PLAN

MATERIAL STUDIES FOR PULSED HIGH-INTENSITY PROTON BEAM TARGETS

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CHALLENGES FOR THE INTEGRATED TARGET SYSTEMS

AS WE GET TO 1+ MW SYSTEM

- Heat generation and removal from the target system
- Target thermo-mechanical response from energetic, high intensity protons
- Irradiation and corrosion effects on materials
- Beam window survivability

SOLUTION:

Look for new materials that are continuously being developed for other applications but seem to fit the bill as targets

There is a catch !

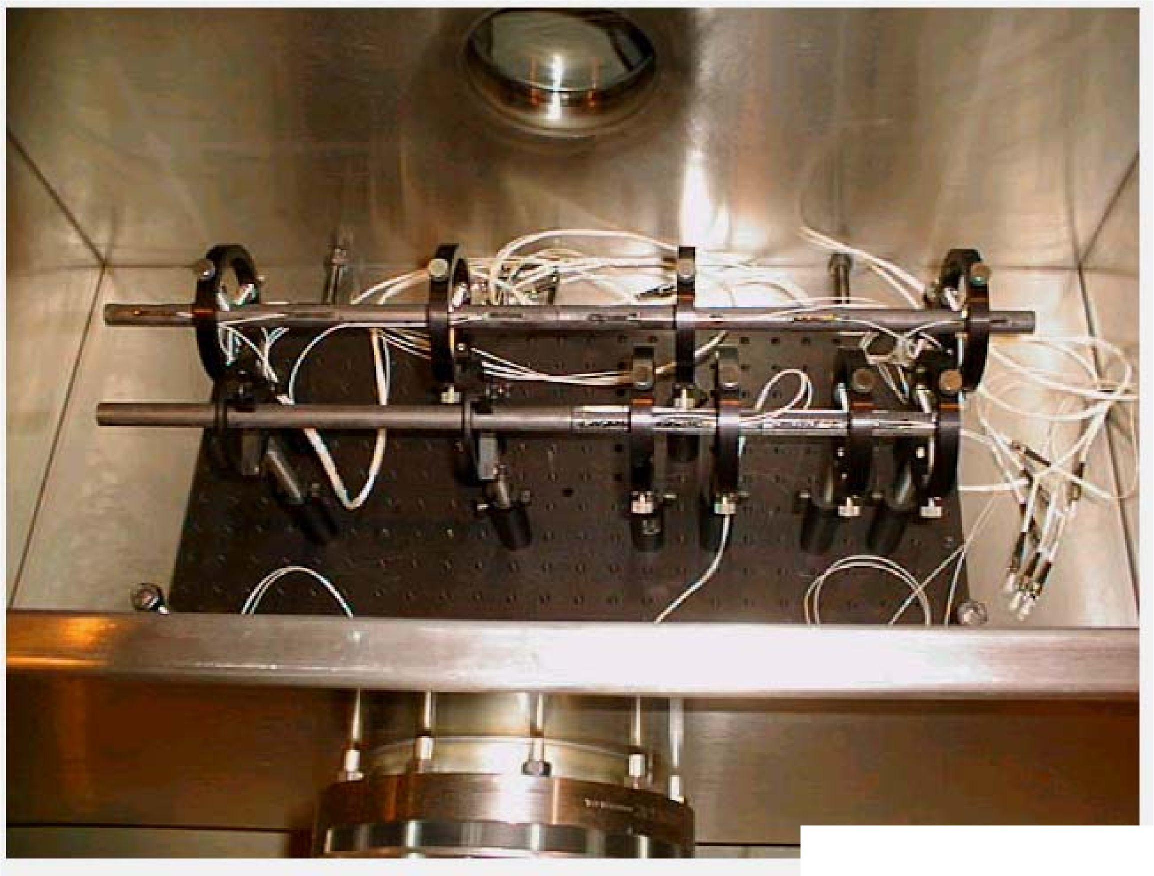
These materials have not been tested for their resilience to radiation exposure

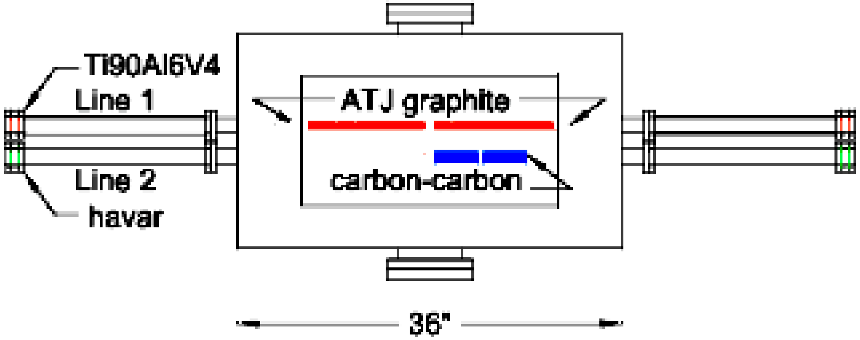
The collaboration has been looking into these materials for some time

Candidate materials studied for applications as targets windows are:

- Inconel-718
- Aluminum-3000
- Havar
- Ti-6Al-6V
- Graphite (ATJ)
- Carbon-Carbon
- SuperInvar

PHASE I: Graphite & Carbon-Carbon Targets



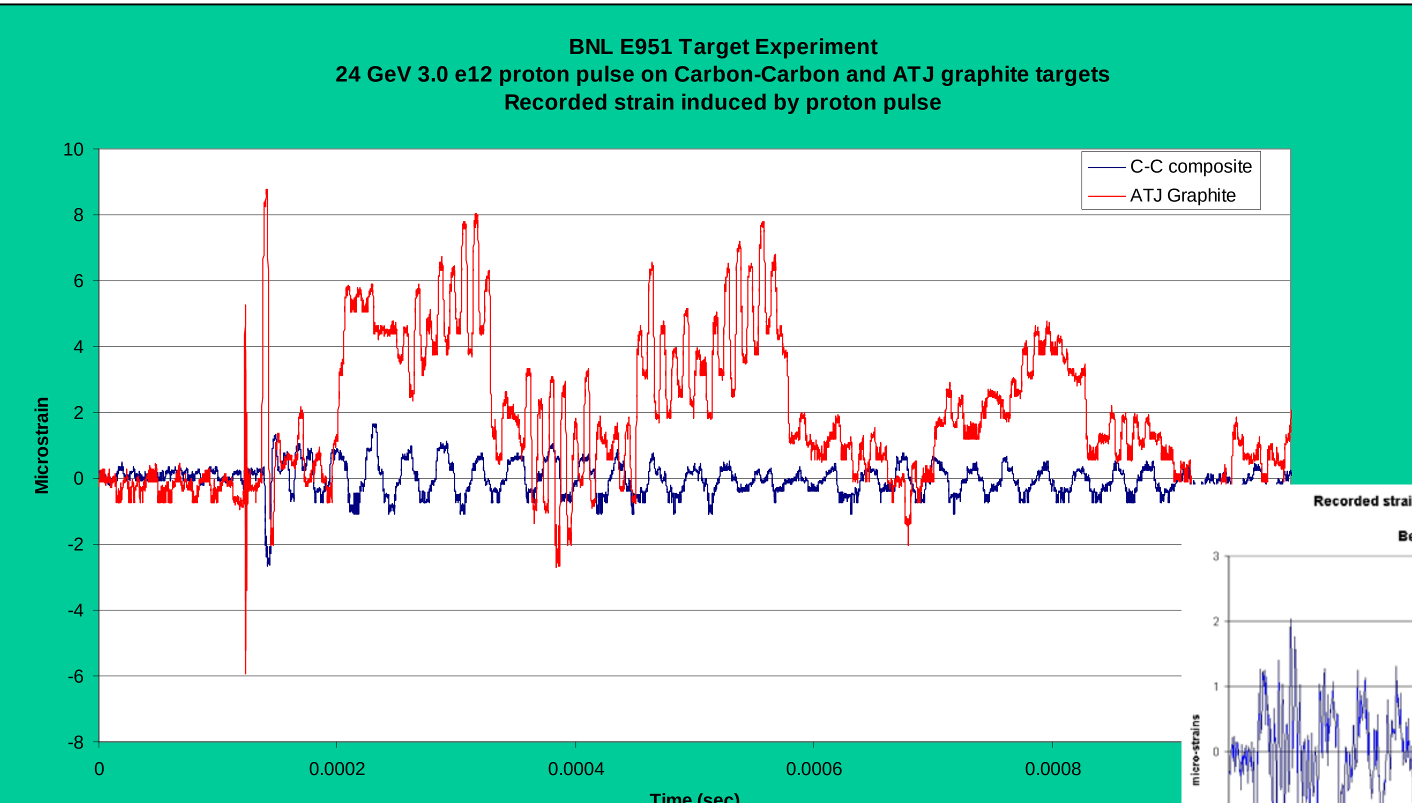


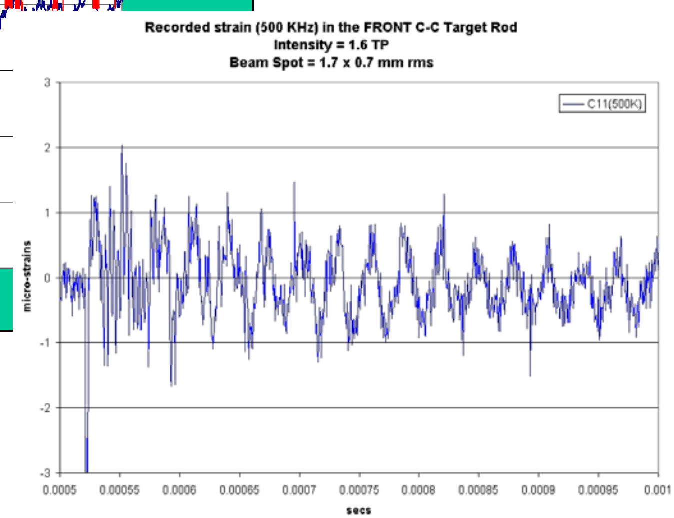
E951 Results: ATJ Graphite vs. Carbon-Carbon Composite

The results demonstrate the superiority of CC in responding to Beam SHOCK.

