# Engineering Disasters: Learning from Failure

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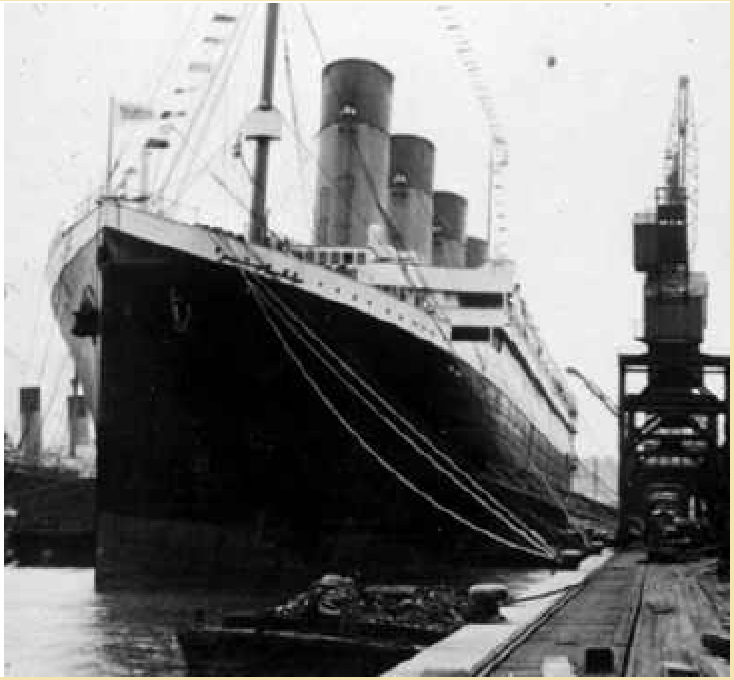
# Engineering Disasters: Learning from Failure

- Engineering disasters have resulted in loss of life, injuries, and billions of dollars in damage.

- Primary causes for engineering disasters:
  - Design flaws
  - Material failures
  - Extreme conditions or environments (not necessarily preventable)
  - Some combinations of the reasons above.

- Three major disasters:
  - Sinking of the ship Titanic
  - Collapse of the World Trade Center buildings
  - Explosion of the Space Shuttle Columbia

# Chronology of Events Leading to Sinking of the *Titanic*



- Titanic began its maiden voyage to New York at noon on April 10, 1912, from Southampton, England.
- On night of April 14, at 11:40 p.m., crew sighted an iceberg immediately ahead of ship.
- In about 40 seconds it collided with an iceberg estimated to have a gross weight of 150,000-300,000 tons.
- Iceberg struck the *Titanic* near bow and raked side of ship's hull damaging hull plates and popping rivets,
- At 2:20 a.m., April 15, 1912, *Titanic* sank within two hours and 40 minutes, with the loss of more than 1,500 lives.

# Why did the *Titanic* sink?

- Theory 1

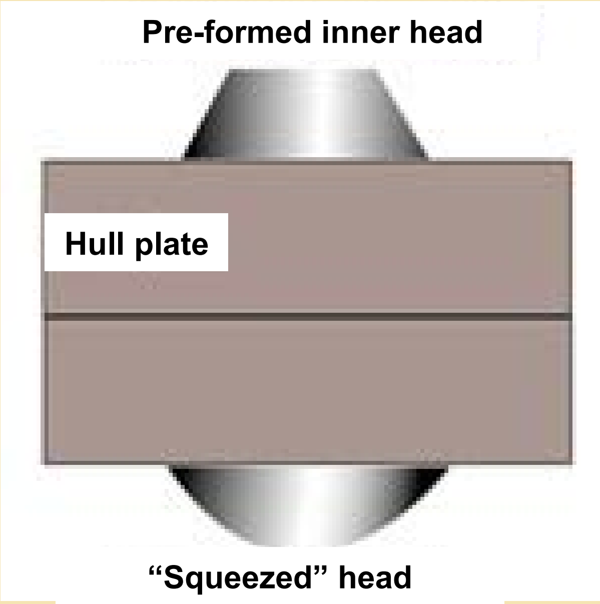
  Multiple rivet failures upon collision with iceberg.

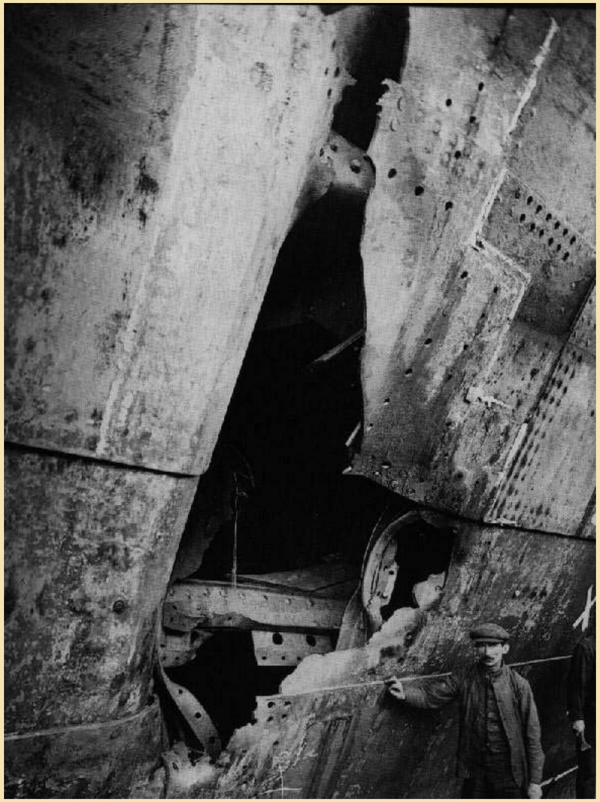
- Theory 2

  Failure of the steel hull upon collision with iceberg.

# Remains of the *Titanic*

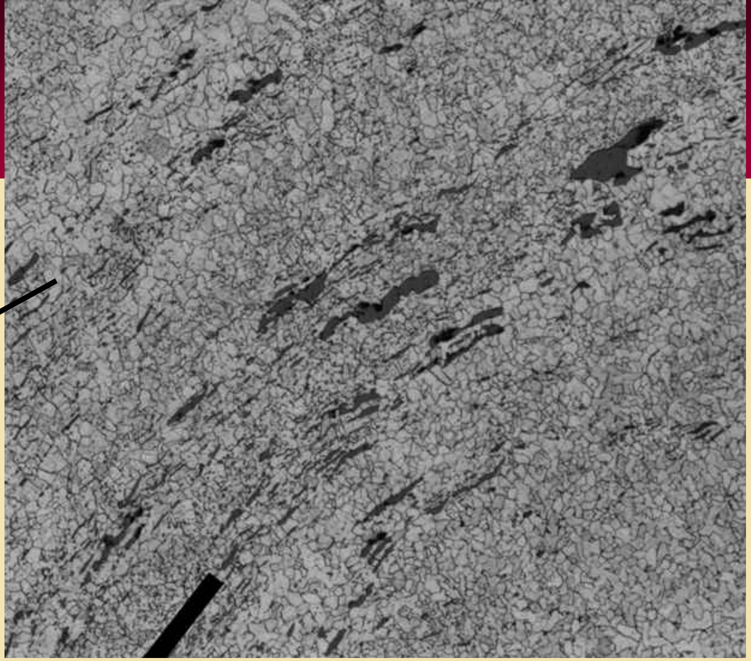
# Theory 1: Multiple wrought-Fe rivet failures upon collision with iceberg.



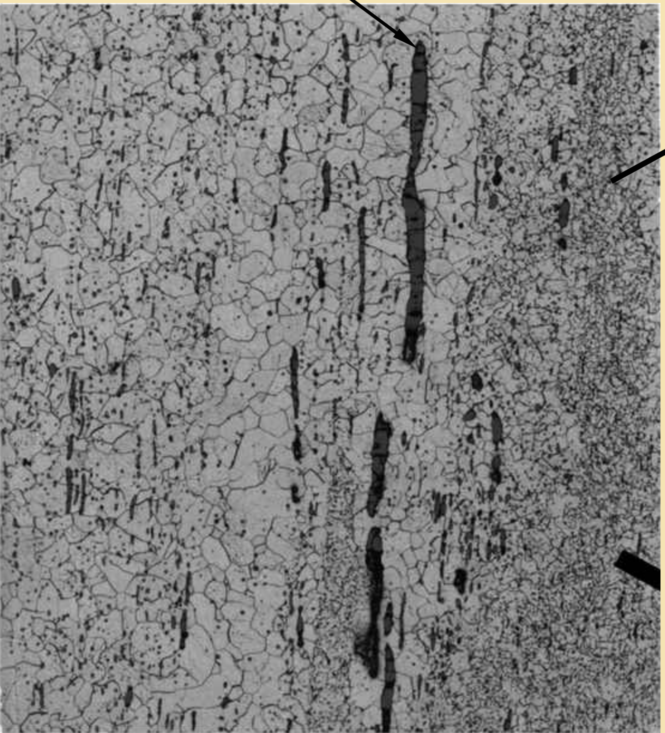



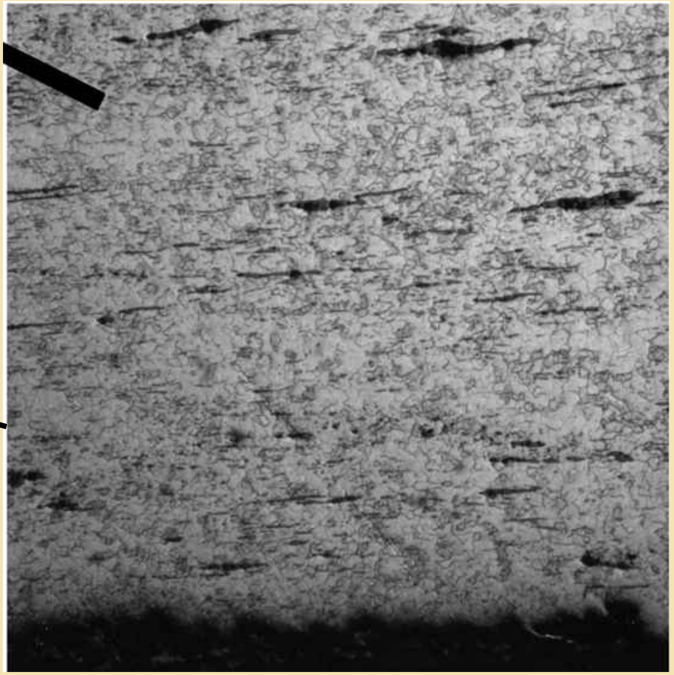
**Hull of the *Olympic*, *Titanic's* sister ship after a collision in 1911.**

# Microstructure of Titanic Rivet



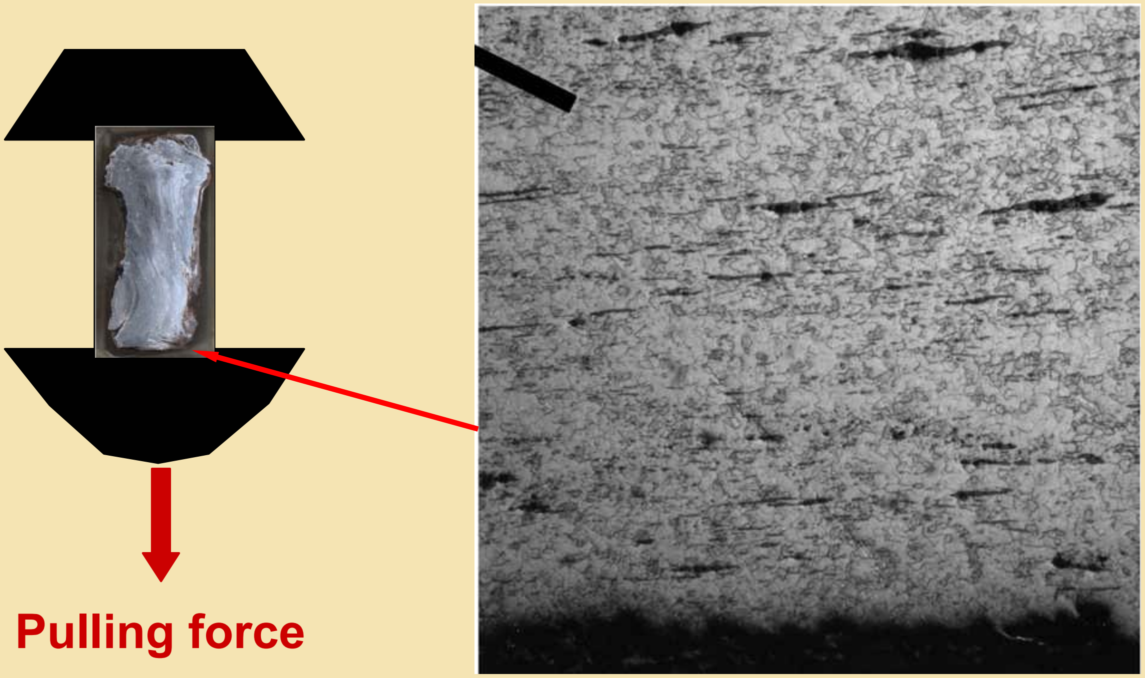
**Fe-silicate “stringers”**





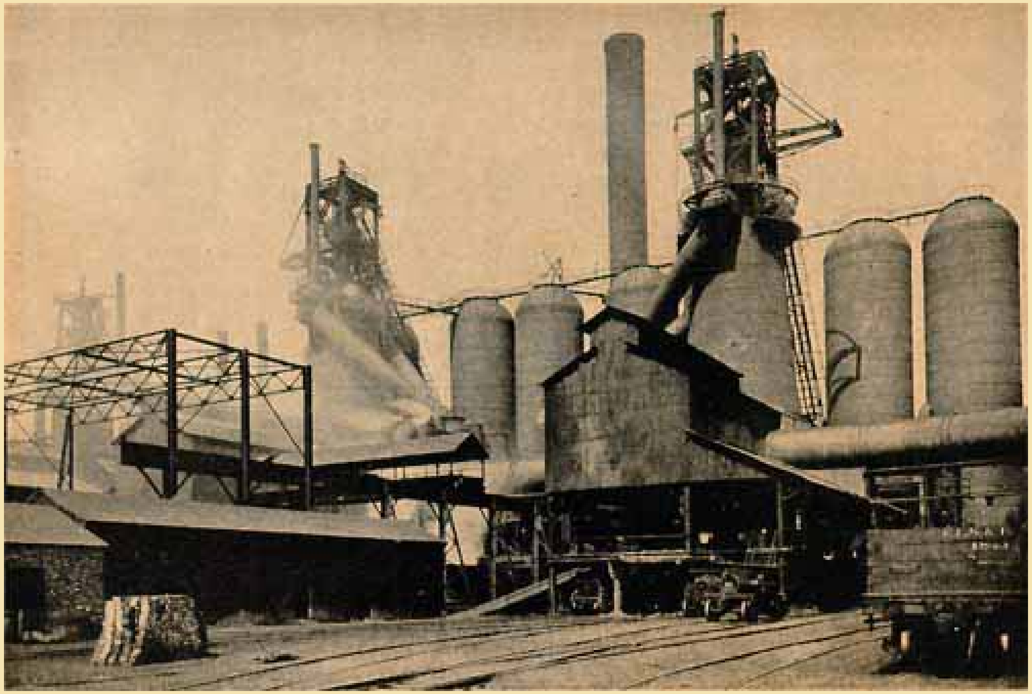
# Microstructure of Titanic Rivet

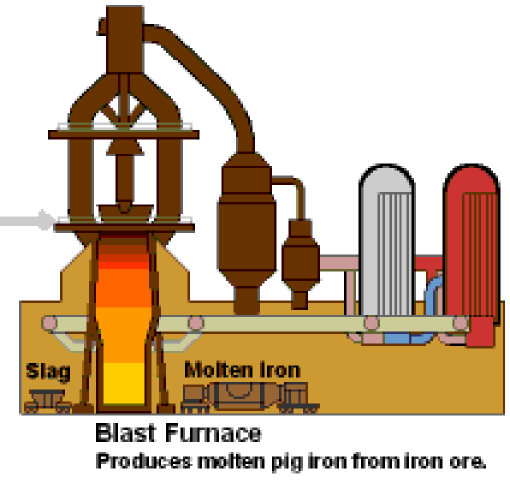
- Orientation of Fe-silicate stringers is perpendicular to loading axis at the end of the rivet
  - Much lower strength and inferior resistance to crack propagation



# Theory 2: Hull Fracture the low carbon steel hull upon collision with iceberg.

## Blast Furnace Process

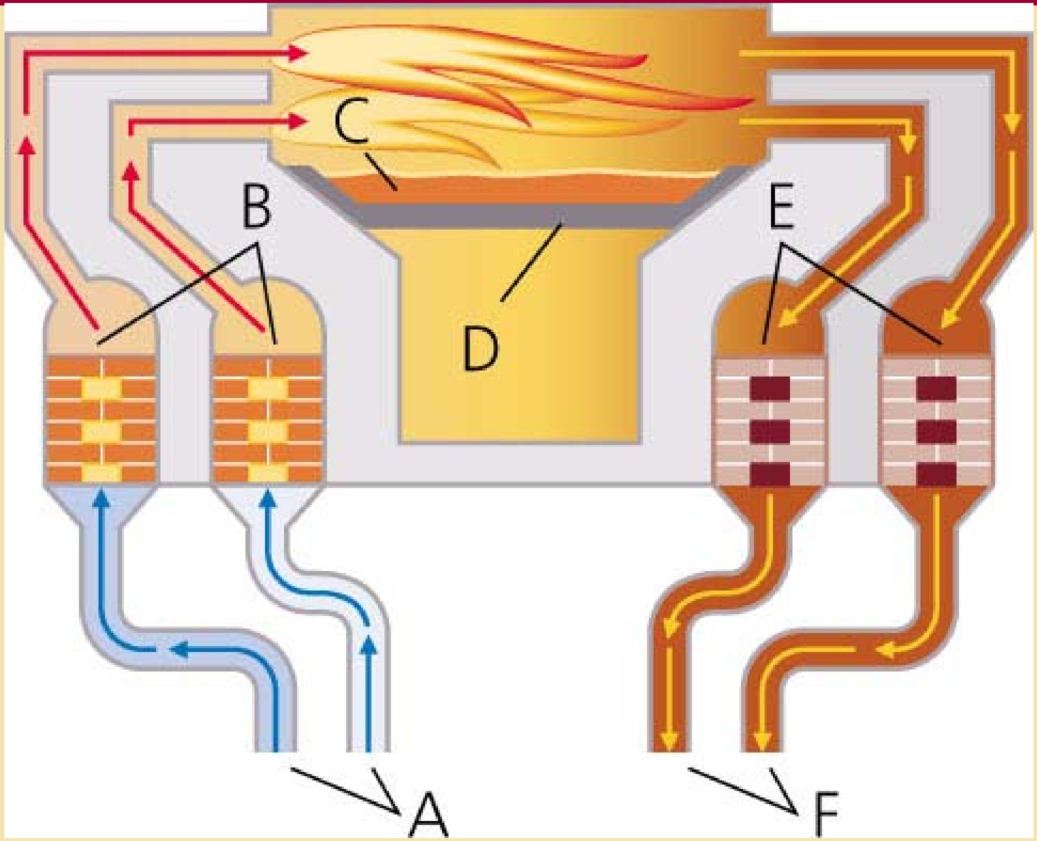





• Iron ore, coke, and limestone are raw materials which are charged at the top of the blast furnace.

