Thermal and Structural Analysis of Targets and Windows

Materials, Irradiation Data and Fracture Toughness

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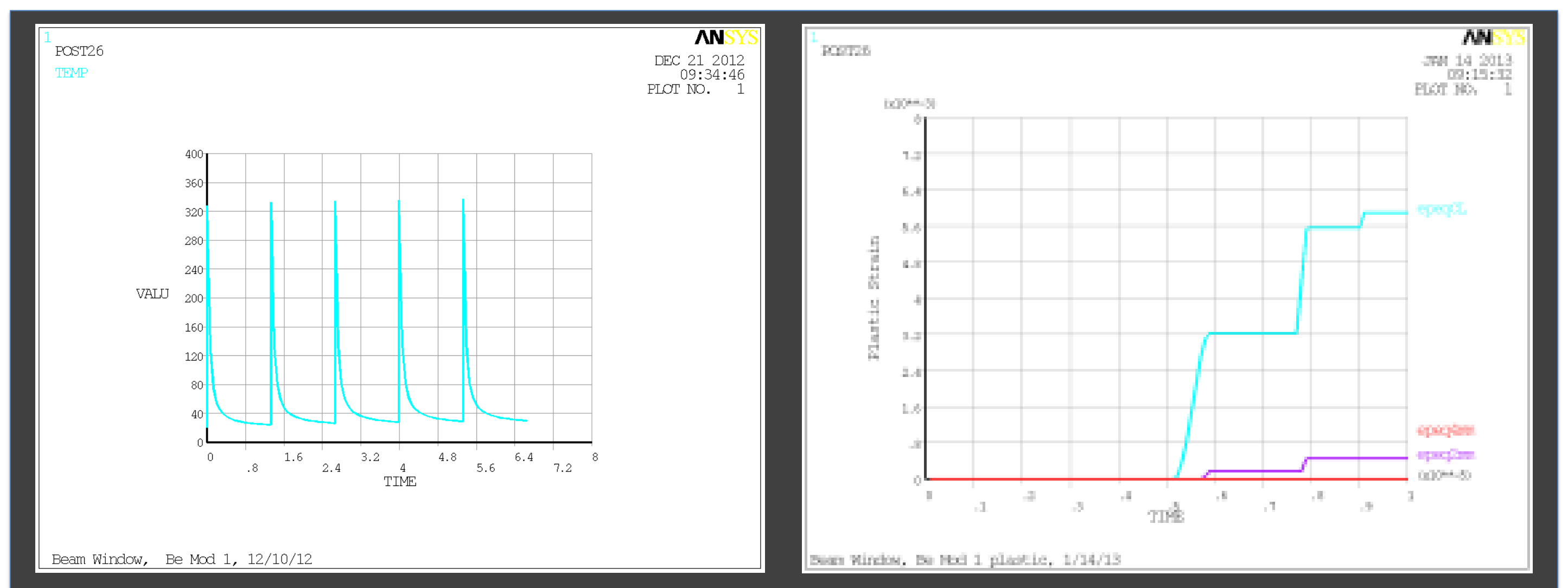
Approach

Integrated Design Analysis and Simulation, Thermal, Mechanical, and Irradiation Effects: PNNL has extensive capabilities with proven performance of target designs in challenging complex nuclear/thermal environments. Core design expertise includes molecular dynamics, and kinetic Monte Carlo modeling. Radiation transport and heating is typically accomplished with MCNPX. The primary thermo mechanical modeling tools include ANSYS and MathCad. Three dimensional component modeling is completed using SolidWorks 3D modeling capabilities interfaced with ANSYS facilitating rapid parametric modeling. Advanced numerical methods to address nonlinear dynamics is completed using LSDYNA if required. Multi-physics modeling capabilities address complex conditions including irradiation energy deposition, heat conduction, convection, radiation, thermal gradients, dynamic transient analysis, linear and nonlinear stress analysis, modal analysis, and irradiated material property changes over the lifetime of the component. PNNL applies an integrated analytical modeling approach compliant with intent of ASME Codes, meeting QA requirements, and correlated with experimental data to confirm the integrity and safety of complex in-reactor and accelerator driven components.



Pulsed Be Beam Window Results - Peak Transient ∆Temp. 320 K Below Creep Range , Plastic Strains at Center ~5.9%, 2mm and 4mm < 1%. Irradiated Be Elongation is 1-3%, Unirradiated YS at 320 C is ~200 Mpa (29 ksi). Irradiated YS and UTS are Higher than Unirradiated

Additive Manufacturing - Benefits

Fabrication of Extremely Complex Near Net Shape Components – Geometric Lattice Structures, Cooling Channels that Conform, Design for Function

