finite element modeling would support that loads necessary for fastener shear failures in the access door would be consistent with shear loading induced into the spanwise beam as a result of the keel beam downward loading and displacement. The analysis was set up to replicate the prior failure of SWB#3, Front Spar, fuselage lower lobe, and keel beam attachment to the lower panel ahead of SWB#2 as documented in the Sequence Team findings.	
	Manufacturing Access Door failure due to uniform pressurization of Center Wing Tank or differential pressure across SWB#2.	<25%	<25%	<25%	• Finite element modeling of Wing Center Section with equal pressure loading forward and aft of SWB#2 would produce predominately tension loading in the spanwise beam web. This would not be consistent with shear loads required to shear rivets between access door and spanwise beam web. • No known scenario relating to differential overpressure would produce fastener shear failures in the attachment of the manufacturing access door. In-plane rivet shear failures would have had to precede out-of-plane rivet tension failures.	
	Partial (<10%) failure of Spanwise Beam as a result of "later" keel beam driven damage. (Note: 10% relates to an increase in the vented area across the Spanwise Beam.)	75%	75%	75%	• The keel beam failure and separation that resulted in some level of partial failure of the spanwise beam would result in the loss of the manufacturing access door. This level of loss of structural integrity would not significantly increase the vented area in the beam other than the area of the door itself. Sooting on the right side of the beam generally indicated later failures. Few direct observations or inspections other than the loss of the door were made that would increase or decrease the confidence of percentage failure of the spanwise beam. • The majority of the left side of SWB#2 was not recovered or identified and some portions recovered were heavily burned.	

Location	Observation	Confidence: Inspection	Confidence: Calculation	Combined Confidence	Comments	Action
	Pressure differential separated manufacturing access door.	90%	---	90%	• In-plane rivet shear failures would have had to precede out-of-plane rivet tension failures. • Out-of-plane loading was assumed to be resultant from pressure differential since no mechanical damage was observed on the door that would be consistent with a forward acting force necessary to separate the door.	
	Manufacturing Access Door impact upper skin panel	100%	---	100%	• Impact damage on lower inboard edge of the access door matches closely with two sets of witness marks on the underside of the upper skin panel and stringer and is geometrically consistent with proposed door separation motion.	
Midspar	Beam did not experience general or significant partial failure due to an overpressure gradient (i.e. typical failure mode involving failed upper shear ties, stiffener free flanges, and vertical leg of upper Midspar chord.) Consequently, no significant increase in venting area through the beam would have occurred.	90%	90%	90%	• Observations made with regards to sooting of mating fracture faces, crack morphology, and deformation patterns indicate that the Midspar failure is consistent with compression buckling of the aft upper wing panel during major airplane breakup. • Large right hand portion of Midspar remains attached to the upper skin panel with the upper chord relatively intact. • Stress analysis would indicate that the Midspar was required to be intact or have sustained a low level of damage to retain the ability to provide upper skin panel stability and carry wing bending loads capable of failing the wingtips prior to the complete failure of the Wing Center Section. The Midspar provides a continuous load path from the Wing Center Section into the wing. The spanwise beams are terminated at the Side of Body Rib and therefore do not provide the wing bending continuity that is required of the Midspar.	
	Maintenance access door pressure differential	***	***	***	• No major distinguishable difference in level of damage indicated on left or right maintenance access door. • Examination of the Midspar maintenance access doors do not provide insight into direction or levels of overpressure differential. • Analysis was done to indicate level of pressure gradient required for door failure or yielding.	

Location	Observation	Confidence: Inspection	Confidence: Calculation	Combined Confidence	Comments	Action
	Doors did not fail (may have plastically deformed)	75%	***	75%	• No apparent heat damage on the exposed core of the access doors indicating extensive damage on water impact. • Edge band deformation and subsequent soot trails on SWB#1 are prime indicators of overpressure differential direction and level. Midspar maintenance access doors are retained with approx. twice as many fasteners and would therefore be less likely to provide the indications that SWB#1 doors provided. The access door are also attached on the forward side of the Midspar and would not provide indications of aft acting pressure differentials.	
SWB#1	Beam did not experience general or significant partial failure due to an overpressure gradient (i.e. typical failure mode involving failed upper shear ties, stiffener free flanges, and vertical leg of upper SWB chord.) Consequently, no significant increase in venting area through the beam would have occurred.	90%	90%	90%	• Observations made with regards to sooting of mating fracture faces, crack morphology, and conductivity measurements indicate that SWB#1 failure likely occurred during major airplane breakup. • Stress analysis would indicate that structural integrity of SWB#1 would be required to the extent of providing sufficient upper skin panel stability required to carry wing bending loads capable of failing the wingtips prior to the complete failure of the Wing Center Section	
	Deformation of access doors (aft direction) as a result of pressure gradient.	100%	TBD	100%	• Residual deformation of the access door edgeband between fasteners and soot patterns on the aft side of the spanwise beam web between the fasteners would indicate a pressure differential greater forward of SWB#1 than aft of the beam. The access door is also fastened on the aft side of the beam which would allow for deformation of the edgeband during an aft acting pressure differential. Residual edgeband deformations were greater on the left access door than on the right access door. • Since the access doors are fastened on the aft side of the spanwise beam, edge band deformations would only result from aft acting pressure differentials. Any forward acting pressure differentials, whether part of an initial pressure pulse or a secondary pulse, would not result in edge band deformations.	Boeing

