NE 591: Advanced Reactor Materials

Fall 2021

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Last Time

- Thermal conductivity degradation
  - fission gas swelling/porosity, sodium infiltration
- Fuel-cladding mechanical interaction
  - fuel swelling, creep, internal pressure, etc.
- Fuel-cladding chemical interaction
  - phase diagrams and kinetics, low melting points, intermetallics, etc.

FCCI

- The burnup of a fuel pin is another parameter that impacts the size of the fuel–cladding interaction zone
- Larger interaction zones are observed for higher burnup fuel elements
- The larger inventories of fission products allow more lanthanides to diffuse down the temperature gradient, thereby increasing the inventory of fission products at the interface
- For high burnup fuels, temperature effects also exacerbate FCCI due to thermal cond. degradation producing higher temperatures, and more rapid FP diffusion
- Fuel elements at the hotter core positions can exhibit increased interdiffusion at the fuel–cladding interface over those at colder positions

FCCI Compositions

- Fe and Cr are the major constituents in HT-9 cladding and should show up as major constituents in the FCCI zones of irradiated HT-9-clad fuel elements
- For D9-clad fuel elements, Fe, Ni, and Cr are major constituents that should be present in FCCI zones
- There have been some irradiated fuel samples that were specifically destructively analyzed to observe FCCI
- The lowest and highest determined temperatures at the fuel–cladding interface were 540 and 660 C, respectively
- The thickest interaction zone measured was 170 μm, and the lanthanide fission products were the primary fuel constituents observed in the interaction layers

Table 1 Nominal compositions for stainless steel cladding materials (wt%)[a]

	HT9	*D9*	*316*
Ni	0.5	15.5	10–14
Cr	12.0	13.5	16–18
Mn	0.2	2.0	2 (max)
Mo	1.0	2.0	2–3
Si	0.25	0.75	1 (max)
Ti	–	0.25	–
C	0.2	0.04	0.08 (max)
W	0.5	–	–
V	0.5	–	–
S	–	–	0.03 (max)
P	–	–	0.045 (max)

