

# **Overview of Pyroprocessing**

#### March 2024

Guy L Fredrickson





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#### **Overview of Pyroprocessing**

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March 2024

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# **OVERVIEW OF SPENT FUEL TREATMENT**

(ELECTROCHEMICAL SEPARATIONS)

BRIGHAM YOUNG UNIVERSITY

AMERICAN NUCLEAR SOCIETY MEETING

Export Control Review: INL/CON-24-76889



#### **Outline**

# Please Ask Questions at Any Time

- Copper Electrorefining (Analogy)
- Fission Yield
- Experimental Breeder Reactor II
- Uranium Electrorefining

# **Copper Electrorefining**

#### Smelting of Copper Sulfide Ores



150 to 400 kg No Industry Standard



#### Casting Impure Cu Anodes



# **Copper Electrorefining**

 $Cu_{(impure\ Cu)} = Cu^{+2} + 2e^{-}$ Oxidation at the Anode

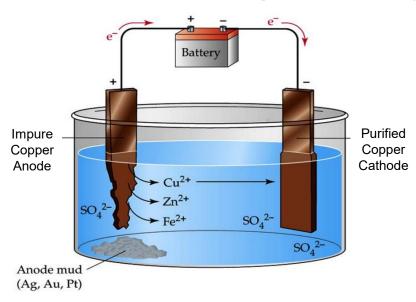


 $Cu^{+2} + 2e^{-} = Cu_{(purified\ Cu)}$ Reduction at the Cathode



# **Electrorefining Comparison**

#### Cu Electrorefining Chemistry U Electrorefining Chemistry



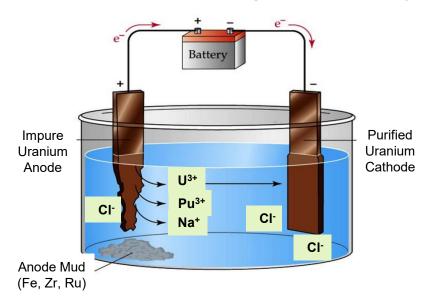
 $98-99\% \text{ Cu} \rightarrow 99.95\% \text{ Cu}$ 

Media: Aqueous Sulfuric Acid Solution

Temperature: 50 to 60°C Density: 1.1 to 1.3 g cm<sup>-3</sup>

Color: Clear

Dynamic Viscosity: 1.2 mPa·s



 $80-90\% U \rightarrow 99.99\% U$ 

Media: LiCl-KCl Eutectic Salt

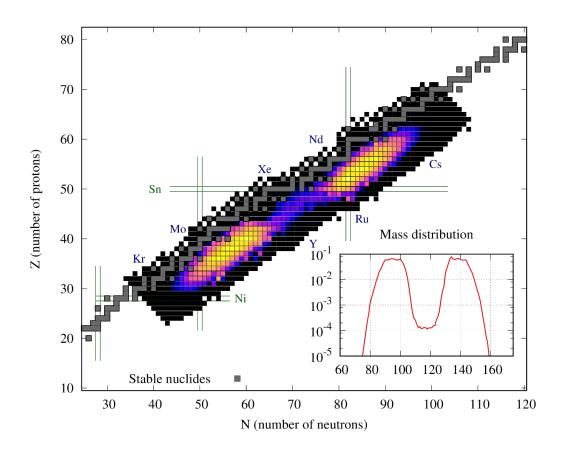
Temperature: 500°C

Density: 1.6 to 1.8 g cm<sup>-3</sup>

Color: Clear

Dynamic Viscosity: 2.2 mPa·s

#### **Fission Yield**



1 kg d<sup>-1</sup> fission is approximately 1000 MWt or 400 MWe.

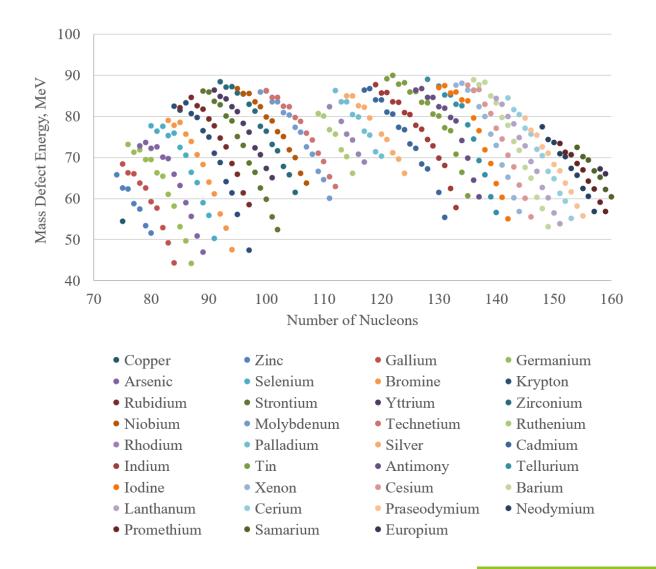
# **Uranium Fission Primary Daughters**

Daughter A	Z	Daughter B	Z
Copper	29	Europium	63
Zinc	30	Samarium	62
Gallium	31	Promethium	61
Germanium	32	Neodymium	60
Arsenic	33	Praseodymium	59
Selenium	34	Cerium	58
Bromine	35	Lanthanum	57
Krypton	36	Barium	56
Rubidium	37	Cesium	55
Strontium	38	Xenon	54
Yttrium	39	lodine	53
Zirconium	40	Tellurium	52
Niobium	41	Antimony	51
Molybdenum	42	Tin	50
Technetium	43	Indium	49
Ruthenium	44	Cadmium	48
Rhodium	45	Silver	47
Palladium	46	Palladium	46

