An Overview of Spray-On Foam Insulation Applications on the Space Shuttle's External Tank: Foam Applications and Foam Shedding Mechanisms

Roy M. Sullivan* ‡
Research Engineer

Bradley A. Lerch*
Research Engineer

Patrick R. Rogers†
Aerospace Engineer

Jeffery S. Sparks†
Materials Engineer

The Columbia Accident Investigation Board (CAIB) concluded that the cause of the tragic loss of the Space Shuttle Columbia and its crew was a breach in the thermal protection system on the leading edge of the left wing. The breach was initiated by a piece of insulating foam that separated from the left bipod ramp of the External Tank and struck the wing in the vicinity of the lower half of Reinforced Carbon-Carbon panel No. 8 at 81.9 seconds after launch. The CAIB conclusion has spawned numerous studies to identify the cause of and factors influencing foam shedding and foam debris liberation from the External Tank during ascent.

The symposium on the Thermo-mechanics and Fracture of Space Shuttle External Tank Spray-On Foam Insulation is a collection of presentations that discuss the physics and mechanics of the ET SOFI with the objective of improving analytical and numerical methods for predicting foam thermo-mechanical and fracture behavior. This keynote presentation sets the stage for the presentations contained in this symposium by introducing the audience to the various types of SOFI applications on the Shuttle's External Tank and by discussing the various mechanisms that are believed to be the cause of foam shedding during the Shuttle's ascent to space.

*Mechanics and Lifing Branch, NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH 44135

†NASA Marshall Space Flight Center, Marshall Space Flight Center, AL 35812

‡Corresponding Author; Contact Email: Roy.M.Sullivan@nasa.gov

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Roy M. Sullivan and Bradley A. Lerch
NASA Glenn Research Center

Patrick R. Rogers and Jeffery S. Sparks
NASA Marshall Space Flight Center

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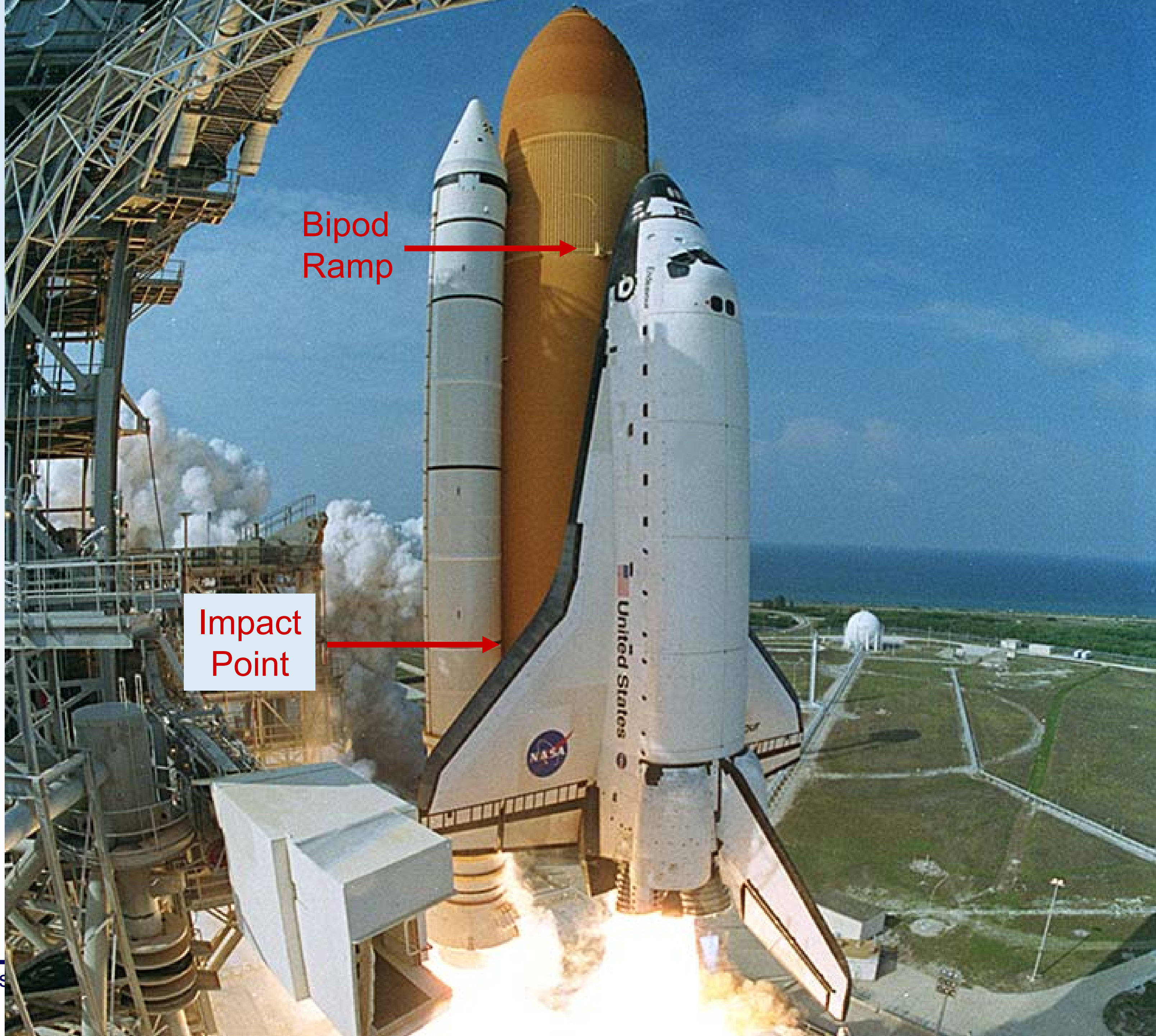
The Columbia Accident Investigation Board (CAIB) found that ……

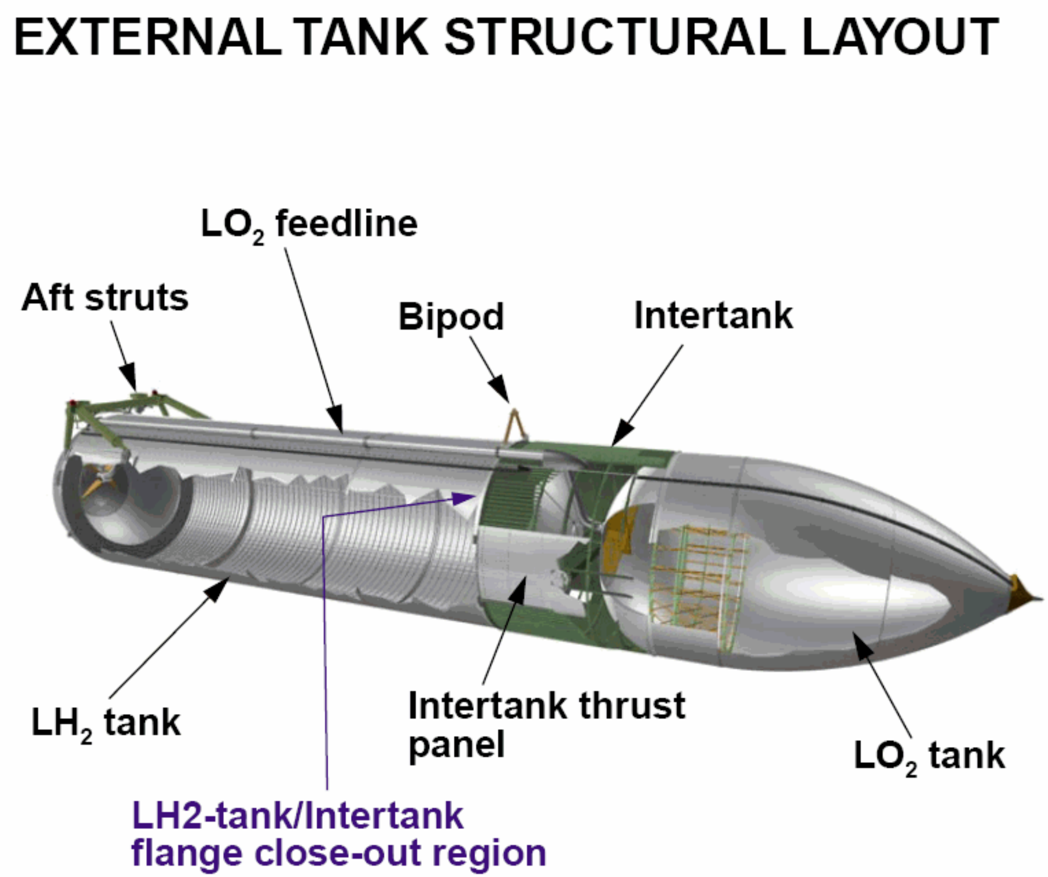
"the cause of the loss of Columbia and its crew was a breach in the Thermal Protection System on the leading edge of the left wing. The breach was initiated by a piece of insulating foam that separated from the left bipod ramp of the External Tank and struck the wing in the vicinity of the lower half of Reinforced Carbon-Carbon panel #8 at 81.9 seconds after launch."


Bipod Ramp
Impact Point
United States

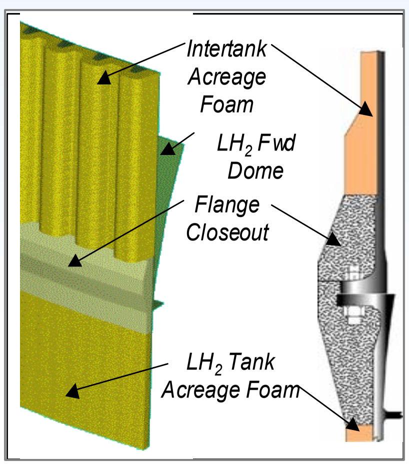
Post-Mission Testing Confirmed the Potential for Damage to Reinforced Carbon-Carbon Wing Leading Edge from Foam Impacts

The Space Shuttle’s External Tank

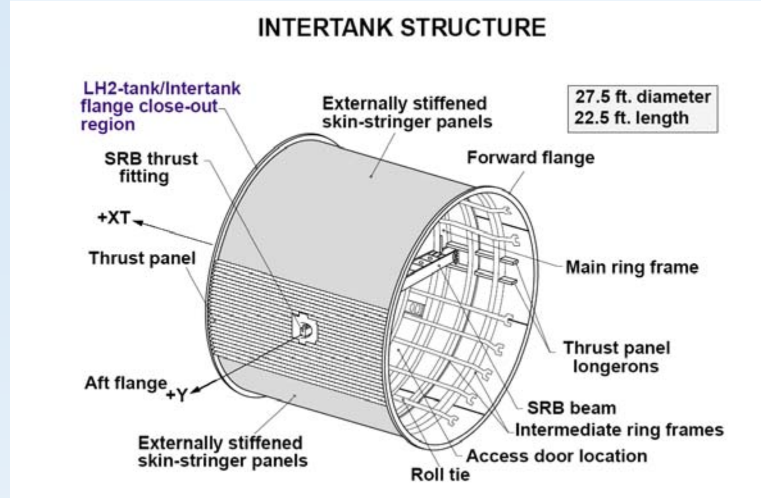
- Length: 154 ft
- Diameter: 27.6 ft
- Gross weight: 1,674,000 lbs.
- Empty weight: 58,000 lbs.
- Contains 526,000 gallons of liquid hydrogen and oxygen
- Average thickness of metallic tank wall: 1/8 inch
- Average thickness of foam insulation: 1.0 inch



