Materials Challenges for Deployment of Thorium Dioxide Fuel

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Assuming all Other Challenges are Solved… What is Needed for Solid Th Fuel Deployment?

Sub Assumption:

ThO_2

$(Th,U)O_2$

$(Th,Pu)O_2$

- **Production**
  - Source powder *(FEEDSTOCK)*
  - Dense bodies *(PELLETS)*
  - Dense bodies… at scale
- **Characterization**
  - Properties for reactor design
  - Optimization of microstructure and chemistry
  - Validation of performance code predictions
  - Response to accident / off-normal scenarios
- **Disposal**
  - Reprocessing
  - Long term storage

General Overview: UO_2 to ThO_2

- **Much ‘better’ behaved oxide (Th^{4+} versus $U^{4,5,6+}$)**
- **Higher melting point**
- **Higher processing temperatures**
- **Generally adaptable to UO_2 infrastructure**
- **Pure ThO_2 contains superior unirradiated properties**
- **Good irradiation performance as observed**
  - Robust pellet mechanical response
  - Fission gas retention is superior (degrades w/U)
- ***Far smaller (or nonexistent) database***

Historic Thorium Dioxide (ThO_2) Materials Studies

- **Early (<1960) basic studies**
- **Fabrication data (when available) for historic test irradiations**
- **Westinghouse (1970-1985)**
- **BARC (IAEA) (1980 – current)**
- **Russian VVERT (1995-2000)**
- **INL (2000-2002)**
- **Infrequent other contributors**
  - US national labs and universities
  - ITU $(Th,Pu)O_2$
  - JAERI, KAERI

ThO_2 / $(Th,U)O_2$ Feedstock

- **Synthesis of ThO_2 feedstock powder poses no appreciable technological challenge**
- **Options for production of $(Th,U)O_2$ feedstock**
  - *A.* Separate oxide feedstock lines followed by mechanical solutionization (identical to laboratory scale)
  - *B.* Coprecipitation of $(Th,U)O_2$ powders using various carrier streams
  - Synthesis routes will affect processing and resultant microstructures
  - Compatibility with industrial scrap recycle must be considered
- **Baseline studies / characterization of synthesis routes for optimization readily achievable**

Processing Considerations
(10^0… 10^2… 10^7)

- **Fabrication of ThO_2, $(Th,U)O_2$ material on the laboratory scale**
  - Straightforward within existing national infrastructure
  - Mechanically solutionized material readily obtained
  - Processing temperatures elevated 100-200°C above those used for UO_2
  - Principle area of focus will be exploration of pressing conditions, use of sintering agents (e.g. MgO & Nb_2O_5), sintering temperatures, and sintering atmospheres on resultant chemistry and microstructure
- **Fabrication studies relevant to industrial deployment**
  - Focus on effect of lubricants, waxes, sintering aids on composition and structure
  - Role of sintering temperature on grain size, residual porosity (% and morphology) must be understood
  - Potential property effects of ThO_2 and UO_2 grains (versus full solutionization)
  - Exploration of need for resintering
- **Focus for industry is development of acceptable performance windows and identification of dominant variables to postulate necessary process controls**

Baseline Material Properties

- **Thermal conductivity is most critical property for ceramic fuels**
  - Despite numerous investigations, dissenting reports of thermal conductivity for stoichiometric $(Th,U)O_2$ as a function of U content; no exploration of stoichiometry
  - Published reactor design studies utilize $(Th,U)O_2$ solid solution thermal conductivities calculated using non-applicable rule of mixtures
- **Melt point, CTE, heat capacity also require verification**
- **Mechanical properties sparsely studied, but of less importance to reactor design and operation**
- **Species transport (oxygen, FP) also require exploration**

In Pile Fuel Performance

- **Assumed BU goal is 100 MWd/kg – need properties of previous slide *f* (BU)**
- **Gap closure reduced for ThO_2 fuels (reduced CTE and lower thermal creep) but the specifics must be known for performance codes**
- **Centerline temperatures & thermal gradients reduced – leads to more limited restructuring**
- **Fission gas release**
  - Existing (limited) data shows excellent retention
  - ^{233}U versus ^{235}U FP yield shift may have important consequences (gas > nobles)
- **Thermochemistry of fuel/fission products may pose significant challenge**
  - Dioxide phase stability limit of Th-U-O system has been sparsely studied but is much narrower than U-O
  - Example: for UO_{2+X} at 1300°C, dioxide phase limit is O/M = 2.23 but for $Th_{0.8}U_{0.2}O_{2+X}$ O/M limit = 2.07
  - Significant repercussions for grey phase fission product formation, decomposition of solid solution, or Zr-based cladding oxidation

Fuel Performance Under Transient / Accident Scenarios

- Commonly cited advantage of ThO_2 is enhanced thermophysical properties in comparison to traditional UO_2… BUT these must be evaluated *f* (chemistry) at high temperatures
- Important to note that even heterogeneous loading (i.e. UO_2 and ThO_2 pellets) material of concern is in reality $(Th,Pa,U)O_2$ with far less understood properties (e.g. melt point)
- FCCI / FCMI virtually unknown for ThO_2 based fuels
- Chemical stability of $(Th,U)O_2$ in water vapor at temperature has not been studied – $U^{4,5,6+}$ vs. Th^{4+}

Waste Form Performance

- **Minimal consideration in historic evaluations (assumption was reprocessing/^{233}U recycle)**
- **Spent fuel storage**
  - Baseline property advantages may improve performance
  - Solubility of ThO_2 in liquid water five orders of magnitude better than UO_2
  - $(Th,U)O_2$ pellets exhibit two orders of improvement over UO_2
  - Burnup has been demonstrated to have no effect on this performance
- **Oxygen solubility limit offers benefits and drawbacks for long term storage**

Returning to Introductory Slide… Assuming Materials Challenges are Considered for Deployment of Solid Th Fuels

- **LWR ACCIDENT TOLERANCE**
  - $(Th,U)O_2$ oxidation kinetics under steam
  - Oxygen and FP thermochemistry
- **ECONOMICS**
  - *Factors beyond material performance*
  - Fabrication at scale
  - Allowable BU
- **NEAR TERM LICENSING FOR ADVANCED FORMS**
  - Property verification as required by performance codes
  - Test rods / bundles / assemblies

The Reality for Solid Th Fuel Development in the US… the Challenges

- **Political (funding) reality**
  - Accident tolerance and fuel storage dominates current attention
  - No specific funding for FY12 Th materials R&D
- **Infrastructure reality**
  - Pu work extremely challenging and expensive
  - Post irradiation examination (hot cells) limited in availability and capabilities
  - Facilities likely required for licensure of revolutionary concepts unavailable (e.g. LOCA facility)
  - Use of commercial reactors to test evolutionary concepts unlikely
- **International collaboration reality**
  - BARC…
  - Difficult beyond basic science / LWR applications

The Reality for Solid Th Fuel Development in the US… the Promise

- **Increasing dialogue between experiment and modeling**
  - Both informing,
  - May change depending on possible use in current LWR fleet
- **NRC giving hints of becoming more progressive**
  - Coordination between industry, other organizations, and R & D may offer path forward for
  - US currently does not have ability to perform many of the tests that NRC would (likely) require e.g. no LOCA facility
  - Insertion of evolutionary fuel forms in commercial reactors unlikely
- **Trend of field still pointing upward**
  - Capabilities, expertise at labs and universities growing
  - Growing interest and awareness of Th from funding agencies and scientific community