Increasing CERMET Fuel Thermal Margin with Thoria for Nuclear Thermal Propulsion

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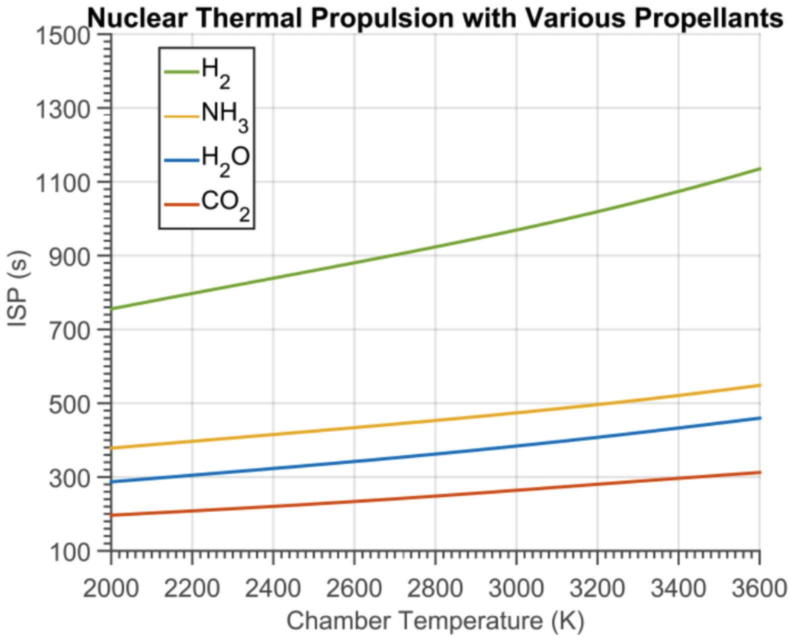
Nuclear Thermal Propulsion (NTP)

Nuclear Thermal Propulsion:

1. Higher achievable specific impulse
2. Flexible choice of propellant

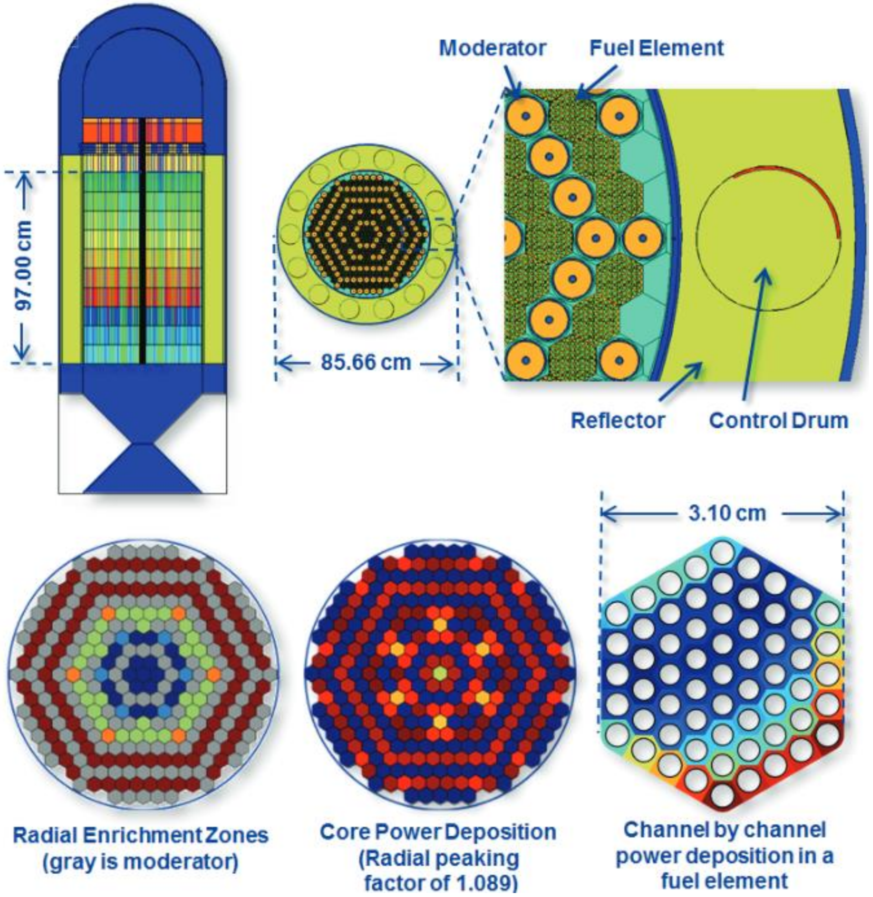
Requires:

1. High exhaust temperature
2. High-temperature-resistant materials



Ideal Specific Impulse of different propellants as a function of propellant temperature from Ref. 5

Space Capable Cryogenic Thermal Engine (SCCTE)



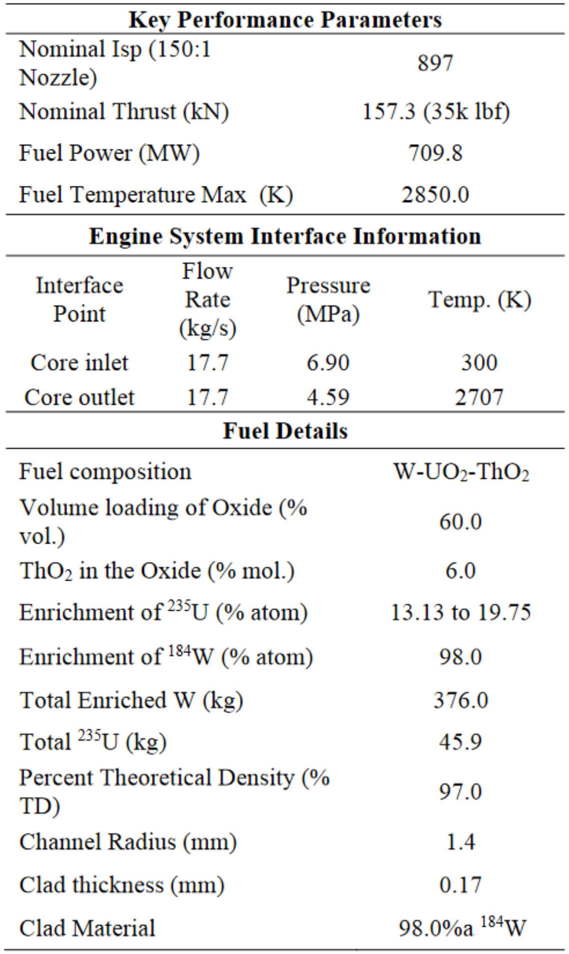
Radial Enrichment Zones (gray is moderator)

Core Power Deposition (Radial peaking factor of 1.089)

Channel by channel power deposition in a fuel element

SCCTE Reactor Design and Description from Ref. 1 [1]

SCCTE Key Properties from Ref. 2 [2]



Key Performance Parameters

Nominal Isp (150:1 Nozzle)	897
Nominal Thrust (kN)	157.3 (35k lbf)
Fuel Power (MW)	709.8
Fuel Temperature Max (K)	2850.0

Engine System Interface Information

Interface Point	Flow Rate (kg/s)	Pressure (MPa)	Temp. (K)
Core inlet	17.7	6.90	300
Core outlet	17.7	4.59	2707

Fuel Details

Fuel composition	W-UO_2-ThO_2
Volume loading of Oxide (% vol.)	60.0
ThO_2 in the Oxide (% mol.)	6.0
Enrichment of ^{235}U (% atom)	13.13 to 19.75
Enrichment of ^{184}W (% atom)	98.0
Total Enriched W (kg)	376.0
Total ^{235}U (kg)	45.9
Percent Theoretical Density (% TD)	97.0
Channel Radius (mm)	1.4
Clad thickness (mm)	0.17
Clad Material	98.0%a ^{184}W

Why Thorium?

