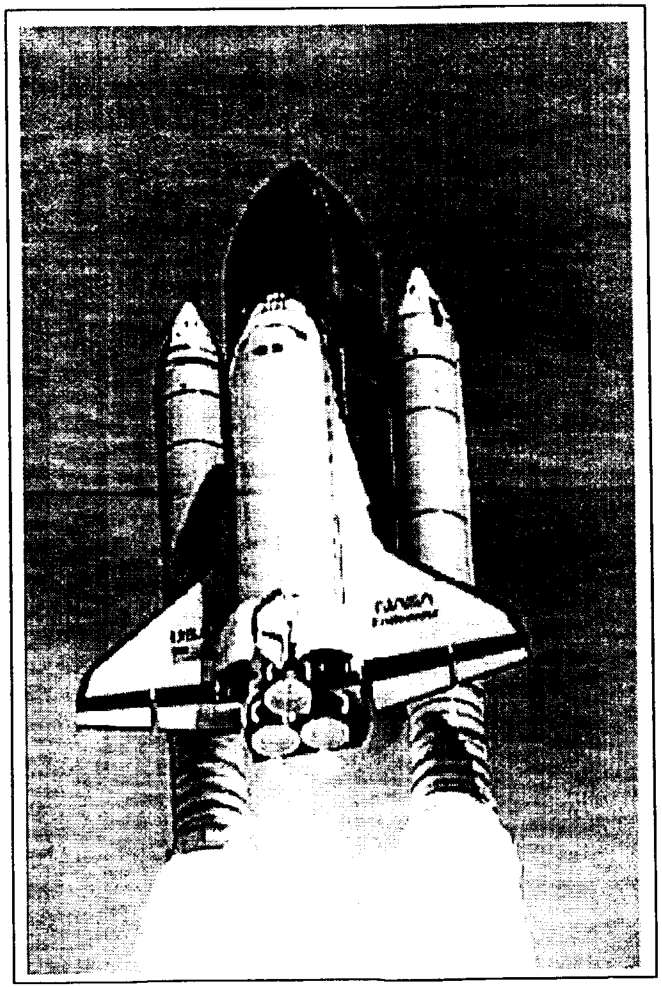
LOCKHEED MARTIN

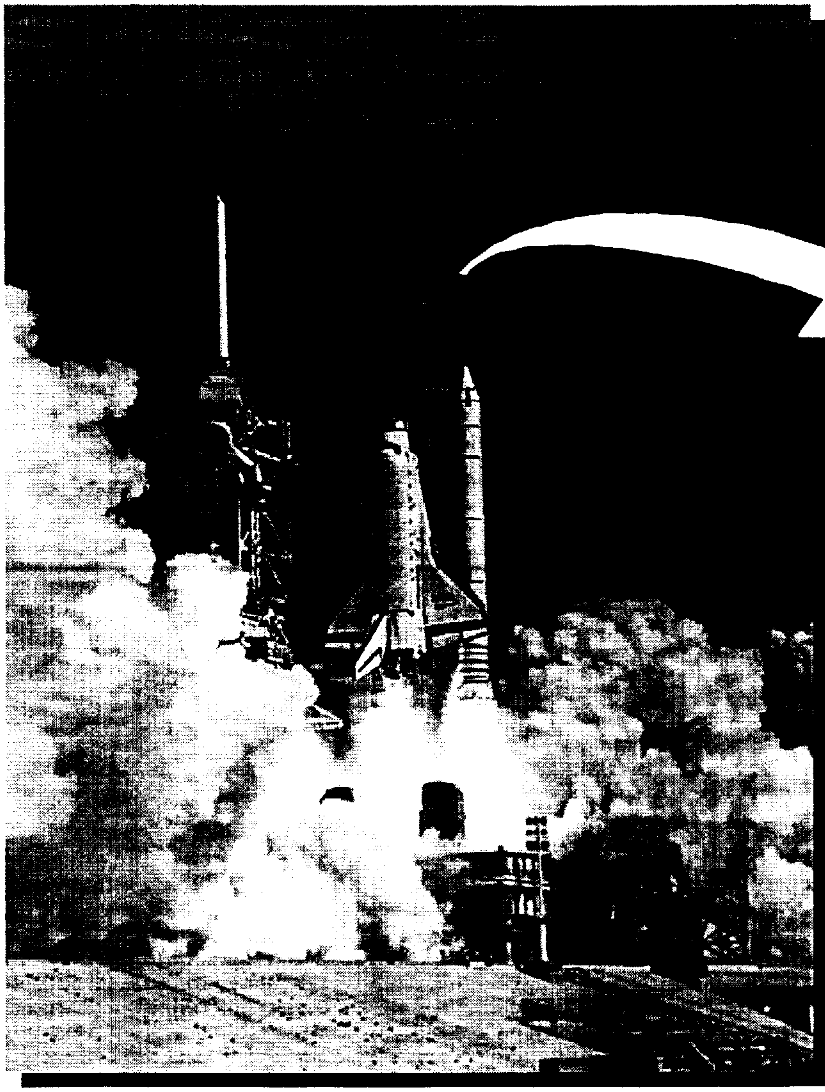
Michoud Operations

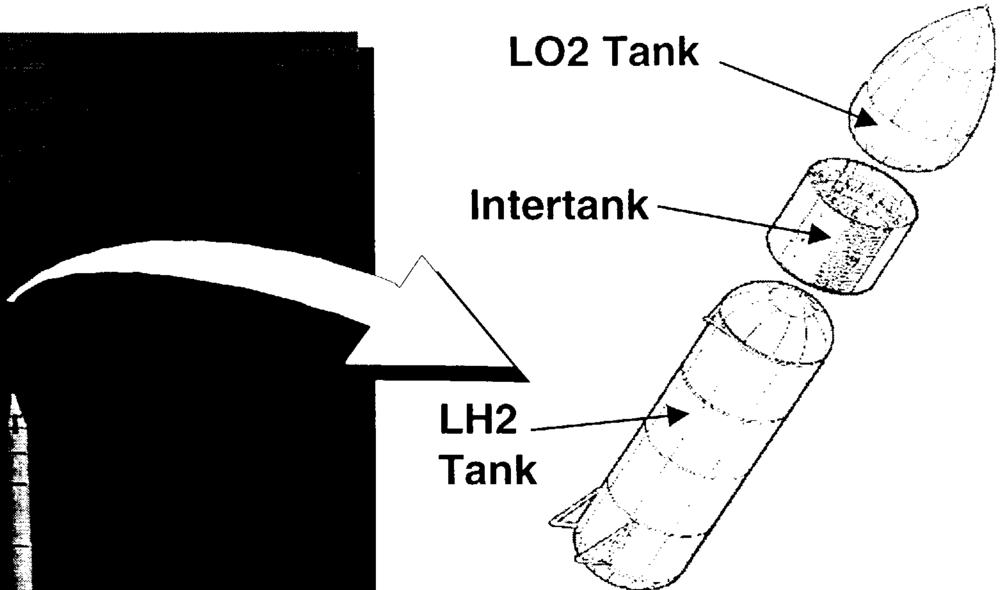


Modification to the Space Shuttle External Tank Thermal Protection System to Comply with New Environmental Laws

Tulane Engineering Forum
Friday, September 13, 2002
Hilton Riverside
New Orleans, Louisiana
Energy and the Environment

External Tank Overview





- The External Tank(ET) is the structural backbone of the Space Shuttle System providing attachment points for the Orbiter and Solid Rocket Boosters
- Made of welded aluminum alloy panels and frames
  - Length = 153.8 ft.
  - Diameter = 27.6 ft
- Contains 1.6 million pounds of cryogenic fuel fed to the Orbiter engines at 1,035 gallons/second

Function of ET TPS

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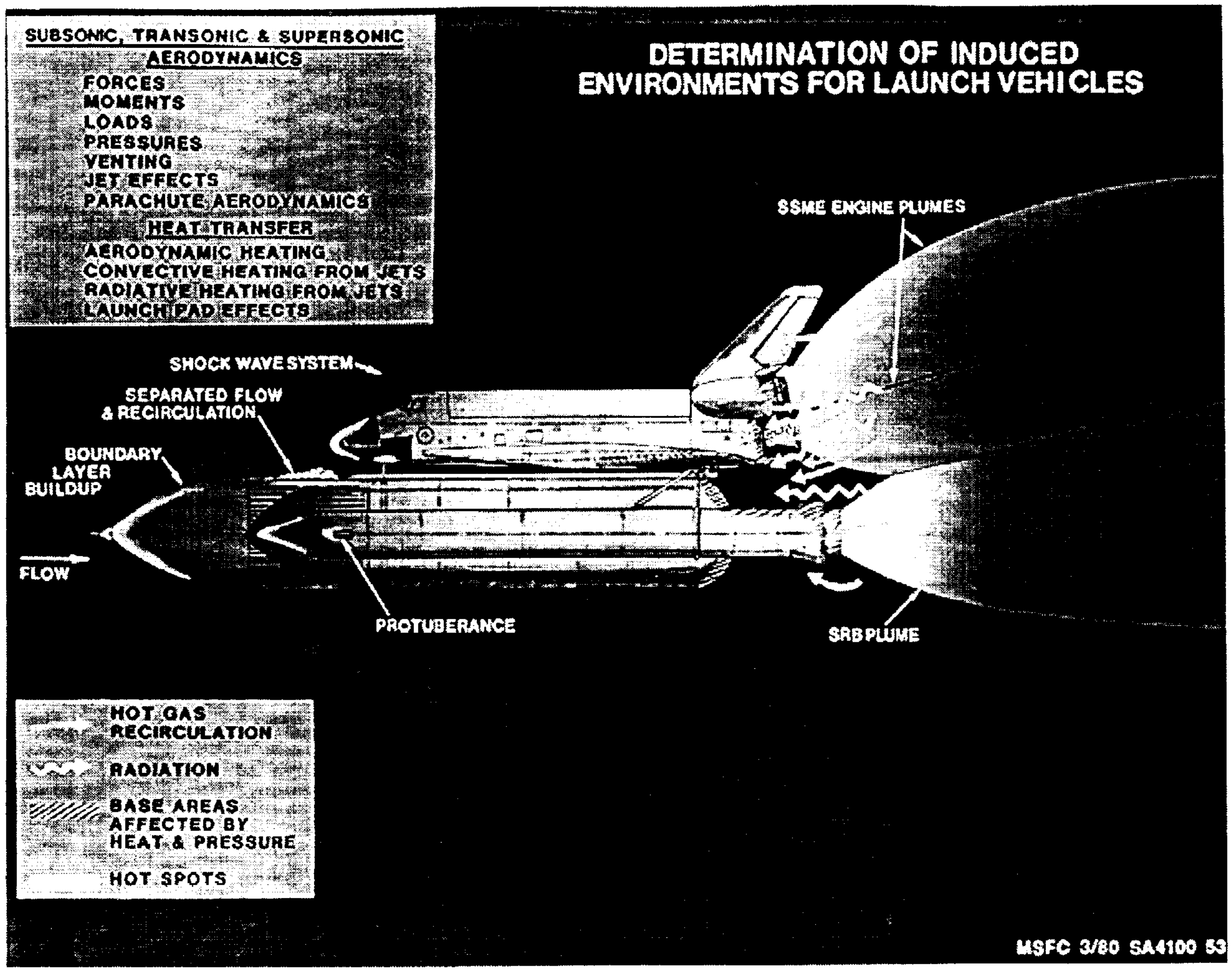
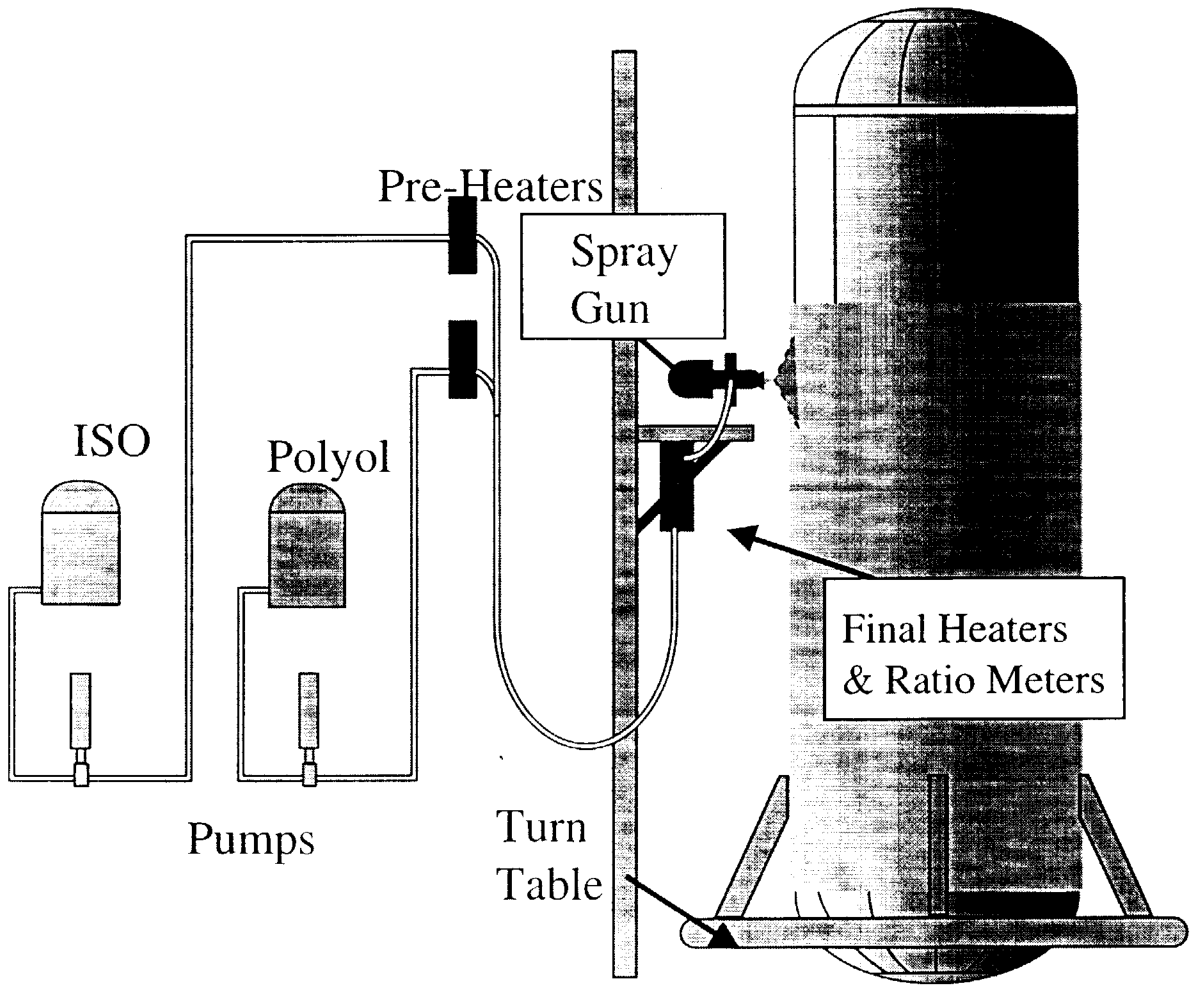
The External Tank requires a thermal protection system (TPS) to maintain the quality of the cryogenic propellant, minimize the formation of ice/frost, and protect the structure from ascent and plume heating.