The question is: Will it maintain this key feature under irradiation ???

We will find out in the course of this irradiation phase

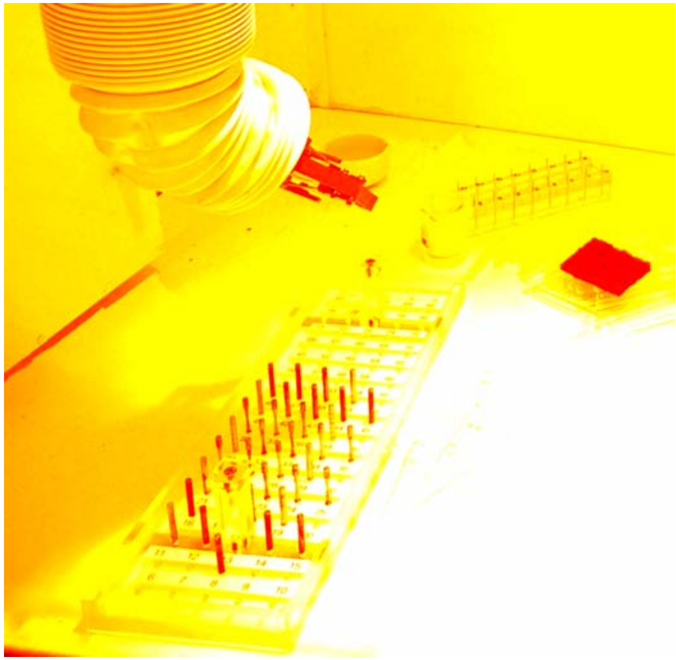


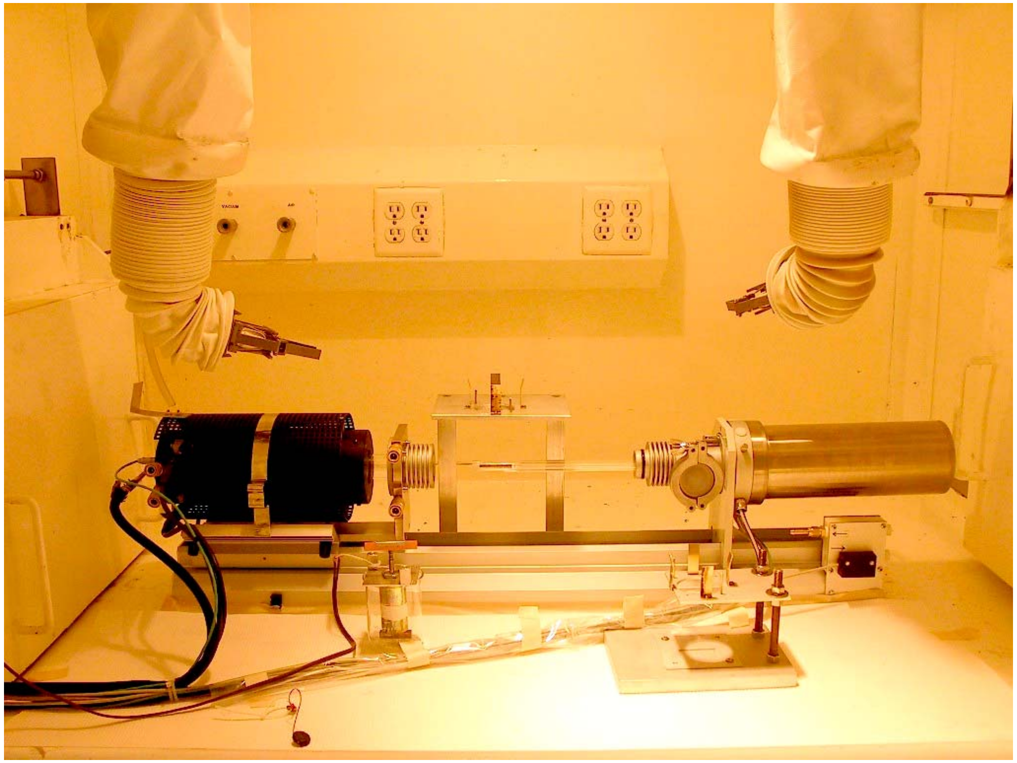


Irradiation Studies to Assess how Super-Invar responds to radiation.

