# MATERIAL IRRADIATION STUDIES FOR HIGH-INTENSITY PROTON BEAM TARGETS

## BNL AGS/BLIP/Hot Cell FACILITY

**Nicholas Simos, BNL**

**H. Kirk, P. Thieberger, H. Ludewig, P. Trung (BNL)**

**K. McDonald, Princeton U.**

**J. Sheppard, SLAC**

**K. Yoshimura, KEK**

# SCOPE

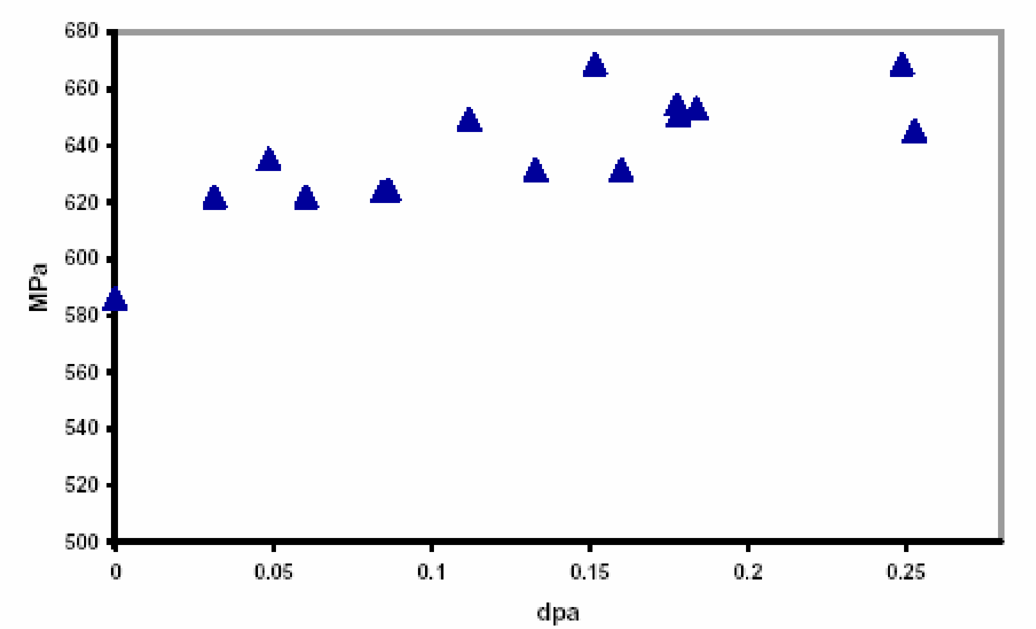
- ASSESS the effects of proton irradiation on material properties that are key in the design and operation of high power targets

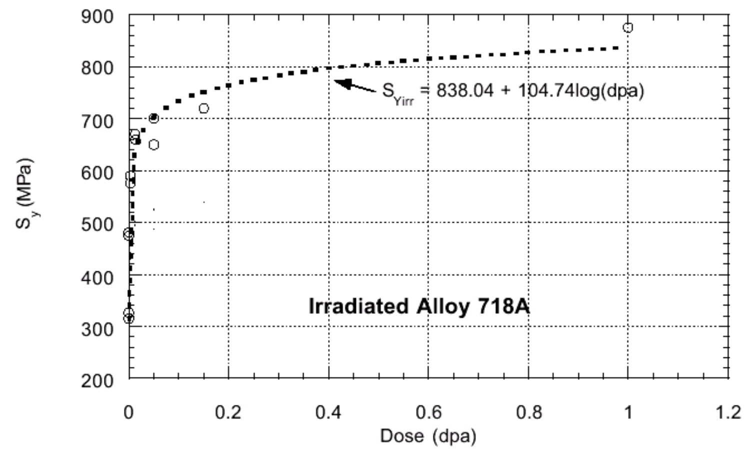
- Is Carbon-Carbon the alternative to Graphite?

- How about these new “smart” materials? (Gum metal, AlBemet, etc.)

# PAST STUDIES: Super-Invar Irradiation

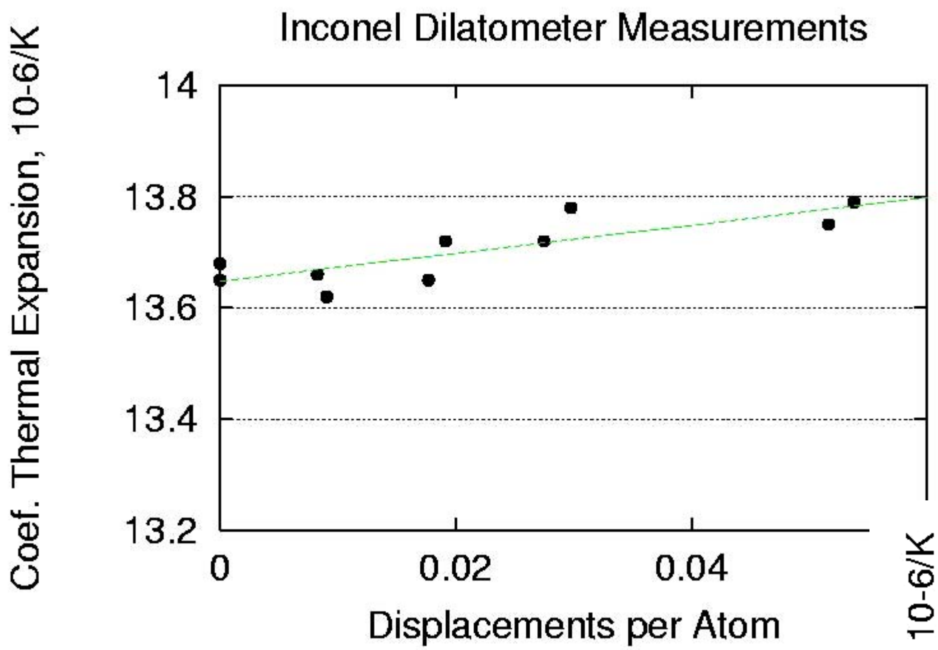
## What did we learn ?

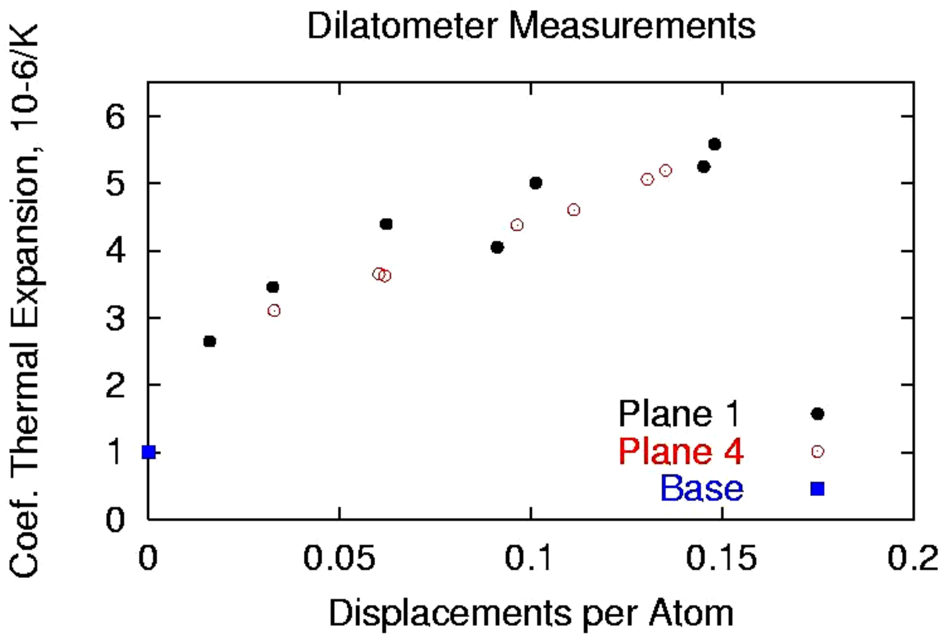



**Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A**

# Some Alloys Change Drastically and some Don't



# PHASE-II TARGET MATERIAL STUDY

## Material Matrix

**Carbon-Carbon composite**

**GRAPHITE (IG-43)**

**Titanium Ti-6Al-4V alloy**

**Toyota "Gum Metal"**.

**VASCOMAX**

**AlBeMet**

**Nickel-Plated Aluminum**

## TESTS (on-going + upcoming)

**Mechanical property changes**

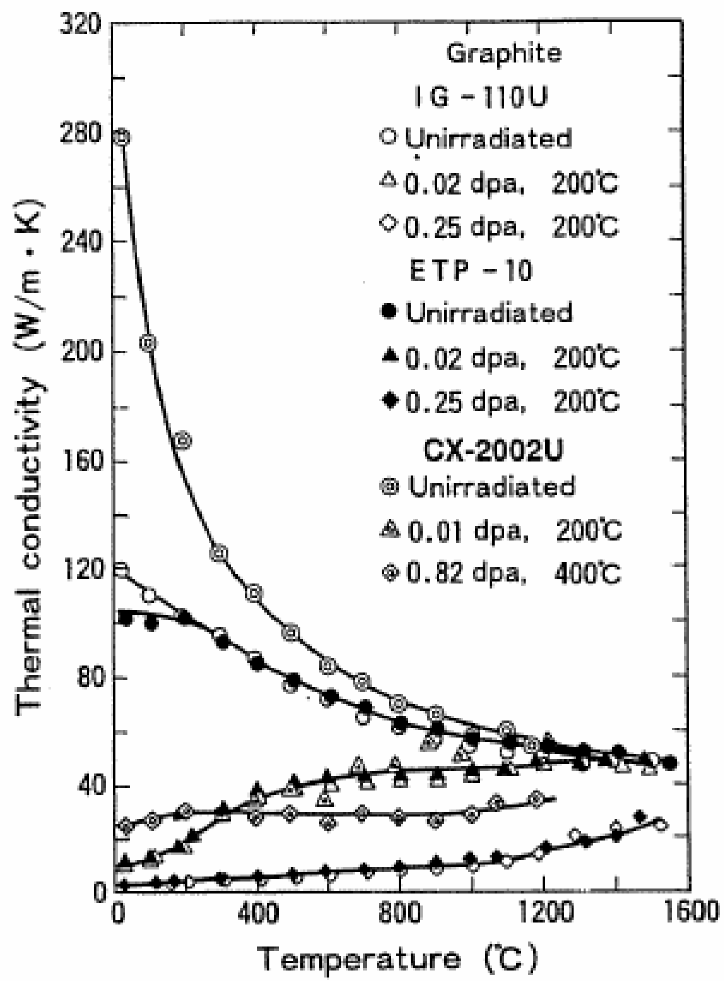
- Ductility loss
- Strength loss/gain
- Fracture toughness