Advantages:

1. Lower Density
2. Higher thermal conductivity
3. Higher melting point
4. Improves fuel stability (chemical and irradiation)

Concerns:

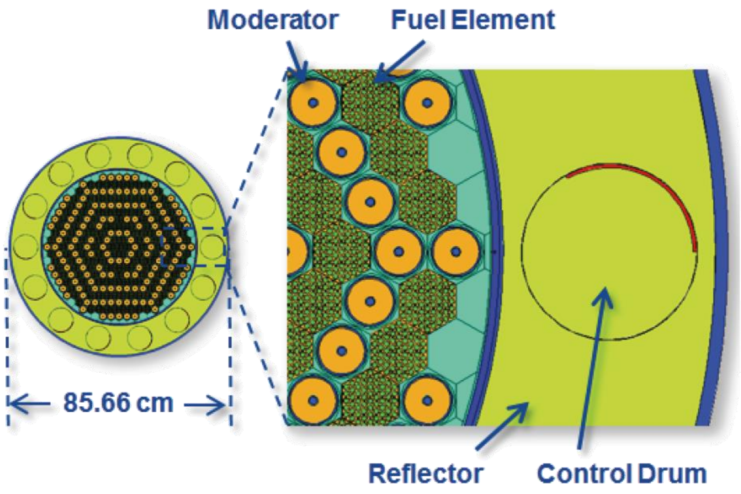
1. Reduces fissile inventory

Urania and Thoria material properties of interest

Property	UO_2	ThO_2
Density (300K)	10.96 g/cm^3	10.00 g/cm^3
Melting Point[7]	3120 ± 30 K	3640 ± 30 K
Thermal Conductivity[8] (500~2000K)	8~2.5 W/m·K	14~3 W/m·K

Methodology

1) Reproduce SCCTE core using SERPENT[6]
2) Axially introduce thorium to fuel composition
3) Adjust reactor design for criticality
4) Tally Heat deposition
5) Calculate 1D Axial Temperature profile



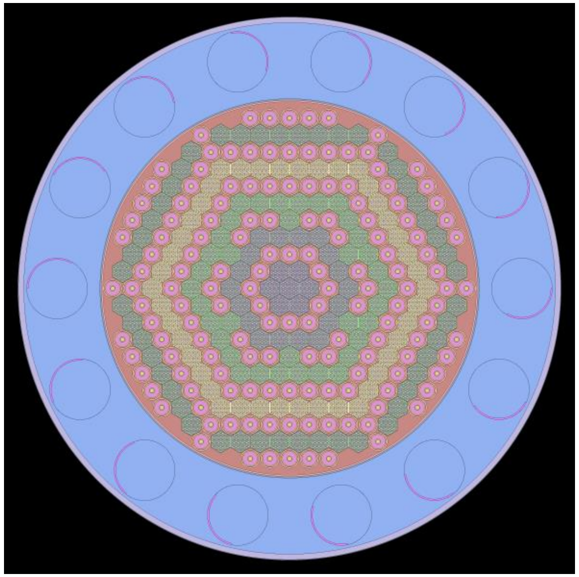


Figure 5. Reference and Replicated SCCTE core [1]

Temperature Calculation

1D fuel pin + coolant axial temperature was considered for a single average fuel pin.

Assumptions:

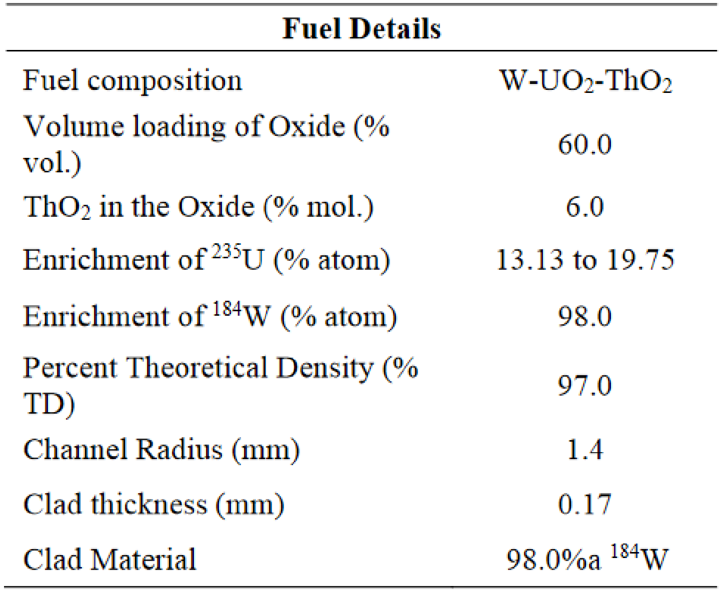
- Tally heat deposition normalized to reactor operation power
- Radially Constant Heat Deposition within single fuel pin
- Radiative and Convective Heat Transfer between fuel and coolant