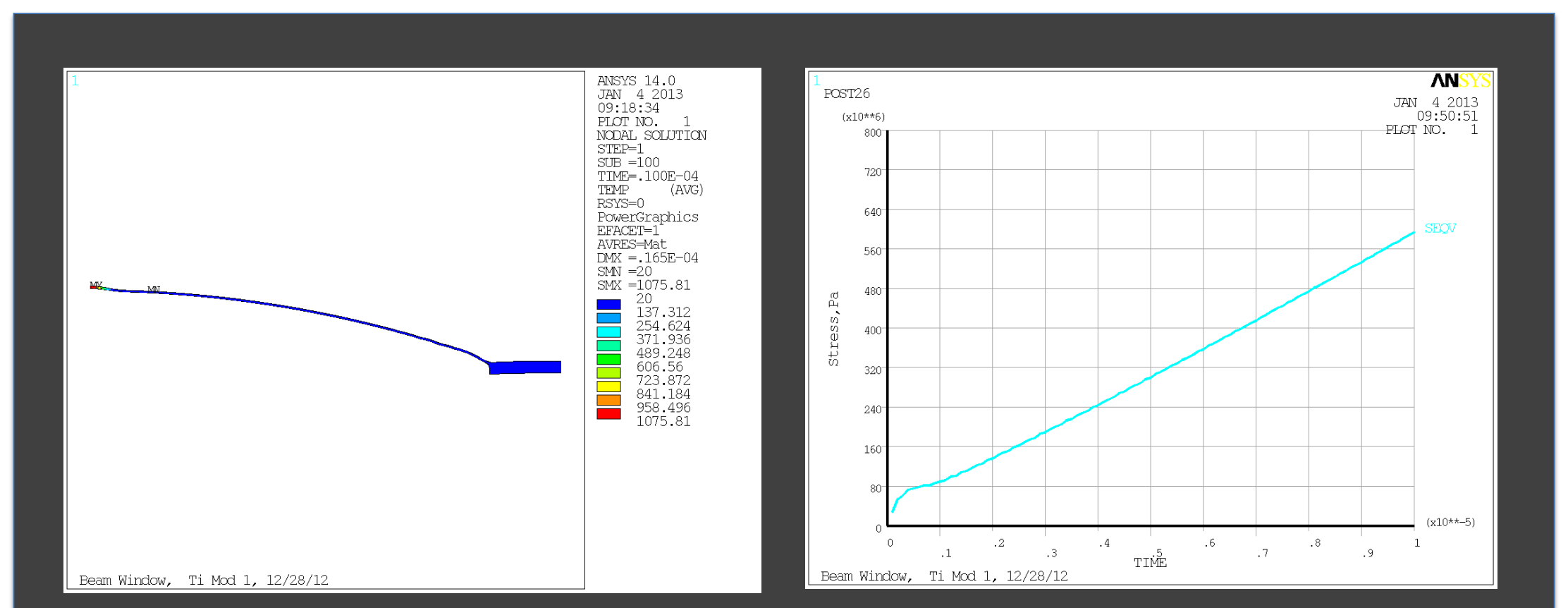
Innovative Integrated Window and Target Designs with Thermally and Structurally Optimized Components. High Strength and Stiffness with Low Density

Methods – Laser Deposition, E-Beam Deposition, Shaped Metal Deposition

Concerns – Fatigue Life May be Lower than Wrought Components. Limited Alloys Ti, Al, SS but growing

Material	E Modulus of Elasticity Pa	UTS Tensile Strength Pa	Delta T (K) = EDD/Cp	Applied Thermal Stress Pa CTE*E*DeltaT	Thermal Resistance Rts=UTS/(CTE*E *DeltaT)	Thermal Shock Empirical Parameter, (UTS*K)/(E*CTE)
Beryllium	3.03E+11	4.48E+08	308	1.07E+09	0.418	27771
Carbon Reinforced Carbon	8.00E+10	2.00E+08	449	2.87E+07	6.967	125000
Graphite	8.00E+09	1.40E+07	951	1.14E+07	1.227	192500
Silicon Carbide Graphite Composite	1.40E+11	1.40E+08	740	3.11E+08	0.450	41667
Beryllium Copper	1.15E+11	1.21E+09	1367	2.62E+09	0.459	90979
Invar - Fe Ni	1.48E+11	7.17E+08	1150	7.11E+08	1.008	12169
CVD Diamond	1.05E+12	1.50E+09	1305	1.37E+09	1.095	2857143
Titanium Ti-6Al-4V	1.12E+11	1.14E+09	1147	1.16E+09	0.984	7445

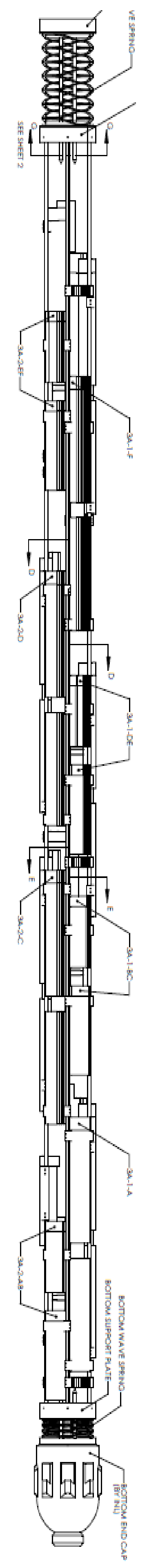
Candidate Materials - Young's Modulus, UTS, Delta T, Thermal Stress, Resistance and Shock Parameters



