Principles of Cryogenic Adhesive Bonding

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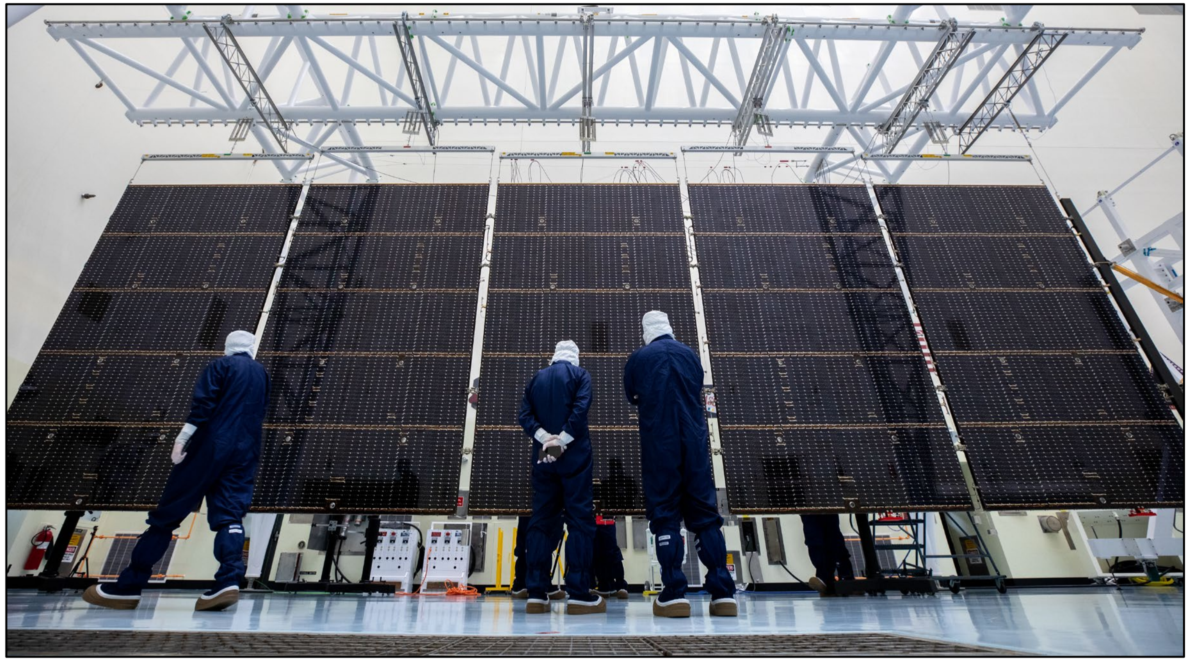
Introduction

Missions to outer planets and cryogenic instruments necessitate bonds that will survive cryogenic temperatures