ET Thermal Protection Requirements

Flight Requirement	Derived Requirement	Verification Method
• Maintain structural temperature	• Thermal conductivity • Recession rate	• Conductivity measurement • Wind tunnel/HGF/ablation tests • Analysis
• Ice/frost prevention	• Thermal conductivity	• Conductivity measurement • Flat tank cryogenic test • Analysis
• Maintain propellant quality	• Thermal conductivity • Recession rate	• Conductivity measurement • Wind tunnel/HGF/ablation tests • Analysis
• No debris generation	• Flexure capability • Recession rate • Bond tension strength • Cryogenic strain compatibility	• Wind tunnel/HGF/ablation tests • Bond tension strength measurements • Cryoflex tests • Combined environments test • 3 and 4 point bend test • PAL ramp flexure tests

Spray Gun Setup



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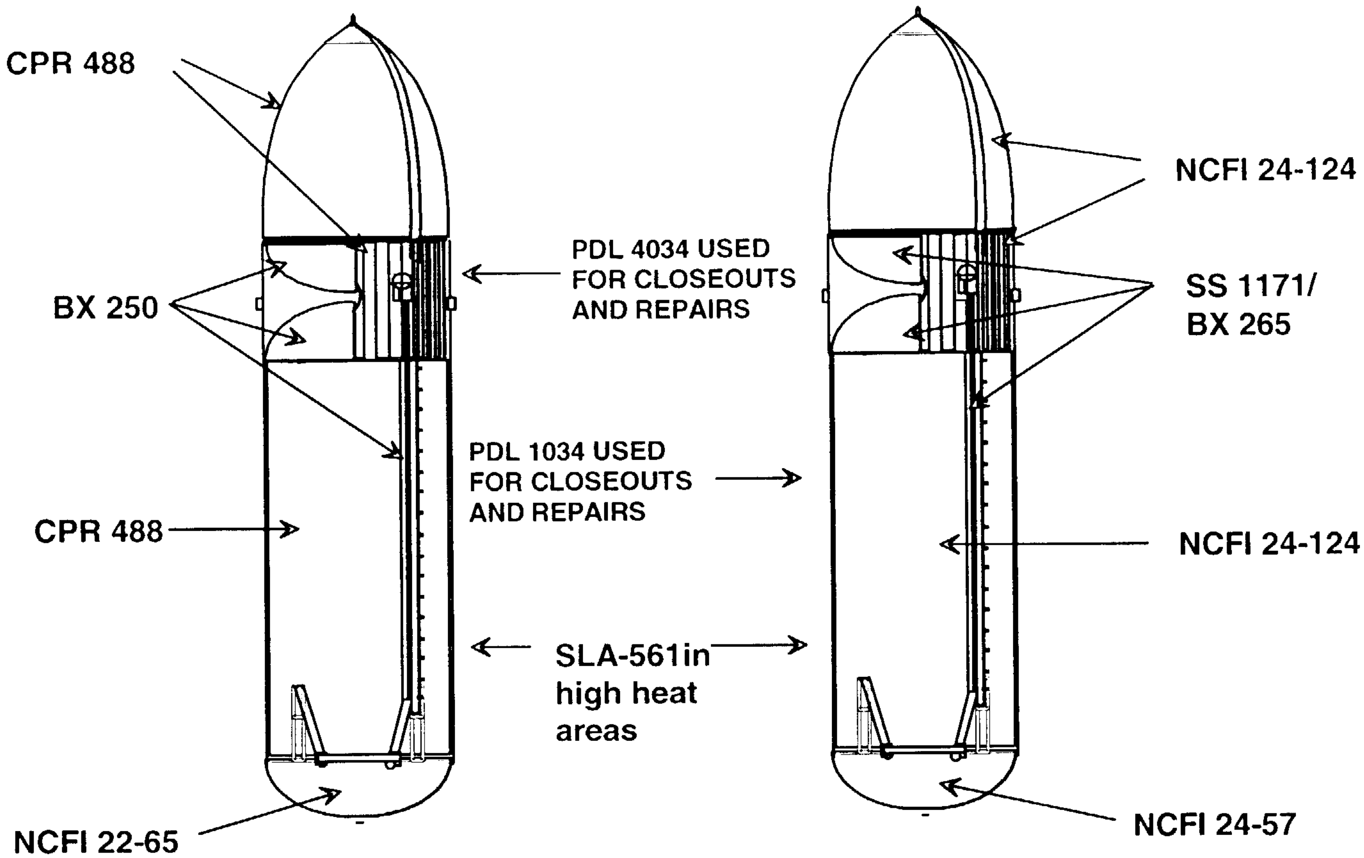
TPS Blowing Agents

- TPS is applied to most of the ET exterior surface, covering 16,750 square feet
  - Consists of four low density polyurethane and polyurethane-modified isocyanurate foams engineered to meet numerous stringent technical requirements
  - The blowing agent provides critical insulation and cell structure properties of the foams
- CFC 11 was the original foam blowing agent
  - EPA regulations established a 12/95 phaseout due to its high ozone depleting potential
  - Replacement efforts initiated in 1988
- HCFC 141b selected as best replacement blowing agent after extensive testing
  - Implementation initiated in 1993 with plan to complete by 1996
  - Viewed as an interim solution; EPA phaseout on 1/1/2003
- Replacement of CFC 11 with HCFC 141b resulted in unanticipated program impacts, such as foam loss during flight

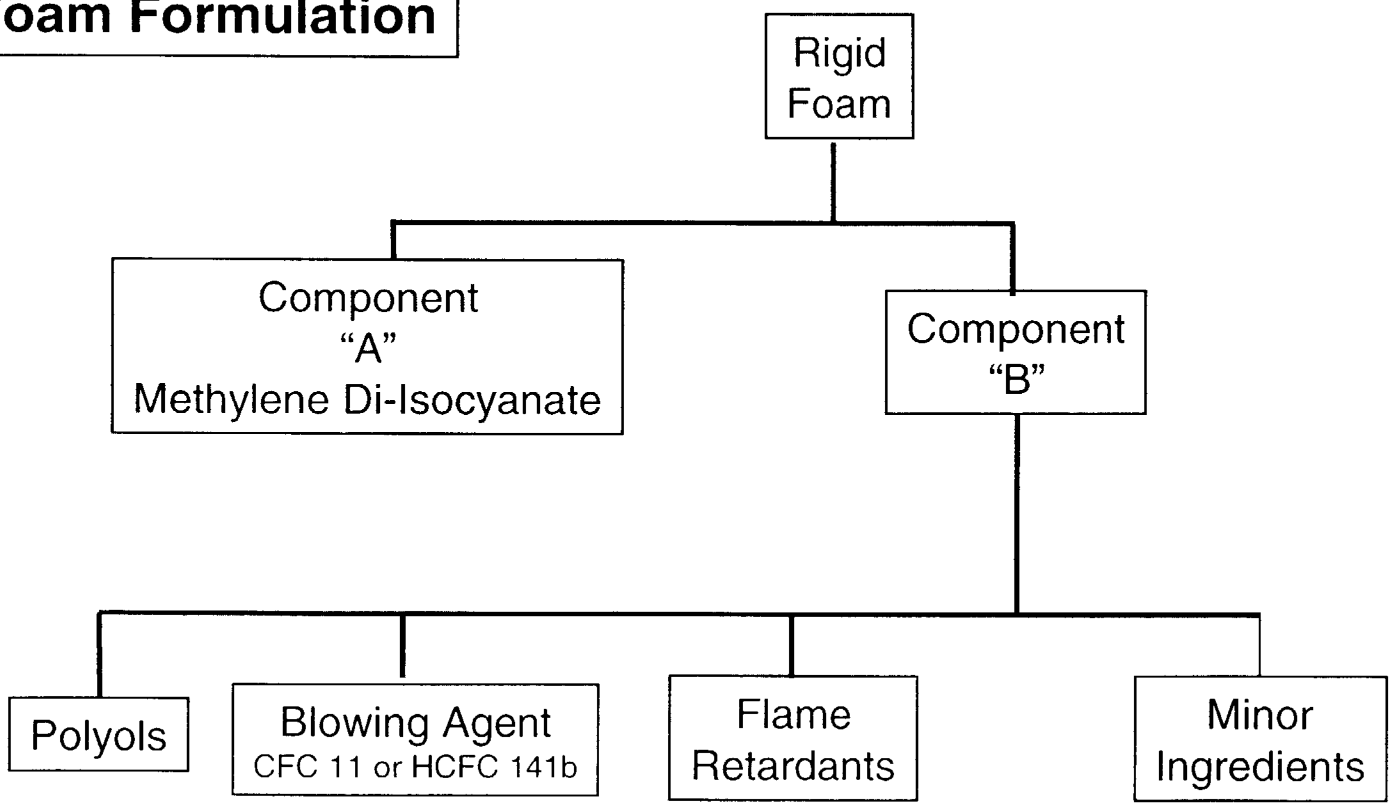


WAS
CFC 11 Foams

NOW
HCFC 141b Foams

Raw Materials of Polyurethane Foams

Foam Formulation

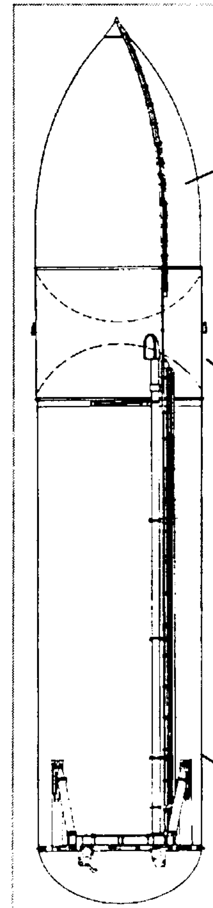


Blowing Agent	CFC-11	HCFC-141b
Formula	CCl_3F	Ch_3CCl_2F
Boiling Temp (°F)	74.8	90
Thermal Conductivity* (btu in/hr ft^2 °F)	0.064	0.067
Thermal Conductivity* (btu in/hr ft^2 °F)	0.015 @ R.T. 0.019 @ 250°F	0.017 @ R.T. 0.022 @ 250°F

NCFI 24-124 Implementation

1990 Clean Air Act Legislated Phase Out of CFC-11 (Freon)

- *Staged implementation of new foams started with STS-78/ET-79*
  - *Optimize weight performance*
  - *Loss of oxychem polyol resulted in loss of supply*
- *Intertank foam implemented on STS-86/ET-88*
- *Replacement of HCFC 141b for CFC-11 in CPR-488 gave higher recession rates in wind tunnel tests*
- *NCFI 23-66, a qualified back-up foam containing CFC-11 was successfully reformulated and qualified with HCFC-141b*



LO2 Tank Sidewall
- Implemented on STS-94/ET-86
- Total area = 2822 ft^2

Intertank Sidewall
- Implemented on STS-86/ET-88
- Total area 2700 ft^2
  - Each thrust panel = 340 ft^2