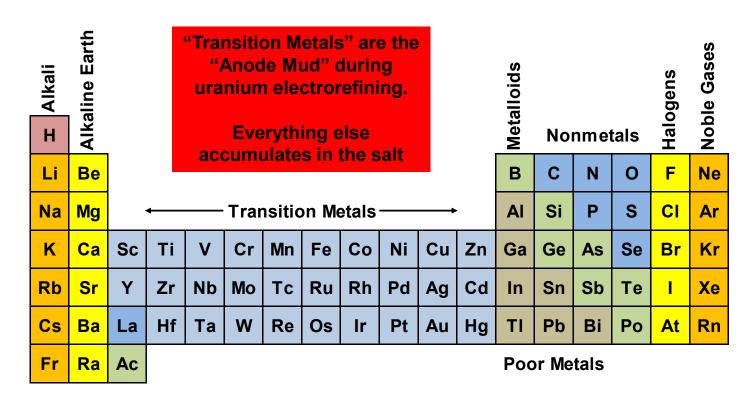
# **Primary Daughter Isotopes**

Н																	Не
Li	Ве											В	С	N	0	F	Ne
Na	Mg											AI	Si	Р	S	CI	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Со	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Мо	Тс	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Те	-	Xe
Cs	Ва	La	Hf	Та	W	Re	Os	Ir	Pt	Au	Hg	TI	Pb	Bi	Ро	At	Rn
Fr	Ra	Ac															
			Се	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

# **Primary Daughter Isotopes**



#### **Electrochemical Behavior of the FPs**

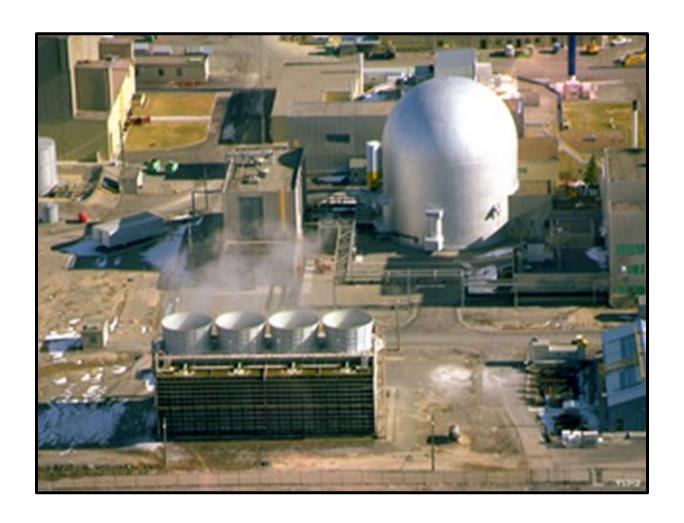


Lanthanides	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb	Lu
Actinides	Th	Ра	C	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
	Transuranics →													

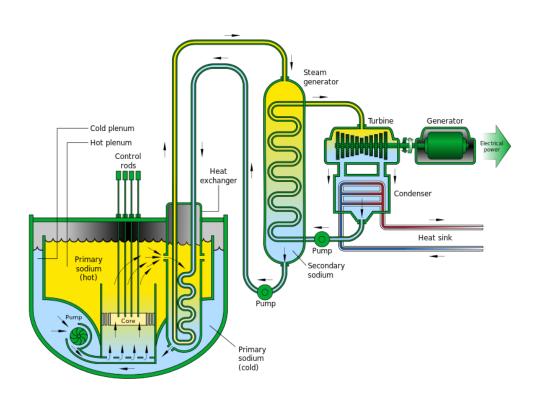
# **Experimental Breeder Reactor II**



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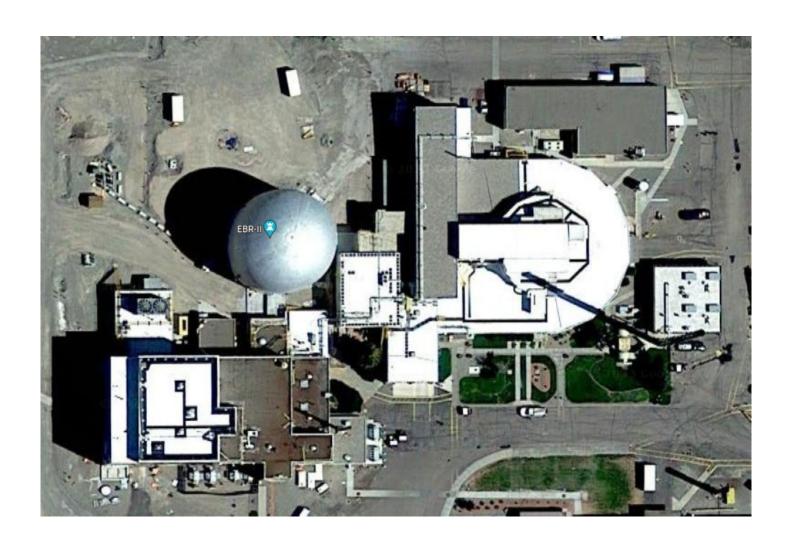
# **Experimental Breeder Reactor II**