Its key feature (low CTE up to 150 ^{o}C) needed to be scrutinized

Specimens and dilatometer in hot cell

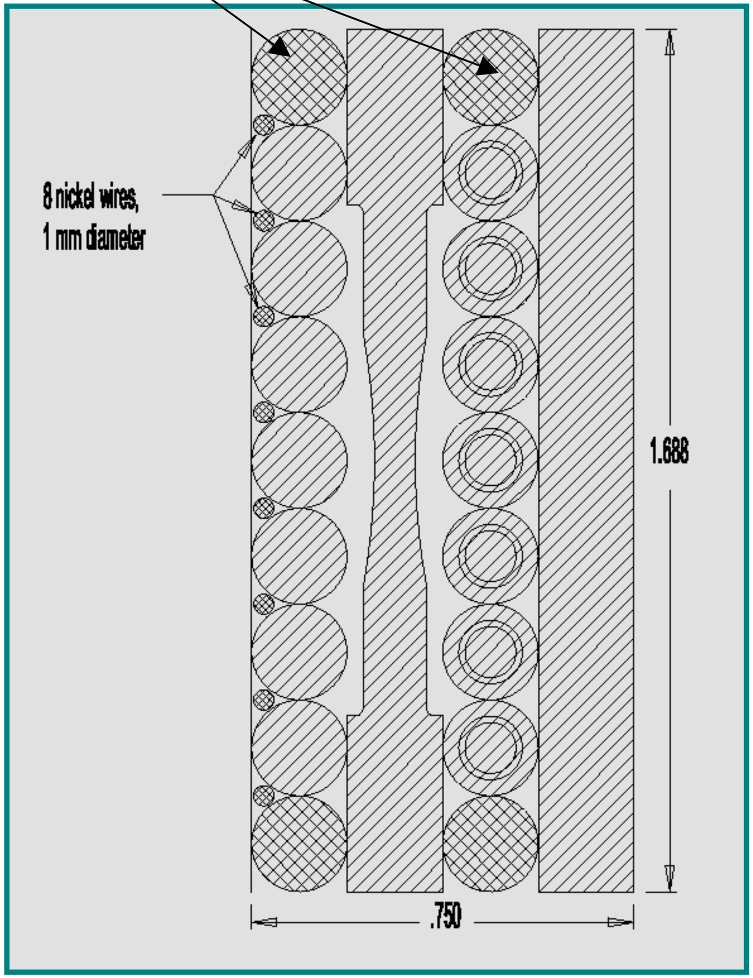


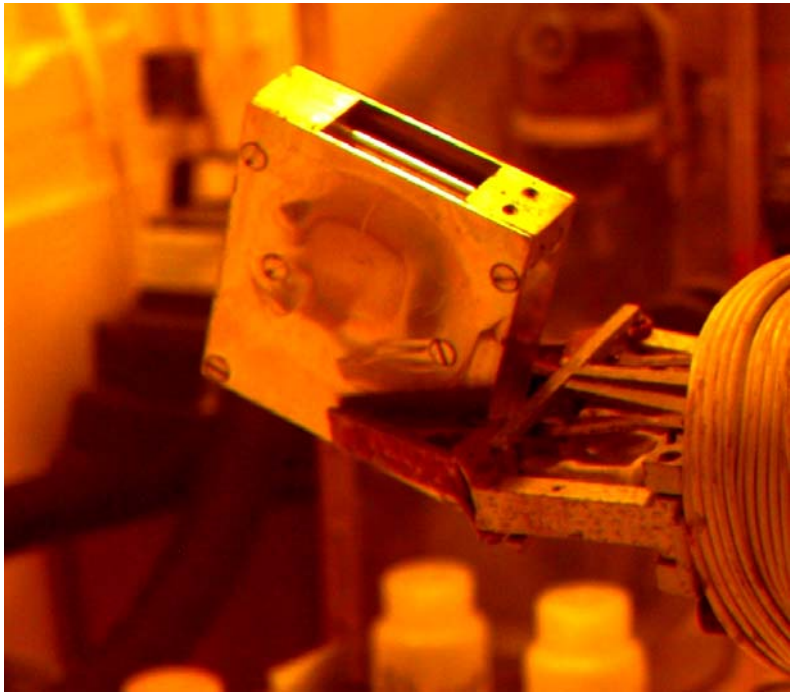


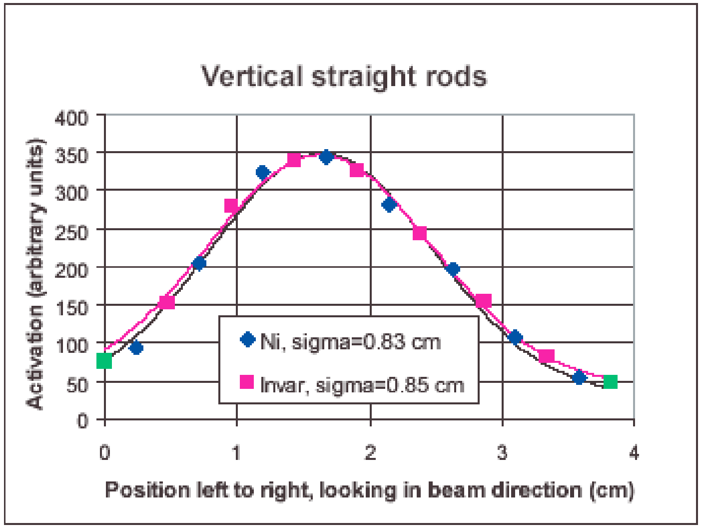
BNL Irradiation Studies

Super Invar & Inconel-718

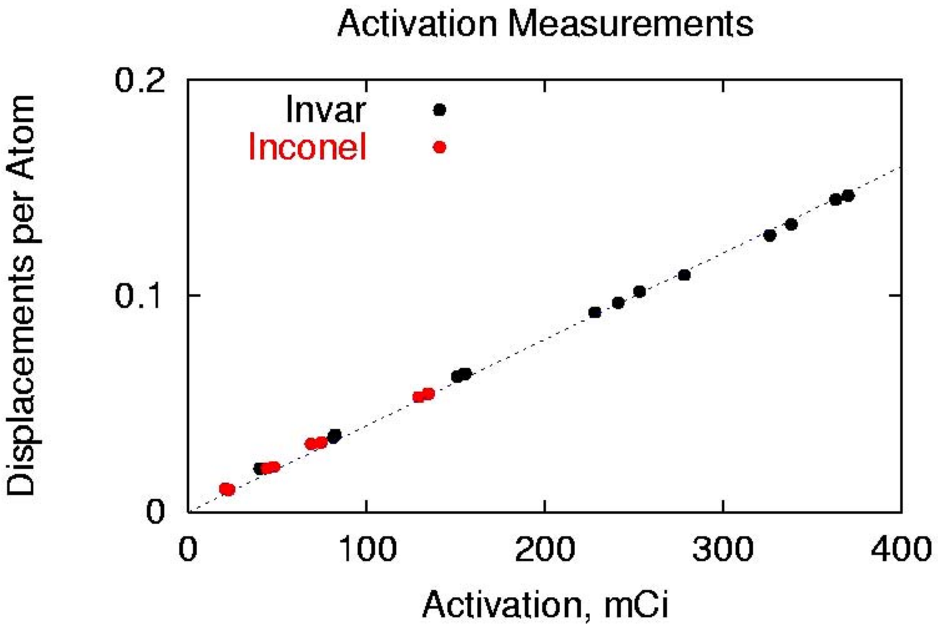
Inconel-718 rods





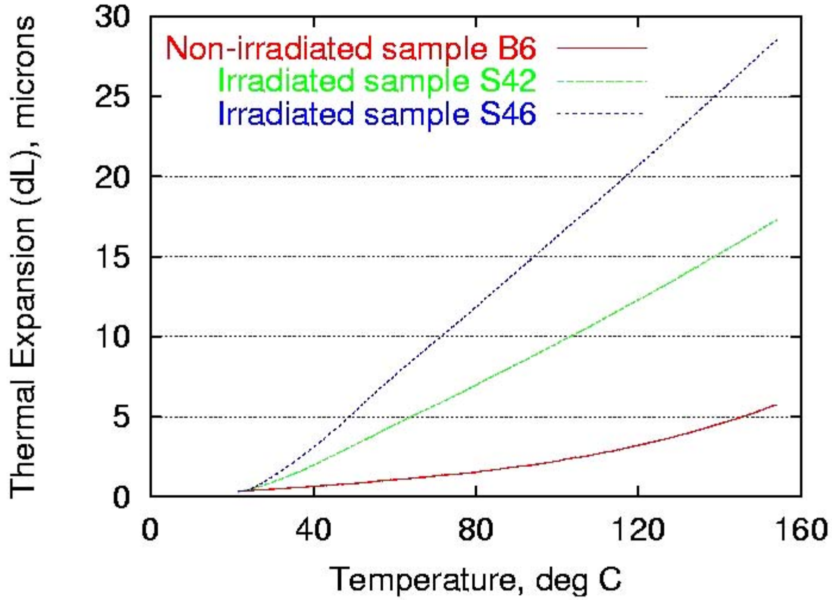


Vertical straight rods
Activation (arbitrary units)
400
350
300
250
200
150
100
50
0
0
1
2
3
4
Ni, sigma=0.83 cm
Invar, sigma=0.85 cm
Position left to right, looking in beam direction (cm)

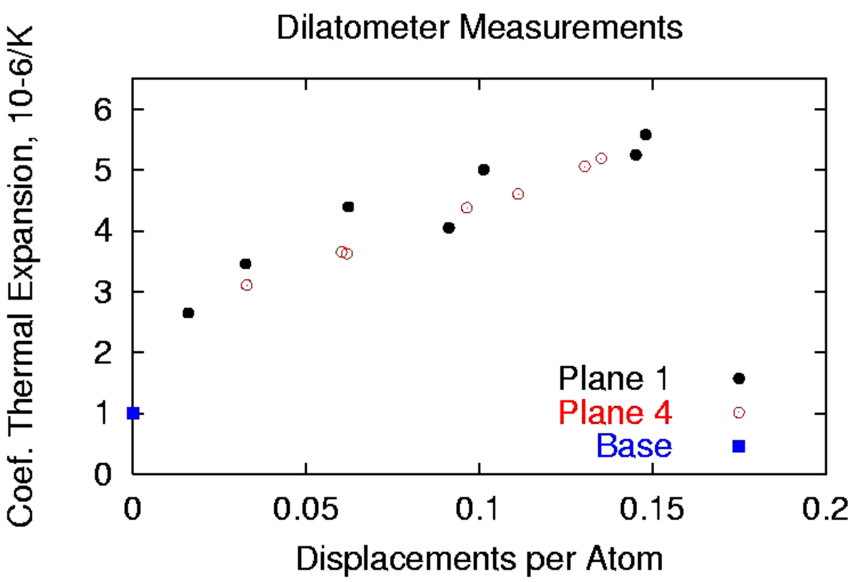


Activation Measurements
Displacements per Atom
0.2
0.1
0
Invar
Inconel
0
100
200
300
400
Activation, mCi