• Molten "pig iron" and slag are collected at the bottom and are tapped out at intervals.

# Open-Hearth Furnace Process




A. Gas and air enter

B. Pre-heated chamber

C. Molten pig iron

D. Hearth

E. Heating chamber (cold)

F. Gas and air exit

- In acid open-hearth steel process, an acid material, silica, is used as the furnace lining.
- Pig iron (92% Fe and about 3.5% C) is charged in. Impurities, including carbon, are oxidized and float out of the iron into the slag.
- Siliceous refractory material in the lining will not react with P or S so the content of these elements in the steel will be extremely high.

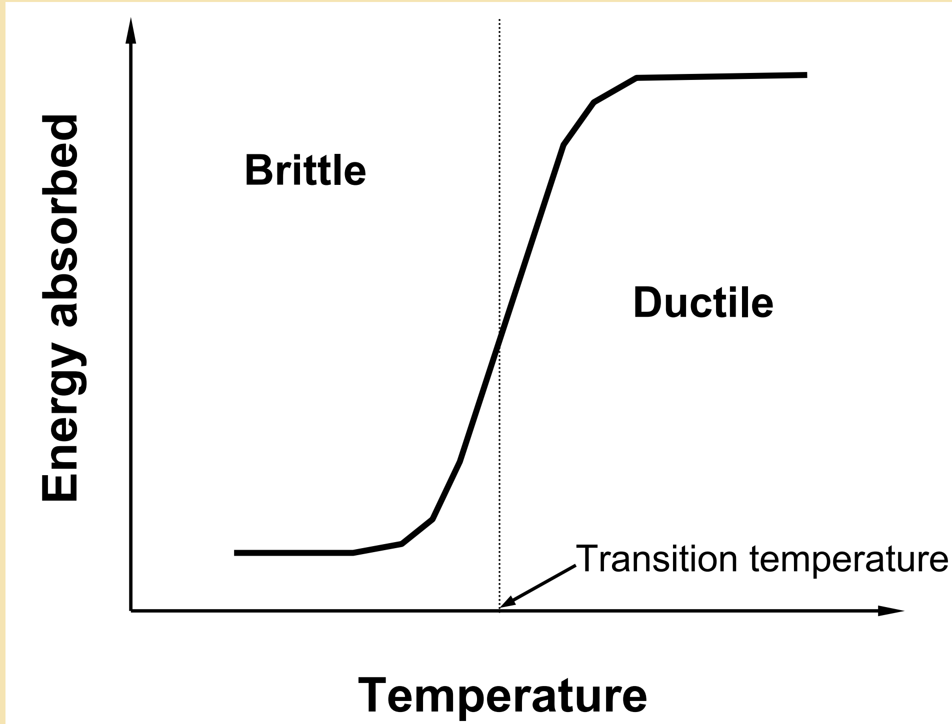
# Comparison of Chemical Composition of *Titanic* Hull Steel vs. Modern Steels

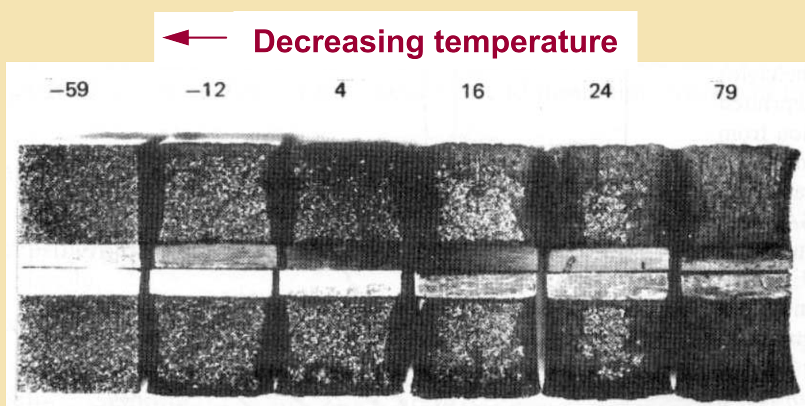
| **Material** | C | **Mn** | **P** | **S** | Si | Cu | O | N | **Mn-to-S Ratio** |
|---|---|---|---|---|---|---|---|---|---|
| ***Titanic* Hull Plate** | 0.21 | **0.47** | **0.045** | **0.069** | 0.017 | 0.024 | 0.013 | 0.0035 | **6.8:1** |
| **ASTM 36** | 0.20 | **0.55** | **0.012** | **0.037** | 0.007 | 0.01 | 0.079 | 0.0032 | **14.9:1** |

- **Mn-to-S ratio is lower and P content slightly higher in Titanic Hull Plate than in modern steels of similar composition.**

- **Higher S and P amounts can be attributed to acid furnace lining used in open-heart furnaces of that time period.**

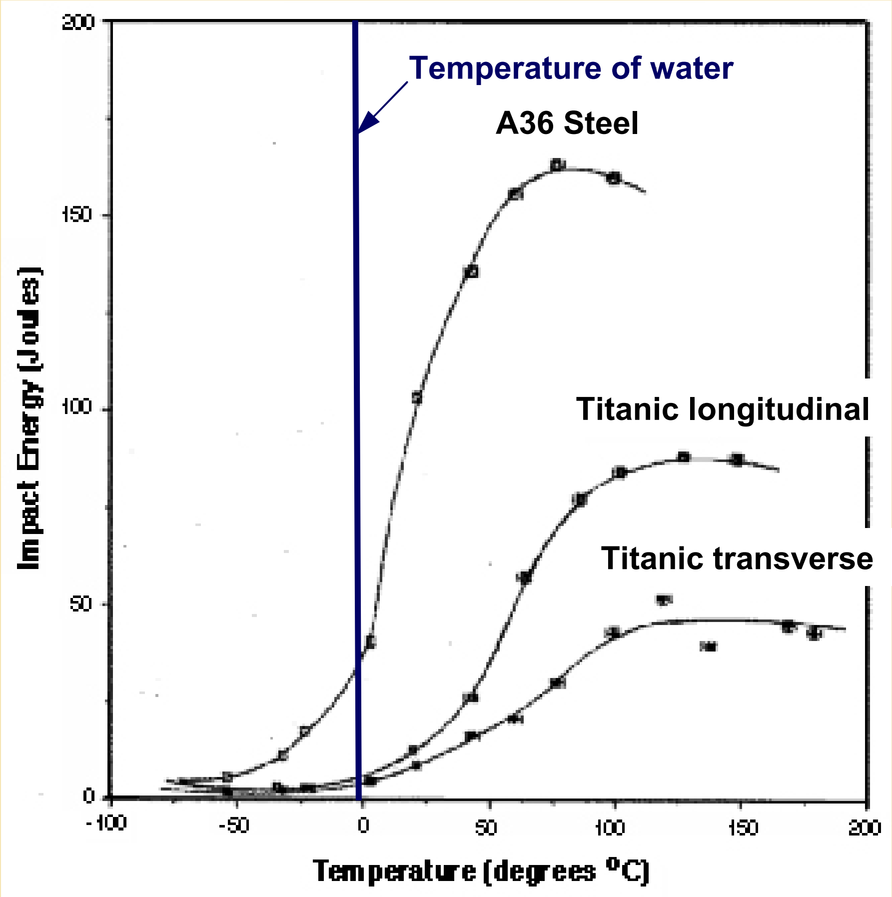
# Ductile-to-Brittle Transition



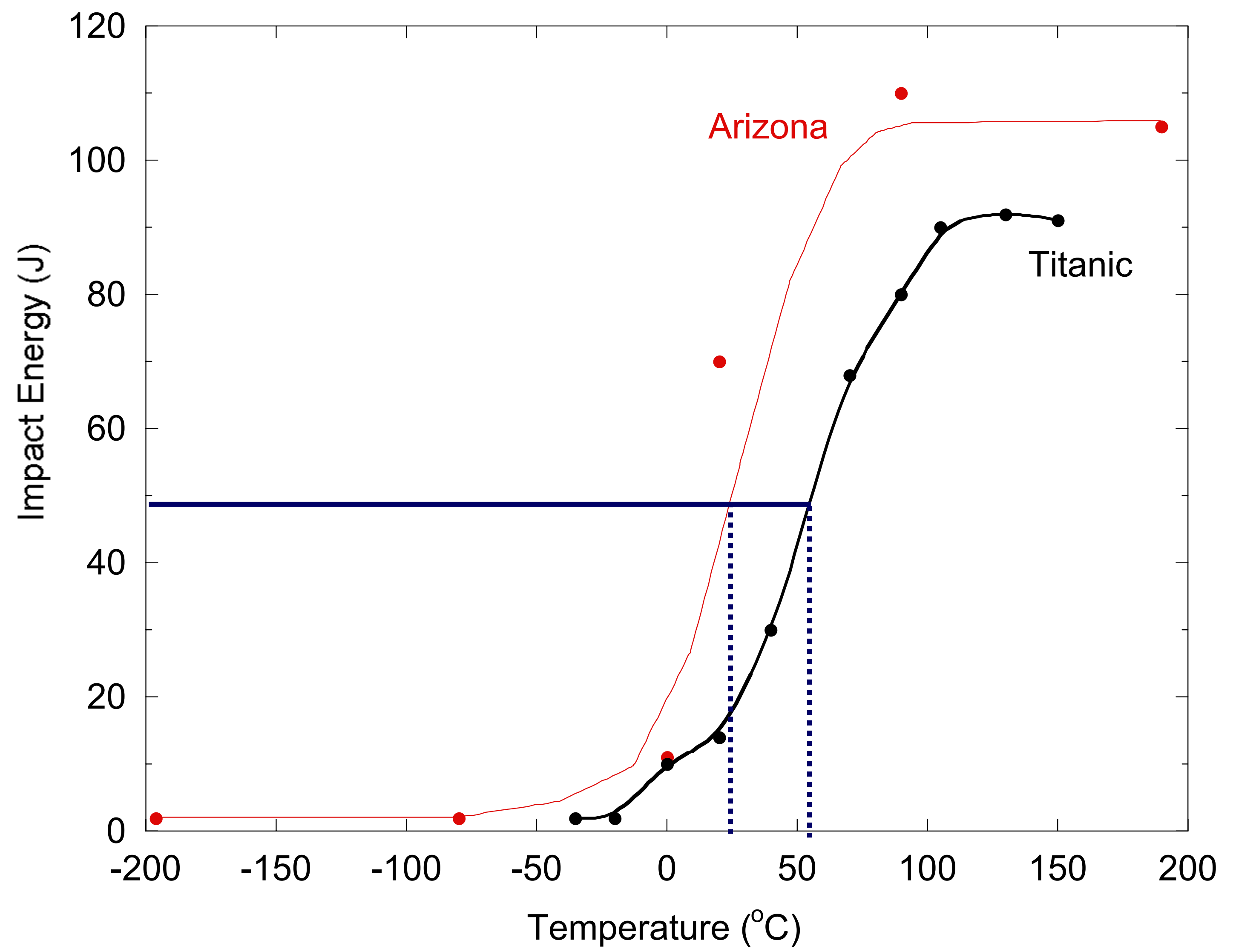

**Fracture is more "brittle" with decreasing temperature**

# Impact Energy versus Temperature



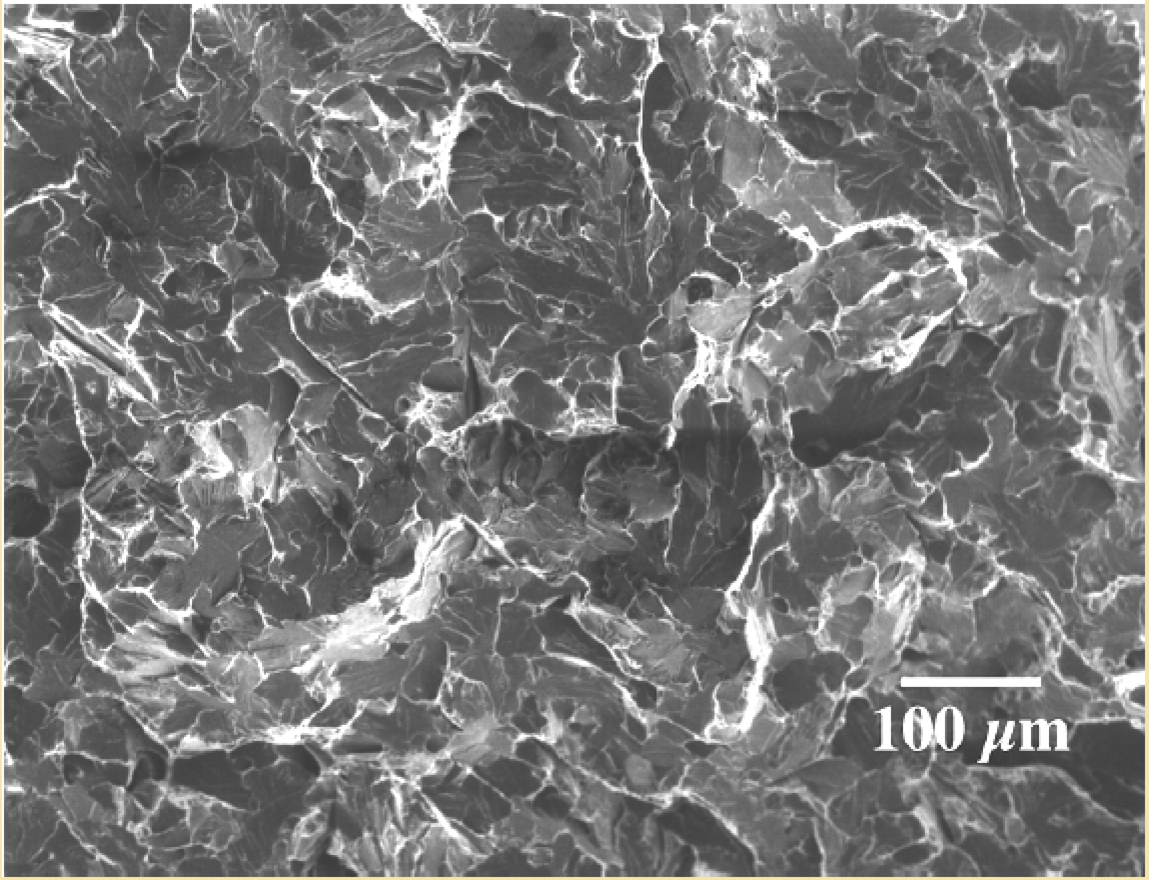

**Temperature of the water was –2°C!!**

# Impact Toughness of Steel in *Titanic* vs. *U.S.S. Arizona*




**Steel of U.S.S. Arizona had lower DBTT!**

# Fracture Surface of Titanic Steel (Longitudinal) Impacted at $0^oC$




**Characteristic brittle fracture is observed**

# Lessons Learned from the Sinking of the *Titanic*

- Mn significantly decreases DBTT.
  - Titanic steel was low in Mn, most of which likely combined with S to form MnS
- Finer grain size improves toughness and decreases DBTT. Fine grain structure is achieved by deoxidation practice.
  - Titanic steel appears to be only partially deoxidized (note high oxygen content)

**These factors appear to have contributed to a higher DBTT in Titanic Steel, which made it extremely brittle at the water Temperature (-2°C)**