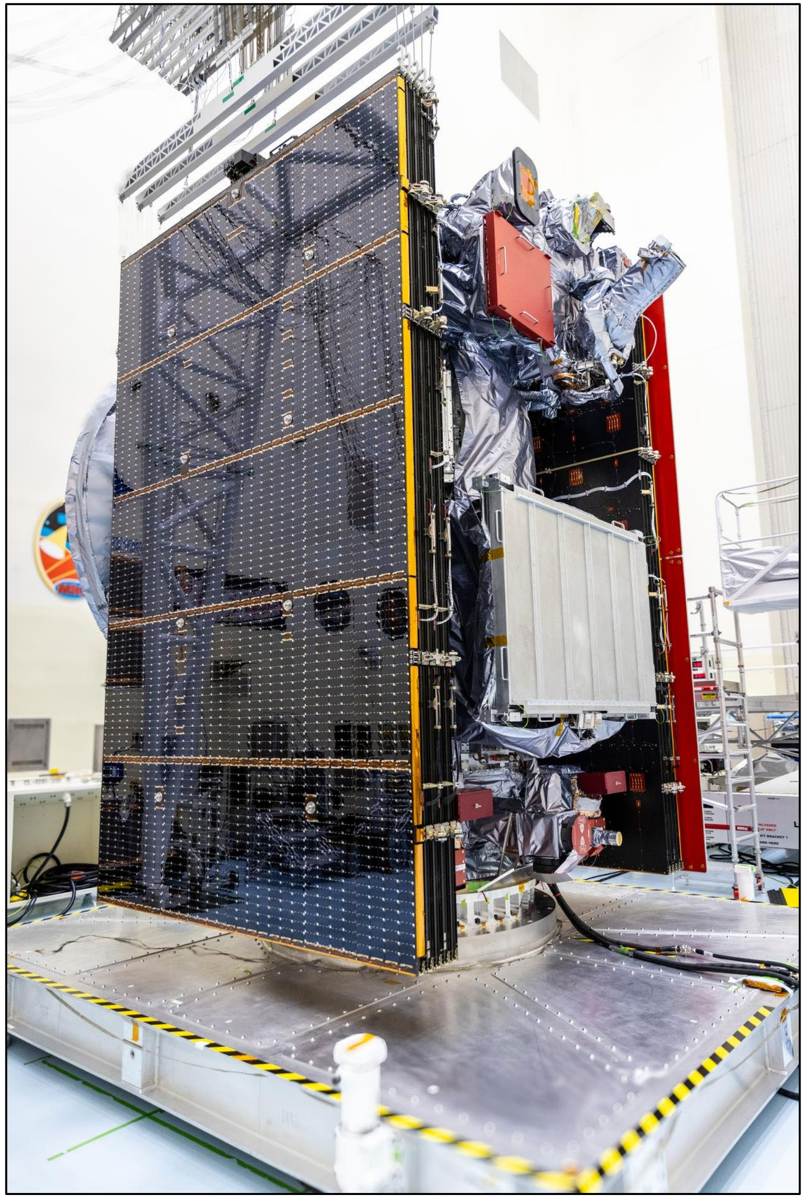
- Critical for maintaining structural integrity in deep space
- Essential for instruments operating sub-100K

It is necessary to account for system environmental requirements and optical tolerances

Recent Applications



Solar Arrays for Europa Clipper during Deployment Testing at KSC
Image Credit: NASA/Ben Smegelsky
https://science.nasa.gov/mission/europa-clipper/europa-clipper-multimedia/



Europa Clipper during Deployment Testing at KSC
Image Credit: NASA/Frank Michaux
https://science.nasa.gov/mission/europa-clipper/europa-clipper-multimedia/

Recent Applications

NEO Surveyor in Deep Space (Artists Concept)
https://science.nasa.gov/mission/neo-surveyor/multimedia

