External Tank Foam

Dr. Roy M. Sullivan and Dr. Brad Lerch
Materials and Structures Division
NASA Glenn Research Center

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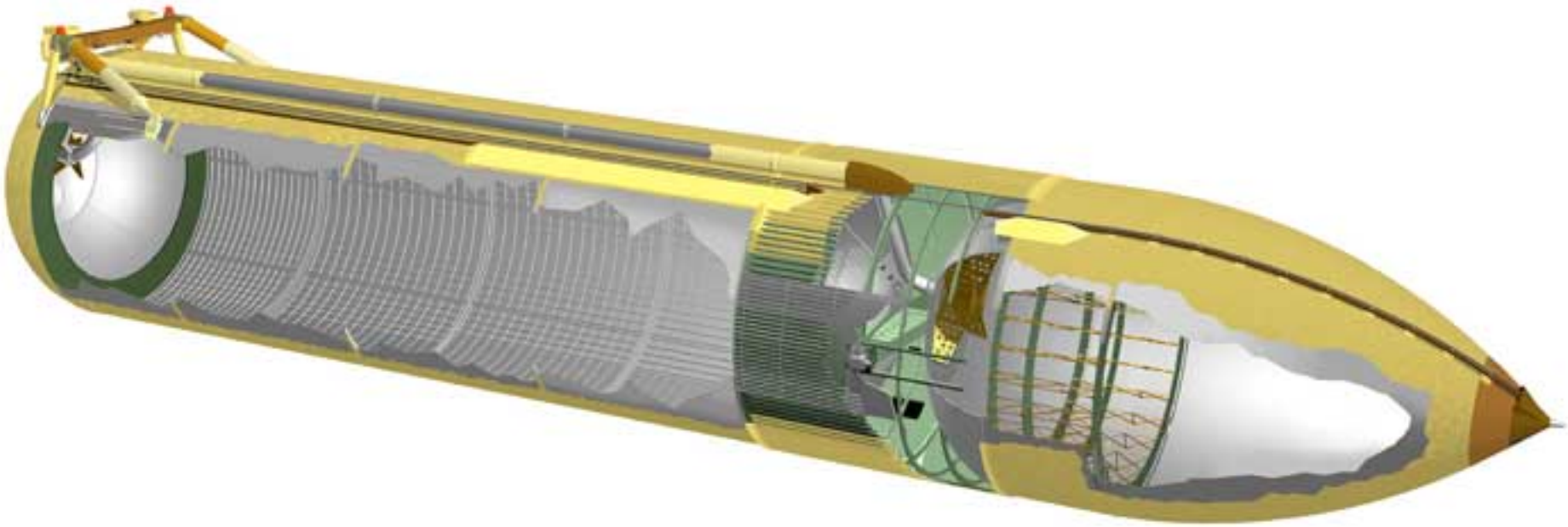
ET Foam Modeling Team

NASA:	Dr. Roy Sullivan Dr. Brad Lerch
OAI:	Dr. Louis Ghosn Dr. John Thesken Dr. Brett Bednarcyk
CRT:	Joe Palko
QSS:	Chris Burke Dan Scheiman

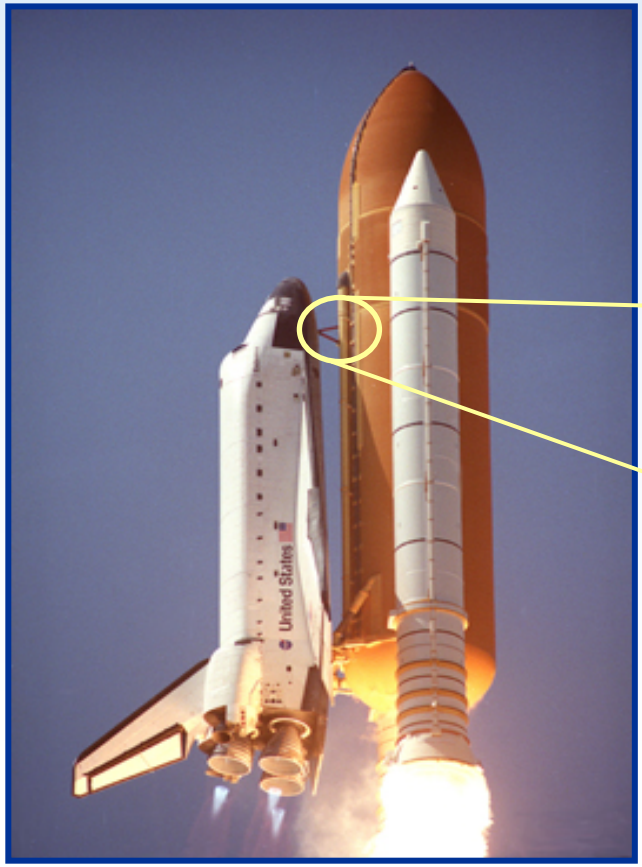
The External Tank (ET)

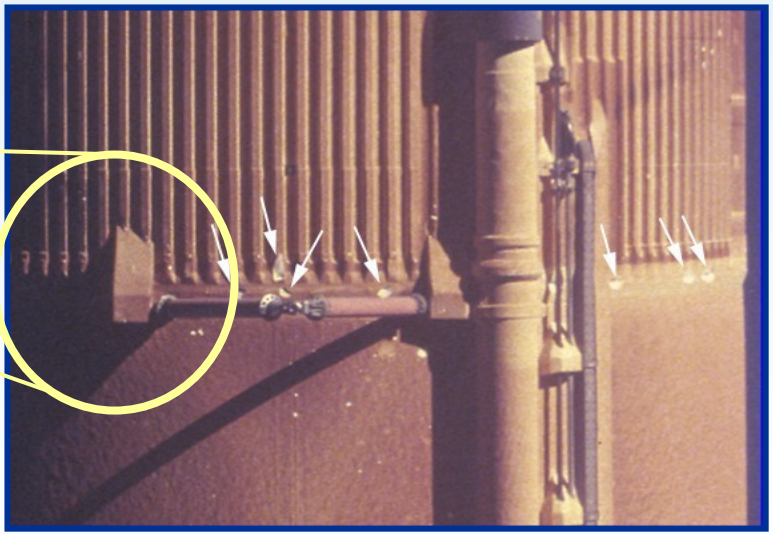
External Tank's Spray On Foam Insulation (SOFI) is applied to maintain cryogenic propellant quality, minimize ice/frost formation, and protect the structure from ascent, plume and reentry heating.



Columbia Accident Investigation Board (CAIB) found that ……

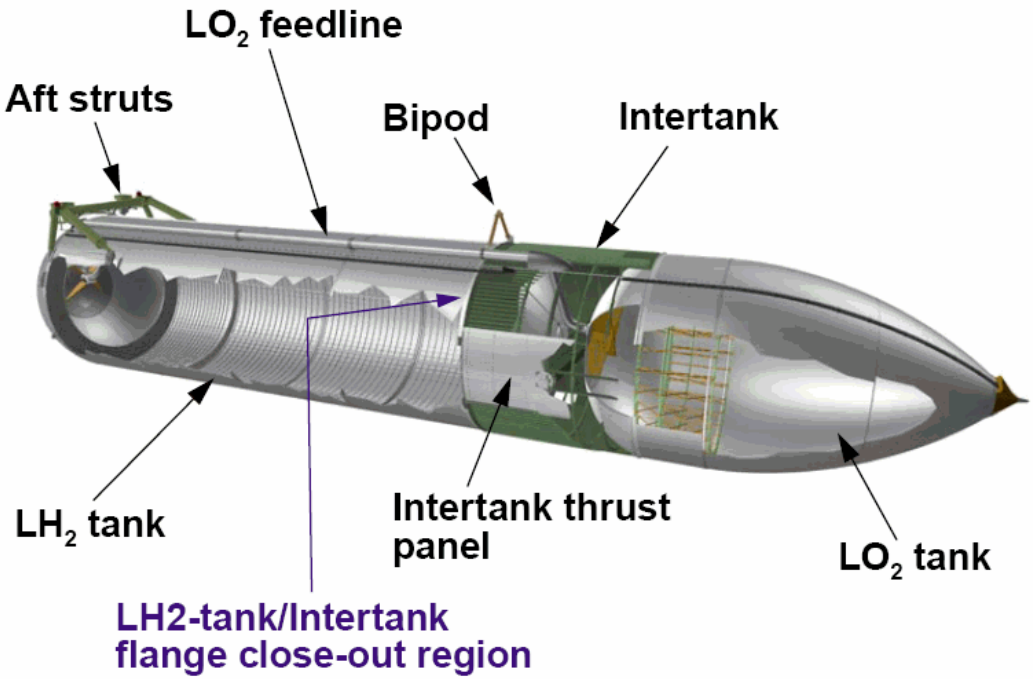
"the cause of the loss of Columbia and its crew was a breach in the Thermal Protection System on the leading edge of the left wing. The breach was initiated by a piece of insulating foam that separated from the left bipod ramp of the External Tank and struck the wing in the vicinity of the lower half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