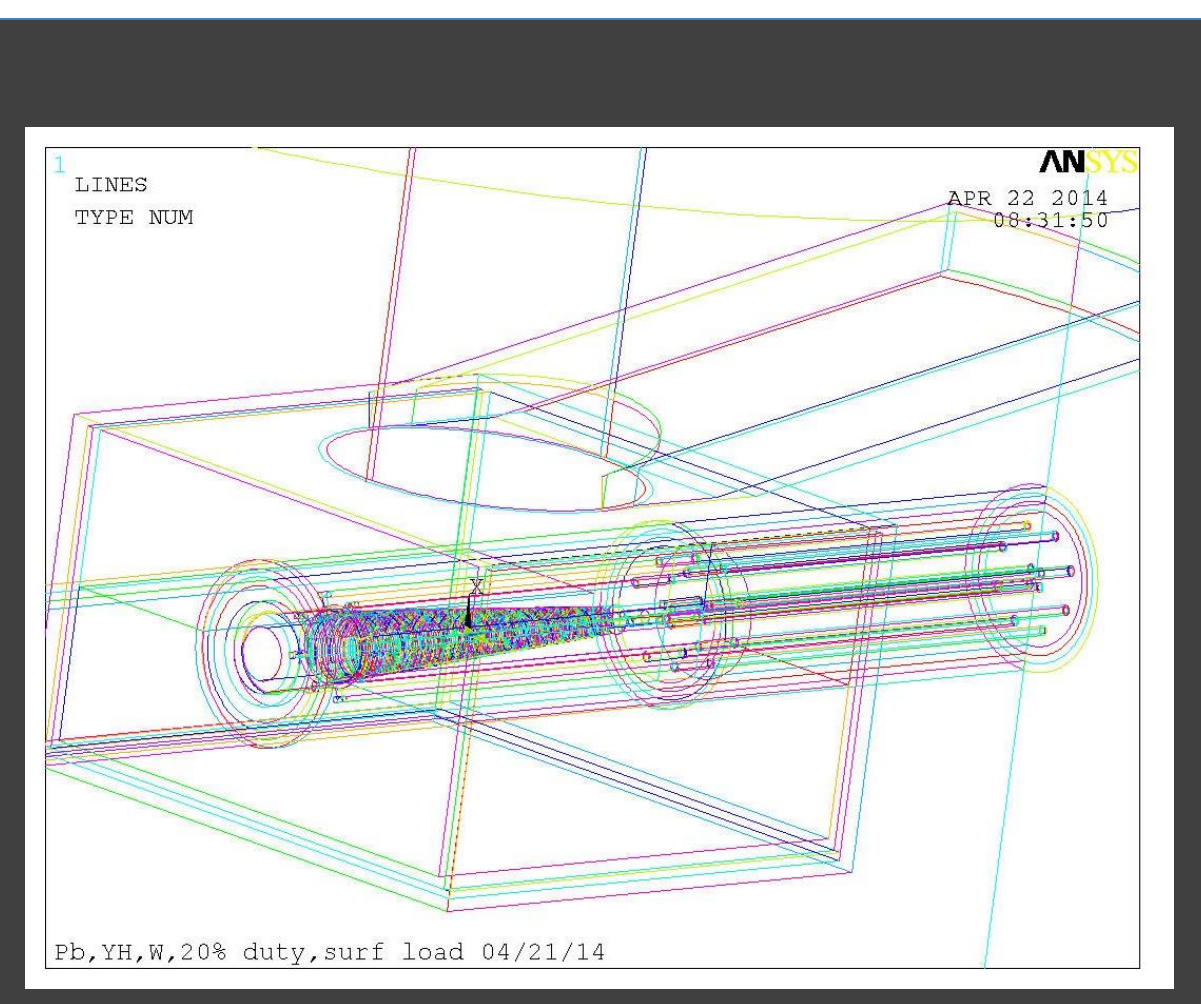
Ti-6Al-4V Beam Window Results – Peak ∆Temp.1075 C and Stress 600 Mpa, (87 ksi) at Center, Requires Cooling, Exceeds YS, UTS at Temp

Energy	120	GeV
sigma radius	1.5	mm
period	1.3300	sec
pulse	1.60E+14	protons
power	2.3	MW
current	0.0193	mA
pulse length	10	micro-sec