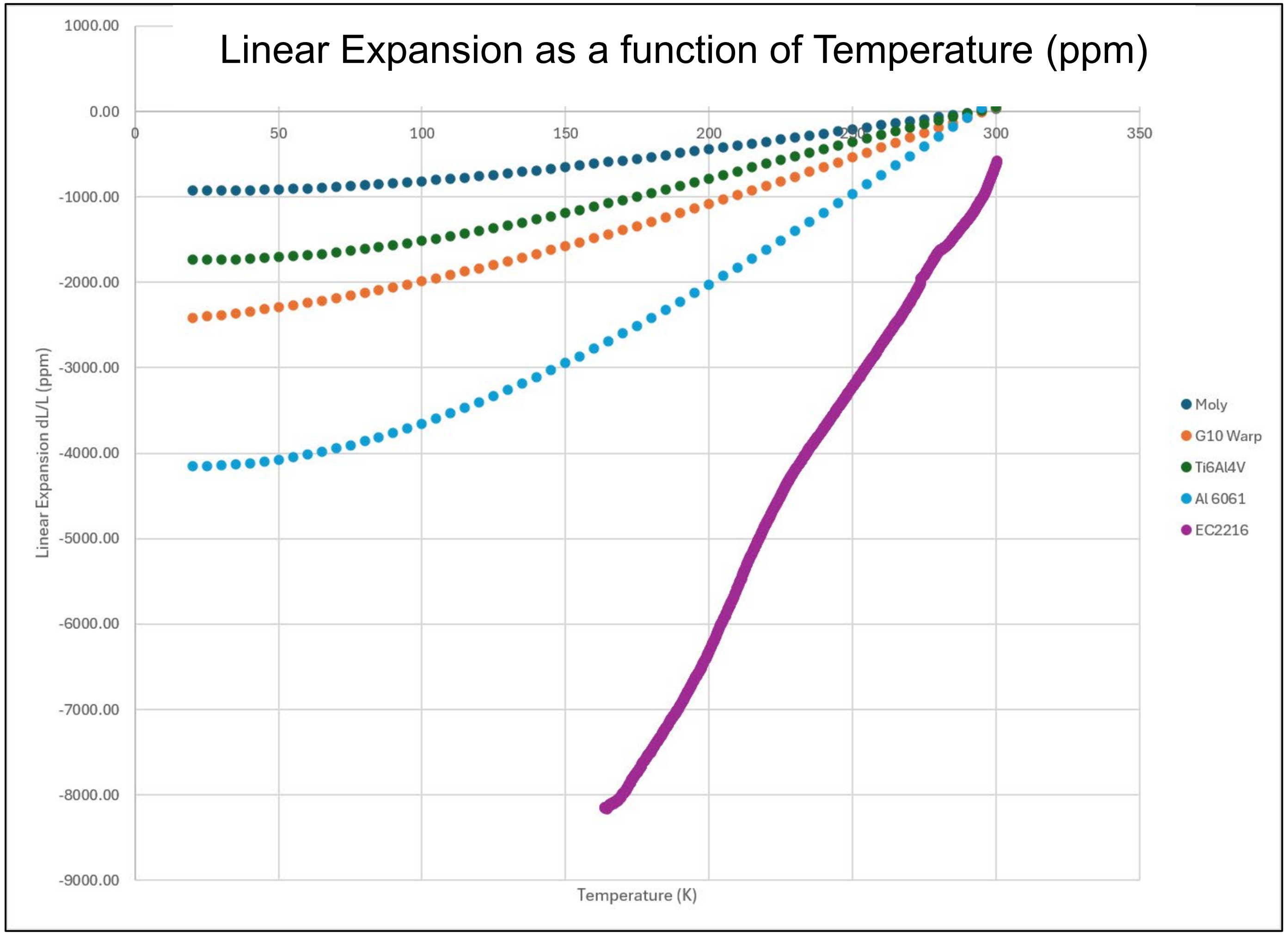
Aluminum telescope during integration
Image Credit: Space Dynamics Laboratory/Allison Bills
https://science.nasa.gov/mission/neo-surveyor/multimedia

Bonding Application Analysis

Early substrate identification is necessary

- Identify substrate combinations for thermal compatibility
    - Mismatch in Coefficient of Thermal Expansion (CTE) is a primary failure driver
- Common substrates include glass, composites, single crystal optics, and specialty metals
    - Glass and Glass-Ceramics, such as Zerodur, BK-7, CaF2
    - Molybdenum and Molybdenum TZM
    - Aluminum and Aluminum alloys
    - Titanium and Titanium Alloys
    - Invar

The CTE Challenge



Adhesives produce more pronounced dimensional changes than metals

Contraction is essentially complete by 20K

Most thermal contraction occurs by the time the system reaches 77K.