**Physical property changes**

- CTE
- Diffusivity
- Heat capacity

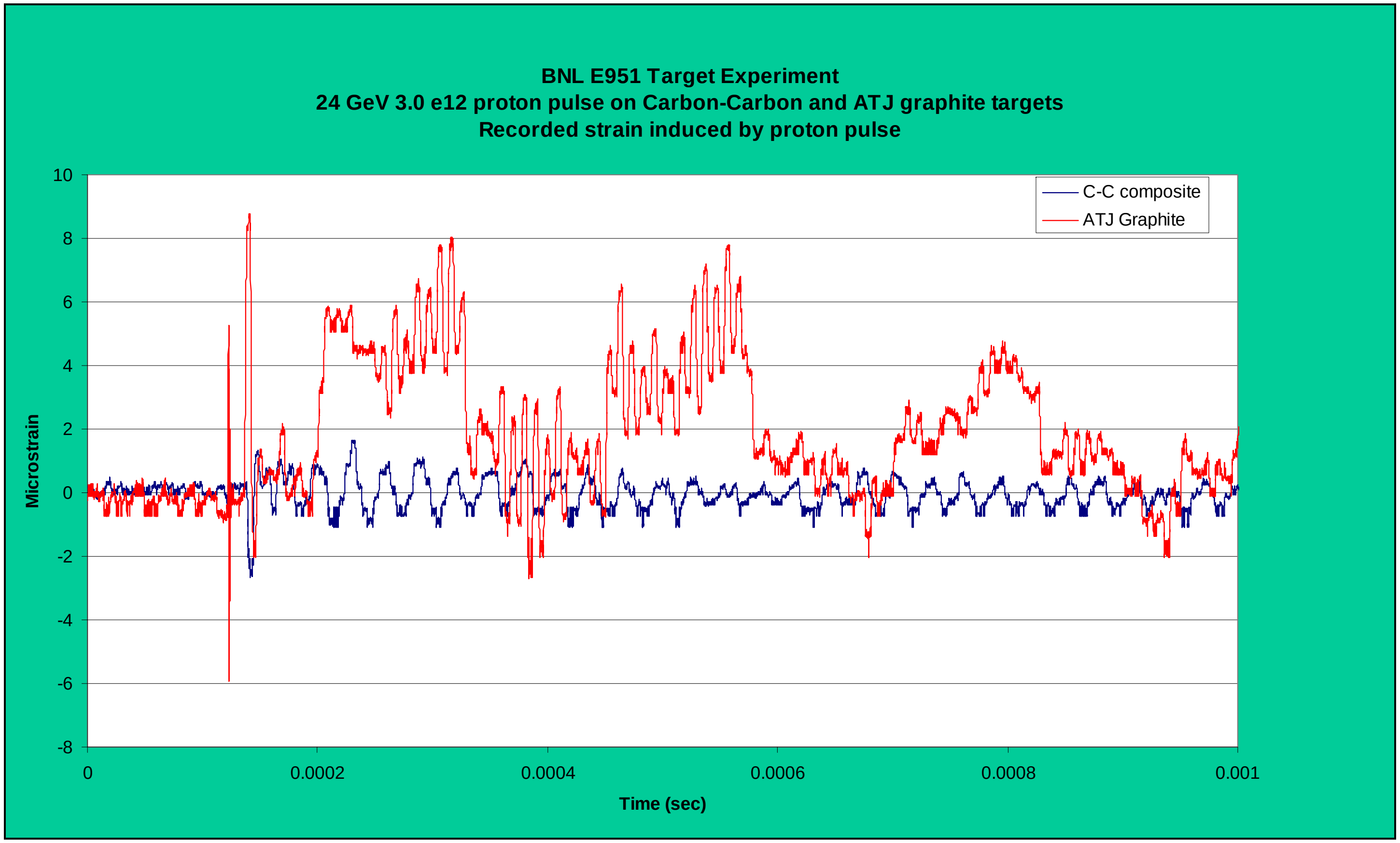
**Shock resilience**

# WHY DO WE WANT TO DO THESE TESTS?



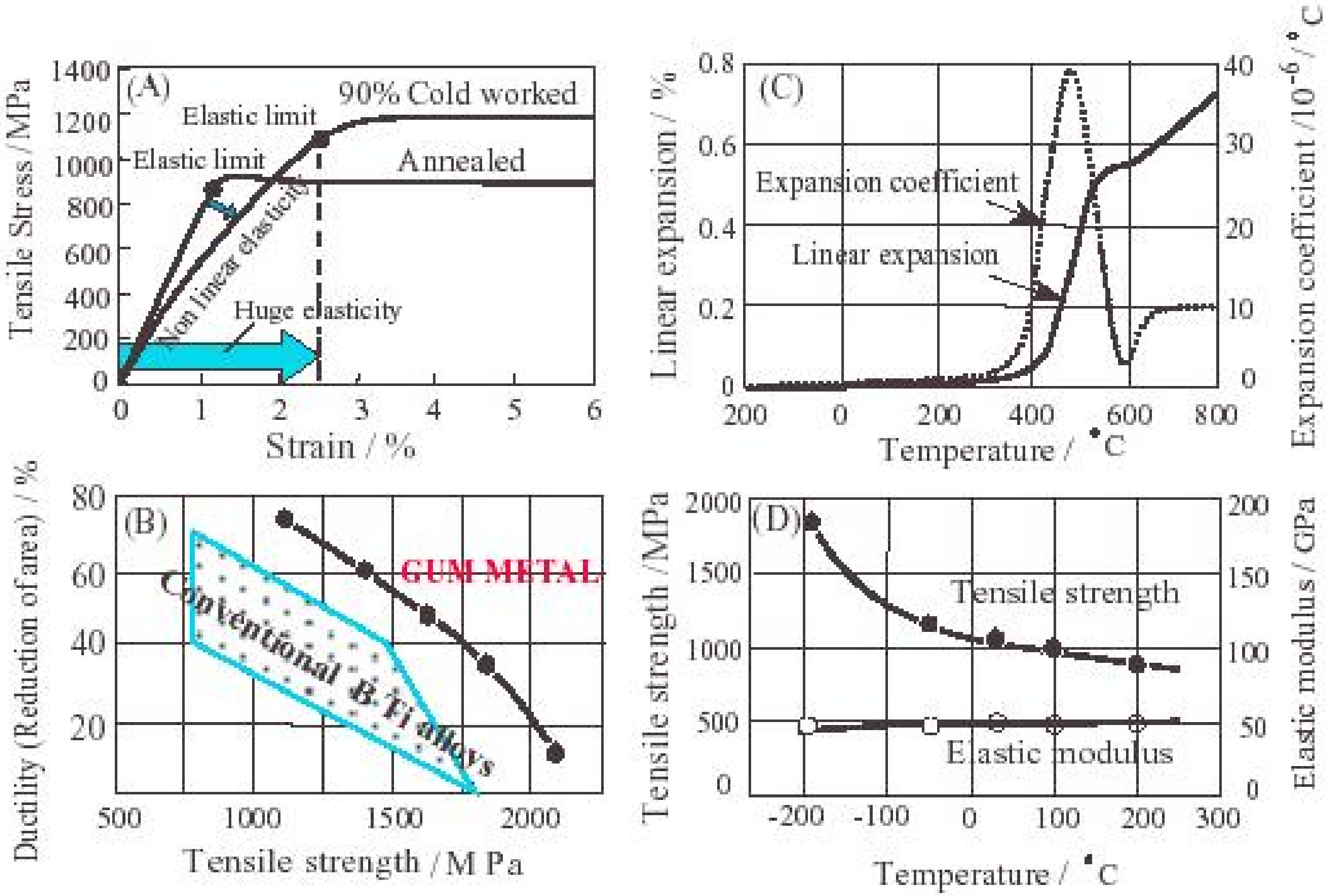
Thermal conductivity of neutron-irradiated graphites.

# ATJ Graphite vs. Carbon-Carbon Composite



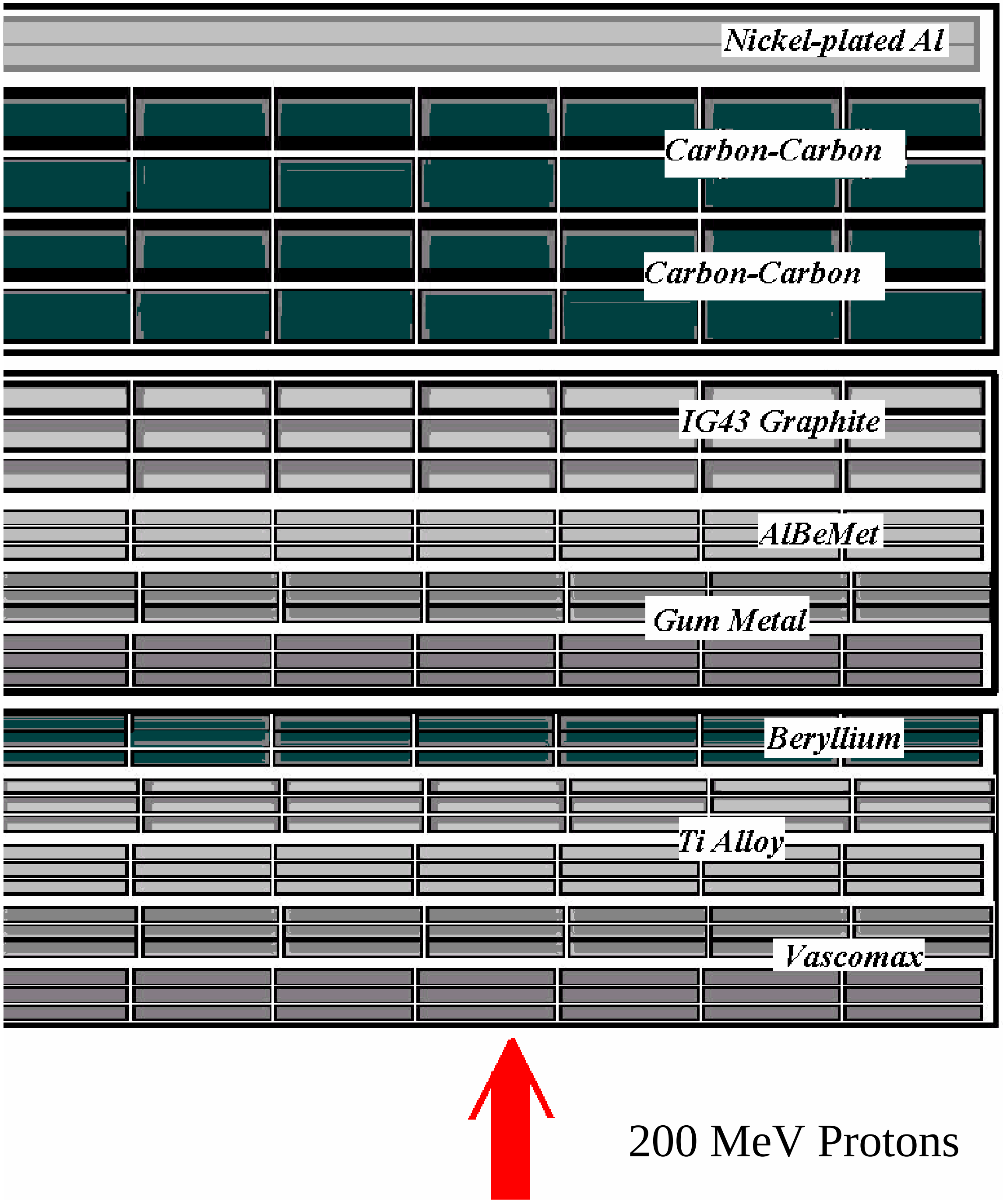

E951 assessment: CC is the way to go
if we care to absorb shock.
Do things hold true after irradiation?