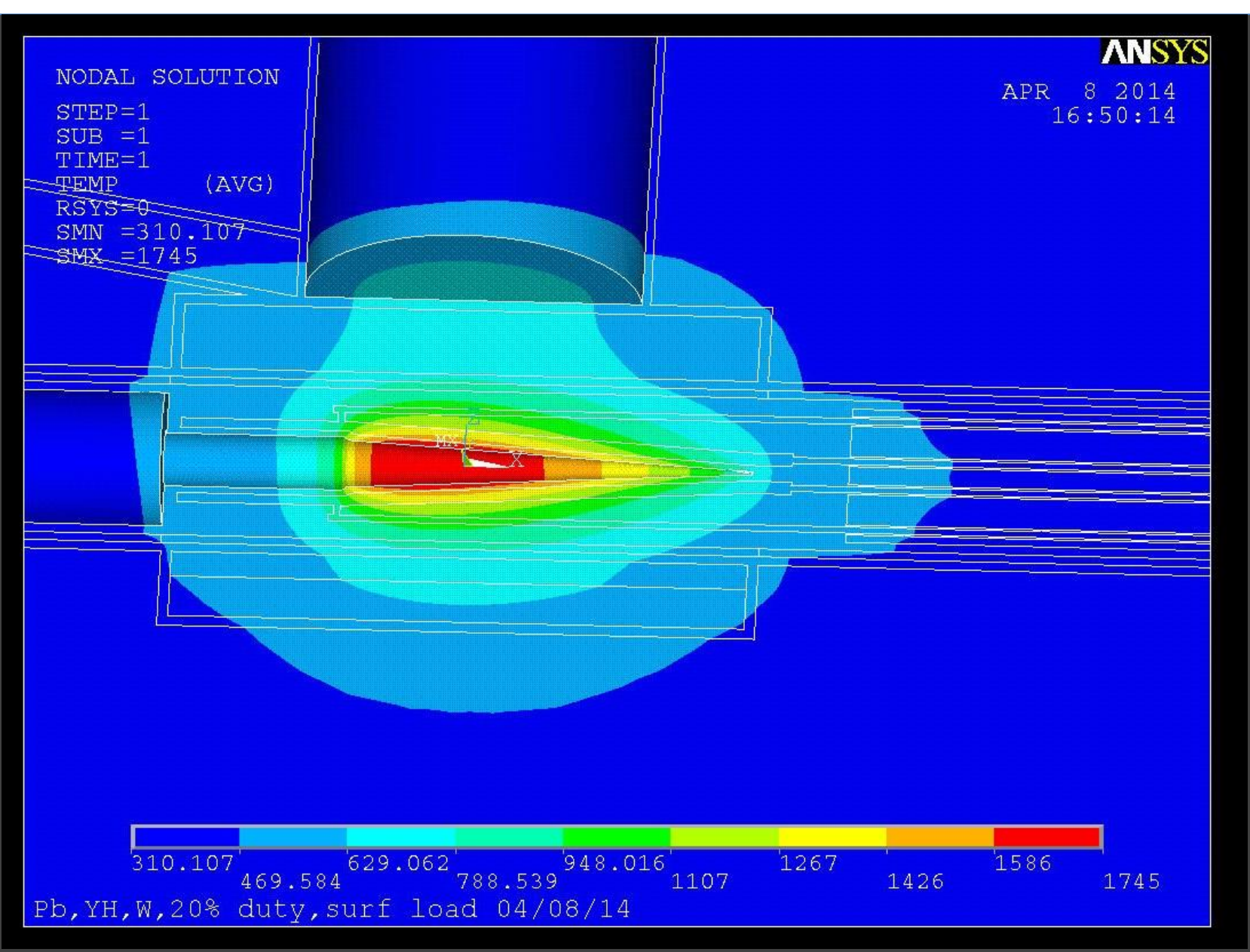
2.3 MW Beam Parameters used for Window Designs