Design Changes – Axial Fuel Composition

Goal:

1. Introduce thoria while compensating for reduced fissile material
   - Add thoria only near the higher temperature regions (near coolant exit)

SCCTE Key Properties from Ref. 2 [2]



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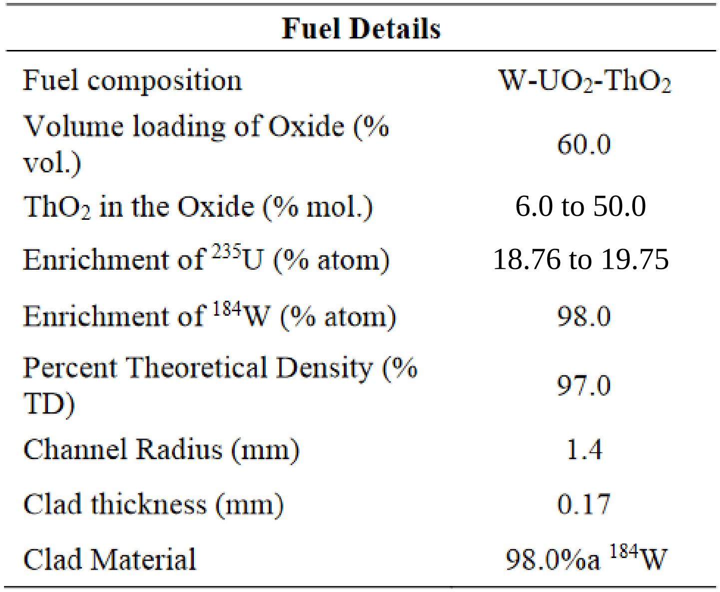
SCCTE Adjusted Properties



Fuel Details	
Fuel composition	W-UO_2-ThO_2
Volume loading of Oxide (% vol.)	60.0
ThO_2 in the Oxide (% mol.)	6.0 to 50.0
Enrichment of ^{235}U (% atom)	18.76 to 19.75
Enrichment of ^{184}W (% atom)	98.0
Percent Theoretical Density (% TD)	97.0
Channel Radius (mm)	1.4
Clad thickness (mm)	0.17
Clad Material	98.0%a ^{184}W

Design Changes – Axial Fuel Composition

SCCTE Reference core's radial and axial UO_2 enrichment

Radial Axial	Inner				Outer
Inlet	0.1975	0.188	0.1975	0.188	0.1975
	0.1975	0.188	0.1975	0.188	0.1975
	0.1975	0.188	0.1975	0.188	0.1975
	0.1975	0.188	0.1975	0.188	0.1975
	0.1975	0.188	0.1975	0.188	0.1975
	0.158	0.150	0.158	0.150	0.158
	0.13825	0.131	0.138	0.131	0.138
	0.13825	0.131	0.138	0.131	0.138
Outlet	0.13825	0.131	0.138	0.131	0.138