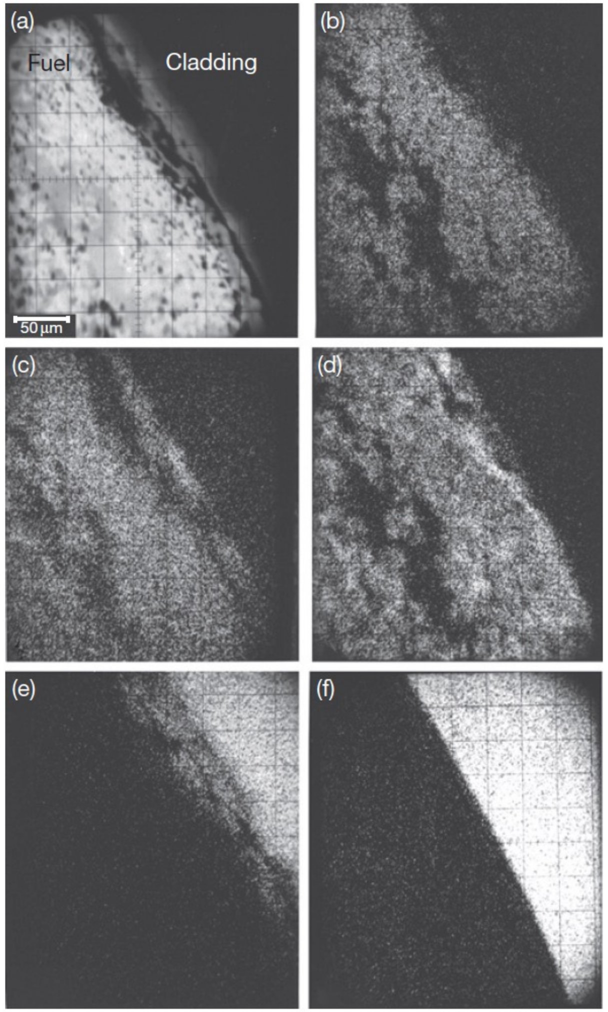
FCCI Examinations

Fuel element ID	*Cladding material*	*Fuel composition (at.%)*	*Burnup (at.%)*	*Temperature at fuel–clad interface at BOL (°C)*[a]	*Maximum zone thickness observed (μm)*	*Type of analysis*	*Components originating in the fuel that are found in cladding layers*
DP-81	HT-9	U–23Zr	5.0	660	70	EPMA	Ce, Pr, Nd
DP-11	HT-9	U–23Zr	10.0	660	90	EPMA	Ce, Pr, Nd, La, Sm, Pd
DP-04	HT-9	U–23Zr	10.0	660	90	EPMA	Ce, Pr, Nd, La, Sm, Pd
DP-70[b]	HT-9	U–23Zr	10.0	660	140	EPMA	Ce, Pr, Nd, La, Sm, Pd
DP-75	HT-9	U–23Zr	10.0	660	170	EPMA	Ce, Pr, Nd, La, Sm, Pd
T459	HT-9	U–16Pu–23Zr	3.0	ND[c]	10	EPMA	Ce, Pr, Nd
DP-16(1)	HT-9	U–16Pu–23Zr	9.7	540	40	SEM	Ce, Nd, La, U, Pu, Pd
DP-16(2)	HT-9	U–16Pu–23Zr	10.1	550	40	EPMA	Ce, Nd, Pr, Pu
DP-21	HT-9	U–16Pu–23Zr	11.4	ND	ND	EPMA	ND
C709	D9	U–23Zr	9.3	650	111	EPMA	Ce, Nd, La
T225	D9	U–23Zr	10.0	ND	25	OM	ND
T141	D9	U–23Zr	11.9	ND	17	OM	ND
T-159	D9	U–16Pu–23Zr	3.0	ND	ND	EPMA	Ce, Pr, Nd, Pu
[d]	D9	U–16Pu–23Zr	6.0	ND	75	EPMA	Ce, Pr, Nd, La
T042	D9	U–7Pu–23Zr	6.0	540	20	EPMA	Ce, Pr, Nd, La
T-087	D9	U–16Pu–23Zr	10.0	ND	50	EPMA	Ce, Pr, Nd, La, Pu
A-850	D9	U–16Pu–23Zr	10.1	550	100	EPMA	Ce, Nd, La, Pu
T-112	D9	U–16Pu–23Zr	11.9	ND	72	EPMA	ND
T-106	D9	U–16Pu–23Zr	17.0	ND	20	EPMA	Ce, Pr, Nd, La
T341	316SS	U–16Pu–23Zr	0.4	ND	ND	EPMA	ND

FCCI Compositions

- Element DP-16 was the only fuel element in which a sample was generated for analysis using SEM/EDS, in addition to the more typical OM and EPMA analyses usually performed on fuel elements
- U-16Pu-23Zr and HT-9 cladding
- X-ray analysis maps at the right

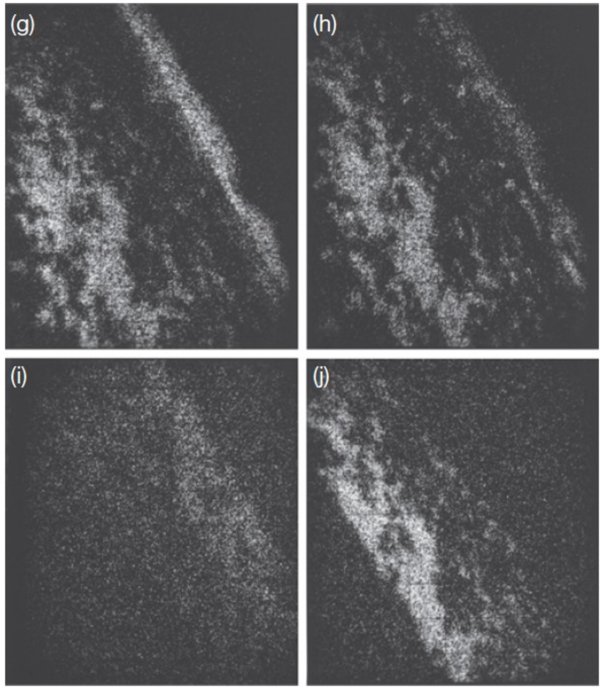
DP-16(1)	HT-9	U–16Pu–23Zr	9.7	540	40	SEM	Ce, Nd, La, U, Pu, Pd
DP-16(2)	HT-9	U–16Pu–23Zr	10.1	550	40	EPMA	Ce, Nd, Pr, Pu