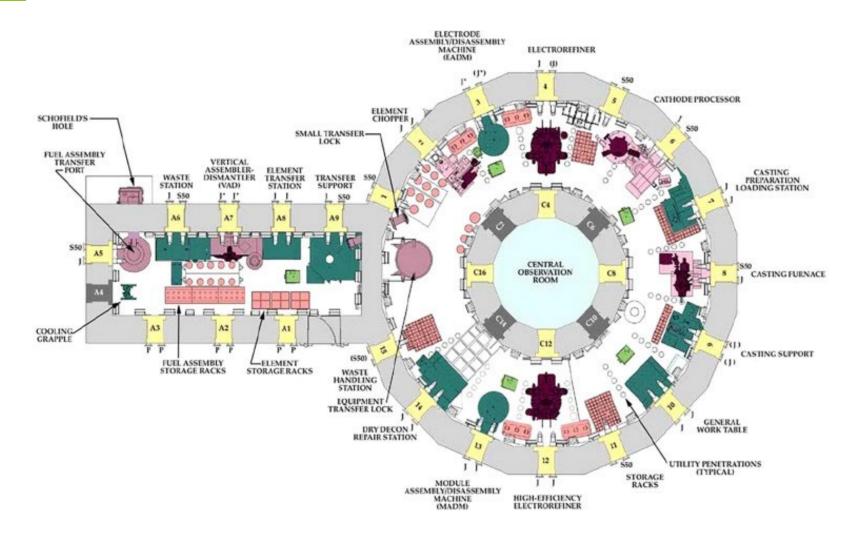


- 637 subassemblies in the core
- 47 to 59 driver fuel subassemblies
- 3 kg enriched uranium per driver fuel subassembly
- 47 kg depleted uranium per blanket subassembly

# **Fuel Conditioning Facility (FCF)**



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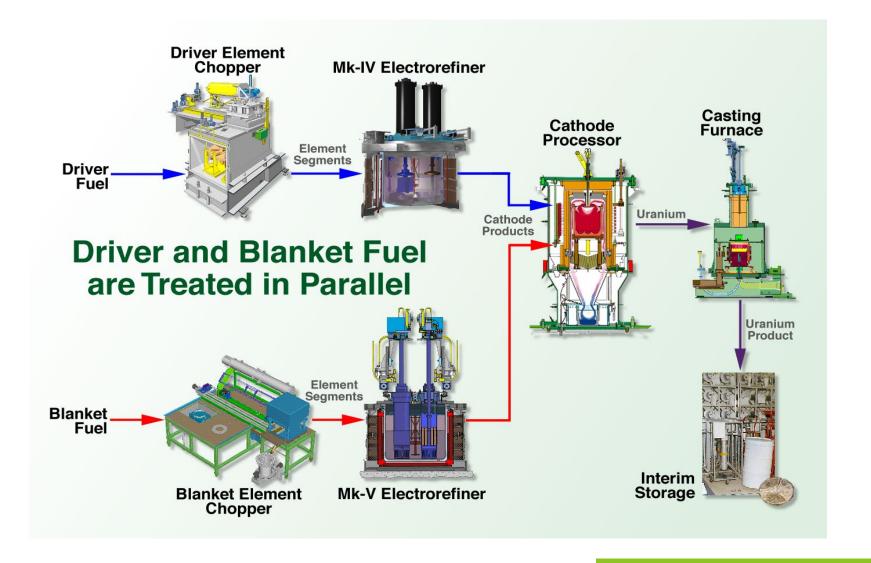