LH2 tank during fab



LH2/Intertank Flange



LOx tank

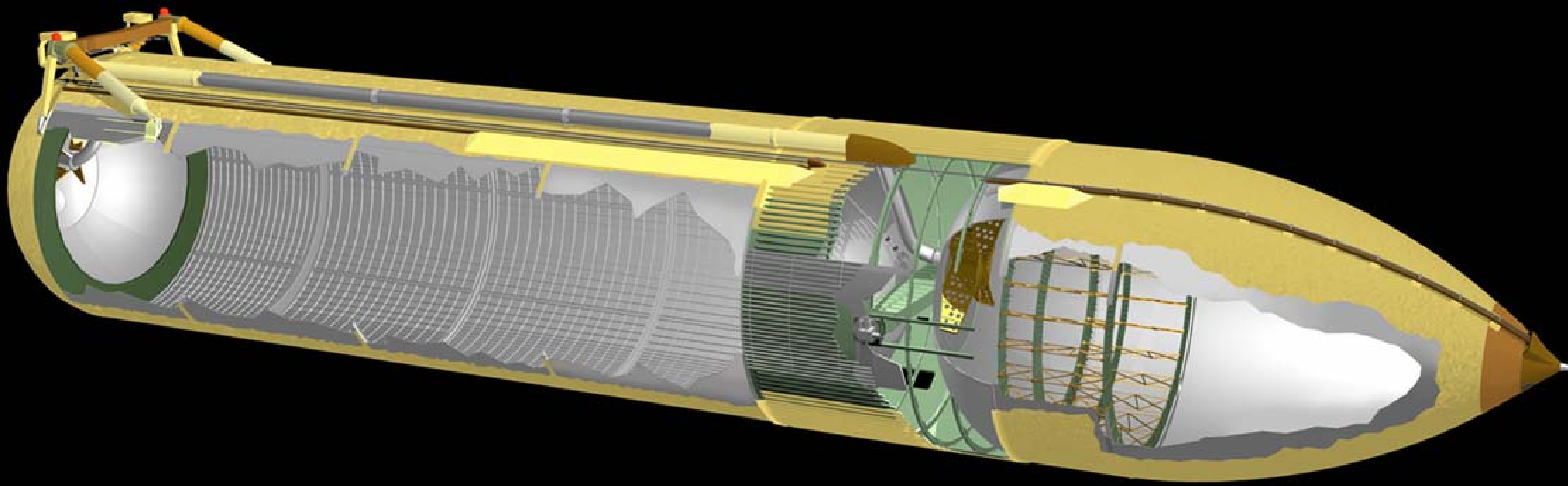
Forward SRB interface

Aft end of tank showing SRB attachment fittings

Orbiter interface (fwd)

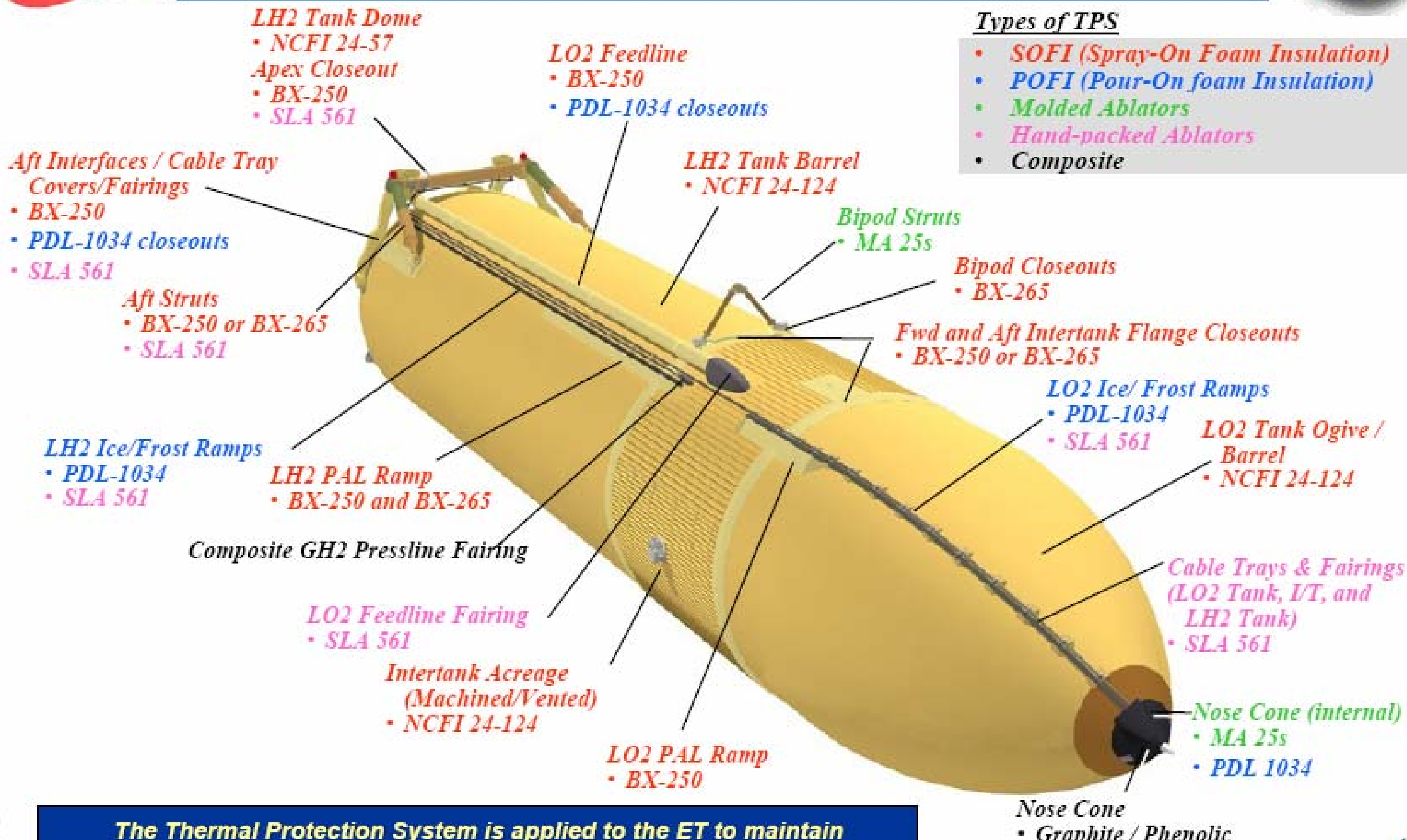
Orbiter interface (aft)

External Tank Spray-On Foam Insulation



External Tank's Spray On Foam Insulation (SOFI) is applied to maintain cryogenic propellant quality, minimize ice/frost formation, and protect the structure from ascent, plume and reentry heating.

Thermal Protection System Overview



The Thermal Protection System is applied to the ET to maintain cryogenic propellant quality, minimize ice/frost formation, and protect the structure from ascent, plume, and re-entry heating

3-2

The information contained in this briefing is should be considered as 'preliminary' and subject to ITAR control

Mission Support_RTF_FCB_March2004

External Tank Spray-On Foam Insulation (SOFI)

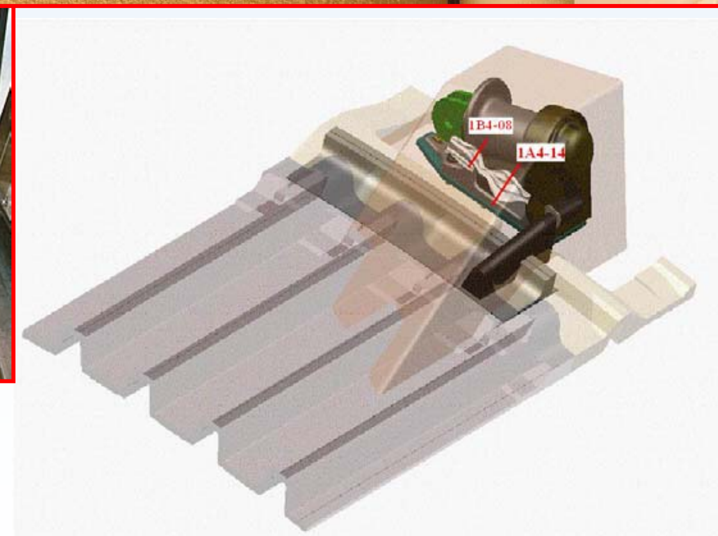
Acreage Foam

- Automated spray
- NCFI24-124 (Polyisocyanurate)

Manual Close-outs

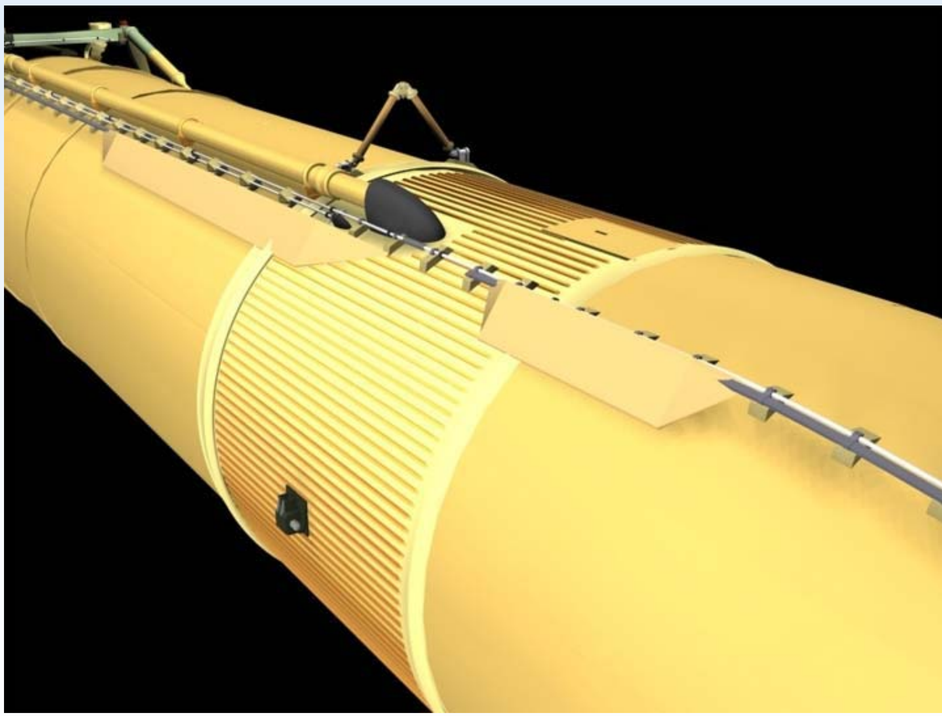
- Sprayed or molded around fittings/flanges where automated spraying is not possible.
- Manual Sprayed Close-outs: BX-265 (Polyurethane)
- Molded Close-outs: PDL-1034 (Polyurethane)