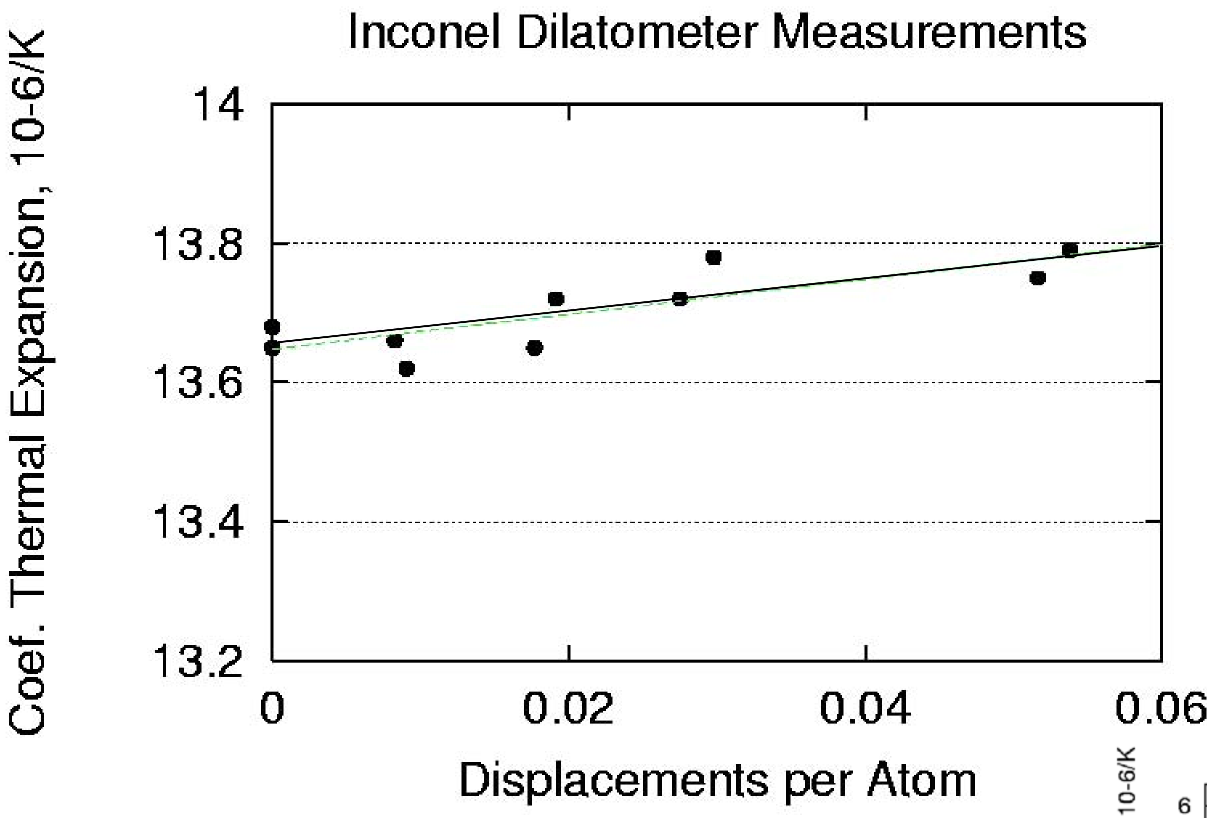
Super-Invar Irradiation Study – CTE assessment

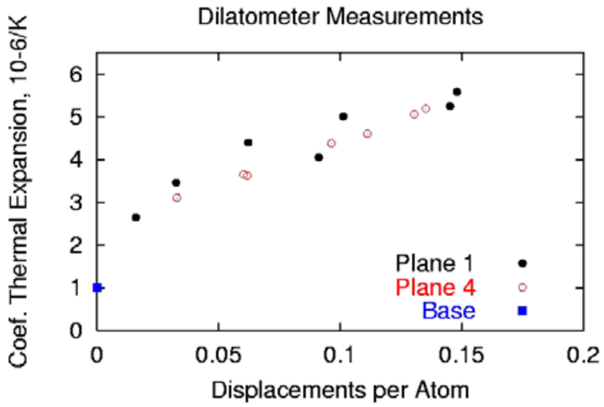


Super-Invar

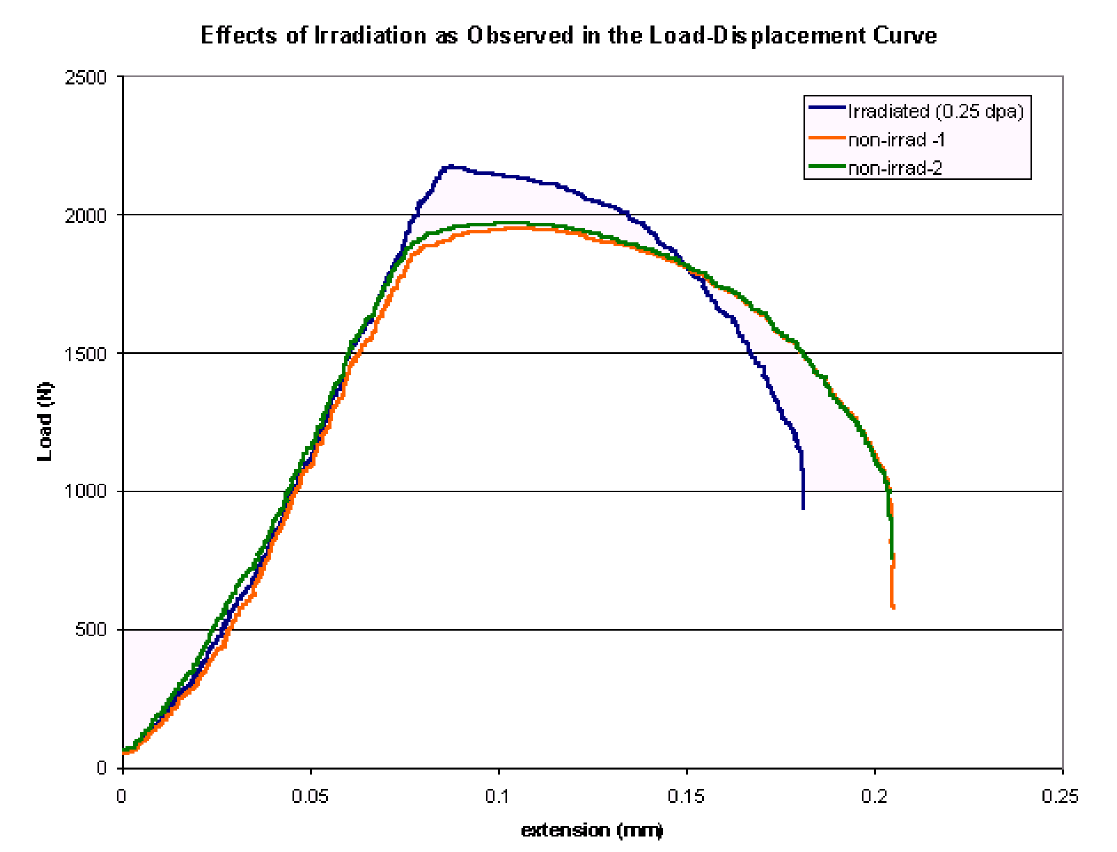


Inconel-718 CTE assessment

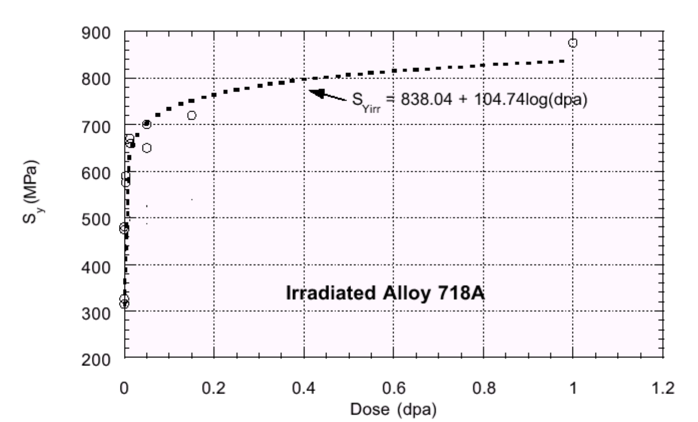




Super-Invar Irradiation Study -
Effects of Irradiation on stress-strain behavior



While the dpa received where as high as .25, they were enough to capture the tendency of the material to change. Similar effects at such low dpa can be seen in Incinel (Figure below)

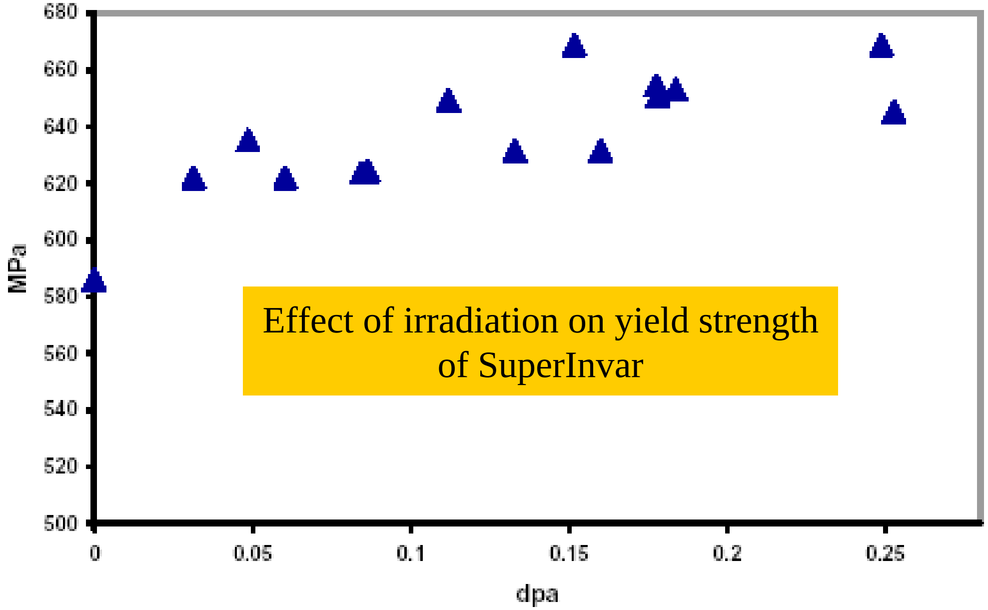


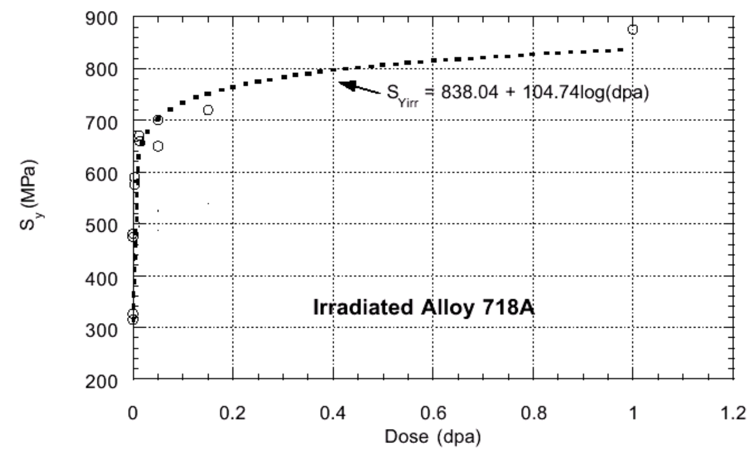
Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A

WHY STUDY super Invar ?