LH2 Tank Sidewall
- Implemented on STS-84/ET-85
- Total area = 6582 ft^2

STS-87 Orbiter Lower Surface Tile Damage

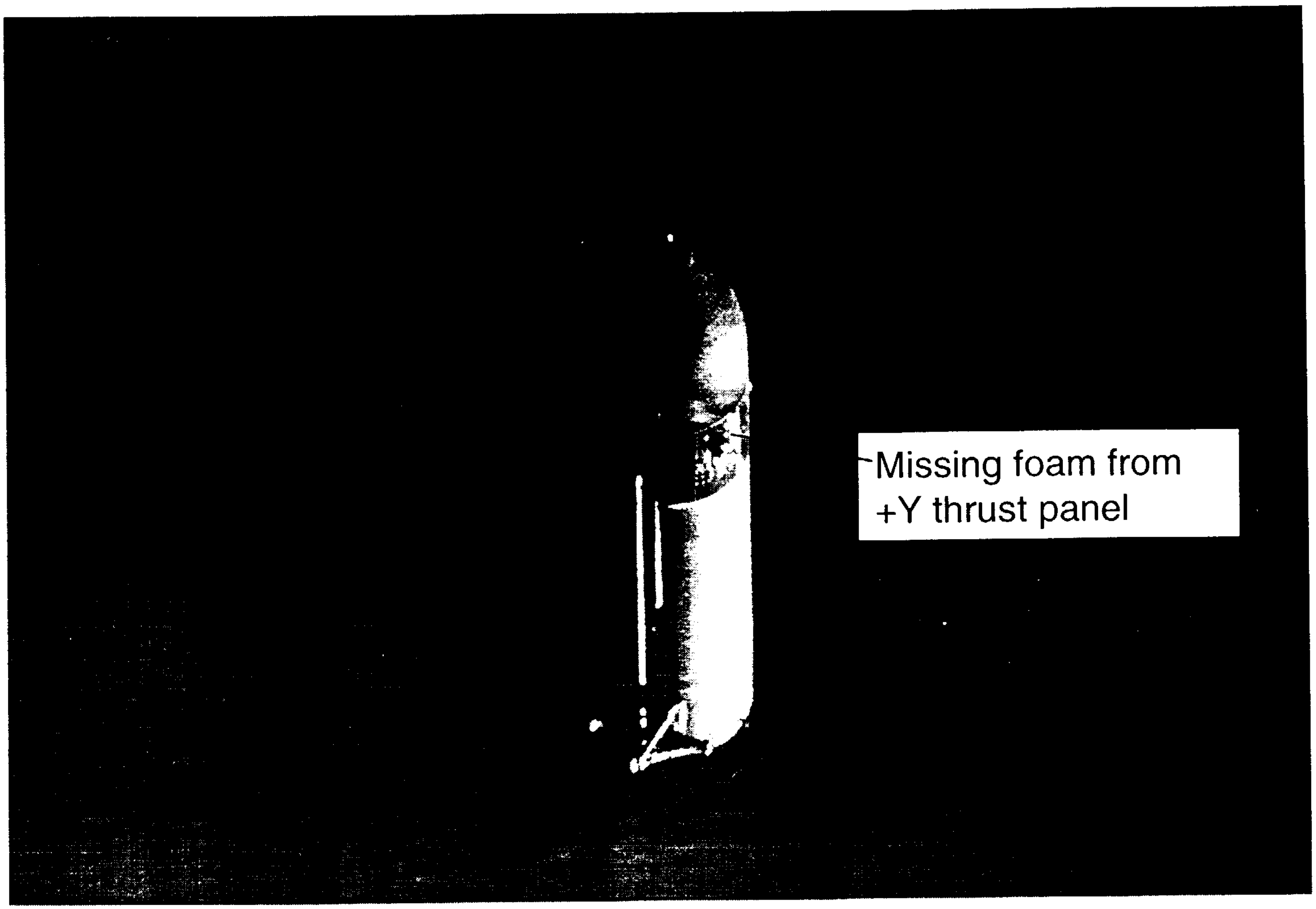
NCFI 24-124 Performance, HCFC 141b

Lower Surface Damage Sites >1"
- STS-87: 109
- Average: 13

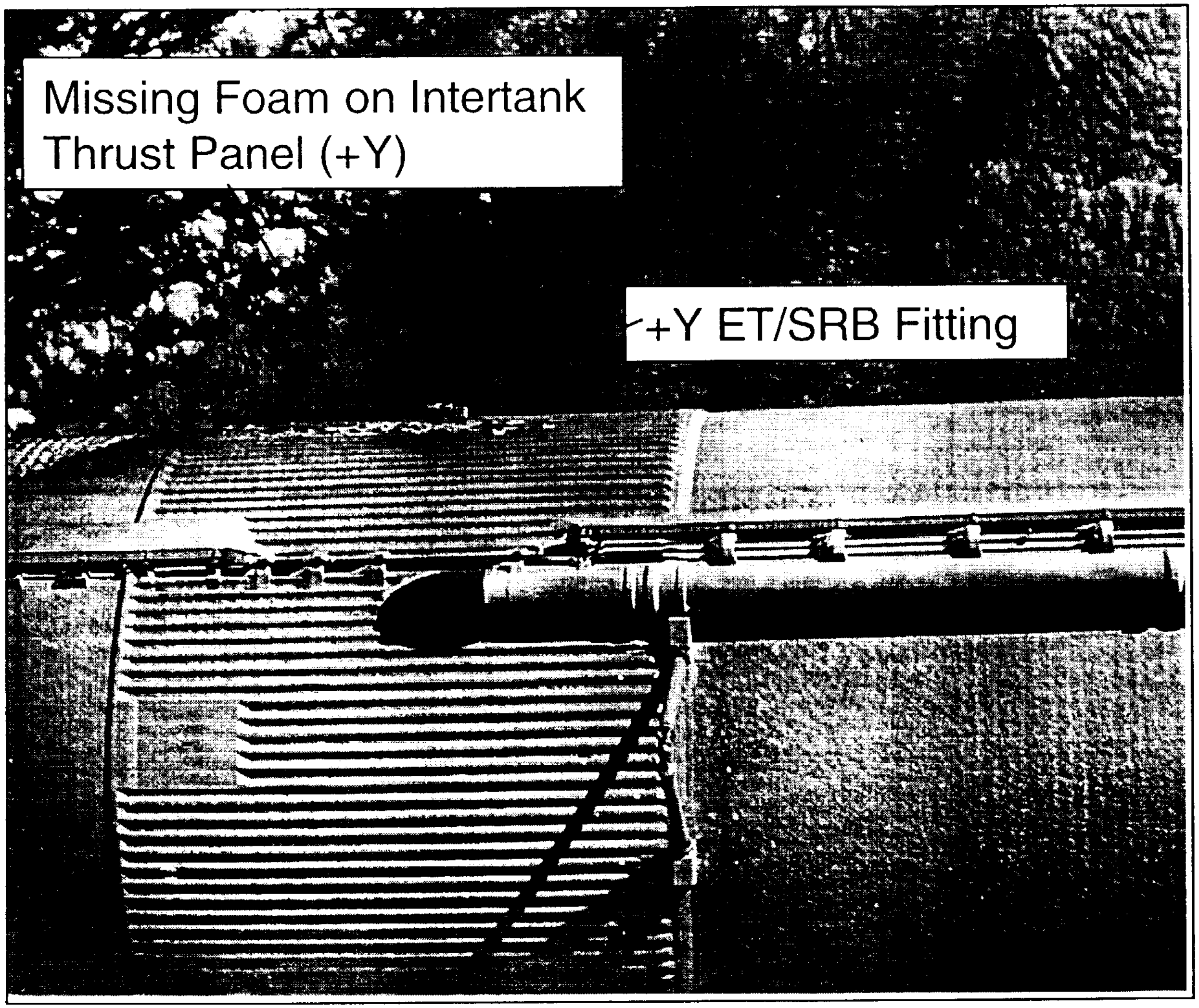
CPR Performance, CFC 11

Lower Surface Damage Sites >1"
- STS-57: 10
- Average: 13

STS-87/ET-89 Post Separation Photo

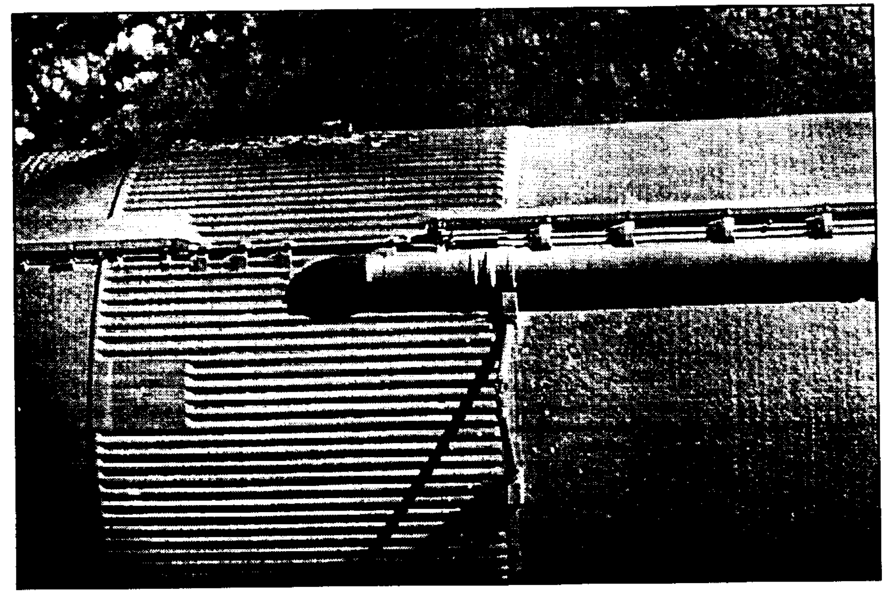


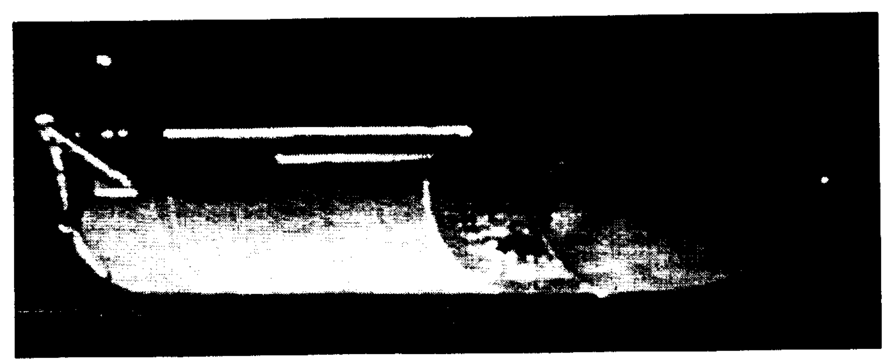
STS-87/ET-89 Post



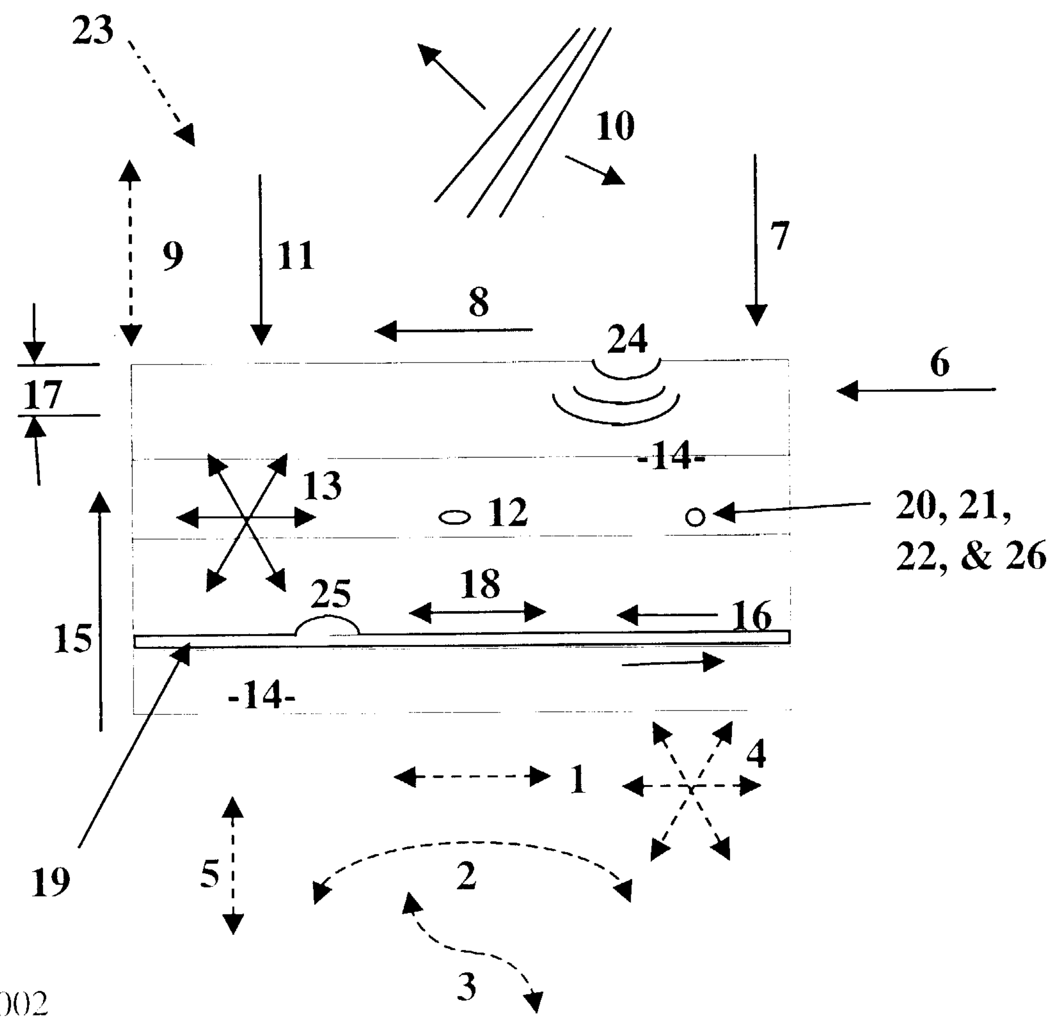
Flight Performance History

- Summary of STS-87/ET-89 Photographic Review
  - Numerous divots visible in the +Y thrust panel forward and aft of the ET/SRB forward attach point





Loads, environments, and other factors affecting foam systems

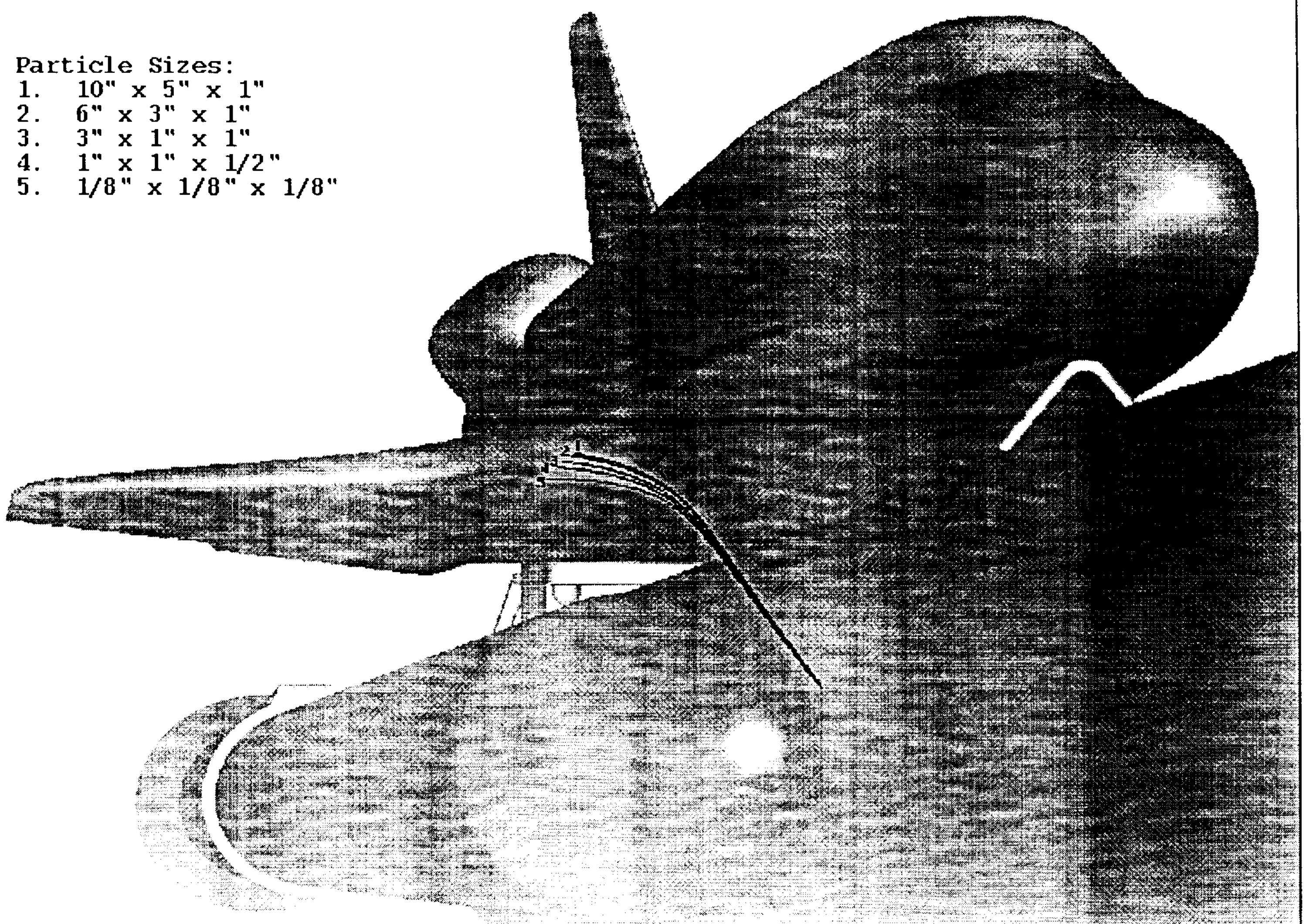


1 - Substrate strain
2 - Substrate bending
3 - Substrate flexure
4 - Substrate vibration
5 - Pyro shock
6 - Airloads (axial)
7 - Airloads (normal)
8 - Aeroshear
9 - Acoustics
10 - Oscillating shocks
11 - Crush pressure
12 - TPS cell burst pressure
13 - Accelerations
14 - Temperature
15 - Thermal gradient
16 - Differential expansion
17 - TPS recession
18 - Residual stresses
19 - Bondline adhesion
20 - Material cohesion
21 - Aging effects
22 - Humidity effects
23 - UV exposure effects
24 - Mechanical damage effects
25 - Internal voids effects
26 - Non-homogeneous material effects