Bipod Fitting and Ramp Closeout



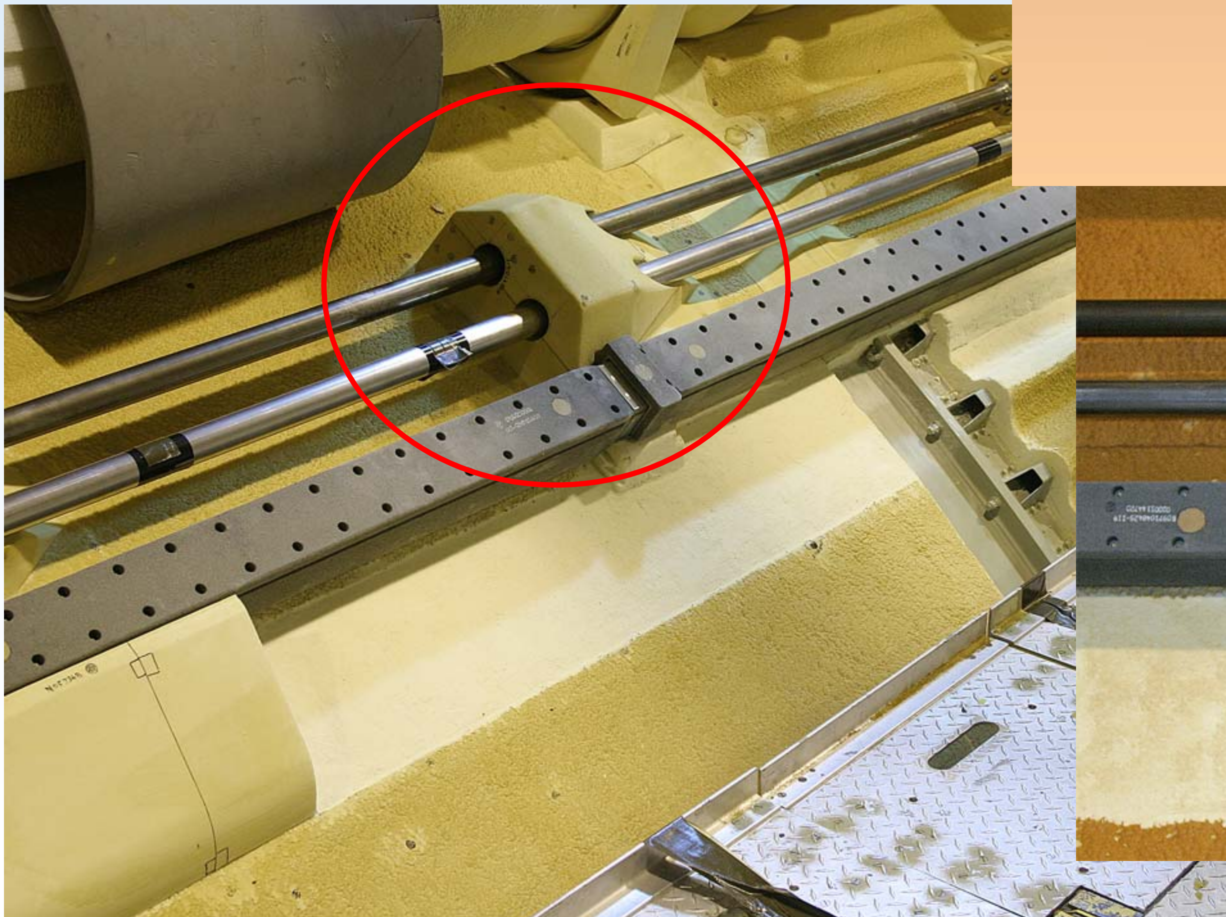
Protrusion Air Load (PAL) Ramp

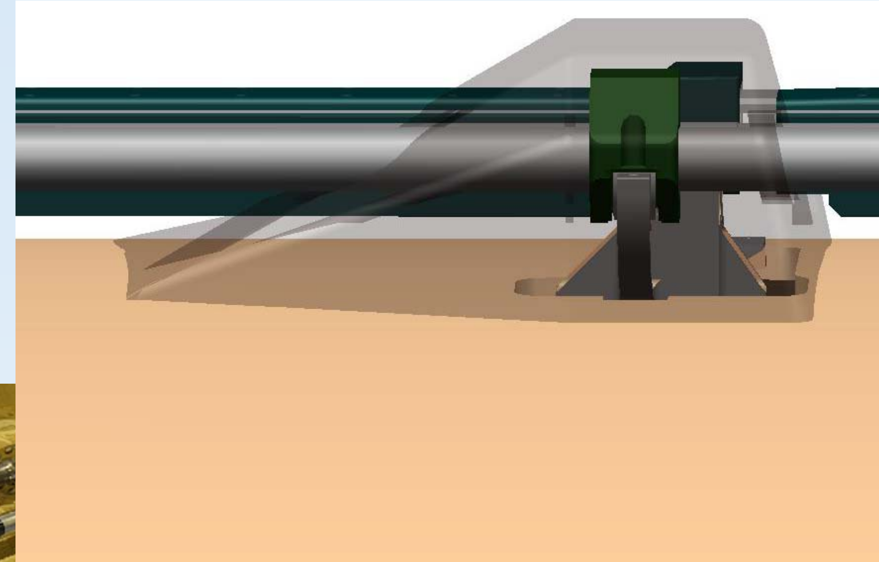
Added early in Shuttle Program to avoid any potential aerodynamic instability resulting from the pressurization lines and cable tray

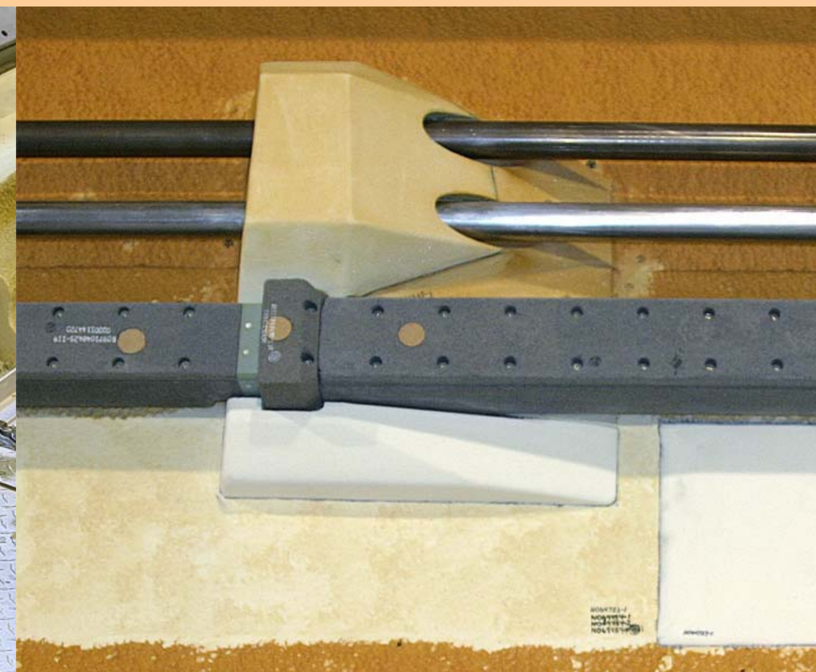


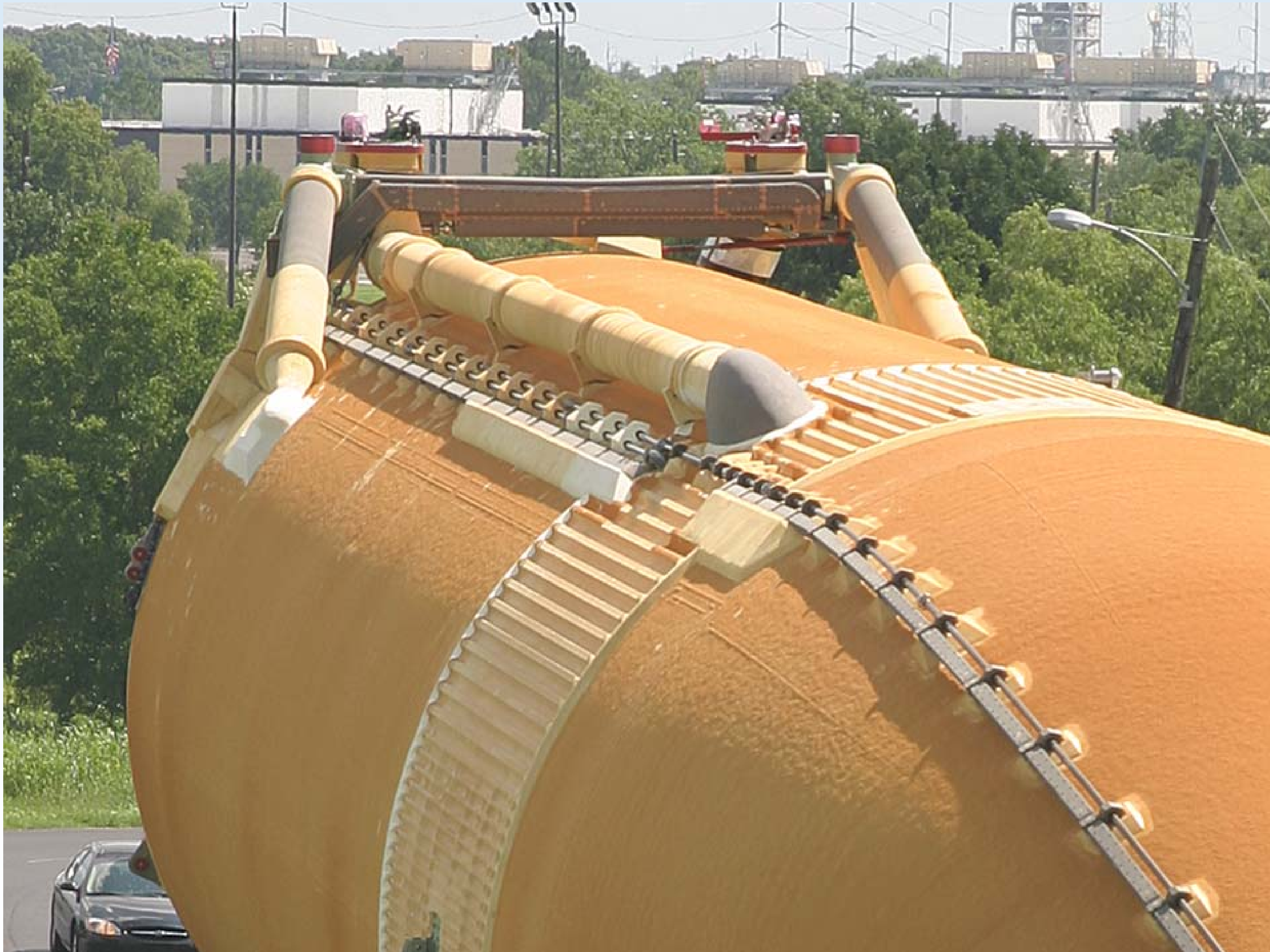
Ice Frost Ramps

Cover the pressurization line and cable tray support fittings to prevent ice formation.