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

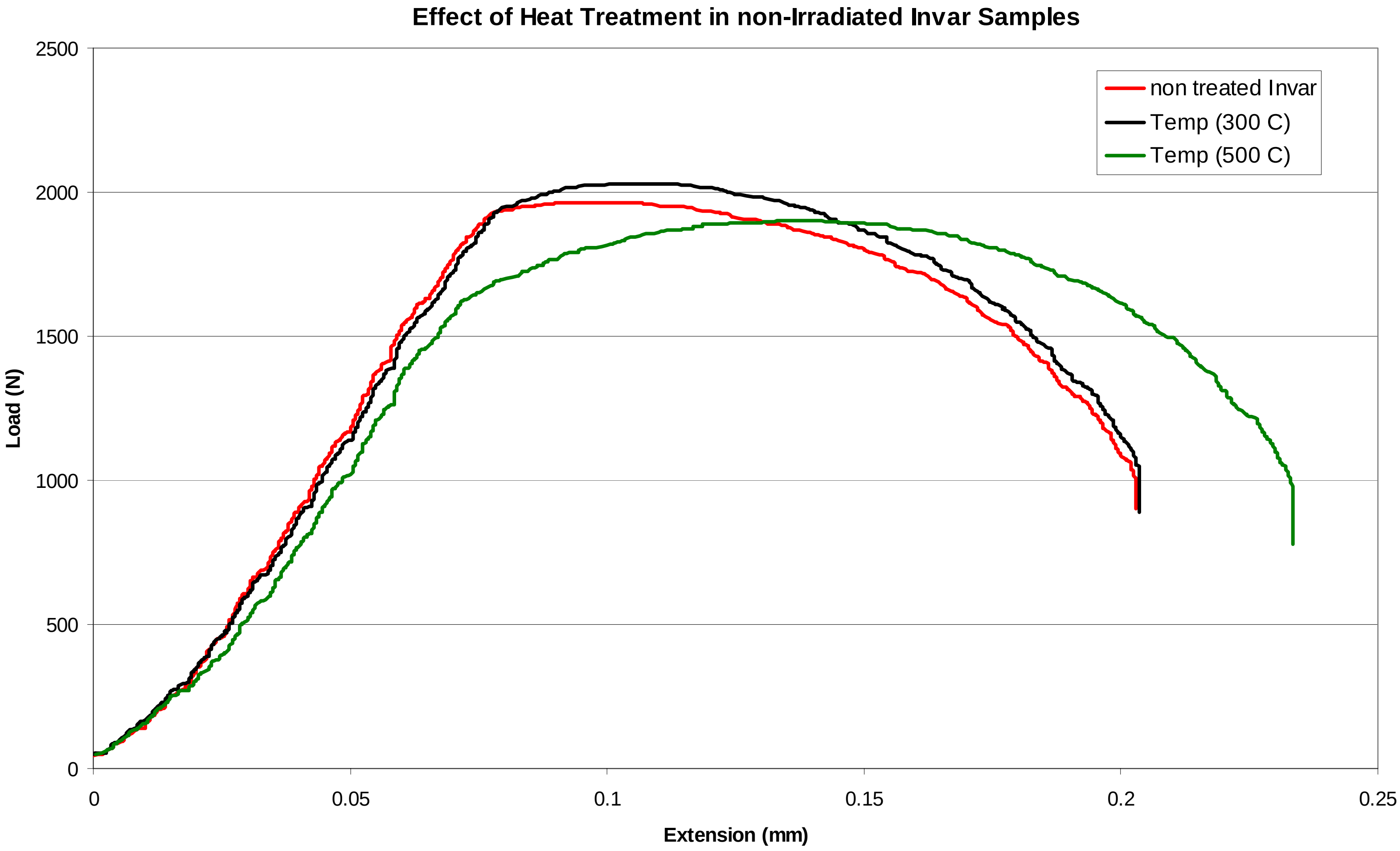
Super-Invar Irradiation Study - Irradiation vs. Yield Strength



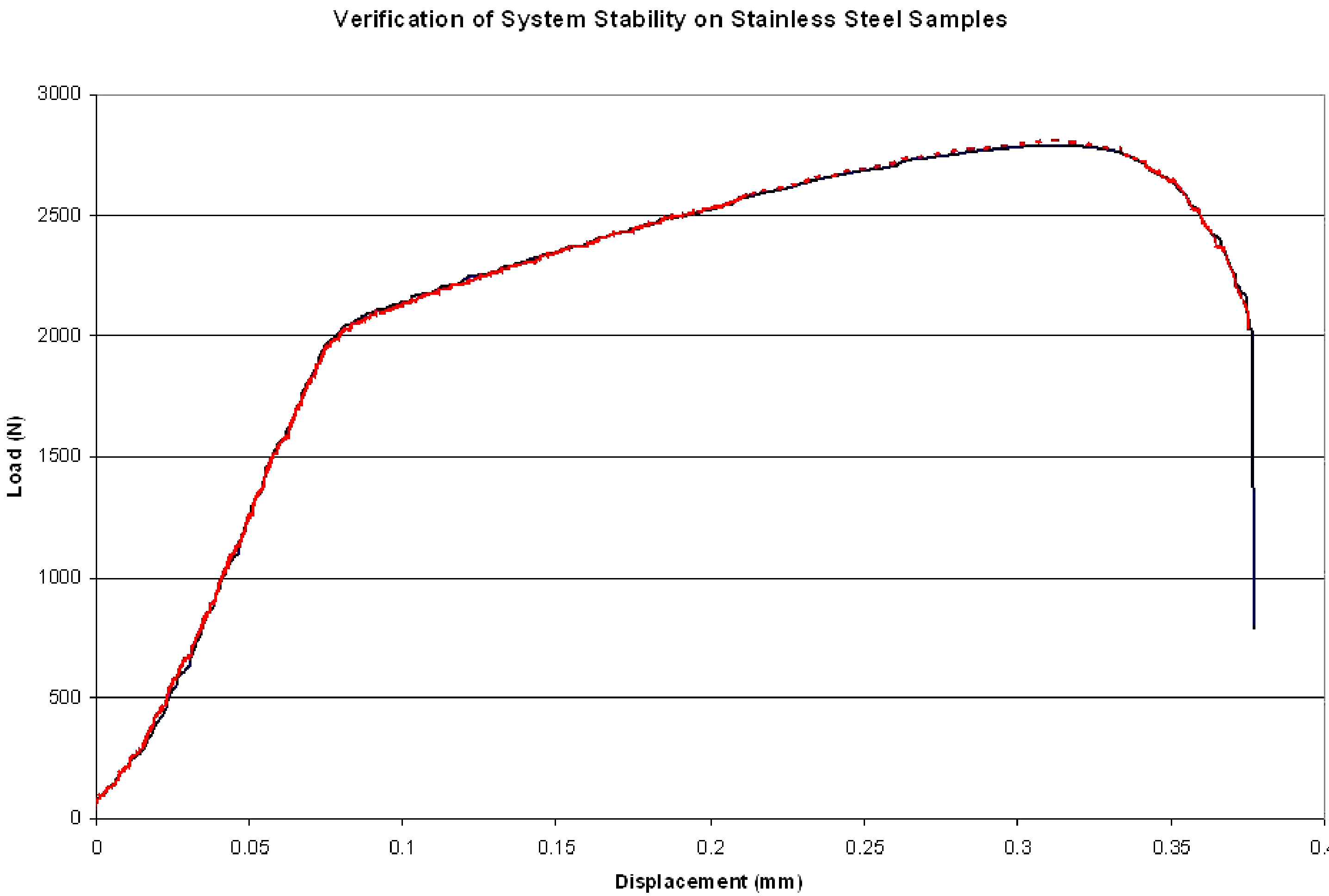


Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A

Super-Invar Irradiation Study – Temperature Effects



Super-Invar Irradiation Study
Stress-strain (load-displacement) in stainless steel samples to test system stability



PHASE-II TARGET MATERIAL STUDY

WHAT'S NEXT ? Repeat irradiation/mechanical property changes experiment for baseline materials

Carbon-Carbon composite

This low-Z composite gives the indication that it can minimize the thermal shock and survive high intensity pulses. Because of its premise it is the baseline target material for the BNL neutrino superbeam initiative. The way its key properties (such as CTE or strength) degrade with radiation is unknown.