**Modern Steels Have Much Higher Toughness and Lower Ductile-To-Brittle Transition Temperature**

# The World Trade Center Buildings

**Height: 1,368 and 1,362 feet (417 and 415 meters)**

**Owners: Port Authority of New York and New Jersey**

**Architect: Minoru Yamasaki**

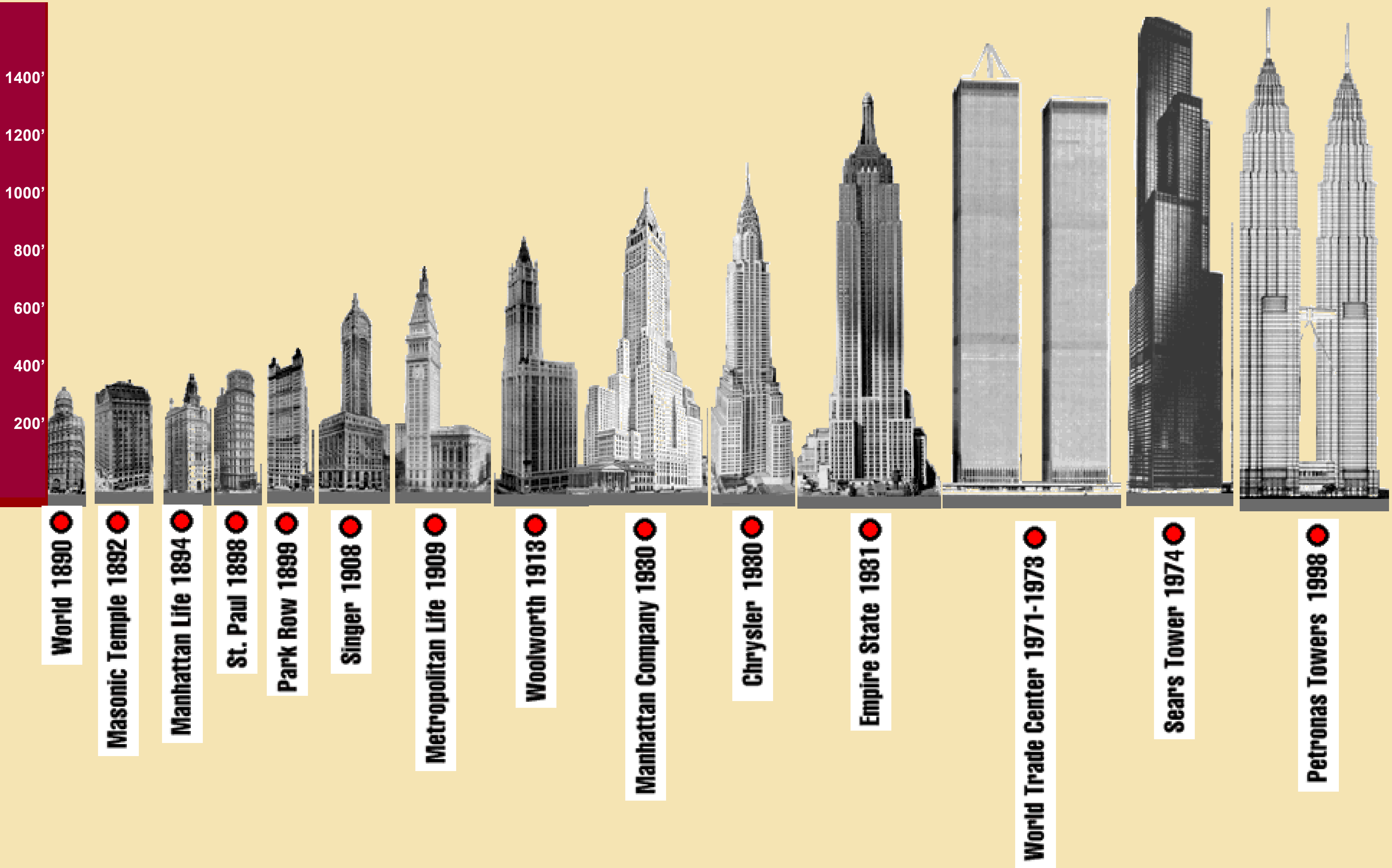
**Ground Breaking: August 5, 1966**

**Opened: 1970-73; April 4, 1973 ribbon cutting**

# WTC Interesting Facts

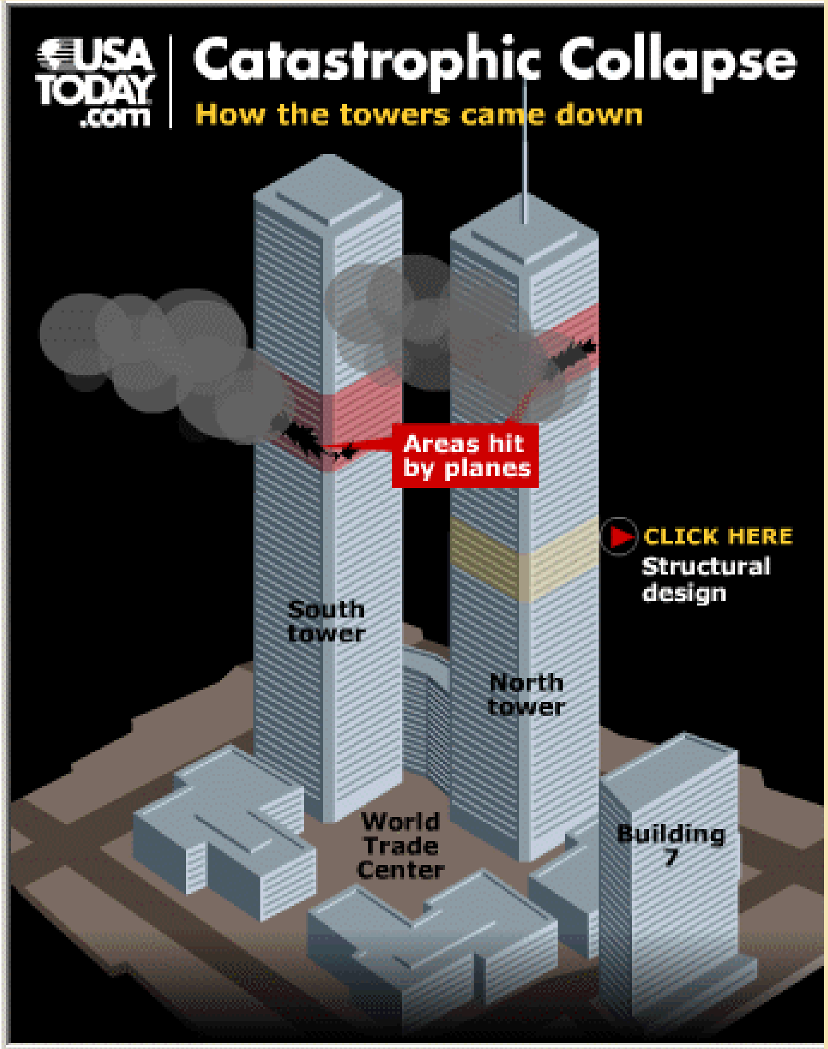
- Construction cost an estimated $1.5 billion.
- Engineers employed an innovative structural model: a rigid "hollow tube" of closely spaced steel columns with floor trusses extending across to a central core.
  - The columns were finished with an aluminum alloy to give a the silver-like coloring
- The twin towers were the first skyscraper buildings designed without any masonry.
- For the elevators to serve 110 stories with a traditional configuration would have required half the area of the lower stories be used for shaftways.
  - Elevators were designed such that passengers would change at "sky lobbies" on the 44th and 78th floors, halving the number of shaftways.

# History of Skyscrapers

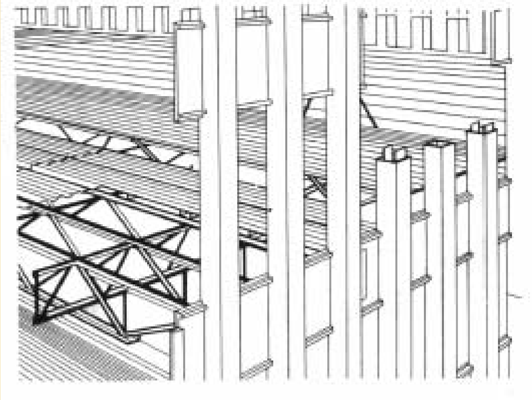



www.skyscrapers.com

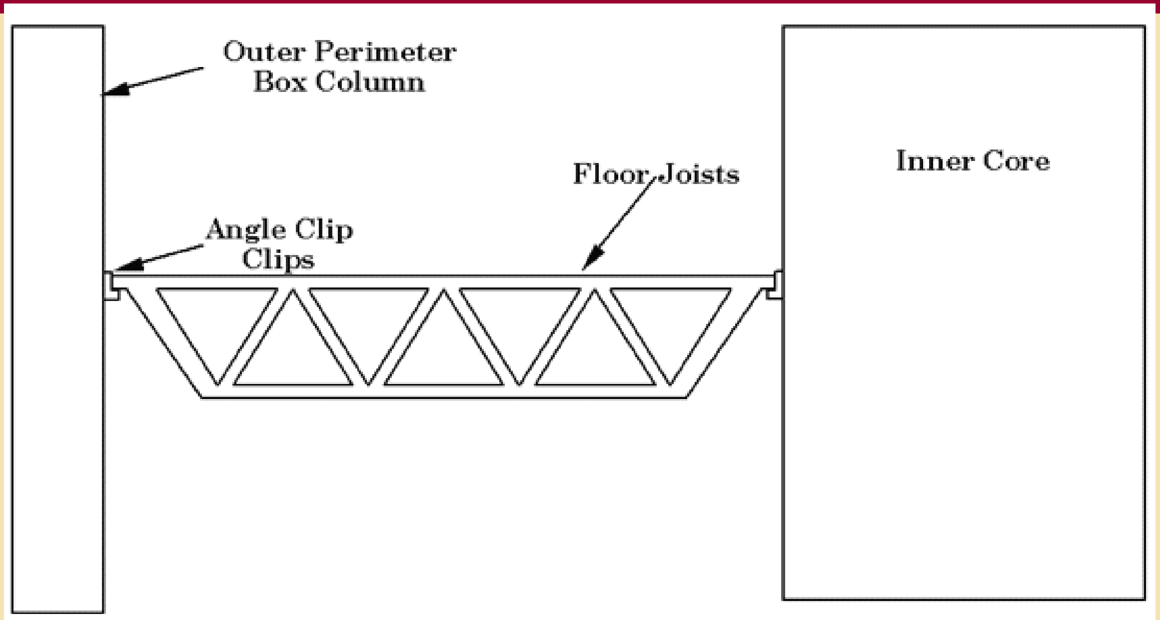
# The Tragedy of September 11, 2001



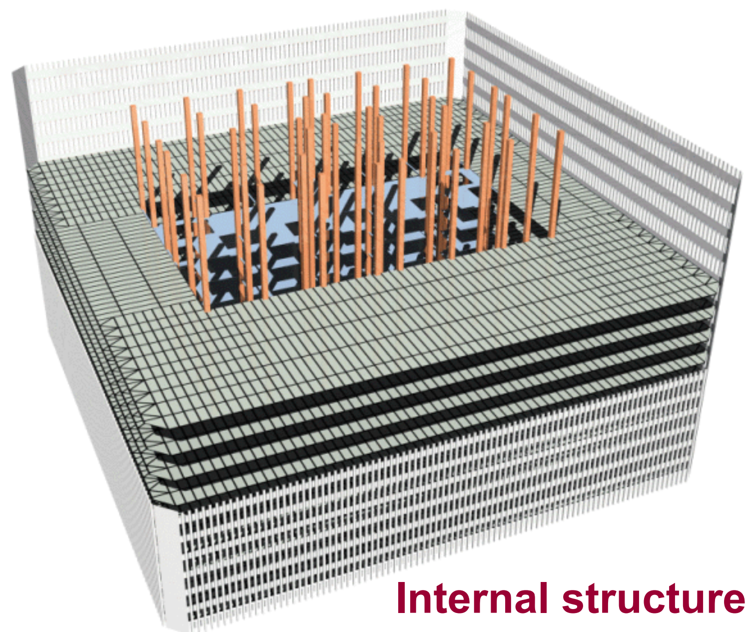
# Schematic of Structure of WTC



External wall




Cross-section of WTC building structure



Internal structure

# Boeing 767


**Passengers – 375**

**Fuel Capacity – 23,980 gallons**

**Engines – PW 4062 63,300 lb thrust**

**GECF6- 80C2B8F 63,500 lb**

**Cruise Speed at 35,000ft – 530 mph**

**Take-off Weight – 450,000 lbs**

# Energy of Impact vs. Fuel of Aircraft

## Energy of Impact

$$\text{Kinetic energy} = \frac{1}{2} m v^2$$

$$\text{Mass} = 204 \times 10^3 \text{ kg}$$

$$v = 197 \text{ m/s}$$

$$KE = 39.6 \times 10^8 \text{ J}$$

## Energy Associated with Fuel

Energy per

$$\text{gallon of fuel} \sim 132 \times 10^6 \text{ J/gal}$$

Energy of fuel

$$\text{in aircraft} = \left[20{,}000 \text{ gal} \cdot 132 \times 10^6 \text{ J/gal}\right]$$

$$= 2.64 \times 10^{12} \text{ J}$$

**3 sticks of dynamite is 1 MJ, so**

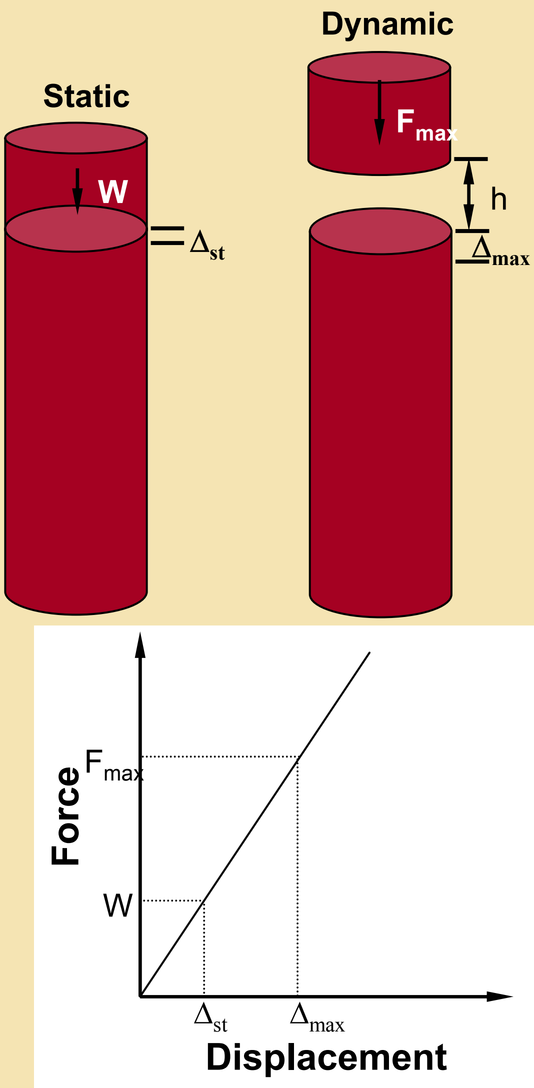
**energy content of the fuel ~ 7,920,000 sticks of dynamite!**

Energy of impact was much lower than that of the burning fuel of the aircraft.