# **Fuel Conditioning Facility (FCF)**

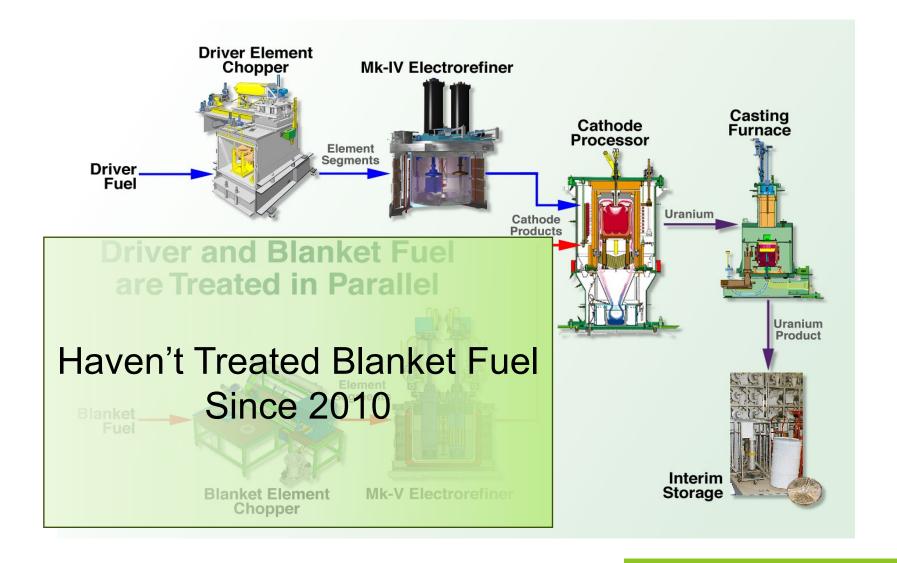




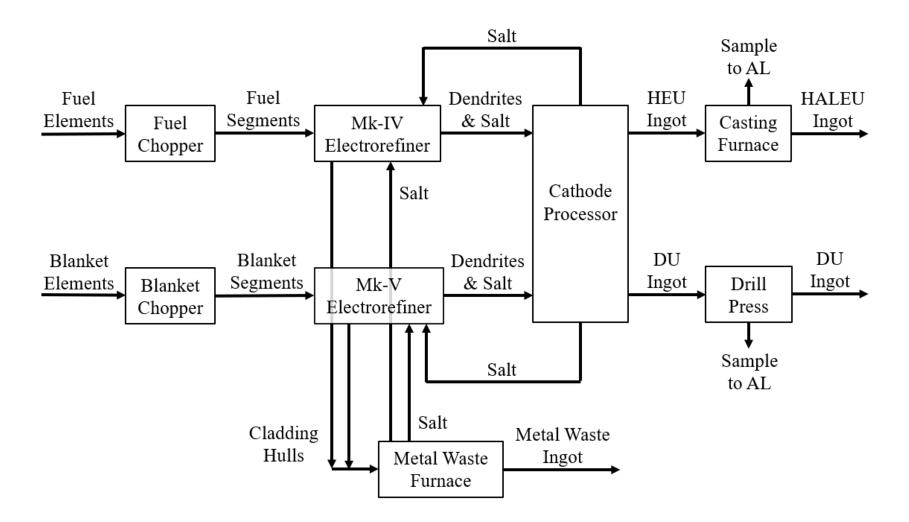
# **Spent Fuel Treatment at FCF**



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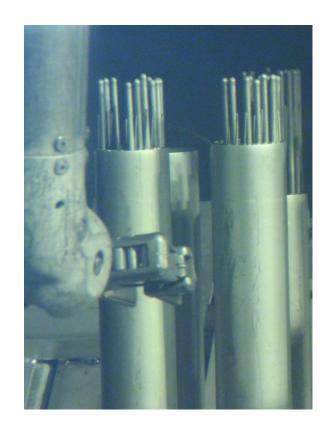


# **Spent Fuel Treatment at FCF**

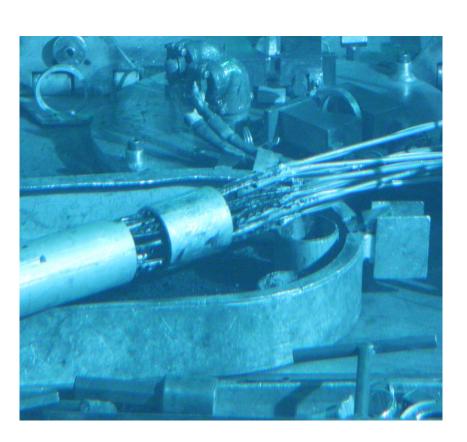


- Shipped 1/78 to 1/91
- 3644 Bottles Remained
- CPP-666 Water Pool
- Some Corroded Fuel