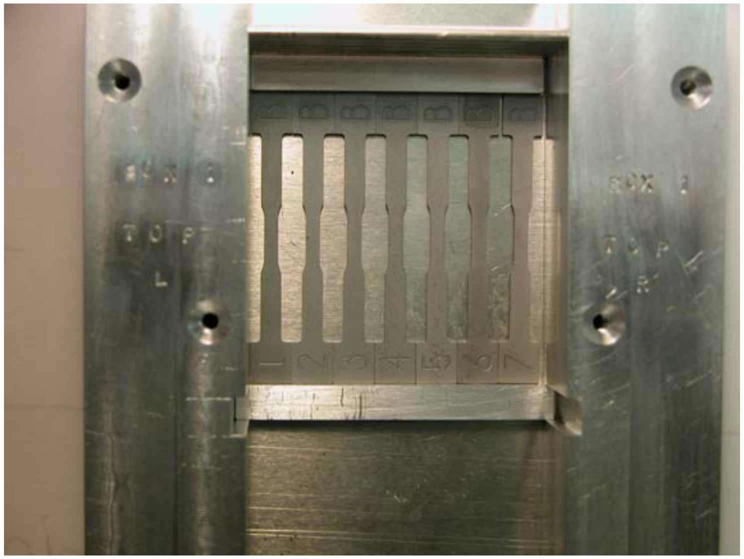
# Gum Metal (Toyota Ti alloy)

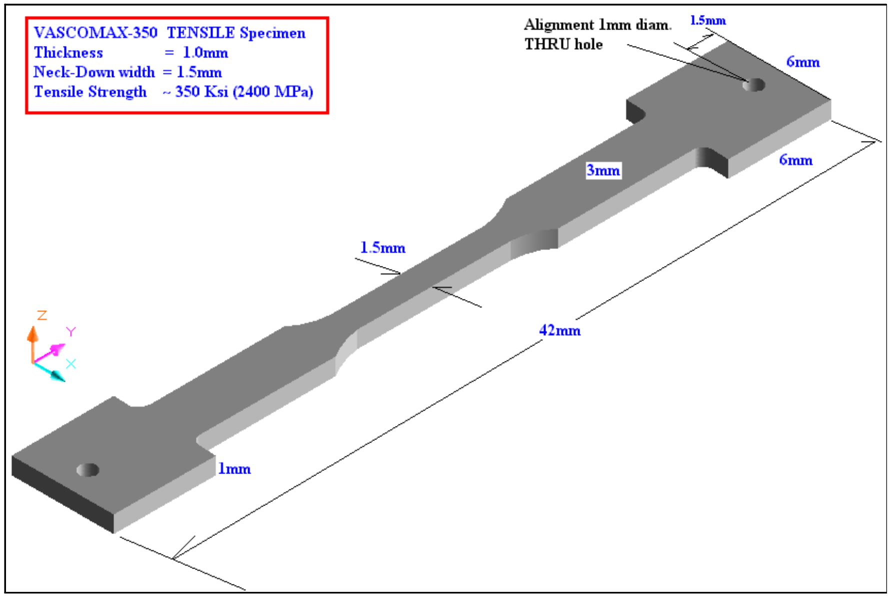


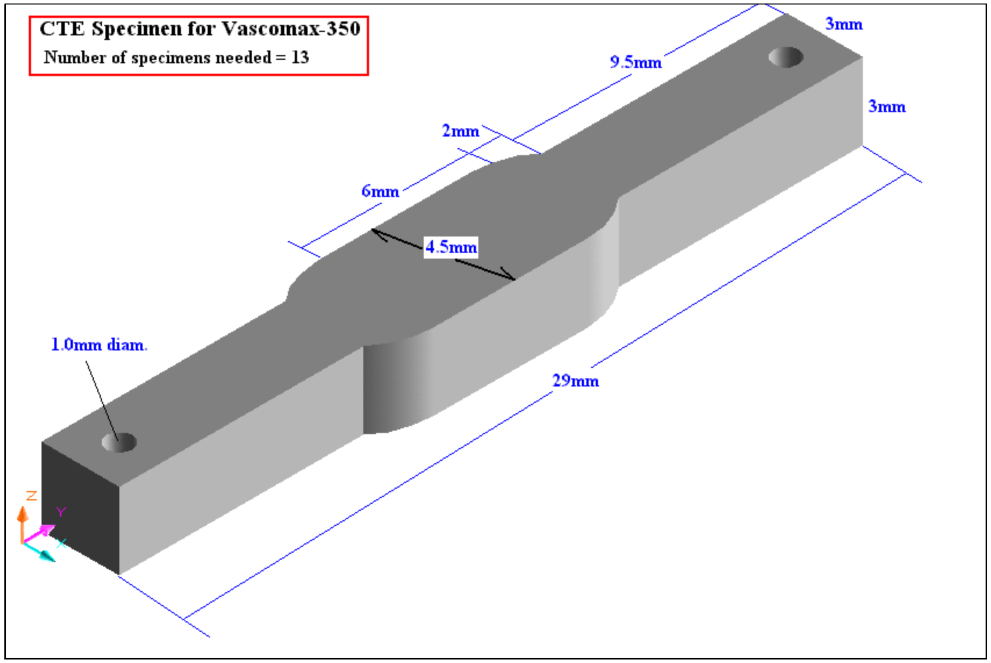
# AlBeMet® Property Comparison

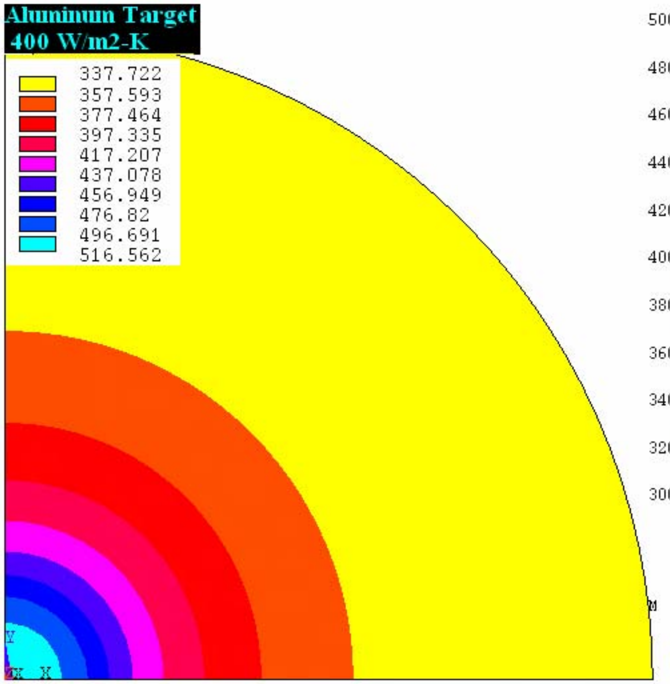
| Property | Beryllium S200F/AMS7906 | AlBeMet AM16H/AMS7911 | E-Material E-60 | Magnesium AZ80A T6 | Aluminum 6061 T6 | Stainless Steel 304 | Copper H04 | Titanium Grade 4 |
|---|---|---|---|---|---|---|---|---|
| Density lbs/cuin (g/cc) | 0.067 (1.85) | 0.076 (2.10) | 0.091 (2.51) | 0.065 (1.80) | 0.098 (2.70) | 0.29 (8.0) | 0.32 (8.9) | 0.163 (4.5) |
| Modulus MSI (Gpa) | 44 (303) | 28 (193) | 48 (331) | 6.5 (45) | 10 (69) | 30 (205) | 16.7 (115) | 15.2 (105) |
| UTS KSI (Gpa) | 47 (324) | 38 (262) | 39.3 (273) | 49 (340) | 45 (310) | 75 (515) | 45 (310) | 95.7 (660) |
| YS KSI (Gpa) | 35 (241) | 28 (193) | N/A | 36 (250) | 40 (276) | 30 (205) | 40 (275) | 85.6 (590) |
| Elongation % | 2 | 2 | < .05 | 5 | 12 | 40 | 20 | 20 |
| Fatigue Strength KSI (Gpa) | 37.9 (261) | 14 (97) | N/A | 14.5 (100) | 14 (95) | N/A | N/A | N/A |
| Thermal Conductivity btu/hr/ft/F (W/m-K) | 125 (216) | 121 (210) | 121 (210) | 44 (76) | 104 (180) | 9.4 (16) | 225 (391) | 9.75 (16.9) |
| Heat Capacity btu/lb-F (J/g-C) | .46 (1.95) | .373 (1.56) | .310 (1.26) | .251 (1.05) | .214 (.895) | .12 (.5) | .092 (.385) | .129 (.54) |
| CTE ppm/F (ppm/C) | 6.3 (11.3) | 7.7 (13.9) | 3.4 (6.1) | 14.4 (26) | 13 (24) | 9.6 (17.3) | 9.4 (17) | 4.8 (8.6) |
| Electrical Resistivity ohm-cm | 4.2 E-06 | 3.5 E-06 | N/A | 14.5 E-06 | 4 E-06 | 72 E-06 | 1.71 E-06 | 60 E-06 |

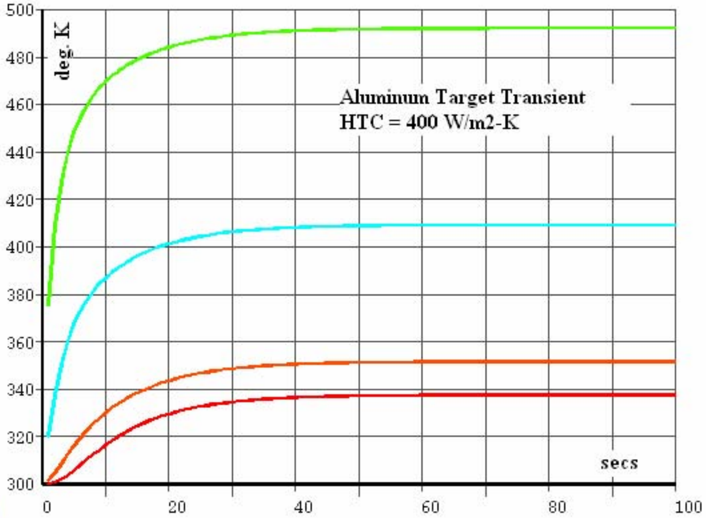

Nickel-plated Al
Carbon-Carbon
Carbon-Carbon
IG43 Graphite
AlBeMet
Gum Metal
Beryllium
Ti Alloy
Vascomax
200 MeV Protons




VASCOMAX-350 TENSILE Specimen
Thickness = 1.0mm
Neck-Down width = 1.5mm
Tensile Strength ~ 350 Ksi (2400 MPa)
Alignment 1mm diam.
THRU hole
1.5mm
6mm
6mm
3mm
1.5mm
42mm
1mm

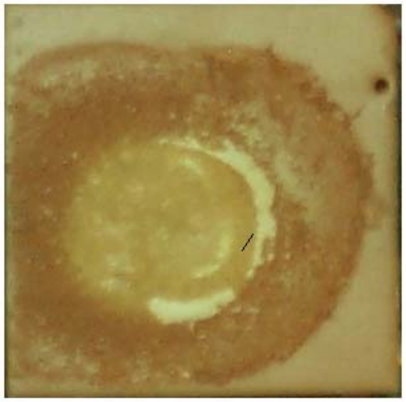

CTE Specimen for Vascomax-350
Number of specimens needed = 13
3mm
9.5mm
3mm
2mm
6mm
4.5mm
1.0mm diam.
29mm