***Adapted from T. Mackin, U. Illinois, (2001).***

# Engineering Analysis of WTC Collapse

At the instant that the moving object strikes the stationery object:

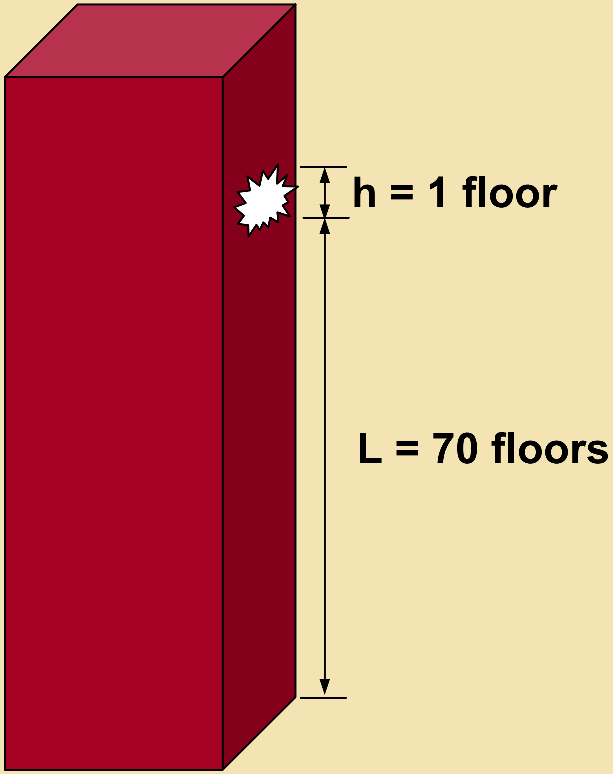



$$U_{weight} = U_{strain}$$

$$W\left(h + \Delta_{max}\right) = \frac{1}{2} F_{max} \Delta_{max}$$

$$F_{max} = 2W\left(1 + \frac{h}{\Delta_{max}}\right)$$

# Engineering Analysis of WTC Collapse




$$F_{max} = 2W\left(1 + \frac{1}{\varepsilon_{max}} \cdot \frac{h}{L}\right)$$

**Assume creeping and softened steel yields at $\varepsilon_{max}$ = 0.001**

$$= 2\,Mg\left(1 + \frac{1}{0.001} \cdot \frac{1}{70}\right)$$

$$= 30.6\,Mg$$

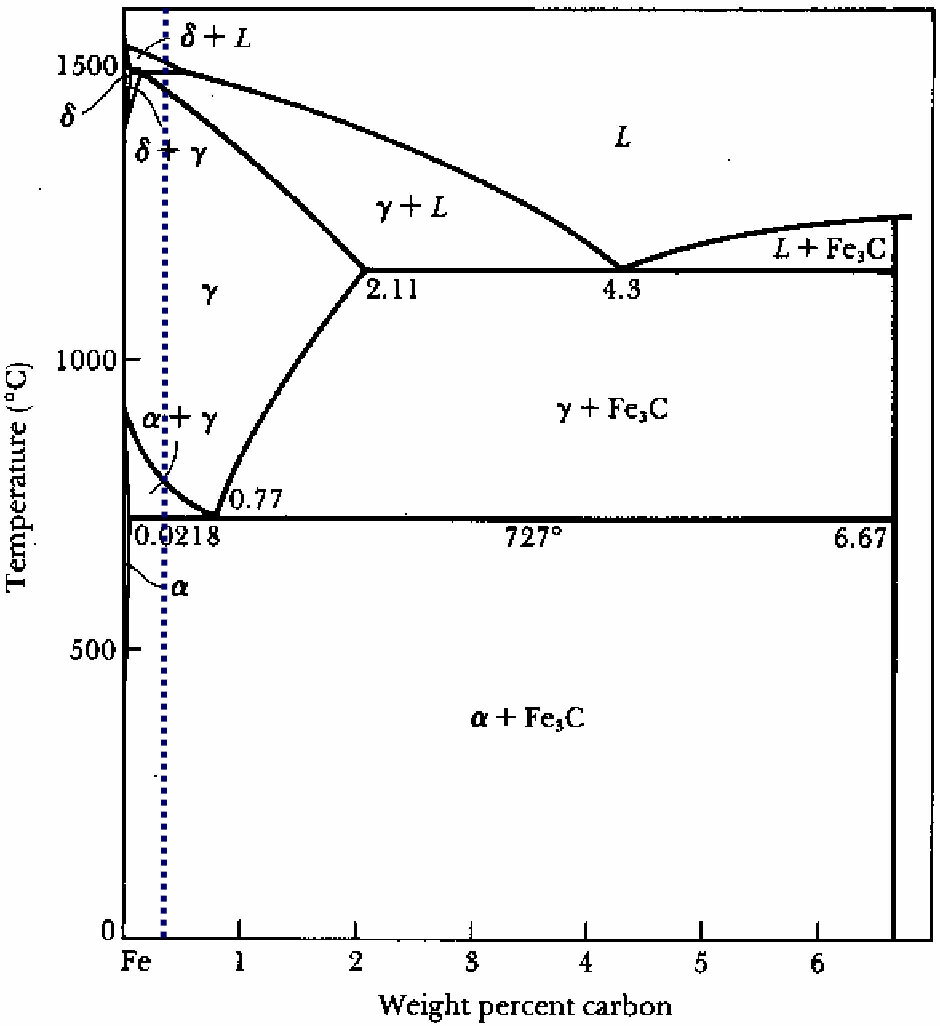
***Impact force is at least 30 times mass of floors above impact!***

# Composition and Properties of A36 Steel Used in Core of WTC

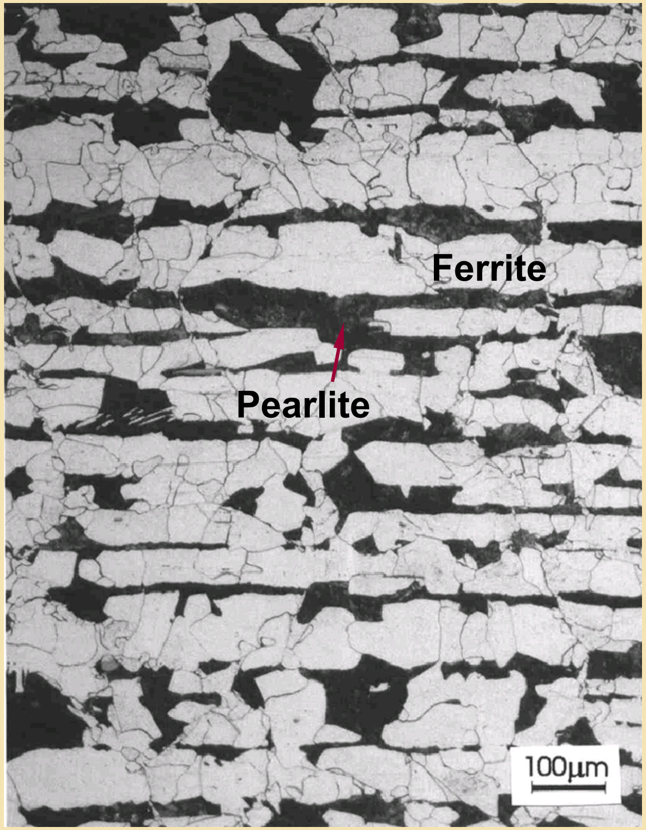
| | |
|---|---|
| 0.30 % | C |
| 0.15-0.3% | Si |
| 0.8-1.2% | Mn |
| 0.04% | P |
| 0.05% | S |
| Balance | Fe |

| Tensile Strength | Yield Strength | Elongation (50 mm gage length) |
|---|---|---|
| 400-550 MPa | 220-250 MPa | 23% |

# Fe-$Fe_3C$ Phase Diagram

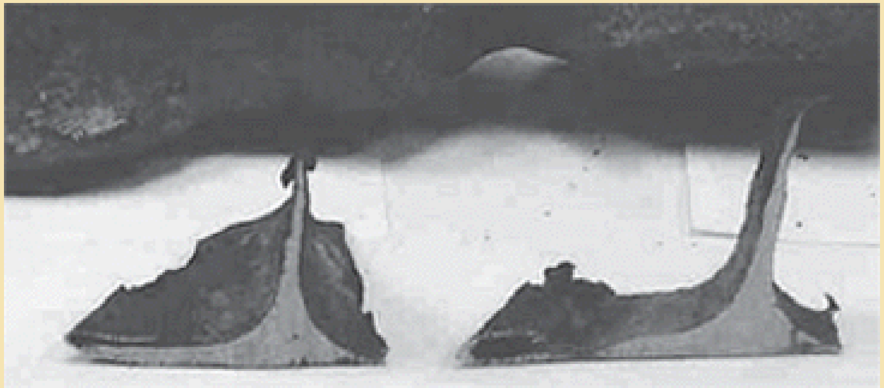



**Microstructure of Unaffected A36 Steel**

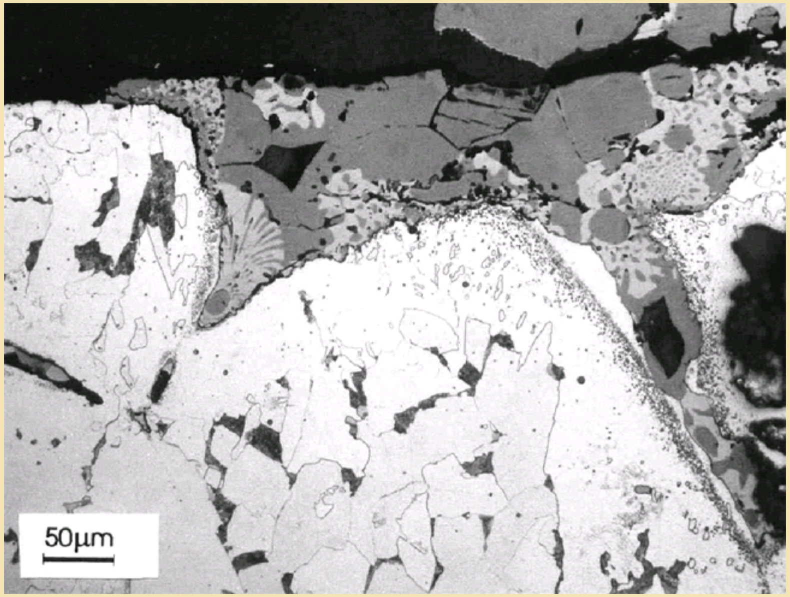



**Banding of ferrite and pearlite are observed due to hot working of plate**

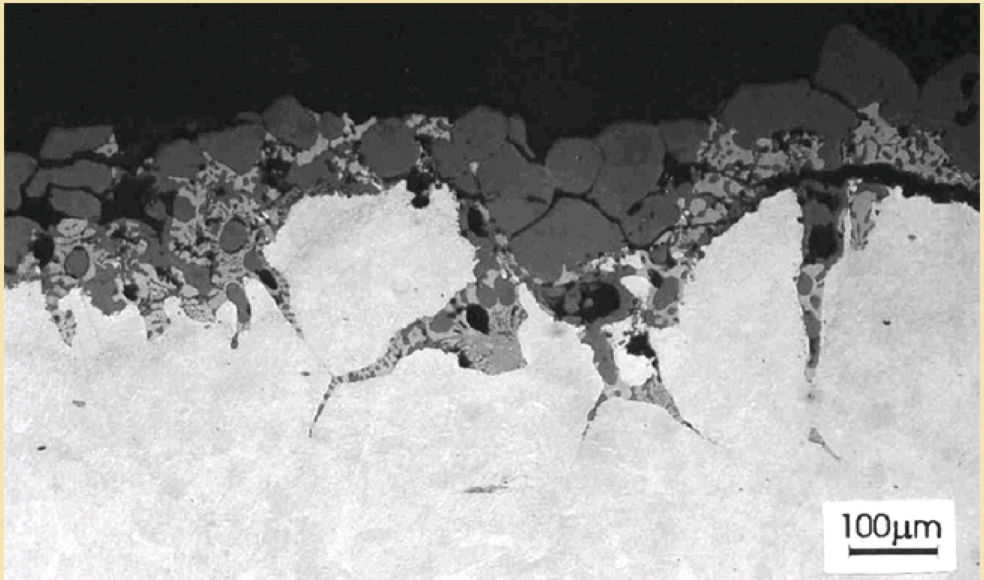
# I-Beam Cross-Sections of A36 Steel from WTC 7



**The beams appear severely eroded.**

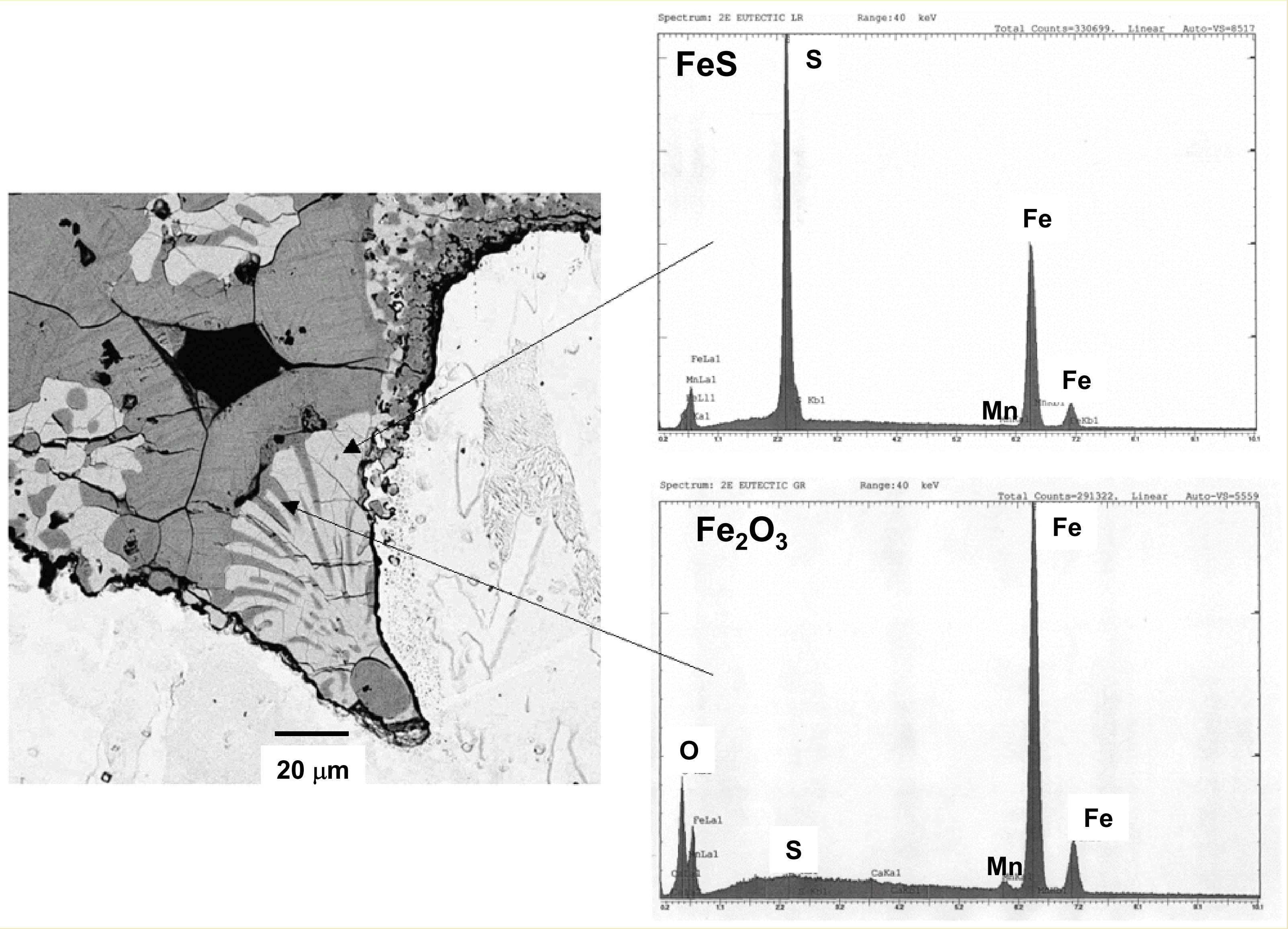



**Surface microstructure appears to be eutectic mixture of FeS and $Fe_2O_3$**




**Severe oxidation and intergranular melting is observed**

# Composition Analysis of A36 Steel from WTC-7



# Preliminary Mechanical Testing of WTC Steel

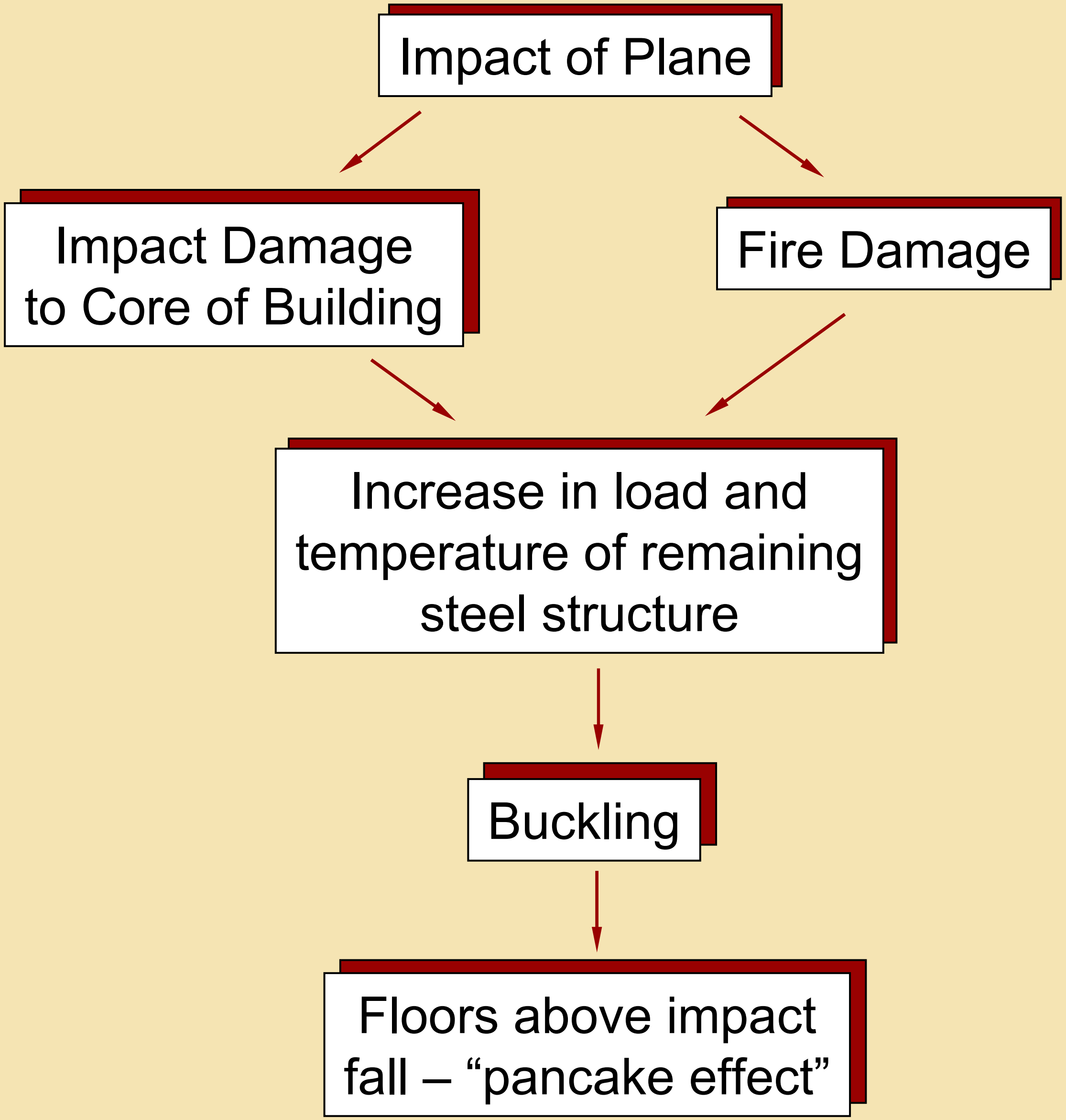
- National Institute of Standards and Technology have conducted preliminary tests on 236 pieces of steel from WTC wreckage.