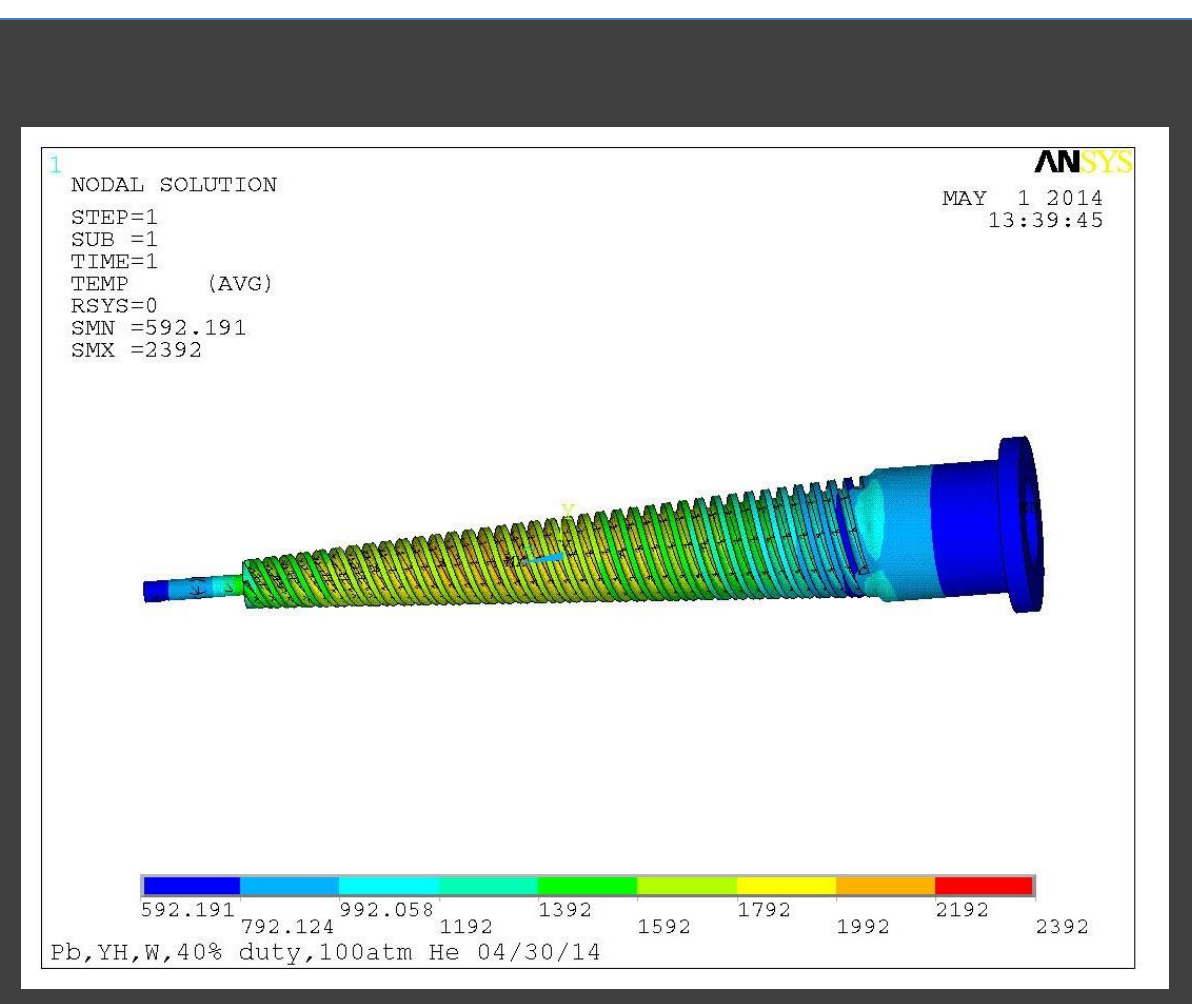


Thermal Heat Transfer Modeling – ANSYS transient heat transfer modeling used to calculate thermal profiles accounting for material properties, proton beam energy deposition, beam pulse rates, conduction, convection, radiation and gap conductance. Cooling methods are dependent on specific configurations and include, air, helium, pressurized helium, helium-neon gas mixtures, liquid metals, water and steam.



Tailoring of Accelerator Driven Neutron Target Simulating a Nuclear Reactor Spectrum





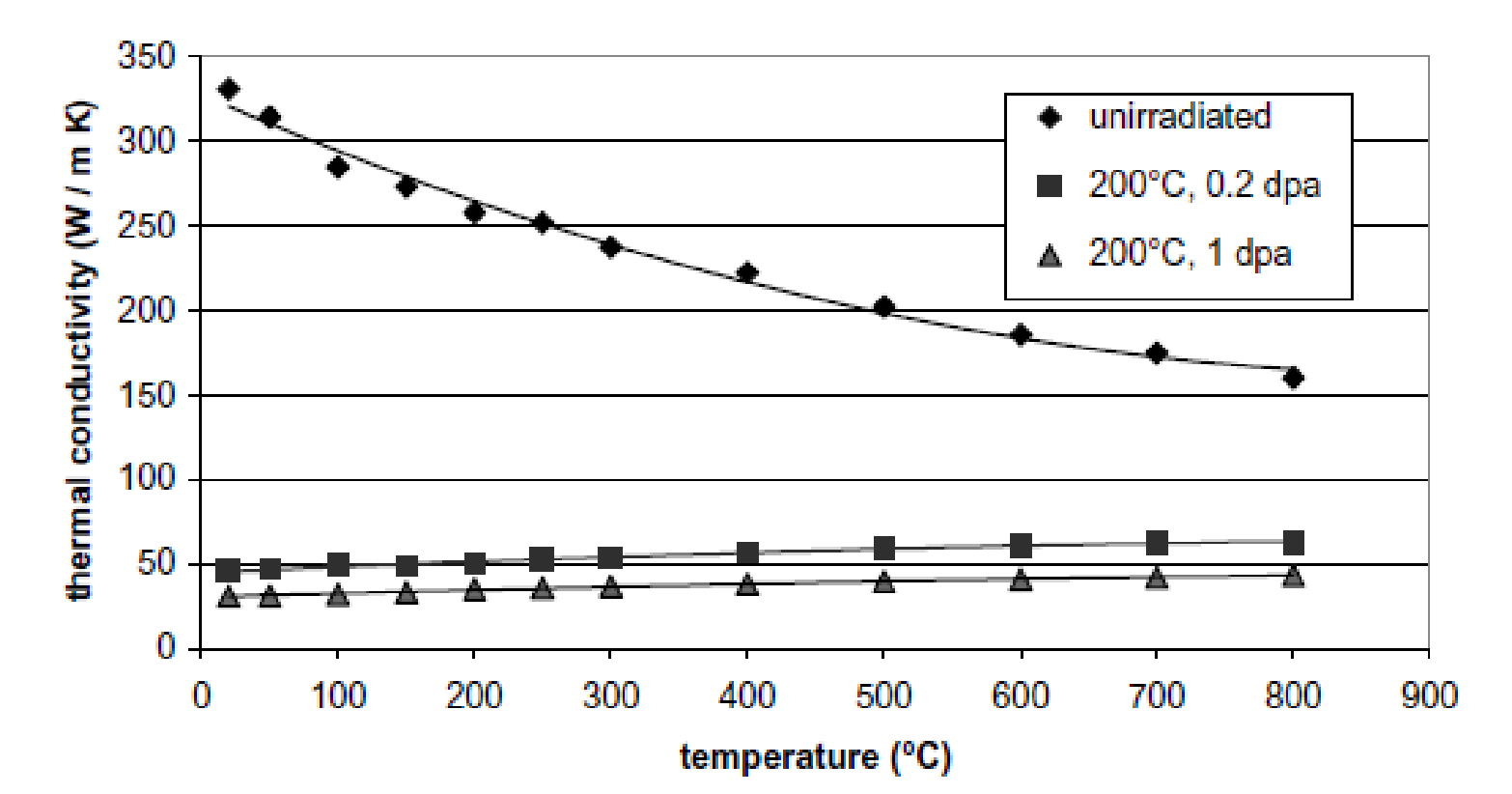
Zr-4 or W Target Cone with Helical Cooling Fins. Allows for Higher Temperatures , Pressures and Duty Factors.