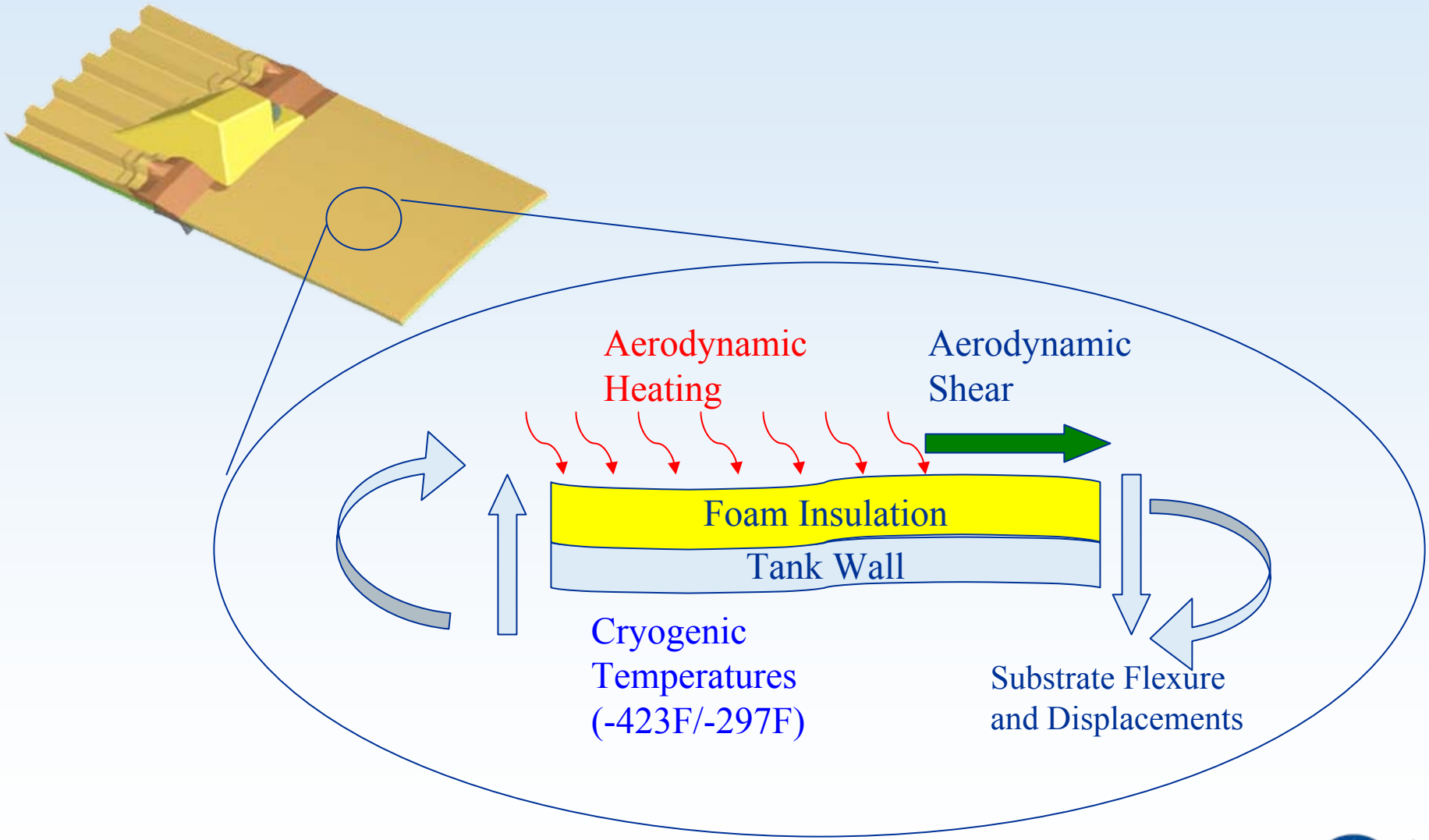


- Gross weight 1,667,677 lbs.
- Empty weight 78,100 lbs.
- Contains 526,000 gallons of liquid hydrogen and oxygen
- Average thickness of metallic tank wall: 1/8 inch
- Average thickness of foam insulation: 1.0 inch

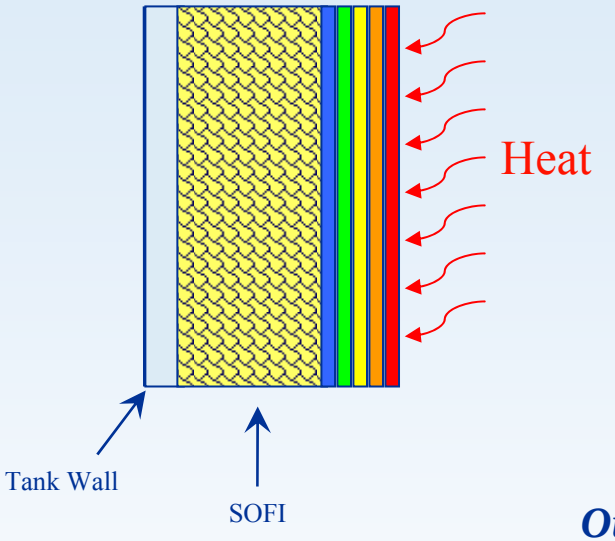
EXTERNAL TANK STRUCTURAL LAYOUT

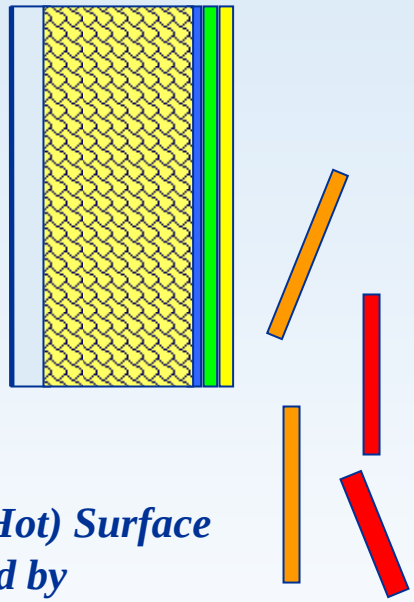


Generic Flight Loads on ET Foam Applications

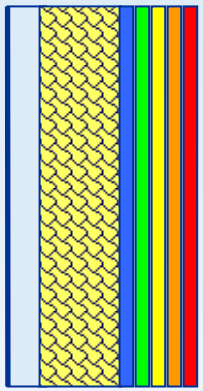


Nominal Foam Insulation Performance



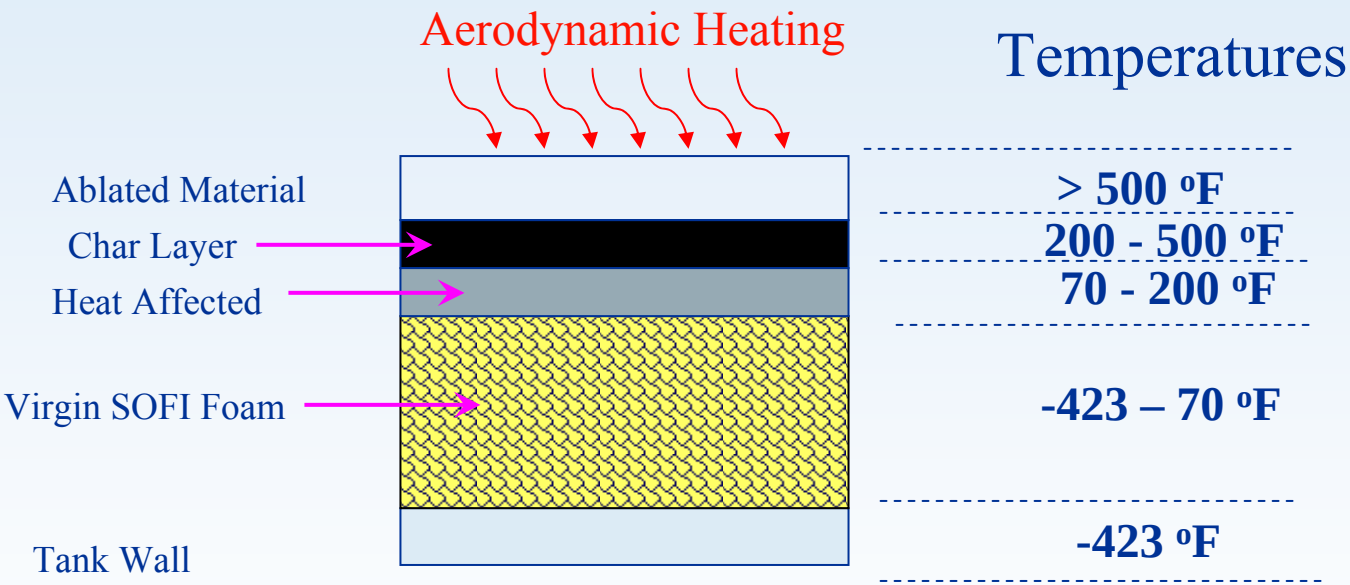


Outer (Hot) Surface Removed by Ablation/Recession



Thickness of the SOFI Insulation Decreases with Time.