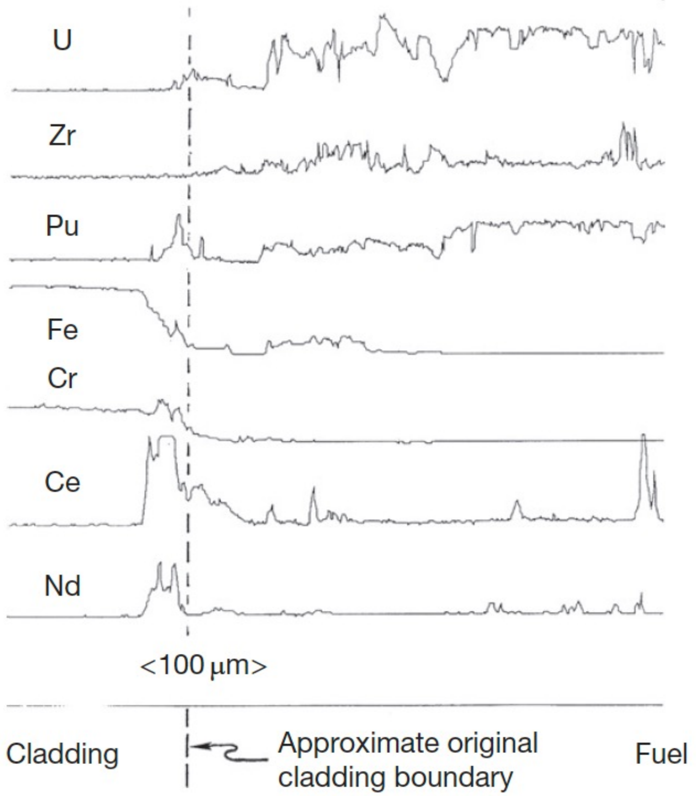
(b) U,
(c) Pu,
(d) Zr,
(e) Fe,
(f) Cr

FCCI Compositions

- X-ray map for fission products
- EPMA analysis for key species
- Fe diffuses into the fuel, Ce and Nd diffuse into the cladding, and Pd enriches in localized areas of the fuel near the fuel–cladding interface
- The lanthanides penetrated the farthest into the cladding (40 mm) of any components originating in the fuel