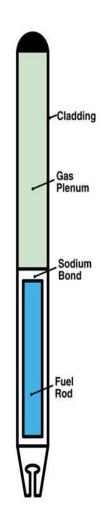




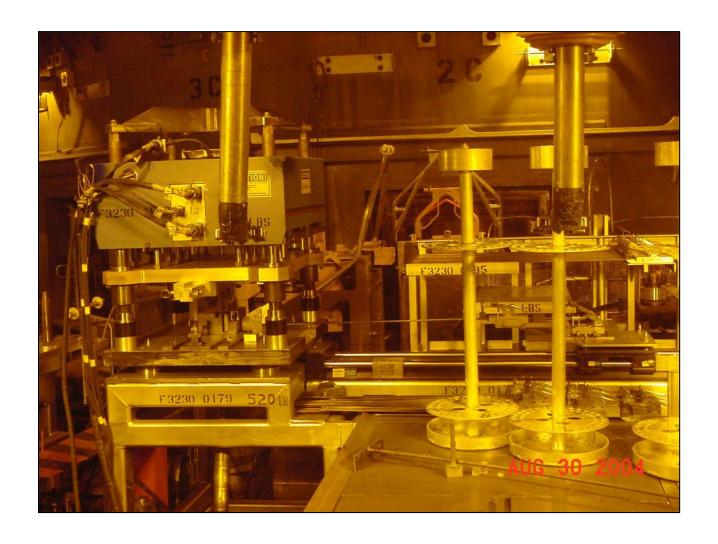
**Pristine Fuel** 



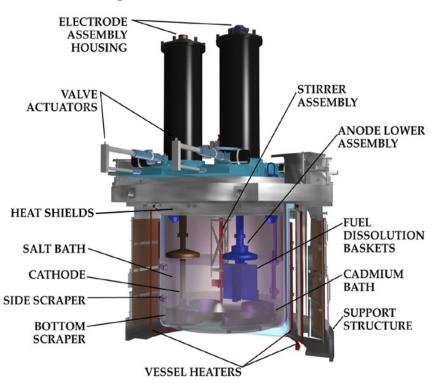
**Corroded Fuel** 

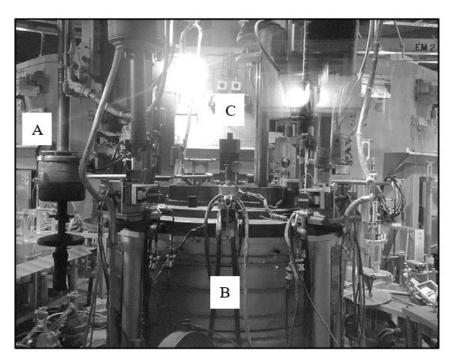






#### Designed for Driver Fuel





63% 235U



**Driver Anode Basket** (DAB)

0.2% 235U



Ingot Dissolution Container Solid Cathode Mandrel (IDC)

42% 235U

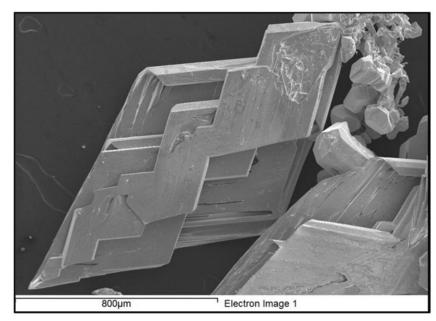


(SCM)

