Transverse Rupture Strength of CeO_2 as a Surrogate Nuclear Fuel

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Background

Nuclear Energy

- Currently, 20% of the US energy demand is supported by nuclear energy and is increasing, creating a growing interest in fully understanding the relationship between microstructure and performance of ceramic nuclear fuels[1].
- Plutonia (PuO_2), recovered as a by-product from the fission of uranium, is of particular interest.
- Because of significant challenges involved in studying radioactive materials, cerium oxide (CeO_2) is being investigated as a surrogate nuclear fuel for PuO_2 due to having similar chemical and thermodynamic properties[2].

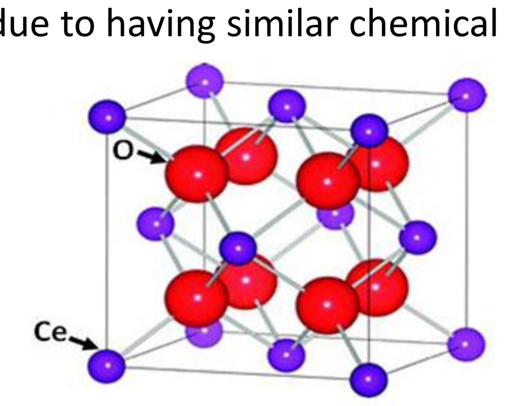

Figure 1. *Cerium oxide has the same crystal structure as plutonium oxide, which is an Fm3m fluorite structure[3].*

Surrogate Nuclear Fuel Study of CeO_2

- Mechanical properties of CeO_2 were studied through developing and validating a testing method for testing its flexural strength.
- Test method was validated using commercially available alumina (Al_2O_3), with known properties, as a benchmark.
- CeO_2 pellets were fabricated and characterized prior to measuring flexural strength.

Methods

CeO_2 Pellet Synthesis

- Materion (-325 mesh) CeO_2 powder was high energy ball milled to reduce particle size and improve pellet density.
- CeO_2 powder and EBS binder were mixed and green pellets were pressed at 100 MPa and sintered at 1600 °C.
- CeO_2 powder and pellets were characterized via scanning electron microscopy (SEM), x-ray diffraction (XRD) and particle size analysis (PSA).
- Sintered pellets were ground down to 169 μ" and 11 μ" surface roughness.
- CeO_2 and Al_2O_3 were tested using the test fixture and Materials Test System 810 in Figure 7.

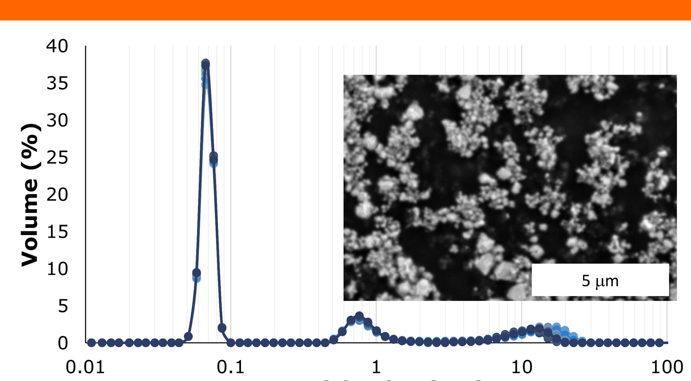

Figure 2. *SEM of CeO_2 powder and particle size distribution .*

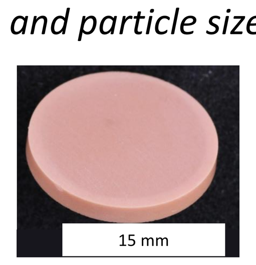

Figure 3. *Sintered ceria pellet pressed at 100 MPa.*

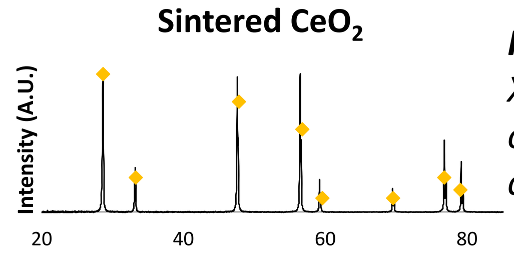

Figure 4. *XRD pattern of sintered ceria pellet.*

Al_2O_3 Benchmark Preparation

- 99.8% purity Al_2O_3 rods (Figure 5) were cut at 1.5, 2.25, and 3 mm heights and ground down to 169 μ" and 11 μ" surface roughness.