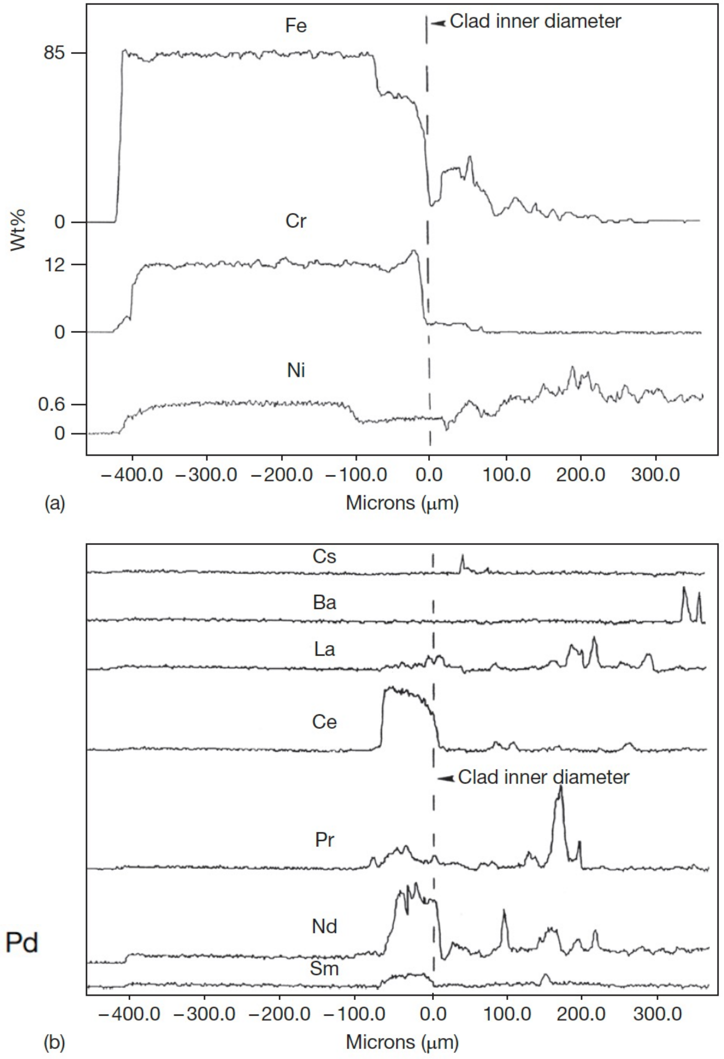


(g) Ce, (h) Nd, (i) Ru, and (j) Pd



FCCI Compositions

- The DP-11 fuel element was irradiated to about 10 at.% burnup at elevated cladding temperatures (630–660 C), binary U-Zr
- There is a 50-μm-wide zone of the cladding that is high in Cr and low in Fe and Ni
- In the fuel, Fe has interdiffused around 250 μm
- In the cladding band containing high Cr and low Fe and Ni, lanthanide concentrations are elevated



DP-11	HT-9	U–23Zr	10.0	660	90	EPMA	Ce, Pr, Nd, La, Sm, Pd

FCCI

- A variety of phases have been observed to form locally where swelled fuel has contacted the cladding
- At the interface between the fuel and the cladding, the observed phases on both sides combine the cladding elements Fe, Ni, and Cr with the fuel components U, Zr, and Pu and the lanthanide fission products
- In the cladding, the developed phases are enriched with cladding components, and they contain differing amounts of the primary fuel components and fission product components
- Lanthanides penetrate farthest into the cladding, specifically Ce and Nd
- Fe and Ni depletion zones are observed in all the fuel elements

FCCI

- In the fuel, some phases are observed that are enriched with the fuel constituents and contain Fe or Ni as the major nonfuel or components
- Other phases are observed that primarily contain lanthanides
- The interaction zone formation is localized
- Temperature and power variations along the length of a fuel element appear to impact the amount of FCCI that occurs

Two different locations in DP-16

Layer	Fe	Cr	Si	Pd	Ce[b]	Nd[b]	Zr	Pu	Other[b]
1	2	2	0	24	16	34	19	1	–
1	1	1	5	35	19	33	5	1	–
1	–	–	5	38	13	26	7	2	9La
1	–	–	–	20	10	16	31	–	6La, 17Pb
2	–	34	6	–	11	23	–	–	3Mo, 6La, 8U, 9Sn
2	2	28	7	–	16	28	–	–	La, 7U, 1Ag, 10Sn
3	28	20	5	15	10	12	–	11	–
4	63	10	4	–	7	13	–	0.3	1La
4	66	15	6	–	5	7	–	0.2	1Ag
4	67	13	6	–	5	7	–	0.2	1Ag
4	69	16	4	–	5	5	–	0.3	1Ag

Layer	Fe	Cr	Mo	Si	Pu	U	Ce	Nd	La	Other
1	41	–	–	2	15	–	10	21	4	7Pd
1	66	2	–	7	22	–	2	2	2	1Ni, 1Ba
1	55	14	0.4	2	3	1	7	15	2	0.4Ni
2	–	28	1	–	5	4	15	39	6	–
3	37	39	2	2	8	2	5	3	1	0.5Mn
4	69	17	–	1	0.2	–	5	6	–	1Mn, 0.4Ni

Melting Experiments

- One potentially significant impact that the presence of FCCI zones is the melting of phases inside the cladding
- This will limit the allowable coolant temperature that can be used for the reactor, but it can become more important when considering transients and accidents
- This illustrates the effect of the relatively low quantities of Fe required to cause melting on the uranium-rich side of the U–Fe phase diagram
- In general, no liquid phase formation is observed below heating at 700C

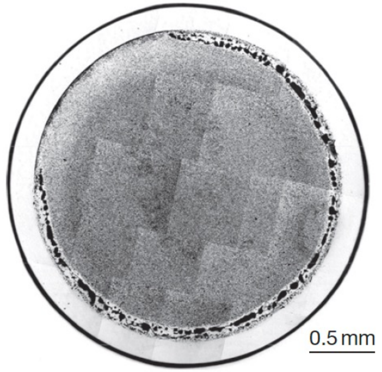


Figure 11 FBTA test result showing an HT-9 clad U–10 wt% Zr fuel pin segment (~3 at.% BU) after being heated at 750 °C for 1 h.