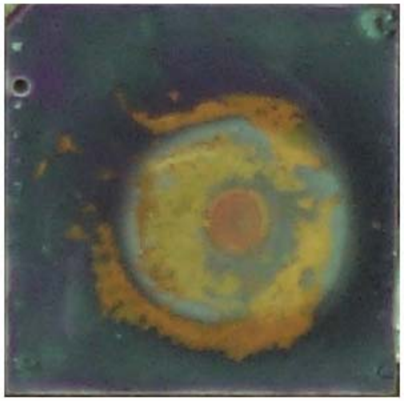


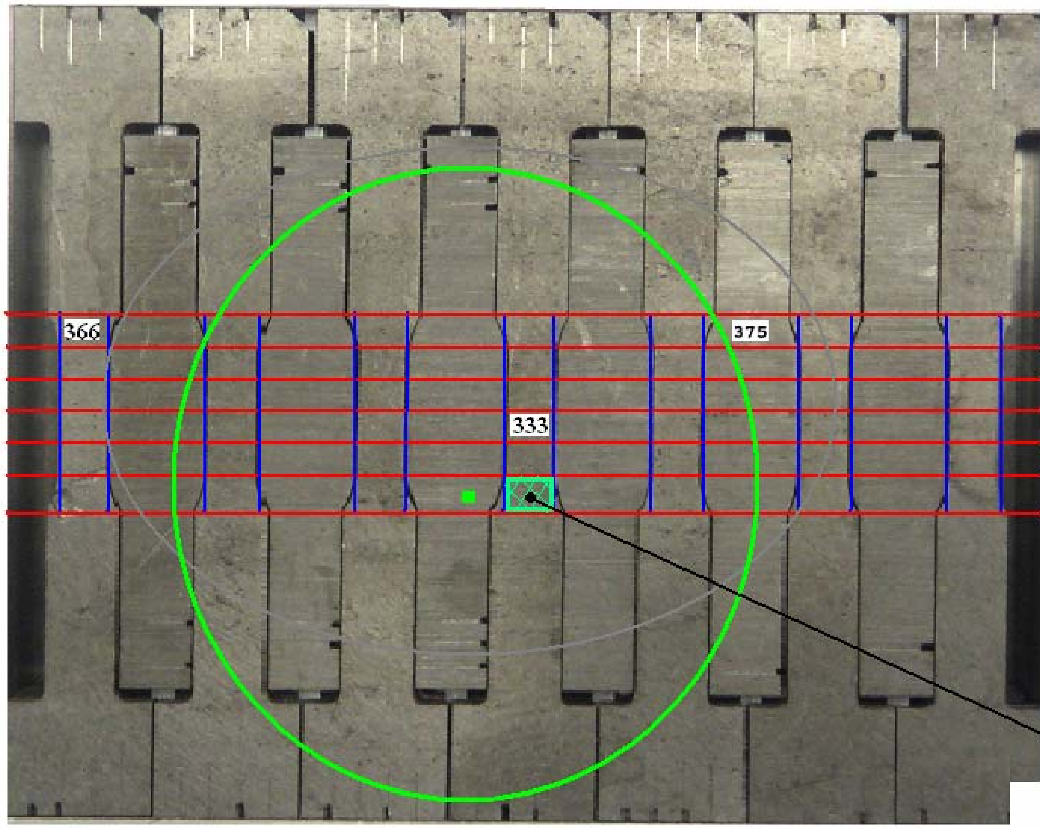




Establishing Irradiation Temperature

**Thermal Sensitive Paint Technique**









Results of autoradiographic beam profile measurements for the 2004 BLIP irradiation, using the "downstream" nickel foil.

| Horizontal position looking at the surface where the beam enters the foil | Vertical position | Horizontal rms width (σ) | Vertical rms width (σ) |
|---|---|---|---|
| 2.9 ± 0.5 mm left of center | 4.5 ± 0.5 mm below center | 8.1 ± 0.3 mm | 8.4 ± 0.3 mm |

**Irradiation Damage Analysis (dpa) showed that this cell associated with the tensile specimenn experiences most damage**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 266 | 267 | 268 | 269 | 270 | 271 | 272 | 273 | 274 | 275 | 276 | 277 | 278 |
| 253 | 254 | 255 | 256 | 257 | 258 | 259 | 260 | 261 | 262 | 263 | 264 | 265 |
| 240 | 241 | 242 | 243 | 244 | 245 | 246 | 247 | 248 | 249 | 250 | 251 | 252 |
| 227 | 228 | 229 | 230 | 231 | 232 | 233 | 234 | 235 | 236 | 237 | 238 | 239 |
| 214 | 215 | 216 | 217 | 218 | 219 | 220 | 221 | 222 | 223 | 224 | 225 | 226 |
| 201 | 202 | 203 | 204 | 205 | 206 | 207 | 208 | 209 | 210 | 211 | 212 | 213 |

## VASCOMAX SAMPLE ACTIVATION

CTEs: 7.52 mCi - 151.2 mCi
Tensile: 5.59 mCi - 42.6 mCi

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 166 | 167 | 168 | 169 | 170 | 171 | 172 | 173 | 174 | 175 | 176 | 177 | 178 |
| 153 | 154 | 155 | 156 | 157 | 158 | 159 | 160 | 161 | 162 | 163 | 164 | 165 |
| 140 | 141 | 142 | 143 | 144 | 145 | 146 | 147 | 148 | 149 | 150 | 151 | 152 |
| 127 | 128 | 129 | 130 | 131 | 132 | 133 | 134 | 135 | 136 | 137 | 138 | 139 |
| 114 | 115 | 116 | 117 | 118 | 119 | 120 | 121 | 122 | 123 | 124 | 125 | 126 |
| 101 | 102 | 103 | 104 | 105 | 106 | 107 | 108 | 109 | 110 | 111 | 112 | 113 |

Tensile Vsc#s 1;8;15

CTE Vsc# 5

Tensile Vsc #s 4;11;18

## VASCOMAX SAMPLE dpa estimates

**Cell 133:**
from neutrons : 0.011336 dpa
from protons: 0.222335 dpa

**Cell 233:**
from neutrons: 0.013827 dpa
from protons: 0.2214 dpa

**Cell 220:**
from neutrons: 0.0157 dpa
from protons: 0.24377 dpa

# Irradiation Damage in Gum Metal

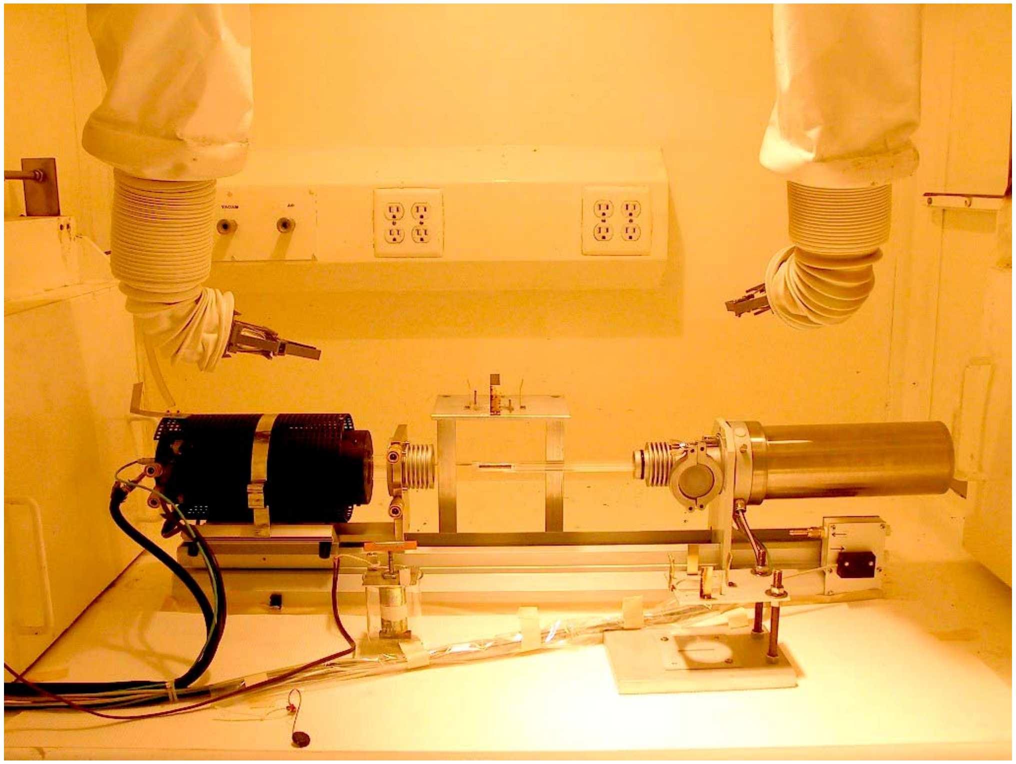
Highest dpa values estimated also near the bottom half of the tensile specimen “gauge” as in Vascomax.

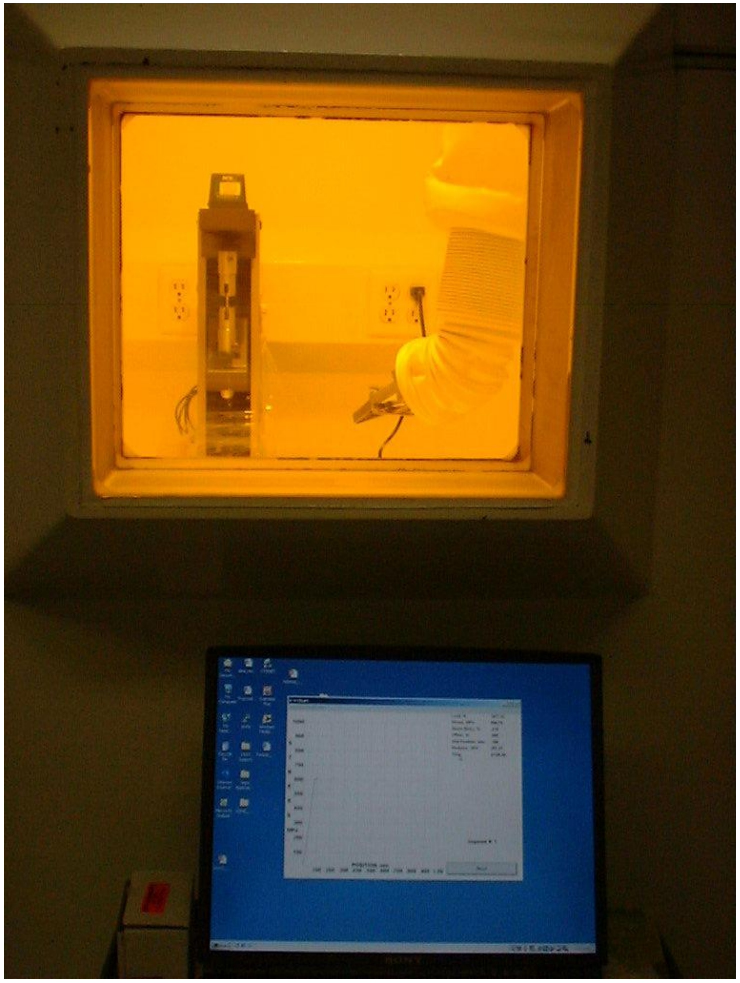
GUM (dpa)_max = 0.242 (protons) + 0.0132 (neutrons)

