MATERIAL R&D FOR HIGH-INTENSITY PROTON BEAM TARGETS

PROGRESS REPORT

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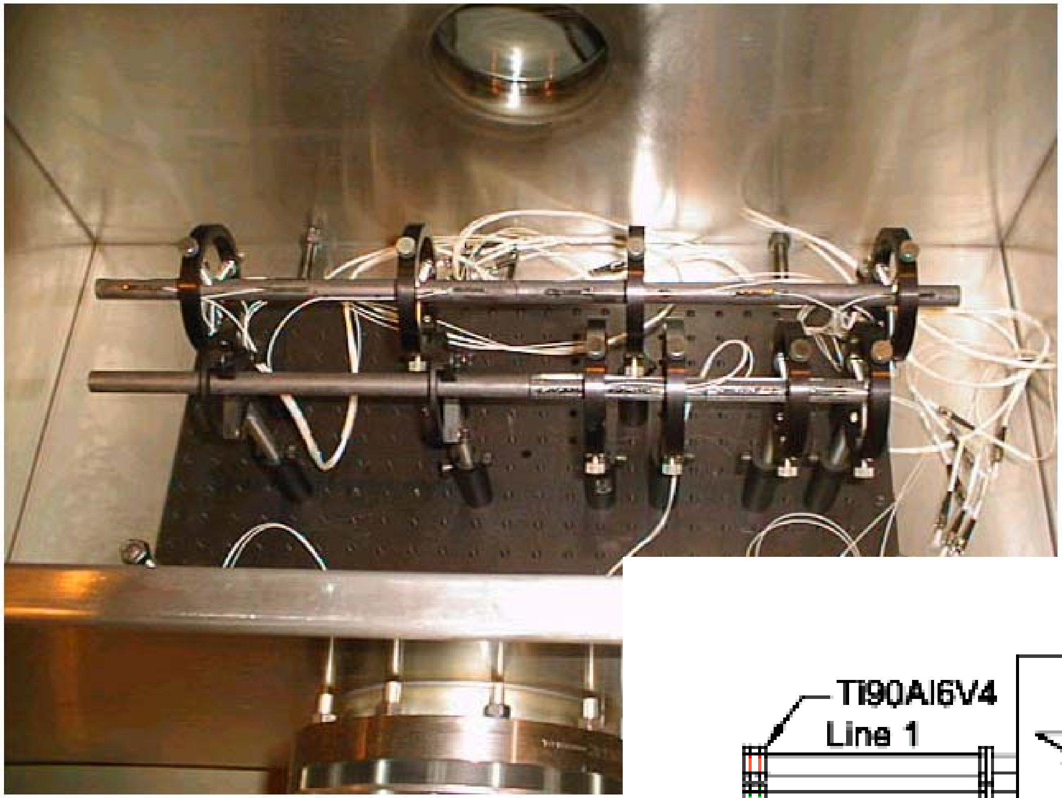
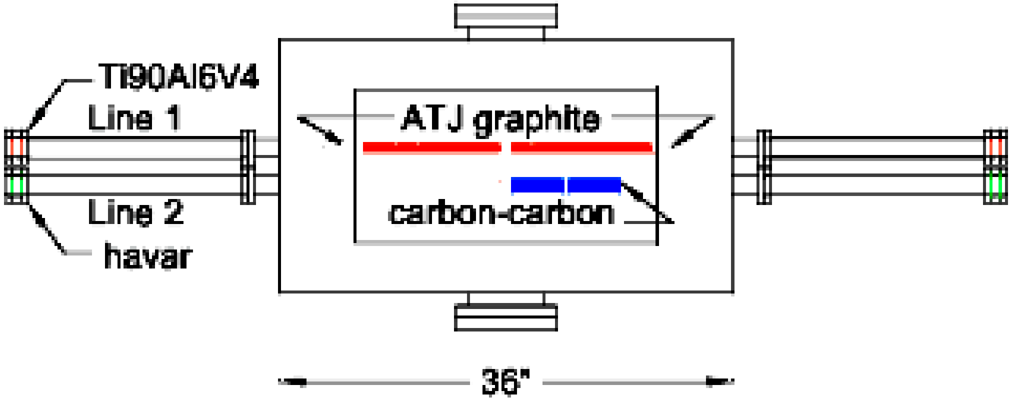
GOAL

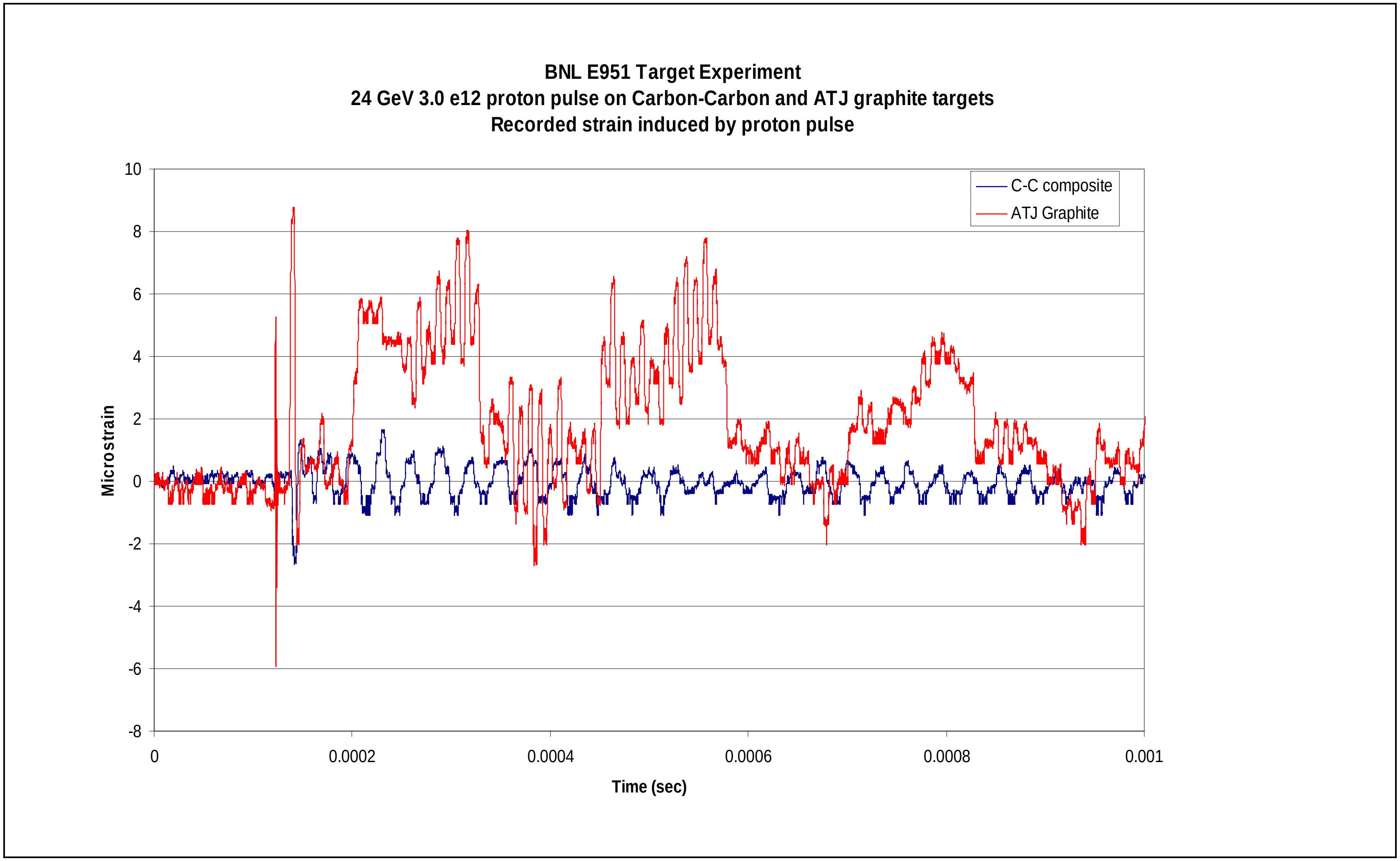
SEARCH for and evaluate under irradiation environment NEW materials or composites that appear to hold the answer the problem of survivability as high power targets by exhibiting unusually high strength, very low thermal expansion or high ductility

Experimentation with Graphite & Carbon-Carbon Targets (BNL E951)

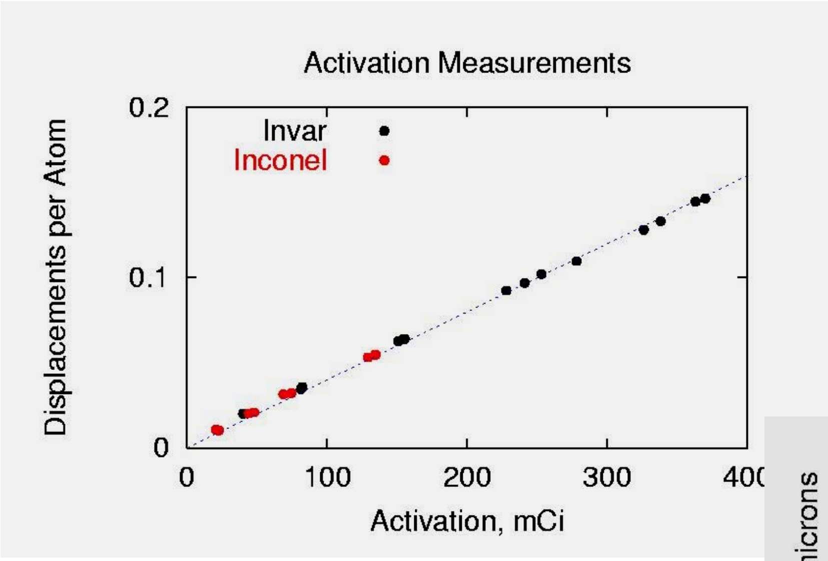


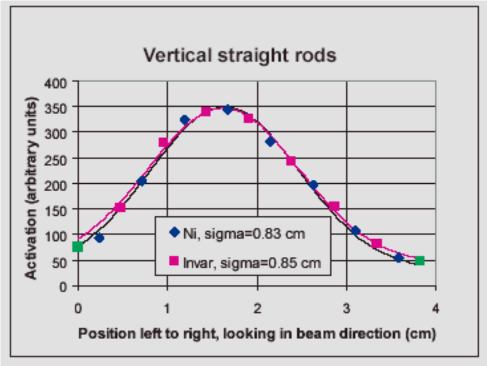


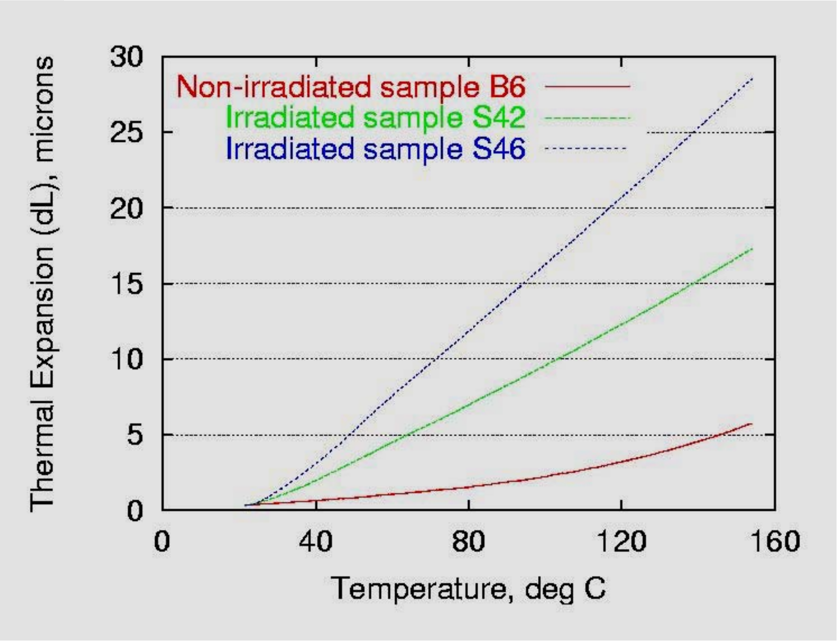
Graphite vs. Carbon-Carbon – A Clear Choice ….. really?

