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VTR Fuel Design Considerations

May 2023

Changing the World's Energy Future

Doug Crawford

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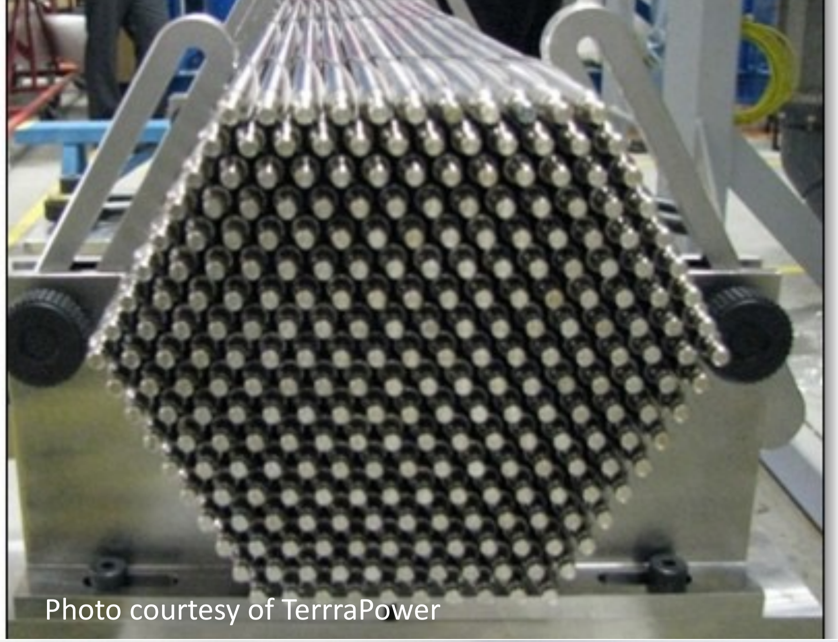

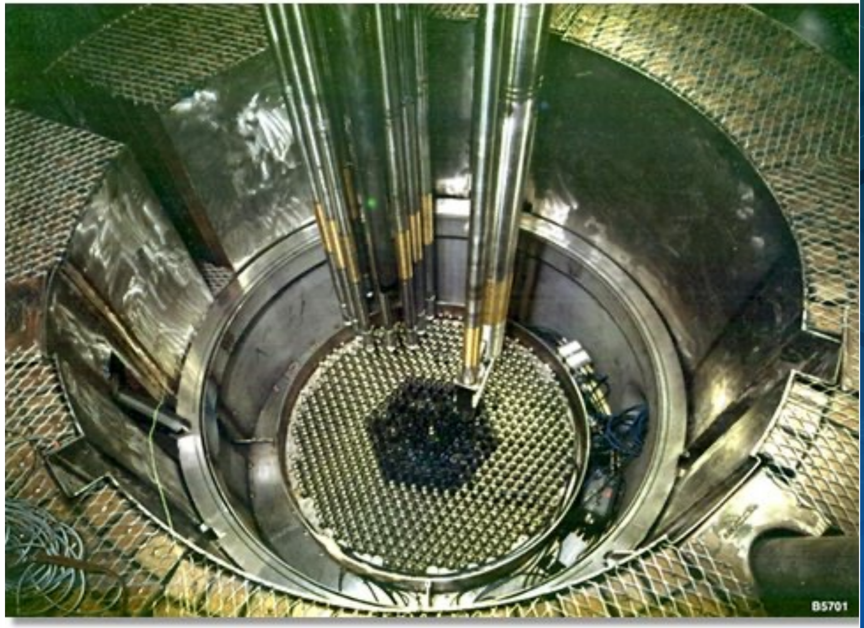

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VTR Fuel Design Considerations

Presented to Advanced Fuels Campaign Metallic Fuels Workshop, Idaho Falls, ID

Idaho National Laboratory

Purpose

- Review design and objectives for VTR fuel
- Briefly discuss key design considerations

VTR Driver Fuel Design Objectives

- A fuel design that supports the VTR mission and design objectives
- A ”boring” fuel design
  - Reliability is very important
    - Minimize uncertainties and potential for surprises
  - First-generation fuel design (startup fuel) based on U.S. SFR fuel database, successful EBR-II and FFTF experience
    - Important to ensure the database is applicable
- Next-generation VTR fuel could/would follow

