HISTORICAL MATERIAL PROPERTY DATA FOR CERMET AND GRAPHITE-BASED NTP FUELS.

M. E. M. Stewart, VPL at NASA Glenn Research Center, Cleveland, Ohio 44145, Mark.E.Stewart@nasa.gov.

Introduction: During the NERVA/Rover and ANL200 programs, graphite-based and cermet fuel elements were constructed and material properties were extensively measured. To understand Nuclear Thermal Propulsion (NTP) fuel performance, this paper attempts to identify predicted and measured property data plus their sources. Property data is crucial for thermal and stress modeling, and understanding experimental results.

The most comprehensive measured property data for graphite-based fuel, (U Zr)C+C graphite, are presented in [1]. For most other materials, data are scattered through multiple sources. Multiple independent measurements establish α, *k* for individual materials [2], i.e. W, W/25%Re, UO_2 [3]. For composite materials, cermets in particular, some properties, including thermal conductivity[4] and expansion, can be predicted mathematically from component data and compared with experiments; other data, (i.e. brittle to ductile transition, mechanical properties) are not predicted from component data.

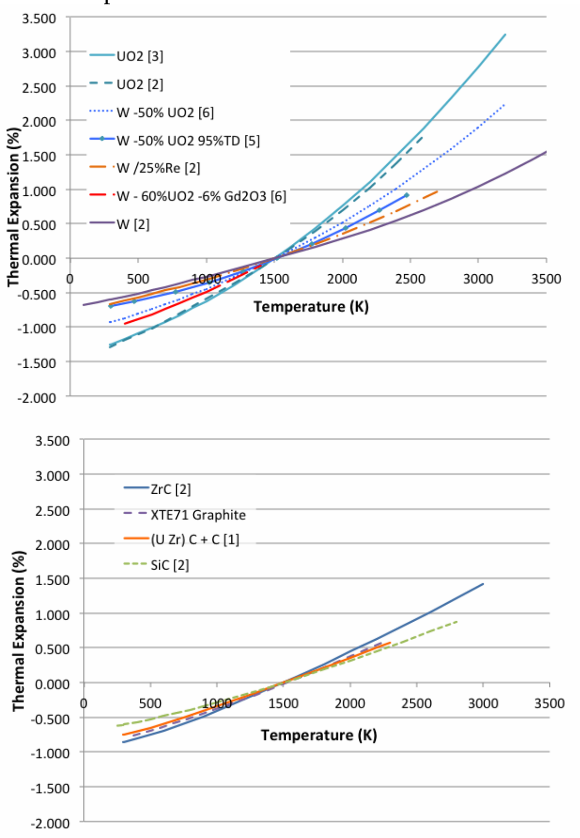

Figure 1: Thermal expansion, α, for cermet (above) and NERVA graphite materials. Zero stress at 1500K.

Thermal Expansion, α: This data is important since stress arises from differential thermal expansion both through a temperature gradient in a material, and between two materials at their interface. Figure 1 compares experimental measurements for W-50% UO_2 [5] with predictions [6]. Experimental data [2] (i.e. W, UO_2) have error estimates ranging from ±5% to ±15%. Note that ZrC coating is in tension at room temperature, while the cermet coatings are in compression.

Thermal Conductivity, *k*: This data is important since it determines the peak fuel temperature and the slope of the temperature gradient (50 K/mm predicted) from the centerline peak temperature to the coolant channel wall. Figure 2 compares experimental measurements for W-60% UO_2 [7] and W-80% UO_2 coated particles [8] with predictions. The graphs show a substantial range in thermal conductivity—1.5 orders of magnitude—from tungsten to the undesireable values of uranium dioxide. Experimental data [2] (i.e. W, UO_2) have an error band of ±5% to ±15%. Interestingly, (U Zr)C+C graphite and W-50% UO_2 have similar thermal conductivity.

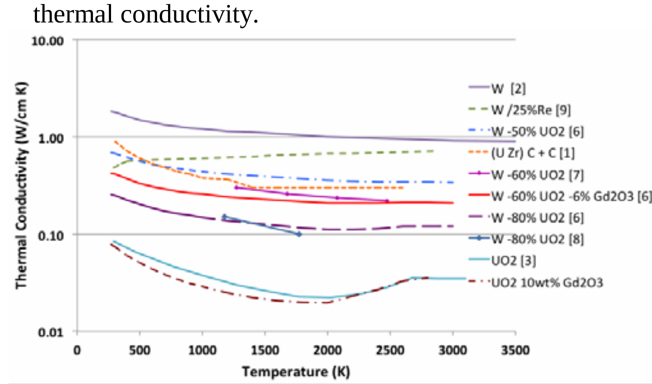

Figure 2: Thermal conductivity, *k*, for NTP materials.