Through-thickness Temperature Gradient



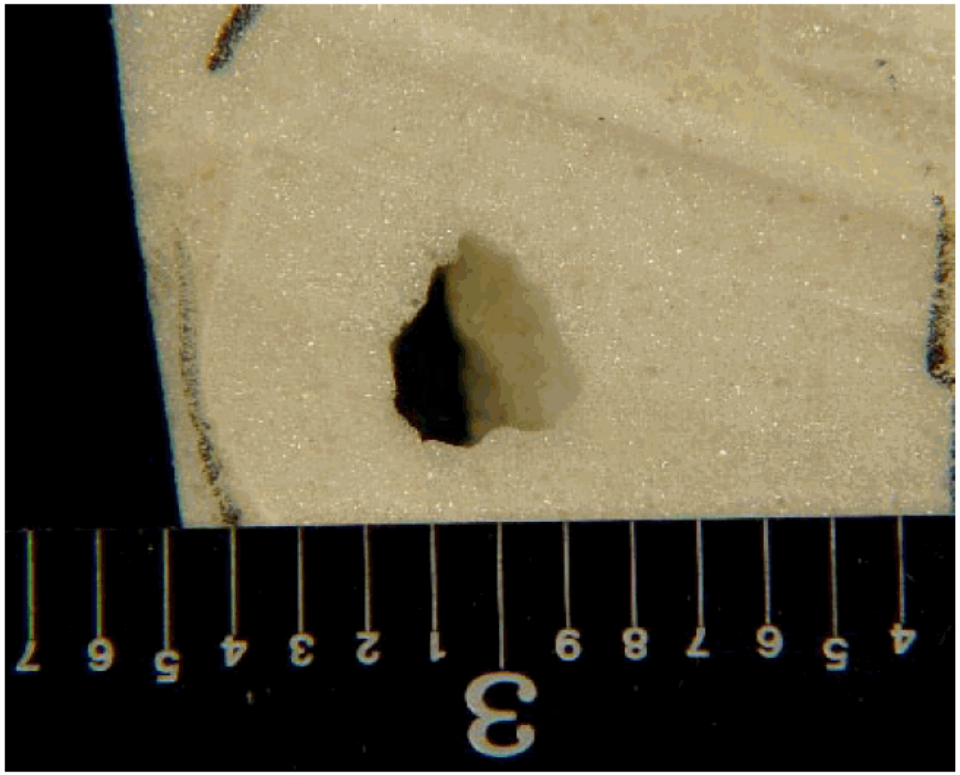
SUMMARY OF PRIMARY FAILURE MODES

Failure Mode	Primary Contributors	Examples
Outer-surface cracking Inner surface cracking	Substrate extension/contraction Substrate bending Thermal-expansion mismatch Cryopumping ?	
Substrate debond/ delamination	Thermal expansion mismatch Substrate bending Temperature gradients	
Divoting and popcorning	Pressure gradients Temperature gradients Internal voids Cryopumping	
Shear	Aerodynamic loads parallel to the flow stream	

Foam Void

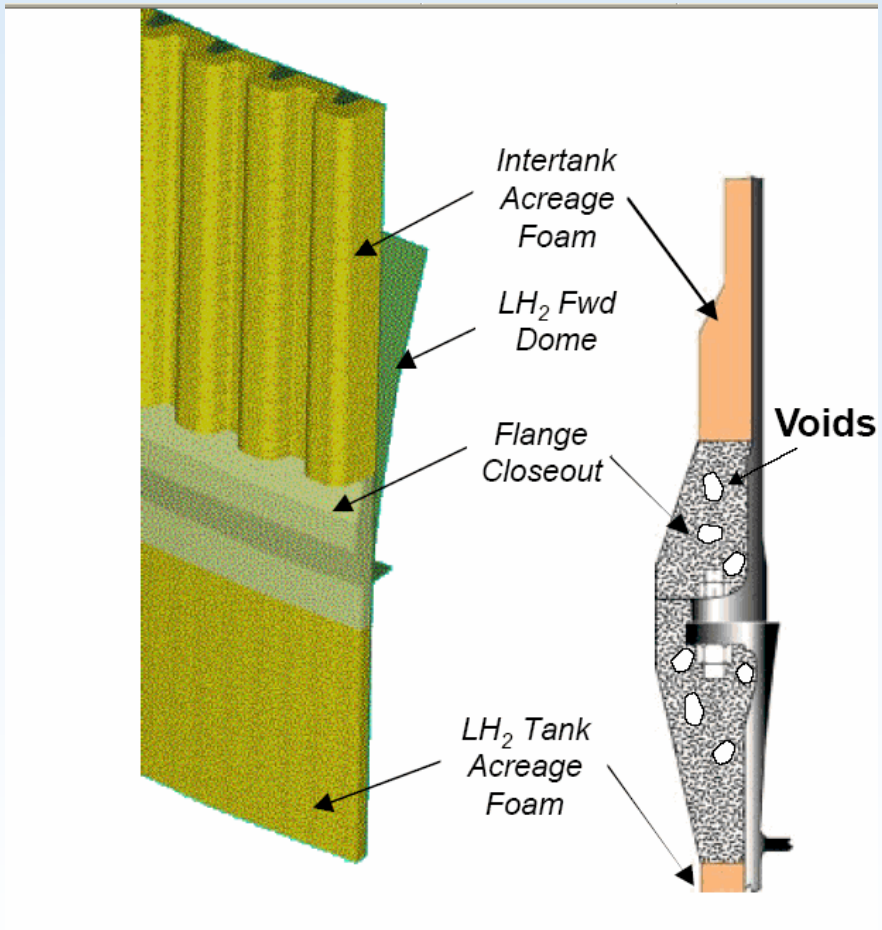
SIGNIFICANT TYPES OF FOAM DEFECTS

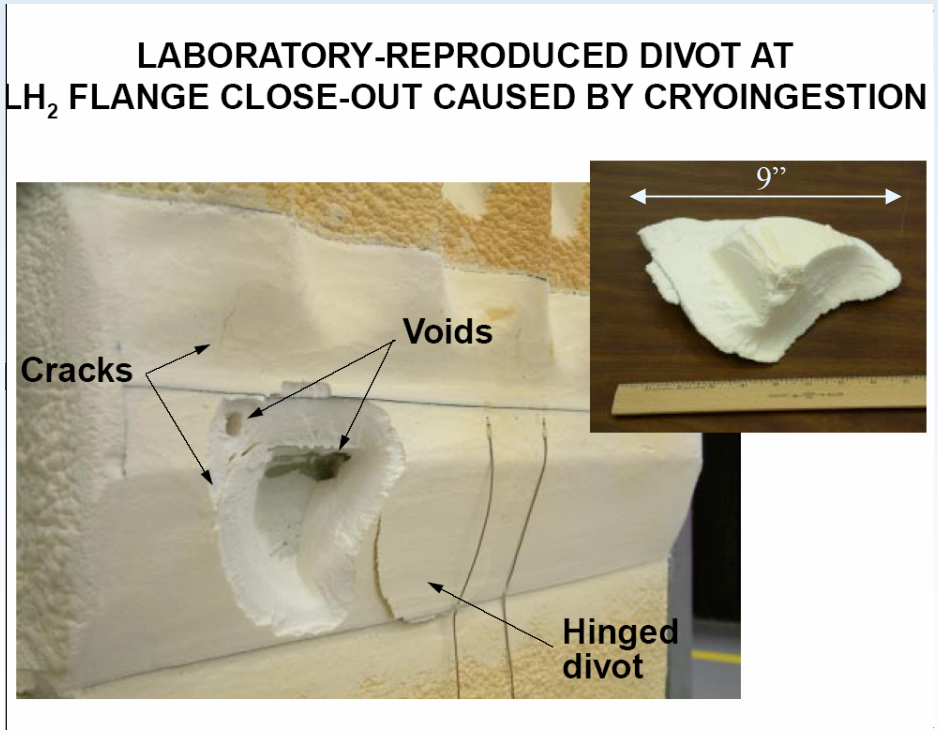
VOID



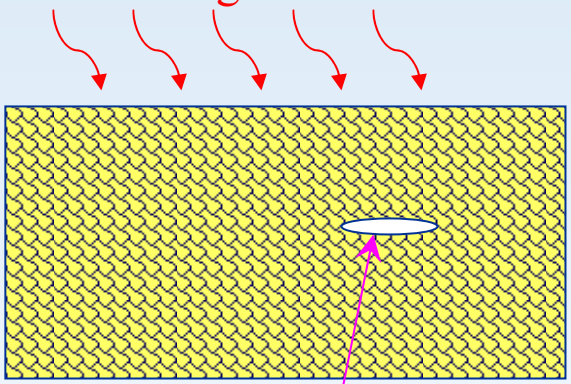
- Rising foam grows together and encapsulates a pocket of gas

