MIT Fission and Fusion Salt Activities: From Theory to Integral Experiments

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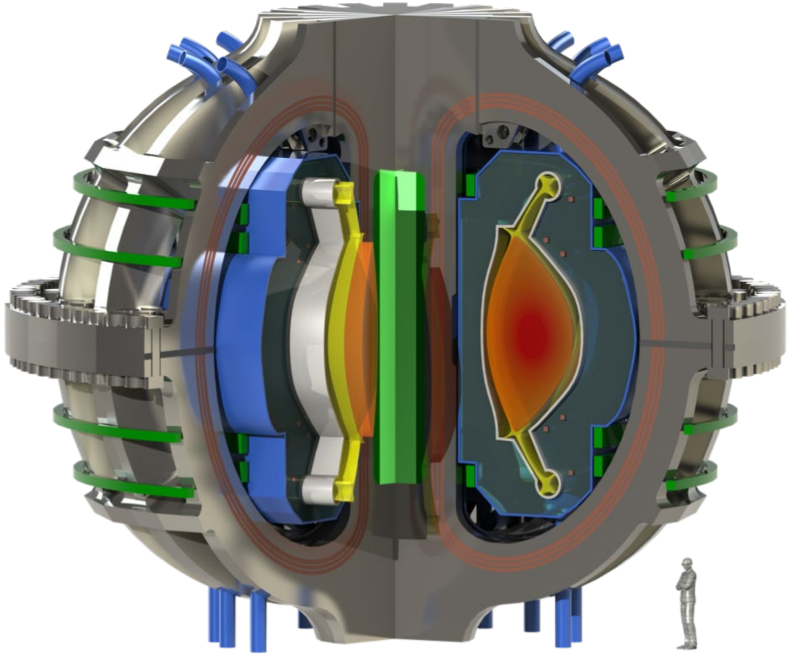
Session: 1:10 PM on October 14
ORNL Molten Salt Workshop
October 14-15, 2020

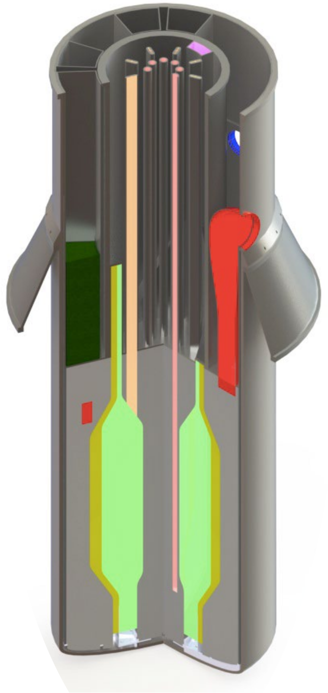
Multiple Markets for Salt Technologies

MIT is Working on Fission and Fusion Applications

All Salt Reactor Concepts Have Much in Common



Commonwealth Fusion ARC



Kairos Power FHR

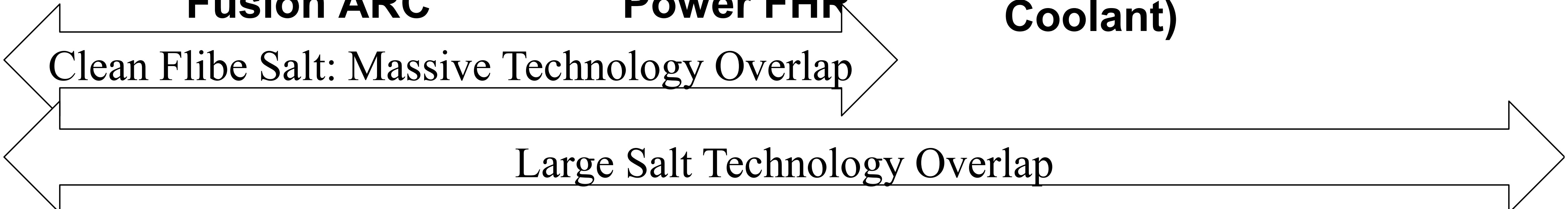
MSR (Fuel in Fluoride Salt)