Target for Reactor Neutrino Anomaly - Thermal Model of 30 MeV Proton Tungsten Target 1745 K (2681 F) ; High Pressure He Cooling , Yttrium Hydride Moderation and U-235 Fission Foils, Dispersion Alloy W-4Re-0.26HfC High Temp Strength, Re Improves Low Temp Ductility (DBTT), 1ppm O2 in He Limits W Oxidation. Stress Rupture Limit at 1745 K and 4000 psi is ~100 hrs. for pure W, ~10,000 psi for Alloy

Irradiation Damage C/C - Trends in Isotropic Graphite and Carbon Reinforced Carbon with Pseudoplatic Fracture Behavior, Resistance to Thermal Shock and Good Creep resistance.

- Elastic Modulus (E) Increases with Increasing dpa
- Coefficient of Thermal Expansion (CTE) Decreases with Increasing dpa
- Thermal Conductivity Decreases with Increasing dpa
- Changes Occur at Relatively Low 1 dpa

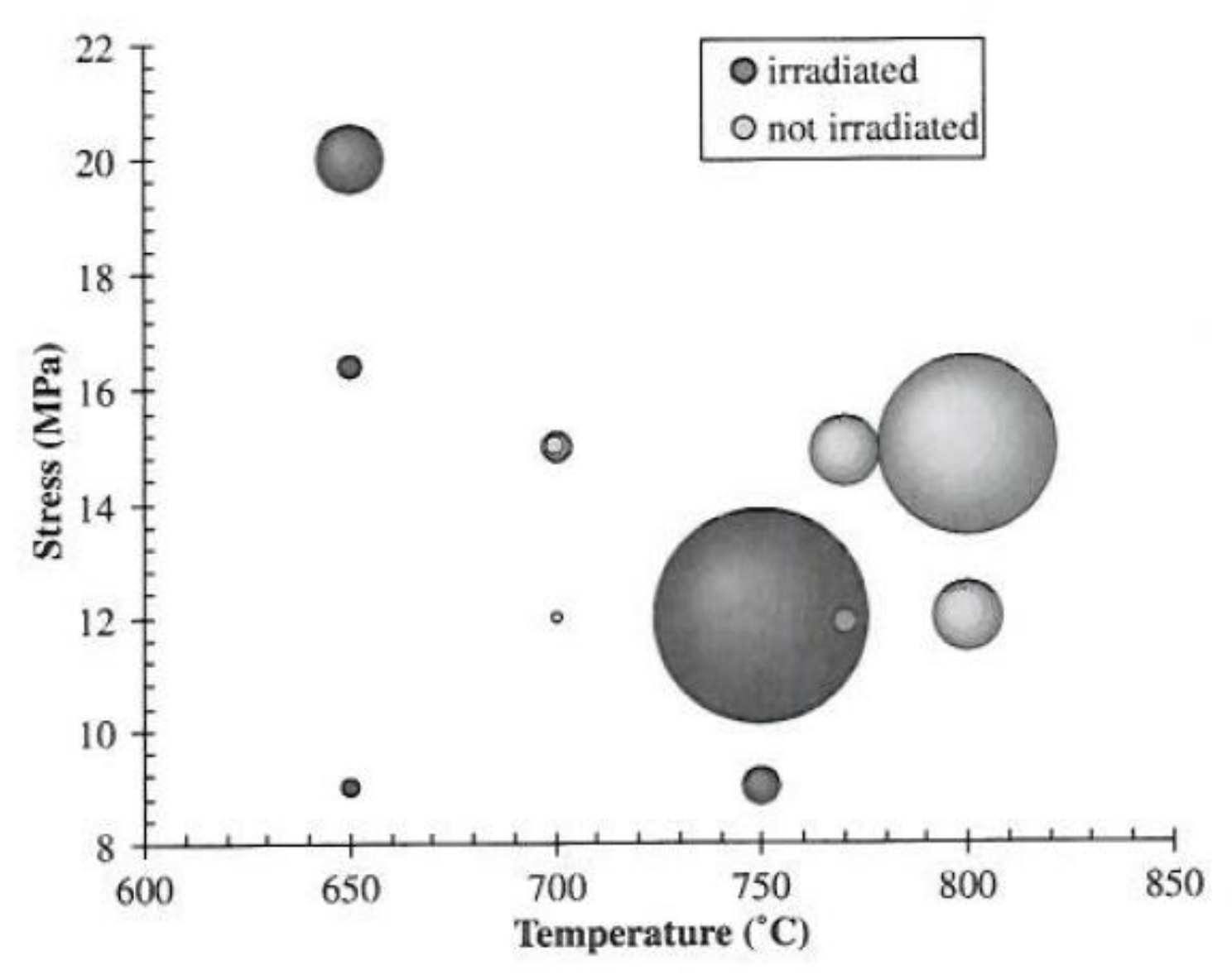
Ref. J.A. Vreeling et.al., "Graphite Irradiation Testing for HTR Technology…" 2008, and M.Roedig et.al., Post Irradiation Testing of Samples from PARIDE 3 and 4..."2004, Journal of Nuclear Materials