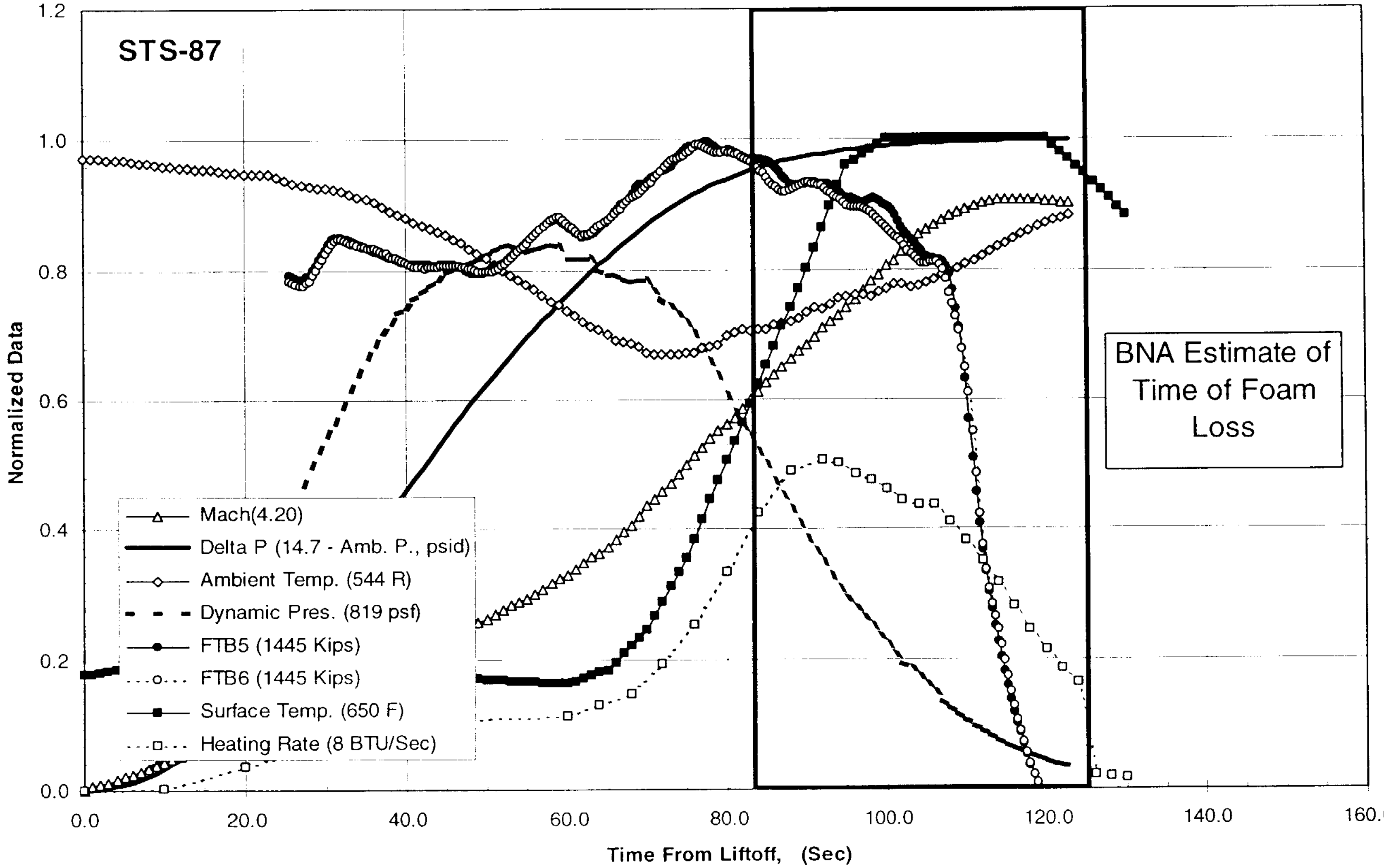
Analysis

EFFECTS OF PARTICLE SIZE ON DEBRIS TRAJECTORIES
NCI 24-124 FOAM, DENSITY 2.3 lb/cu.ft., MACH = 4

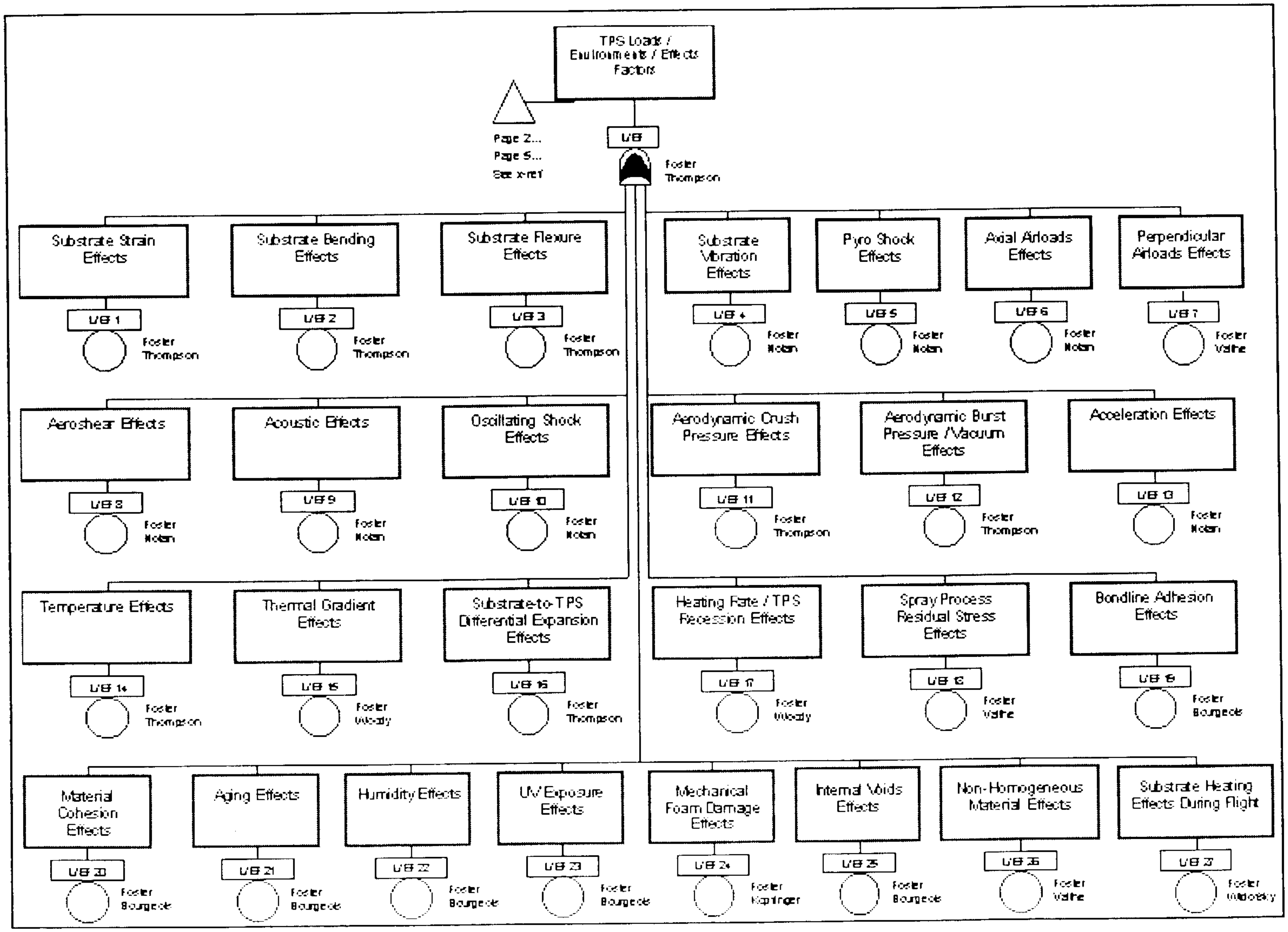
Particle Sizes:
1. 10" x 5" x 1"
2. 6" x 3" x 1"
3. 3" x 1" x 1"
4. 1" x 1" x 1/2"
5. 1/8" x 1/8" x 1/8"



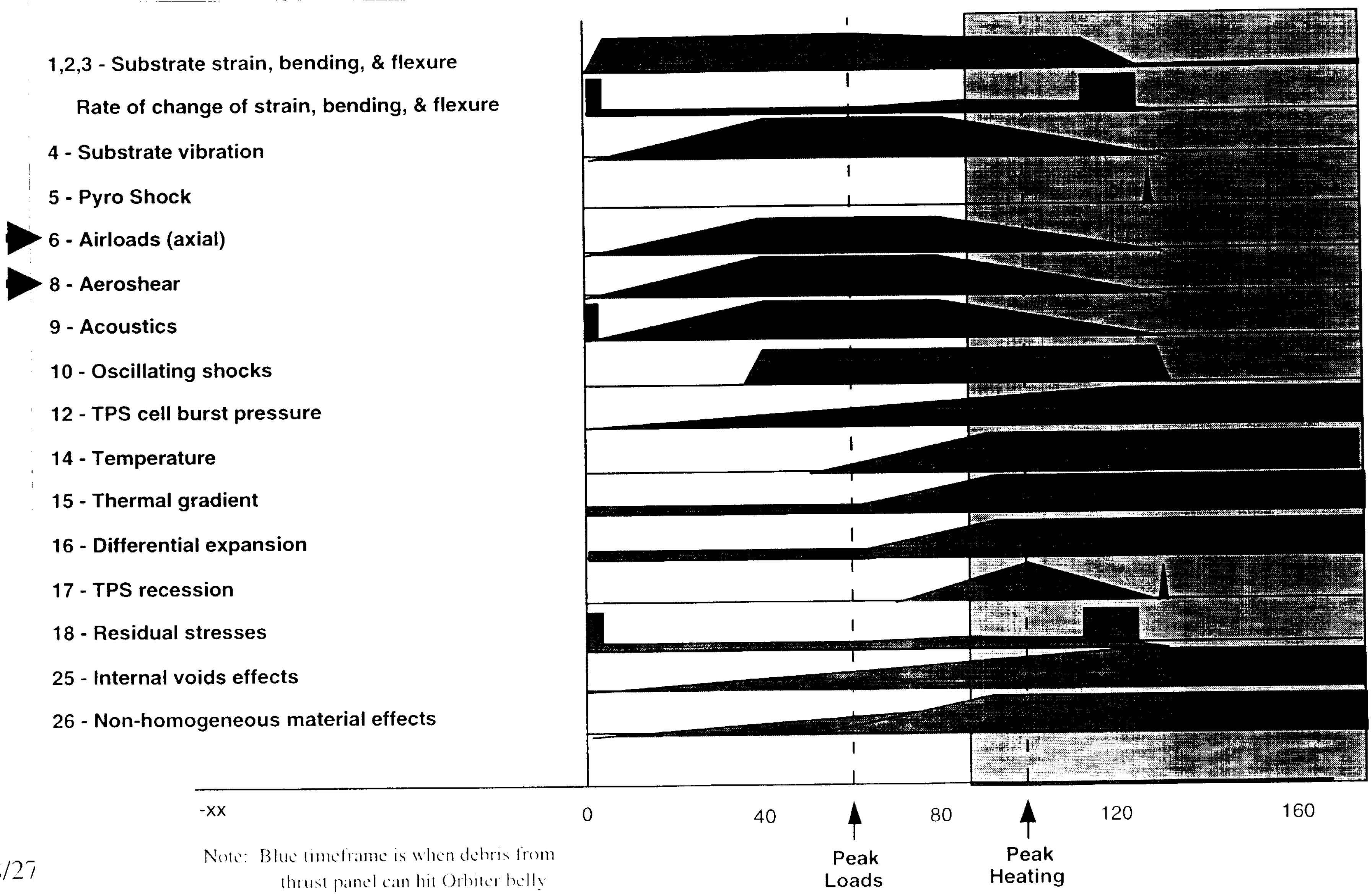
Example of Dynamically Changing Environment