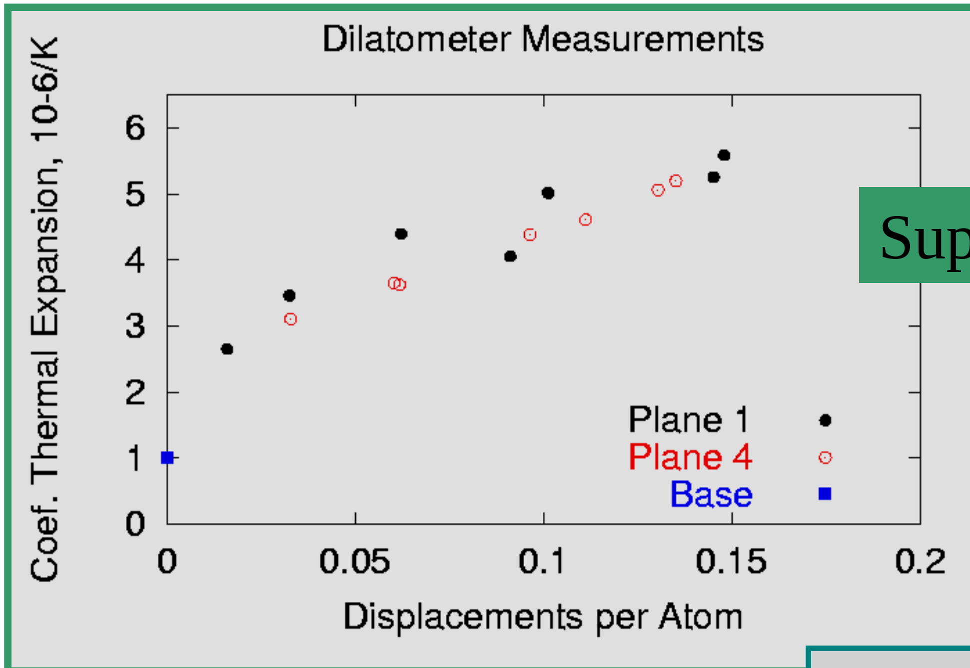


Irradiation of Super Invar Alloy at BNL to Assess Coefficient of Thermal Expansion and Mechanical Properties

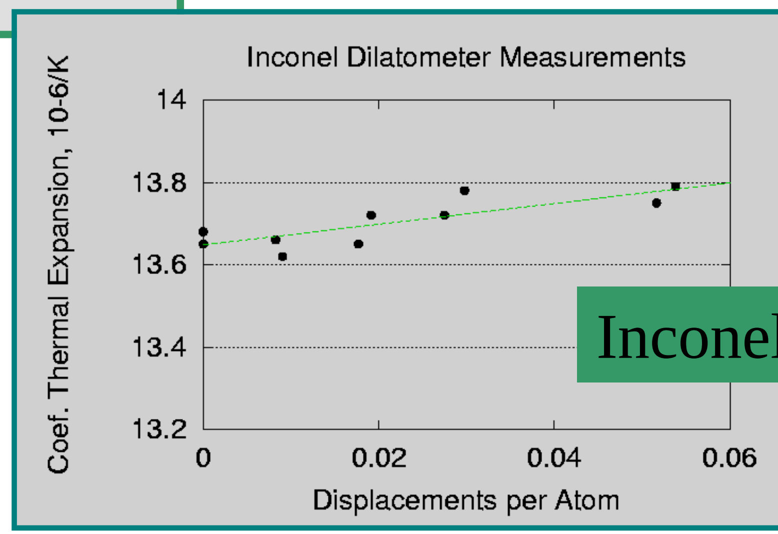




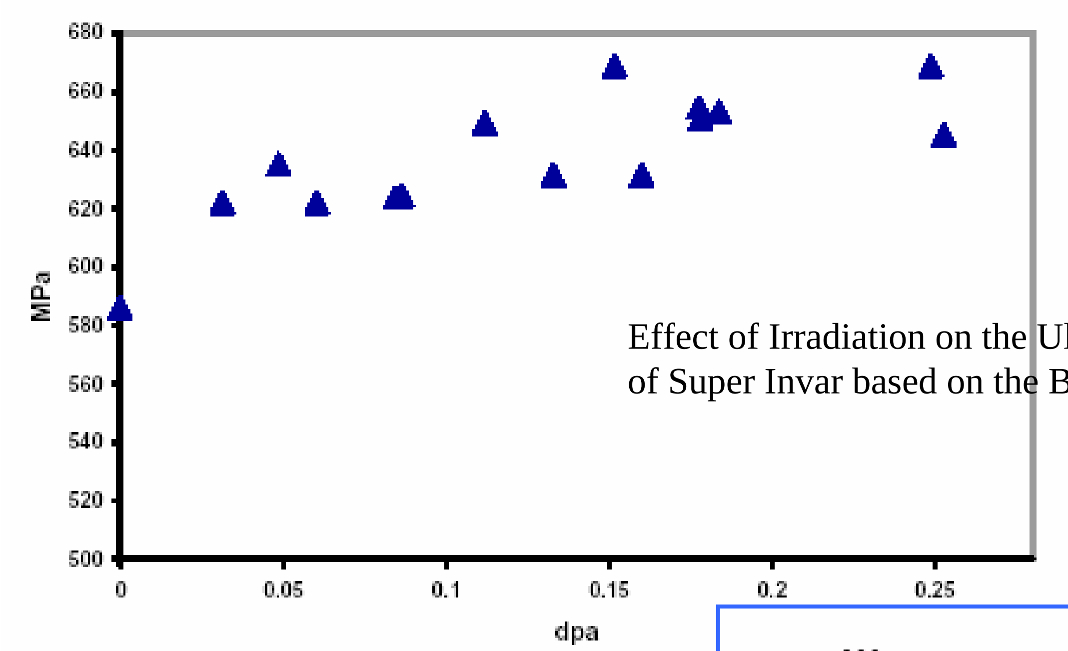




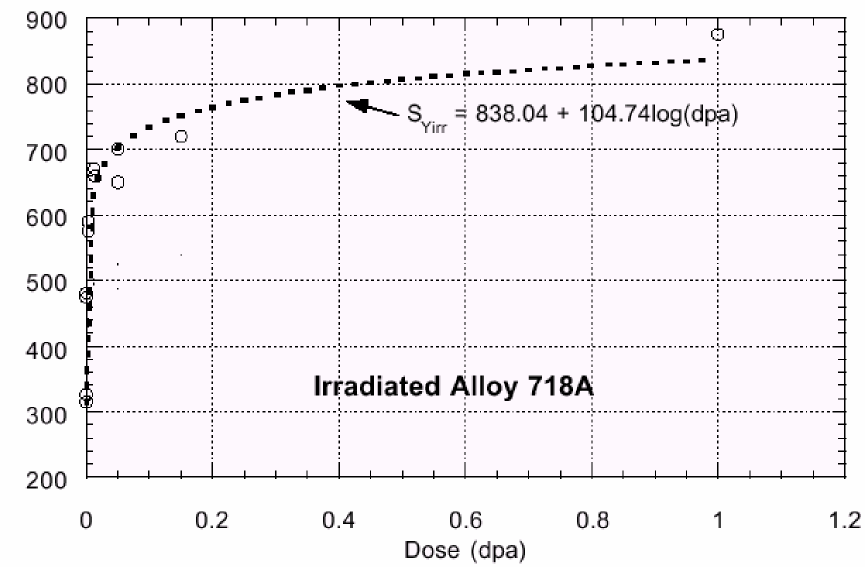
Super-Invar



Inconel-718

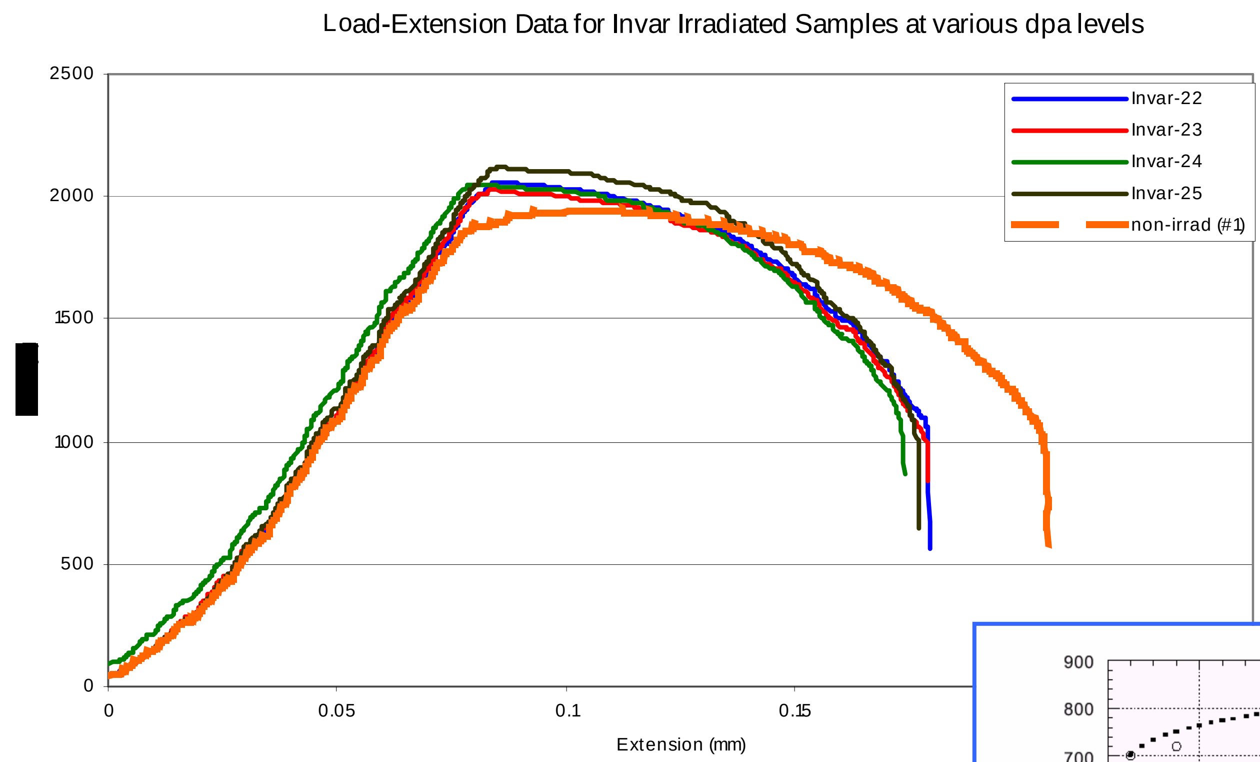


Effect of Irradiation on the Ultimate Stress of Super Invar based on the BNL Test



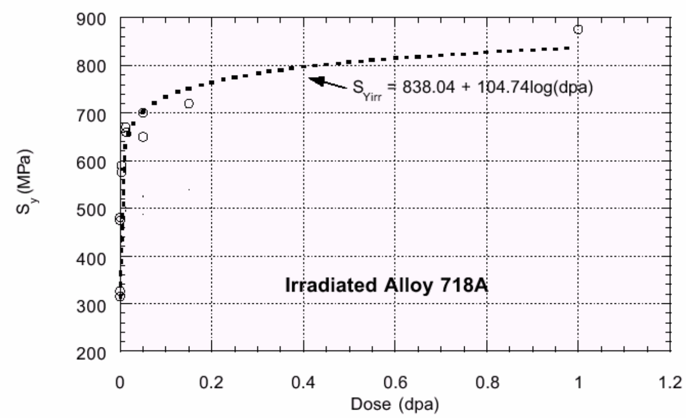
Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A