## Mk-IV Cathode Deposit



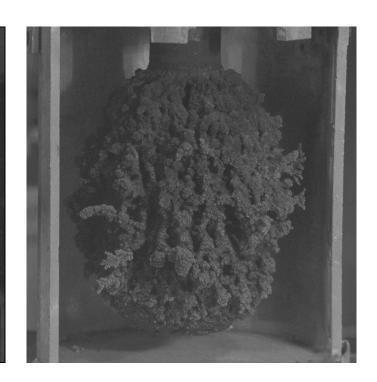




16% Salt







**Bare SCM** 

Clean Uranium

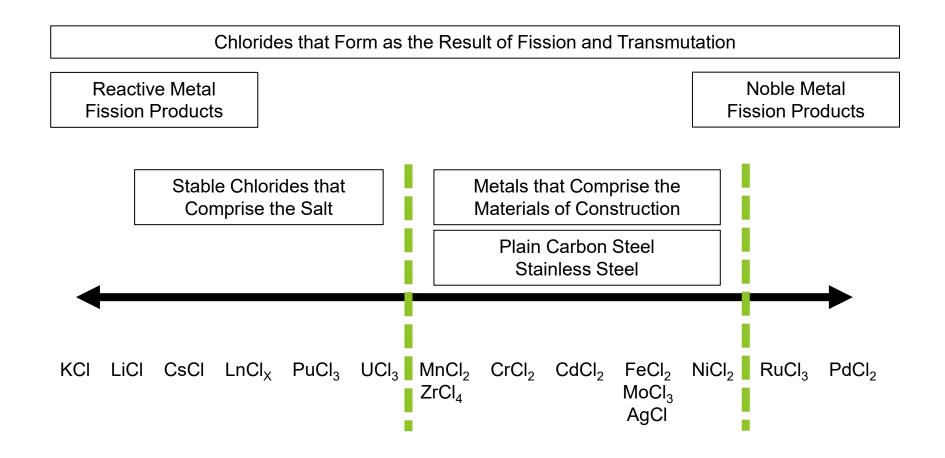
Codeposit of Uranium and Zirconium

# **Salt Distillation from Cladding Hulls**





# **Chemical Separations**



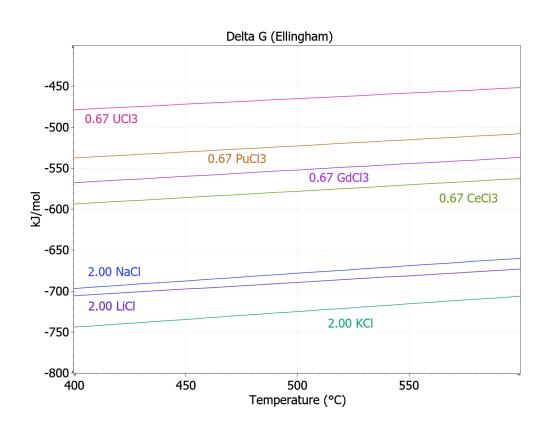
# **Chemical Separations**

#### **Exchange Reactions:**

$$3 \text{ Na} + \text{UCl}_3 = \text{U} + 3 \text{ NaCl}$$

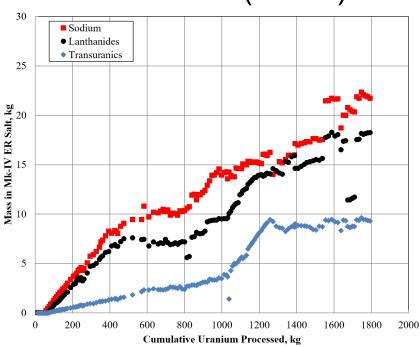
$$Ln + UCl_3 = U + LnCl_3$$

$$Pu + UCl_3 = U + PuCl_3$$

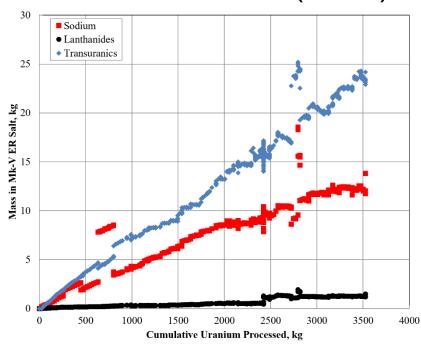


## **Accumulation in the Salt Phase**

#### Driver Fuel (Mk-IV)

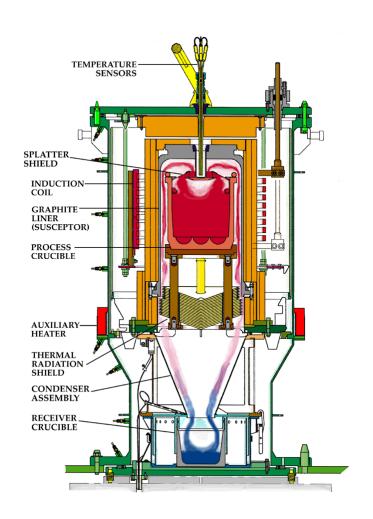


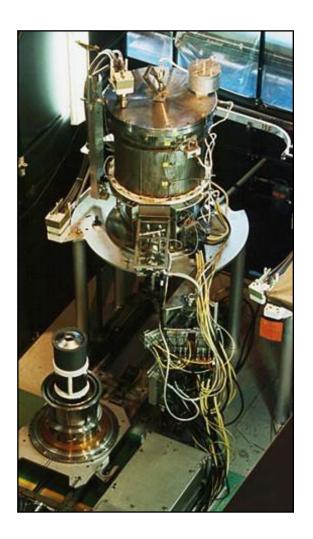
#### Blanket Material (Mk-V)



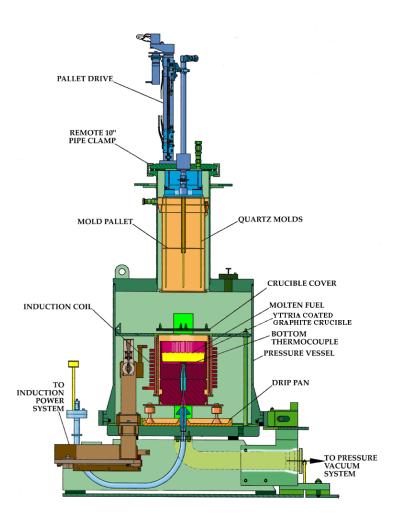
Isotope	Mk-IV wt%	Mk-V wt%				
235U	41.7	0.2				
<sup>239</sup> Pu	97.3	97.9				

## **Cathode Processor**





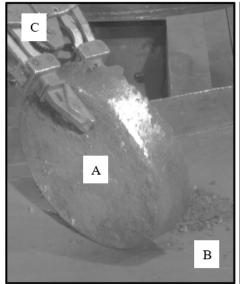
# **Casting Furnace**





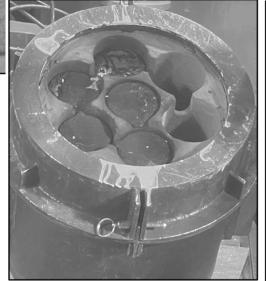
#### **Cast Electrorefined Uranium**

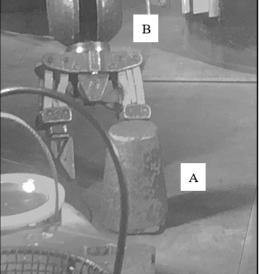
HALEU Ingots (25 to 50 kg)