Location	Observation	Confidence: Inspection	Confidence: Calculation	Combined Confidence	Comments	Action
					• Finite element results would indicate a pressure differential requirement of approx. 50psi on a 20ms pulse to produce the edgeband deformation observed on the left access door. Confidence of finite element model results reduced by level of confidence that SWB#1 has the overall capability to sustain 50psi without subsequent failure of the entire beam.	
Rear Spar	Beam did not experience general or significant partial failure due to an overpressure gradient (i.e. typical failure mode involving stiffener free flanges and vertical leg of upper spar chord.) Consequently, no significant increase in venting are through the spar would have occurred.	75%	90%	75%	• Observations made with regards to sooting of mating fracture faces, crack morphology, and conductivity measurements indicate that the Rear Spar failure likely occurred during major airplane breakup. • Stress analysis would indicate that structural integrity of the rear spar would be required to the extent of providing sufficient upper skin panel stability and wing bending continuity required to carry wing bending loads capable of failing the wingtips prior to the complete failure of the Wing Center Section	
BL0 Rib	Portion of BL0 Rib from Rear Spar to SWB#1 did not significantly deform	75%	---	75%	• Definitive damage or sooting prior to major airplane breakup could not be identified. • Upper skin panel residual deformation had inflection point near centerline rib which would be consistent with the BL0 rib maintaining sufficient structural integrity to maintain local stability of the upper panel during a time period up to major airplane breakup.	
Upper Skin	Relative vertical displacement near SWB#3 of approx. .9" (at time that SWB#3 rotated 5-6" forward)	100%	---	100%	• The aft surface of the recovered pieces of the vertical leg of stringer 29 (just fwd of SWB#3) contained an intermittent witness mark corresponding to impact from the upper edge of the upper chord of SWB#3. Geometric layouts along with measured location of impact marks would indicate relative movement of the upper panel in relation to the lower panel of approx. .90" near SWB#3. No attempts were made to determine how much of the relative displacement was absolute upper panel movement vs. lower panel and keel beam movement.	

Location	Observation	Confidence: Inspection	Confidence: Calculation	Combined Confidence	Comments	Action
	Large permanent deformation	***	---	***	• While the upper panel did show residual deformations, levels of curvature and deformations resultant from major airplane breakup would overshadow any smaller permanent deformations associated with the early event damages.	
Keel Beam	Failed at location between Midspar and SWB#1	100%	75%	100%	• Keel beam portion (LF14A) forward of fracture between Midspar and SWB#1 was recovered from the red zone. Aft keel beam segments were recovered from the green zone. • Examination of soot accumulation on mating fracture faces of the lower skin panel, aft keel beam segments, and forward keel beam (LF14A) indicate departure of fwd keel beam prior to fire and subsequent soot accumulation. • Stress analysis would indicate that following failure of SWB#3, Front Spar, and fuselage lower lobe as described in the Sequence Team report, the combination of cabin pressure loading on the fuselage forward of the keel beam and continued overpressure loading within the Wing Center Section would be capable of producing bending moments in the keel beam capable of producing a failure at a location between the Midspar and SWB#1.	

747-100 Wing Center Section
Beam Overpressure Capability (updated Jan. 1999)

	Minimum Initial Failure Strength (psi)	Estimated Maximum Initial Failure Strength (psi)
Front Spar	20	25-30
Spanwise Beam #3	20	25
Spanwise Beam #2	20	30-35
Midspar	20	35-40
Spanwise Beam #1	25	45-50
Rearspar	30	45-50

Failure loading condition assumed to be dominated by a bending moment in beam stiffeners (due to overpressure gradient across beam) as opposed to an axial load in beam/stiffeners (due to almost equal overpressure on both sides of beam). Expected failure generally in upper joint between stiffener and wing panel.

Initial failure level shown but subsequent failures resulting in overall beam failure and venting generally expected to immediately follow (providing load gradient maintained)

Uncertainty range intended to also envelope variation in capability for both forward acting pressure gradient and aft acting gradient.

"Minimum initial failure strength" typically determined by conventional stress analysis methods used in commercial airplane design for insuring that minimum strength will always exceed regulatory requirement.

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

Separate analysis of deformations of spanwise beam #1 maintenance access doors indicates that a pressure gradient (aft) of 45-55 psi was probably present at the left door and a gradient of 20 -25 psi at the right door.