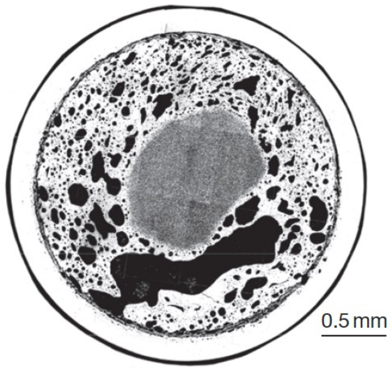
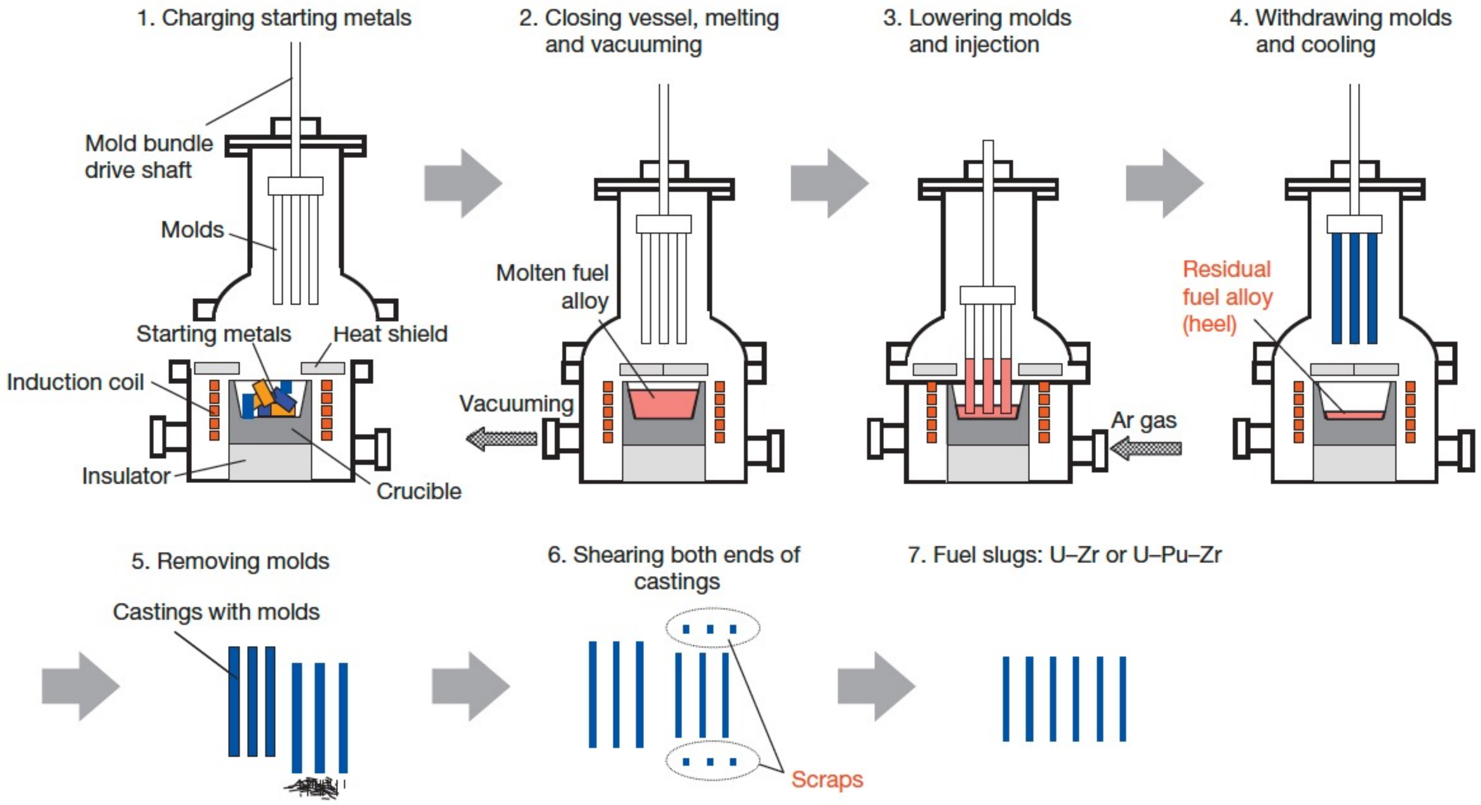


Figure 12 FBTA test result showing an HT-9 clad U–10 wt% Zr fuel pin segment (~3 at.% BU) after being heated at 800 °C for 1 h. Note that all but the fuel center has been at least partially melted, and the cladding has not been fully penetrated.