Molten Fluoride Salt Fast Reactor

Moltex (Chloride Salt in pins, Fluoride Salt Coolant)

Molten Chloride Fast Reactor

Gen III Chloride Salt Concentrated Solar Power



Clean Flibe Salt: Massive Technology Overlap

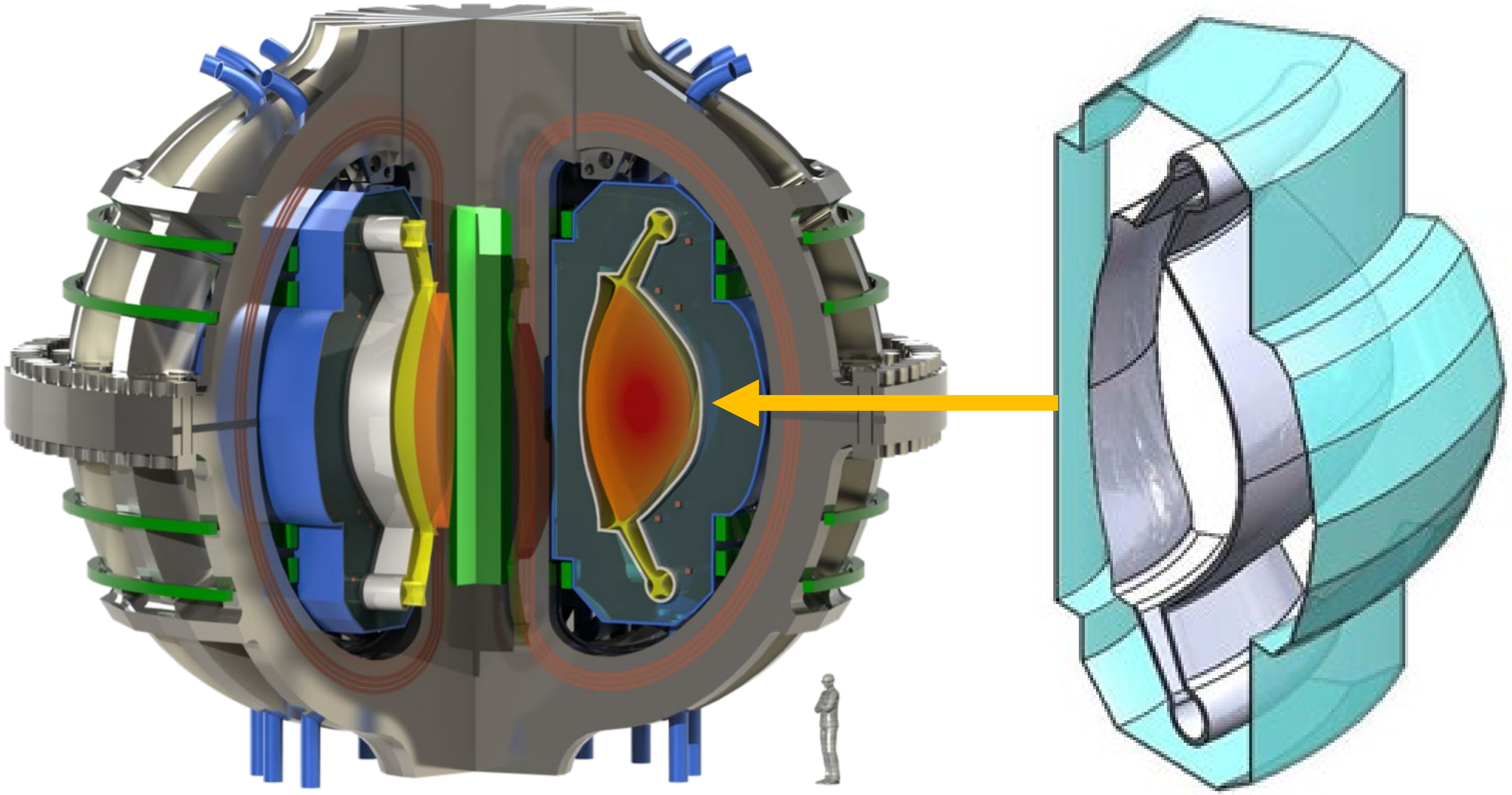
Large Salt Technology Overlap

Fusion Reactors Developing Liquid-Salt Blankets

- Methods have been developed to manufacture REBCO superconducting tape that enables doubling magnetic fields
- **Size of magnetic fusion system for any given power output varies as *one over the fourth power of the magnetic field***
- Higher magnetic fields can shrink fusion system size by an order of magnitude with massive cost savings