→

SCCTE Adjusted core's radial and axial UO_2 enrichment

	Inner				Outer
Axially const.	0.1975	0.188	0.1975	0.188	0.198

SCCTE Reference core's radial and axial ThO_2 fraction in fuel oxide

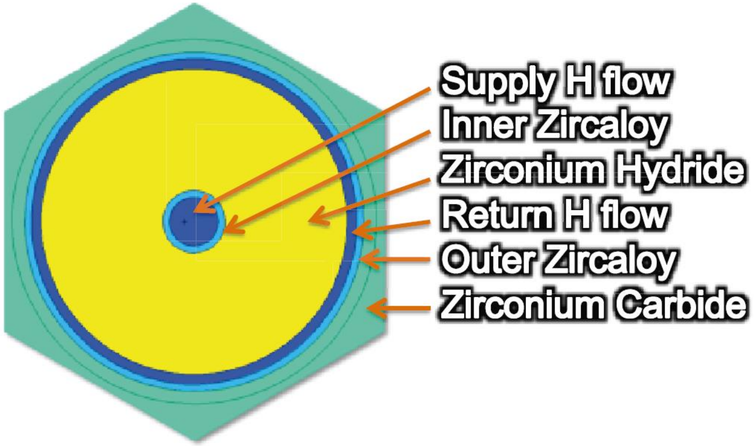
Axial Height	Inlet (0 %)	(20%)	(40%)	(60%)	Outlet (100%)
Radially const.	6 at%	6 at%	6 at%	6 at%	6 at%

→

SCCTE Adjusted core's radial and axial ThO_2 fraction in fuel oxide

Axial Height	Inlet (0 %)	(20%)	(40%)	(60%)	Outlet (100%)
Radially const.	6 at%	6 at%	6 at%	50 at%	50 at%

Design Changes – Tie Tube Dimensions



Tie-tube geometry and material from Ref 1.

SCCTE Reference and Adjusted Tie-tube dimensions [1].

Fuel Pin Component	Inner Radius (cm)	Outer Radius (cm)
Supply H Flow	-	0.330
Inner Zircaloy	0.330	0.413
Zirconium Hydride	0.413	1.120→1.143
Return H Flow	1.120→1.143	1.268→1.288
Outer Zircaloy	1.268→1.288	1.309→1.329
Zirconium Carbide	1.309→1.329	1.495→1.515
Tie tube body	3.10 (flat-to-flat)	

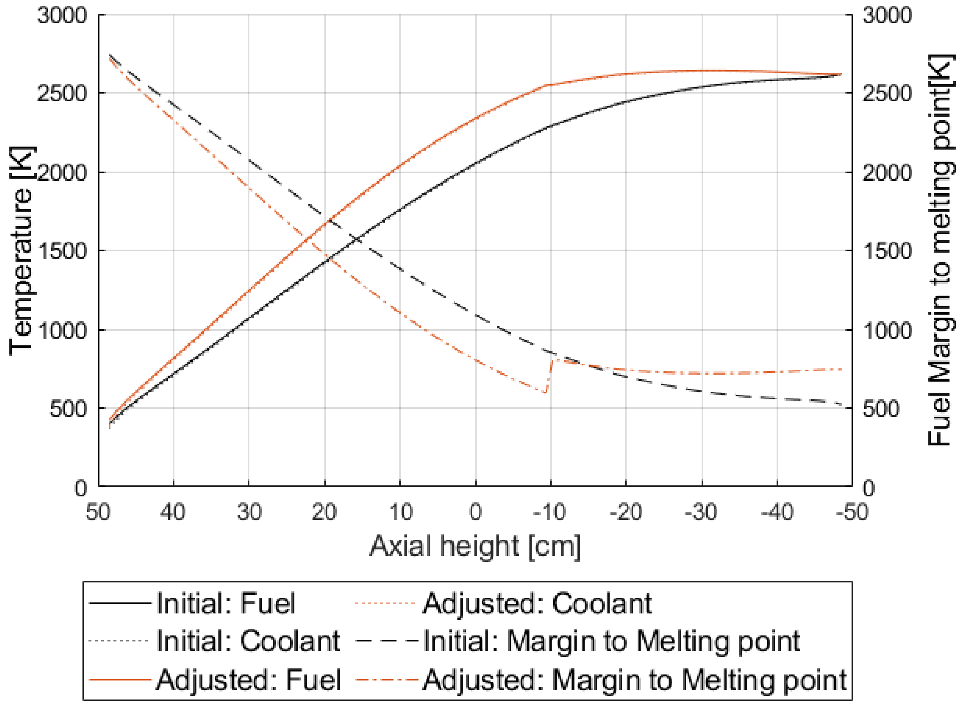
Criticality, Fuel Mass

- Final keff: 1.00223 ± 0.00031
- Fuel Mass Decrease: 6.1 kg
  - Limited change due to tungsten density
- ~ 200 K increase in fuel melting point

SCCTE Reference and Adjusted Tie-tube dimensions [1].