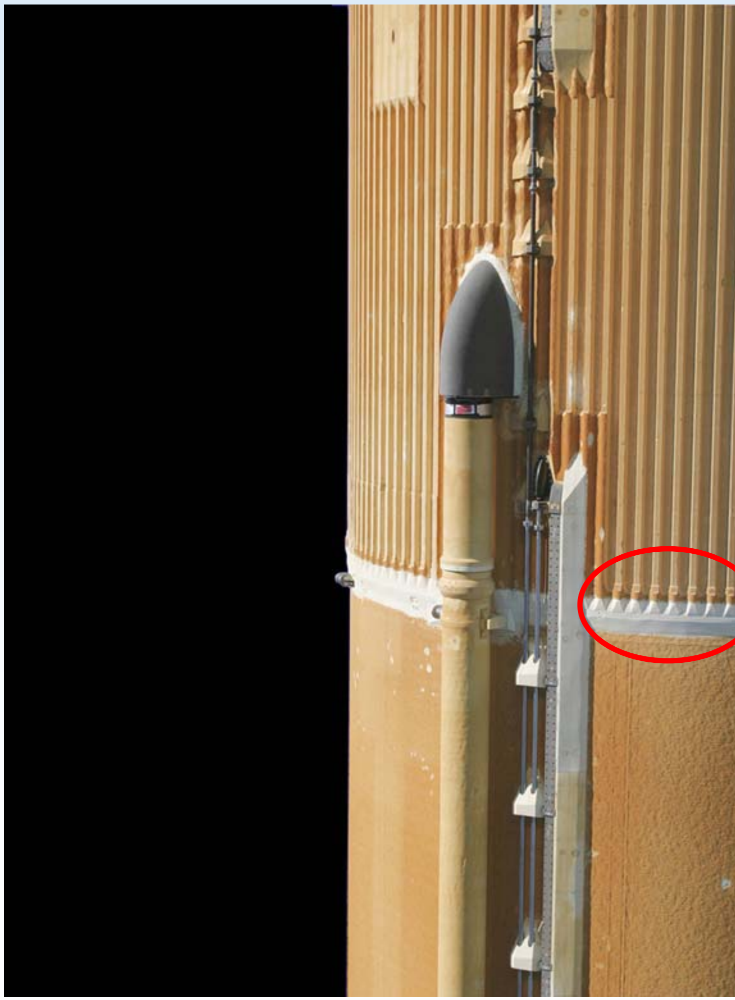


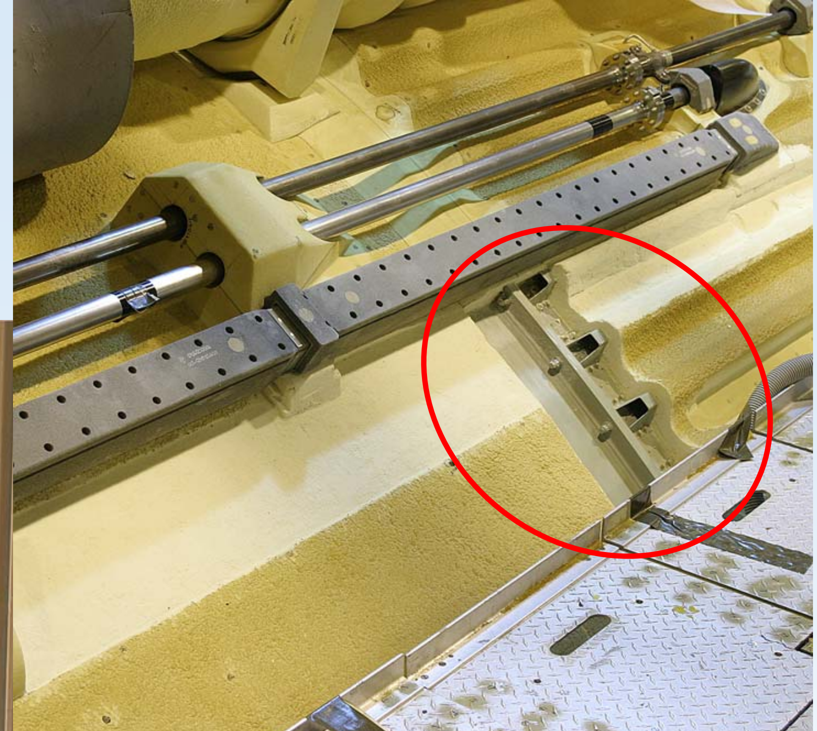




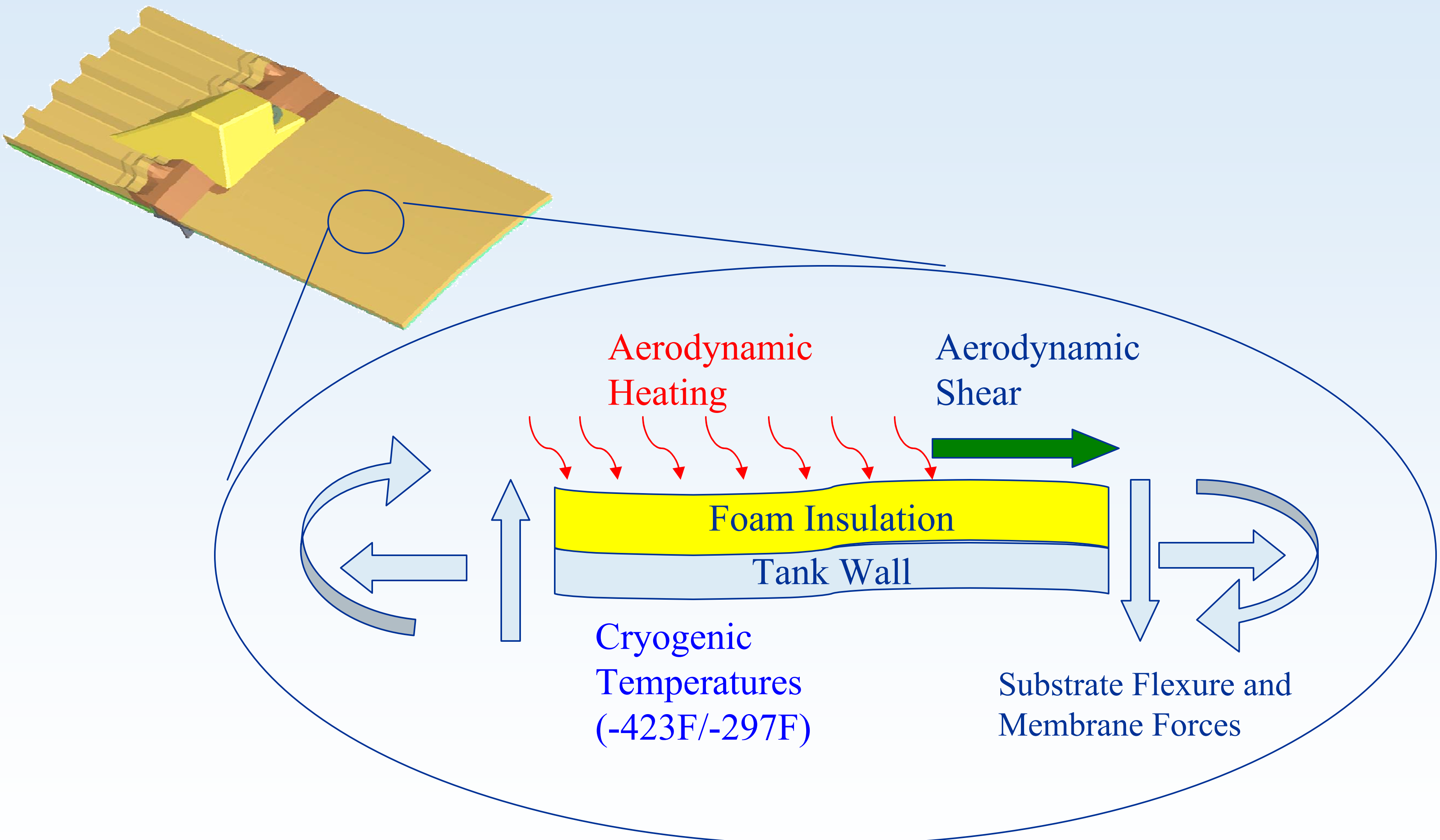


Intertank Flange TPS Closeouts

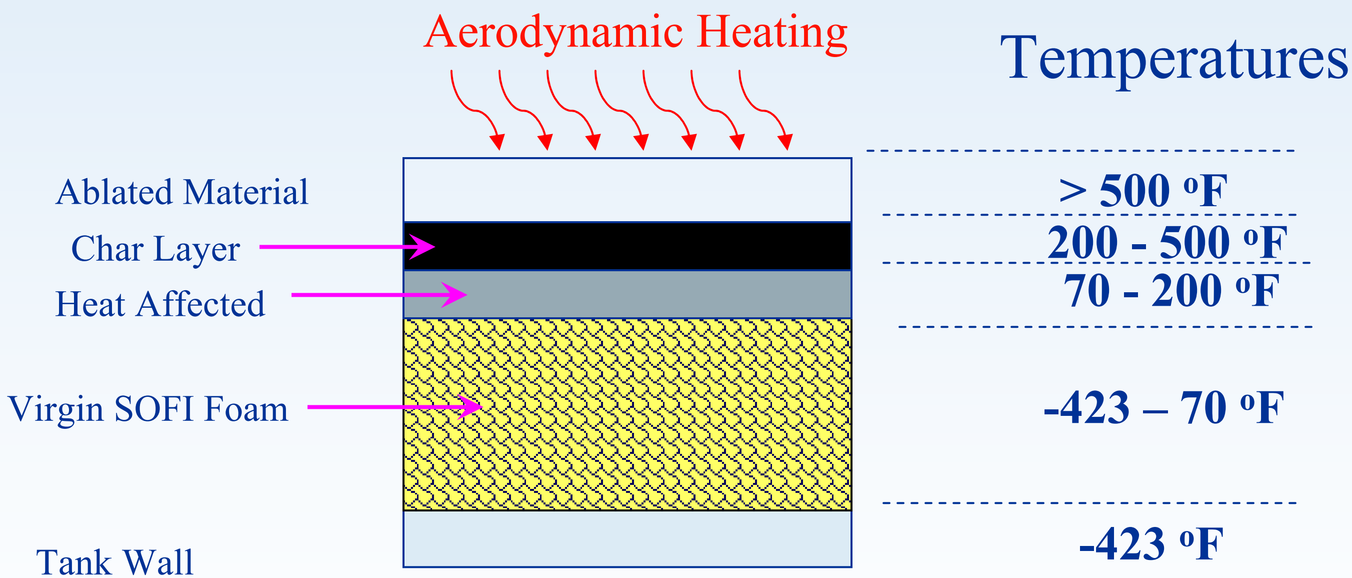




Typical Flight Loads on ET Foam Applications



Expected Foam Temperature Profile



Foam Microstructure

- 97% air; R=0.03
- polymeric cell walls
- due to its microstructure, material is anisotropic (possess different material properties in different directions)

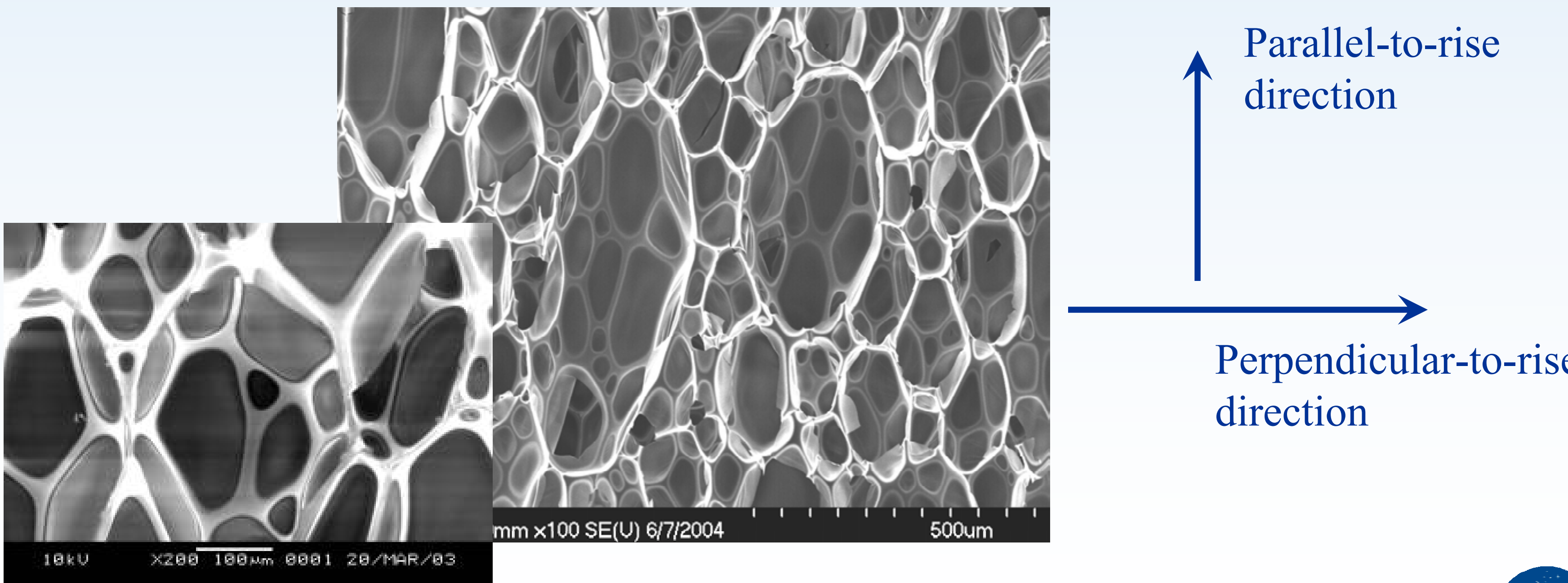