Intertank Flange Area

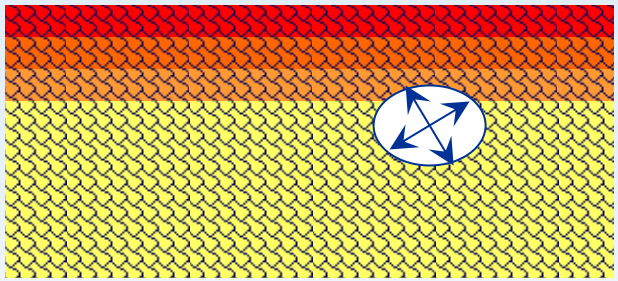




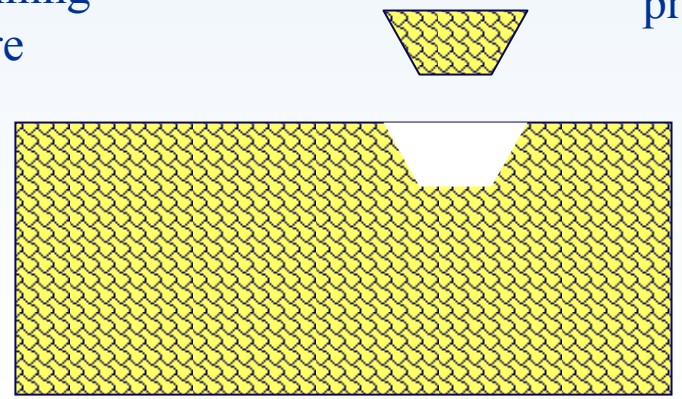
How Spray Defects Can Lead to Divoting



Spray defect containing air at 1 atm pressure

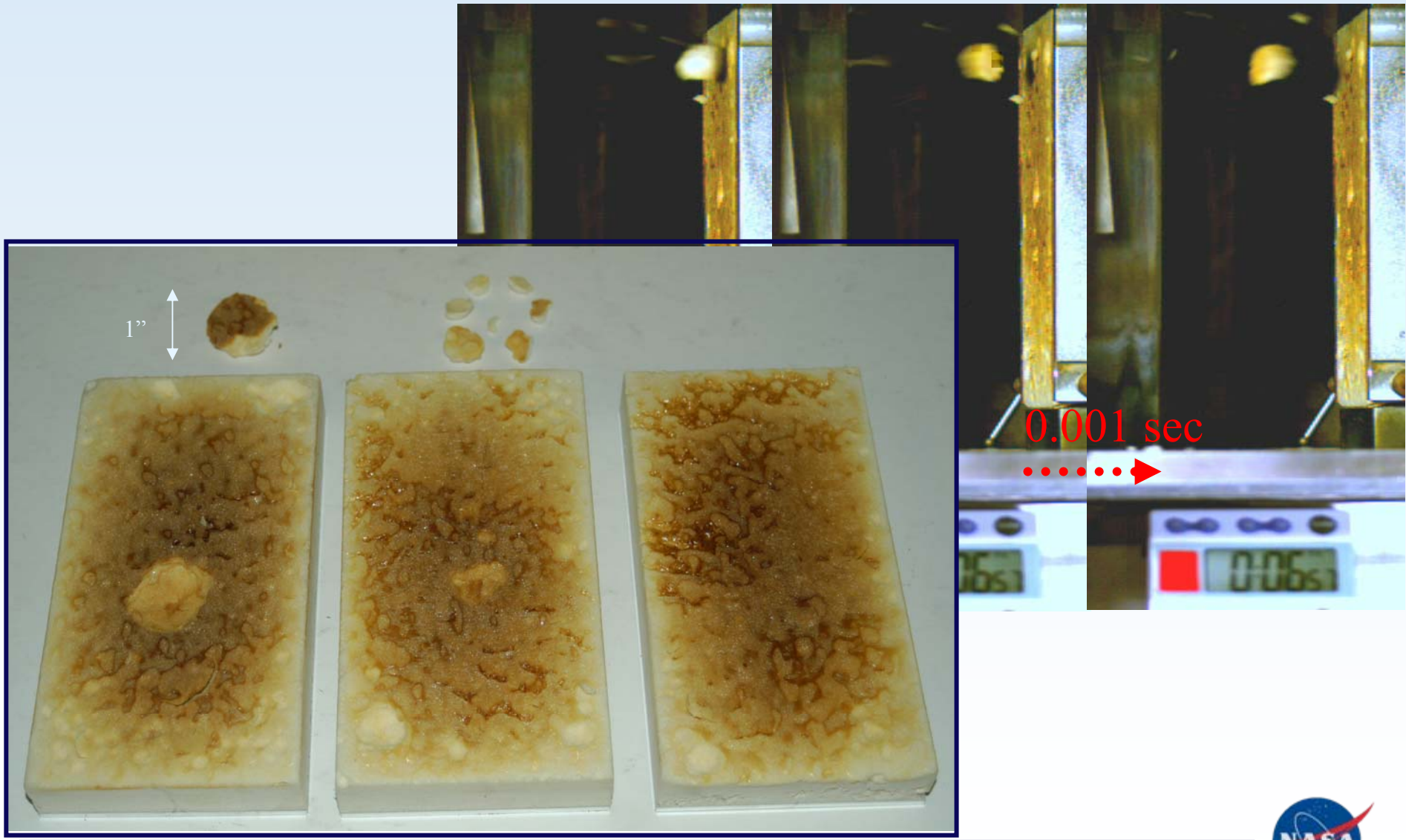


As heat penetrates the foam, pressure in defect void rises.



Possibly resulting in foam failure and divot.

Popcorning

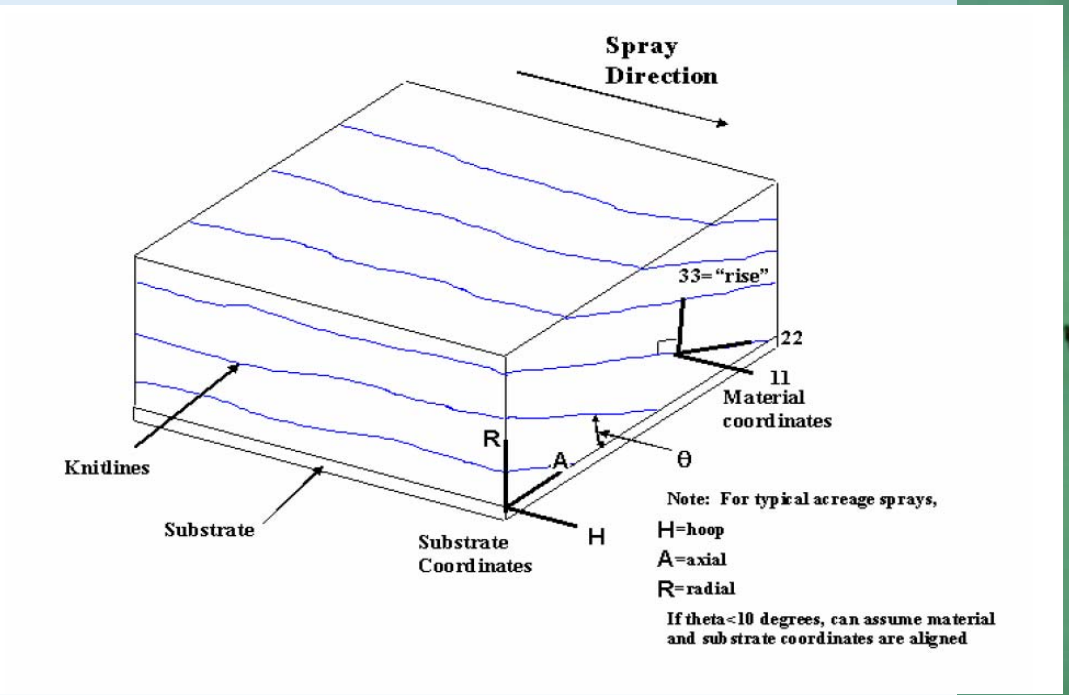


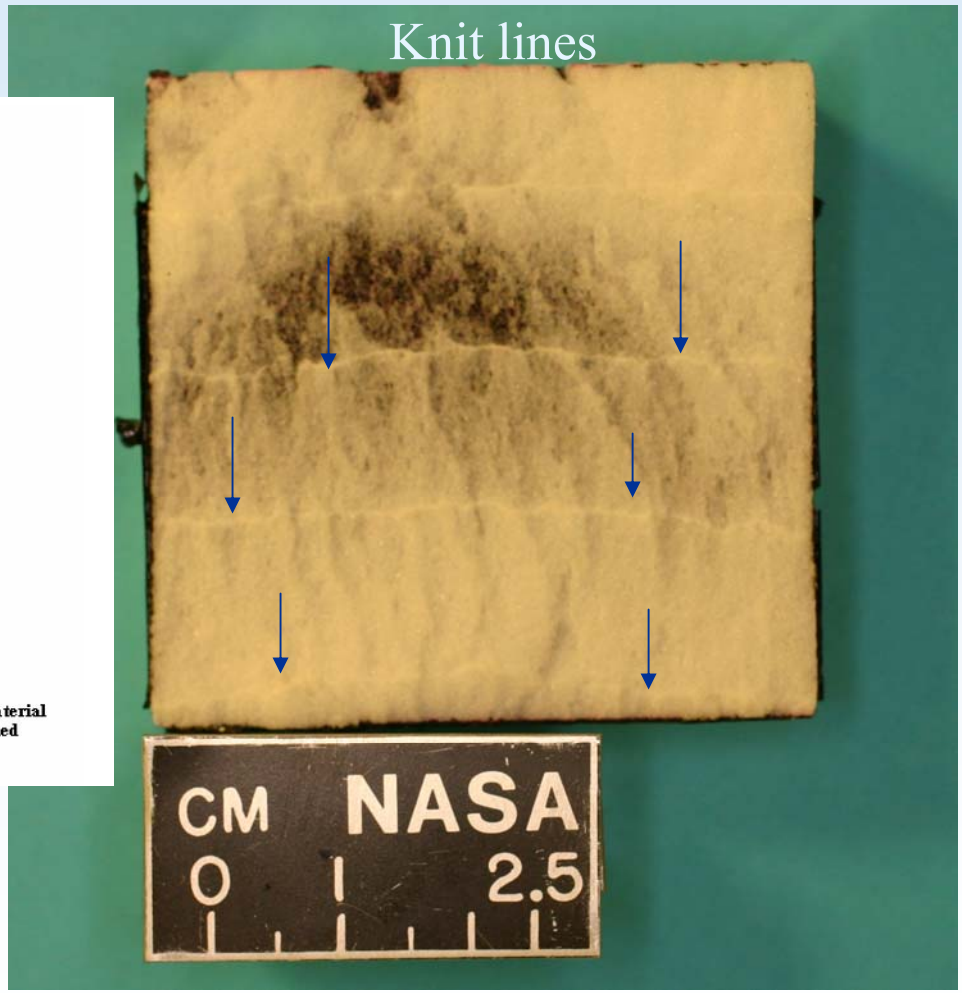
Goal

Performing fundamental research studies to improve ***structural mechanics*** and ***fracture mechanics*** methods for foam will help to improve Shuttle safety by helping to understand foam failure.