VTR Fuel Performance Design basis

	Experience	Significance
U-10Zr, U-5Fs **Driver Fuel Operation**	• ~13,000 U-Zr rods in 316SS 10 at.% bu • ≥ 120,000 U-Fs rods in 304LSS/316SS 1-8 at.% bu	• Established reliability of the fuel design and fabrication process for nominal reactor operating conditions • Sufficient numbers to capture manufacturing variation
U-10Zr **Through Qualification**	• U-Zr in 316SS, D9, HT9 ≥ 10 at.% bu in EBR-II & FFTF	• Established that specific designs operate as designed under design-basis conditions • Established that the fuel fabrication processes produce fuel that meets the specification • (Did not capture manufacturing variation)
U-Pu-Zr **Burnup Capability & Experiments** **Safety & Operability testing**	• 600 U-Pu-Zr rods; D9 & HT9 to > 10 - 19 at.% in EBR-II & FFTF • 6 RBCB tests U-Fs & U-Pu-Zr/U-Zr(5) • 6 TREAT tests U-Fs in 316SS (9rods) & U-Zr/U-Pu-Zr in D9/HT9 (6 rods)	• Extended knowledge of metallic fuel phenomena • Established capability for specific design features • Design limits identified • Did not capture manufacturing variation, and did not qualify the design for operation under design basis conditions

Crawford, Porter, Hayes, *Journal of Nuclear Materials*, 371: 202-231 (2007).

- Reliability has been demonstrated in statistically significant numbers with relevant designs in variation of many batches and lots
- We know the fuel degradation and failure mechanisms
- We know how Pu impacts those mechanisms
- We know key limits, or how to ensure margin
- We selected fuel design parameters that were shown to provide ample margin

Startup Fuel Basis

Table 9
Suggested reference design parameters for mixed oxide (MOX) fuel, U–Pu–Zr fuel, and mixed carbide (MC) fuel based on US experience

Parameter	Mixed oxide (MOX)[a]	U–Pu–Zr[b]	Mixed carbide (MC)[c]
Nominal composition	$(U,Pu)O_2$	U–20Pu–10Zr	(U,Pu)C
Pu/(U + Pu) range	22–30%	17–28%	21–23%
Oxygen-to-metal ratio	1.95	n/a	
Fuel theoretical density	92%	100%[d]	80–82%
Fuel smeared density (% TD)	80–85%[e]	75%	78–79%
Plenum-to-fuel volume ratio	1.0	1.4	1.0
Fuel height	91 cm[f]	91 cm[f]	91 cm
Fuel outer diameter, as-fabricated	0.56 cm[g]	0.5 cm[g]	TBD[g]
Fuel inner diameter, as-fabricated	0.15 cm[g]	n/a	n/a
Fuel-cladding bond	He	Na	He
Cladding material	HT9[h] or 20% cw 316SS	HT9[h] or 20% cw 316SS	HT9[h] or 20% cw 316SS
Cladding outer diameter[f]	0.69 cm	0.69 cm	0.94 cm
Cladding inner diameter[f]	0.57 cm	0.57 cm	TBD[g]
Peak linear heat generation rate	44–46 kW/m	49–52 kW/m	66–80 kW/m
Peak inner-wall cladding temperature, nominal	620 °C	620 °C[i]	620 °C
Duct material	HT9[h] or 20% cw 316SS	HT9[h] or 20% cw 316SS	HT9[h] or 20% cw 316SS

Crawford, Porter, Hayes, *Journal of Nuclear Materials*, 371: 202-231 (2007).

Metal fuel performance phenomena, failure mechanisms, and key design parameters

Phenomena	Failure Mechanisms	Key Design Parameters
Fuel swelling and fuel-cladding mechanical interaction (FCMI)	Breach by contact-stress rupture	Fuel smeared density, burnup
Axial growth (swelling)	In-cycle loss of reactivity	Fuel smeared density, fuel composition
Fission gas release	Breach by pressurized stress rupture	P/V, burnup
Fuel restructuring and constituent redistribution	Fuel melting leading to slumping w/ reactivity addition, or FCCI cladding effects	Fuel composition & operating temperature
Fuel-cladding chemical interaction (FCCI)	Cladding penetration reducing load-bearing thickness leading to breach by stress rupture	Fuel composition, burnup, fuel operating temperature
Cladding and duct deformation	Flow reduction through fuel assembly, impeding control rod motion, excessive fuel loading/unloading resistance	Cladding & duct material selection, in-service stress, in-service external loads