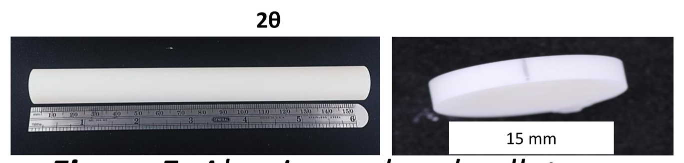

Figure 5. *Alumina rod and pellet.*

Results

Transverse Rupture Strength Setup

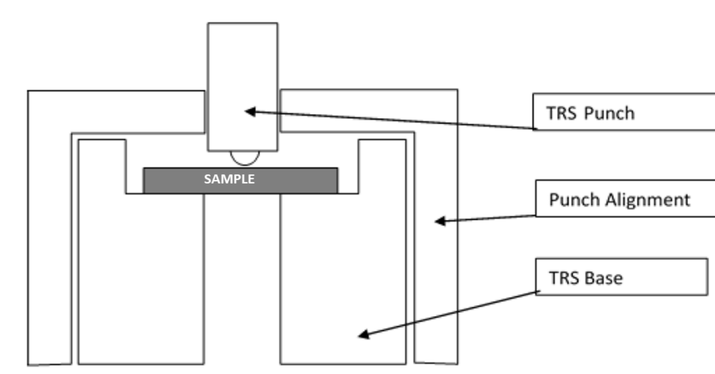

Figure 6. *Schematic representation of transverse rupture strength fixture.*

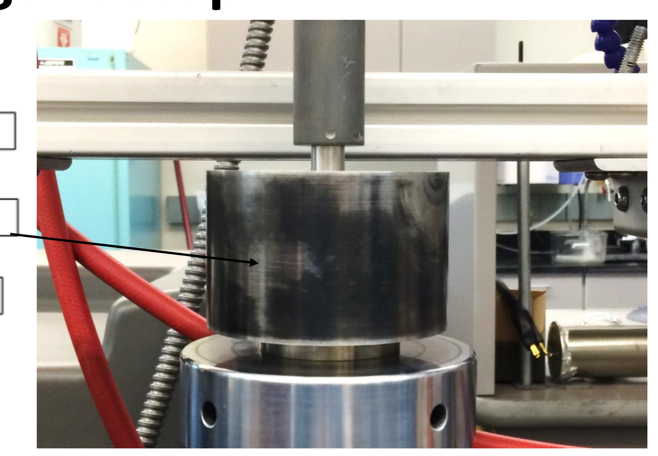

Figure 7. *MTS-TRS setup.*

Transverse Rupture Strength Equation

$$\sigma = \frac{A * F}{t^2}$$

A = effective stress volume
F = force applied to pellet at failure
t = pellet radius
σ= transverse rupture strength[6]