CTE mismatch induces fractures in the bondline at extreme low temperatures

Thermal stress causes distortions in sensitive optics

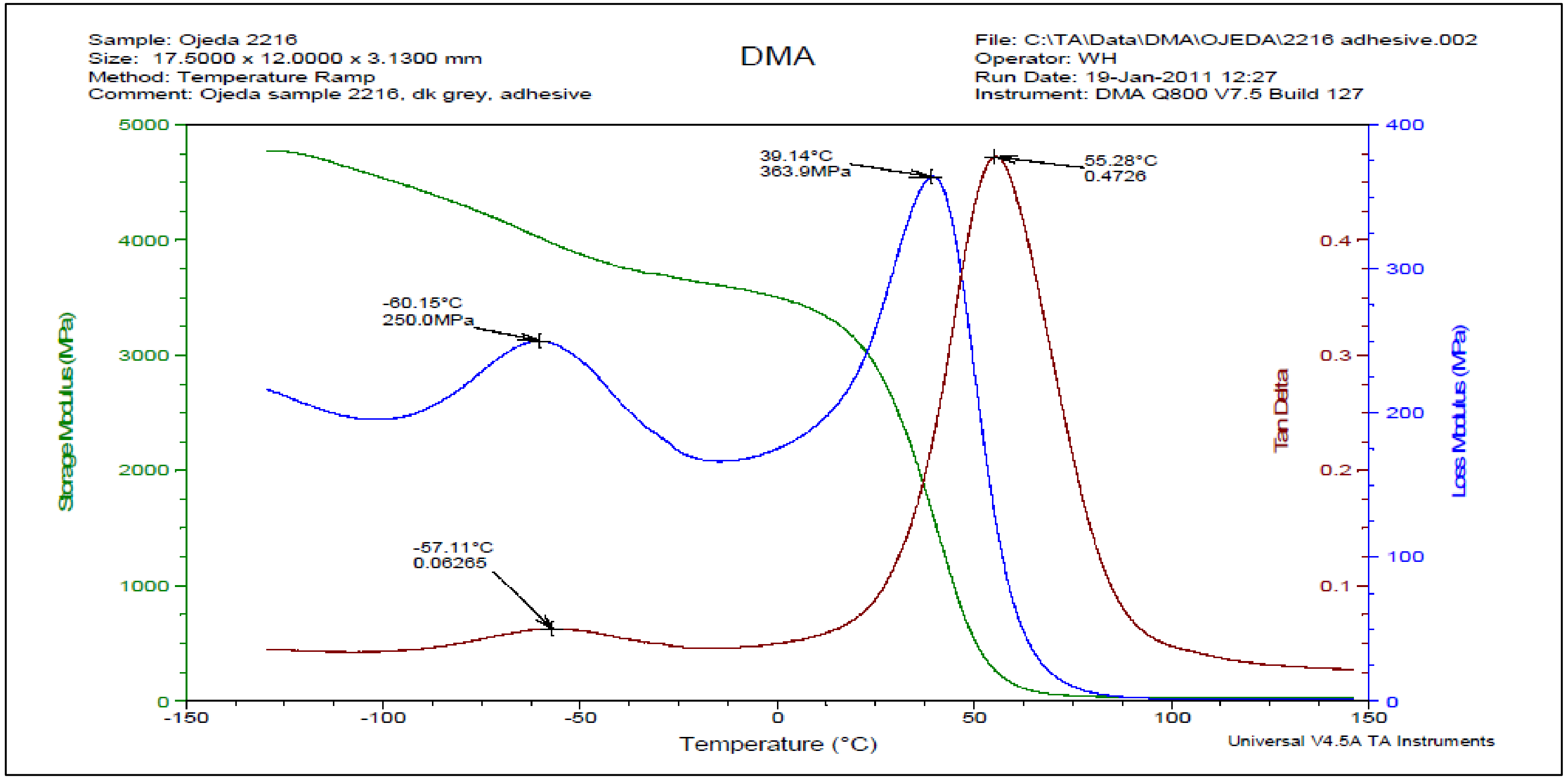
Ref NIST and JPL data [1] and [3]

Thermal Stress Impact

Glass transition temperature (T_g) dictates where largest mechanical changes occur

Fillers can be used to judiciously tune the adhesive CTE to match adherends

- $Zr(WO_4)_2$
- Aramid
- MPGF (Pitch Based Graphite)



Joint Design (I): Maximizing Reliability

Bond joint area should be designed as large as possible

Overlaps must be sized for the worst-case environment: look at entire mission profile

- May not be at launch
- May not be during planned operation (safe hold)
- *Probably* not during ground testing

Adhesive properties shift significantly with temperature reduction

Geometry is often determined by strength and wavefront error requirements

Joint Design (II): Loading Modes

All bond joints should be designed in shear if possible

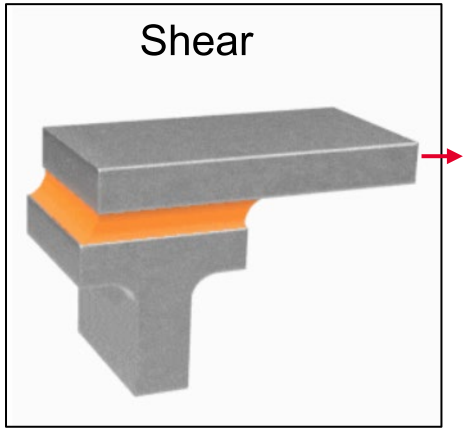
Adhesives generally have limited toughness at cryogenic temperatures