The Foam

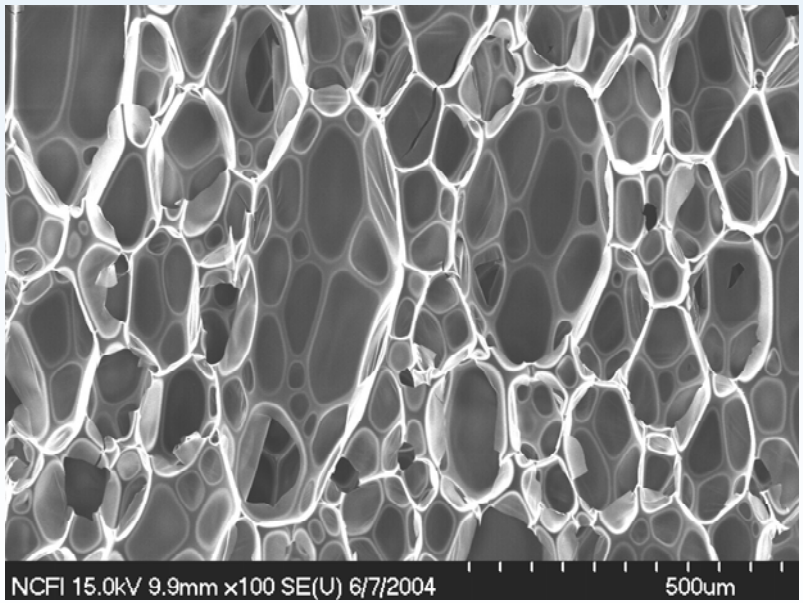
Shingle Spray Process





Foam Material is Unlike Traditional Engineering Materials

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



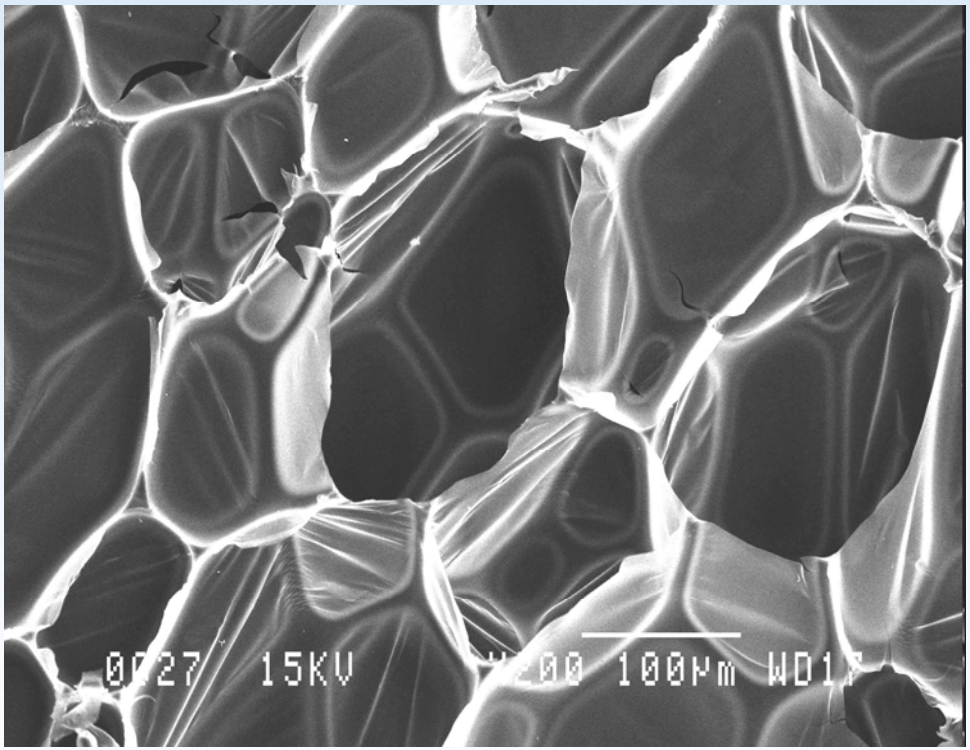
Parallel-to-rise direction

Perpendicular-to-rise direction

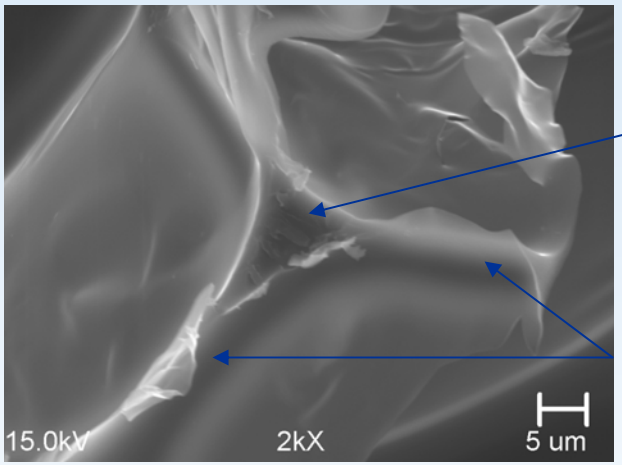
Figure 3.5 – Cell Geometry, NCFI24-124

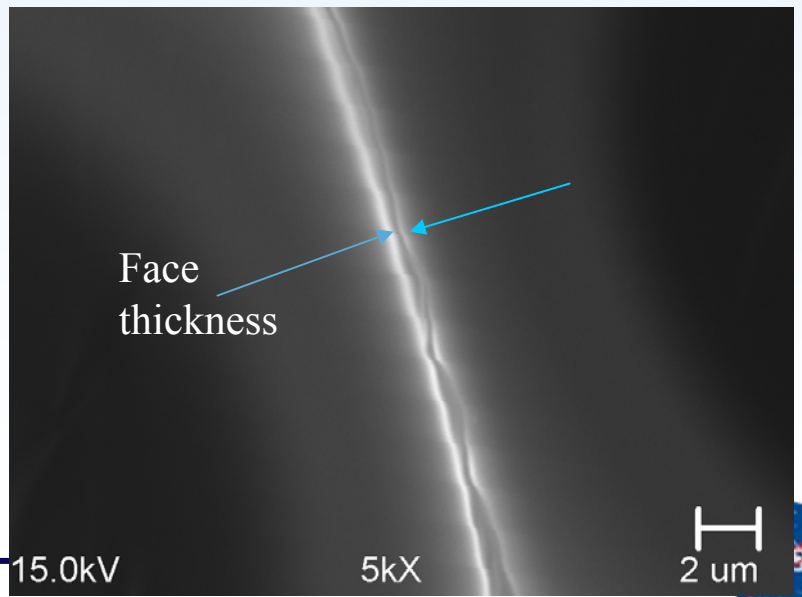
BX-265 Cell Dimensions

Vertices have 17 μm edge length and average radii of 18 μm



Deformed cell faces





Faces are thin membranes
0.1<t<1.0 μm

Development of Foam Unit Cell

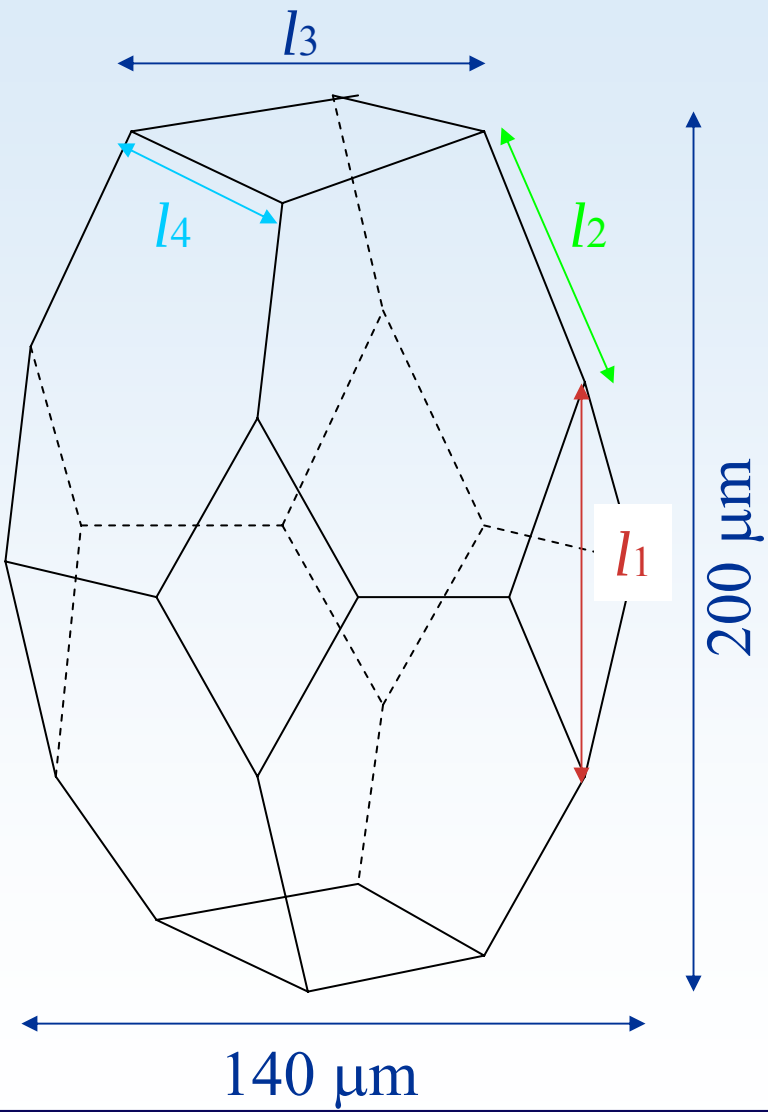
Elongated Tetrakaidechahedron

$l_1 = 109\ \mu m$

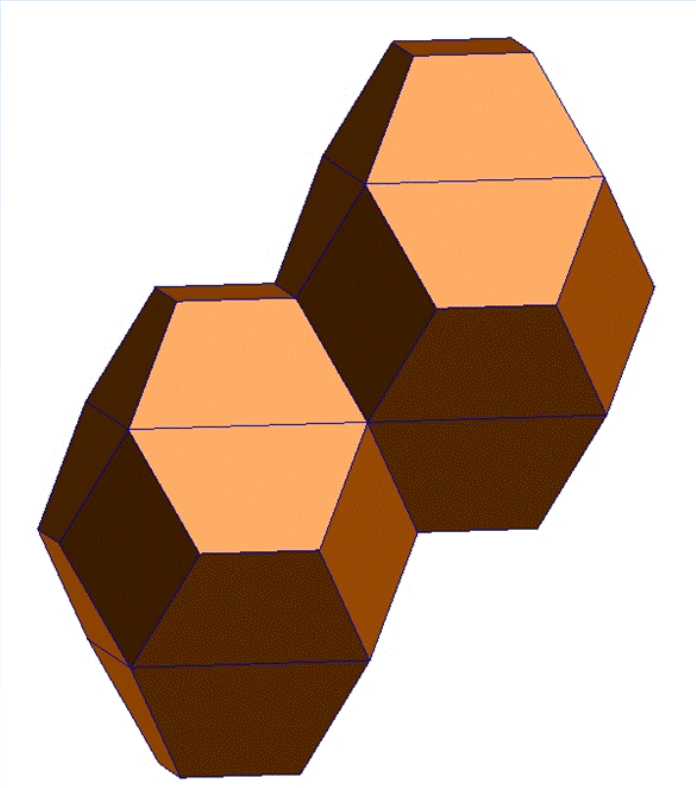
$l_2 = 69\ \mu m$

$l_3 = 39\ \mu m$

$l_4 = 28\ \mu m$



FEM Model



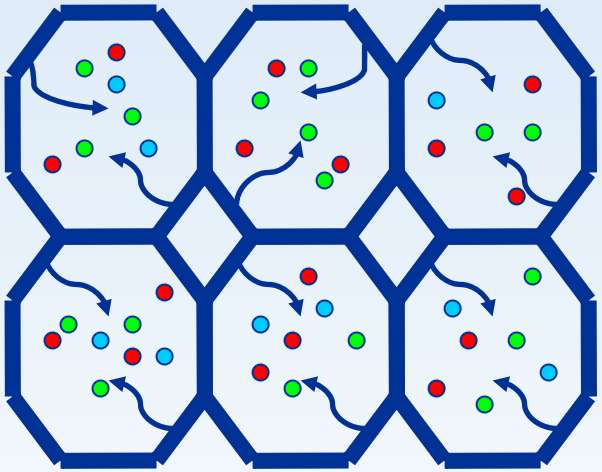
Example – Heating of Foam

- As foam heats (e.g. during ascent) the cell gas expands and exerts pressure on the polymeric skeleton (cell walls)
- Additionally the polymer decomposes and out-gasses to create more cell gas
- Cell pressure can eventually overwhelm polymer strength and cause cell failure

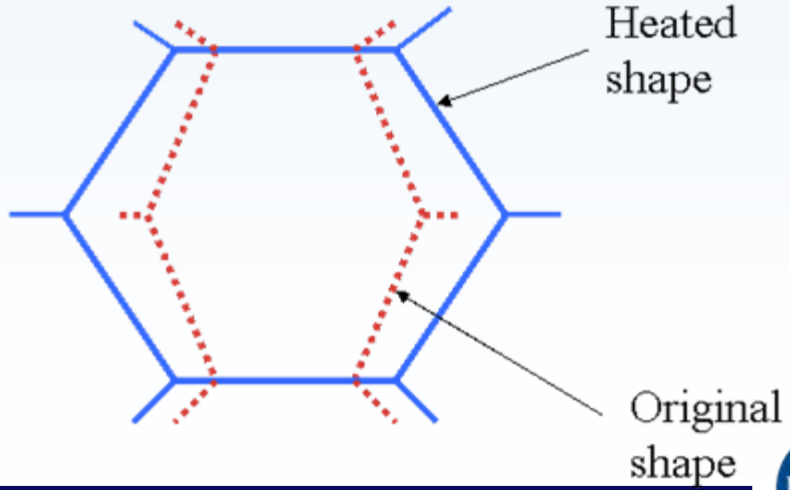
As the foam is a polymer, it undergoes several physical and chemical changes upon heating (namely out-gassing)

Out-gassing upon heating:

- weakens cell walls
- creates significant internal pressures
- results in a unique thermal expansion behavior