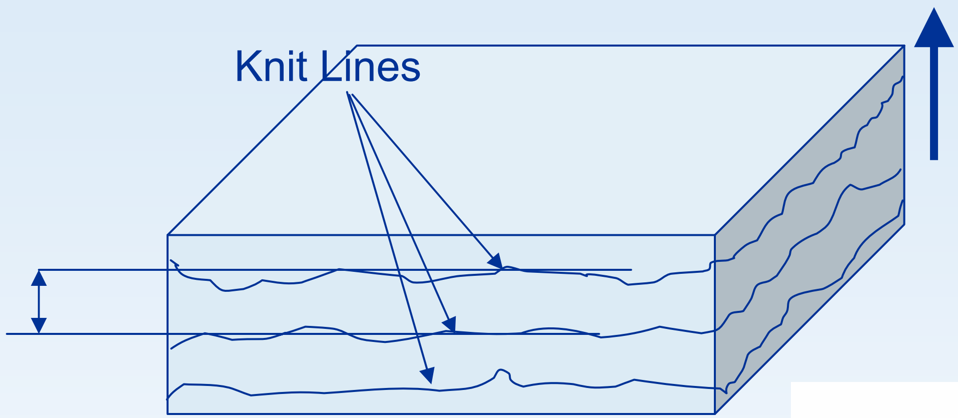
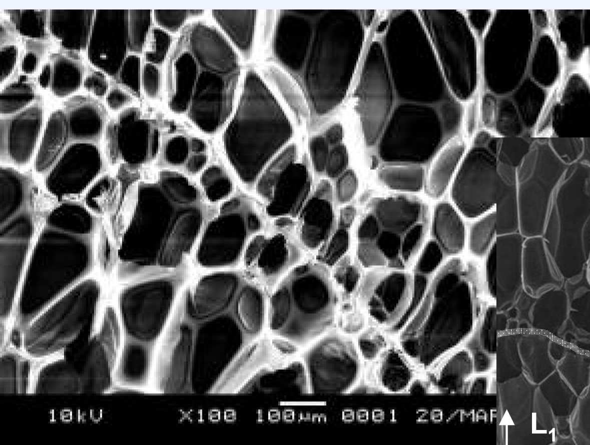
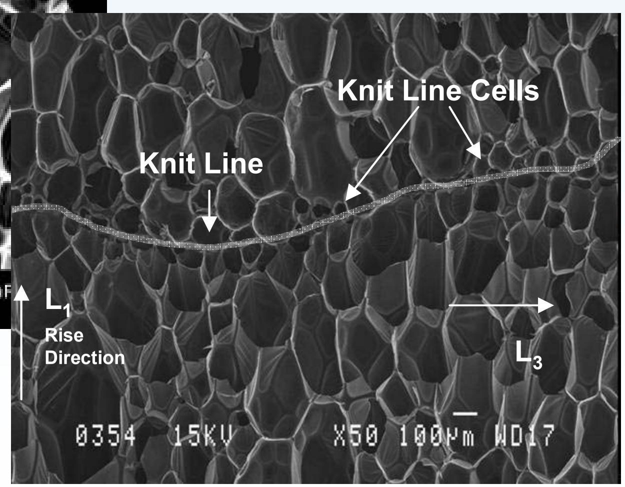


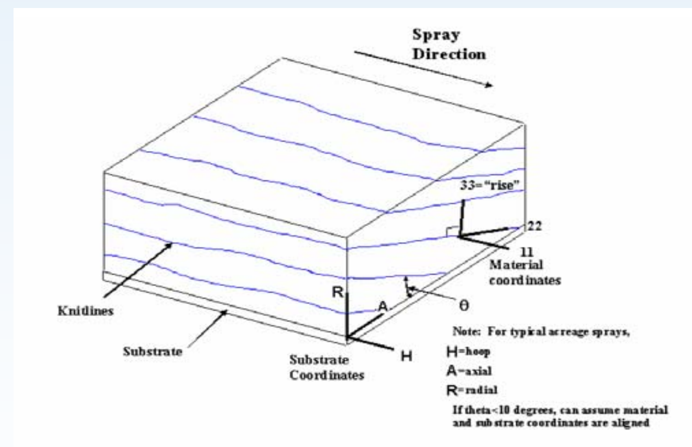
Figure 3.5 – Cell Geometry, NCFI24-124

Local Material Directions and Knitlines

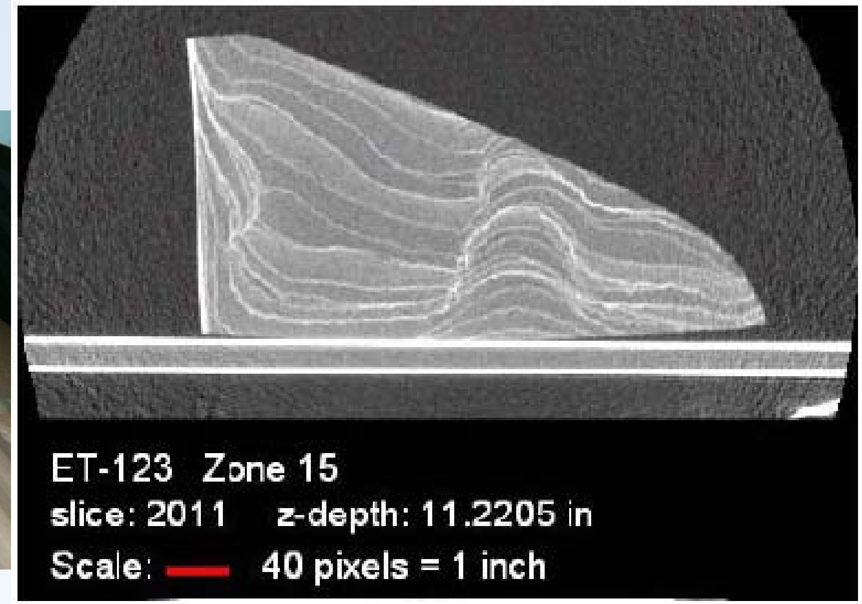




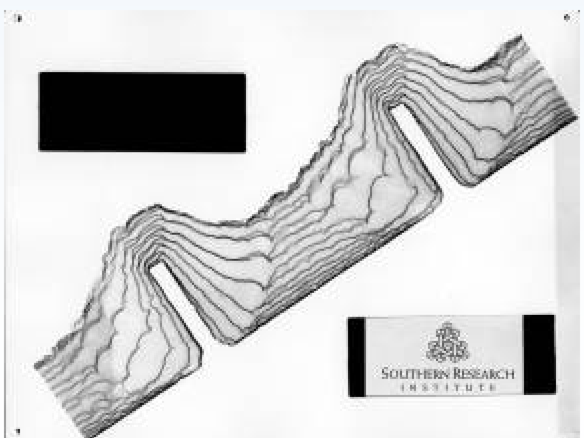




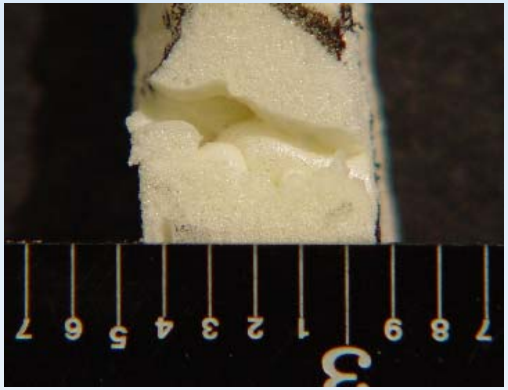
Knitline direction and local material directions vary with position within the foam applications