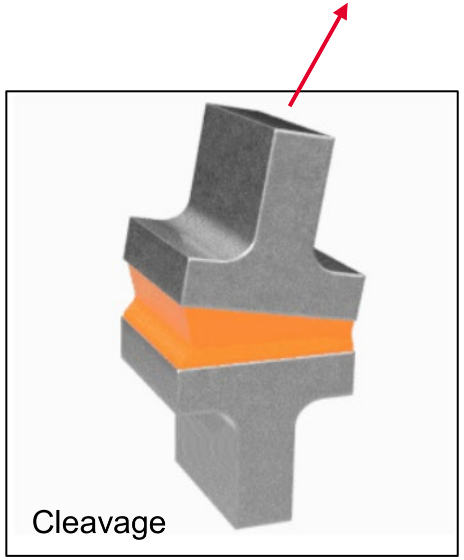
Loads should never be carried in peel or cleavage

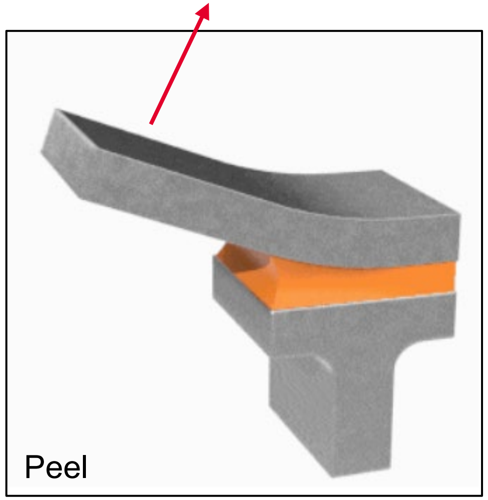
Shear stress distribution is inherently nonuniform for structural joints

- Consider local thickening at overlap ends to alleviate peel
- Consider tapering adherends at overlap ends to alleviate peel

Joints required to act as vacuum seals should be in compression







Images from 3M [3]