Solid Target Option: Super-Invar Irradiation Study



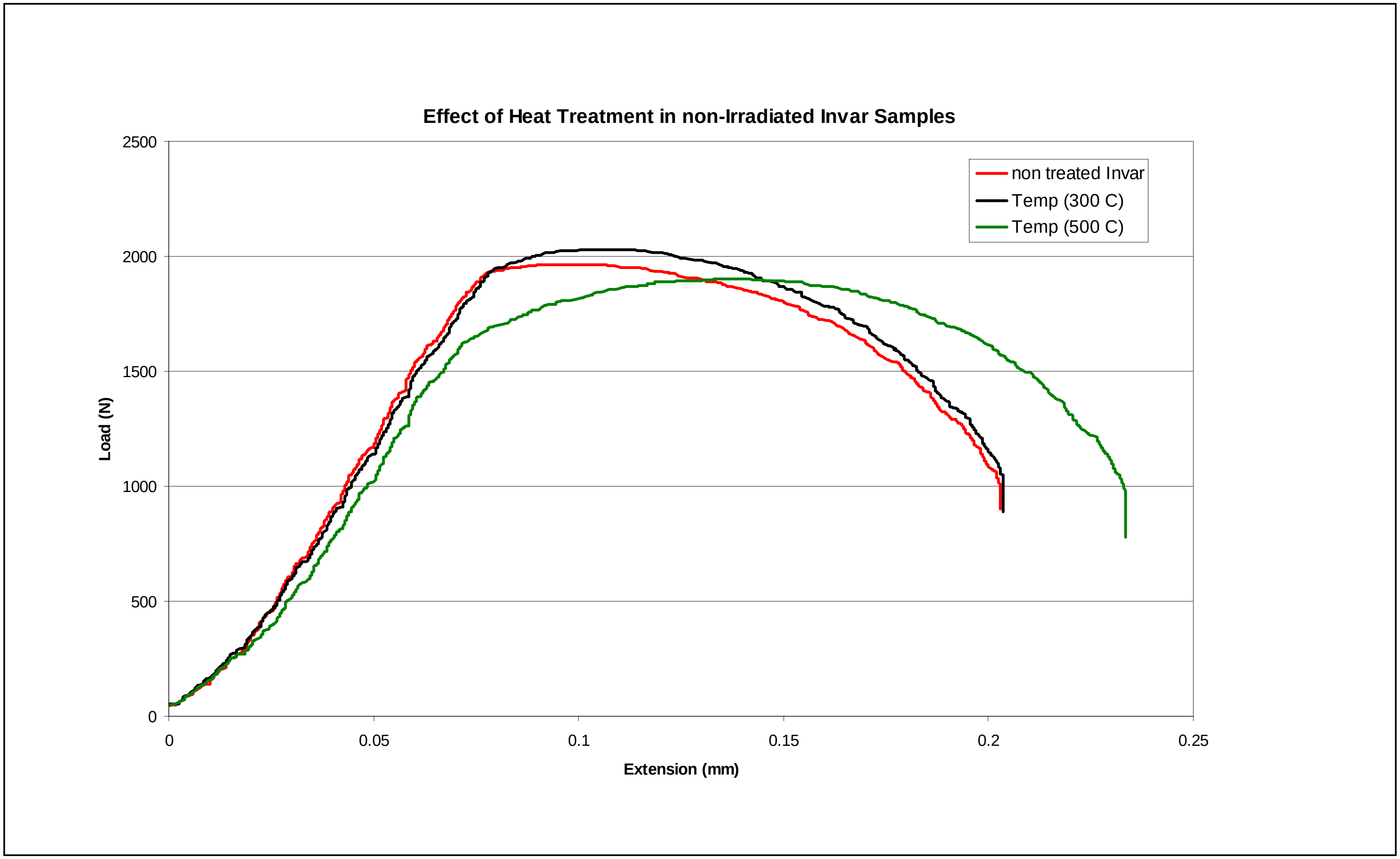
WHY STUDY super Invar ?

- •High-Z with low CTE (0-150 °C)
- •How is CTE affected by radiation?
- •What happens to other important properties?



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

Super-Invar Irradiation Study – Temperature Effects



PHASE II -TARGET MATERIAL R&D

- **Carbon-Carbon Composite (BNL)**
- **Toyota “Gum Metal” (KEK)**
- **Graphite (IG-43) (KEK)**
- **AlBeMet (BNL)**
- **Beryllium (BNL)**
- **Ti Alloy (6Al-4V) (SLAC)**
- **Vascomax (BNL)**
- **Nickel-Plated Aluminum Used in the NUMI Horn (BNL-FNAL-KEK)**

WHAT IS OF INTEREST TO US IN POST-IRRADIATION PHASE

Resilience in terms of strength/shock absorption

- CTE evaluation
- Stress-strain
- Fatigue
- Fracture Toughness and crack development/propagation

•Corrosion Resistance

•De-lamination (if a composite such as CC or plated HORN conductor) – Use of ultrasonic technology to assess changes

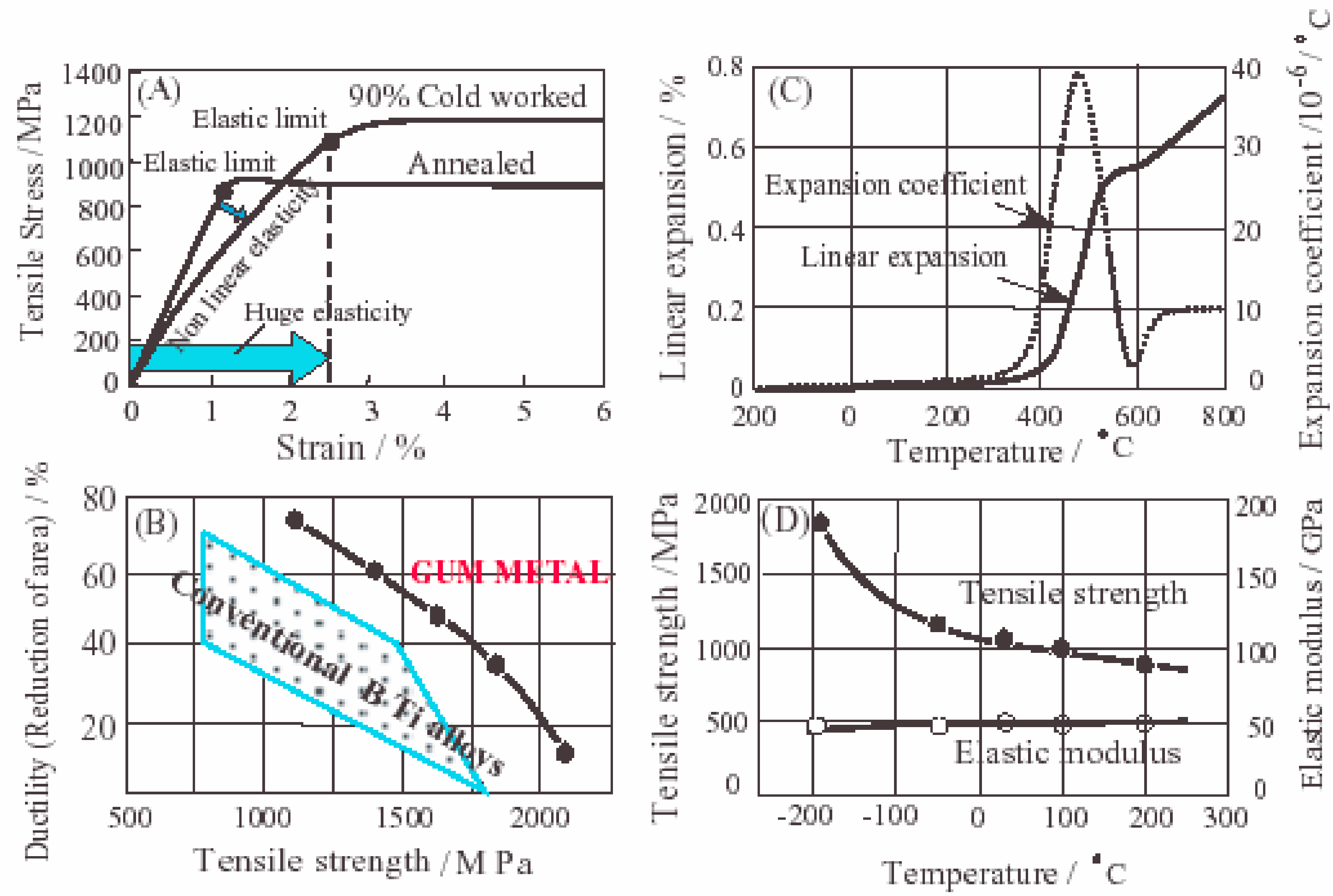
•Degradation of conductivity

Other tests are also in the planning for scrutiny of the successful candidates (laser induced shock and property measurements)

Carbon-Carbon Composite Target

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

The Wonders of Gum Metal
(soon in peppermint flavor !!)



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 (275)	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

Allvac
An Allegheny Technologies Company

TECHNICAL DATA SHEET

VASCOMAX® C-200/C-250/C-300/C-350

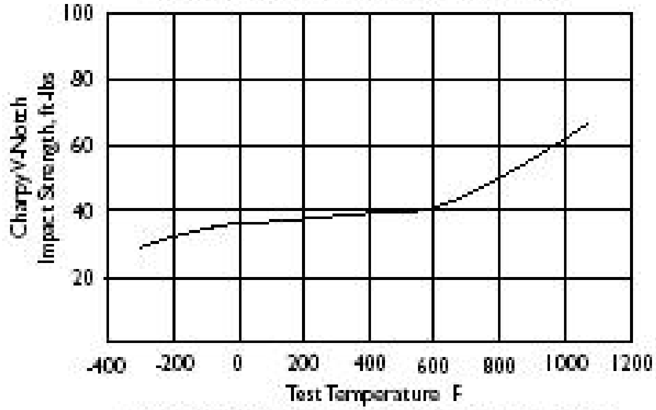
Nominal Mechanical Properties of Small Diameter Bars Following Aging Heat Treatment

Figure 1

	VascoMax C-200	VascoMax C-250	VascoMax C-300	VascoMax C-350
Ultimate Tensile Strength, psi	210,000	260,000	294,000	350,000
0.2% Yield, psi	206,000	255,000	290,000	340,000
Elongation, %	12	11	11	7
Reduction of Area, %	62	58	57	35
Notch Tensile (K_t= 9.0), psi	325,000	380,000	420,000	330,000
Charpy V-Notch, ft-lb	36	20	17	10
Fatigue Endurance Limit (10^8 Cycles), psi	110,000	110,000	125,000	110,000
Rockwell "C" Hardness	43/48	48/52	50/55	55/60
Compressive Yield Strength, psi	213,000	280,000	317,000	388,000

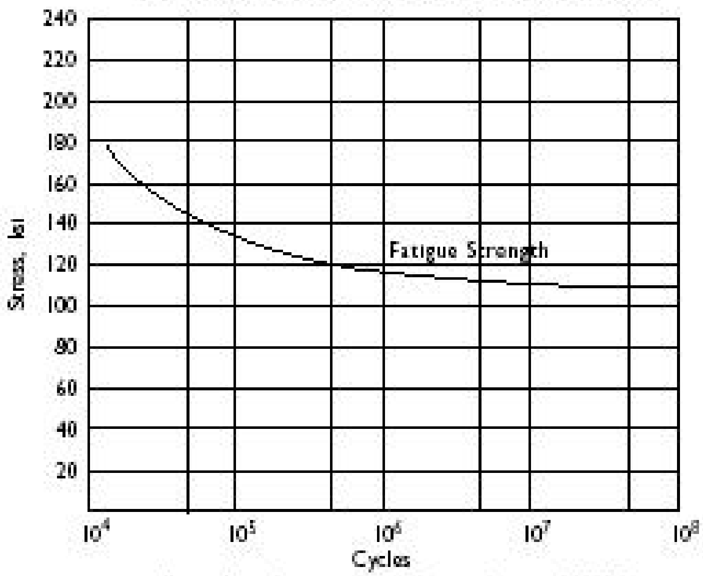
VASCOMAX® C-200

Effect of Test Temperature on Charpy V-Notch Impact Strength



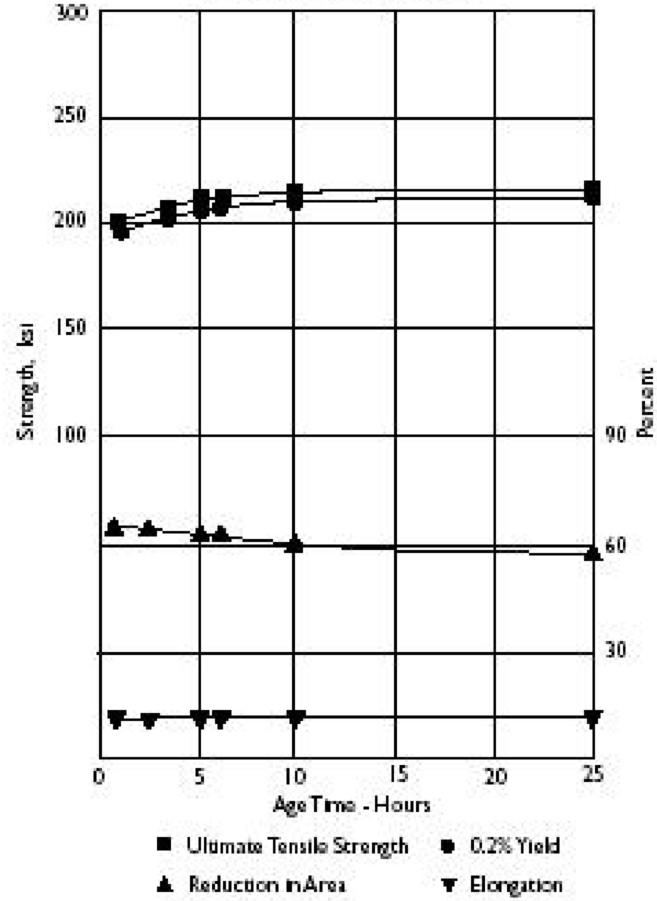
All samples solution annealed for one hour at 1500° F, air cooled and aged at 900° F for three hours.