High-Temperature Elastic (Young's) Modulus, *E*: This data is important since it represents how much elastic stress (force/area) is required for a deformation at each temperature—much like a spring constant. Differences in thermal expansion require an offsetting deformation and stress to maintain continuity.

Experimental data exists for individual materials and (U Zr)C+C, but for cermets, experimental data is lacking, and averages, weighted by volume fraction, were used [6]. One value of elastic modulus, *E*, may not represent tension and compression to yield limits. Saunders [10, p. 40] prefers static data from tensile loading of specimens instead of dynamic Young's modulus. Graphite fuel values depend on direction.

Figure 3 shows that graphite fuel maintains its elastic modulus over a wide temperature range; cermet

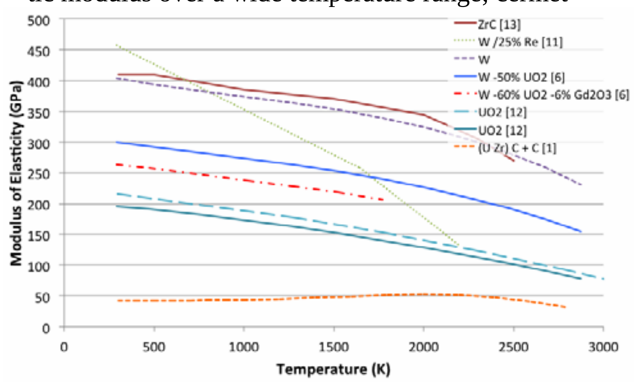

Figure 3: Elastic modulus, *E*, for NTP materials.

materials and ZrC are harder at room temperature but become softer as temperatures increase. This softening reflects the onset of plasticity

Yield and Ultimate Strength: These data are important since they represent the limits of elastic deformation, and indicate stresses beyond which fracture or permanent deformation will occur. Fluid/thermal/structural simulations[14] predict stresses beyond elastic limits for a majority of the fuel element. Beyond elastic limits at lower temperatures, fracture is expected, while at higher temperatures, permanent deformation is expected.

	Temp (K)	0.2% Yield (MPa)	Fracture (MPa)	Mean *E* (GPa)	Ref
(U Zr)C+C	300		49	22	1
	1273		42	22	1
	1773		47	14	1
	2273	60 @ *e*=12%		6	1
W /25 Re	300	1278		639	11
	2200	90		45	11
W	477		316		19
	589	205			19
W-40%UO_2	300		112		21
	2750	22		11	15
W-20%UO_2	300		140		21
	1922	118		59	15
	2750	26		13	15

Table 1: Yield and Ultimate strength, NTP materials

For (U Zr)C+C graphite, Lyon [1] provides data. For cermet materials, valuable experimental data is given in [10][15]. Experimental data for optimizing cermet processing for strength is given by Buzzard [16].

Brittle to Ductile Transition: The importance of the onset of plasticity was recognized and measured [10 p. 41]. In particular, at temperatures below this transition, the material is brittle and prone to cracking, but not above. This transition may explain the mid-passage erosion seen in NERVA graphite fuel elements [1].

Table 2 shows measurements. Note that the testing methods vary; bending to 90^o or 5% elongation, for metals, are demanding tests compared with signs of plasticity.

	Transition Temperature (K)	Criteria/Reference
ZrC	1400-1500	Signs of Plasticity/[17][18]
(U Zr)C + C	1773-2273	No Fract Stress-Strain/[1]
W /25 Re	350	5% Elongation/[19]
W	530	5% Elongation/[19]
W 10% vol UO_2*	530	Bend test to 90^o/[10]
W 20% vol UO_2*	650	Bend test to 90^o/[10]
W 30% vol UO_2*	>1000	Bend test to 90^o/[10]
UO_2	1100	Signs of Plasticity/[20]

Table 2: Ductile to brittle transition temperature for selected materials. Results depend on test and fabrication methods. *Dispersion

High Temperature Creep-Rupture Strength: Considerable measurement data [9] exists for this property, and it is particularly important for long life reactors.

Fabrication Methods: Material properties are presented here with the caveat that they depend on processing. This sensitivity is supported by experimental results from process optimization [16].

Other Data Sources: Also, measurements exists for other materials considered in the designs. Beyond materials of interest to NTP, extensive nuclear fuel development and testing was performed during the 1960's at General Electric[7][9], NASA Lewis [10][22]. Material property research continues today[13].

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