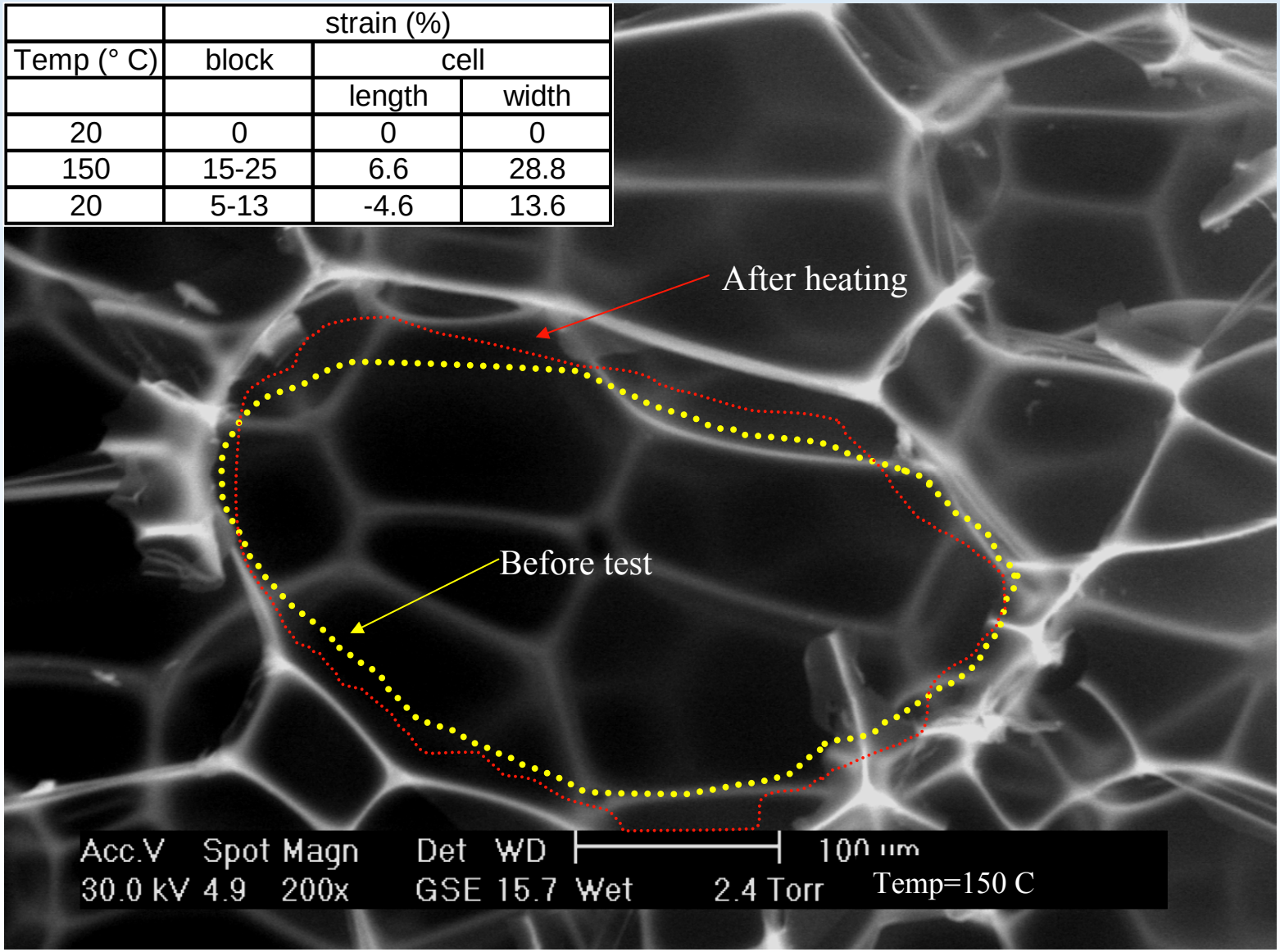


Cell pressure increase → cell expansion → cell failure



Hot Stage Experiments

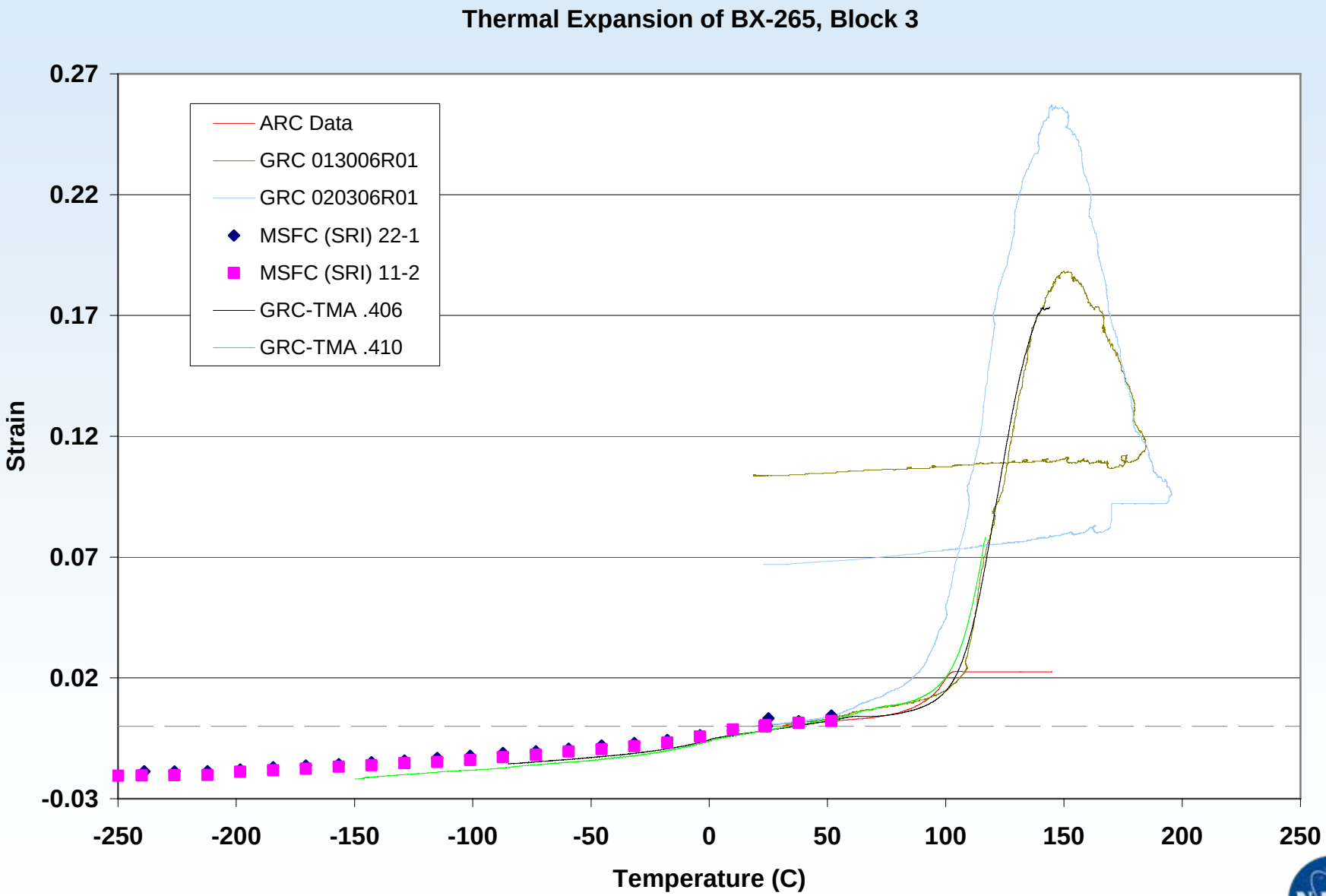
	strain (%)		
Temp (° C)	block	cell	
		length	width
20	0	0	0
150	15-25	6.6	28.8
20	5-13	-4.6	13.6



Cell expansion due to thermal treatment.

Cell expands mostly in the width direction (perpendicular to rise)

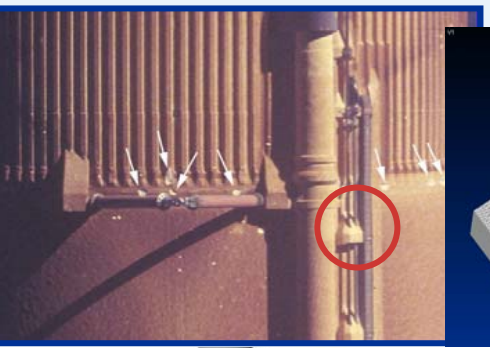
Thermal Expansion Tests

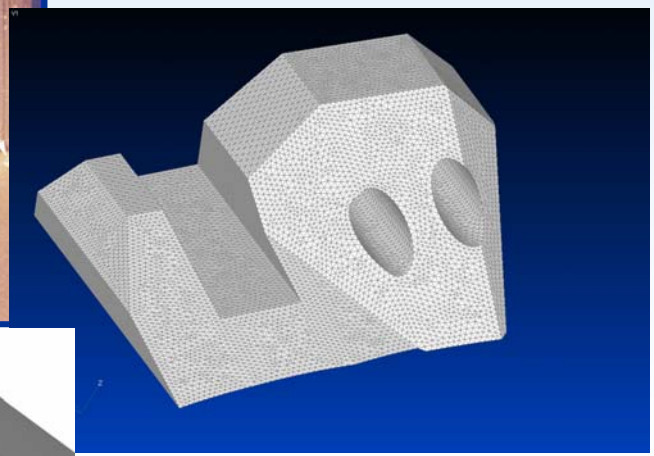


Modeling

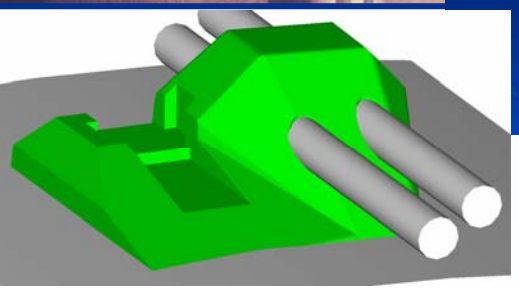
Current ET Foam Analysis Methods

- Finite Element-Based Analysis
- Models foam as a linear elastic solid
  - Generalized Hooke's law for linear elastic solid $\sigma_{ij} = C_{ijkl} e_{kl}$
- Material Testing for Property Characterization to feed FEA
  - Determine strength and stiffness as a function of temperature