- Requirement for tensile strength of steel was ~ 36,000 psi.

  → NIST tests showed steel to be capable of bearing ~ 42,000 psi.

**Steel beams from the World Trade Center generally met or exceeded design strength requirements.**

# Proposed Sequence of Events that Caused Collapse of WTC Buildings



# Thoughts and Speculation about Failure

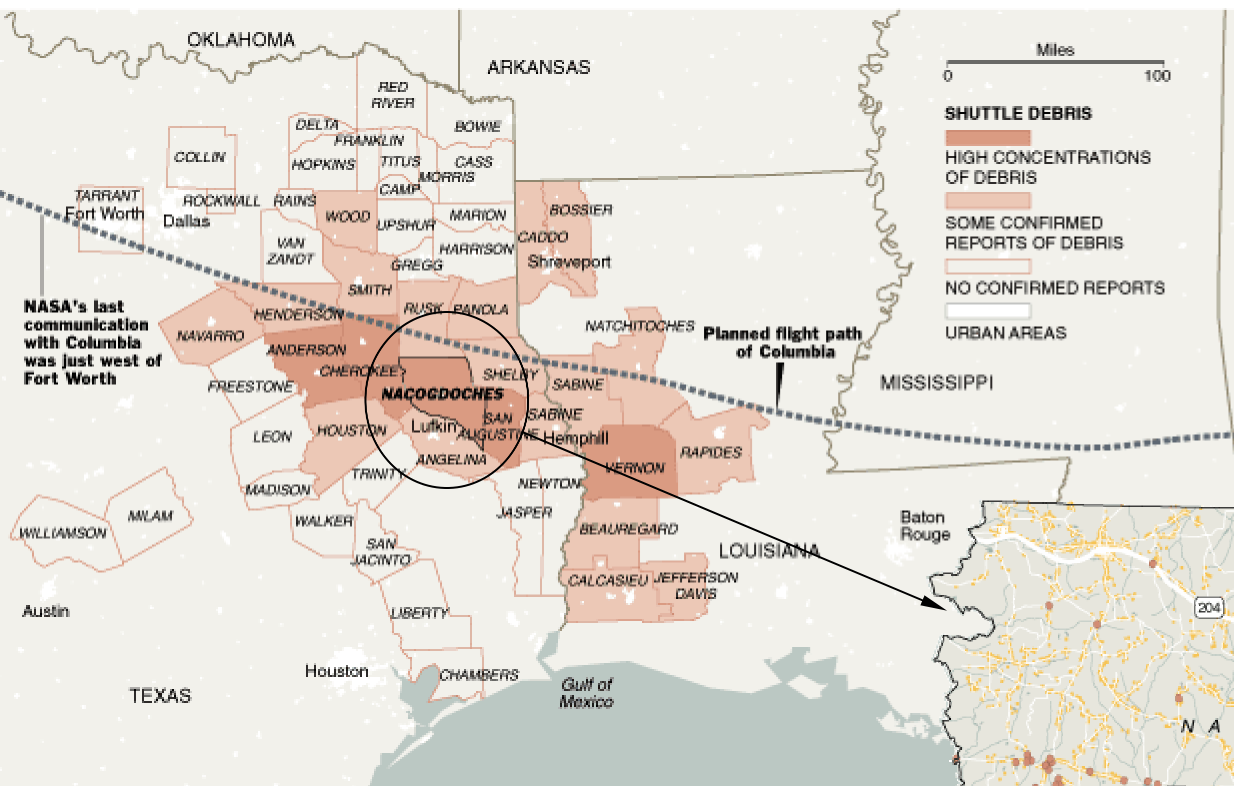
- Buildings were meant to withstand impact of a Boeing 707 – same amount of fuels as 767
- WTC fire was fuel rich (not typical of office fires) – smoke was dark black
  - Temperatures of fuel rich fires are typically < 827$^{o}$C)
- Steel did not melt, but may have been in the austenitic phase field (above eutectoid temperature of 727$^{o}$C).
  - Severe weakening due to creep.
- Thermal stresses may also have played a role.
  - Steel was cool from outside and quite hot inside
- Floors above impact may have caused significant damage to steel joints, with very falling floor, during collapse.

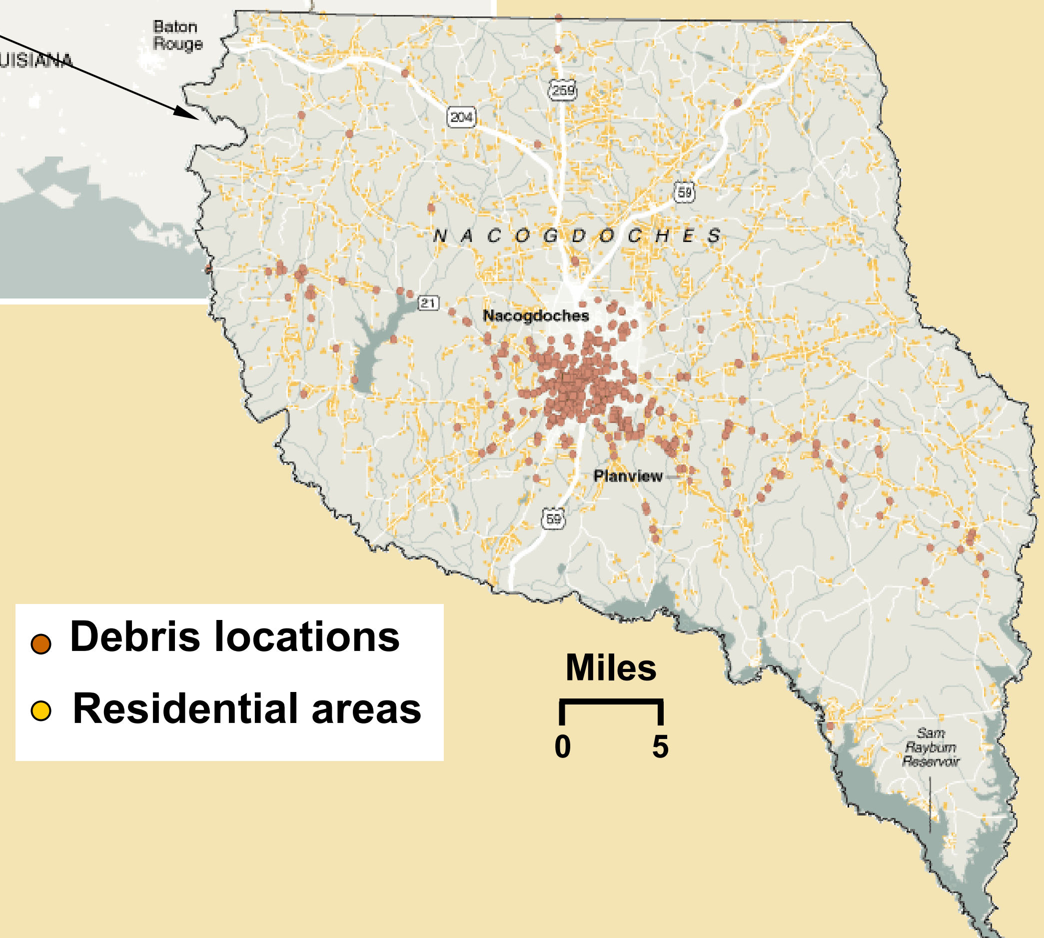
Collapse of the WTC building would not likely have been prevented by better design.