Al_2O_3 Transverse Rupture Strength

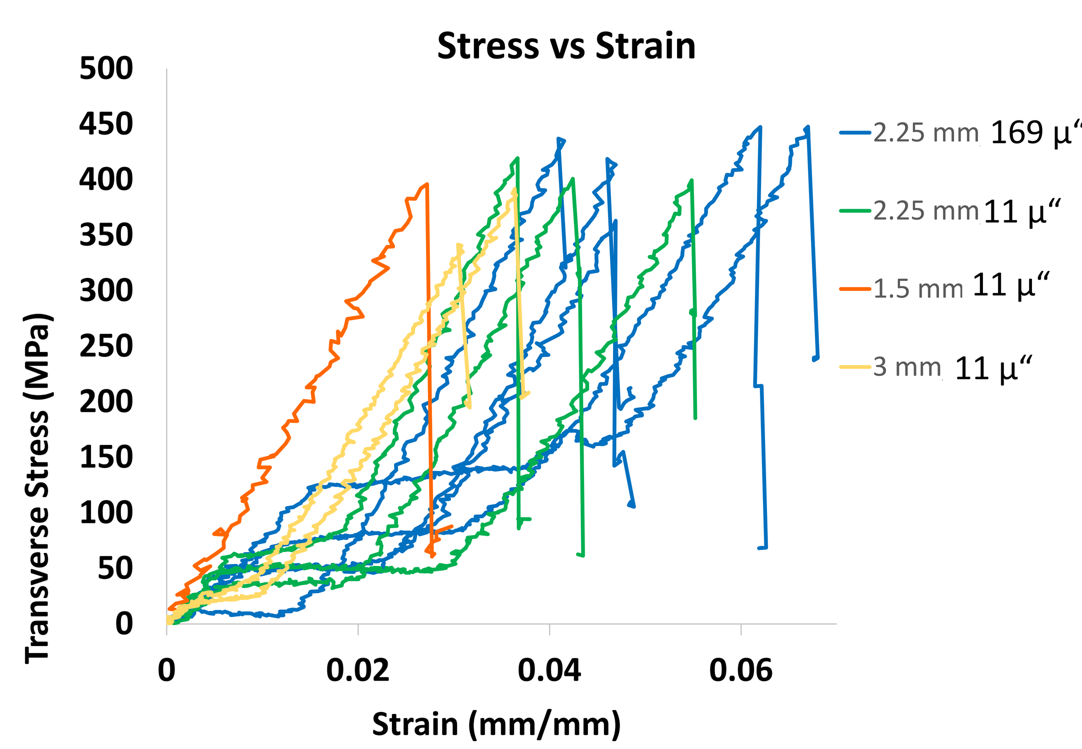

Figure 8. *Transverse stress vs Strain plot of Al_2O_3.*

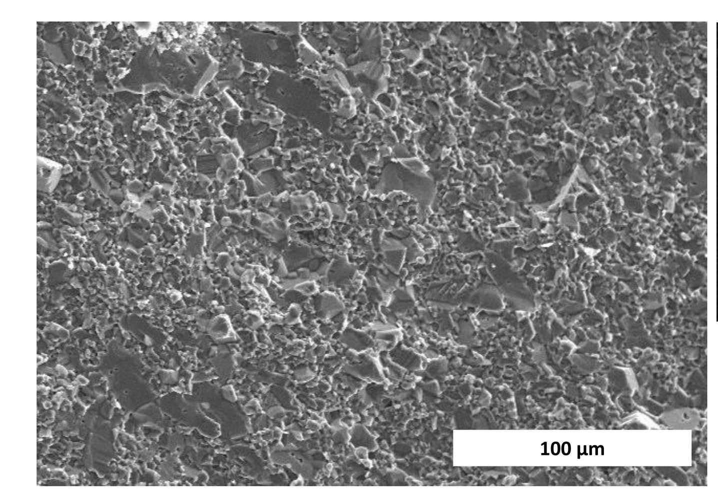

Figure 9. *SEM image of alumina fracture surface.*

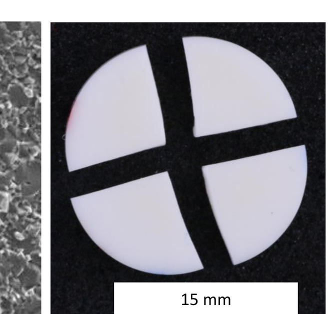

Figure 10. *Fractured Al_2O_3 pellet.*

Number of Tests	Density	Surface Roughness	TD %	Flexural Strength (MPa)
6	3.87 g/cm³	169 μ"	98.8 ± 0.2	363-448
6	3.87 g/cm³	11 μ"	98.8 ± 0.2	341-419

Figure 11. *Alumina pellet data table. Theoretical density based on 3.92 g/cm³ as provided by the vendor[5].*