Loads/Environmental Factors



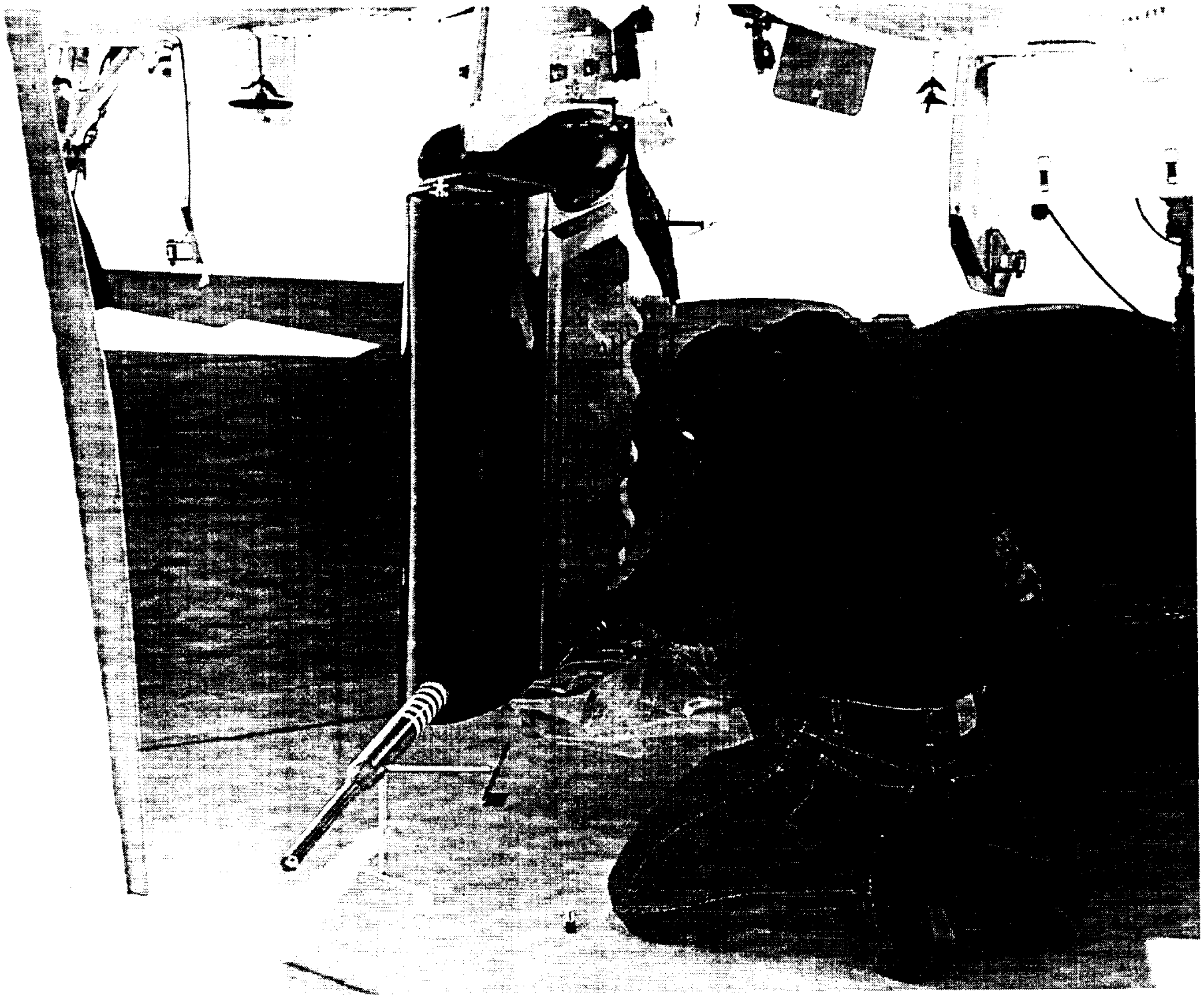
Time phasing of effects



Note: Blue timeframe is when debris from thrust panel can hit Orbiter belly

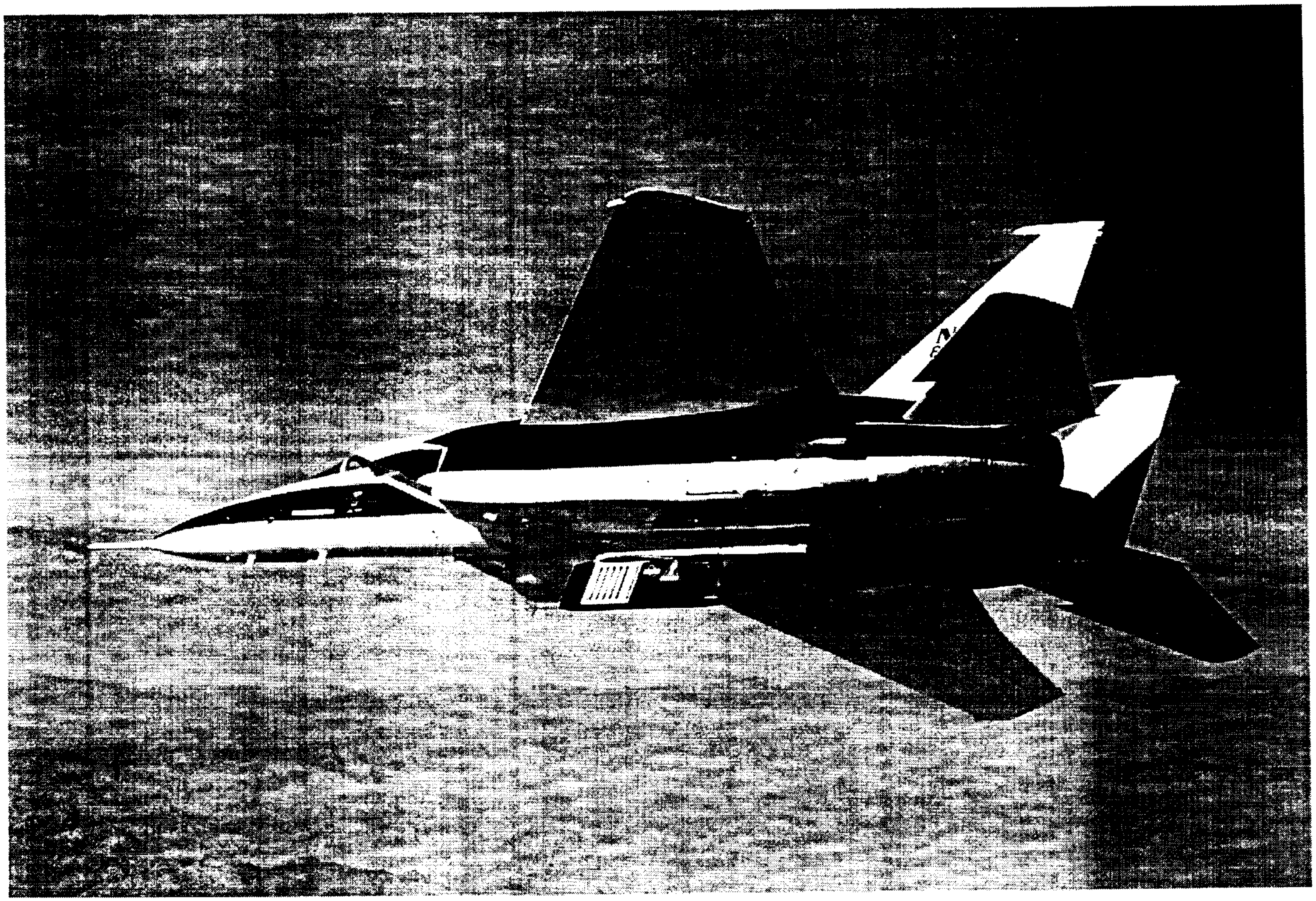
NASA/DFRC F-15B Aerodynamic Test Bed

Test Panel Installation



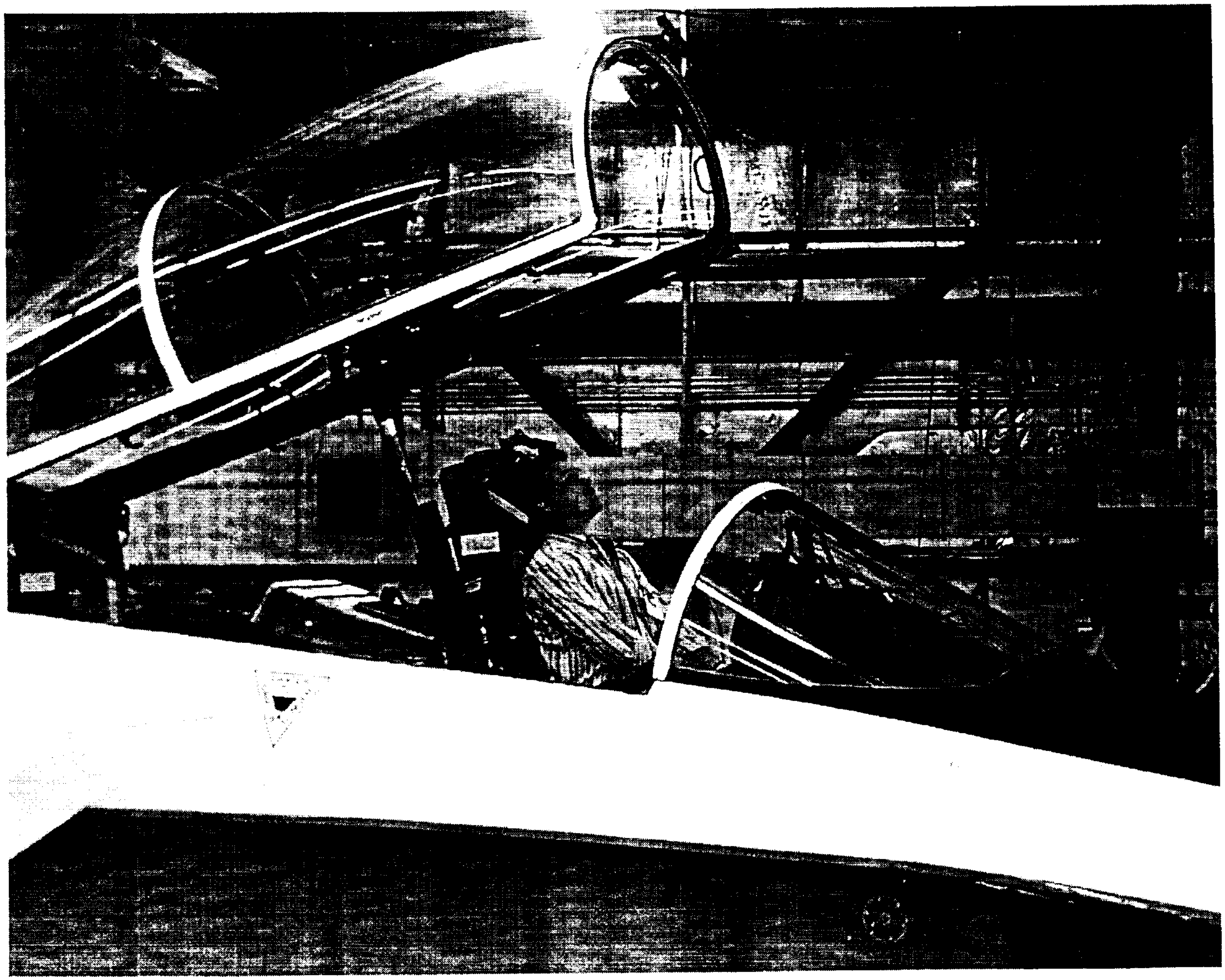
Flight Testing

LOCKHEED MARTIN

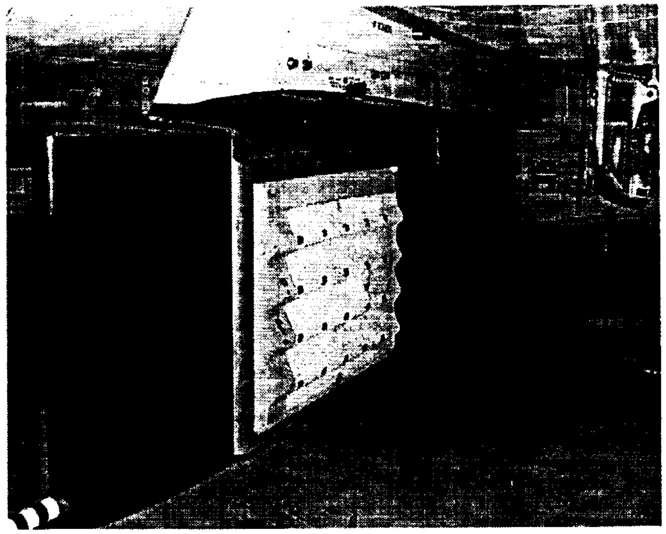


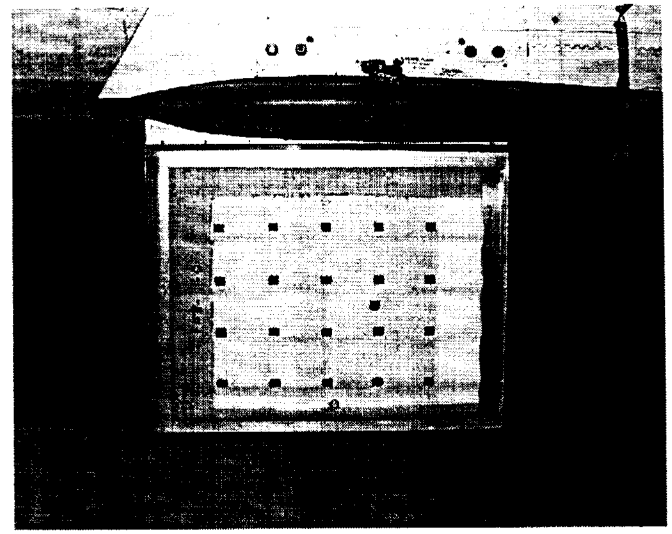
After Hours

LOCKHEED MARTIN

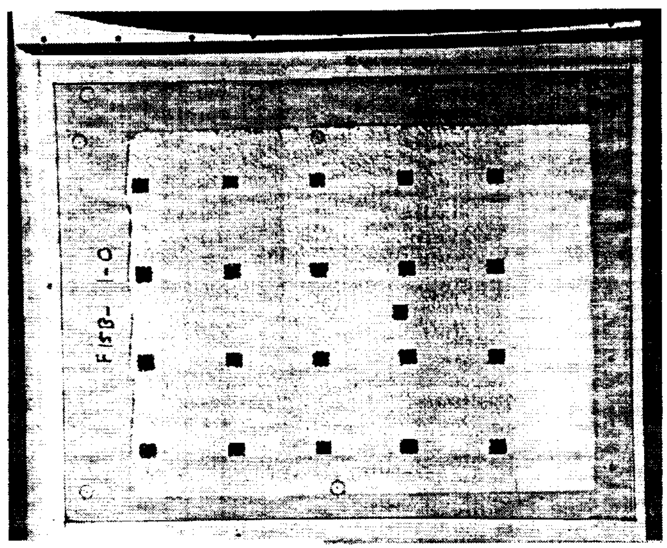


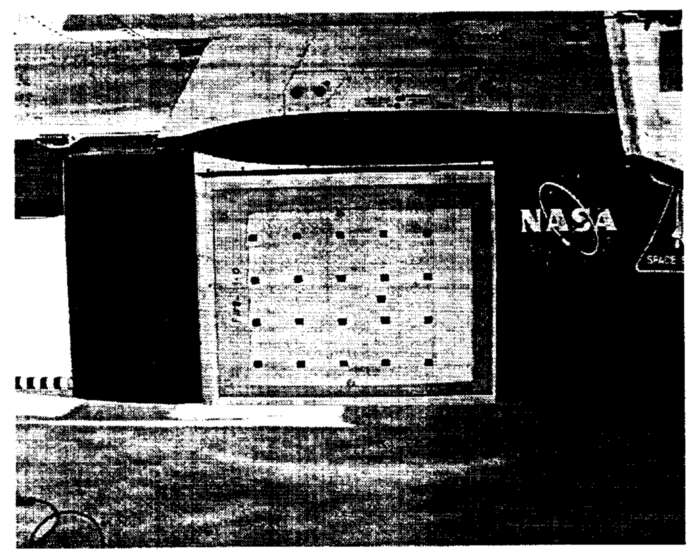
Pre-Test





Post-Test

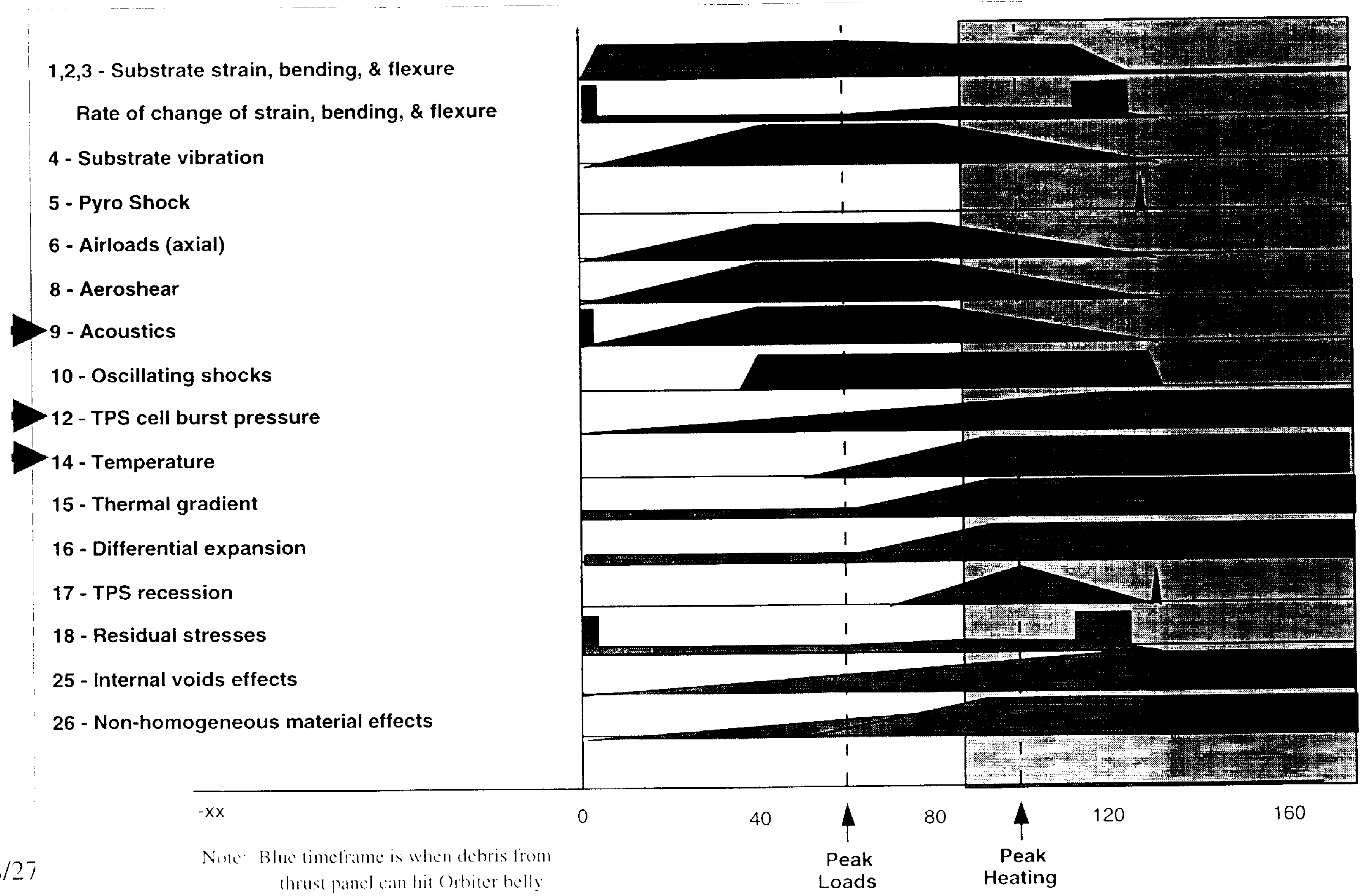




Conclusions From F-15 Testing

- No foam loss observed
- F-15 did not adequately simulate required flight regime

Time phasing of effects



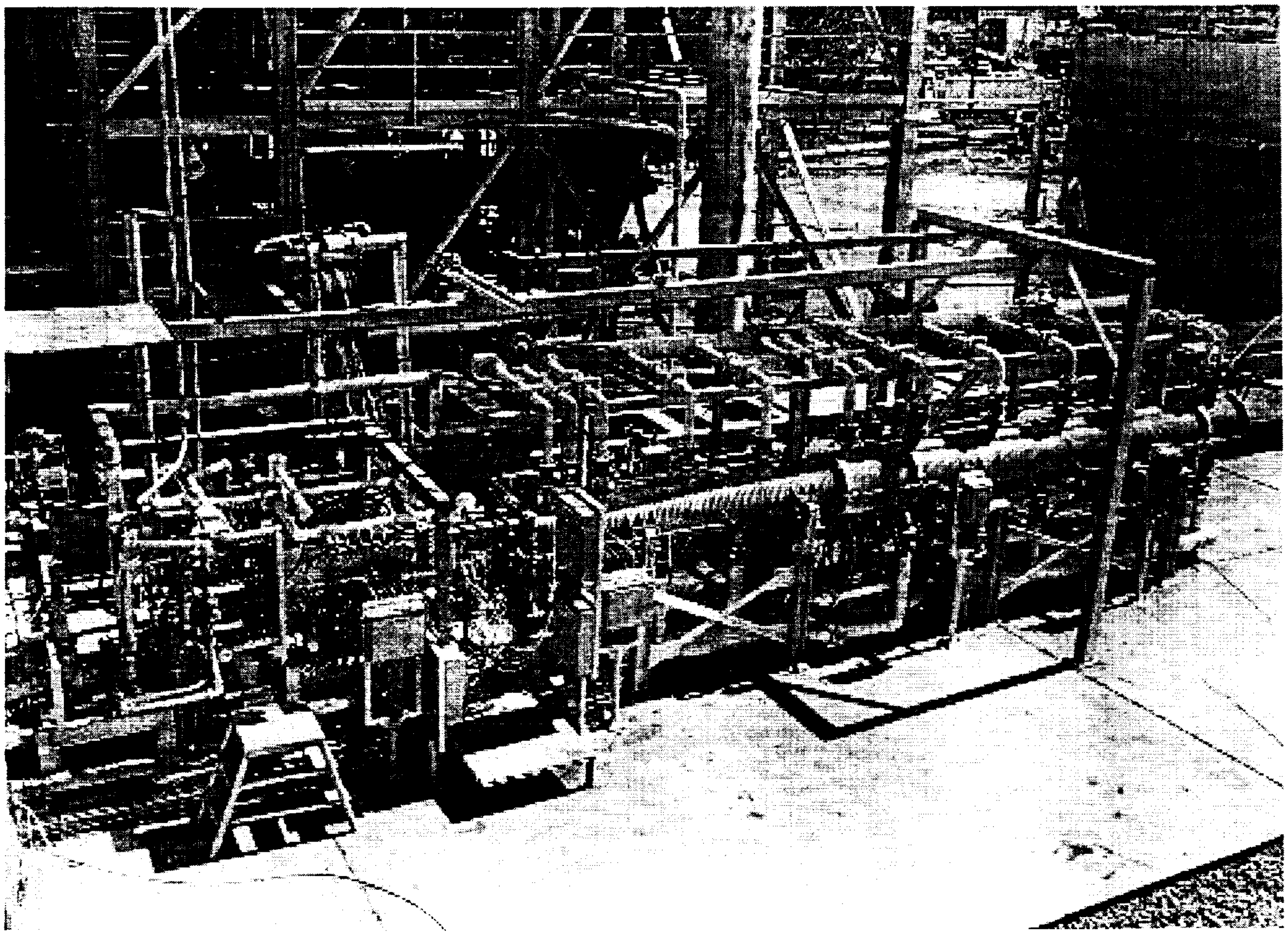
Note: Blue timeframe is when debris from thrust panel can hit Orbiter belly