R.R. Moore Rotating Beam Fatigue Tests



All samples solution annealed for one hour at 1500° F, air cooled and aged at 900° F for three hours.

Effect of Aging Time on Tensile Properties



All specimens solution annealed for one hour at 1500° F, air cooled and aged at 900° F for the times indicated.

VASCOMAX® C-200

Physical Properties

Average Coefficient of Thermal Expansion (70-900° F)	5.6 x 10^{-6} in/in/°F
Modulus of Elasticity	26.2 x 10^{6} psi
Density	.289 lbs/cu. in. (8.0 g/cc)
Thermal Conductivity at 68° F	11.3 BTU/(ft)(hr)(°F)
at 122° F	11.6 BTU/(ft)(hr)(°F)
at 212° F	12.1 BTU/(ft)(hr)(°F)

Nominal Annealed Properties

Hardness	30 Rc
Yield Strength	100 ksi
Ultimate Strength	140 ksi
Elongation	18%
Reduction of Area	72%

Nominal Room Temperature Properties after Aging

Size	Direction	Hardness Rockwell "C"	Tensile Strength ksi	0.2% Yield Strength ksi	Elongation In 4.5 $\sqrt{A}$ %	Reduction of Area %
5/8" Round	Longitudinal	43.4	212.0	207.7	12.5	61.7
1¼" Round	Longitudinal	43.0	214.3	208.5	12.0	60.6
3" Round	Longitudinal	42.8	210.0	204.2	11.9	60.4
6" Square	Longitudinal	43.5	208.4	202.6	11.6	58.8
	Transverse	43.9	206.9	200.1	8.9	41.7
.250" Sheet	Transverse	42.9	218.1	213.0	11.0	45.0

Mechanical Properties

Titanium Ti-6Al-4V (Grade 5), Annealed

Hardness, Brinell	334	334	Estimated from Rockwell C.
Hardness, Knoop	363	363	Estimated from Rockwell C.
Hardness, Rockwell C	36	36	
Hardness, Vickers	349	349	Estimated from Rockwell C.
Tensile Strength, Ultimate	950 MPa	138000 psi	
Tensile Strength, Yield	880 MPa	128000 psi	
Elongation at Break	14 %	14 %	
Reduction of Area	36 %	36 %	
Modulus of Elasticity	113.8 GPa	16500 ksi	
Compressive Yield Strength	970 MPa	141000 psi	
Notched Tensile Strength	1450 MPa	210000 psi	K_t (stress concentration factor) = 6.7
Ultimate Bearing Strength	1860 MPa	270000 psi	e/D = 2
Bearing Yield Strength	1480 MPa	215000 psi	e/D = 2
Poisson's Ratio	0.342	0.342	
Charpy Impact	17 J	12.5 ft-lb	V-notch
Fatigue Strength	240 MPa	34800 psi	at 1E+7 cycles. K_t (stress concentration factor) = 3.3
Fatigue Strength	510 MPa	74000 psi	Unnotched 10,000,000 Cycles
Fracture Toughness	75 MPa-m½	68.3 ksi-in½	
Shear Modulus	44 GPa	6380 ksi	
Shear Strength	550 MPa	79800 psi	Ultimate shear strength

Titanium Ti-6Al-4V (Grade 5), Annealed

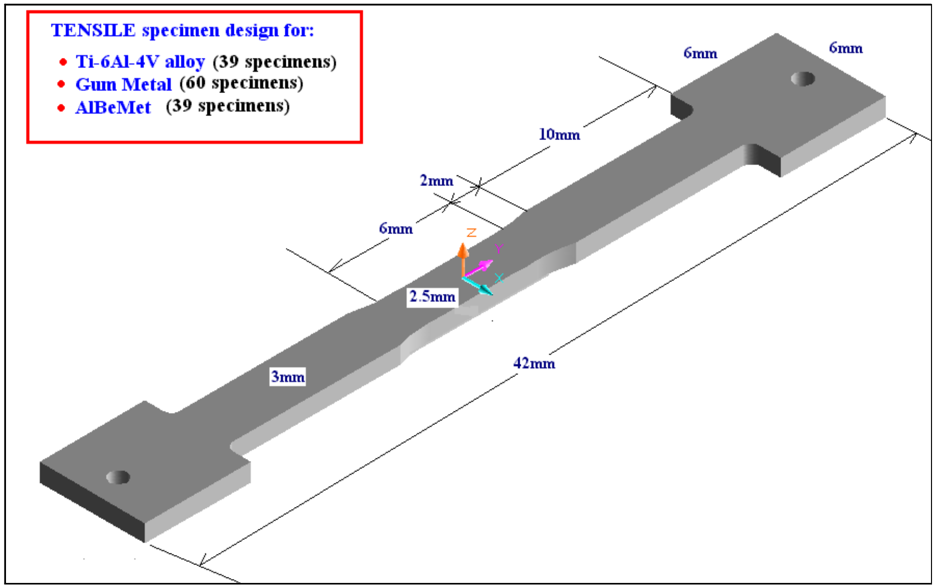
Electrical Properties

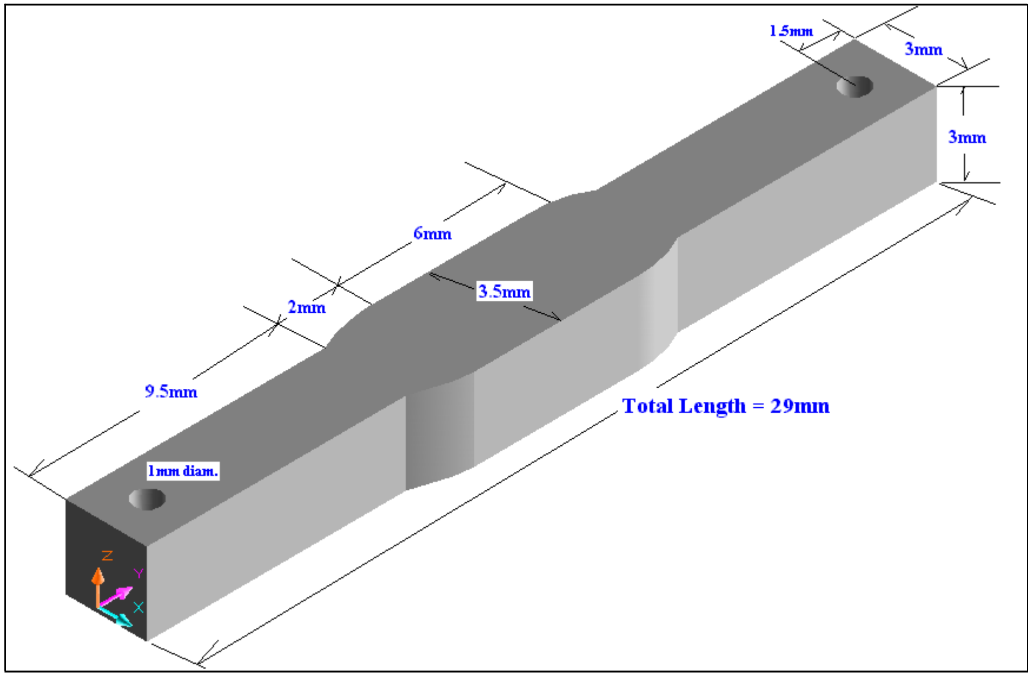
Electrical Resistivity	0.000178 ohm-cm	0.000178 ohm-cm	
Magnetic Permeability	1.00005	1.00005	at 1.6kA/m
Magnetic Susceptibility	3.3e-006	3.3e-006	cgs/g

Thermal Properties

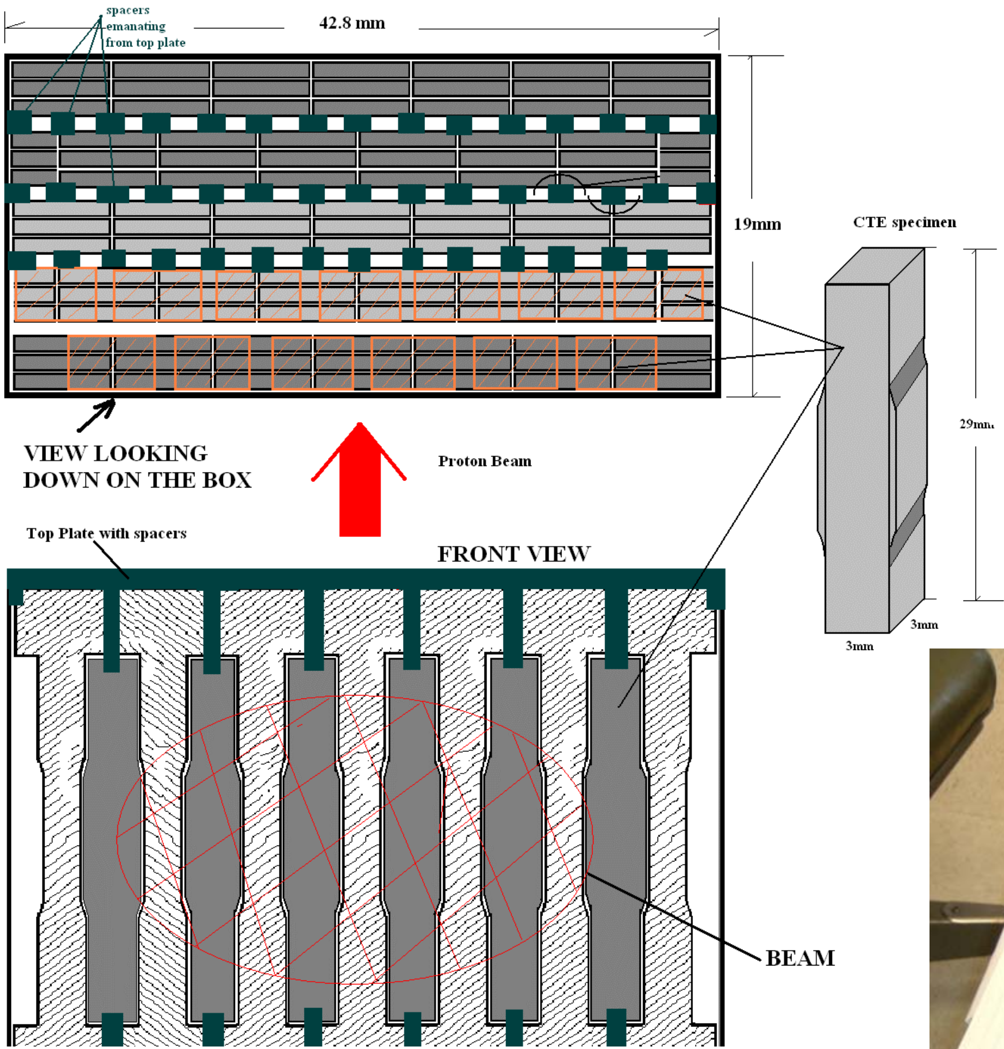
CTE, linear 20°C	8.6 µm/m-°C	4.78 µin/in-°F	20-100ºC
CTE, linear 250°C	9.2 µm/m-°C	5.11 µin/in-°F	Average over the range 20-315ºC
CTE, linear 500°C	9.7 µm/m-°C	5.39 µin/in-°F	Average over the range 20-650ºC
Heat Capacity	0.5263 J/g-°C	0.126 BTU/lb-°F	
Thermal Conductivity	6.7 W/m-K	46.5 BTU-in/hr-ft²-°F	
Melting Point	1604 - 1660 °C	2920 - 3020 °F	
Solidus	1604 °C	2920 °F	
Liquidus	1660 °C	3020 °F	
Beta Transus	980 °C	1800 °F	