  - Accounts for directional dependence



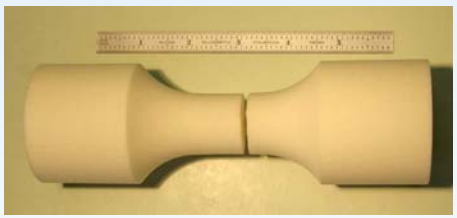


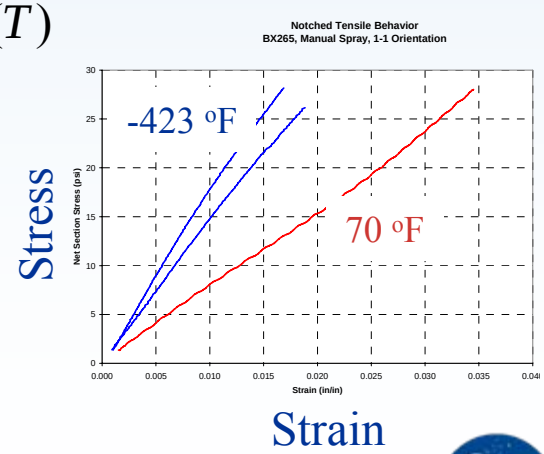
Finite Element Mesh of IFR



ET Ice Frost Ramp (IFR)

$C_{ijkl} = f(T)$



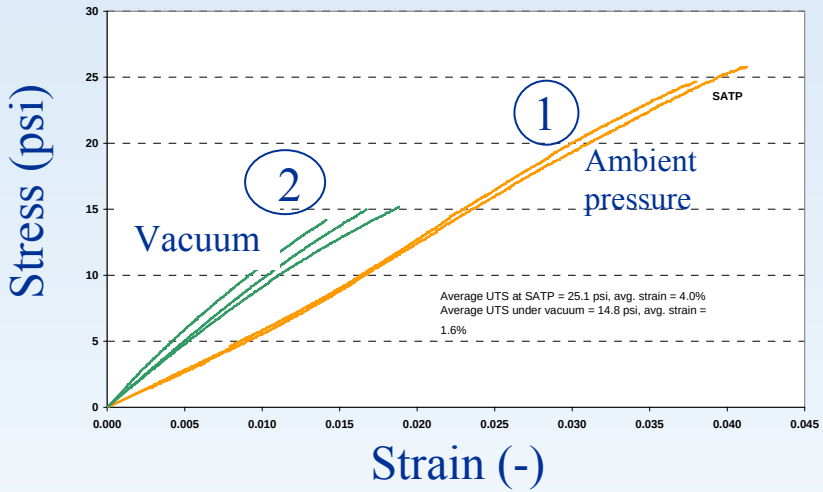


Material Physics/Mechanical Behavior

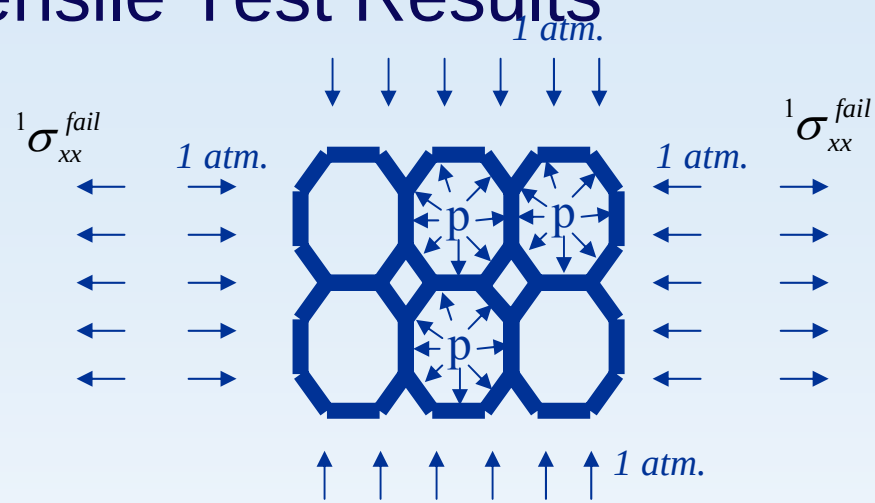
- Foam is a cellular material
  - Foam failure initiation is due to the solid skeleton stresses exceeding the strength of the polymeric walls and struts
- Elongated cells result in directional dependence
- Material behavior is highly temperature dependent
  - Polymer walls and struts "*soften*" with increasing temperature (e.g., glass transition temperature)
  - Temperature dependent internal cell gas pressure
  - Internal cell gas pressure increases due to out-gassing from the polymer solid skeleton at elevated temperatures.