# The Columbia Space Shuttle Disaster


Planned Re-entry Path of Shuttle

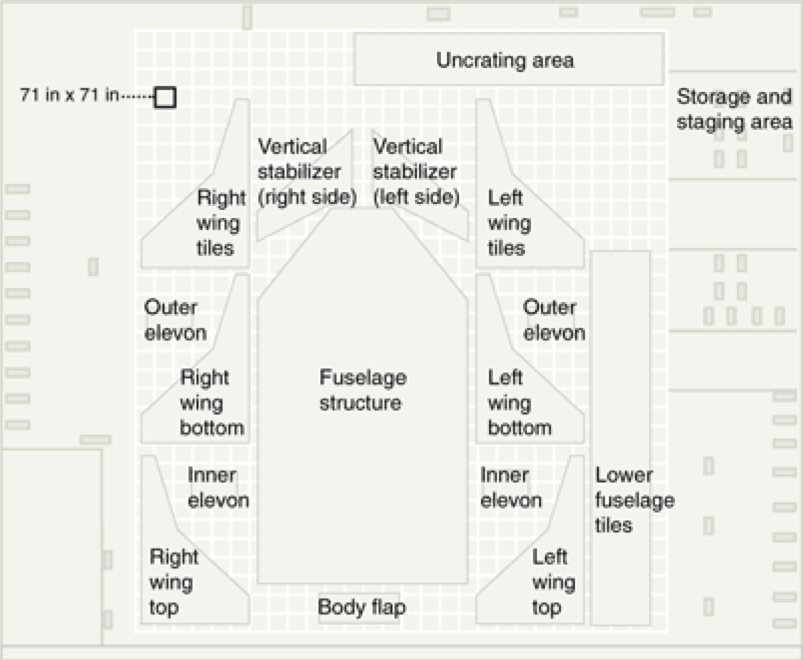
# Map of Debris Field



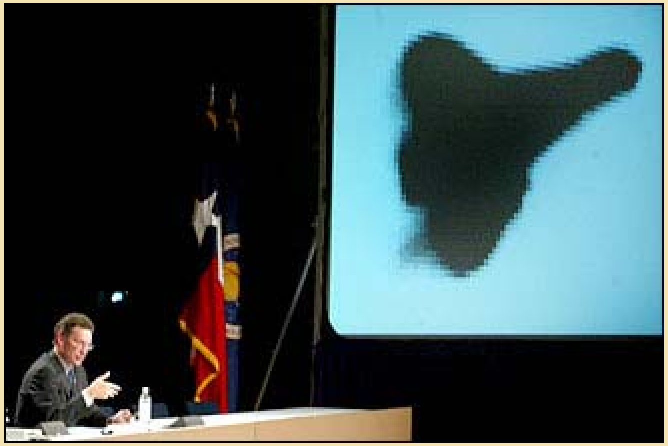
# Reassembling the Shuttle

Reassembly of Shuttle at NASA hangar

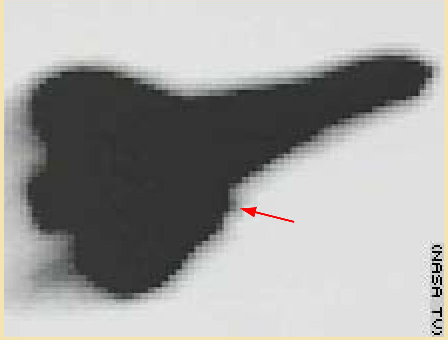



Schematic of shuttle parts for reassembly

# Satellite Photograph of Shuttle in Space

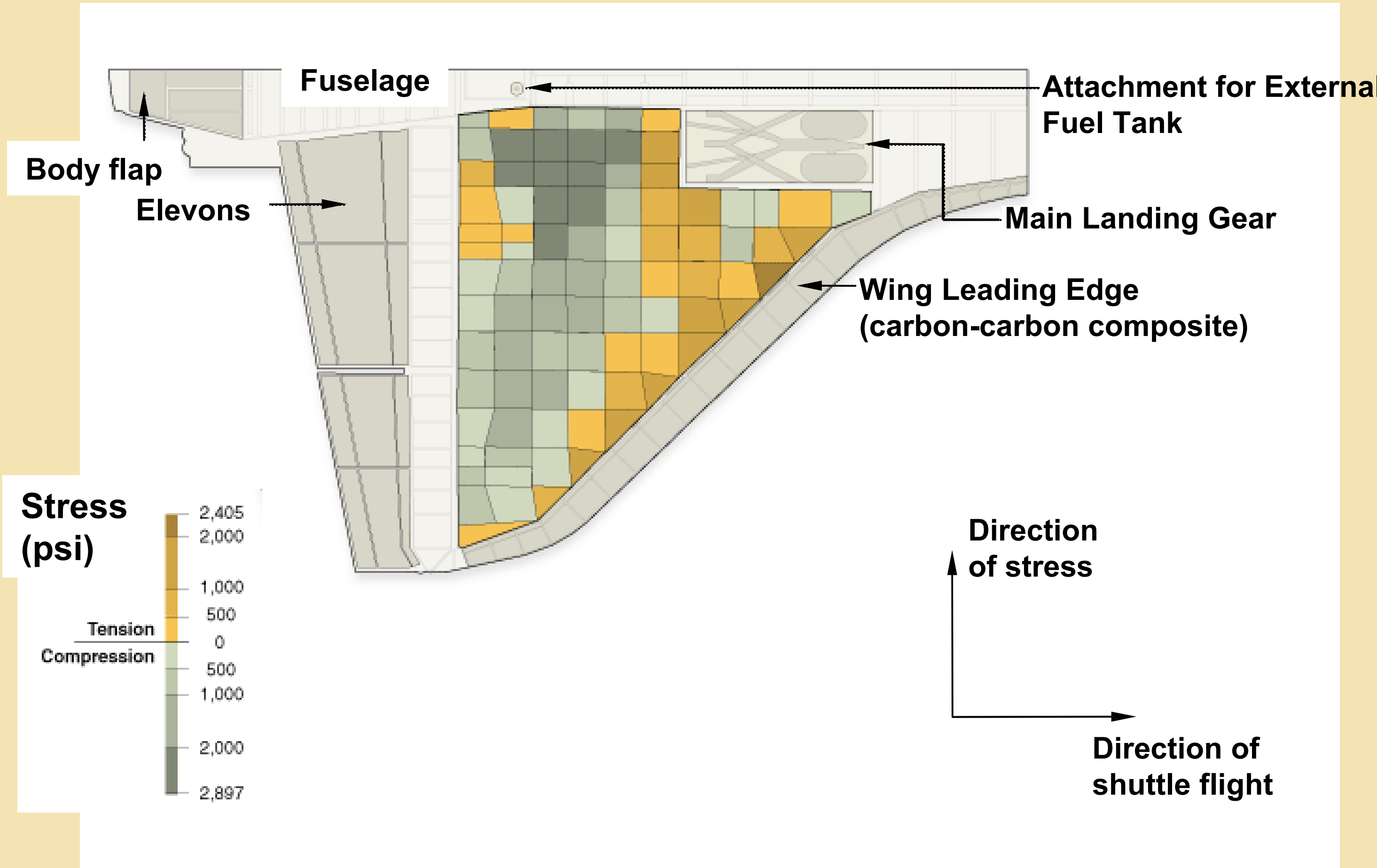


**NASA Briefing by**
**Ron Dittemore, Shuttle Program Manager**

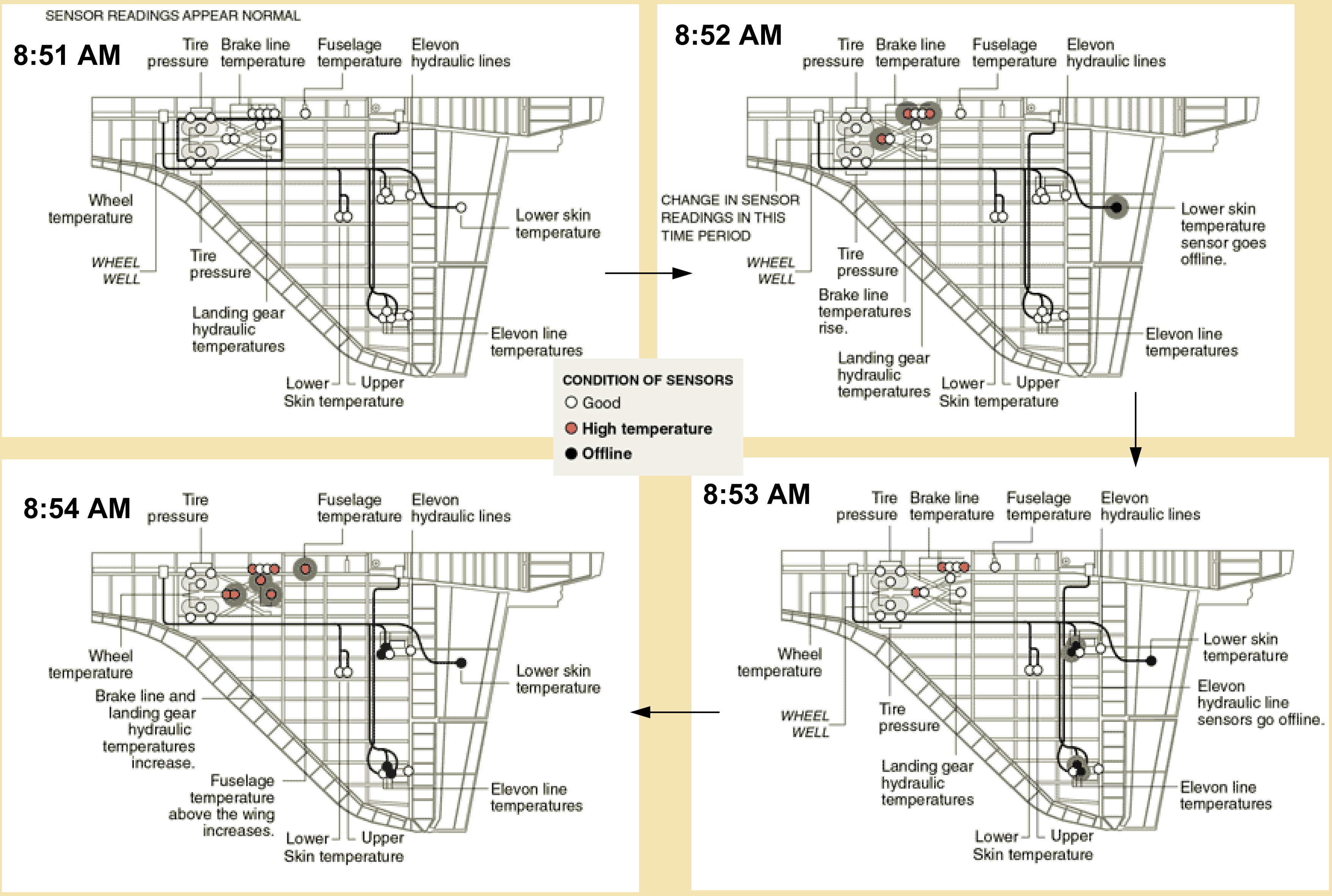


**What is the protrusion on the leading edge of the left wing?**

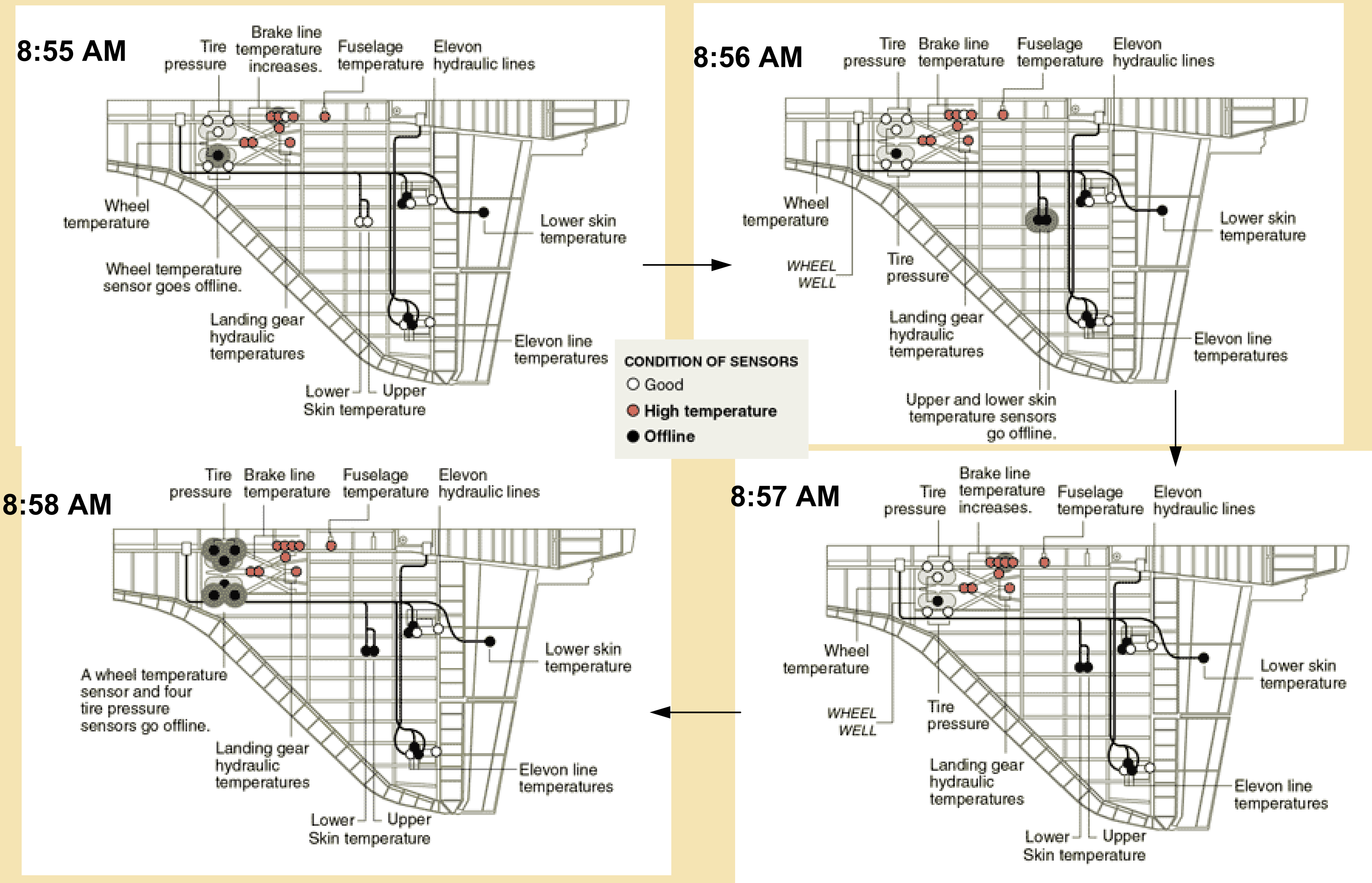
# Thermal Stresses in Shuttle Wing During Re-entry