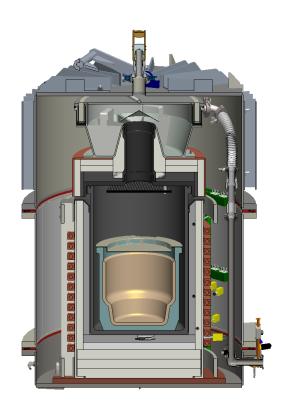


HALEU Reguli (3 kg)

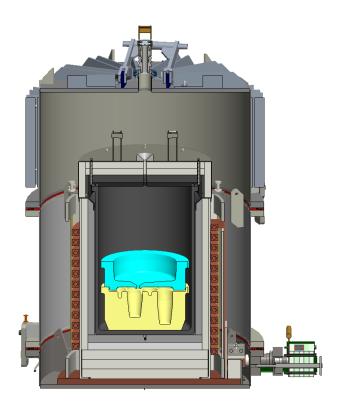




#### The "New" Multi-Function Furnace

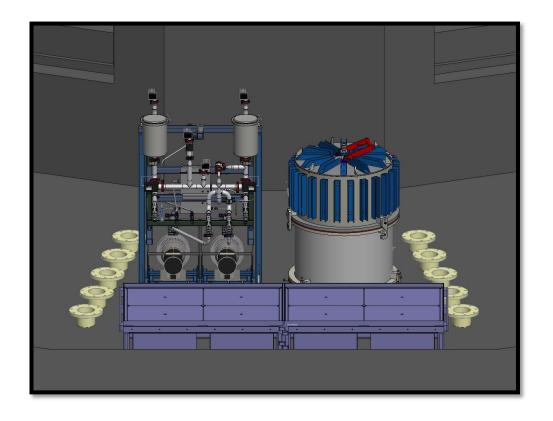


**Distillation Configuration** 



**Casting Configuration** 

## **Design Phase (1 of 5)**



The multi-function furnace was designed using computer aided design and thermal modeling software.

#### **Phase I (2 of 5)**



Includes assembly and testing. Fit-up and functionality were tested and refined in a non-radiological facility.

# **Phase II-A (3 of 5)**



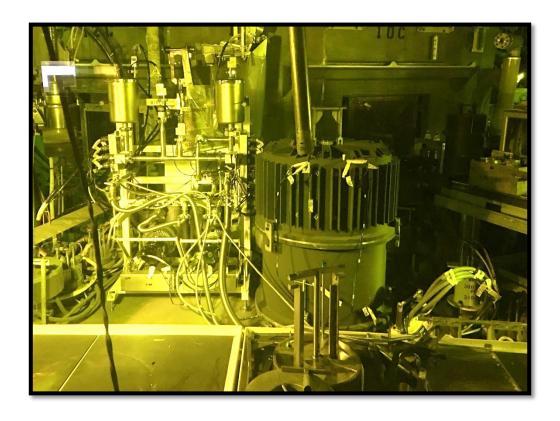
Surrogate materials including depleted uranium were used to validate the functionality in a radiological facility.

# Phase II-B (4 of 5)



Remote operability was tested to ensure that the telemanipulators could perform the necessary operations.

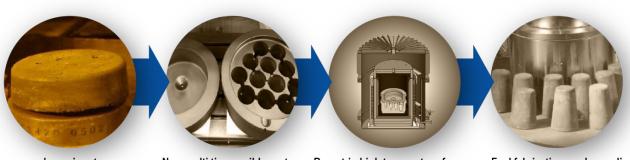
## Phase III (5 of 5)



Installation and acceptance testing in the hot cell. Documented operator instructions prepared.

## **HALEU** "Pyro Polishing"

- Uranium recovered from treatment process originally intended for remote fuel fabrication equipment.
- Expanding reuse applications for advanced reactors led to process treatment innovations.
- Uranium casting revision resulted in reduced radiological dose and smaller physical size.
- HALEU metal regulus suitable for glovebox fuel fabrication for advanced reactors.



Large ingot Diameter = 20 cm Thickness = 2.5 - 7.5 cm Weight = 30 - 40 kg

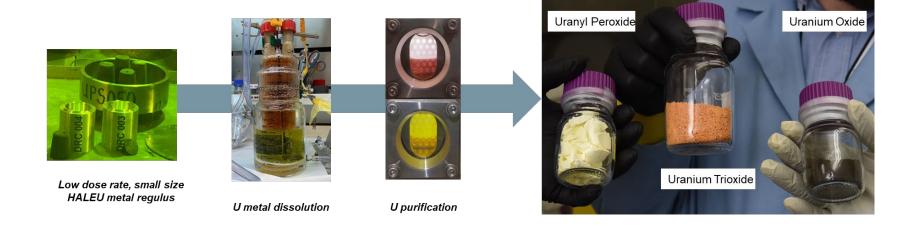
New multi tier crucible system Recast in high temperature furnace Converts the large ingot into fuel fabrication-ready reguli

Multi tier crucible used to recast ingot into reguli Fuel fabrication-ready reguli Diameter = 6 - 8 cm Height = 9 - 11 cm Weight = 3 - 7 kg