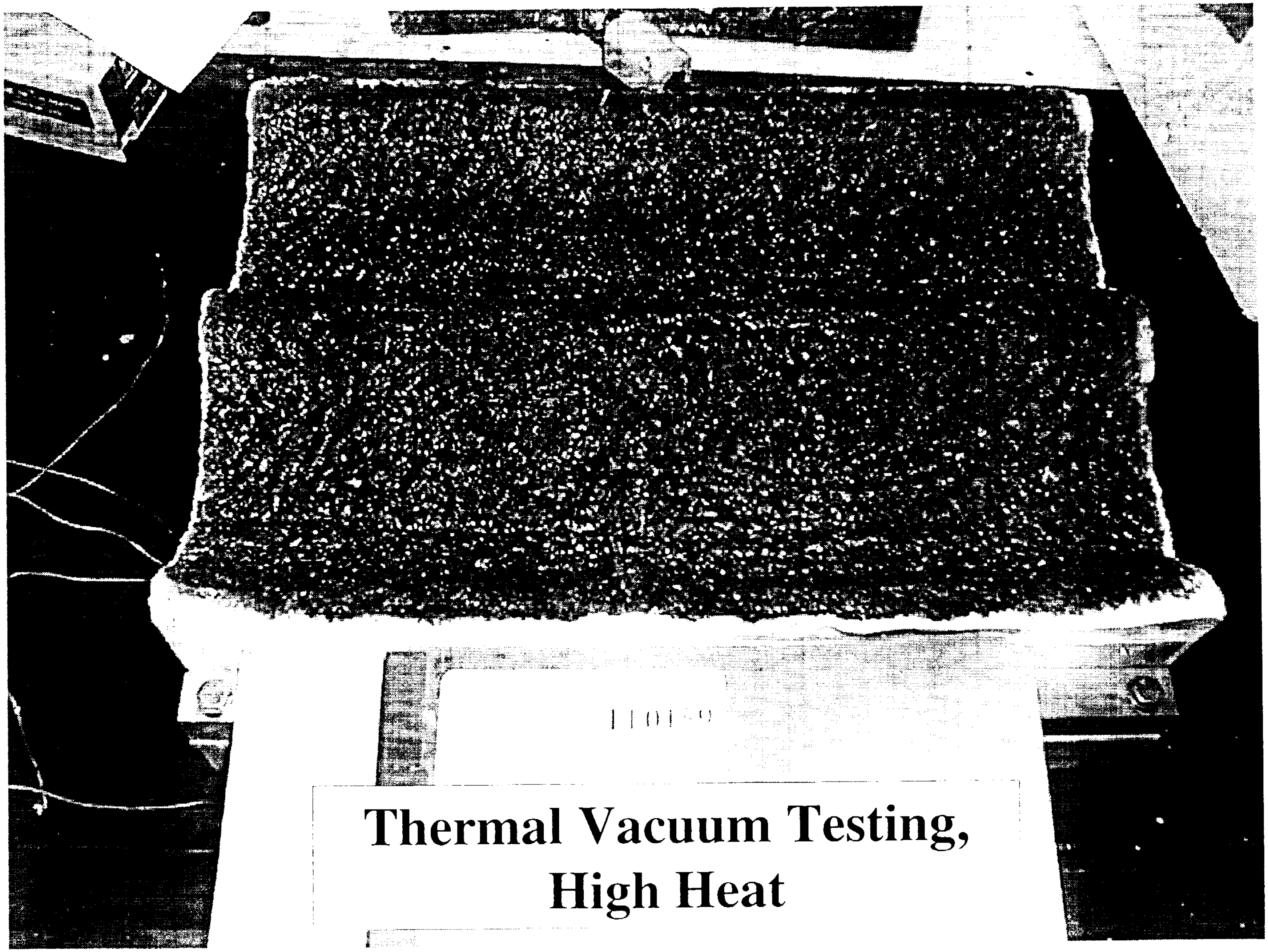
Thermal Vacuum Chamber (TVC) Facility

Test specimen exposure to radiant heat & vacuum conditions

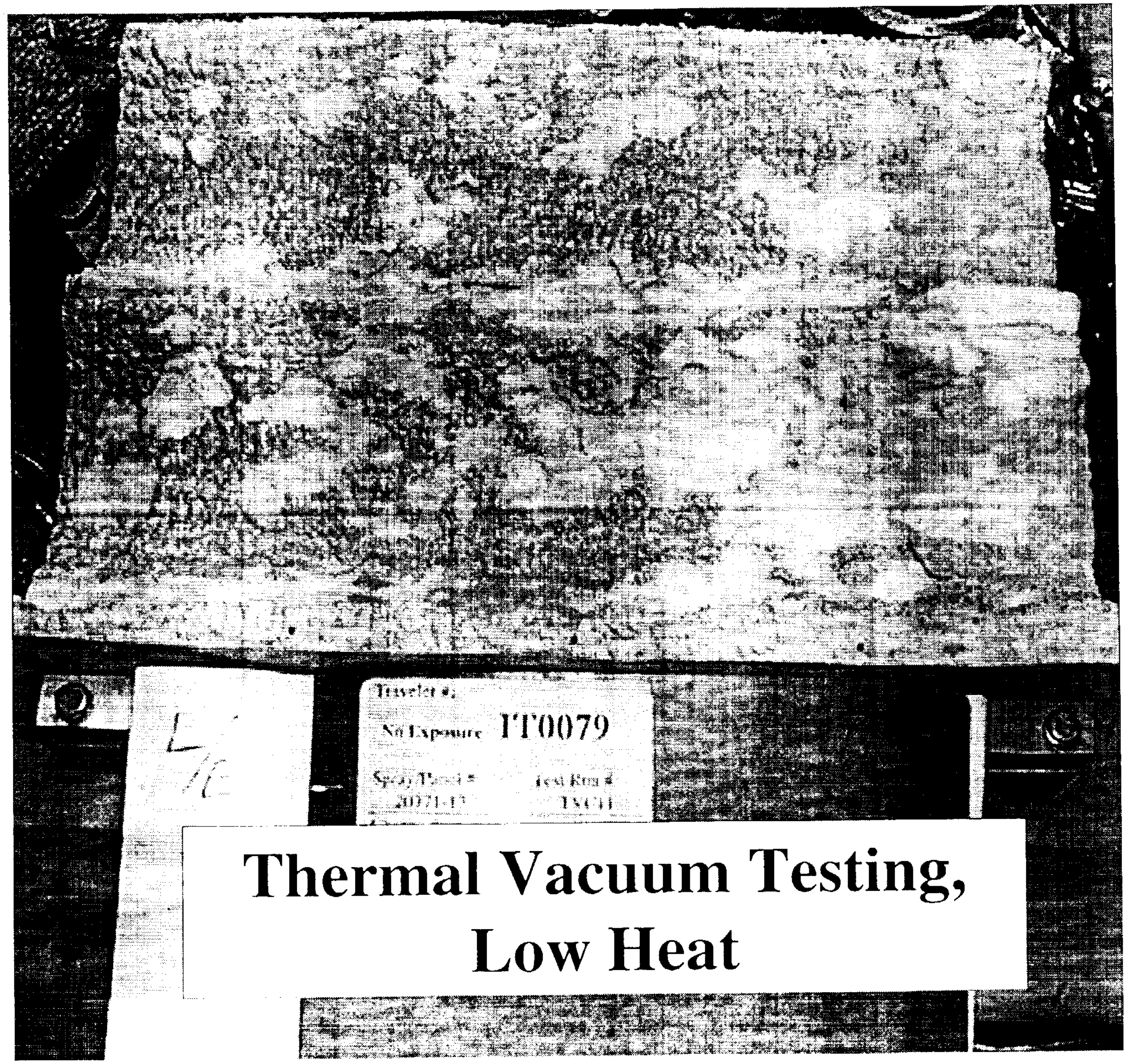
- Up to 20 Btu/ft^2sec specimen exposure condition
- Quartz Lamp Assembly accommodates a specimen exposure area of 12 by 12 inches

Mach 4 Combustion Driven Wind Tunnel



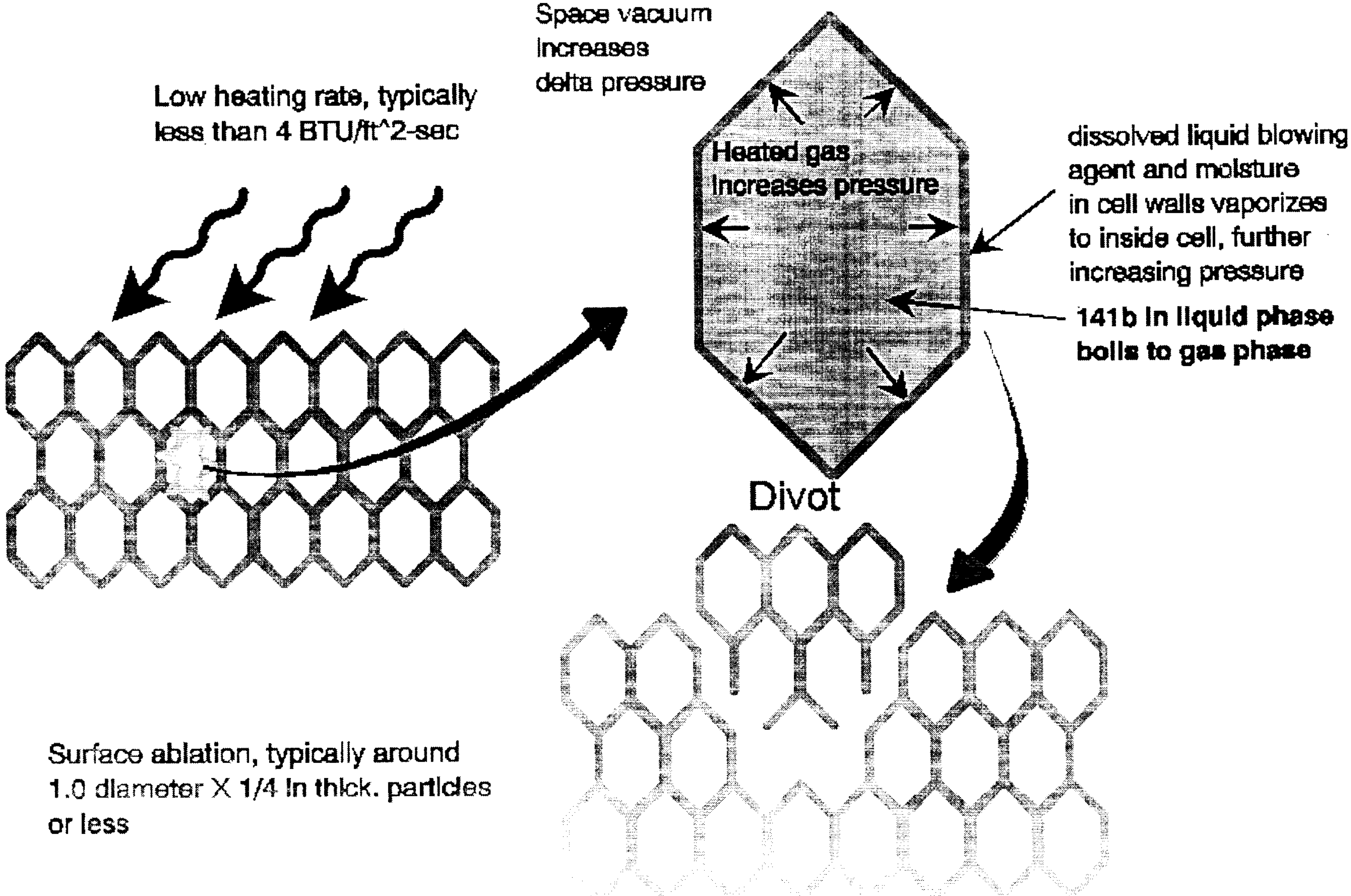


Thermal Vacuum Testing,
High Heat

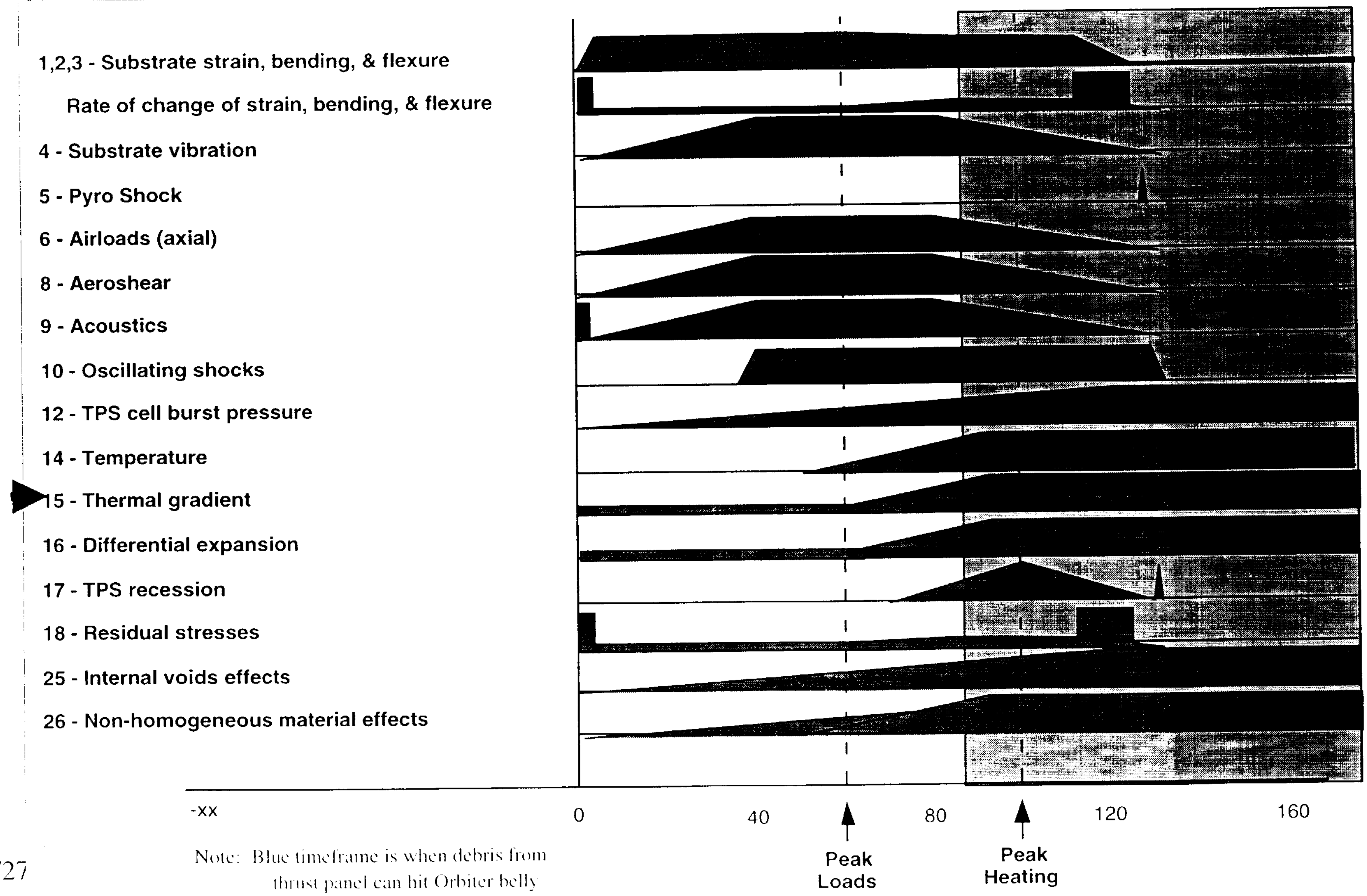


Thermal Vacuum Testing, Low Heat

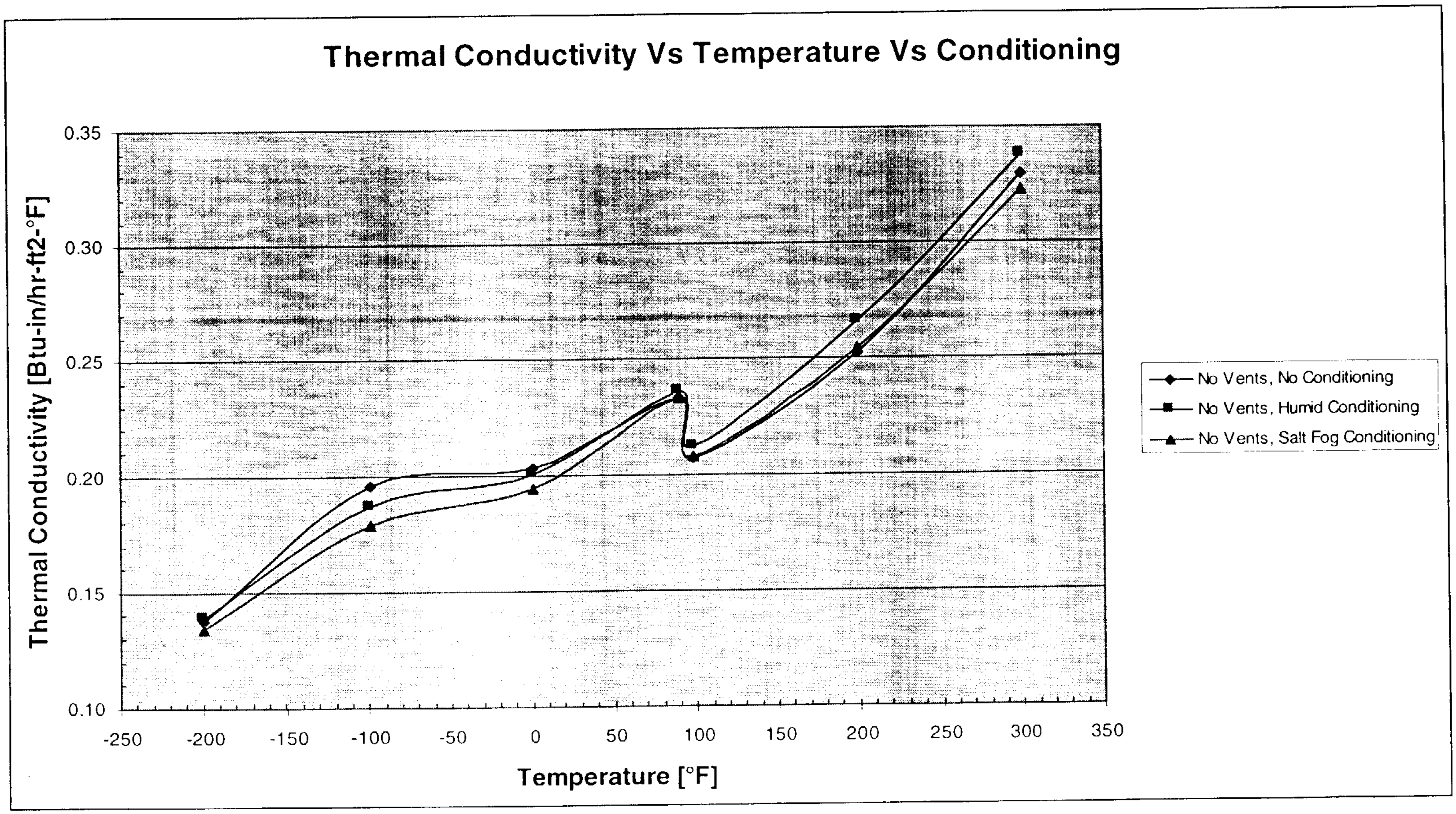
TPS "Popcorning"