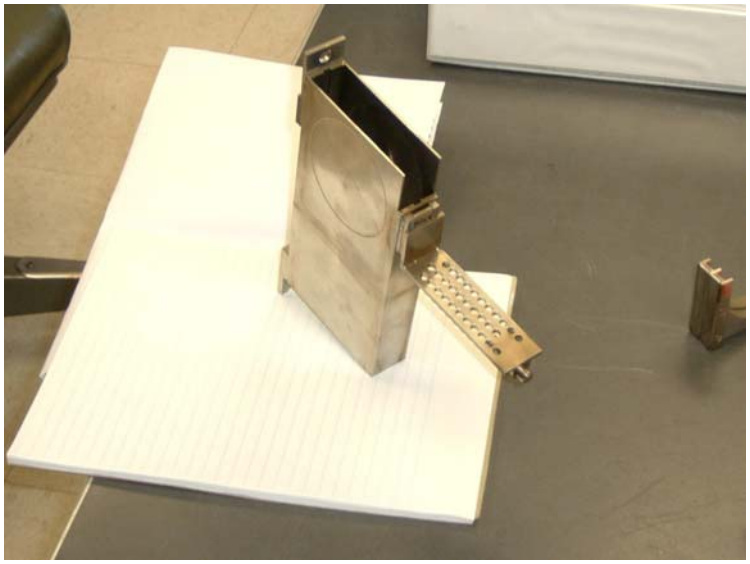
Tensile and CTE Specimen Design



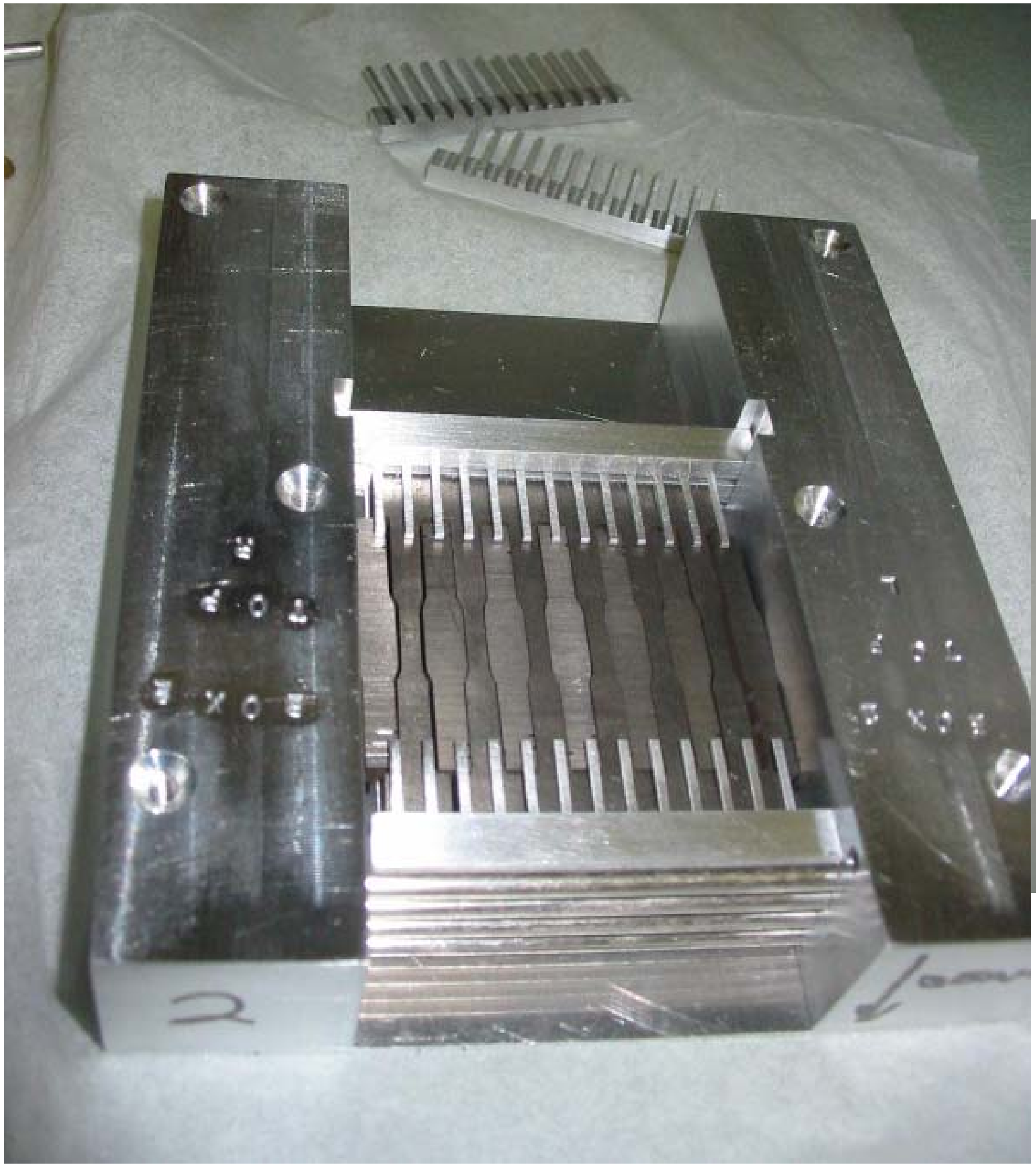


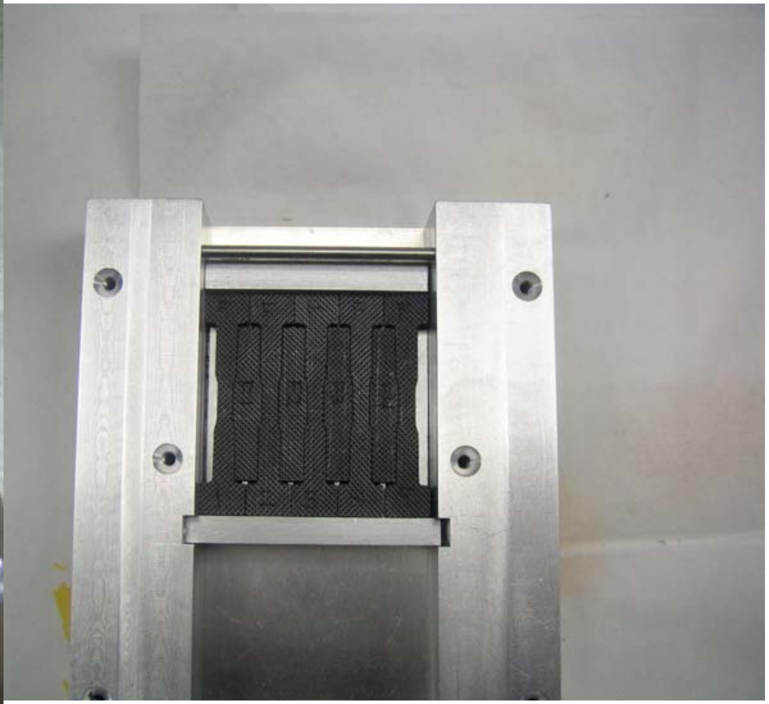
Tensile and CTE Specimen Assembly into the Target Box During Irradiation



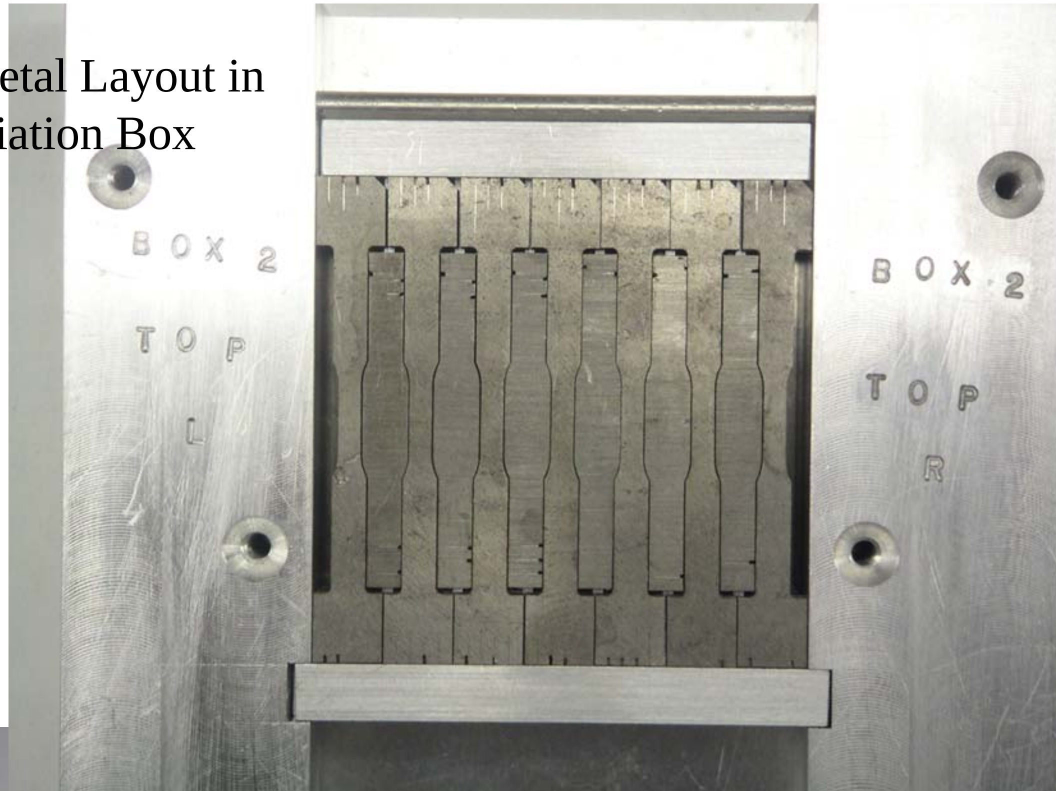


TARGET BOX ASSEMBLY DETAILS

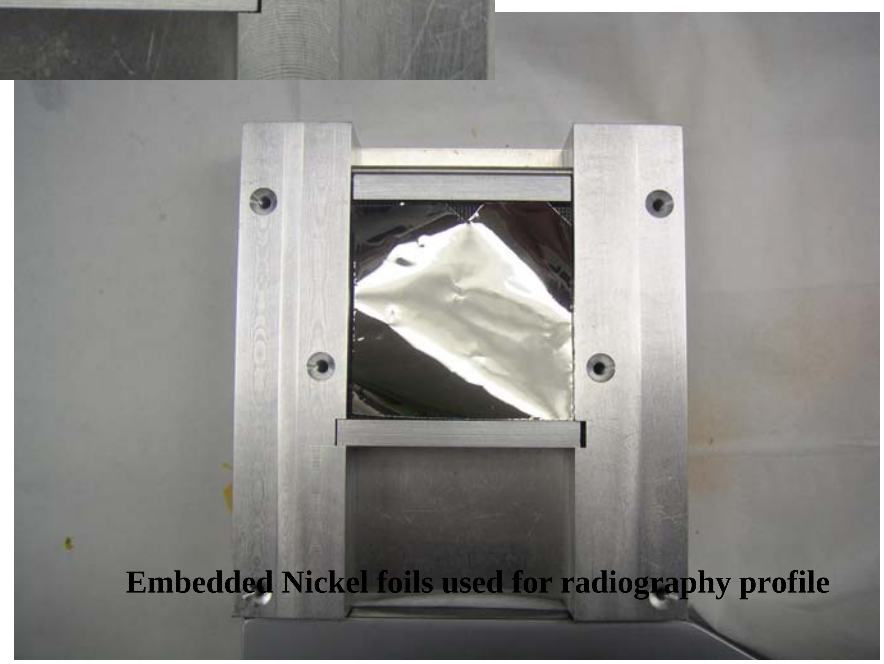




GUM Metal Layout in Irradiation Box

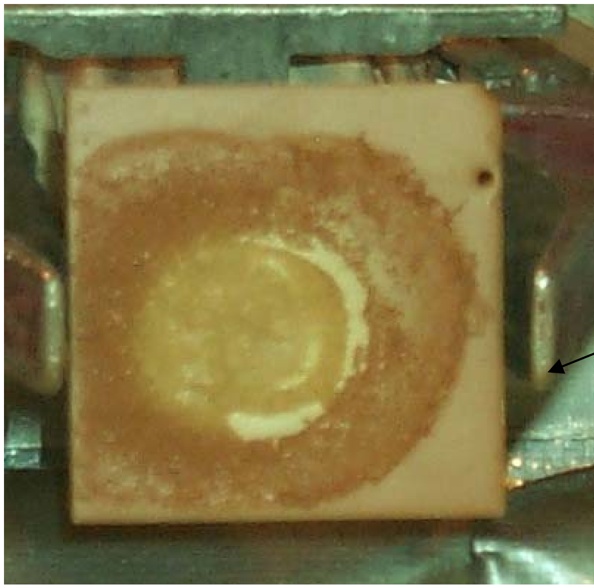


Nickel-Plated Aluminum Specimens (NUMI Horn Material)