ThO_2 fraction in oxide (mol%)	Multiplication factor (k_{eff})	Fuel melting point (K)
6.00 (Reference)	1.00537 ± 0.00038	3142.1
20.0	0.99987 ± 0.00033	3210.0
30.0	0.99690 ± 0.00036	3260.0
40.0	0.99419 ± 0.00027	3310.0
50.0	0.99184 ± 0.00032	3360.0
50.0 w/ Tie Tube	1.00223 ± 0.00031	3360.0

Adjusted Temperature Margins



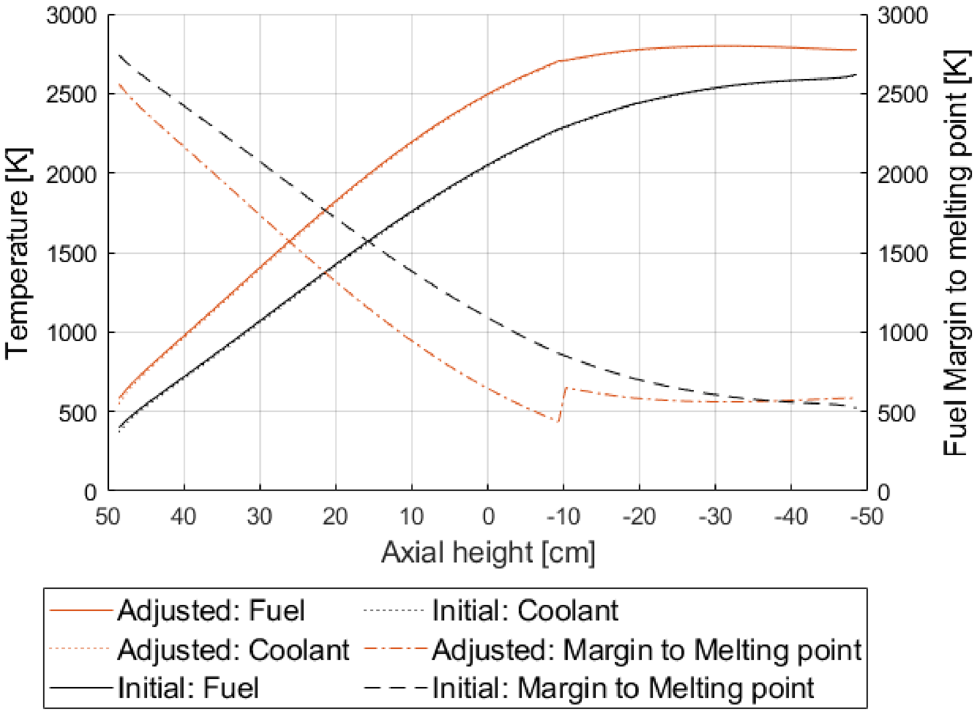
Replicated and Adjusted fuel and coolant temperature of a single average fuel pin with fuel margin to melting point.

- ~ 200 K of additional fuel margin to melting point
- Lower energy deposition near coolant exit
- Adjusted moderator design produces more power near inlet

Adjusted Temperature Margins

- Theoretical Operation Temperature:
  - Assuming higher inlet coolant temperature
  - Same reactor power
  - Same fuel margin to melting point at outlet
  - Outlet Temperature: 2774.07 K

(increased by 159 K)



Replicated and Adjusted fuel and coolant temperature of a single average fuel pin with fuel margin to melting point for a higher inlet coolant temperature.

Conclusion

1) Axial introduction of thoria with design adjustments can achieve a critical NTP design with greater fuel thermal margin
    - A potential increase of coolant outlet temperature of 159 K while keeping the same fuel margin to melting point.
    - A potential increase of specific impulse of 32 s.
2) Introduction of thoria provides limited benefit to the overall fuel mass
3) Nevertheless, the addition of thoria to fuel composition can provide noticeable benefits.