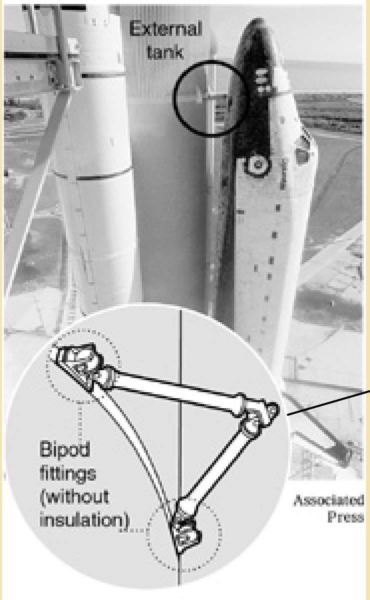
# Temperature Evolution in Left Wing

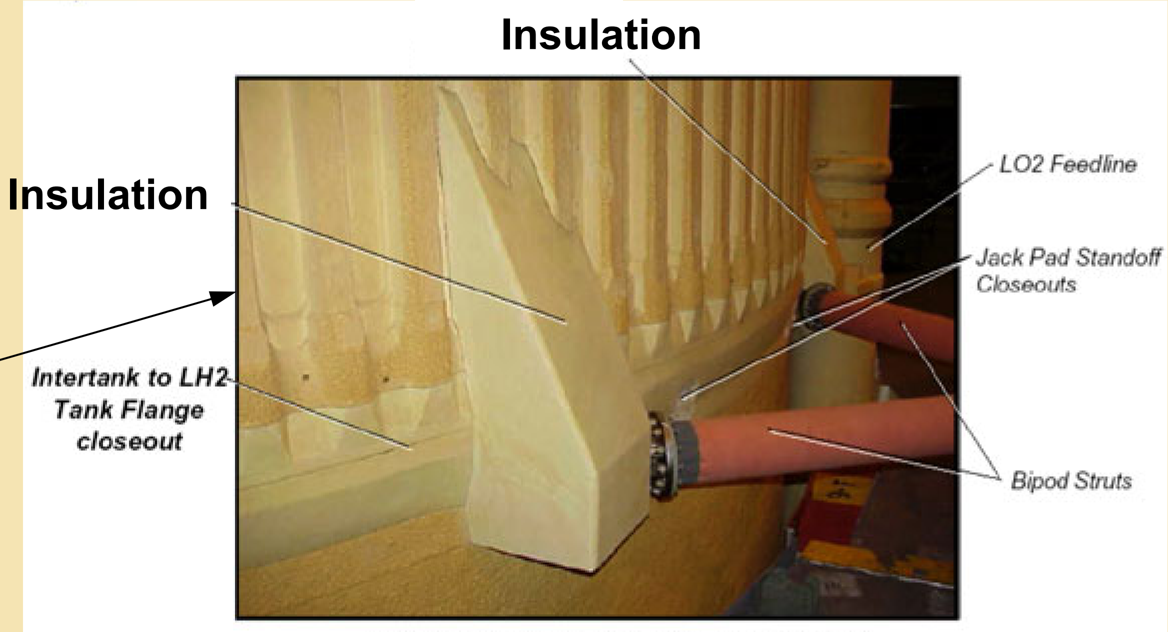


# Temperature Evolution in Left Wing



# Schematic and Photograph of Bipod/Flange Area with Insulation

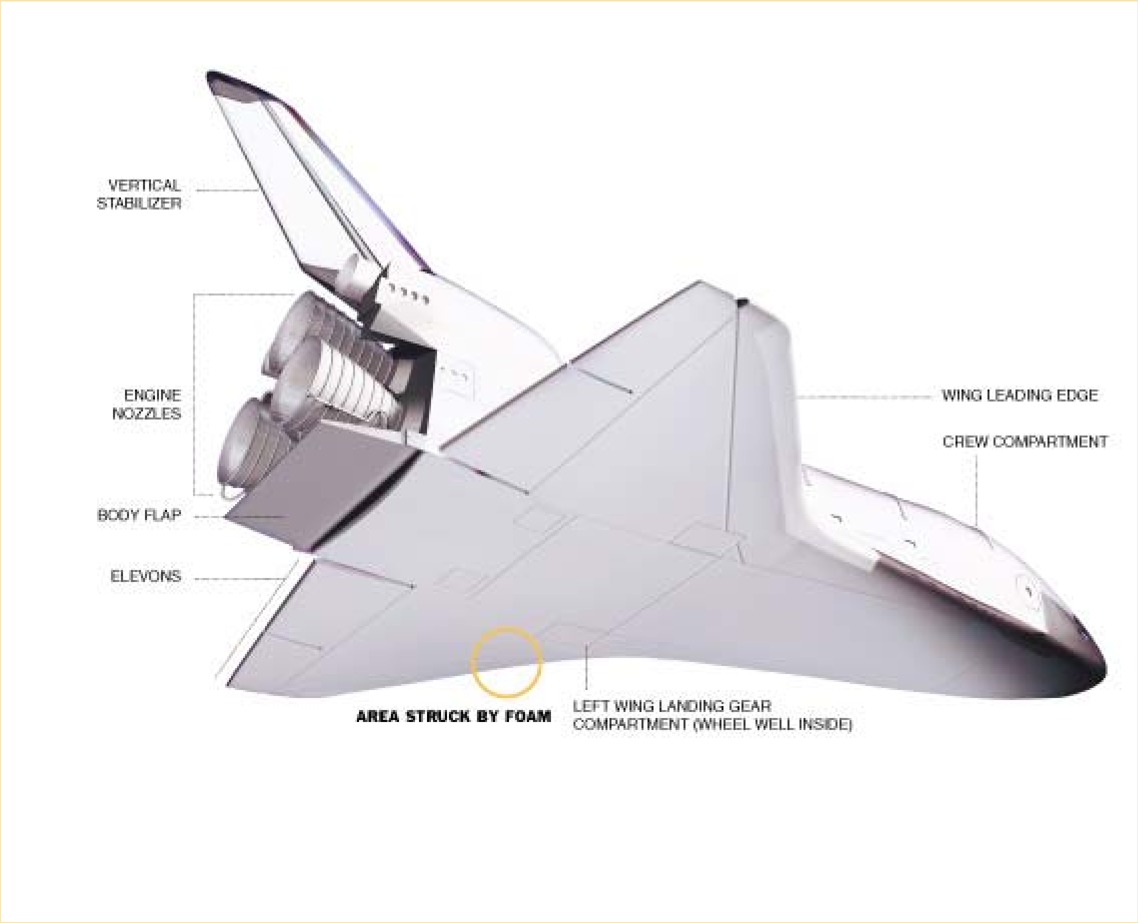


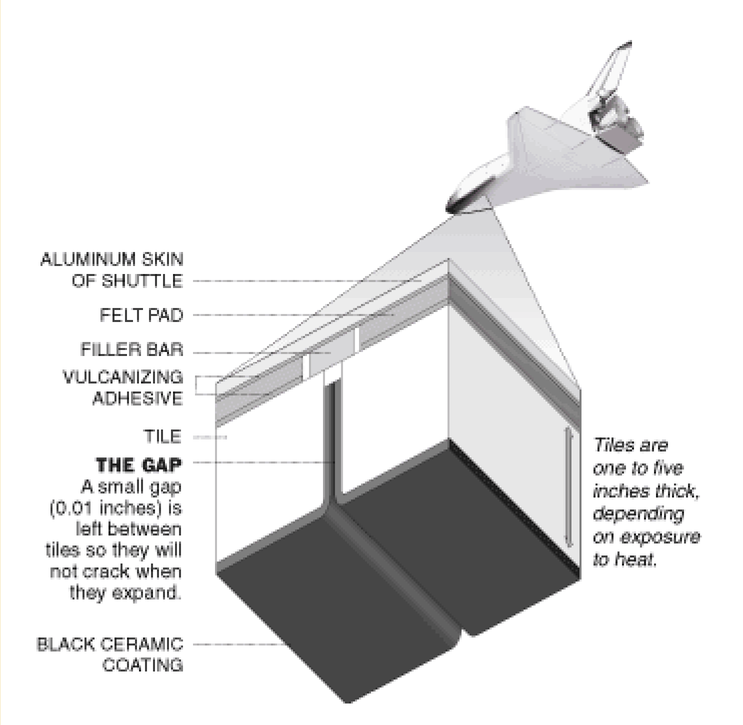

Bipod/Flange Area

# Foam Striking Left Wing of Shuttle

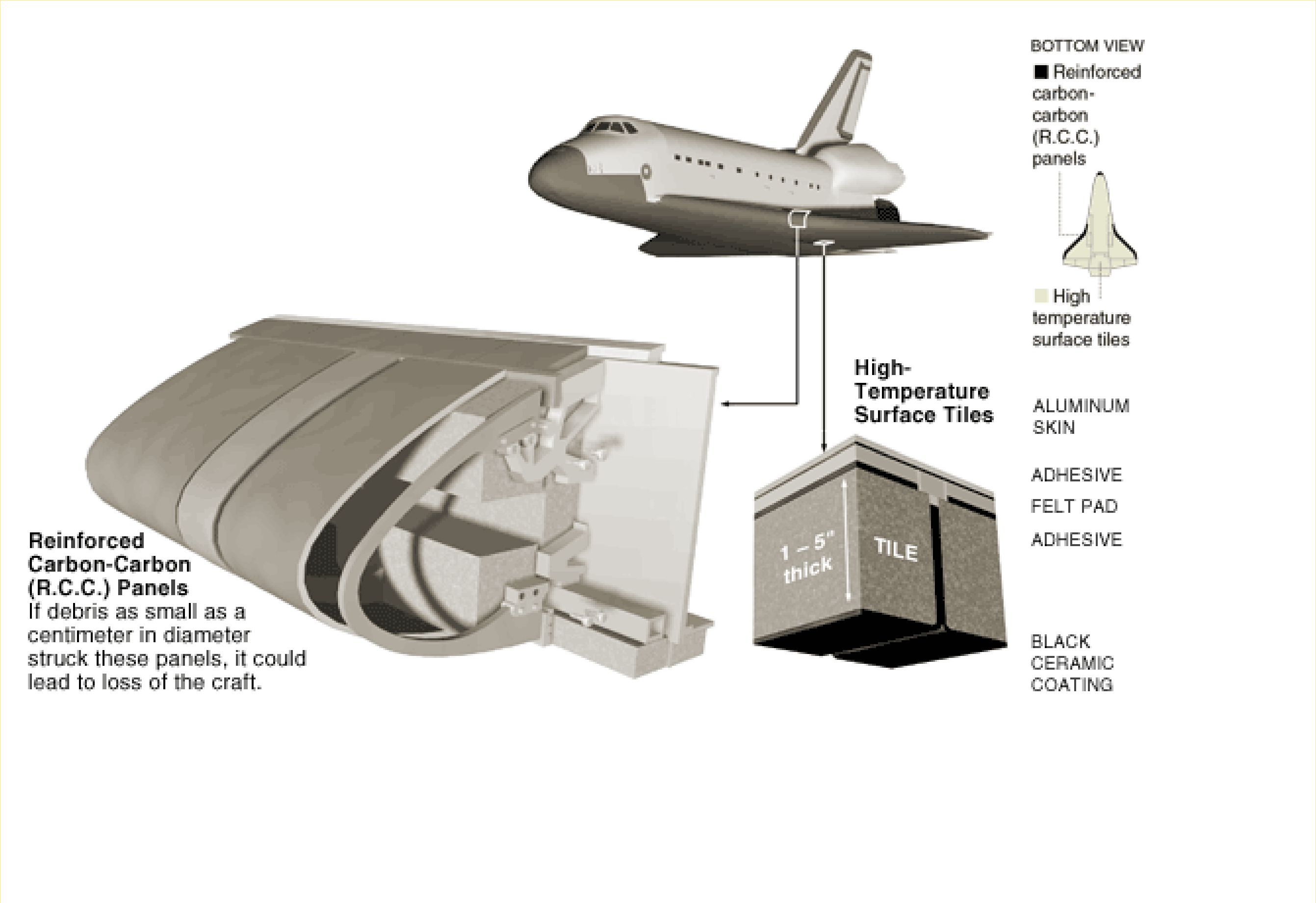

**NASA Flight Video**



# Ceramic Tile used for Thermal Insulation

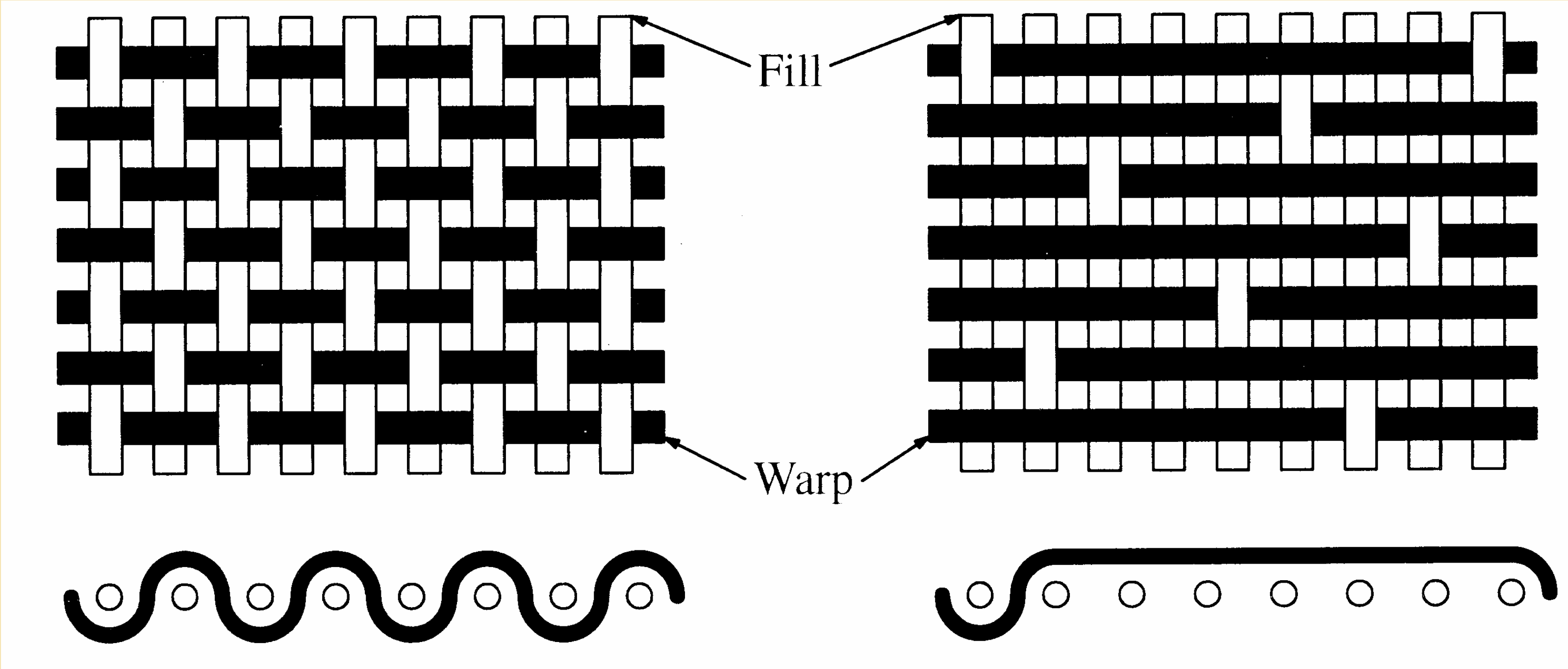
# Carbon/Carbon Composite in Leading Edge of Wing



# Woven Fiber Fabrics

Plain

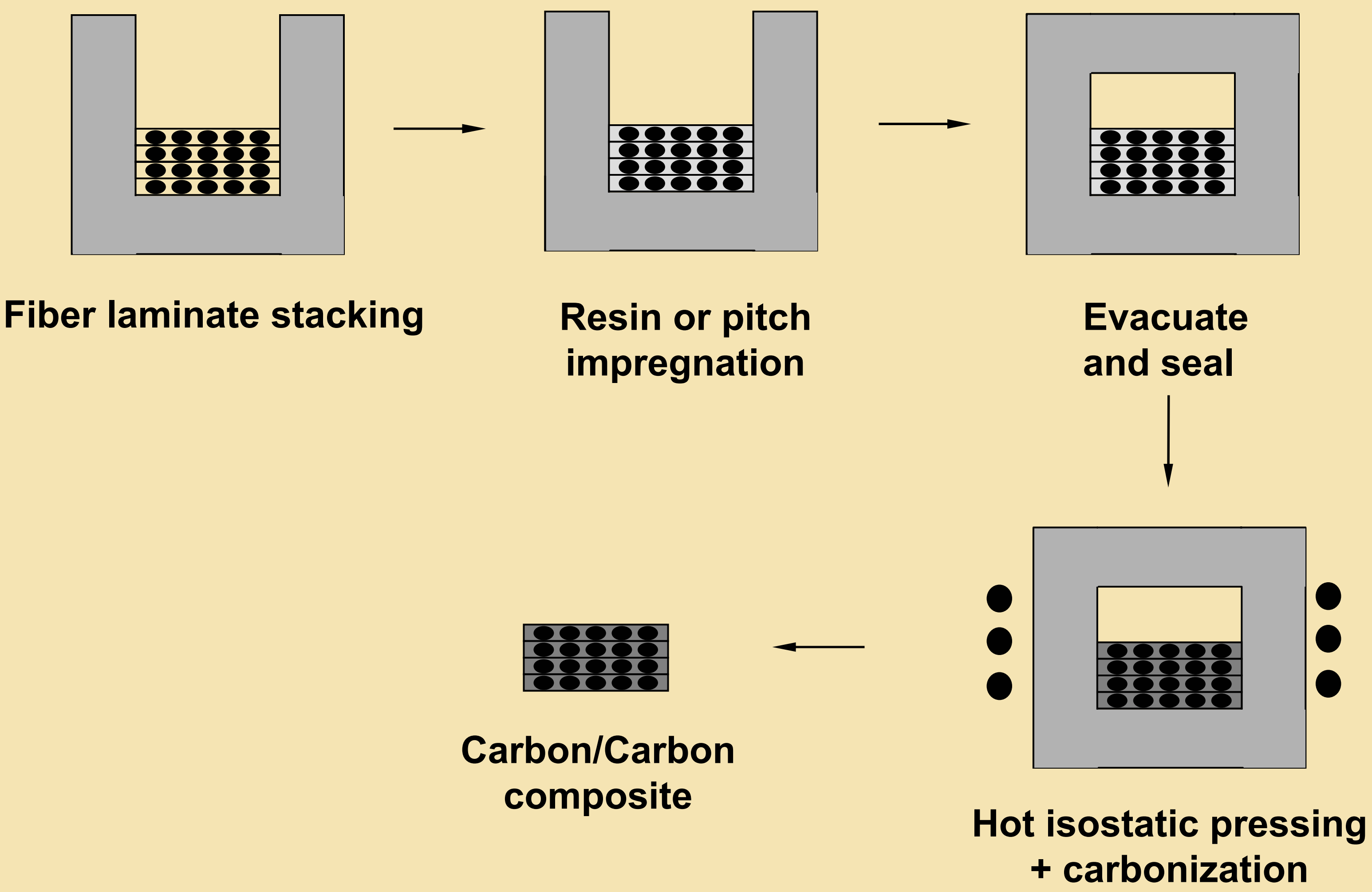
Eight Harness Satin



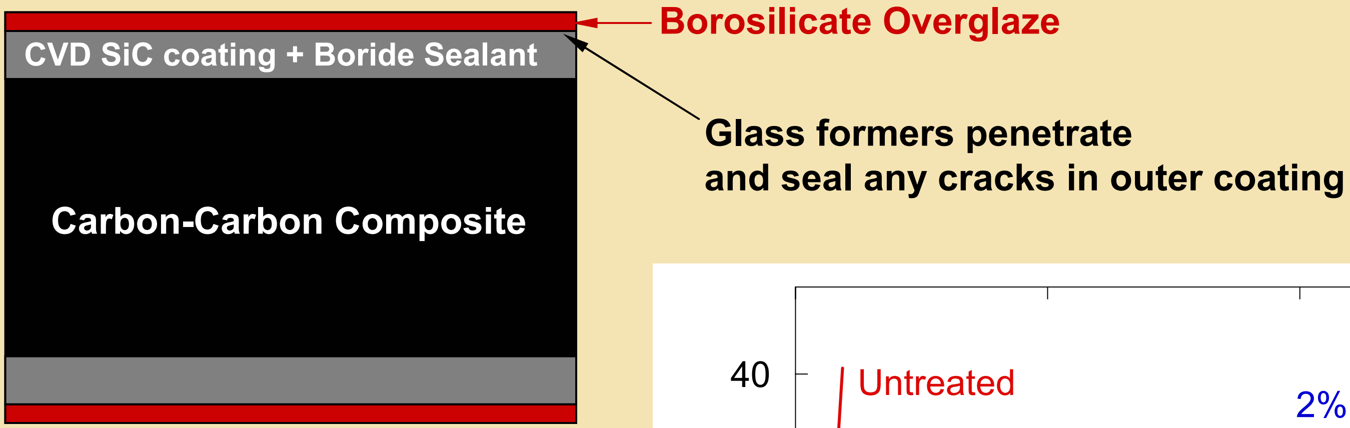

- stable
- handleable
- easier processing

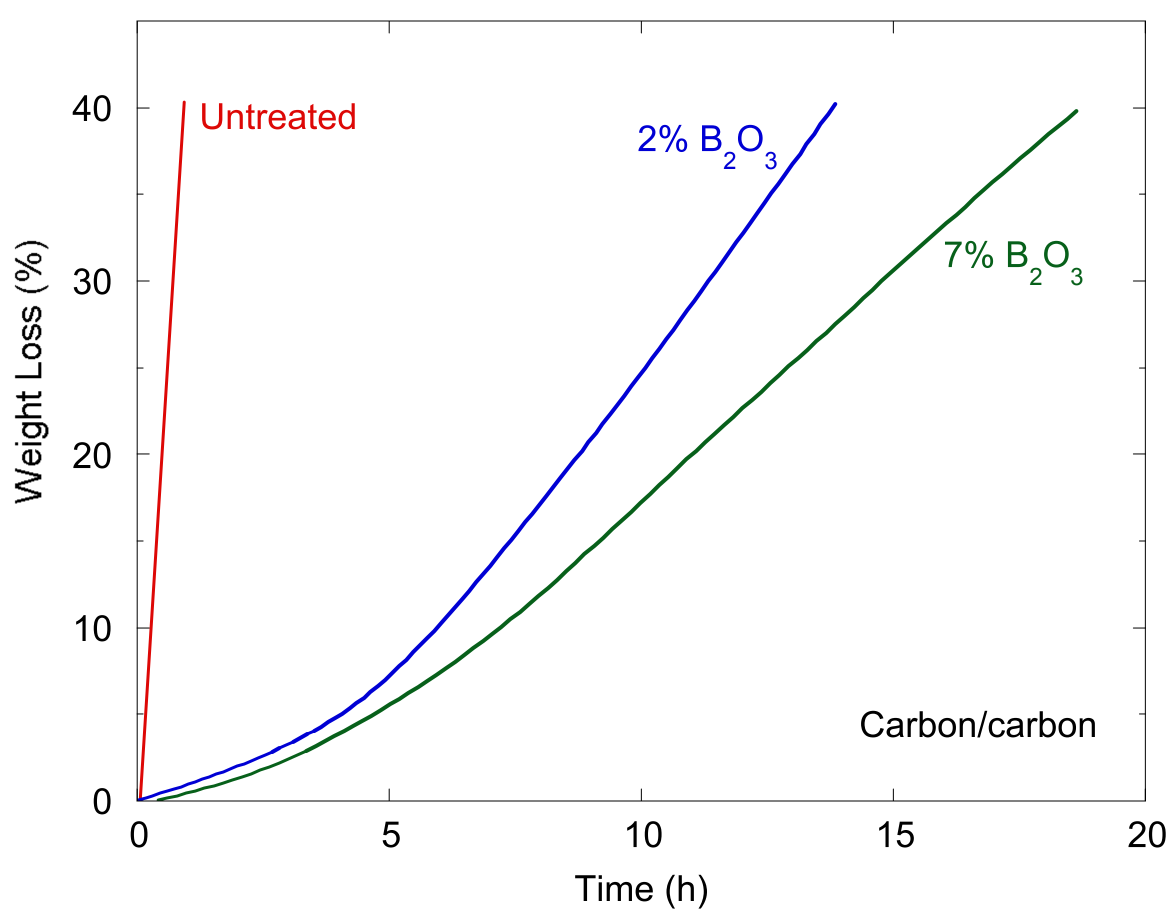
- drapeable(contours)
- distinct faces
- less porous

# Processing of Carbon/Carbon Composites

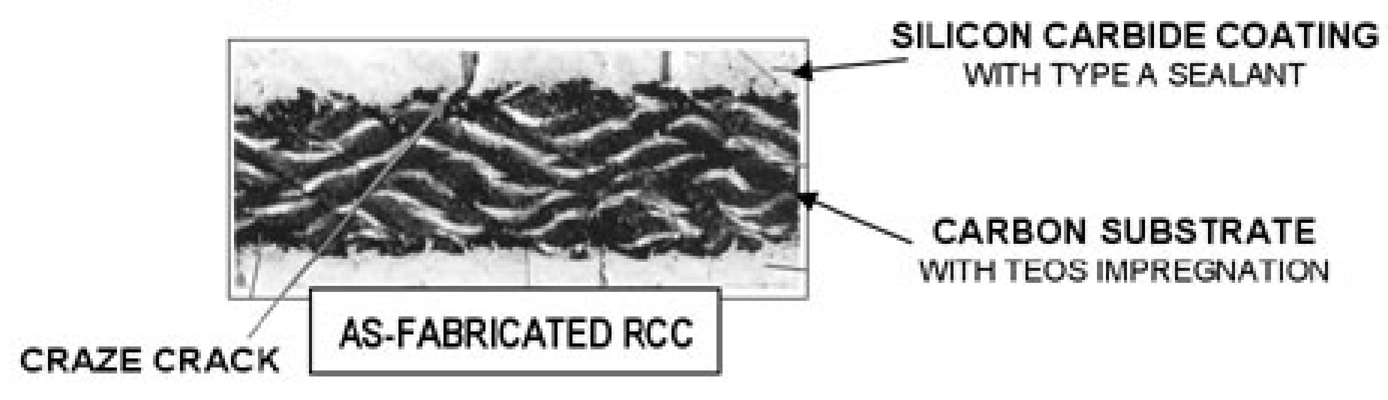


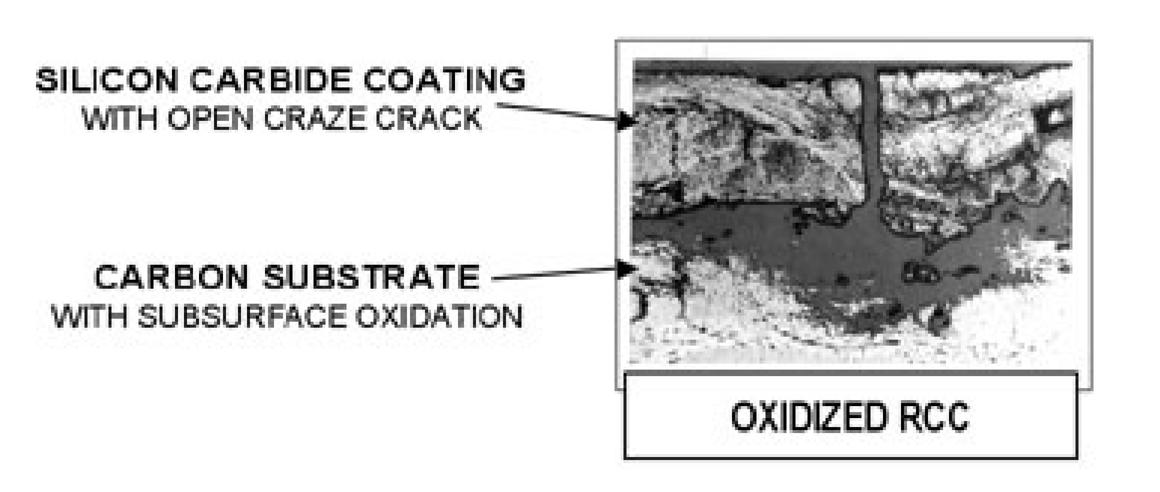
# Thermal Protection Design for Space Shuttle