METAL FUEL FABRICATION

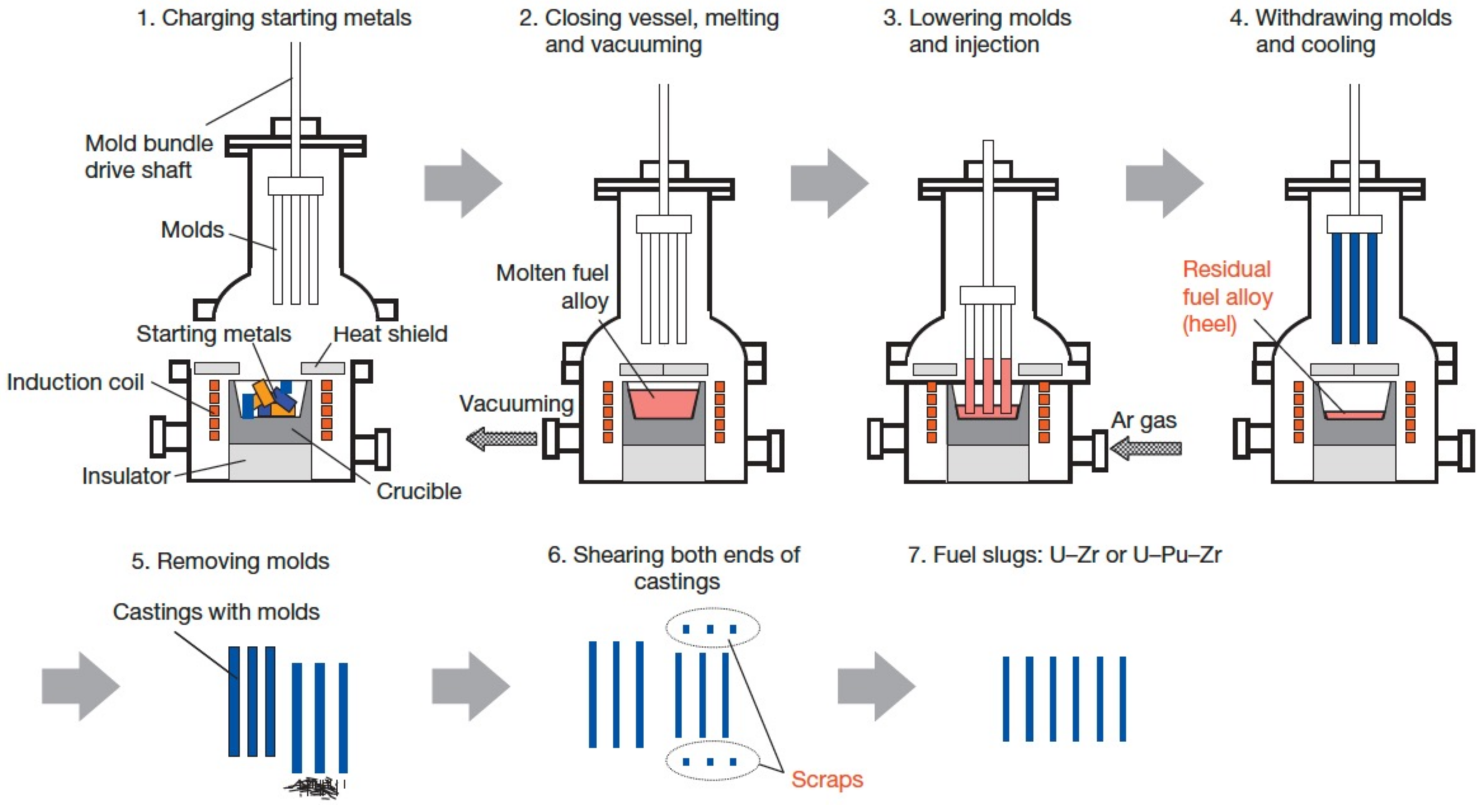
Metal Fuel Fabrication

- Injection casting has been utilized for fuel slug fabrication
- Remote fabrication has been performed inside a hot cell on recovered uranium
- Fuel slugs for EBR II and FFTF were fabrication via injection casting