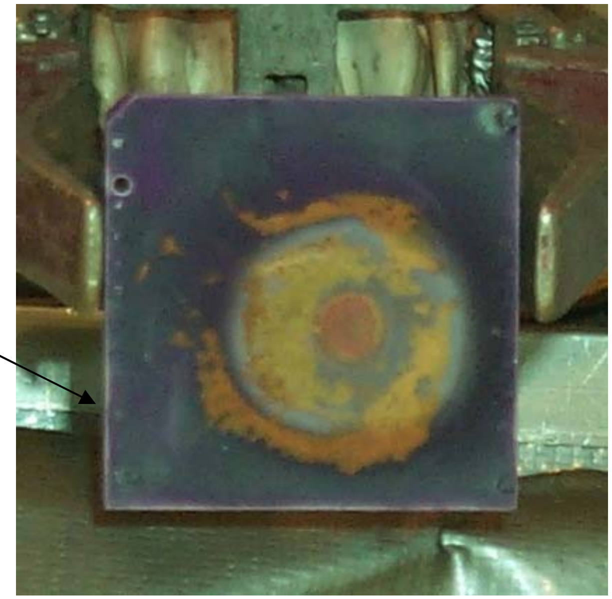


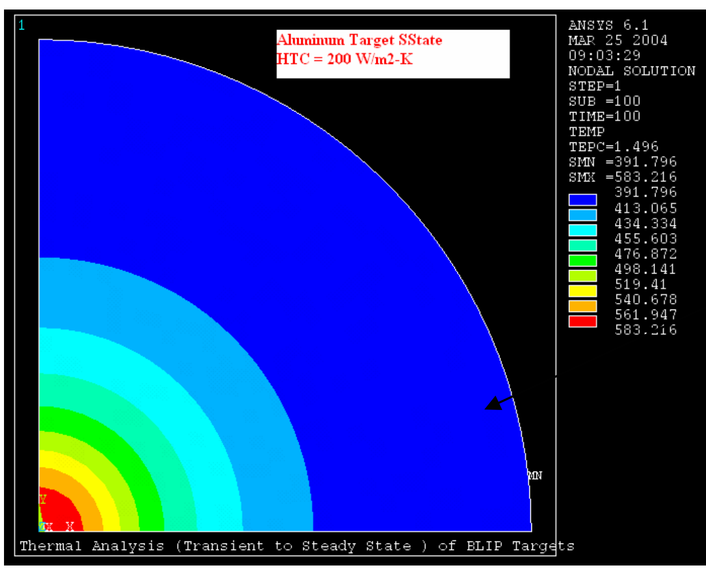
Embedded Nickel foils used for radiography profile

Estimation of Irradiation Temperature Using Aluminum Plate into the BLIP Irradiation Facility and Temperature Sensitive Paint (TSP)