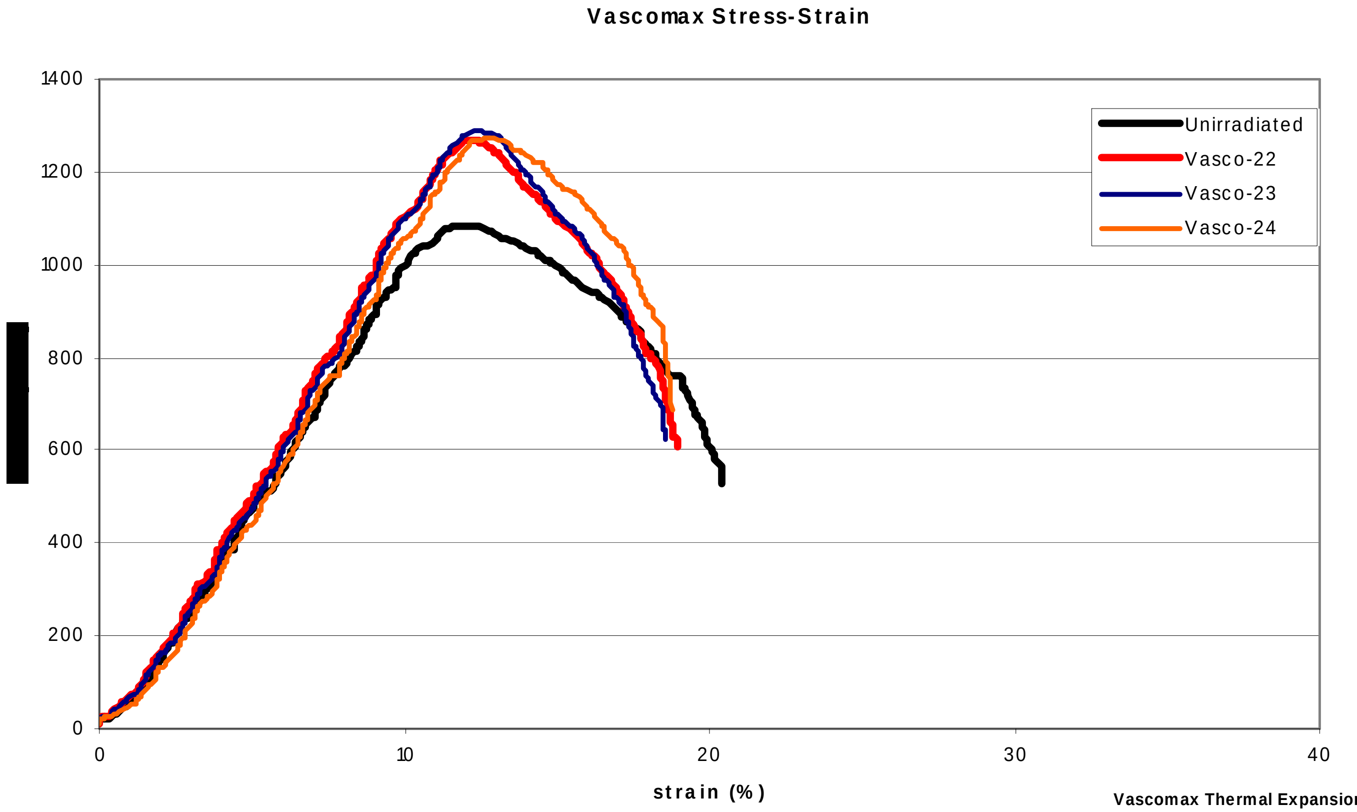
**For the rest of the materials appropriate dpa cross sections are being sought to be introduced into the model.**

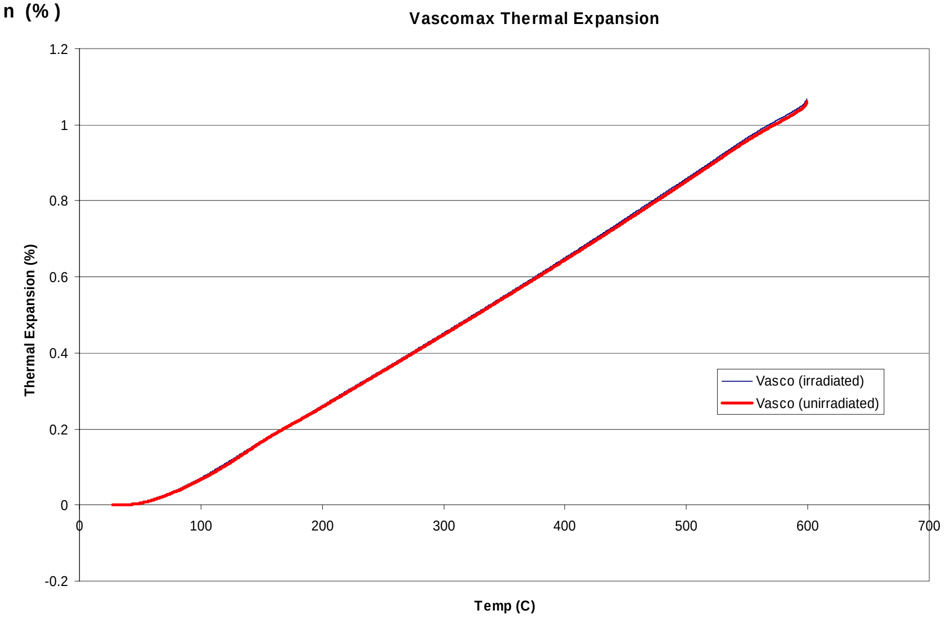
# Post-Irradiation Study at BNL Hot Cell