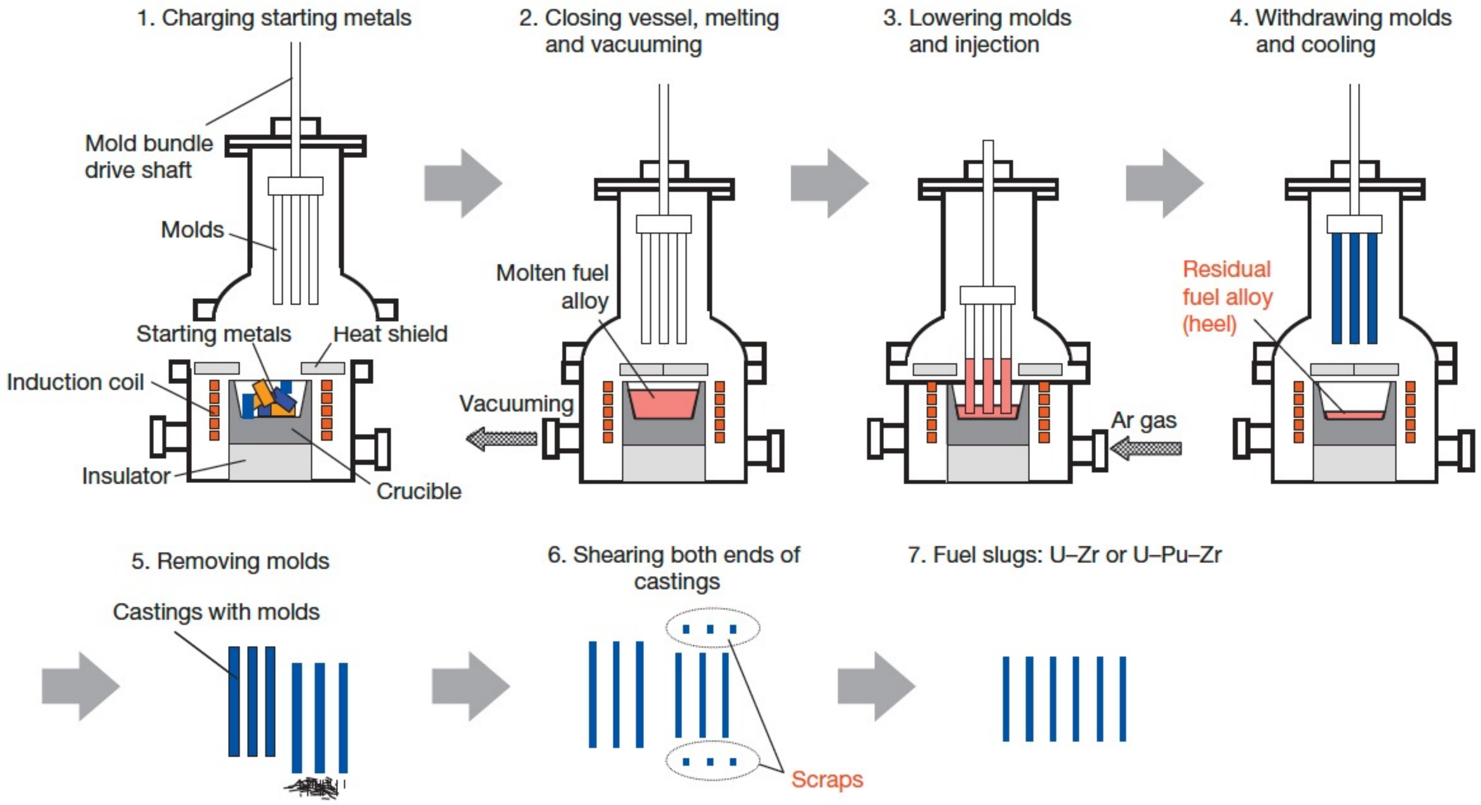
Metal Fuel Fabrication

- Starting materials are charged into the graphite crucible in the furnace
- Silica molds with tops closed are set above the crucible
- Crucible is coated with yttria
- Molds coated with zirconia



Metal Fuel Fabrication

- Furnace closed and filled with Ar gas
- Crucible is inductively heated to 1830K, and stirred electromagnetically
- Ar gas removed, molds are lowered, then Ar gas returned
- Pressure difference injects the melt into the molds



QUESTIONS?