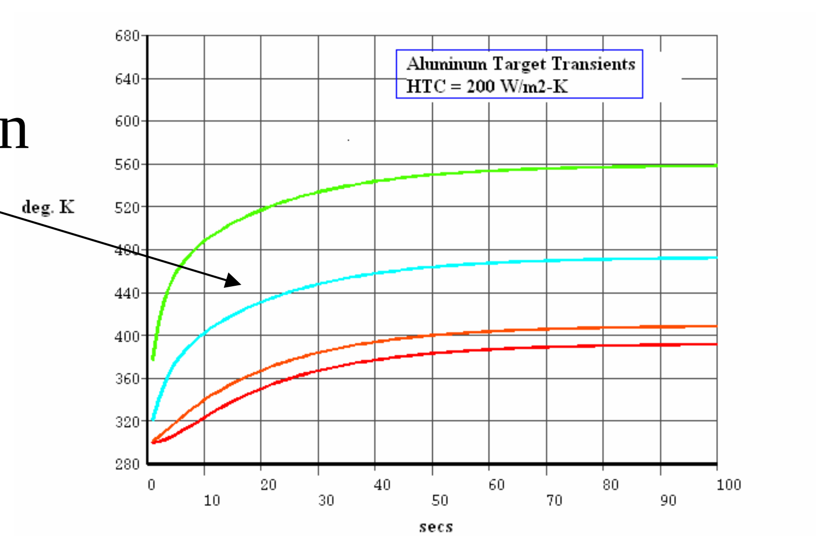


Experiment

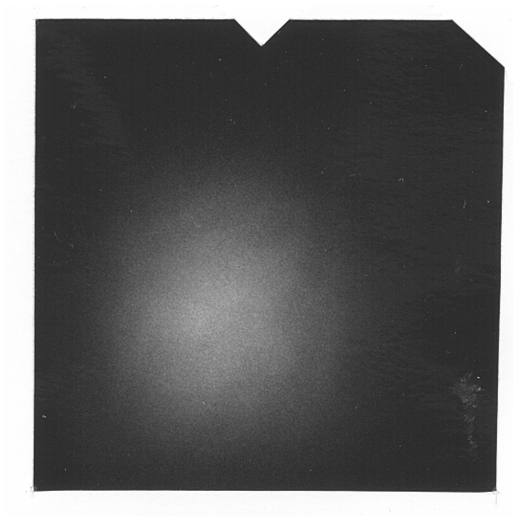


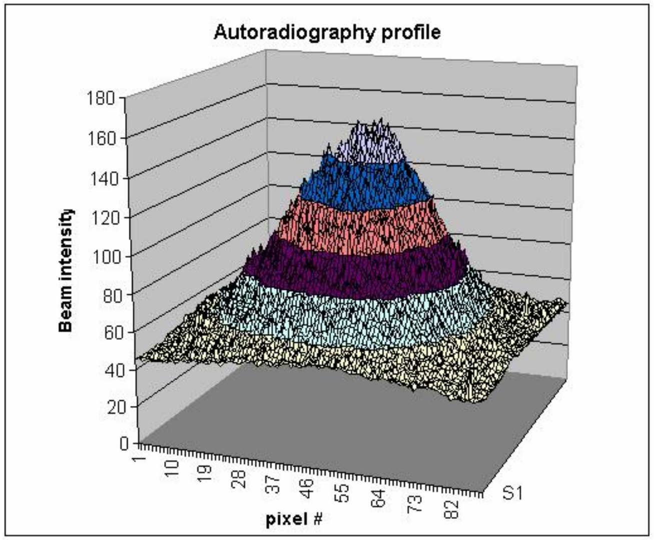


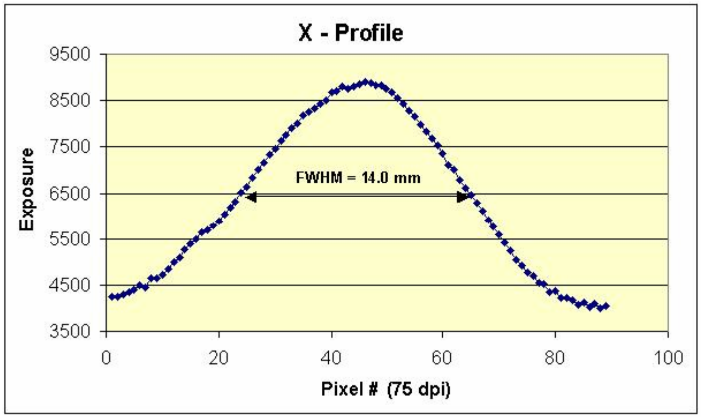
Simulation

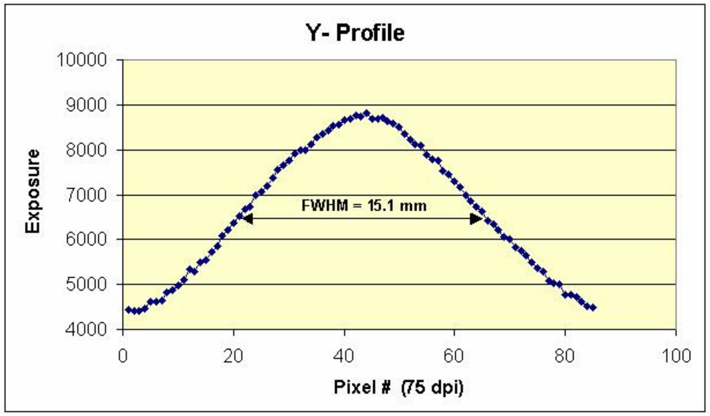


Activation & Beam profile Assessment



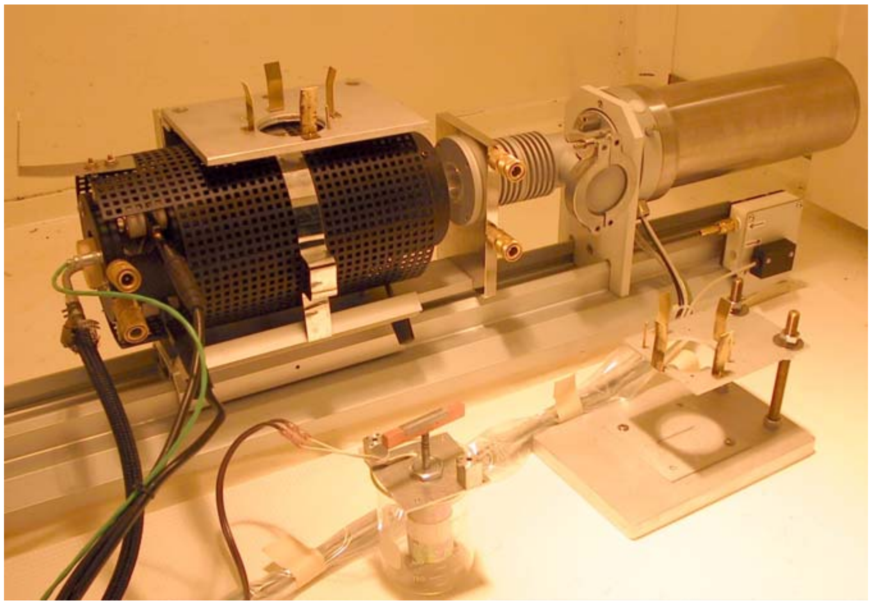


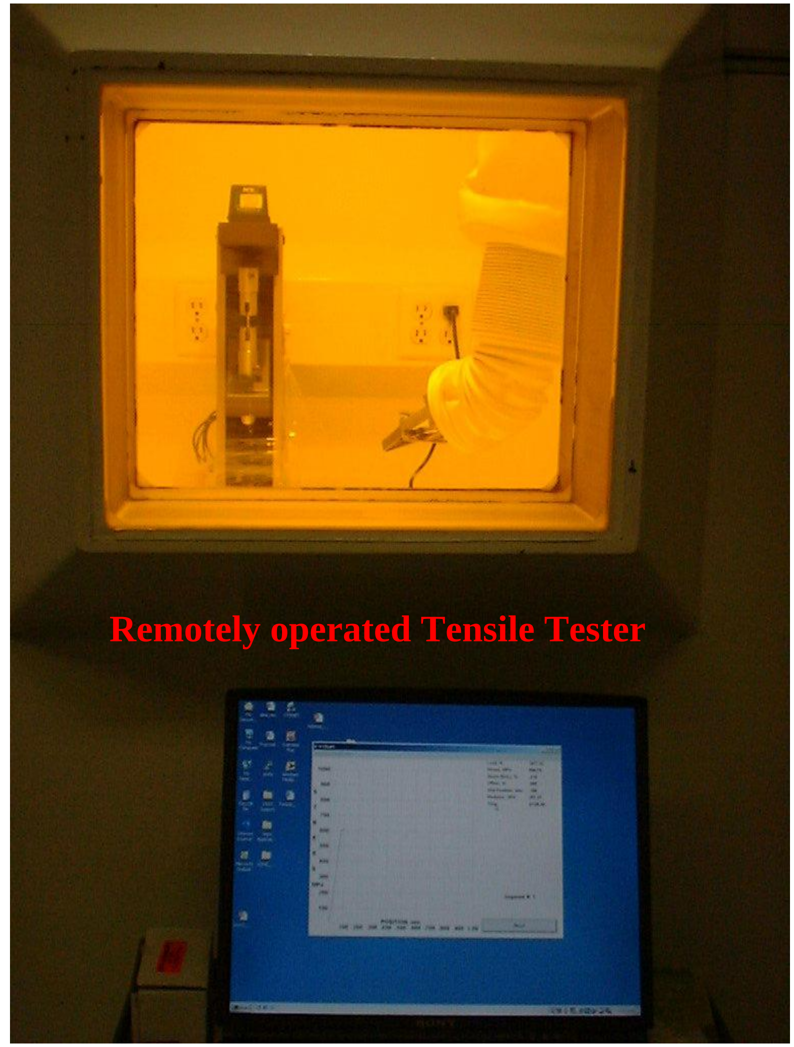




HOT CELL   Specimen Analysis

Dilatometer

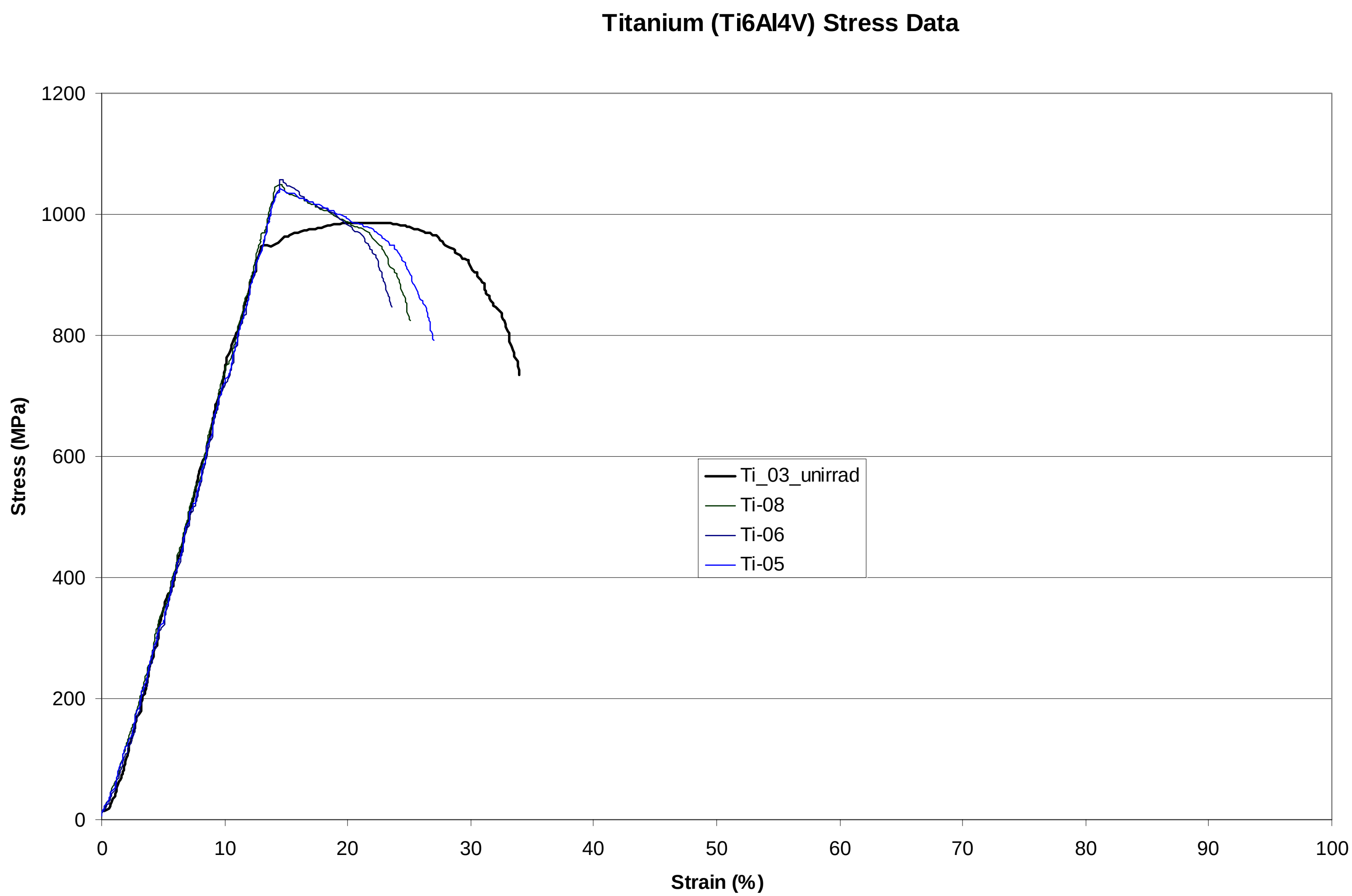




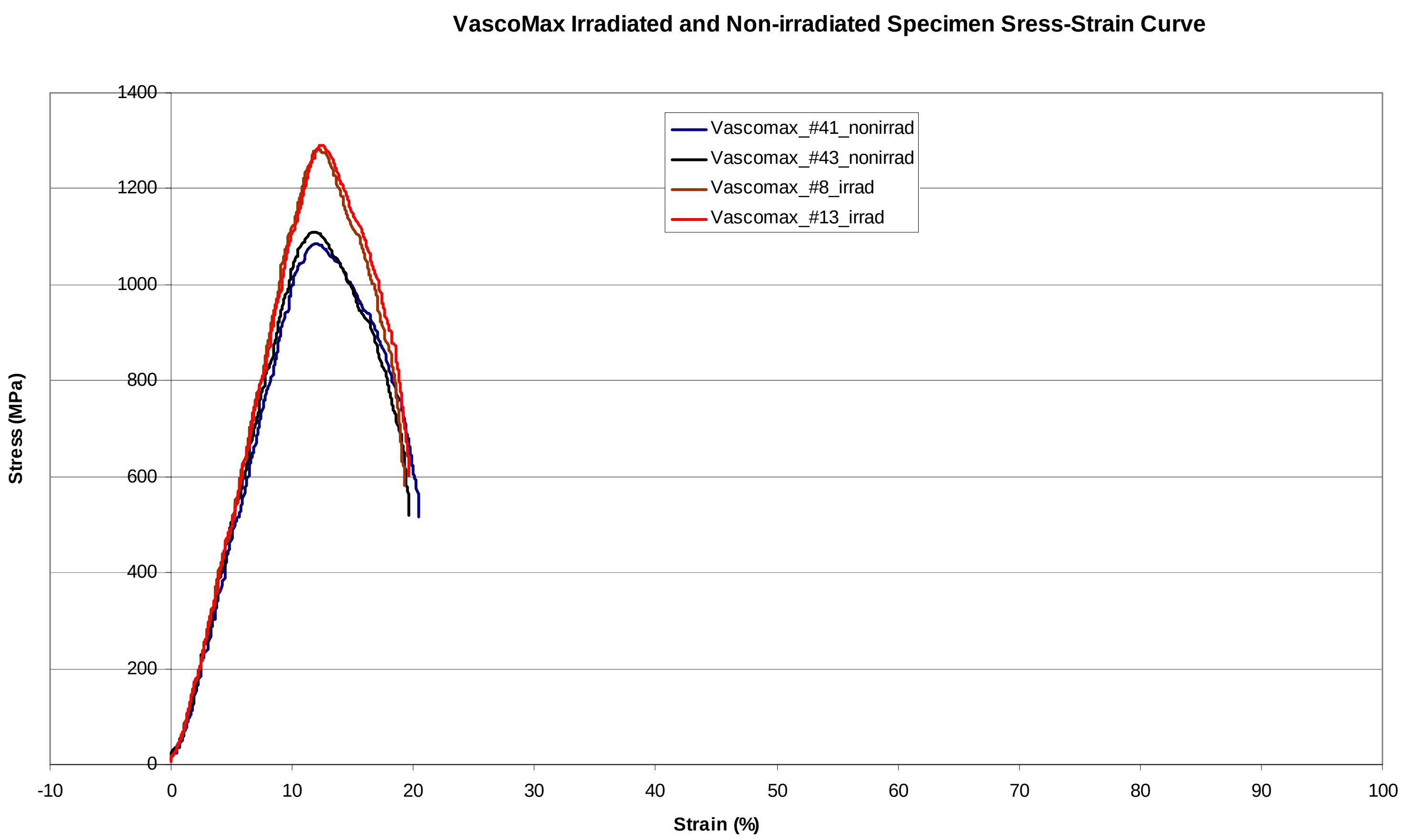
Remotely operated Tensile Tester

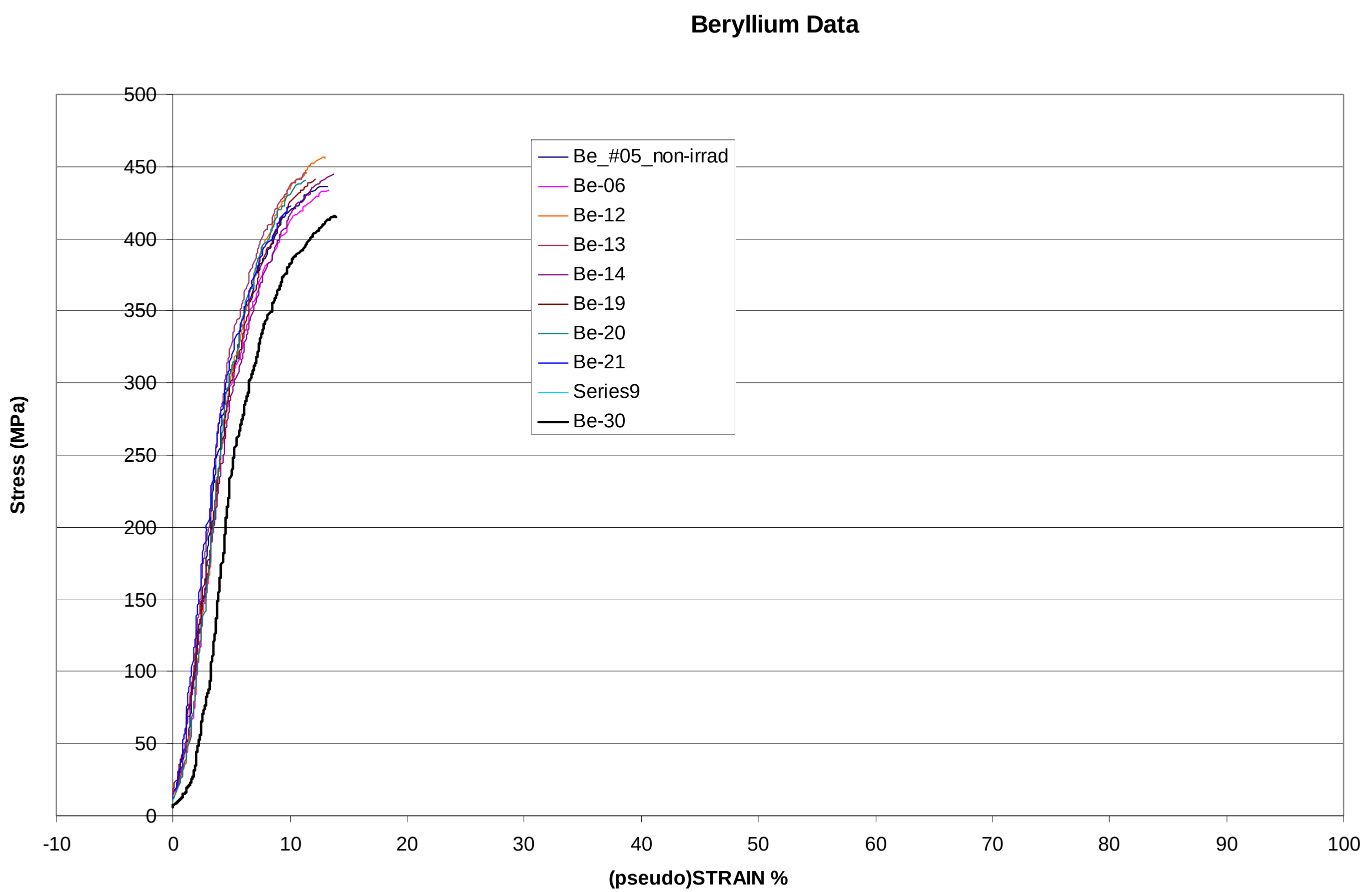
Preliminary Results from Testing Irradiated Specimens at the BNL Hot Cell Facility

- NOTE that just a few of the tested specimens of each material is presented in the following graphs. While most of the irradiated samples have been tested, no correlation with the specimen activation has been made. Further, the non-irradiated specimen testing is incomplete (this will provide a better estimate of what the non-irradiated stress values, such as yield and ultimate, were prior to irradiation)
- The Stress-Strain Curves generated are from RAW data with no adjustment for “effective” strain gauge (results shown assume that only the 6mm neck-down section of the specimen contributes to the total extension of the specimen)
- Given that the position of the proton beam spot was slightly off centered, a second level of correlation will be performed based on the location within the 6mm gauge (neck-down) where rupture occurred.