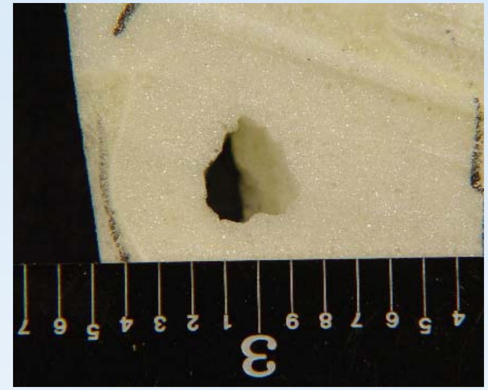
CT Image of PAL Ramp



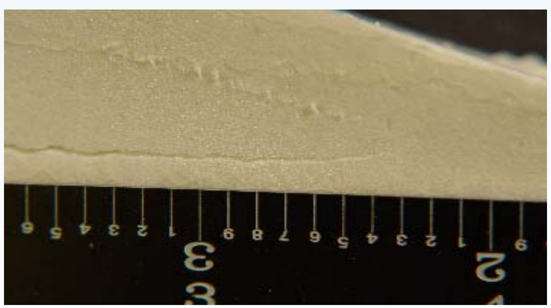
Types of Significant Foam Defects



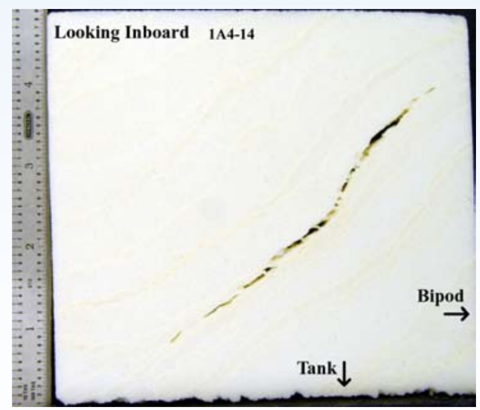
Rollover
- ***Rising foam overlaps and creates long pocket***



Void
- ***Rising foam grows together and seals in a void. More equiaxed shape than a rollover.***



Crack
- ***Stress relief from thick application***

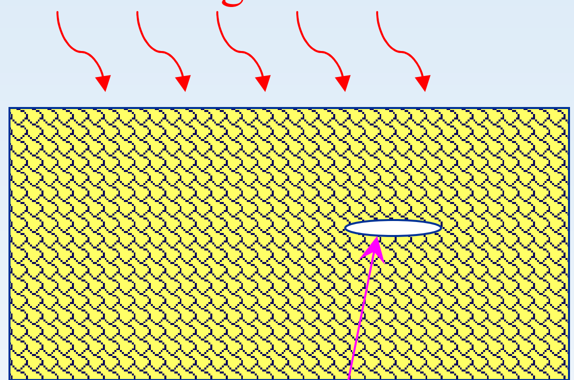


Knitline Delamination
- ***Incorrect overlap time.***
- ***Second pass applied too thin or too thick.***

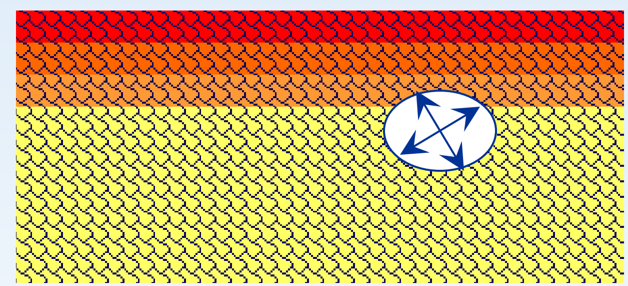
Foam Shedding Mechanisms

How Spray Defects Can Lead to Divoting

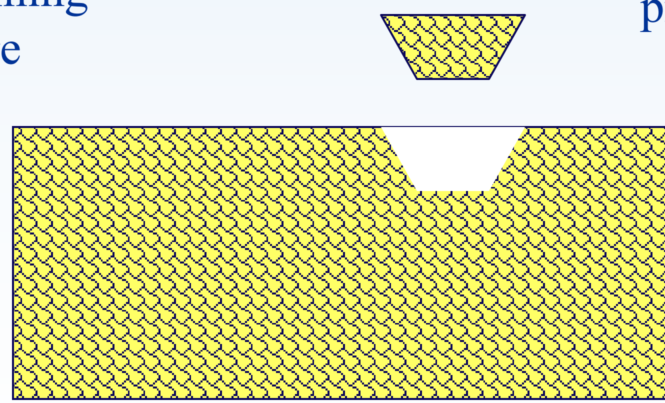
Aerodynamic
Heating



Spray defect containing
air at 1 atm pressure

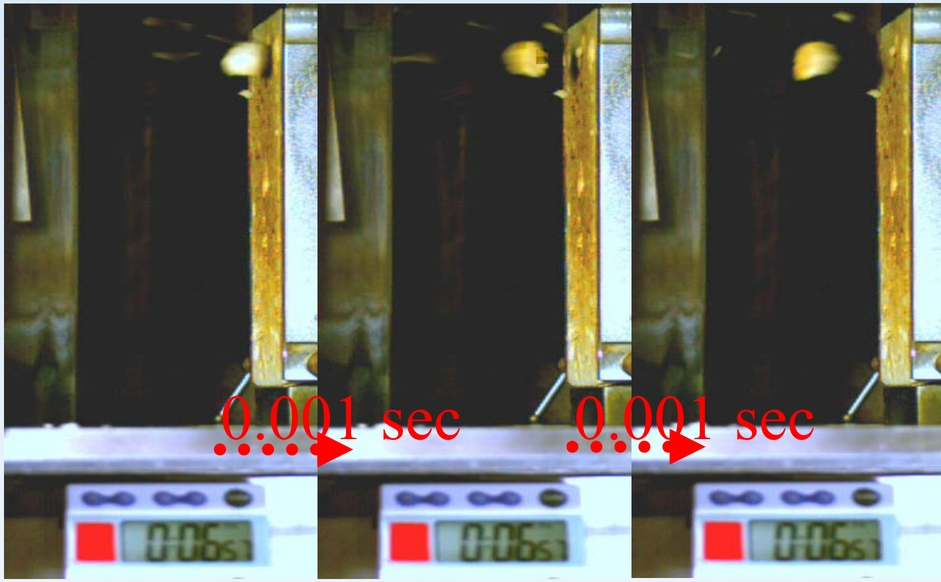


As heat penetrates the foam,
pressure in defect void rises.



Possibly resulting in
foam failure and divot.