## Dilatometer – Mechanical Tester



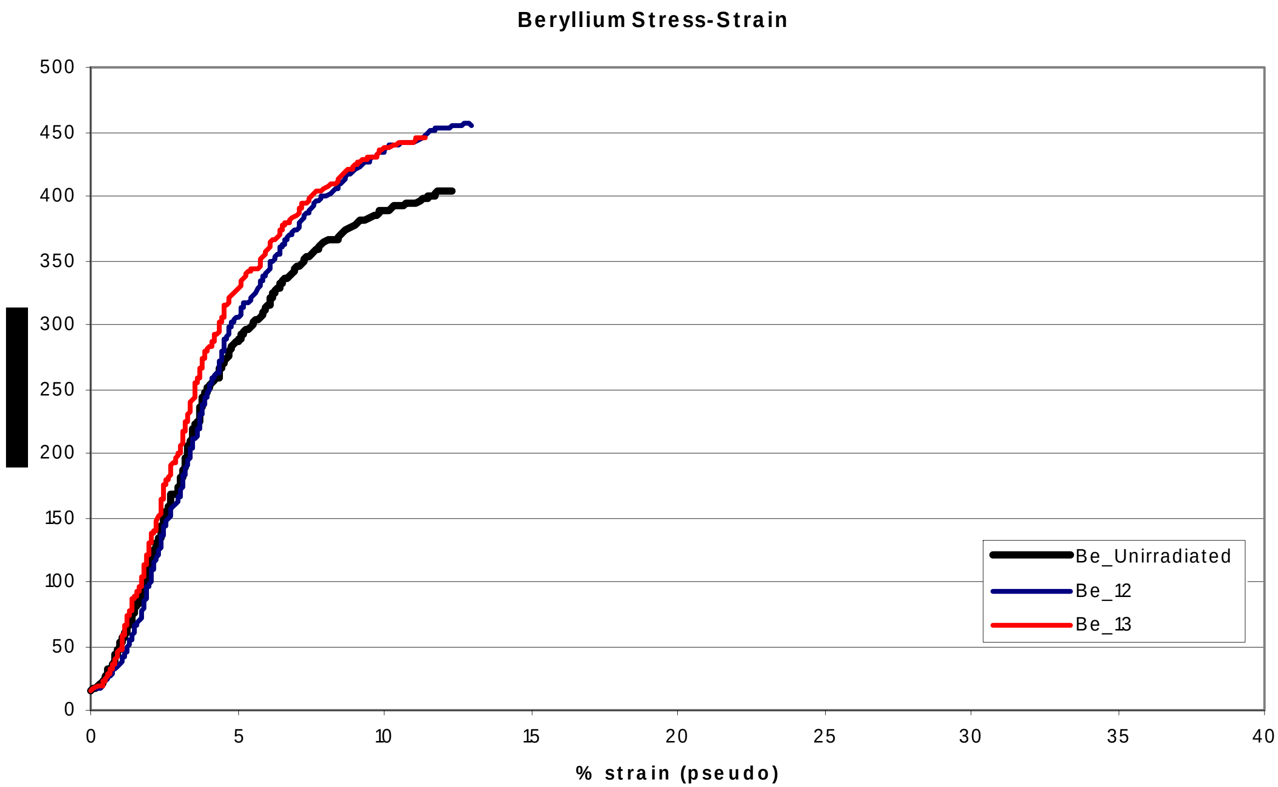


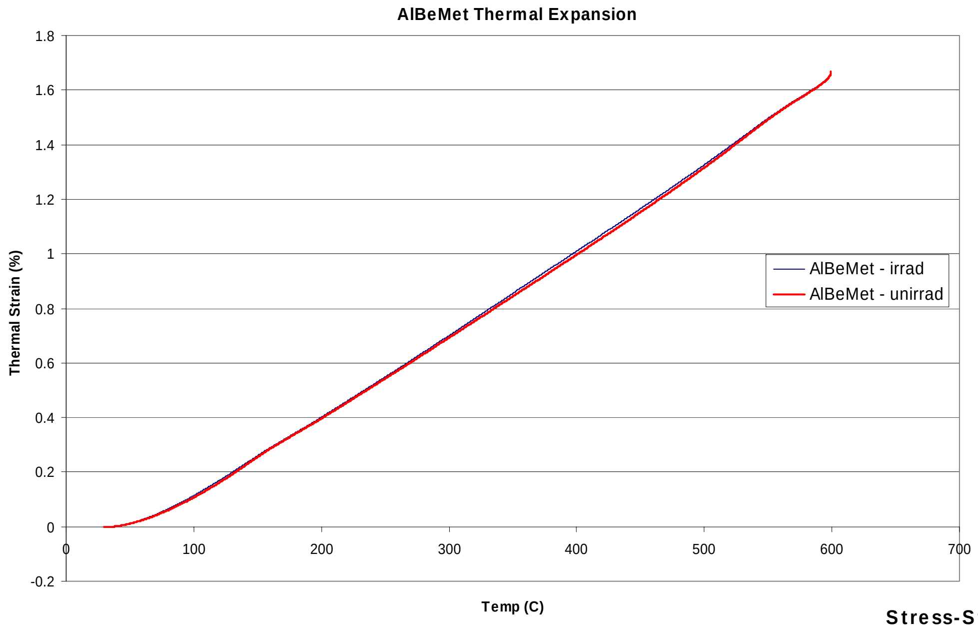


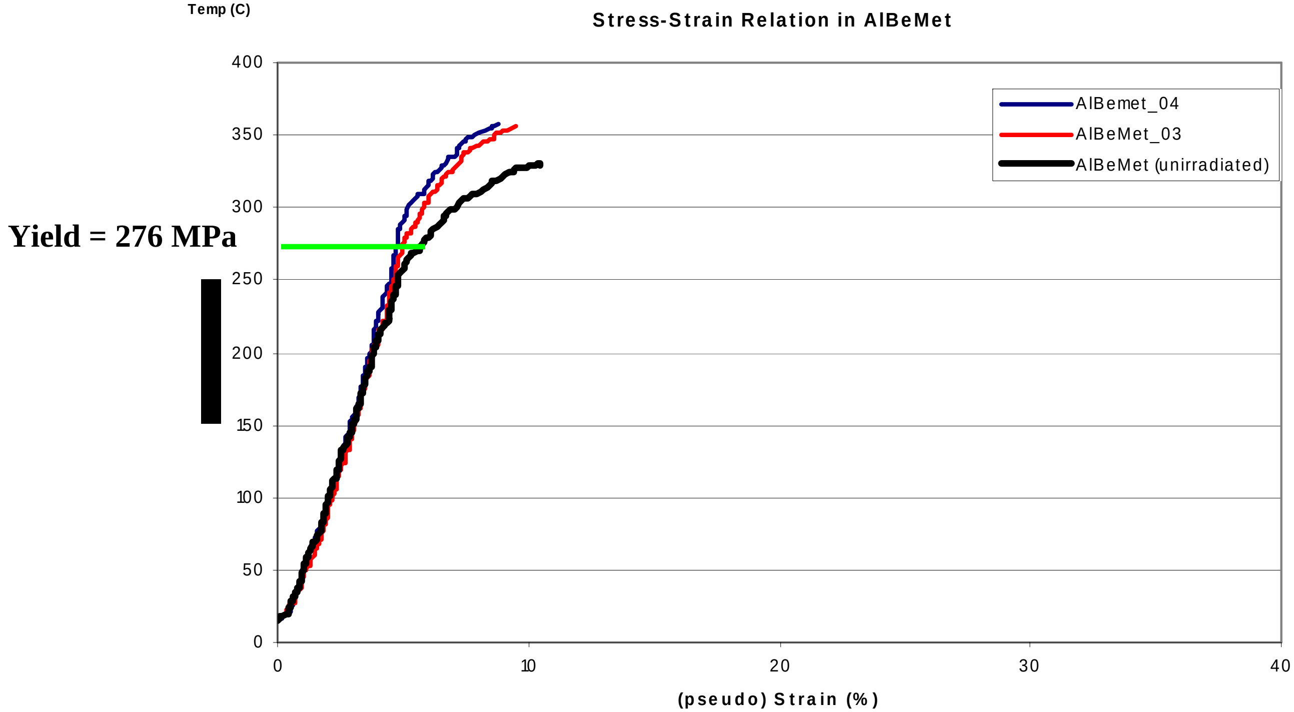



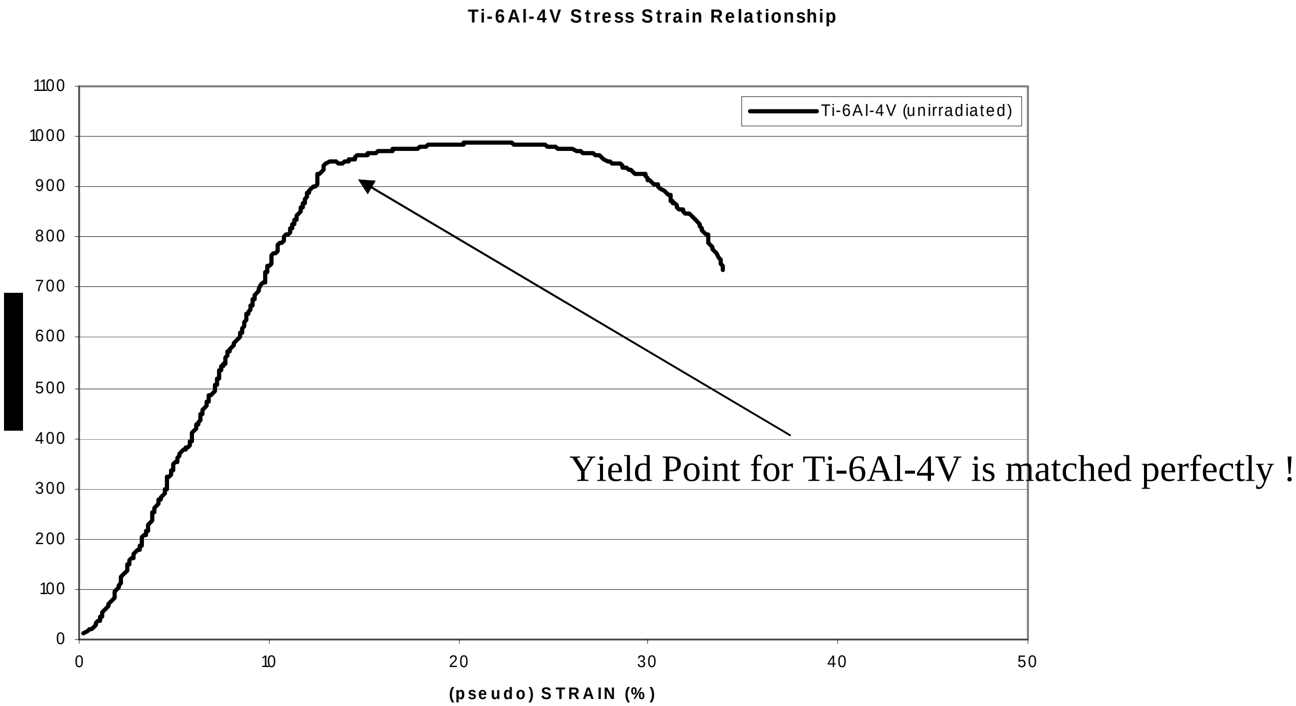

## Vasomax is a very interesting Material

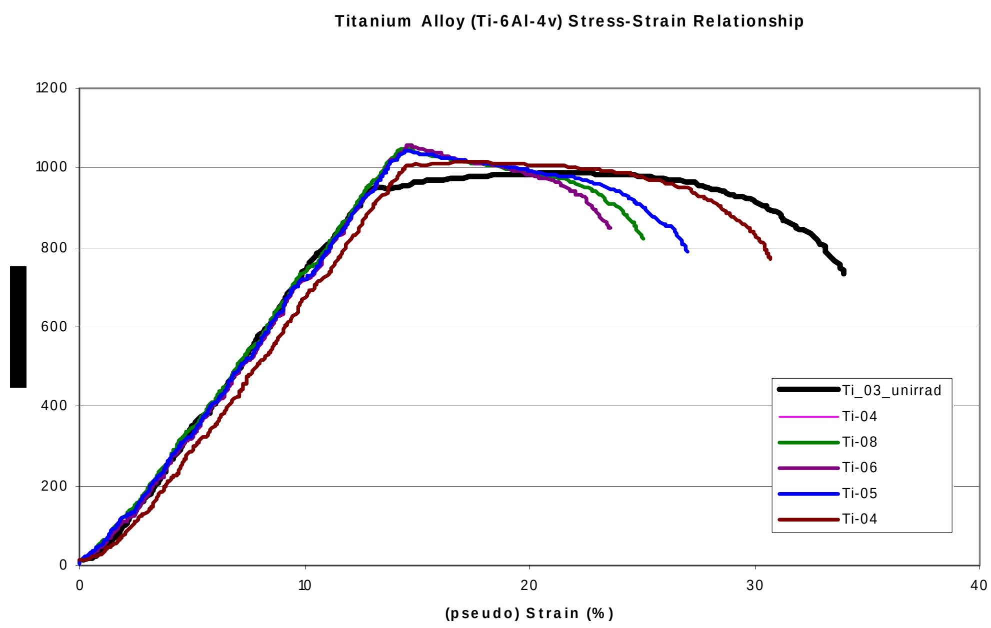
- It strengthens with irradiation without turning brittle
- CTE is not affected by irradiation

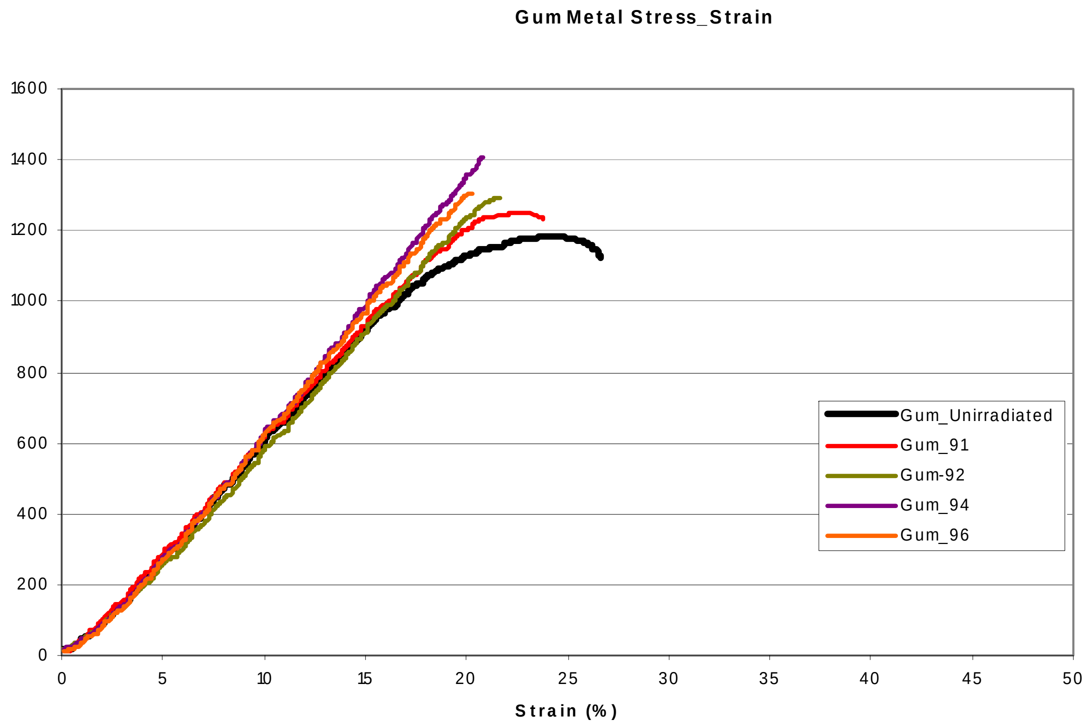

Beryllium Stress-Strain
[redacted]
500
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
40
% strain (pseudo)
Be_Unirradiated
Be_12
Be_13


AlBeMet Thermal Expansion
Thermal Strain (%)
Temp (C)
AlBeMet - irrad
AlBeMet - unirrad
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
100
200
300
400
500
600
700


Stress-Strain Relation in AlBeMet
Yield = 276 MPa
AlBemet_04
AlBeMet_03
AlBeMet (unirradiated)
(pseudo) Strain (%)
400
350
300
250
200
150
100
50
0
0
10
20
30
40


Ti-6Al-4V Stress Strain Relationship
Ti-6Al-4V (unirradiated)
[redacted]
1100
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
(pseudo) STRAIN (%)
Yield Point for Ti-6Al-4V is matched perfectly !

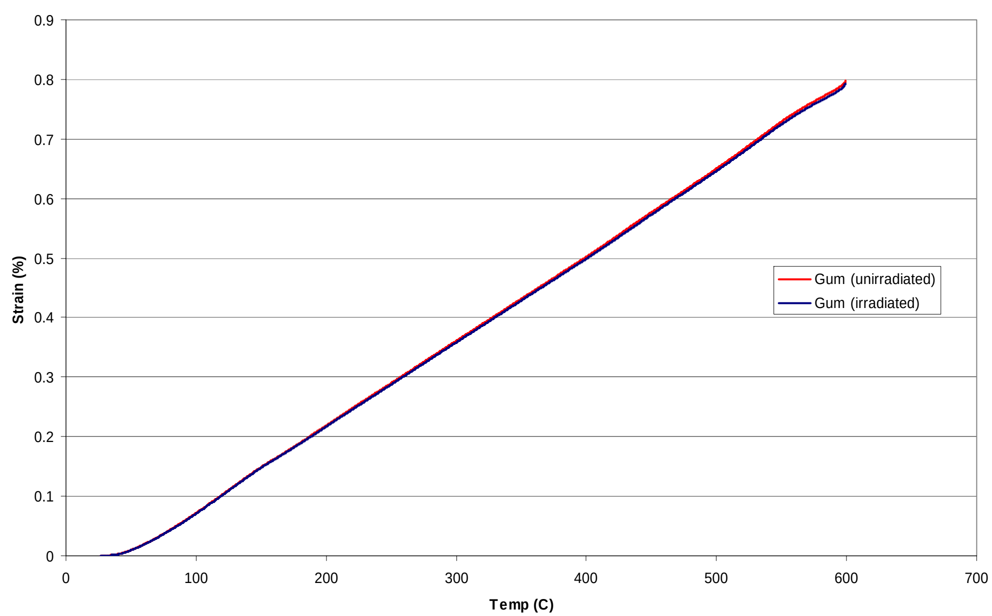

Titanium Alloy (Ti-6Al-4v) Stress-Strain Relationship
[redacted]
1200
1000
800
600
400
200
0
0
10
20
30
40
(pseudo) Strain (%)
Ti_03_unirrad
Ti-04
Ti-08
Ti-06
Ti-05
Ti-04