Epoxies for Cryogenic Use

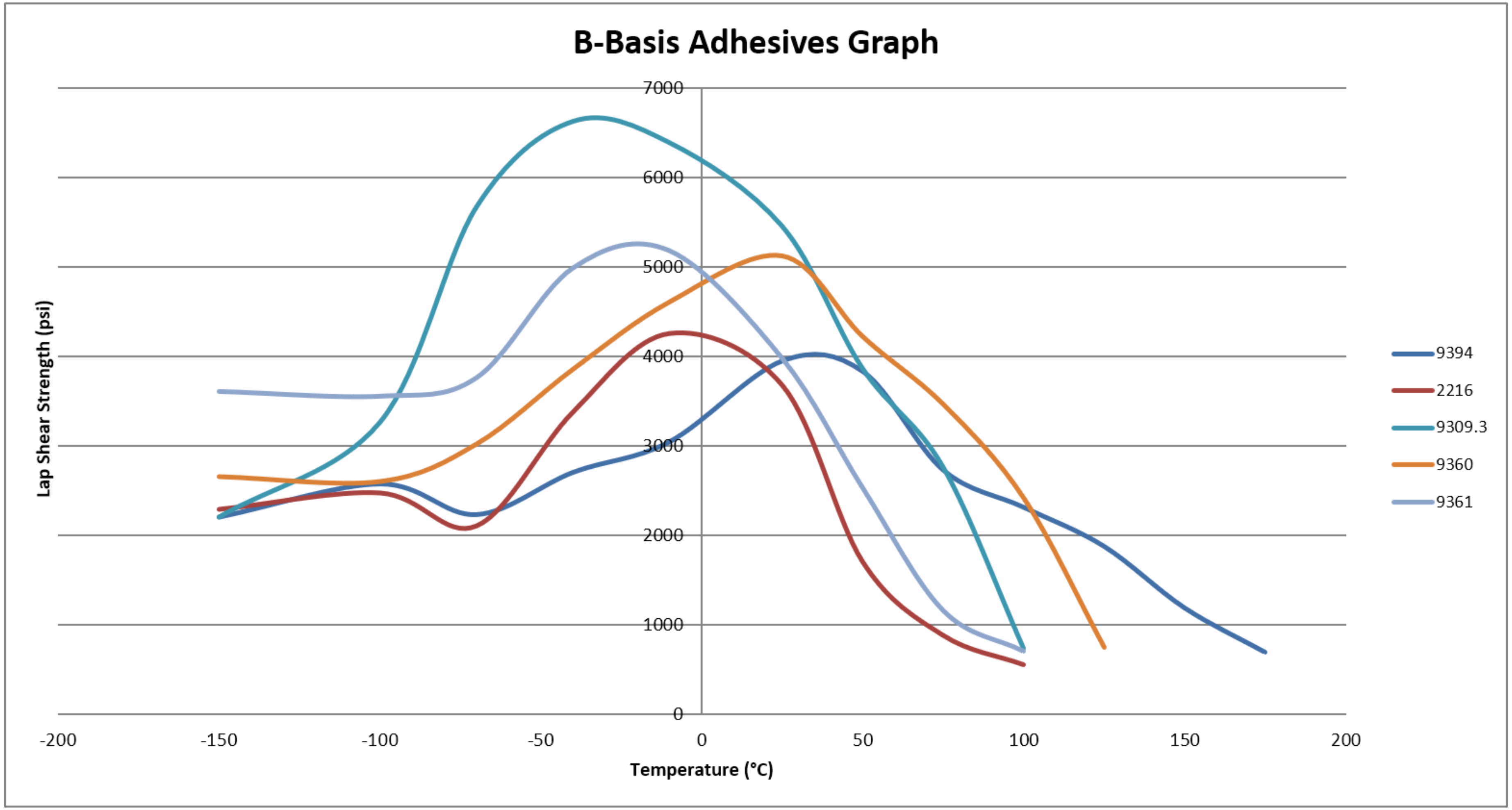
Characterized by high shear strength and low shrinkage

Become brittle at low temperatures as modulus increases

Fillers are commonly used to reduce CTE and improve conductivity

Cure cycles establish the "stress-free" state of the bond

Specific Epoxy Performance



JPL Lap Shear Test Data [2]

Silicones: Low Modulus Solutions

Often selected for having the lowest possible T_g

Remain resilient and provide better strain accommodation

Must be used with recommended primers to ensure adhesion

Avoid RTV silicones that liberate acetic acid (causes corrosion)

Specific Silicone Performance

Name	Type	Shear Strength (psi)	Tg °C
		RT	
RTV-566	Silicone	475	-115
CV-2566	Space Silicone	700	-115
SCV-2585	Space Silicone	500	-115
DC93-500	Silicone	475	-120