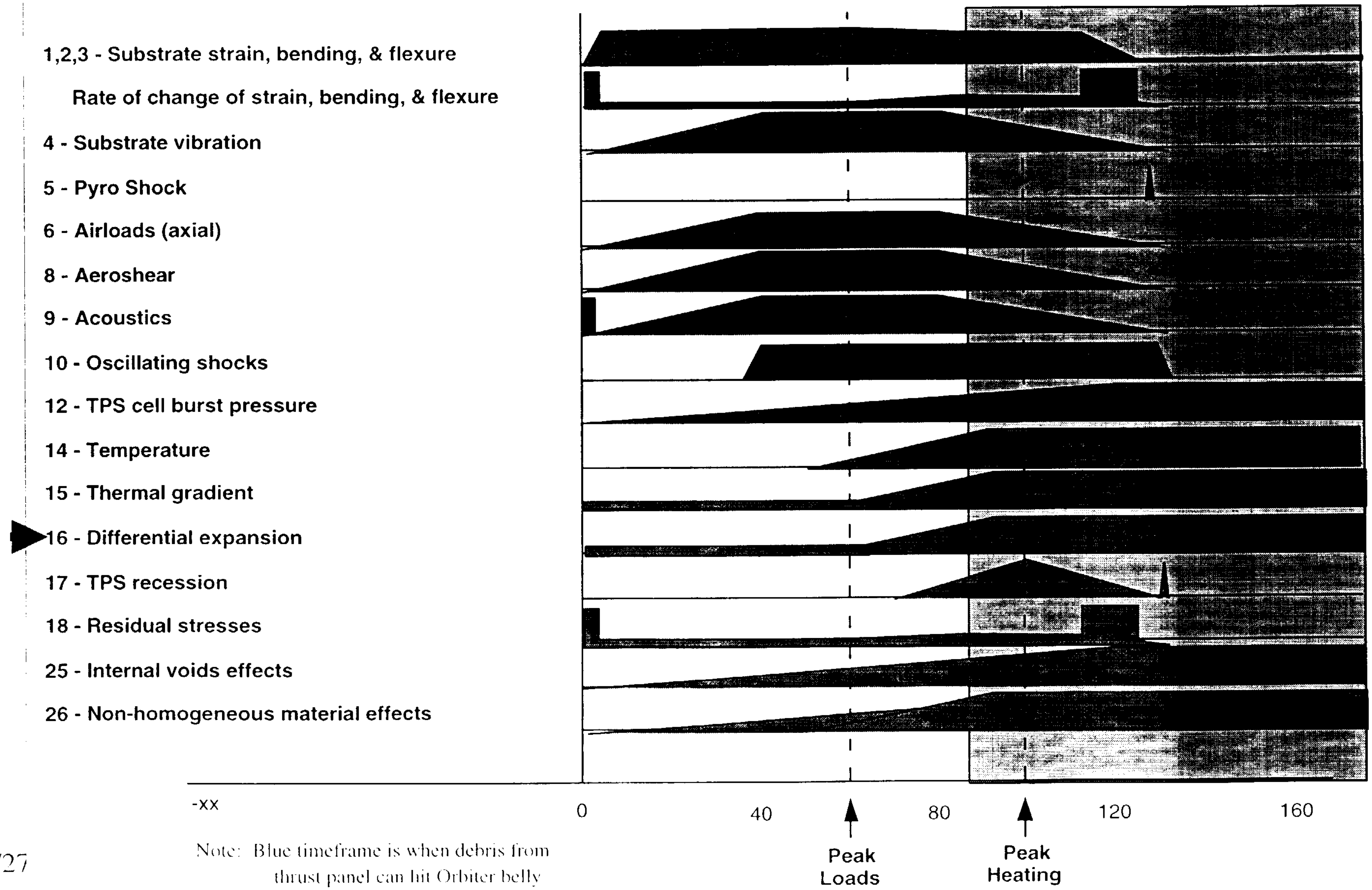
Time phasing of effects



Thermal Properties Testing

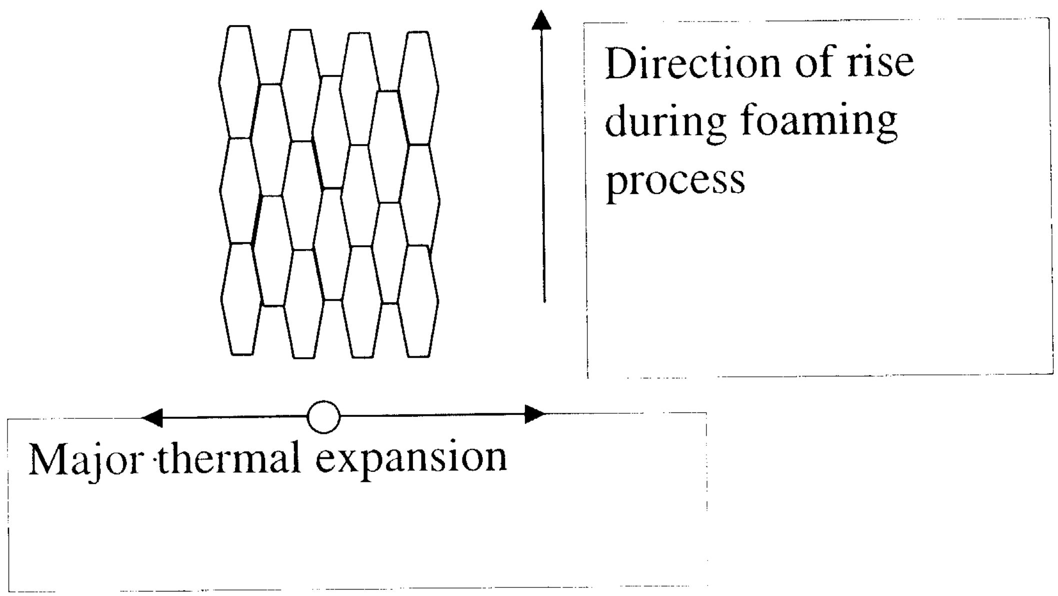


Time phasing of effects



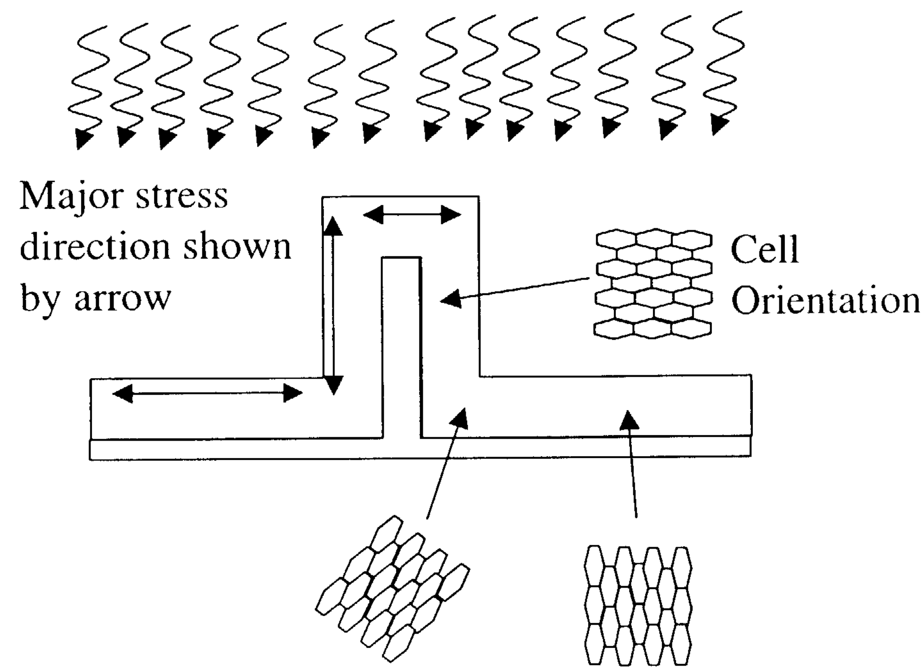
Note: Blue timeframe is when debris from thrust panel can hit Orbiter belly

Differential Thermal Expansion



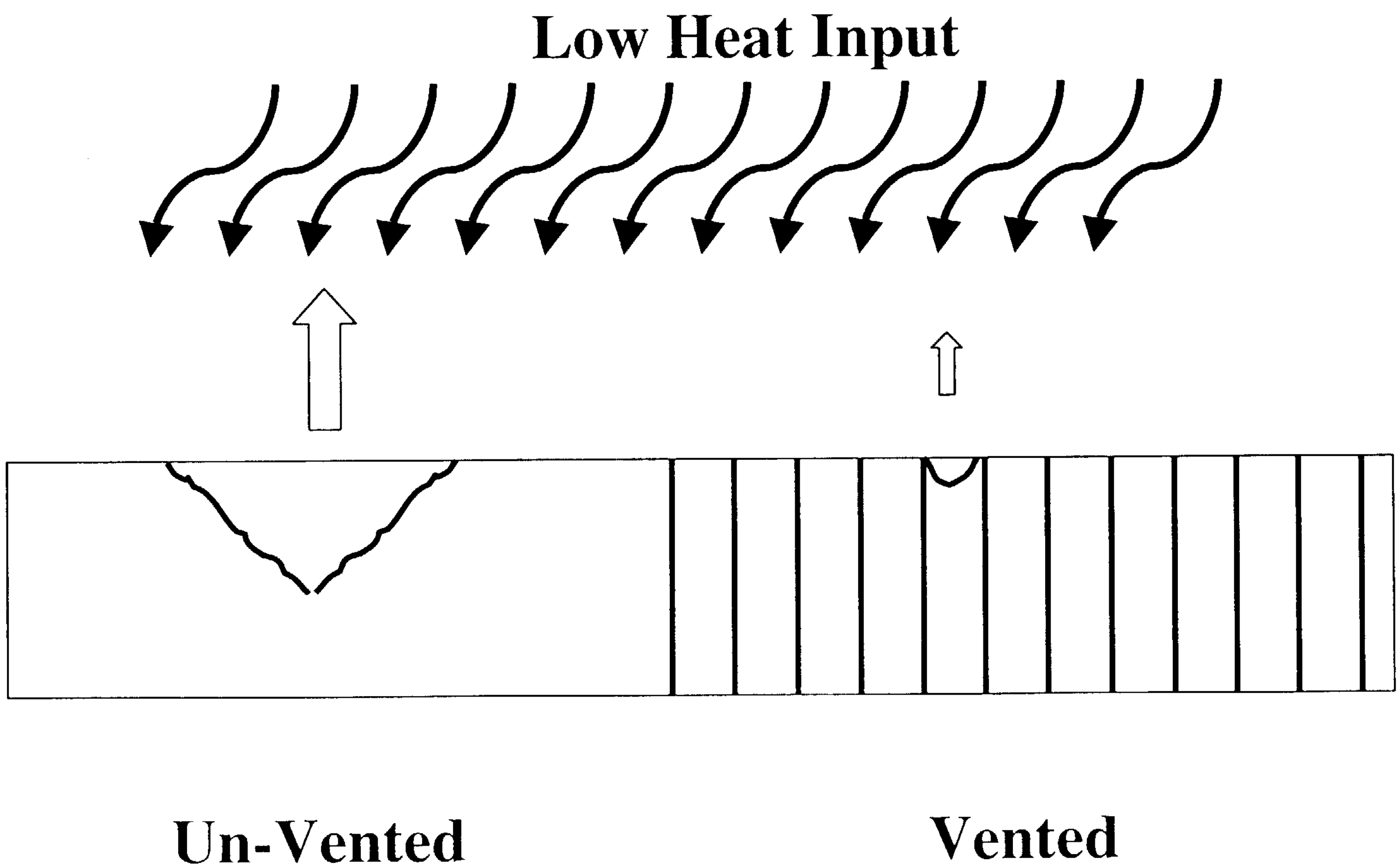
Found that CPR expands in three dimensions while NCFI expands in two dimensions!