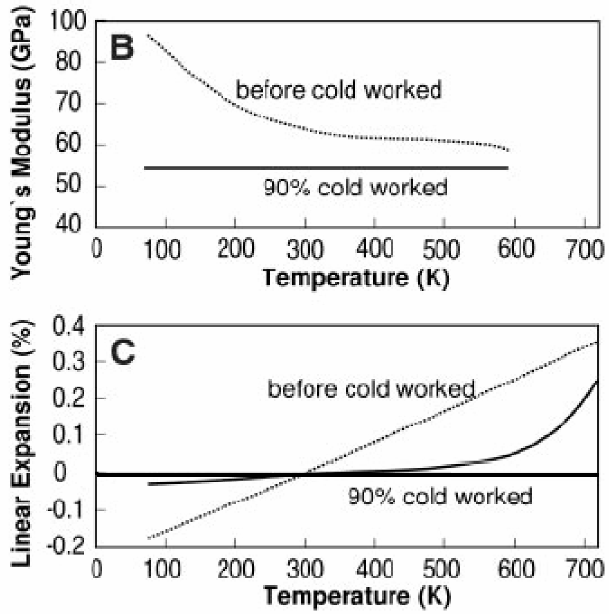

# GUM Metal

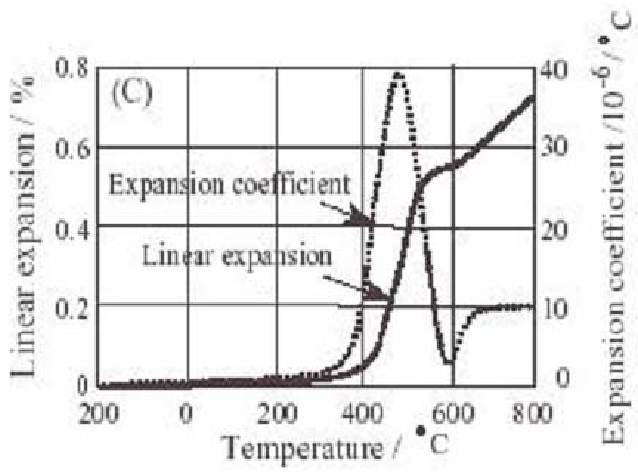
Strengthens but clearly looses the “super-ductility property

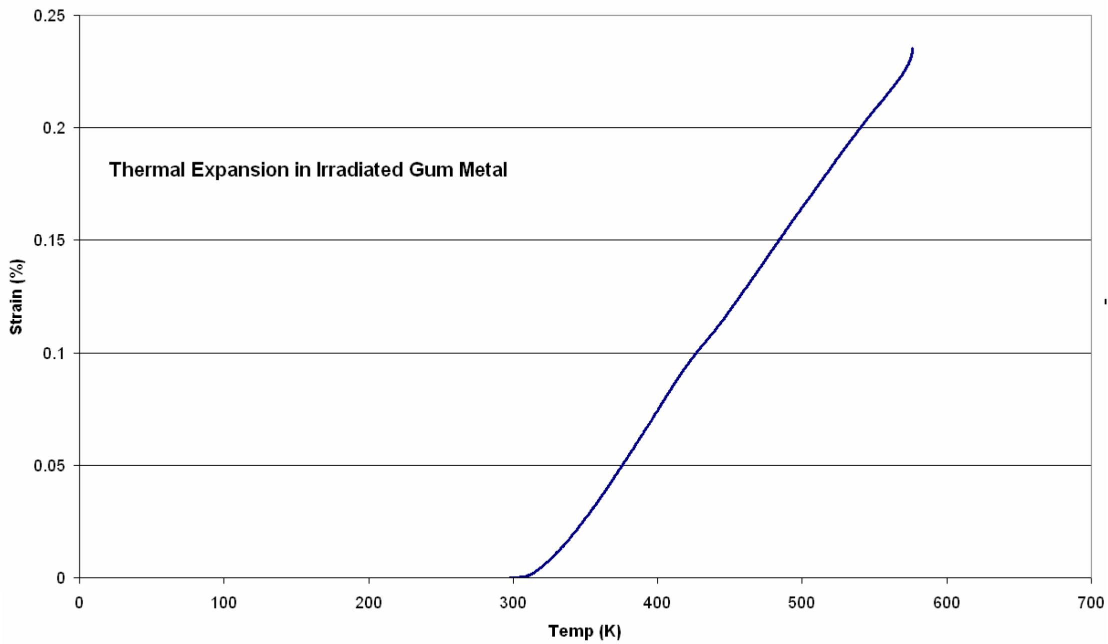
The type of gum metal being tested (between annealed and 90% cold worked ) Appears to hold its CTE characteristics



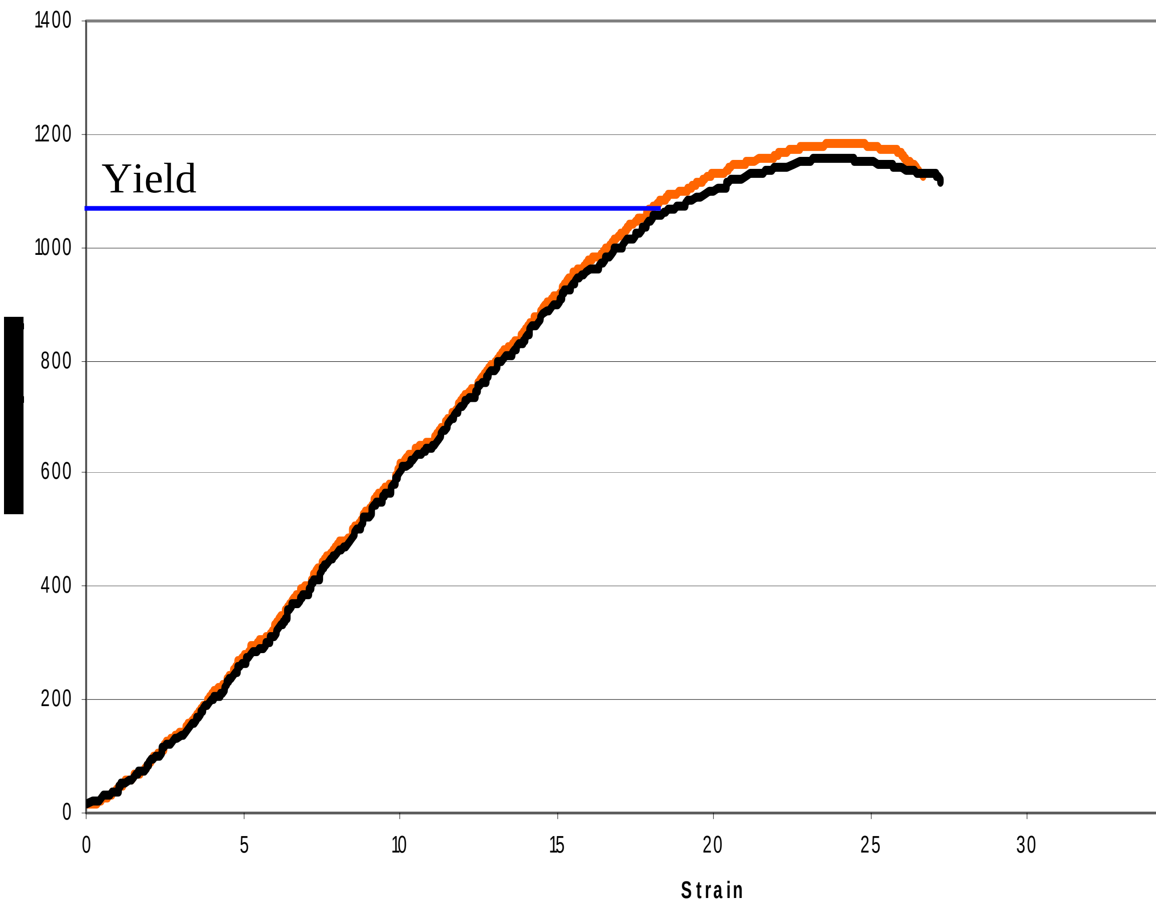
# Effects of Irradiation on Gum Thermal Expansion