Titanium Ti-6Al-4V alloy

The evaluation of the fracture toughness changes due to irradiation is of interest regarding this alloy that combines good tensile strength and relatively low CTE

Toyota "Gum Metal"

This alloy with the ultra-low elastic modulus, high strength , super-elastic like nature and near-zero linear expansion coefficient for the temperature range -200 ºC to +250 ºC to be assessed for irradiation effects on these properties.

VASCOMAX

This very high strength alloy that can serve as high-Z target to be evaluated for effects of irradiation on CTE, fracture toughness and ductility loss

AlBeMet

A low-Z composite that combines good properties of Be and Al. Effects of irradiation on CTE and mechanical properties need to be assessed

TG-43 Graphite

PHASE-II TARGET MATERIAL STUDY

WHAT'S DIFFERENT FROM PHASE-I?

~ 100 MeV of Proton Beam (200 to 100 MeV)

Challenge of inducing UNIFORM Beam degradation

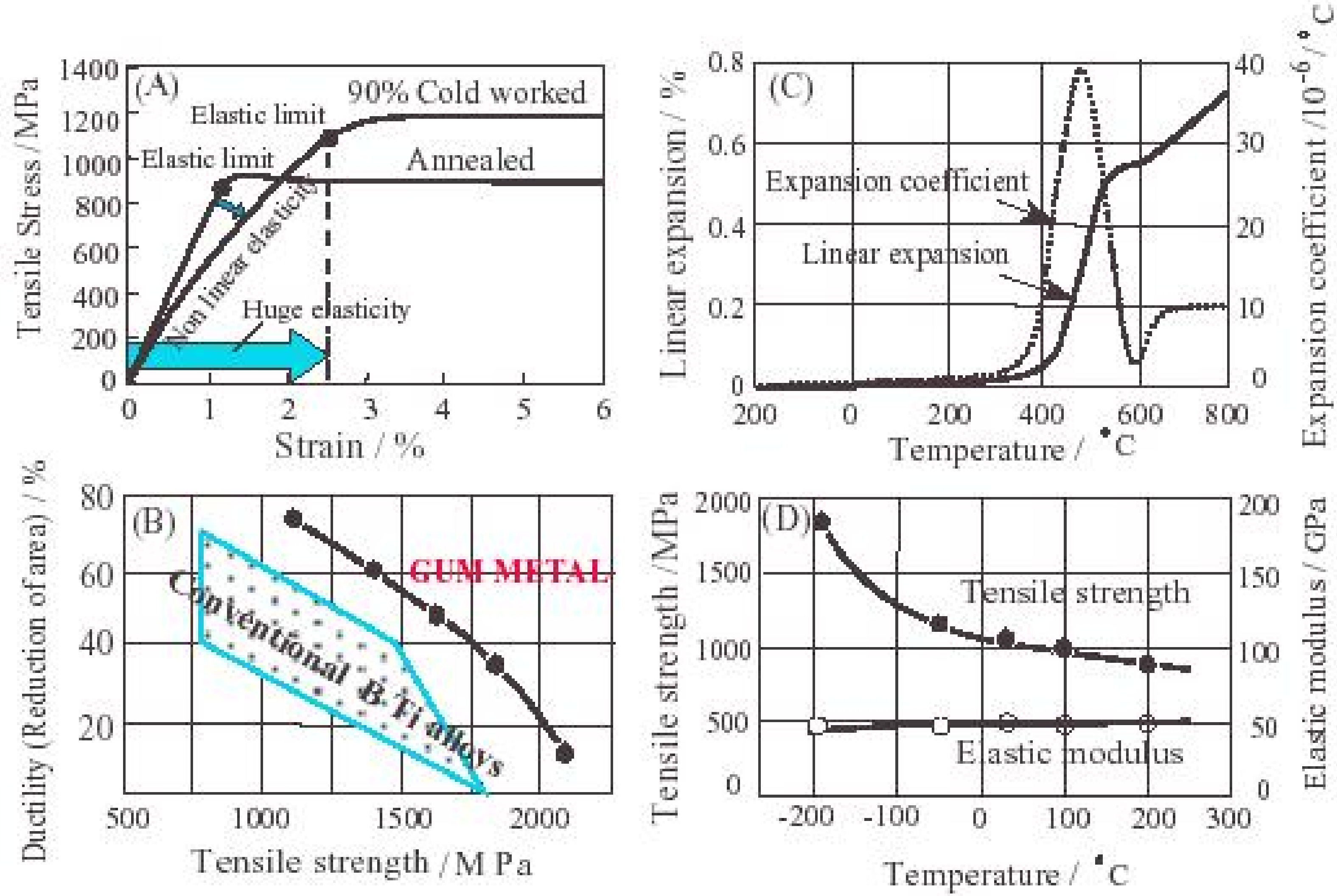
MORE Material to go in (optimization of dE/dx for range 200 MeV-100 MeV)

OPEN Issue: Study of Fracture Toughness for some materials ?

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%

Gum Metal (Toyota Ti alloy)



AlBeMet®

AM162

- By weight, contains 62% commercially pure beryllium and 38% commercially pure aluminum
- By Metallurgical definition, AlBeMet® is an alloy but can be considered a composite
- AlBeMet® sheet, plate and bar are powder metallurgy products
  - The powder is produced by a gas atomization process which yields spherical powder with a fine beryllium structure
  - The powder is densified by three consolidation processes, each resulting in different mechanical properties, while maintaining AlBeMet's unique physical properties.

AlBeMet® Property Comparison

Property	Beryllium S200F/AMS7906	AlBeMet AM162H/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 (276)	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 (96)	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)	226 (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 (.896)	.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

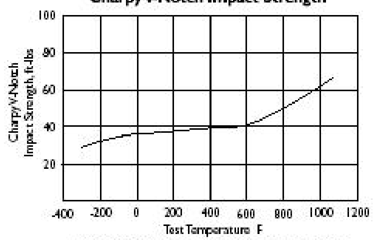
VASCOMAX® C-200/C-250/C-300/C-350

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

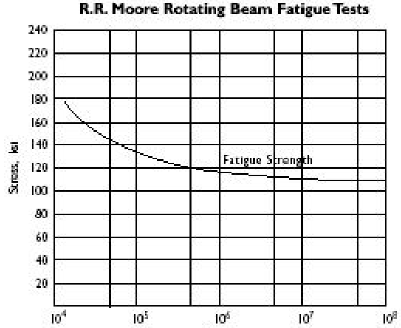
VASCOMAX® C-200

Effect of Test Temperature on Charpy V-Notch Impact Strength



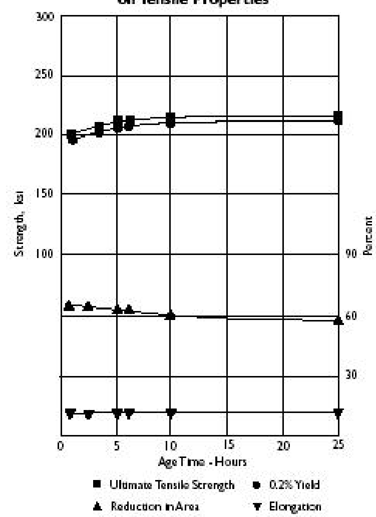
All samples solution annealed for one hour at 1500° F, air cooled and aged at 900° F for three hours.

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 √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	