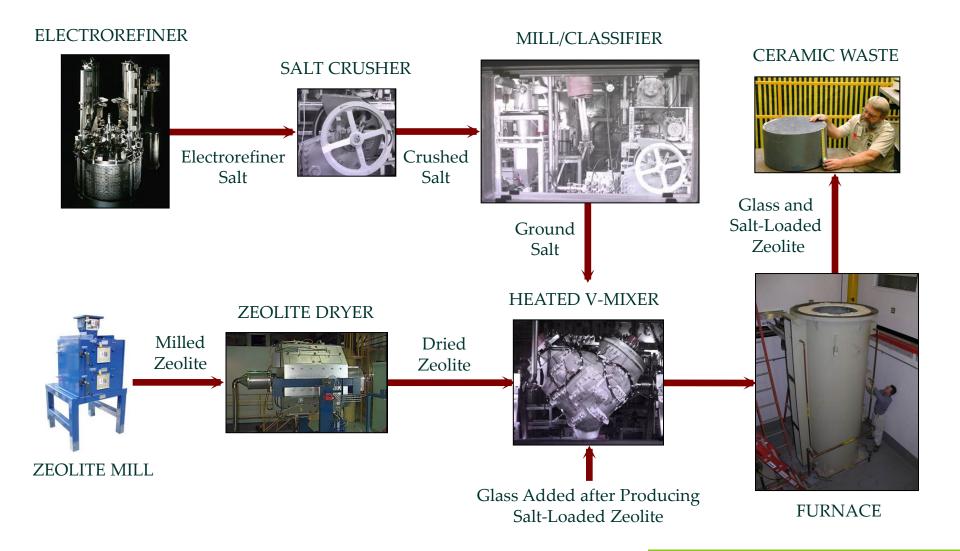


#### **HALEU** "Aqueous Polishing"

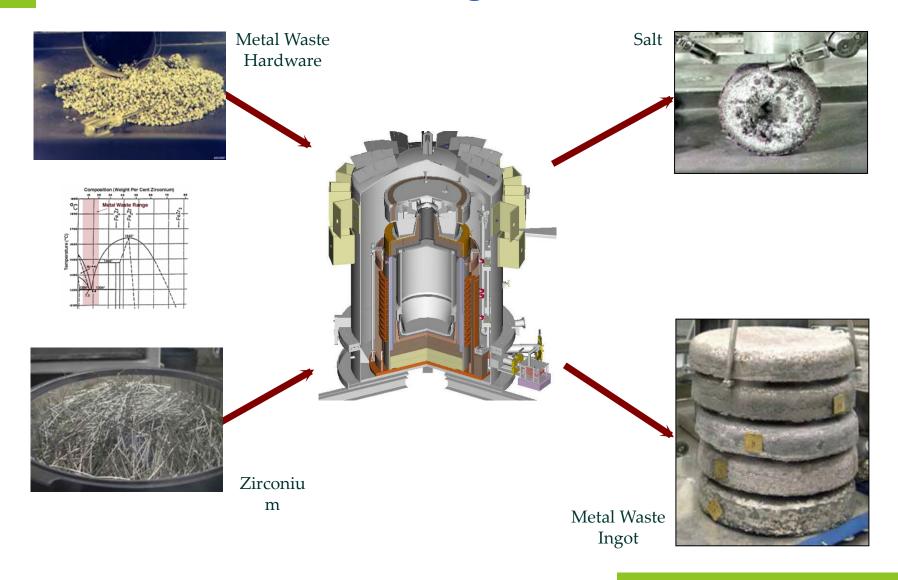
- Aqueous chemistry process converts HALEU metal to HALEU oxide.
- Removes additional contaminations which significantly reduces dose and transuranic content.
- Material can be suitable for oxide-fuel advanced reactors.



#### **Salt Waste Processing**



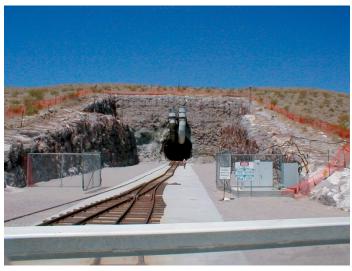
# **Metal Waste Processing**

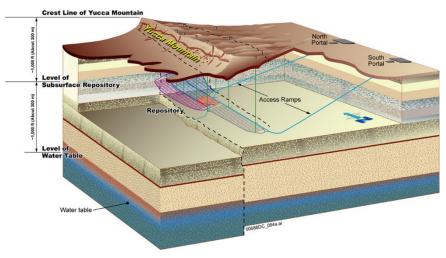


# **Yucca Mountain Nuclear Waste Repository**









#### References

- G.L. Fredrickson, T.S. Yoo, "Review Nuclear Fuels and Reprocessing Technologies: A U.S. Perspective", Idaho National Laboratory, INL/EXT-20-59106, March 2021
- G.L. Fredrickson, M.N. Patterson, D. Vaden, G.G. Galbreth, T.S. Yoo, J.C. Price, E.J. Flynn, R.N. Searle, "History and Status of Spent Fuel Treatment at the INL Fuel Conditioning Facility", Progress in Nuclear Energy, 143 (2022) 104037



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