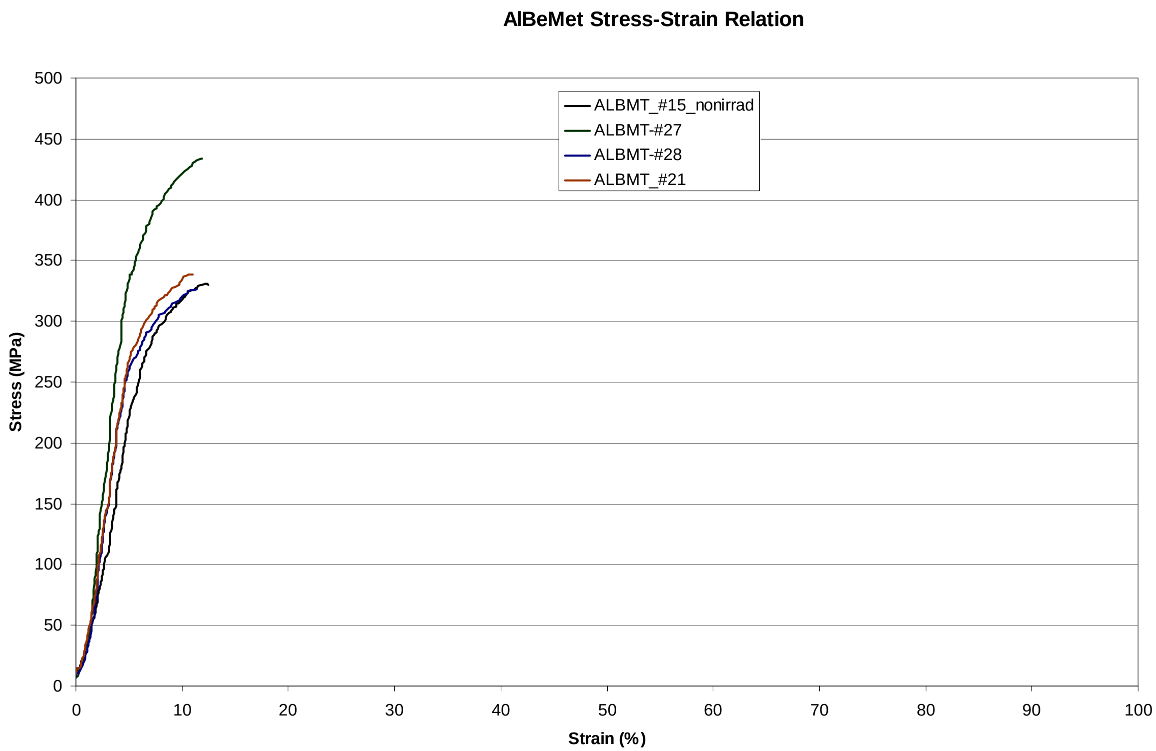


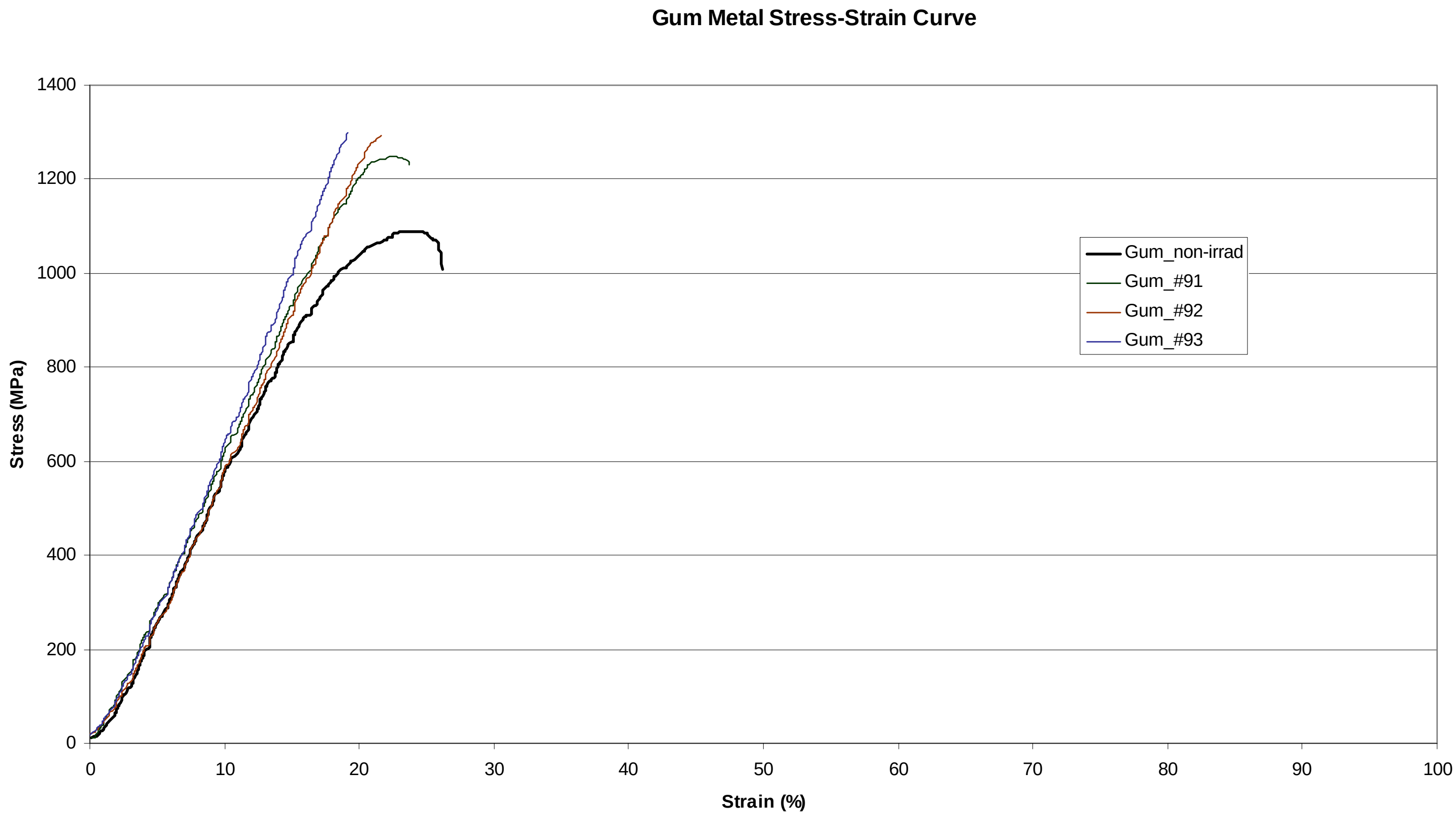
Titanium (Ti6Al4V) Stress Data
Stress (MPa)
0
200
400
600
800
1000
1200
0
10
20
30
40
50
60
70
80
90
100
Strain (%)
Ti_03_unirrad
Ti-08
Ti-06
Ti-05

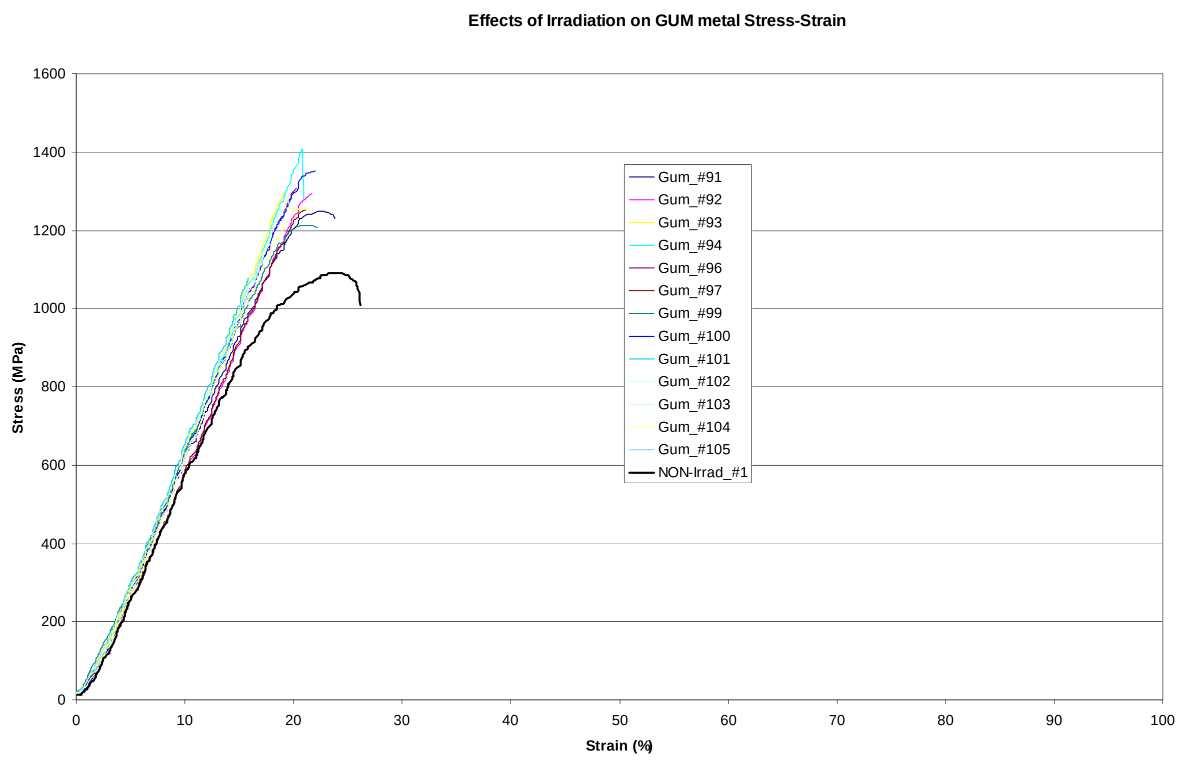

VascoMax Irradiated and Non-irradiated Specimen Sress-Strain Curve
Vascomax_#41_nonirrad
Vascomax_#43_nonirrad
Vascomax_#8_irrad
Vascomax_#13_irrad
Stress (MPa)
Strain (%)
0
200
400
600
800
1000
1200
1400
-10
0
10
20
30
40
50
60
70
80
90
100



Beryllium Data
Stress (MPa)
500
450
400
350
300
250
200
150
100
50
0
-10
0
10
20
30
40
50
60
70
80
90
100
(pseudo)STRAIN %
Be_#05_non-irrad
Be-06
Be-12
Be-13
Be-14
Be-19
Be-20
Be-21
Series9
Be-30


AlBeMet Stress-Strain Relation
ALBMT_#15_nonirrad
ALBMT-#27
ALBMT-#28
ALBMT_#21
Stress (MPa)
Strain (%)
0
50
100
150
200
250
300
350
400
450
500
0
10
20
30
40
50
60
70
80
90
100


Gum Metal Stress-Strain Curve
Stress (MPa)
0
200
400
600
800
1000
1200
1400
Strain (%)
0
10
20
30
40
50
60
70
80
90
100
Gum_non-irrad
Gum_#91
Gum_#92
Gum_#93


Effects of Irradiation on GUM metal Stress-Strain
Stress (MPa)
Strain (%)
0
200
400
600
800
1000
1200
1400
1600
0
10
20
30
40
50
60
70
80
90
100
Gum_#91
Gum_#92
Gum_#93
Gum_#94
Gum_#96
Gum_#97
Gum_#99
Gum_#100
Gum_#101
Gum_#102
Gum_#103
Gum_#104
Gum_#105
NON-Irrad_#1