Electrical Properties

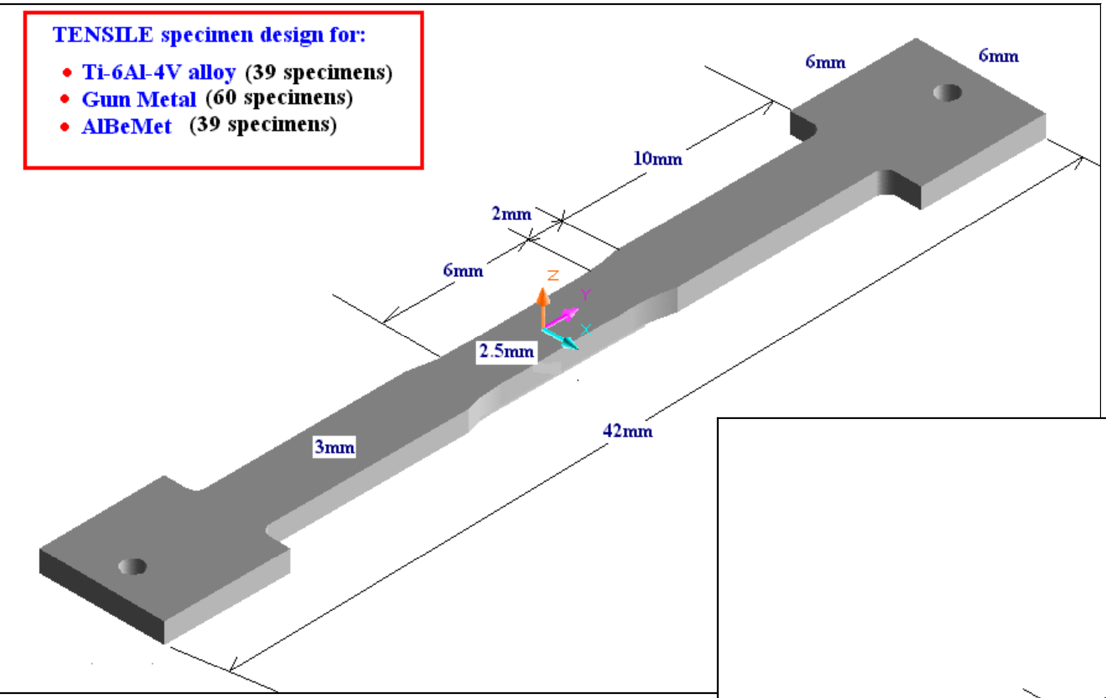
Titanium Ti-6Al-4V (Grade 5), Annealed

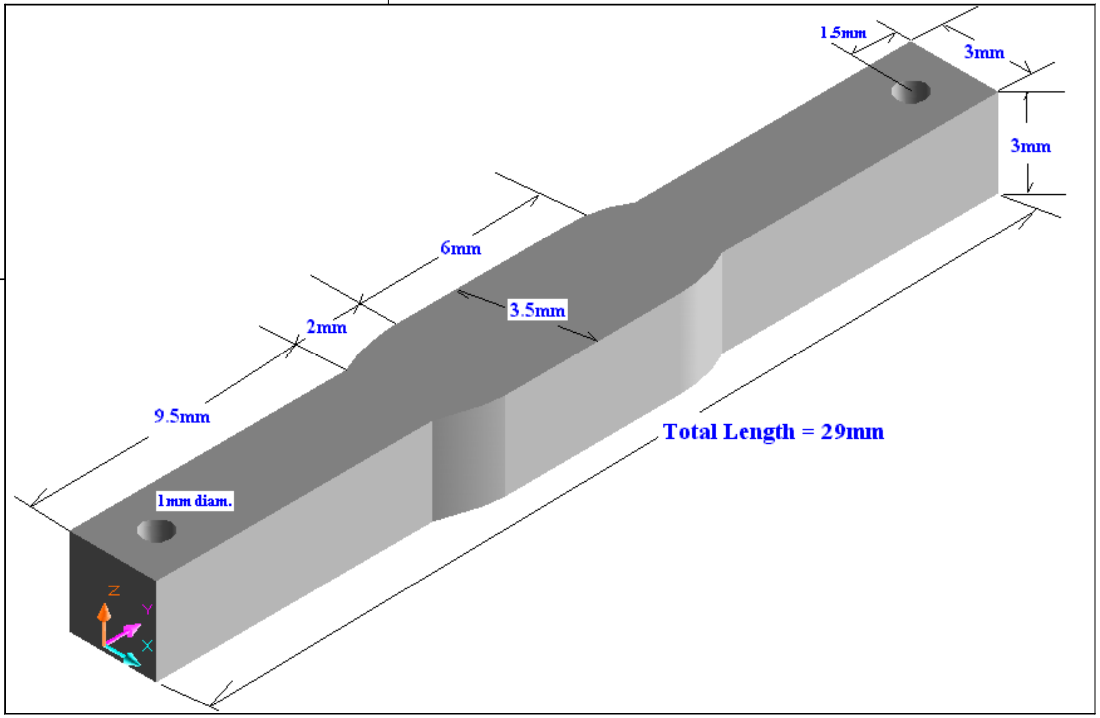
Electrical Resistivity	0.000178 ohm-cm	0.000178 ohm-cm	
Magnetic Permeability	1.00005	1.00005	at 1.6kA/m
Magnetic Susceptibility	3.3e-006	3.3e-006	cgs/g

Thermal Properties

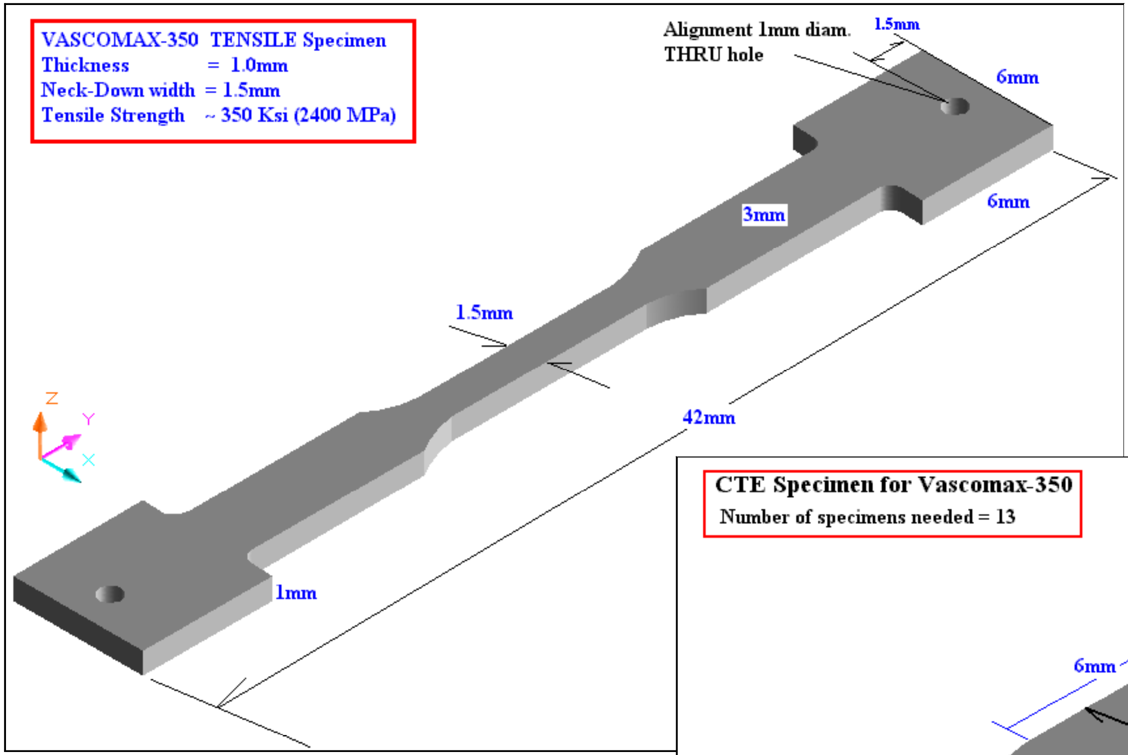
CTE, linear 20°C	8.6 µm/m-°C	4.78 µin/in-°F	20-100°C
CTE, linear 250°C	9.2 µm/m-°C	5.11 µin/in-°F	Average over the range 20-315°C
CTE, linear 500°C	9.7 µm/m-°C	5.39 µin/in-°F	Average over the range 20-650°C
Heat Capacity	0.5263 J/g-°C	0.126 BTU/lb-°F	
Thermal Conductivity	6.7 W/m-K	46.5 BTU-in/hr-ft²-°F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

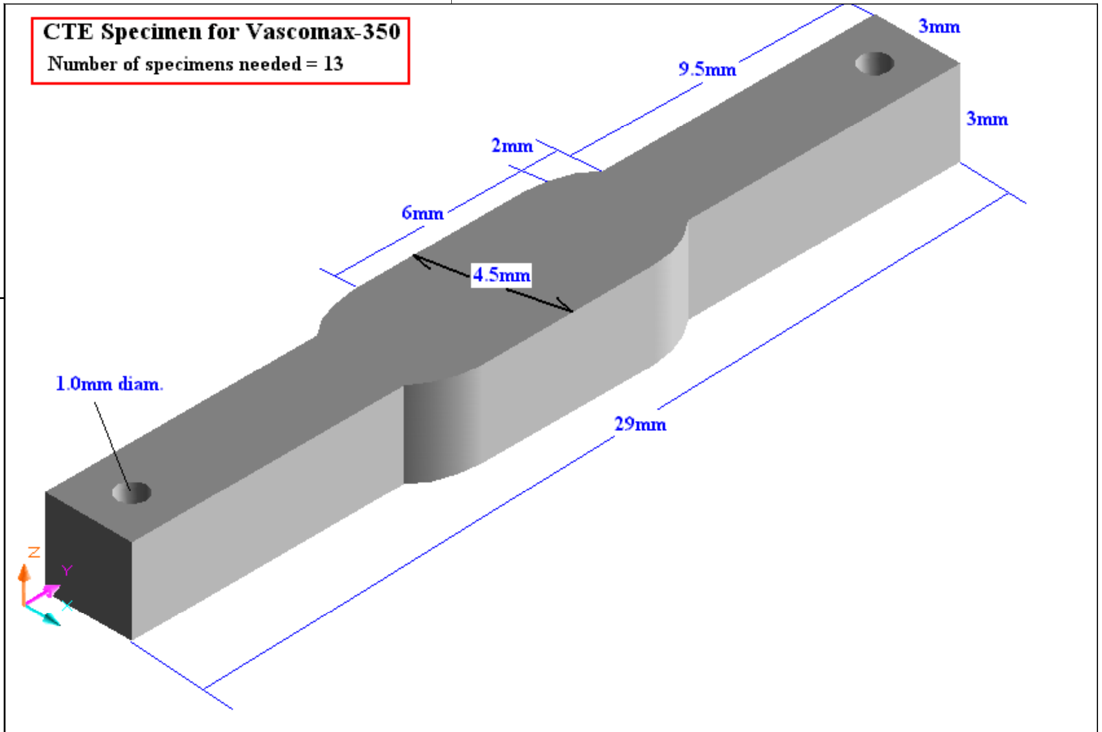
Tensile & CTE Specimen Design for Upcoming Irradiation Study