CeO_2 Transverse Rupture Strength

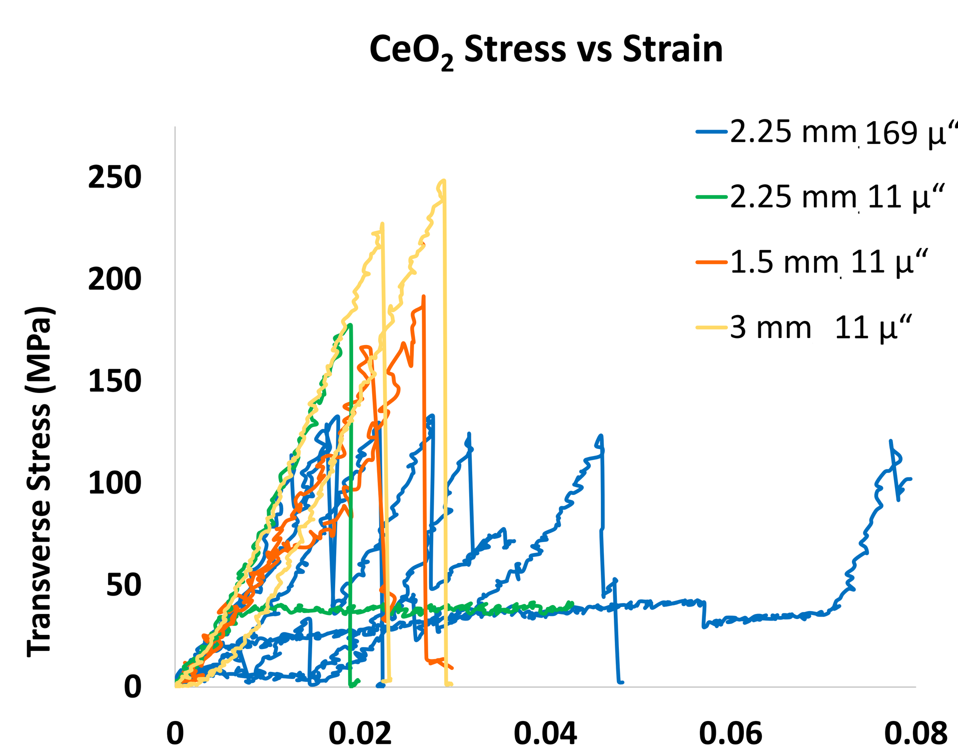

Figure 12. *Transverse stress vs Strain plot of CeO_2.*

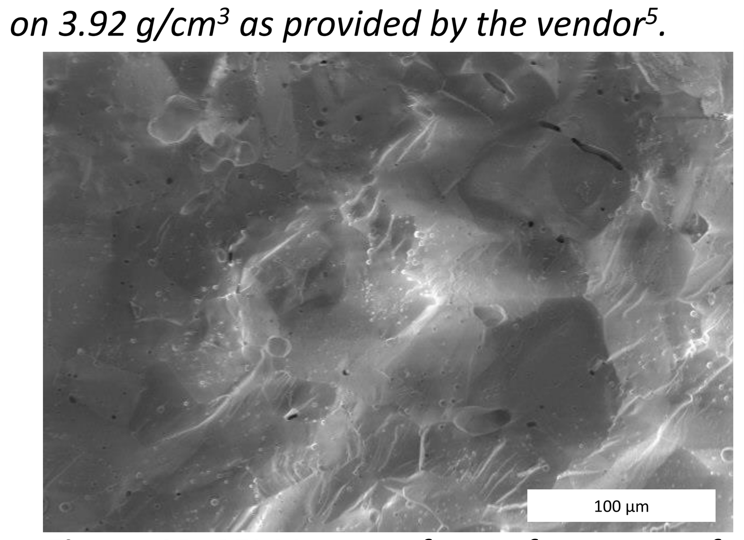

Figure 13. *SEM image of ceria fracture surface.*

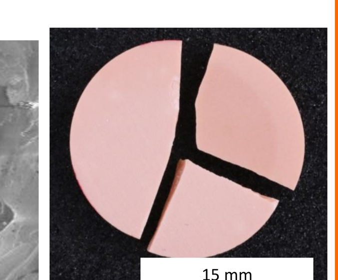

Figure 14. *Fractured CeO_2 pellet.*

Number of Tests	Sintered Density	Grain Size	Surface Roughness	TD %	Flexural Strength (MPa)
6	6.83 g/cm³	28 μm ±2	169 μ"	95.8 ±2	40.5-132
6	6.83 g/cm³	28 μm ±2	11 μ"	95.8 ±2	41.7-248

Figure 15. *Ceria pellet data table. Theoretical density based on literature value of 7.21 g/cm³[3, 6].*

Discussion

Transverse Rupture Strength

$$A = \frac{3}{4 * \pi} * \left[\left(2 * (1 + \nu_S) * \ln\frac{a}{b}\right) + \frac{(1 - \nu_S)(2a^2 - b^2)}{2 * R^2} + (1 + \nu_S)\right]$$

Test Sample
ν_S: 0.21 alumina

Test Fixture
ν_B: 0.21 (tungsten carbide[7])
E: 600 GPa (tungsten carbide)

$$b = \sqrt[3]{\frac{6 * F * (1 - \nu_B) * r}{E}}$$

ν_S: Poisson's ratio of material
a: radius of support circle
R: radius of sample (7.95 mm)
b: contact radius of loading ball
ν_B: Poisson's ratio of loading ball
r: radius of loading ball
E: Elastic Modulus of loading ball