Differential Thermal Expansion

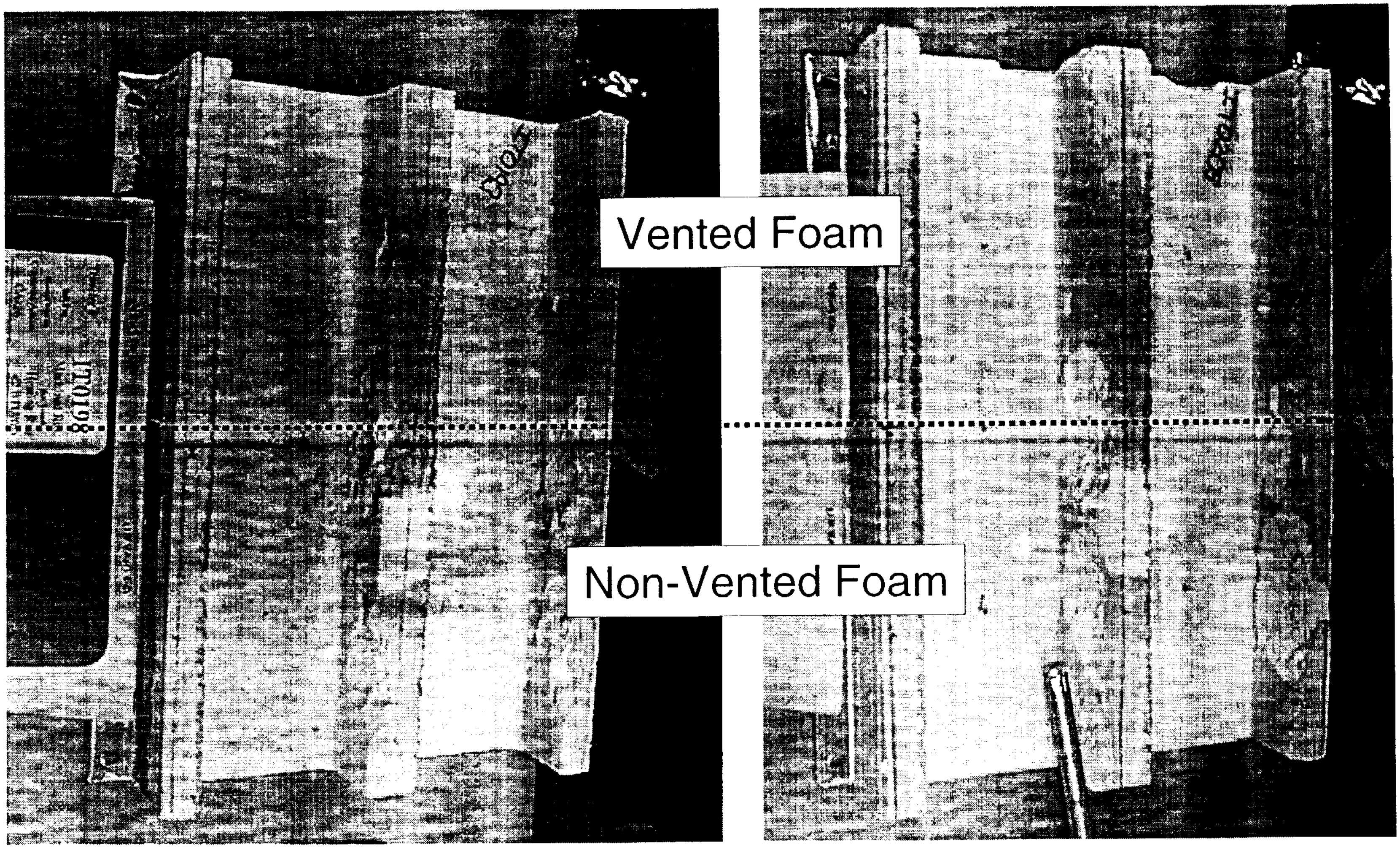


Resolution to Foam Loss Issue:

- **Theory: Venting of foam surface should limit size of divot formation**

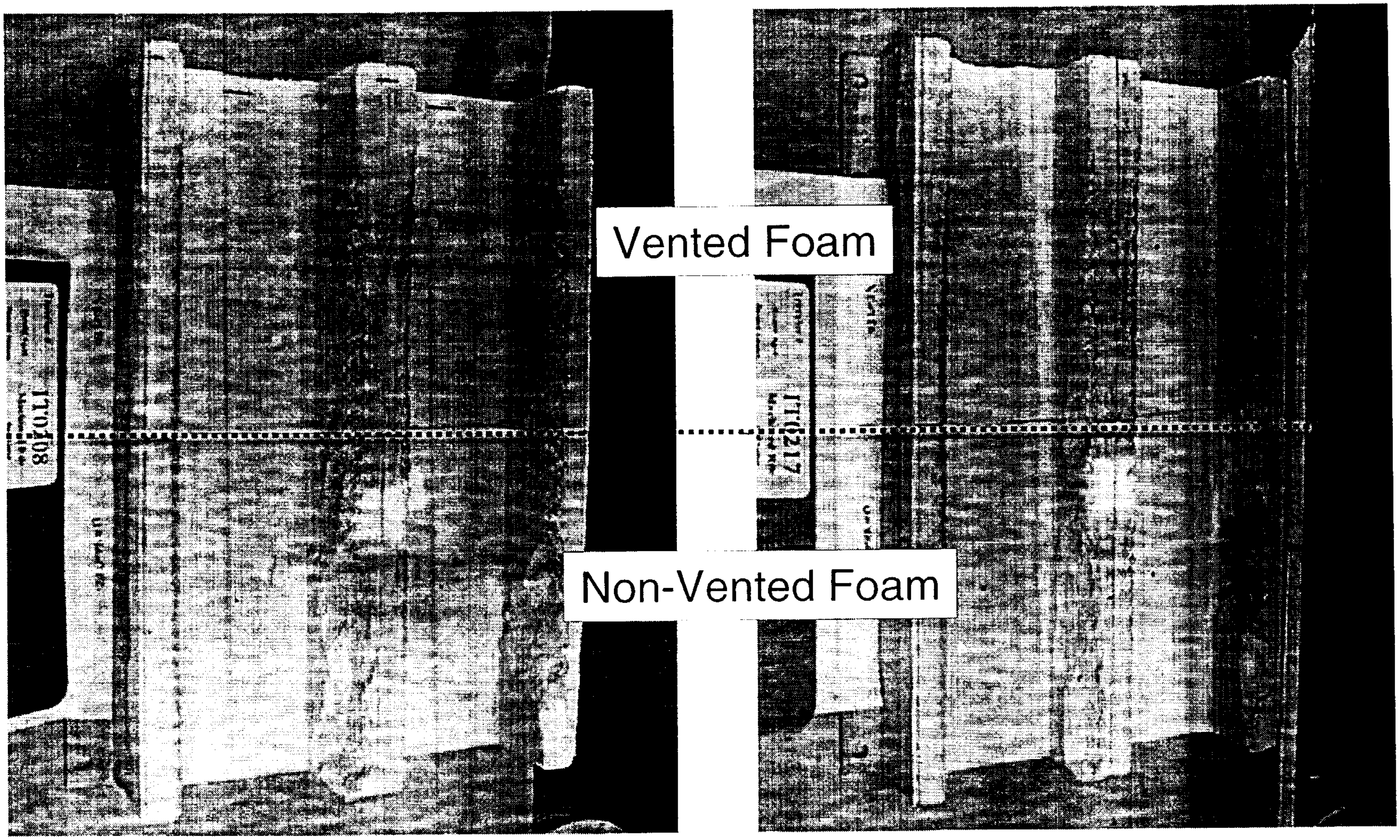


Certification Test Results - Thermal Vacuum



Thermal vacuum tests demonstrated vented foam less susceptible to popcorning

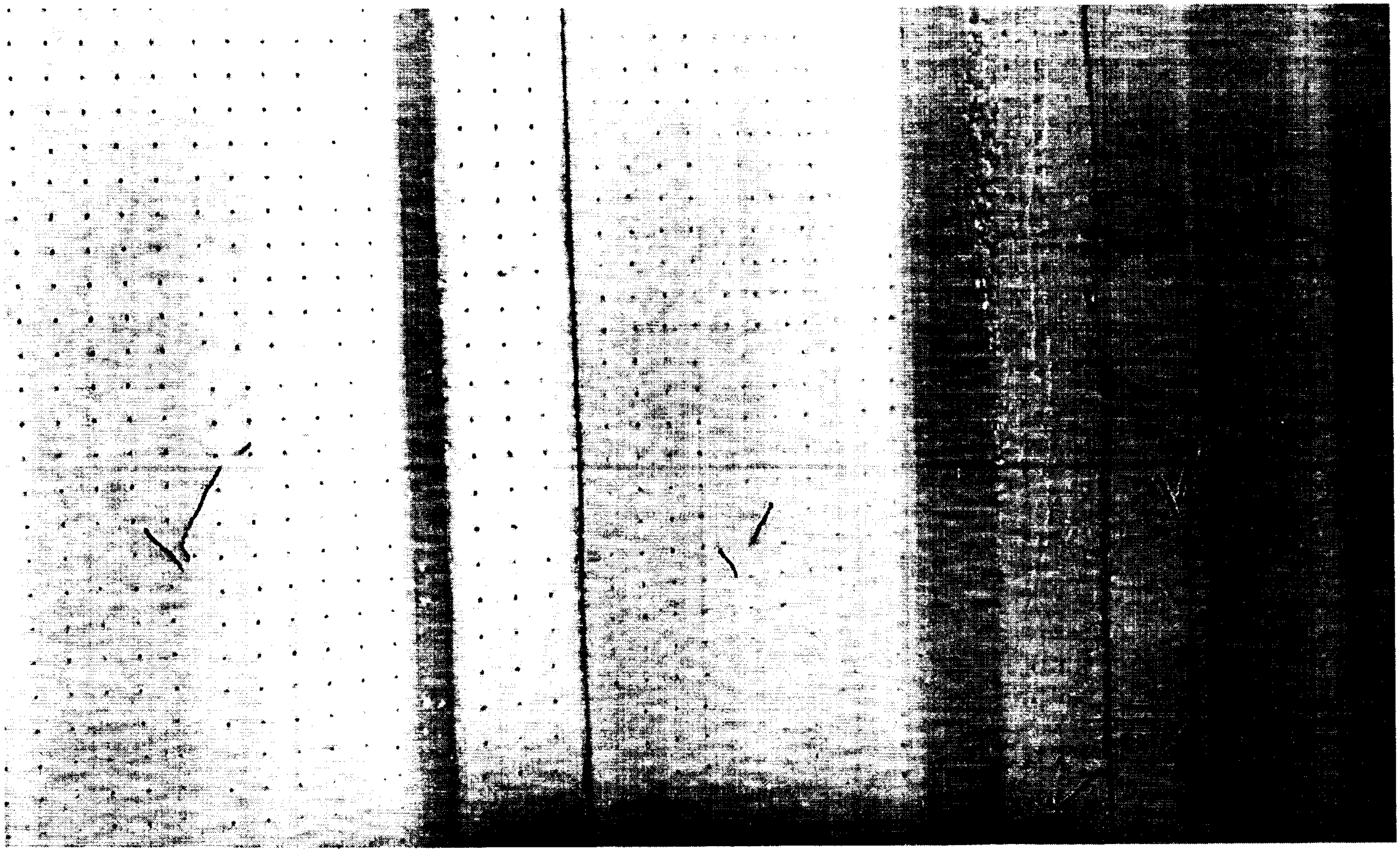
Certification Test Results - Hot Gas



Hot gas tests demonstrated vented foam less susceptible to popcorning

Certification Test

Ground Vibration Test Article Full Scale Venting



Not to Scale

Conclusions

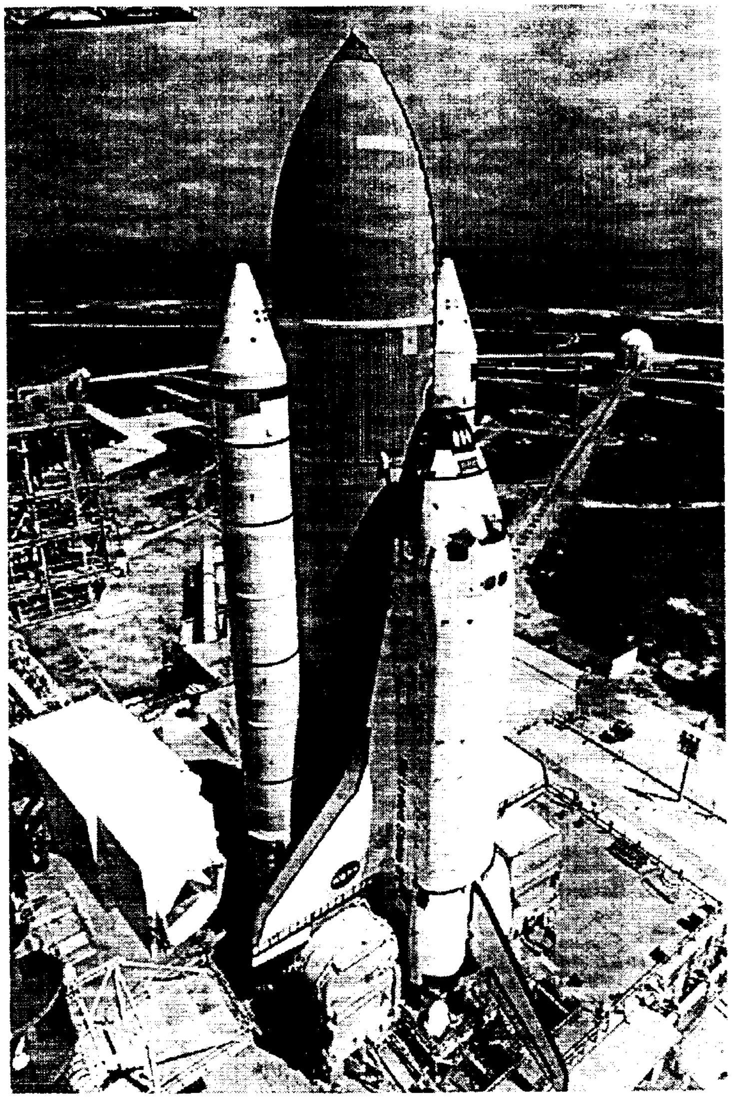
- Certification testing for the "vented" NCFI 24-124 is comprehensive
  - Testing focused on environments that have demonstrated "popcorning"
  - "Vent" holes reduce "popcorning"
  - Test results support "no harm"
  - Structural capability is unchanged
    - No change to substrate temperatures
  - Certification testing will be complete prior to implementation

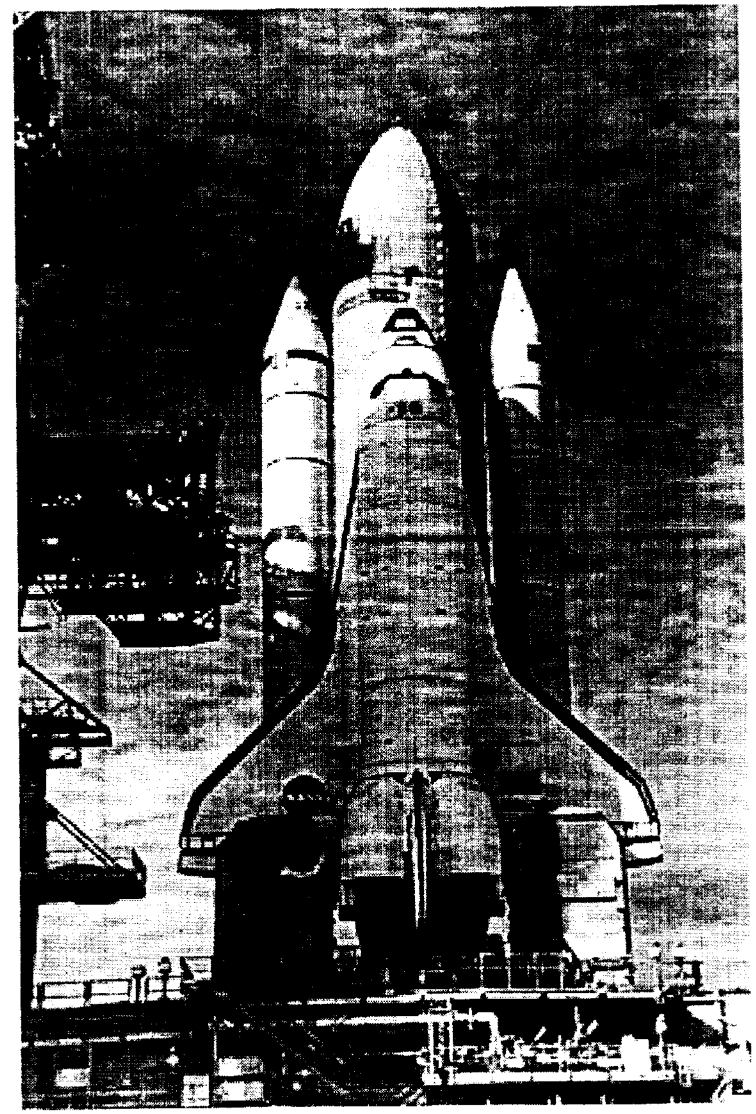
- "Venting" technique demonstrated by production on test article prior to implementation on a flight vehicle

- Recommendation to vent ET-100 (STS-96) Intertank thrust panel

Venting Will Provide Reduced "Popcorning" with No Additional Risk

SRB Camera Installation





NCFI Performance

STS-90 Orbiter Lower Surface Tile Damage

Lower Surface Damage Sites >1"
- STS-90: 11
- Average: 13

Lessons Learned

- Blowing agent replacement in response to EPA regulations has been much more difficult than anticipated
  - Space program requirements are more unique than either ET or EPA realized
  - It is not possible to simulate everything in the labs
  - Materials changes require personnel training and may have unanticipated impacts on manufacturing processes as well as tooling and delivery systems during implementation
  - Need to allow ample time for development, validation, implementation, and contingencies
- Communication with EPA is essential
  - Need to work closely with EPA to keep them informed about progress and development
    - EPA cannot keep up with everyone without help. They will think all is well, replacements are available, and pass regulations you may not like.
    - Formal comments on proposed rules are essential; you must be in the docket
  - Do not underestimate the business value of environmental compliance and stewardship; this opens the door for negotiations

Future Challenges

- Currently testing a new product that does not require venting

- HCFC 141b production ends as of 1/1/2003
  - Anticipate space vehicle exemption provision in upcoming HCFC Allowance Rule that will allow continued production for Shuttle until 2010
  - Must find/develop replacement foams with alternate blowing agents
  - No obvious candidates have emerged in spite of considerable testing