Tensile & CTE Specimen Design for Upcoming Irradiation Study
Vascomax-350 specimen variation due to its high strength



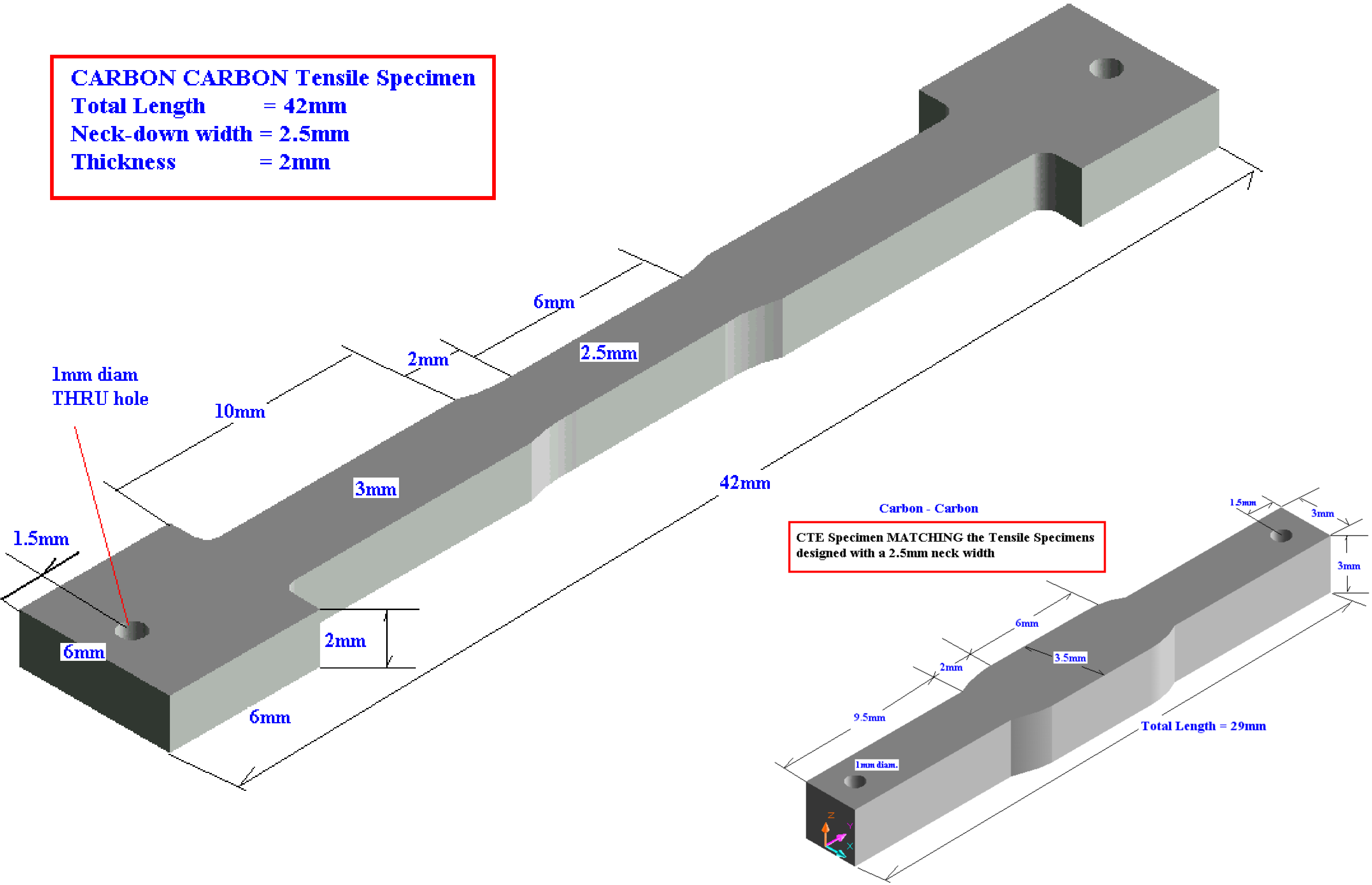


Tensile & CTE Specimen Design for Carbon-Carbon and TG-43 Graphite

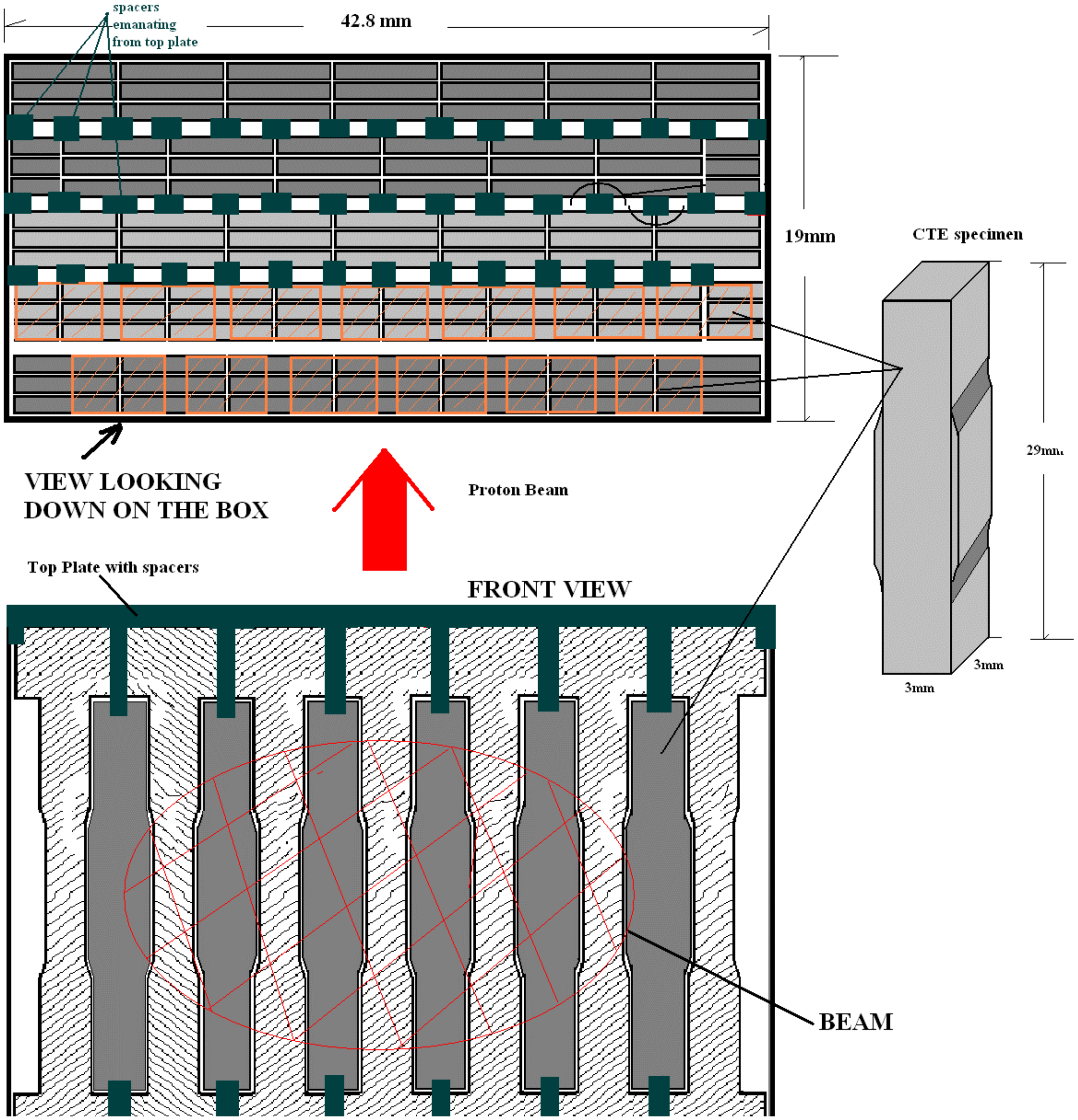
CARBON CARBON Tensile Specimen
Total Length = 42mm
Neck-down width = 2.5mm
Thickness = 2mm

Carbon - Carbon

CTE Specimen MATCHING the Tensile Specimens designed with a 2.5mm neck width



LAYOUT OF Specimen Assembly



Tentative Sample Identification Scheme