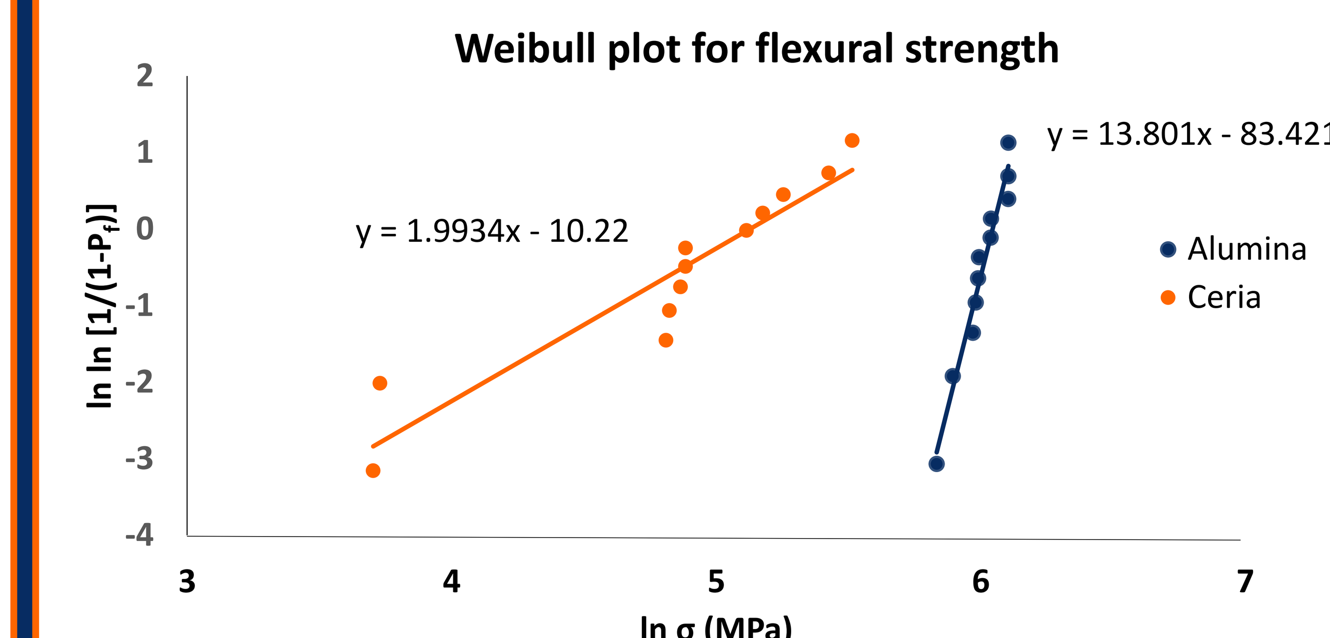

Figure 16. *Weibull plots of the flexural strength data of alumina and ceria.*

Effects of Microstructure

- Grain size, density, porosity, bulk/surface defects, and surface roughness affect flexural strength and Weibull modulus.
- Ceria pellets had an average grain size (Figure 17) of ~28 μm.
- Pellets had an average of 95.8% ±2 theoretical density.
- The high Weibull modulus for alumina demonstrates the validity of the MTS-TRS set up.

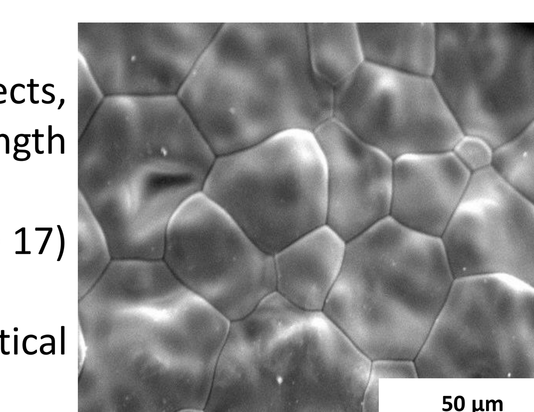

Figure 17. *SEM of CeO_2 grains.*

Challenges

- Alumina grain size for comparison to literature and ceria.
- Further validation tests for the TRS set up using magnesia partially-stabilized zirconia and yttria stabilized zirconia as benchmarks.
- Thermogravimetric analysis to address delamination and stoichiometry issues in ceria.

Conclusions

- Alumina flexural strength is comparable to literature values[5], 375 ± 54 MPa.
- Weibull modulus for alumina supports the MTS-TRS setup.
- Flexural strength for ceria was improved with a finer surface finish and greater height to diameter ratio.
- Weibull modulus for ceria can be improved by microstructure refinement.

References

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