The shortcoming with the current modeling approach is that it is not capable of distinguishing between the solid skeleton stresses and cell gas pressure contributions to the total stress and it is therefore not capable of predicting the solid skeleton stresses.

The Effect of Internal Cell Pressure is Evident in Simple Tensile Test Results

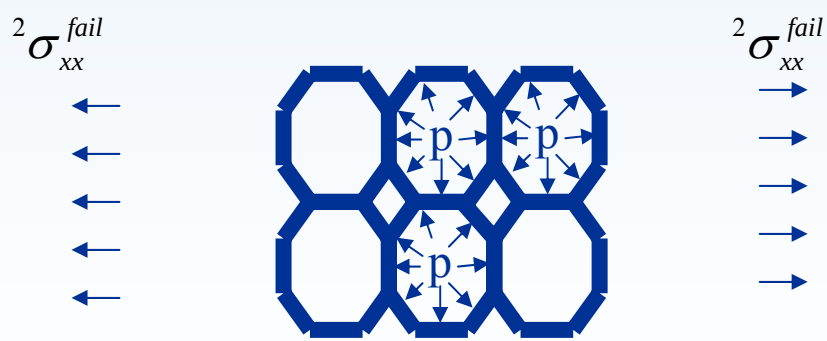


NCFI 24-124 Room Temperature Stress-Strain Response w/ and w/o vacuum



1 atm. amb. pressure

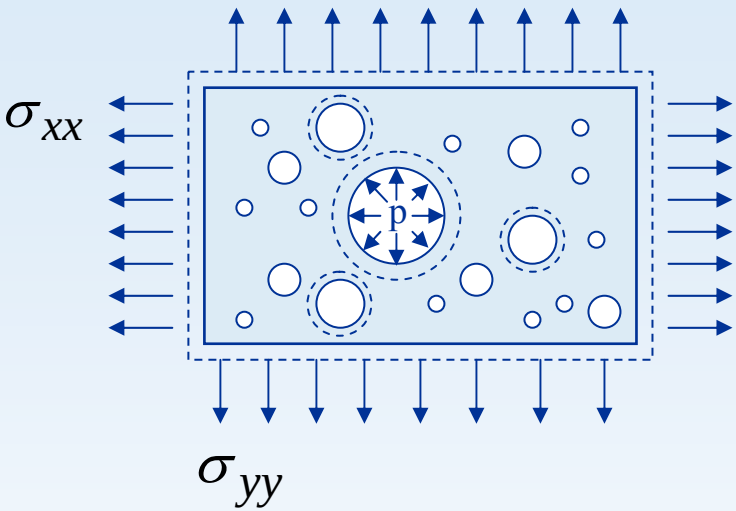
$$^{1}\sigma_{xx}^{fail} > {}^{2}\sigma_{xx}^{fail}$$



Vacuum

1 atm. is a large fraction of the material strength

Application of Porous Media Principles to Foam Thermo-mechanics



$$\sigma_{xx} = C_{11} e_{xx} + C_{12} e_{yy} - \alpha_{xx} p$$

$$\sigma_{yy} = C_{12} e_{xx} + C_{22} e_{yy} - \alpha_{yy} p$$

Generalized 3-D Constitutive Relations for Porous Media

$$\sigma_{ij} = C_{ijkl} e_{kl} - \alpha_{ij} p$$

C_{ijkl} the elastic stiffness tensor

α_{ij} stress-pressure coupling tensor

Internal Cell Gas Pressure is a Function of Temperature and Time-Temperature History

Cell Gas Pressure Calculated with the Ideal Gas Law

$$p = \tilde{\rho}_{gas} RT$$

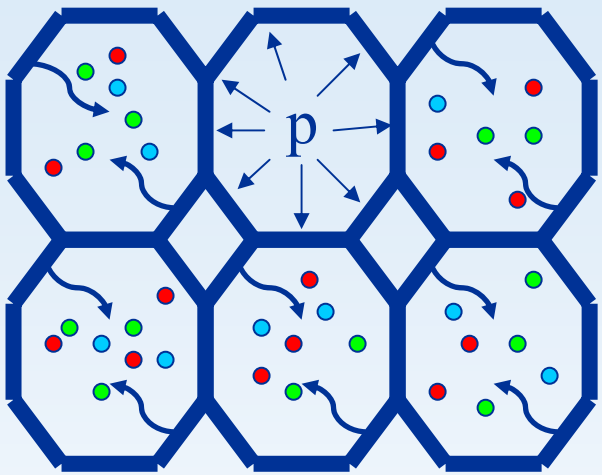
$\tilde{\rho}_{gas}$, the molar density of the gas in the cells, given by

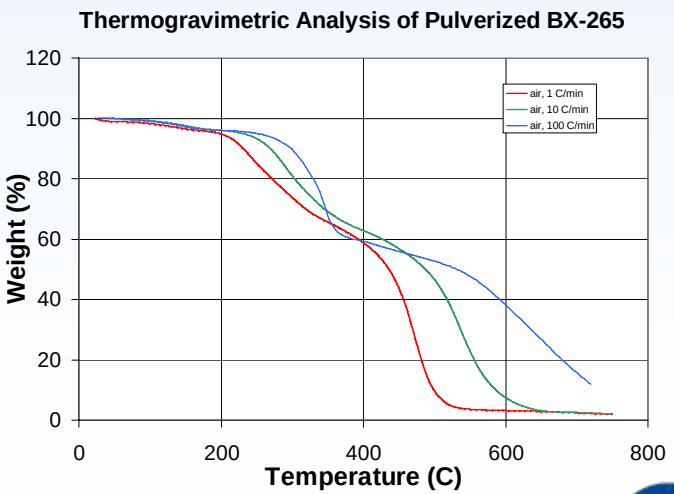
$$\tilde{\rho}_{gas} = \tilde{\rho}^{o}_{gas} + \int \frac{d\rho_s}{dt} dt$$

$\tilde{\rho}^{o}_{gas}$ the initial molar gas density

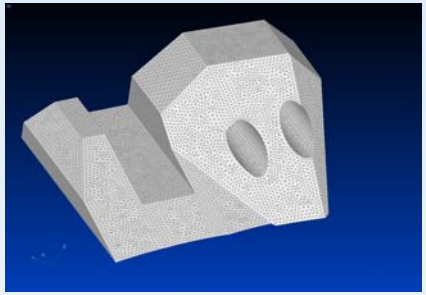
$\frac{d\rho_s}{dt}$ the rate of change of molar density due to out-gassing from the solid

Determined from TGA experiments



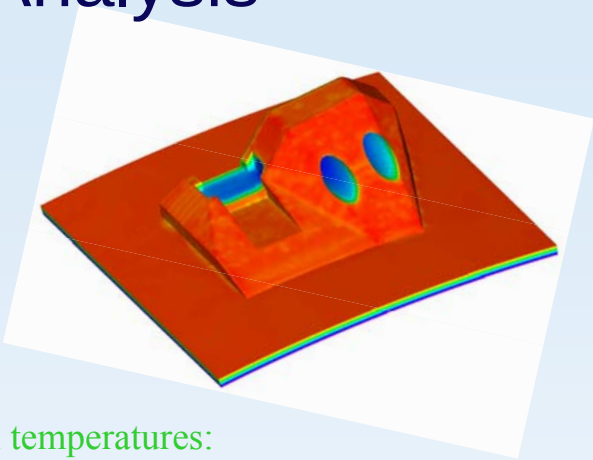


Flow Chart for Pore Pressure Analysis Approach



Finite Element Mesh of Foam Application

ABAQUS FE Thermal Analysis Solution



Nodal temperatures:
Temperature Distributions in the Foam

GRC-Supplied Subroutine

Nodal internal cell gas pressures:
Pressure Distributions in the Foam

ABAQUS FE Structural Analysis Solution

Solid Skeleton Stress Distribution

Summary

- Foam debris is liberated by multiple foam shedding mechanisms.
- Foam defects are a major player in foam loss and debris liberation.
- Fundamental studies of foam material behavior will help to improve Shuttle safety and reliability by improving our understanding of foam structural response, failure modes and debris liberation.
- Modeling External Tank foam material is much more difficult than modeling more traditional engineering materials.

Acknowledgments

This work is funded by MSFC. We appreciate the interactions with and support of ET engineers Scotty Sparks, Pat Rogers and Brian Steeve.