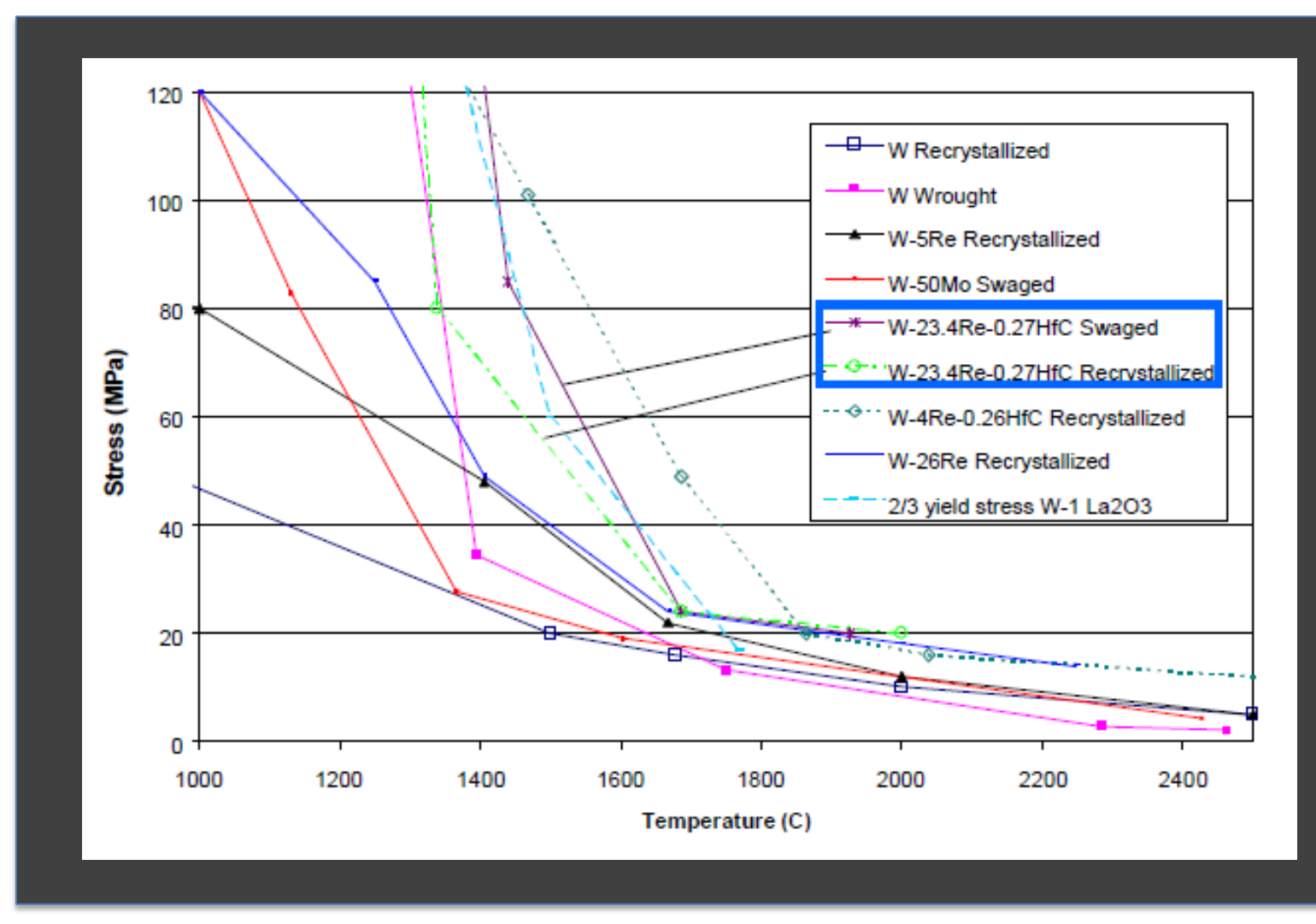
C/C - Change in Thermal Conductivity with Temperature and dpa, M.Roedig et.al

Irradiation Induced Creep in Be – Temperature, Stress and Irradiation Effects on Creep Rate,