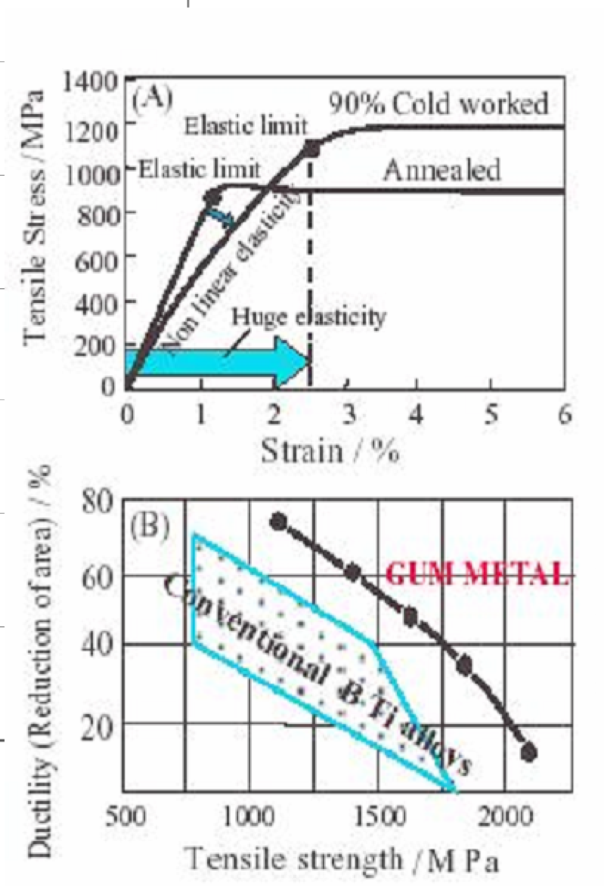


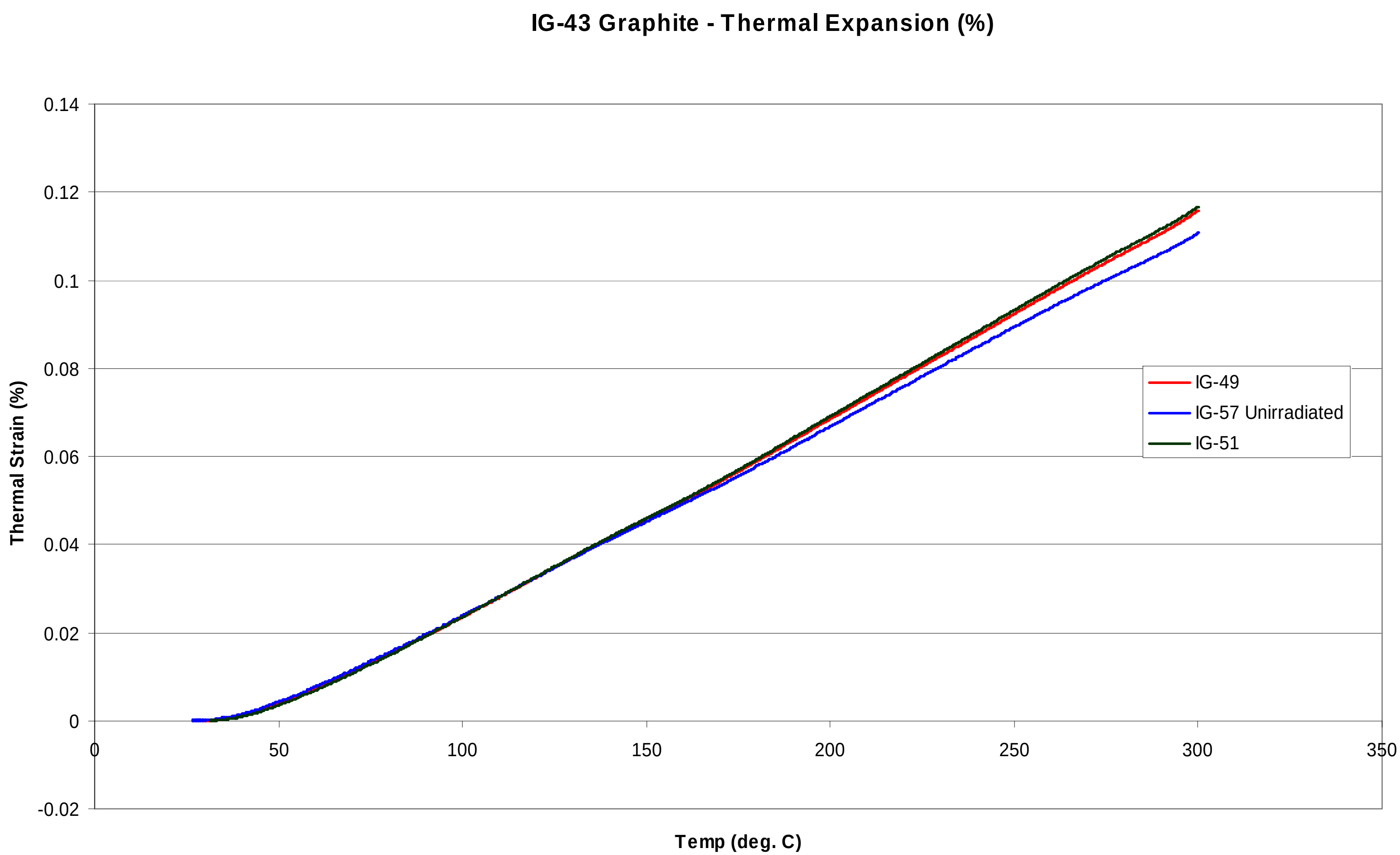



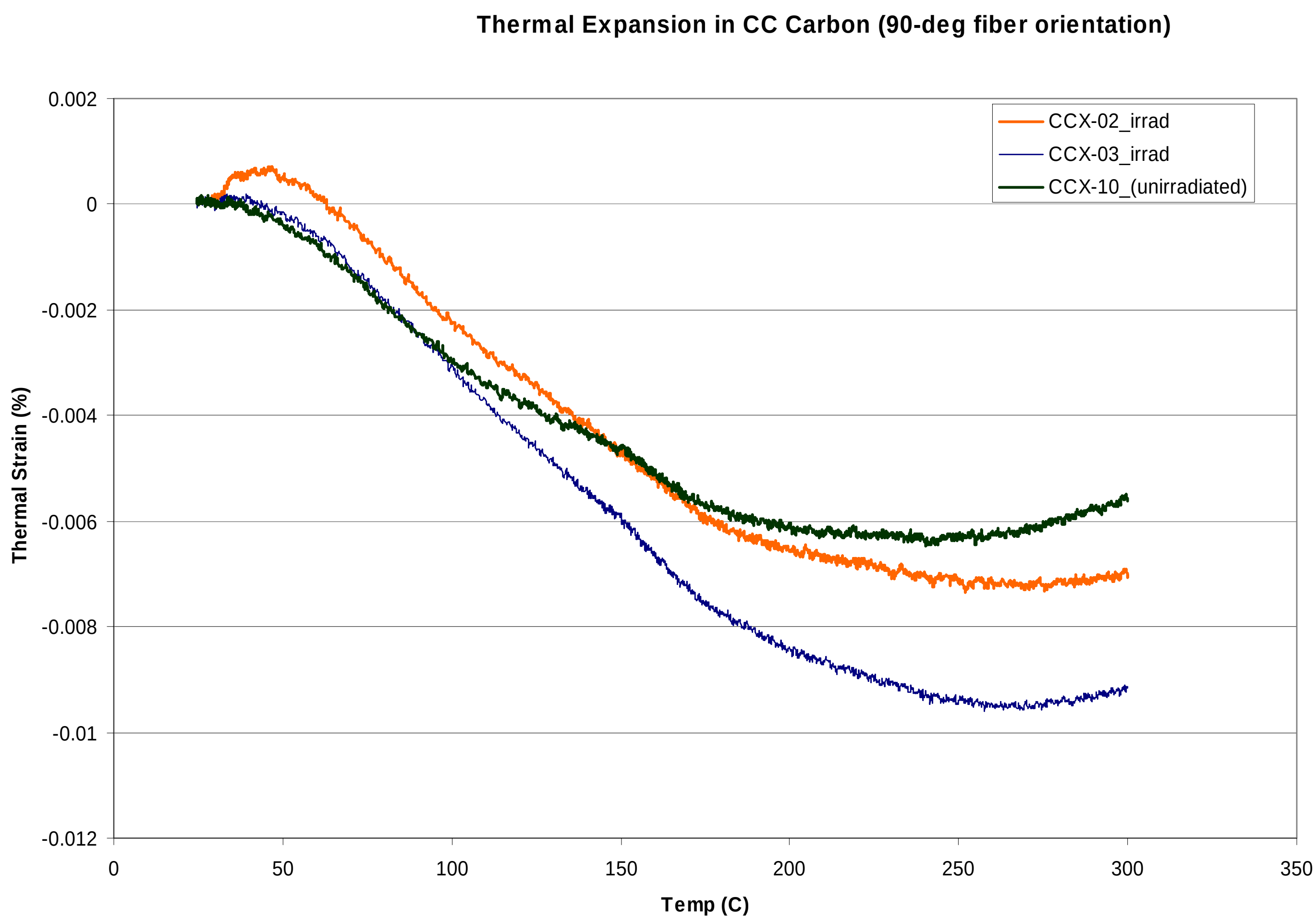



**Unirradiated Gum Metal Stress-Strain**

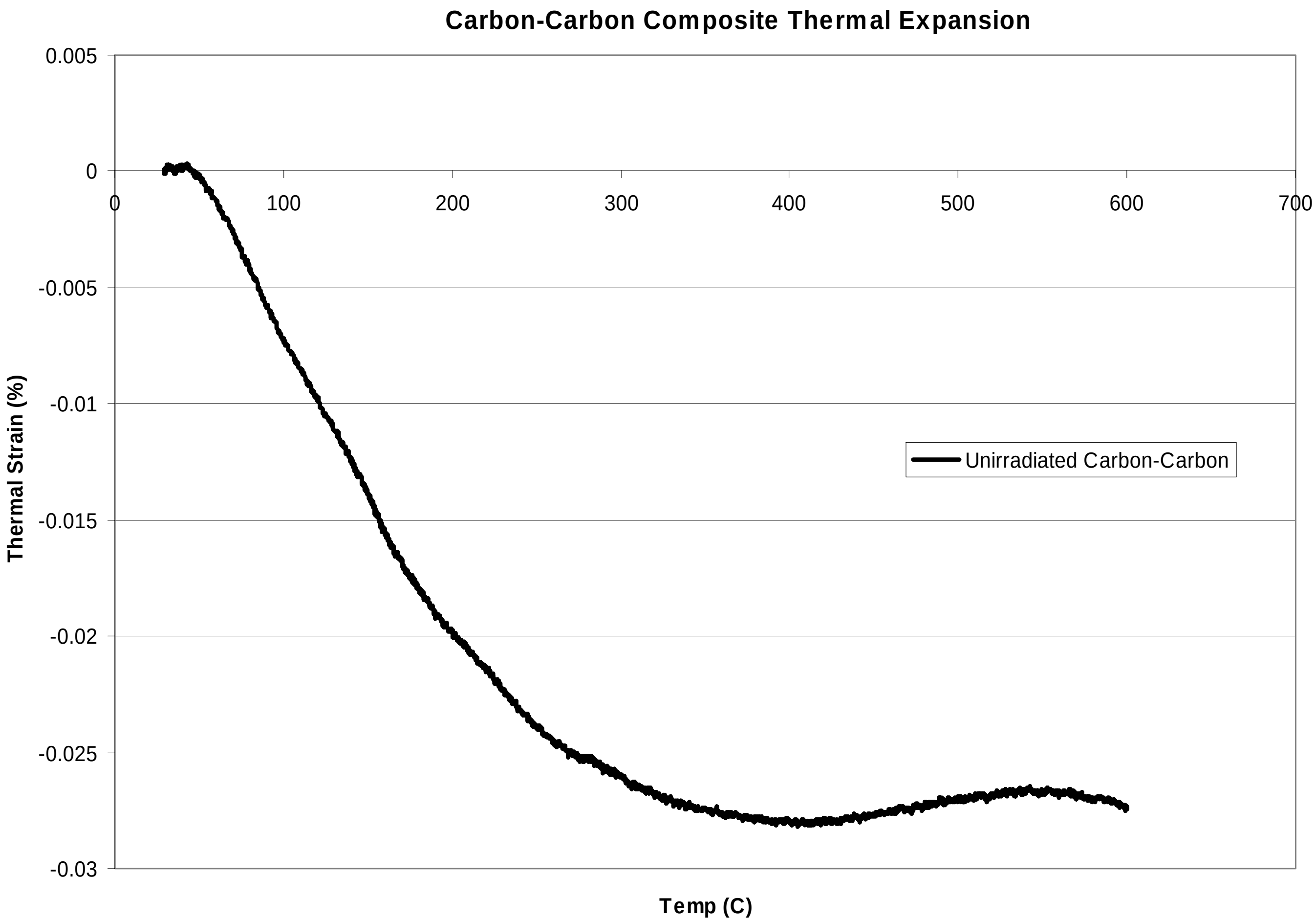



IG-43 Graphite - Thermal Expansion (%)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
Thermal Strain (%)
0
50
100
150
200
250
300
350
Temp (deg. C)
IG-49
IG-57 Unirradiated
IG-51



Thermal Expansion in CC Carbon (90-deg fiber orientation)
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
Thermal Strain (%)
0
50
100
150
200
250
300
350
Temp (C)
CCX-02_irrad
CCX-03_irrad
CCX-10_(unirradiated)




| Temp. | % elongation |
|---|---|
| 23 º C | 0% |
| 200 º C | -0.023% |
| 400º C | -0.028% |
| 600º C | -0.020% |
| 800º C | 0% |
| 1000º C | 0.040% |
| 1200º C | 0.084% |
| 1600º C | 0.190% |
| 2000º C | 0.310% |
| 2300º C | 0.405% |

# REMAINING "TO DO" LIST

- Graphite and Carbon-Carbon to be tested to cycles up to 1100 C
    - in vacuum
    - with forced helium
    - Dilatometer will be upgraded to allow these two runs

- Thermal diffusivity (or conductivity) will be measured using the dilatometer set-up with an implemented modification that allows for diffusivity measurements in transient mode

- Complete the examination of the nickel-plating on aluminum (NUMI horn material) – Preliminary (visual) examination shows serious surface changes

- Assess damage due defect generation/growth on the irradiated specimens using ultrasonic techniques (more of an issue in graphite & CC) – System is available and ready. Tests to be done after diffusivity measurements

- Material resilience to shock: Use of a high power – focused laser beam to excite the materials of the matrix – Lab is set up and laser system is up and ready. Need to borrow fiber-optic recording system from ORNL