Metal Fuel Design Evolution 1964-1994

Design Parameter	Mark-I	Mark-IA	Mark-II	Mark-III	Mark-IIIA	Mark-IV	FFTF Series III.b
Fuel alloy (wt%)	U-5Fs	U-5Fs	U-5Fs	U-10Zr	U-10Zr	U-10Zr	U-10Zr
Fuel rods per assembly	91	91	91	61	61	61	169
Enrichment (% ^{235}U)	48.4	52	67	66.9	66.9	69.6	31
Fuel slug mass (g)	67	64	52	83	83	78	83
Fuel slug(s) height (cm)	36.1	34.3	34.3	34.3	34.3	34.3	91.4
Fuel slug diameter (cm)	0.365	0.365	0.330	0.439	0.439	0.427	0.498
Fuel smeared density (%)	85	85	75	75	75	75	75
Fuel-cladding radial gap (mm)	0.152	0.152	0.254	0.350	0.350	0.325	0.380
Cladding-wall thickness (cm)	0.023	0.023	0.030	0.038	0.038	0.046	0.056
Cladding OD (cm)	0.442	0.442	0.442	0.584	0.584	0.584	0.686
Fuel Rod Length (cm)	46.0	46.0	61.2	74.9	74.9	74.9	240
Cladding material	304L	304L	316	CW D9	CW316	HT9	HT9
Spacer-wire diameter (cm)	0.124	0.124	0.124	0.107	0.107	0.107	0.135
Burnup limit (at%)	1.2	2.6	8	10	10	N/A	N/A
Plenum-to-fuel-volume ratio	0.13	0.18	0.83	1.45	1.45	1.45	1.5
r/t (hoop stress = Pr/t)	9.11	9.11	6.87	7.18	7.18	5.85	5.63

C.E. Lahm, et al., *Journal of Nuclear Materials* 204 (1993) 119-123; B. R. Seidel and L. C. Walters, *Journal of engineering for Power, Trans ASME* 103 (1981) 612-620; D.E. Burkes et al., *Journal of Nuclear Materials* 389 (2009) 458–469; W.J. Carmack, et al., *Journal of Nuclear Materials* 473 (2016) 167-177

Key Design Parameters for VTR Fuel

For a thin-walled tube:

$\sigma_h = \frac{Pr}{t}$ where:

- P = internal pressure or load
- r = radius at midwall
- t = wall thickness

Cladding r/t is an indicator of hoop stress induced by a given loading from fuel swelling and/or internal gas pressure

P/V

$$\sigma_h \sim P \sim \frac{1}{V_{plenum}}$$

Cladding thickness

$$\sigma_h \sim \frac{r}{t}$$

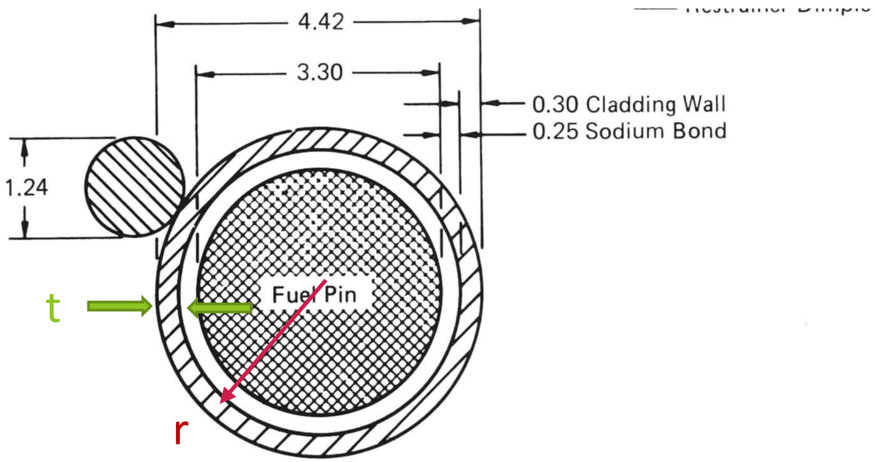


Fig. 1. Mark-II driver-fuel element. All dimensions are in millimetres.

Fuel Smeared Density (SD)

$$SD = r_{fuel}^2 / r_{cladding_{inner}}^2$$

Moral: keep an eye on the reactor physicists

- Core design objectives always drive them to stick as much fissile as they can into as few fuel rods as they can and to reduce pressure drop
- They'll push fuel composition if they can (U-28Pu-10Zr anyone?)
- They'll try to reclaim your fuel-cladding gap
- They'll thin your cladding
- And then, if you let them get away with these things someone will push for higher burnup to reduce fuel costs… there is nothing new under the sun

- Stay strong. Hold your ground.