M. Scibetta et al. Journal Nuclear Materials



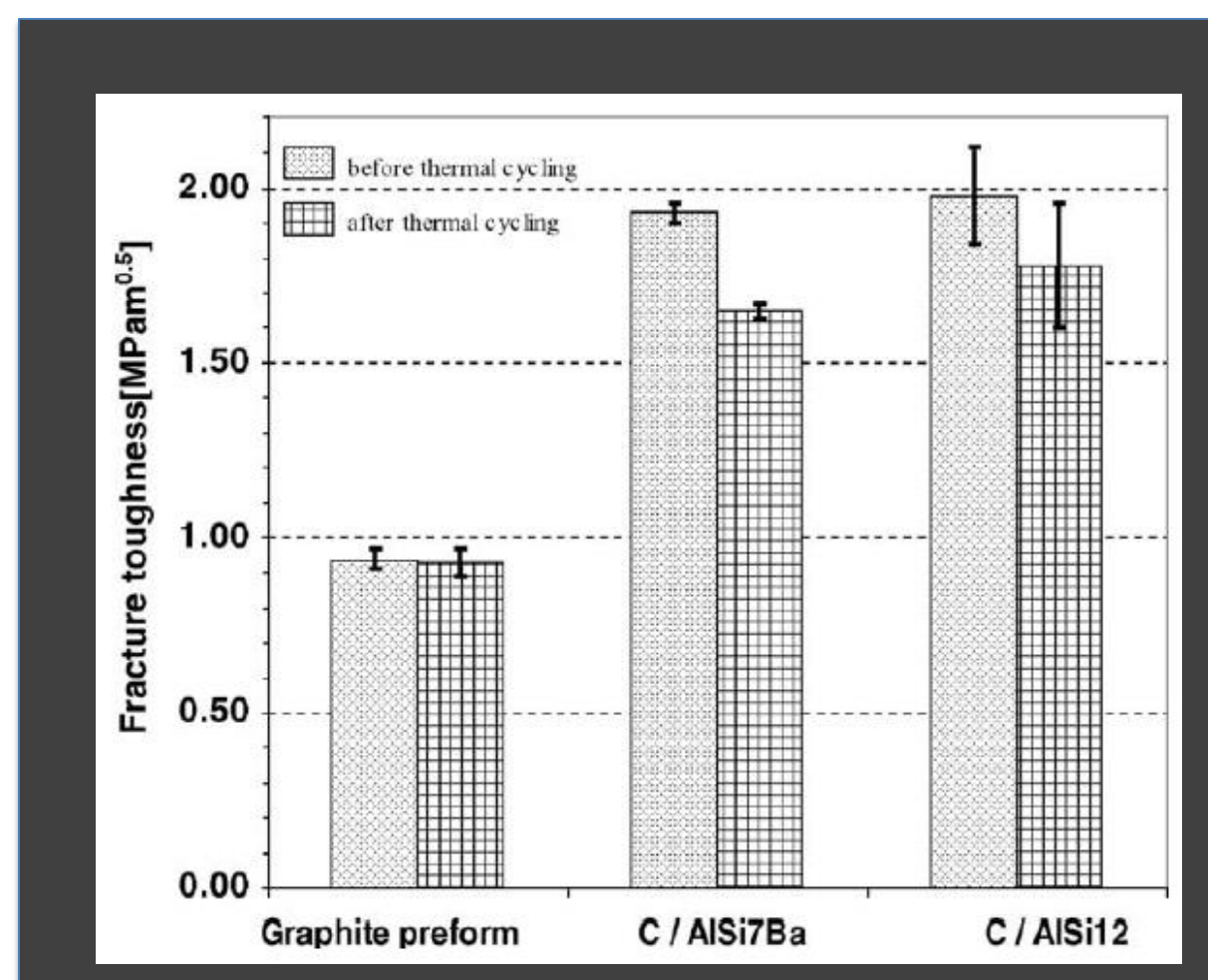
Energy Deposition, implantation depth and irradiation damage (dpa) – calculated using internationally recognized standard methods using SRIM (formerly TRIM), see D.Wootan. Provides a common basis of comparison for data from different irradiation sources. Provides a method of comparing and correlating neutron fluence data parameters from data sources such as the Advanced Test Reactor (ATR) to charged particle, proton beam, parameters.



Design Stress Limitations for Tungsten Alloys

YS of pure W at 500 C ~ 500 Mpa (75 Ksi) at 1773 K the Alloy UTS is ~ 413 Mpa (60 Ksi), The Design Creep Stress Limit is ~20 Mpa (3 Ksi)

S. Sharafat et al, UCLA



Fracture Strength of Interpenetrating Phase Composites – Each phase interconnected e.g. C/Al or Al2O3/Al composites Porous preform (15-25%) infiltrated with light metals at high temps and pressures. Improves properties over monolithic Material Properties:
Low CTE, Higher Thermal Conductivity, Increase in Young's Modulus, Higher Flexure Strengths ~X2, Higher Fracture Toughness than Ceramic Pre-Form, Impact of Thermal Cycling.

T. Etter et al. Materials Science and Engineering

Conclusions:

- High Temperature Properties and Irradiation induced Property Changes, Deformations, Swelling, Creep, Embrittlement Often Dominate Material Selection and Design Process.
- Extending Component Lifetimes Requires Carefully Integrated Solutions for Materials and Design Configurations (beam parameters, cooling, hot gaps, expansion relief, etc.).
- New Additive Manufacturing Techniques Offer Potential Benefits. Design for Function.
- Irradiated Property Testing / Performance is Key

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