Average values from datasheet and JPL internal testing

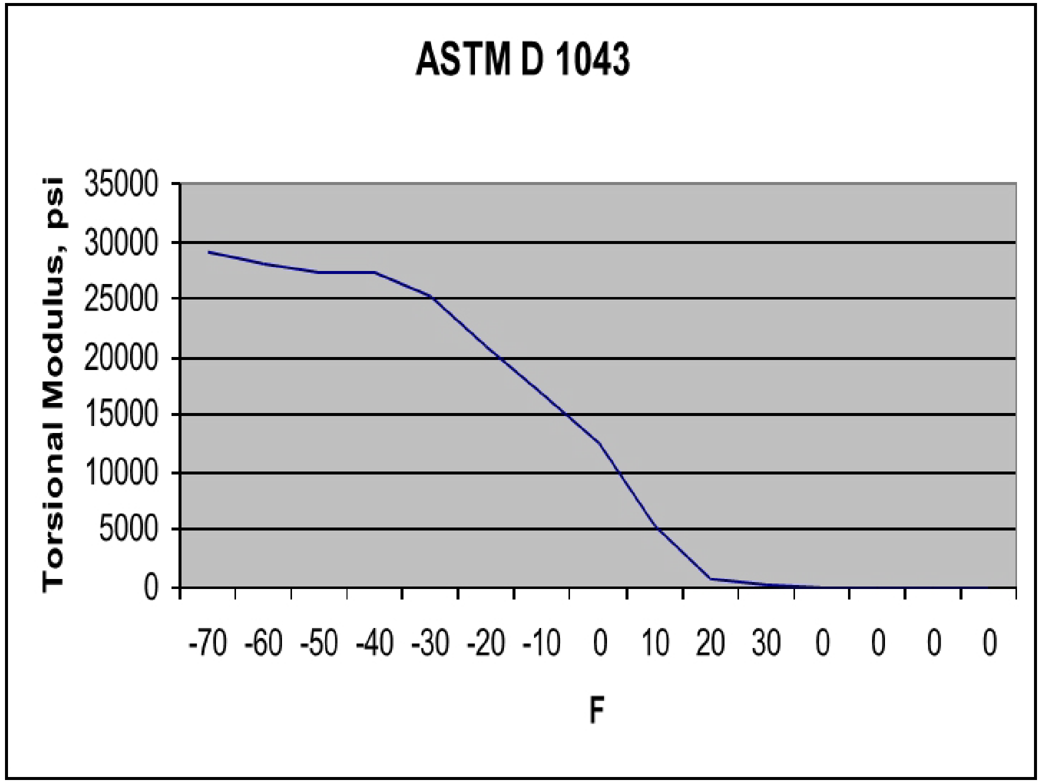
Polyurethanes (PU) at Cryo

Provide a balance of toughness and low-temperature flexibility

Highly sensitive to moisture during the uncured state

Name	Type	T_g °C	Average CTE ppm/°C below Tg
Arathane 5753	Space-Grade Polyurethane	-65	76
Solithane 113/C113-300	Polyurethane Potting	-10	126

Solithane 113 Modulus versus Temperature



Reference Technical Datasheets

Optical Bonding (I): Stability

Bond joint size is often dictated by wavefront error requirements

Thermally induced stresses can cause distortions in optics

- Use low T_g adhesives to improve resiliency in optical mounts
- Low modulus adhesives reduce stress

Index matching and clarity must be maintained through thermal soak

Optical Bonding (II): Glass-to-Metal

Standard interfaces include glass-to-titanium, aluminum or Mo TZM

Large differences in CTE between glass and metal must be managed

Silicones are preferred for mounting to absorb mismatch strains

Adhesive thickness is critical to prevent crushing the optic

Surface Preparation Protocols

The first step is defining bonding surfaces

Preparation success is the foundation of bond reliability

Follow specification JPL D-51978 or NASA equivalent for proper prep techniques

Faying surfaces must be completely clean and free of contaminants

Cure Cycle Management

Bonding and curing should occur under ambient conditions

Ambient cure minimizes thermal mismatch loads at the stress-free state

Complete cure is mandatory for optimum adhesion

Elevated temperature cycles establish the stress-free temperature of the bond

UV Curing systems may provide a room temperature set point while allowing some elevated post-cure

Cryogenic Testing & Validation

Tests should be made at coupon level and higher fidelity

Use simulated environments and loading conditions for validation

Thermal cycling is required to verify elastomeric properties

Witness samples (coupons) should be processed identically to flight hardware

Summary Checklist for Cryo-Bonds

[ ] Match CTE of adhesive to adherends as closely as possible

[ ] Select adhesive with low T_g while possessing sufficient mechanical properties

[ ] Size overlaps for worst-case mechanical/thermal loads

[ ] Verify elastomeric properties through thermal cycling

[ ] Ensure outgassing meets TML/CVCM requirements

References

1. National Institute of Standards and Technology, Cryogenic Material Properties, URL: https://trc.nist.gov/cryogenics/materials/materialproperties.htm
2. Ojeda, C. E., Oakes, E. J., Hill, J. R., Aldi, D., and Forsberg, G. A., "Temperature Effects on Adhesive Bond Strengths and Modulus for Commonly Used Spacecraft Structural Adhesives," *SAMPE 2011*, Long Beach, CA, May 2011
3. Common Stress Types in Adhesive Joints, 3M

https://www.3m.com/3M/en_US/bonding-and-assembly-us/resources/science-of-adhesion/common-stress-types-adhesive-joints/