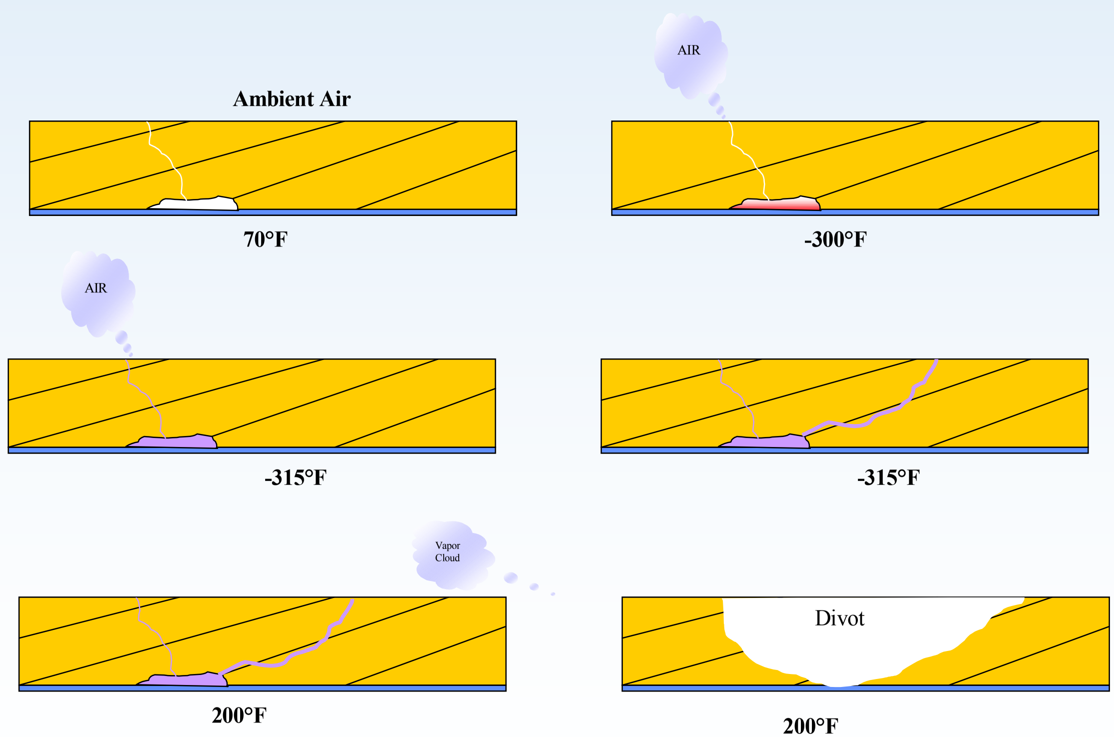
Popcorning



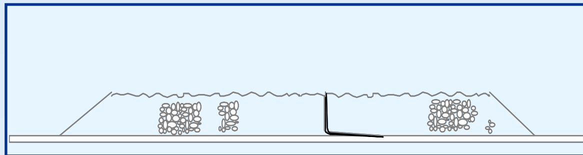
Cryo-pumping

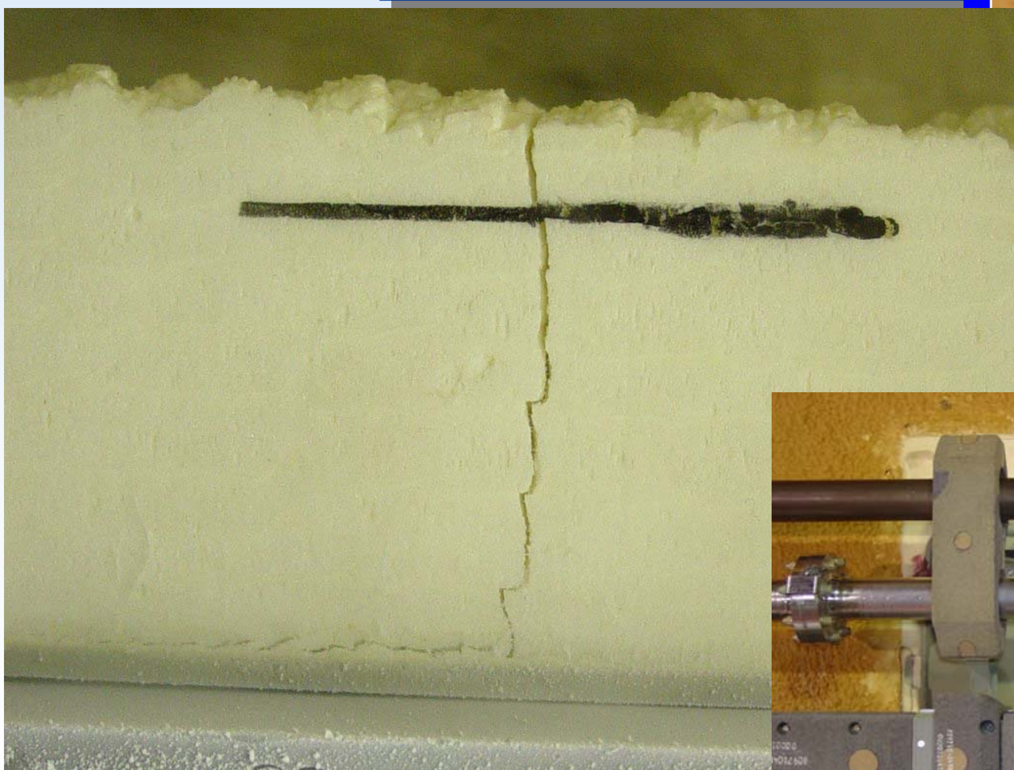
• Internal discontinuities, with a path to the surface, can pull nitrogen or air into the foam through a process of densification.

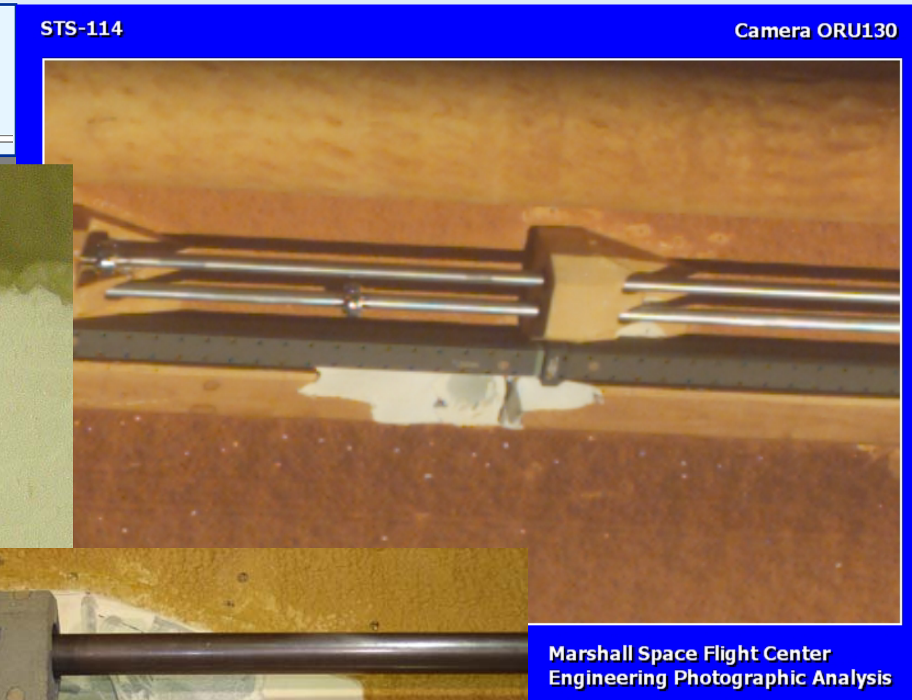
• Rapid warming during ascent can cause vaporization, a rapid rise in pressure and foam divots.

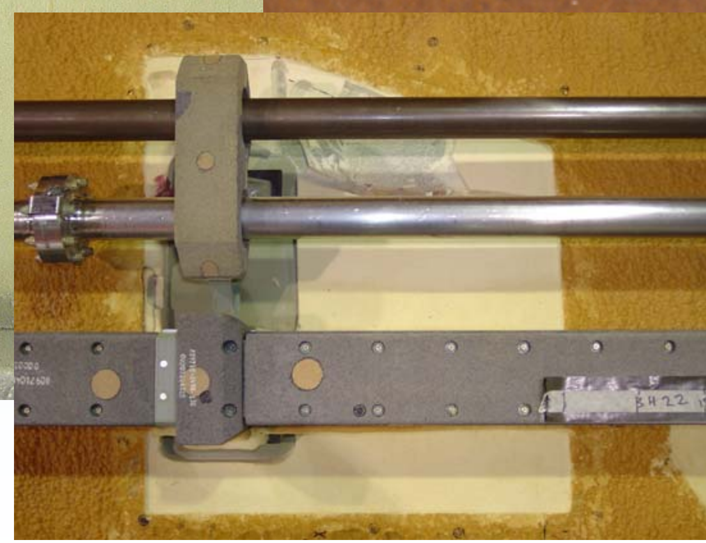


Sub-layer Cracking, Crack Propagation and Subsequent Delamination from Substrate





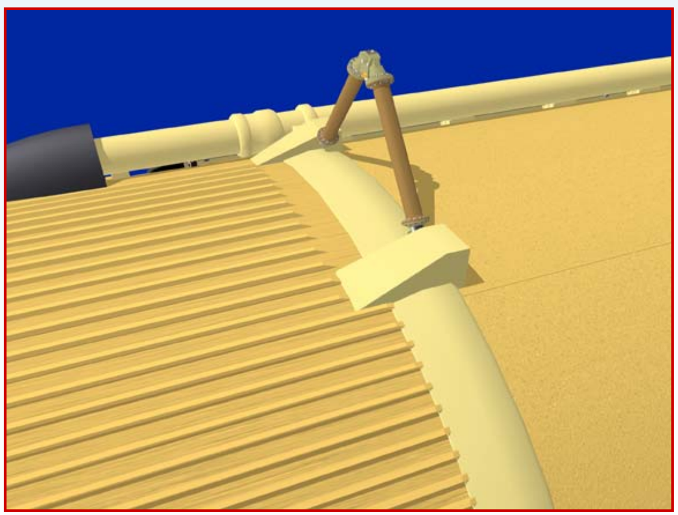




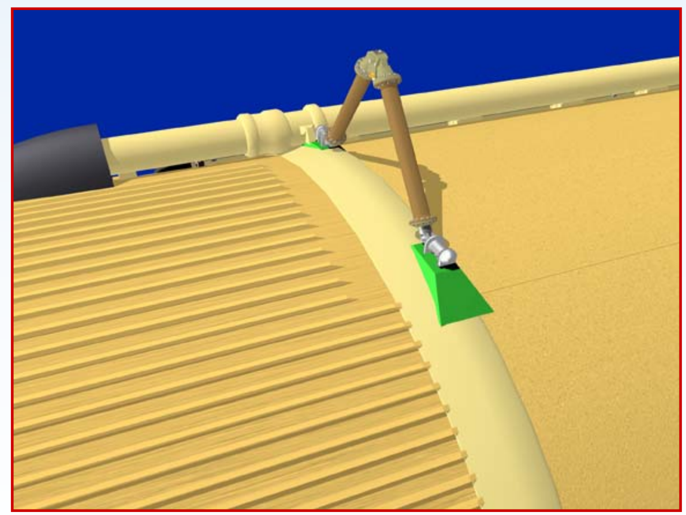
Design and Process Changes to Reduce Propensity and Severity of Foam Loss During Ascent

Redesigned the Bipod Closeout and Fitting

- Remove Foam Ramp
- Add Heaters (to prevent ice formation)
- Inconel fitting (higher temperature metal for external aerodynamic heating)
- Insulated fitting from cold cryogen with phenolic insulator