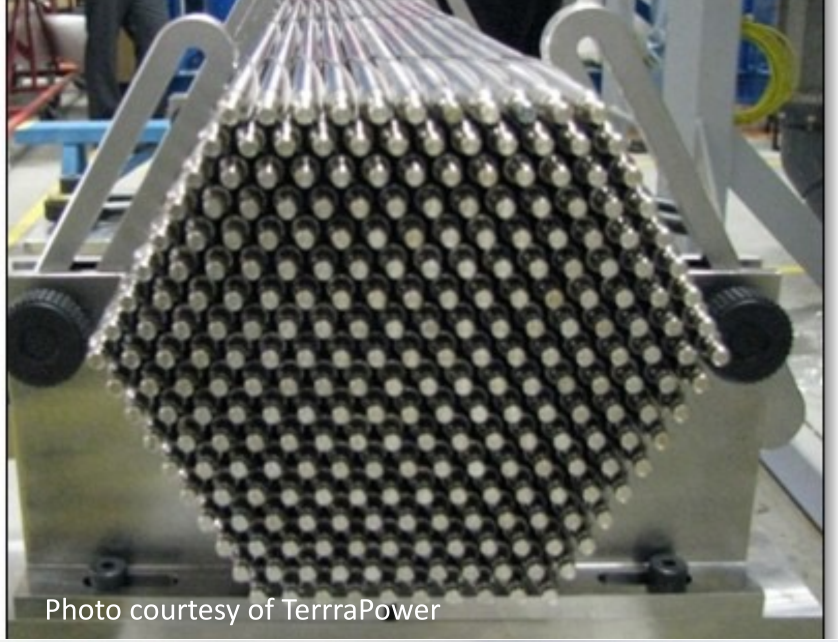
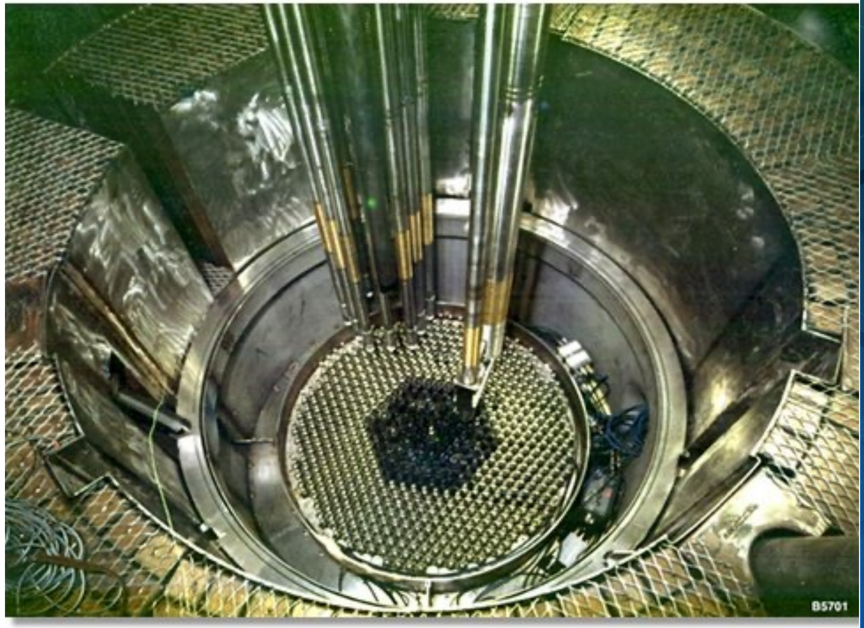


Photo courtesy of TerrraPower



Questions?

VTR Fuel Startup & Qualification Approach

- U-20-Pu-10Zr in HT9 Cladding (VTR Mark-I)
  - Seek startup approval for fuel service to 10 at.% peak burnup, based on prior experience and on safety analysis
  - Fuel monitoring program to establish that fuel behavior meets expectations
    - Power reactivity decrement, fuel handling forces, dimensional measurements, destructive examinations
- Early insertion of lead qualification assemblies
  - U-20Pu-10Zr-0.2Ga – weapons Pu variant
  - U-20Pu-19(Zr-Mo) – ZPPR Pu option
  - U-20Pu-10Zr in 316LSS or D9 cladding (VTR Mark-IA cladding contingency)
  - VTR Mark-II fuel design, possibly including
    - New cladding alloy (such as ORNL NFA)
    - Thinner cladding
    - Non-sodium design