Future Work

1) Further feasibility study of adjusted SCCTE Model
    - Model neighboring tie-tubes to confirm tie-tube temperatures
    - Hottest fuel pin analysis
2) Explore finer axial adjustment of fuel composition
    - Finer axial adjustments in fuel thoria fraction
    - Reintroduce axial U-235 enrichment zoning
3) Investigate radial and axial temperature distribution
4) Consider adjustments of tungsten-to-fuel ratio
5) Compare the optimized Thoria-Urania design to UN cermet and outline the cost/benefits

References

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UO_2-ThO_2 Melting Point

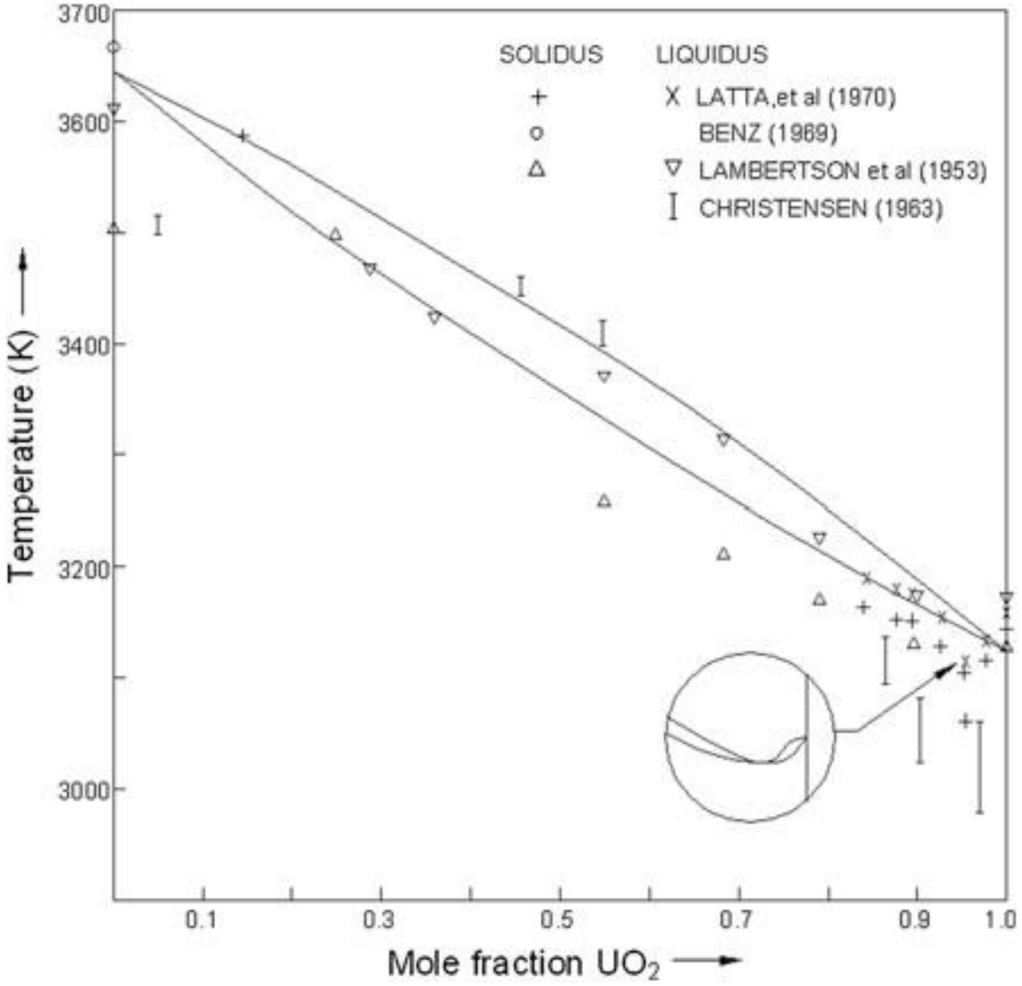

Figure 8. ThO_2-UO_2 mixture solidus and liquidus line from Ref 8.

Commercially available enriched Tungsten

- Urenco
- Buyisotope
- Isoflex