Old Design



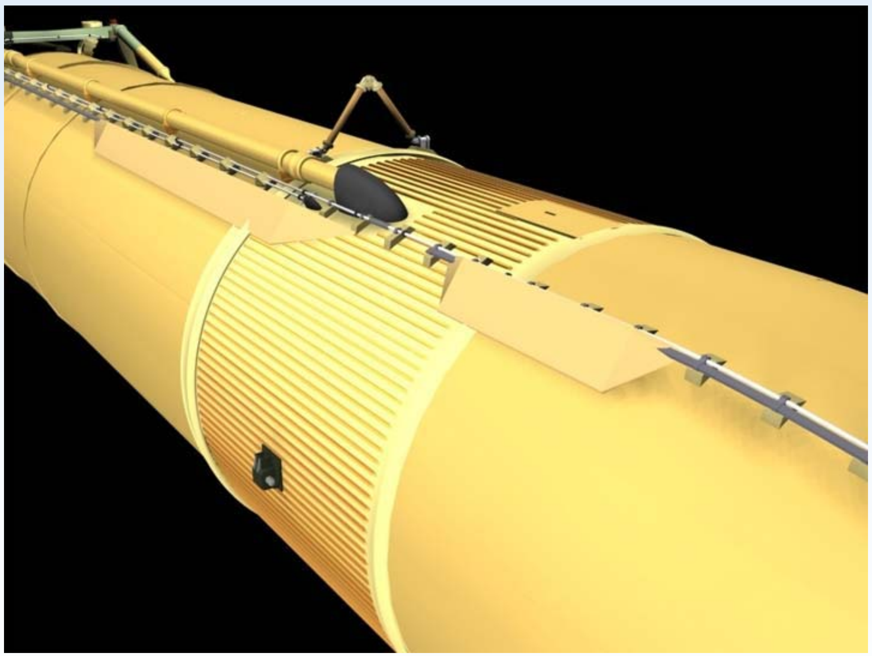
New Design

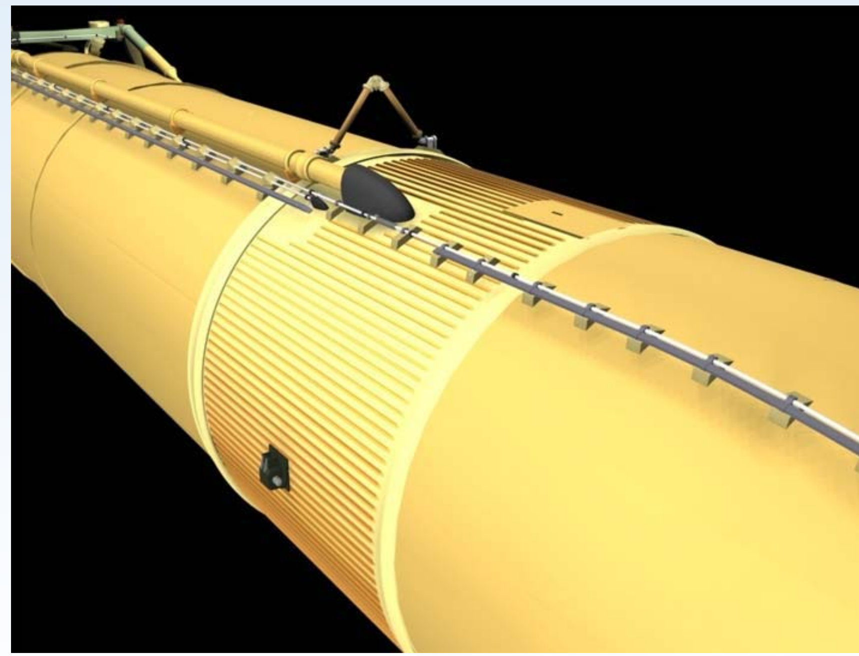
Improved Spray Techniques (Tighter Specs) to minimize occurrence and severity of foam defects and voids.

- Rigorous process validation with dissections
- Tightened spray parameters:
  - Temperature
  - Relative humidity
  - Time between subsequent spray passes
- Two operators for all sprays (“second set of eyes”)
- Witness panels and high-fidelity mockups
- Video reviews

Redesigned Bipod Closeout Mockup Spray in Progress

Removed the LOx and LH_2 PAL ramps





Space Shuttle Flight Safety Certification is Based on…

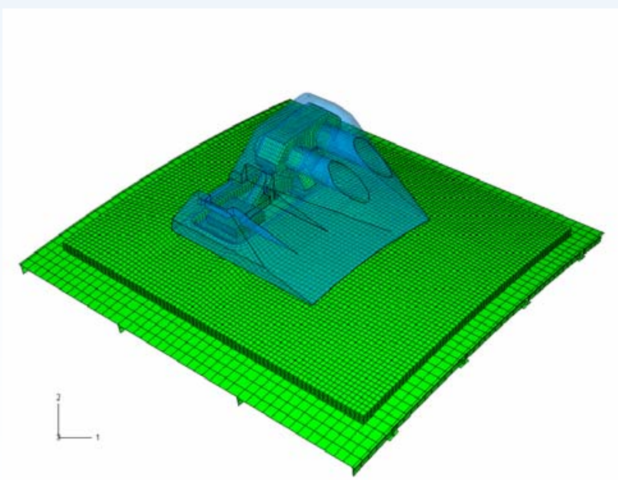
1) Eliminating or mitigating critical sources of debris by design
   - Bipod redesign
   - PAL ramp elimination
   - LH2 flange redesign
2) Understanding the maximum expected size and transport mechanism for remaining debris that is generated.
3) Understanding the impact tolerance for any debris that can still be generated and can reach the shuttle.
4) Contingency plans
   - Impact detection and on orbit inspections
   - Safe haven at International Space Station

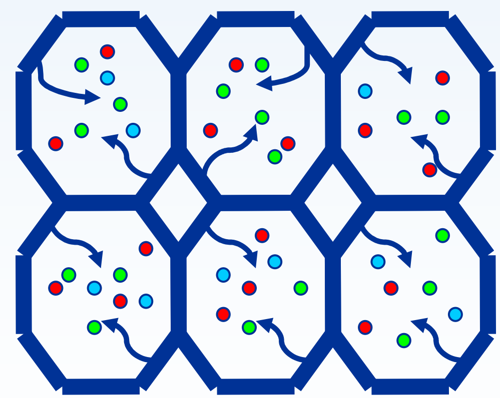
Continue to improve the engineering infrastructure to ensure safe and reliable foam applications by…….

- improving structural analysis methods for spray-on foam applications
- improving ability to detect voids/flaws in foam applications
- improving understanding of crack propagation and fracture behavior of External Tank foams

Improving Structural Analysis Methods for Foam Applications

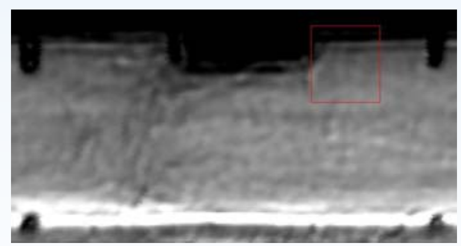
- Accurate representation of thermo-structural response over wide temperature range: cryogenic hydrogen (-423 ^{o}F) to 500 ^{o}F.
- Account for the cellular nature of the material.
- Account for internal cell gas pressures and their effect on structural response.
- Account for orthotropic material behavior and arbitrary orientation of the knitlines w.r.t. global coordinates.
- Method should be embedded in a finite element analysis to be capable of modeling the complex geometries of the various foam applications.

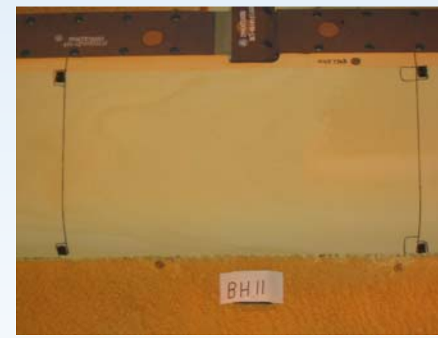


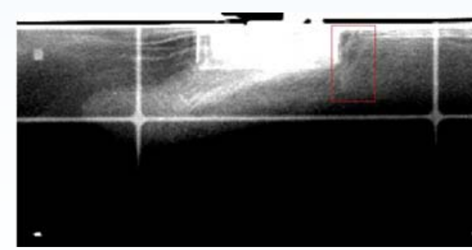


Improving ability to detect voids/flaws in foam applications

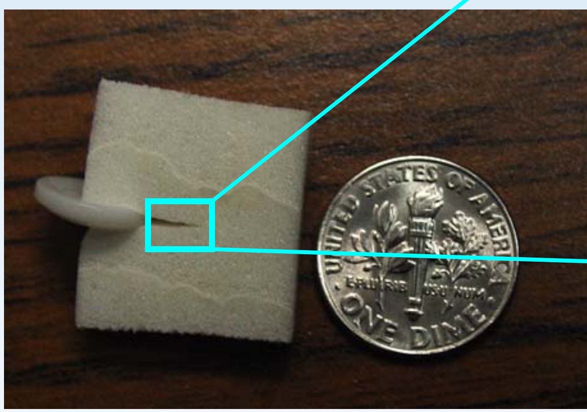
- Non-destructive evaluation (NDE) techniques being developed for ET foam
    - Backscatter X-ray
    - Terahertz
    - Shearography
- Inspection techniques have not yet been certified, data used for engineering information only

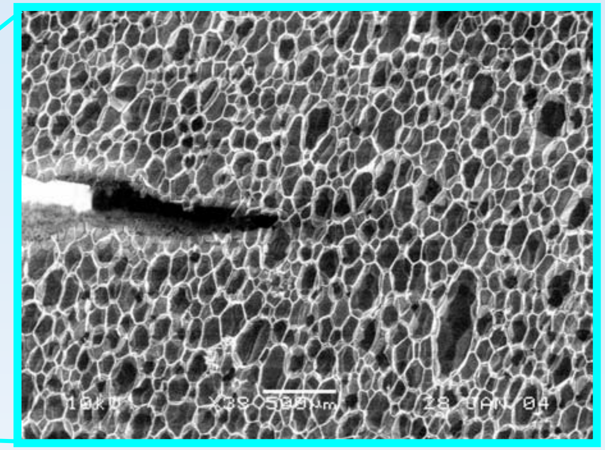


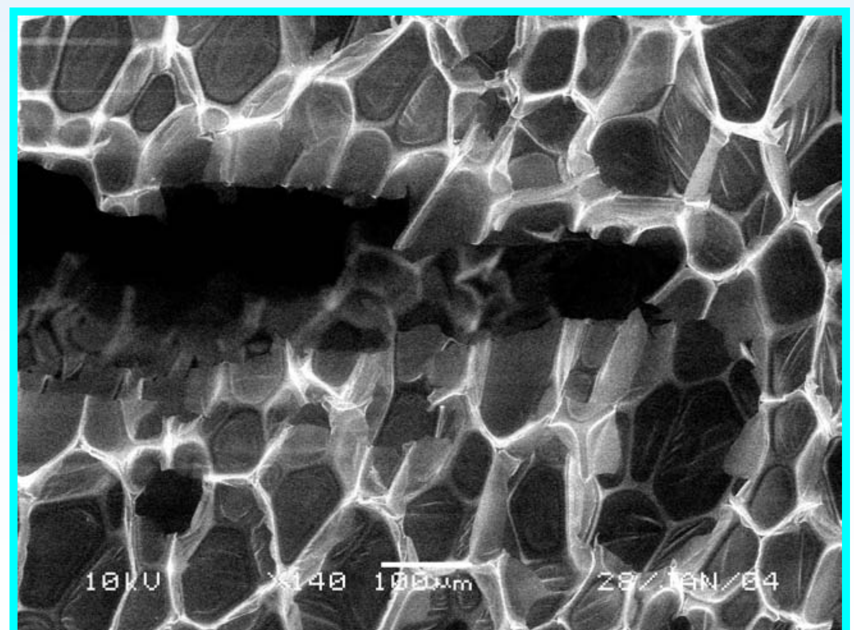




Improving Fracture Mechanics Analysis Methods for Foam







How valid is linear elastic fracture mechanics for ET foams?