# Carbon-Carbon Composite Used in Leading Edge of Shuttle Wing

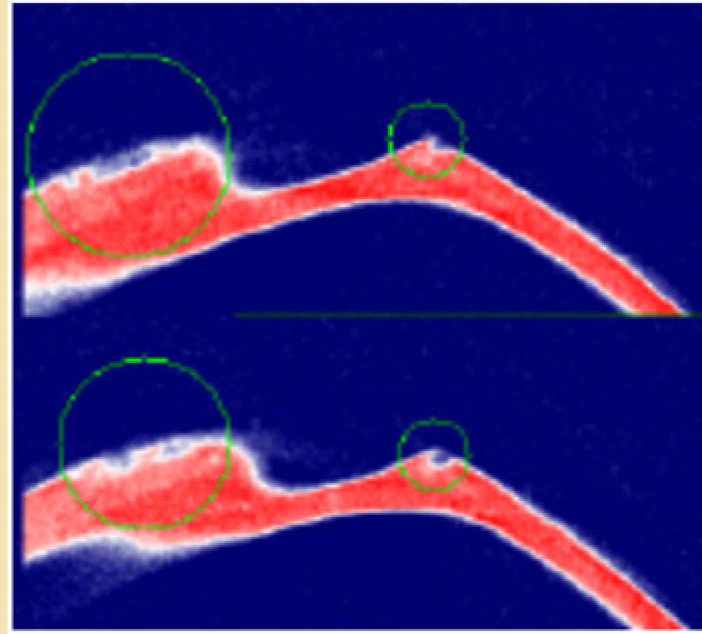



**Space Shuttle Discovery**

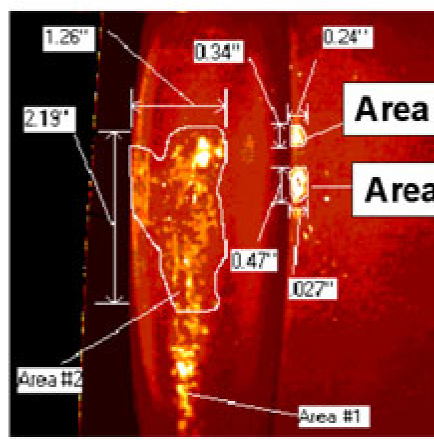
# Foreign Object Damage in Previous Shuttle Mission

- Damage was on the upper edge measuring 0.10"L x 0.15"W
- Defect had large cavity with carbon substrate oxidation

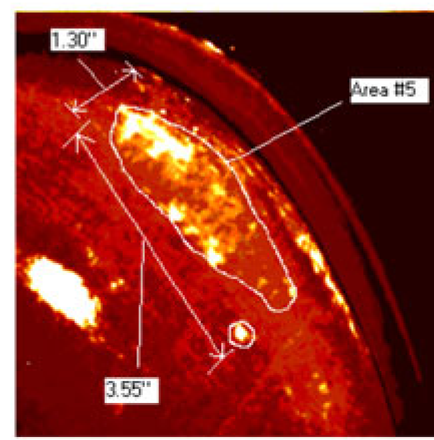



CT Scan (Tomography)

**Space Shuttle Atlantis – 11/2002**



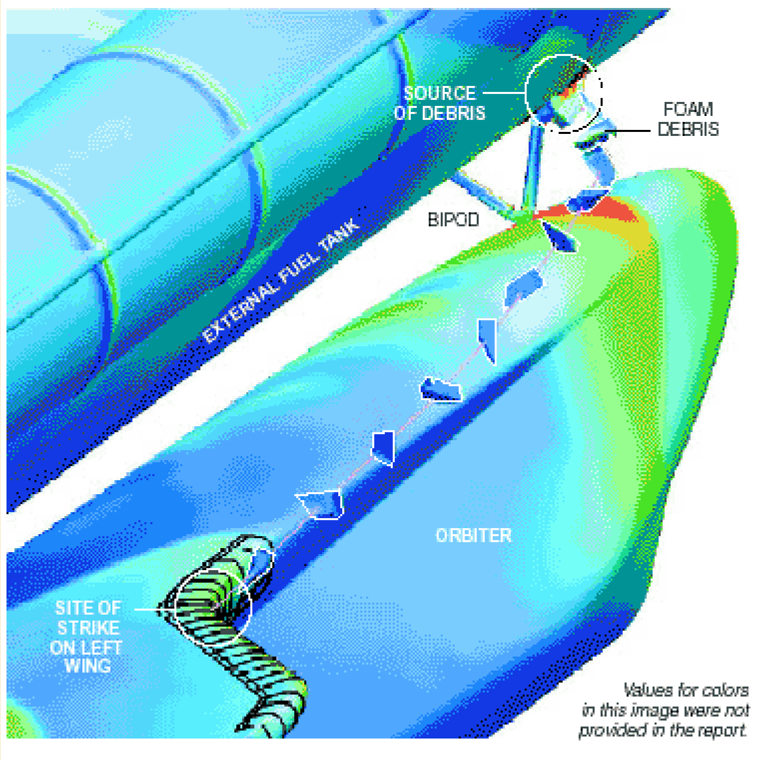

**Front View**




**Side View**

**Oxidation flaws**

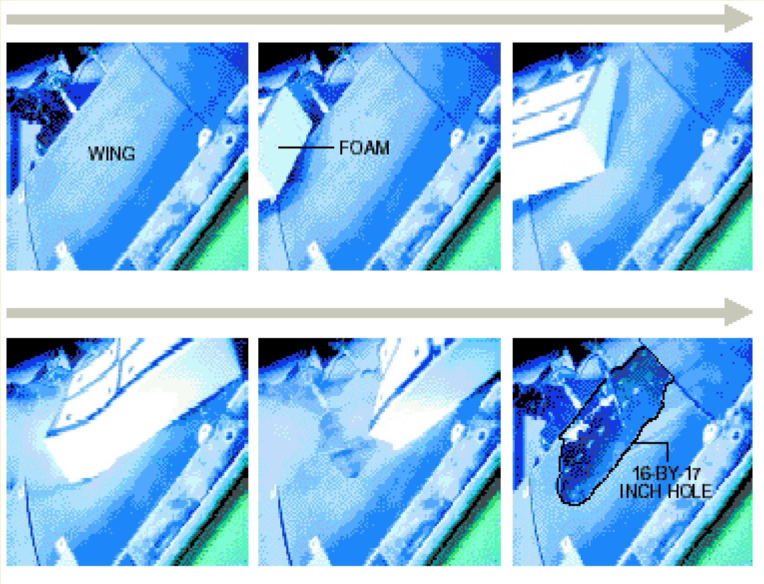
# Summary of Damage Sequence




**81.9 seconds after liftoff, debris hits wing**

Computer models predicted velocity of foam (~1.7 lbs.) to be ~ 500 miles per hour.

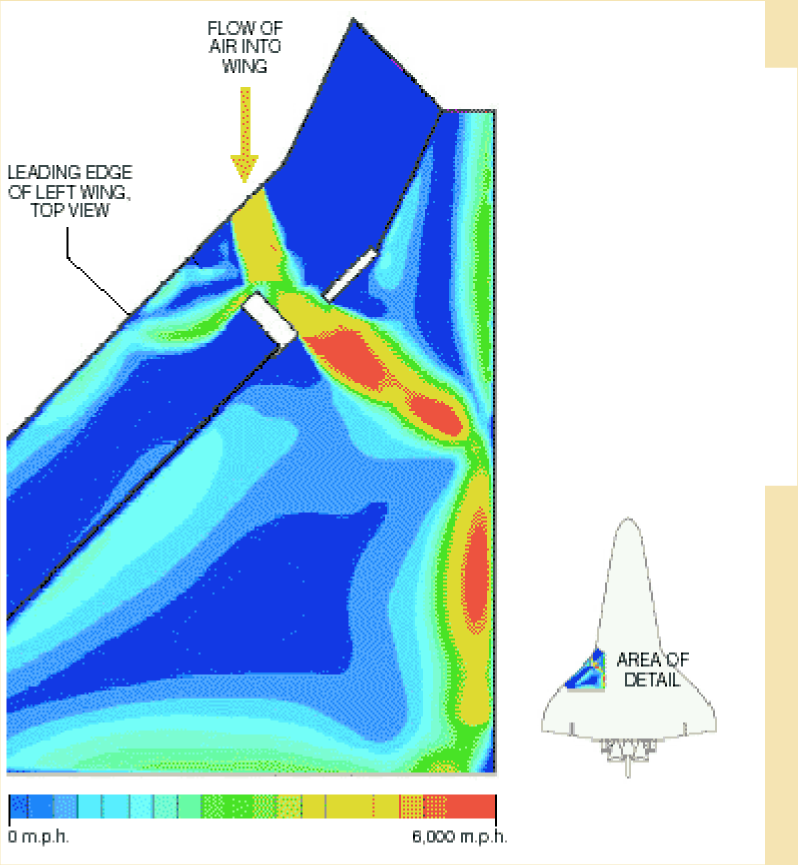
# Estimating the Damage During Impact



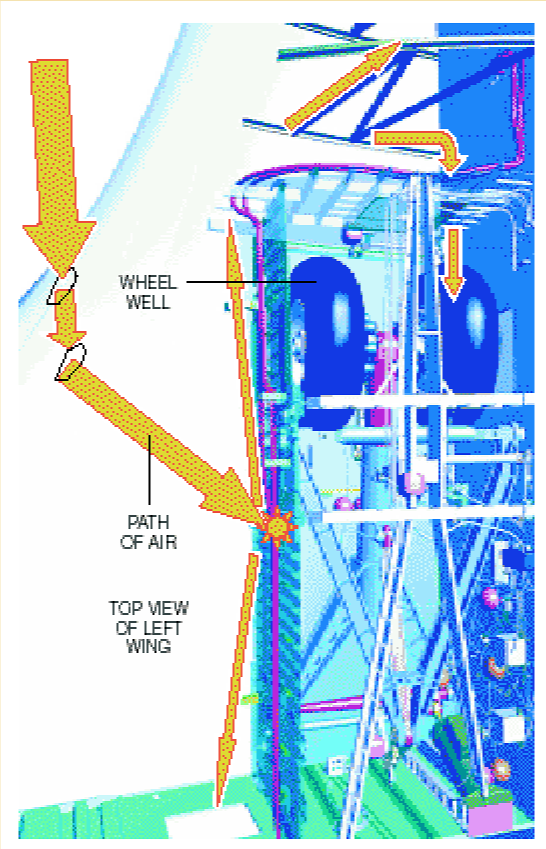



**Foam impact testing on wing of shuttle Atlantis**

# Summary of Damage Sequence (contd.)




**Speed of air moving through wing**




**Superheated air flowed through wheel well**
**- Al trusses melted, weakening shuttle structure**

# Lessons Learned from Shuttle Columbia Explosion

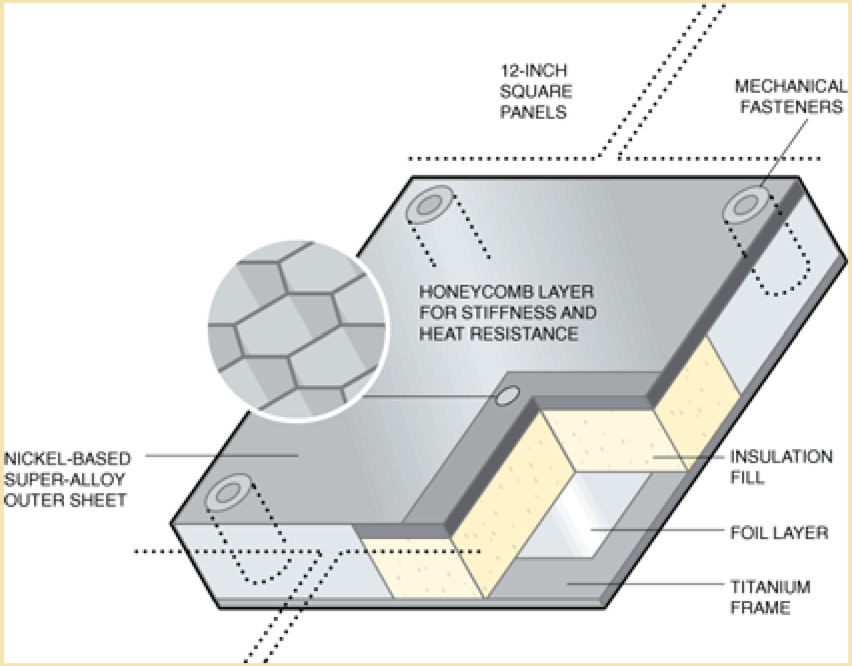
- Space shuttle tiles may not be adequate for impact damage resistance

- Carbon/carbon composite leading edge should be tailored for higher impact damage/oxidation resistance
  - More frequent inspections (after flights) of leading edge should be conducted

- Impact of foam should be addressed in future flights

- Emergency escape system should be devised and incorporated into flight plans

# Alternate Tile Material/Design for Space Shuttle



# Shuttle Accident Board Recommendations for Resuming Flights

- Begin aggressive program to eliminate all shedding of debris from external fuel tank.
  - Increase shuttle's ability to sustain minor debris damage.
- Make it possible to inspect damage to shuttle's thermal protection system and make emergency repairs.
- Upgrade imaging system so it can provide at more useful views of shuttle at liftoff.
- Obtain high-resolution images of external tank after it separates, and images of wings' leading edge and thermal protection system.
- Develop a comprehensive inspection plan to determine the structural integrity of components made of reinforced carbon-carbon.

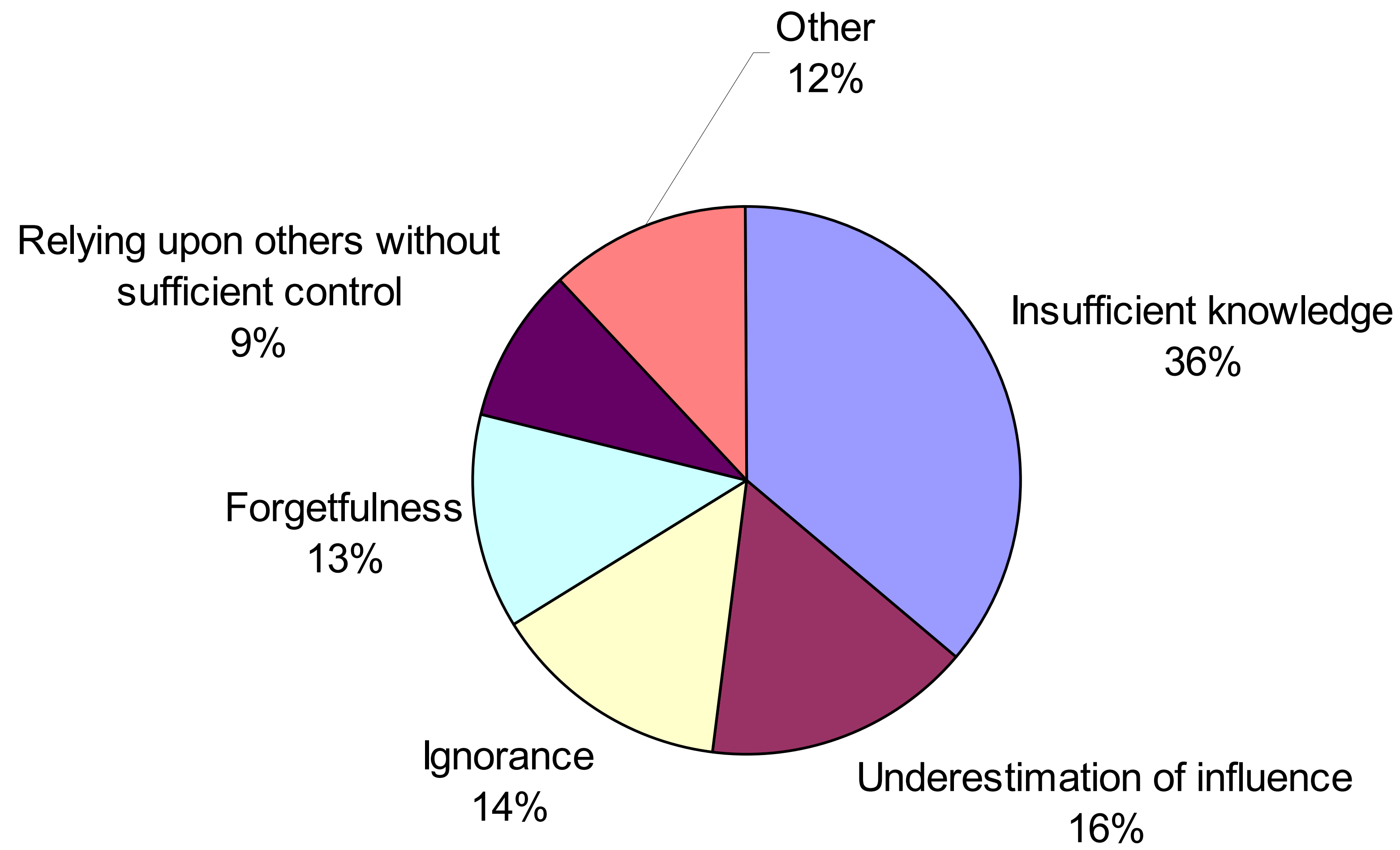
# General Observations for Materials Engineers

- Continue to conduct research/engineering of structural materials.
  - Microstructure-property relationships are the key to understanding material behavior!

- Communicate and collaborate with engineers from other disciplines (civil, mechanical engineers).

- Make general public and public officials aware of the importance of engineering materials to our society (outreach).

# To Engineer is Human




*Study by the Swiss Federal Institute of Technology – Zurich*
*800 cases of structural failure, 504 killed, 592 injured, millions of dollars in damage incurred.*

# Acknowledgments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