- **Power density in the fusion blanket increases by an order of magnitude creating incentive for liquid flibe salt blanket that is coolable, solid blankets may melt**

ARC Fusion with Liquid Flibe Salt Blanket

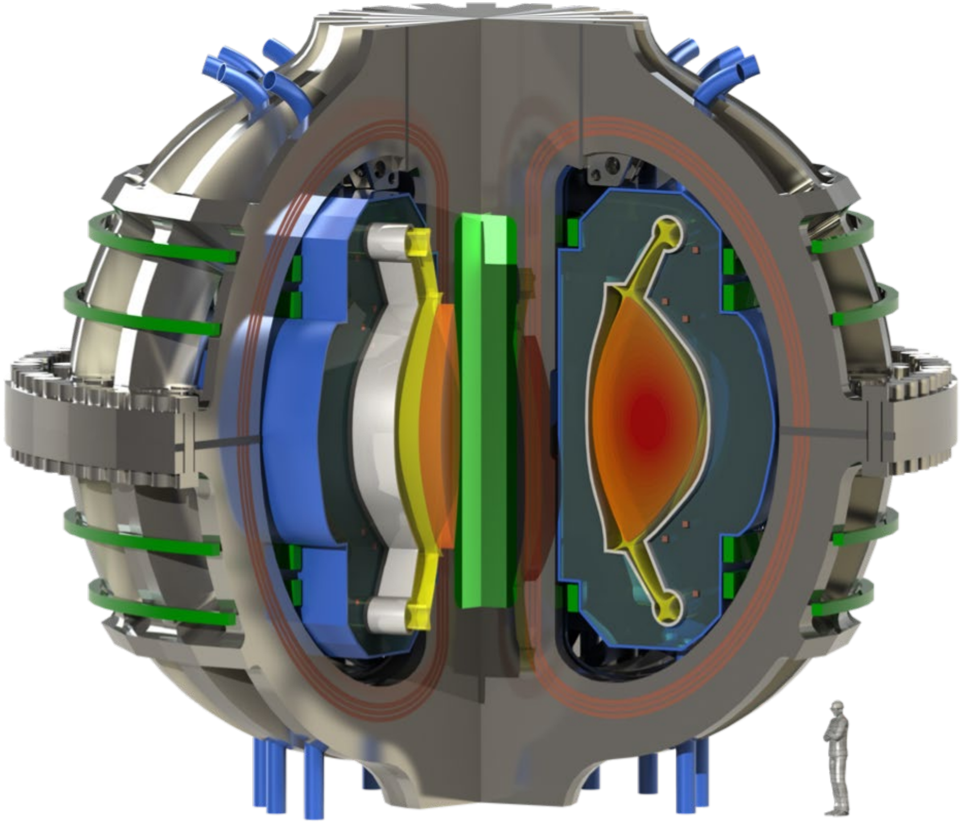


- Breed tritium fusion fuel from lithium in salt
- Convert energy in 14-Mev neutrons to heat for power cycle
- Radiation Shielding

ARC **Flibe Salt Blanket**

Liquid Blanket Minimizes Tritium Inventory Relative to Solid Blanket Reducing Accident Source Term, Safety System Costs and Siting Constraints

MIT ARC Fusion Concept Lead to Commonwealth Fusion: A New Startup Company from the MIT NSE Department



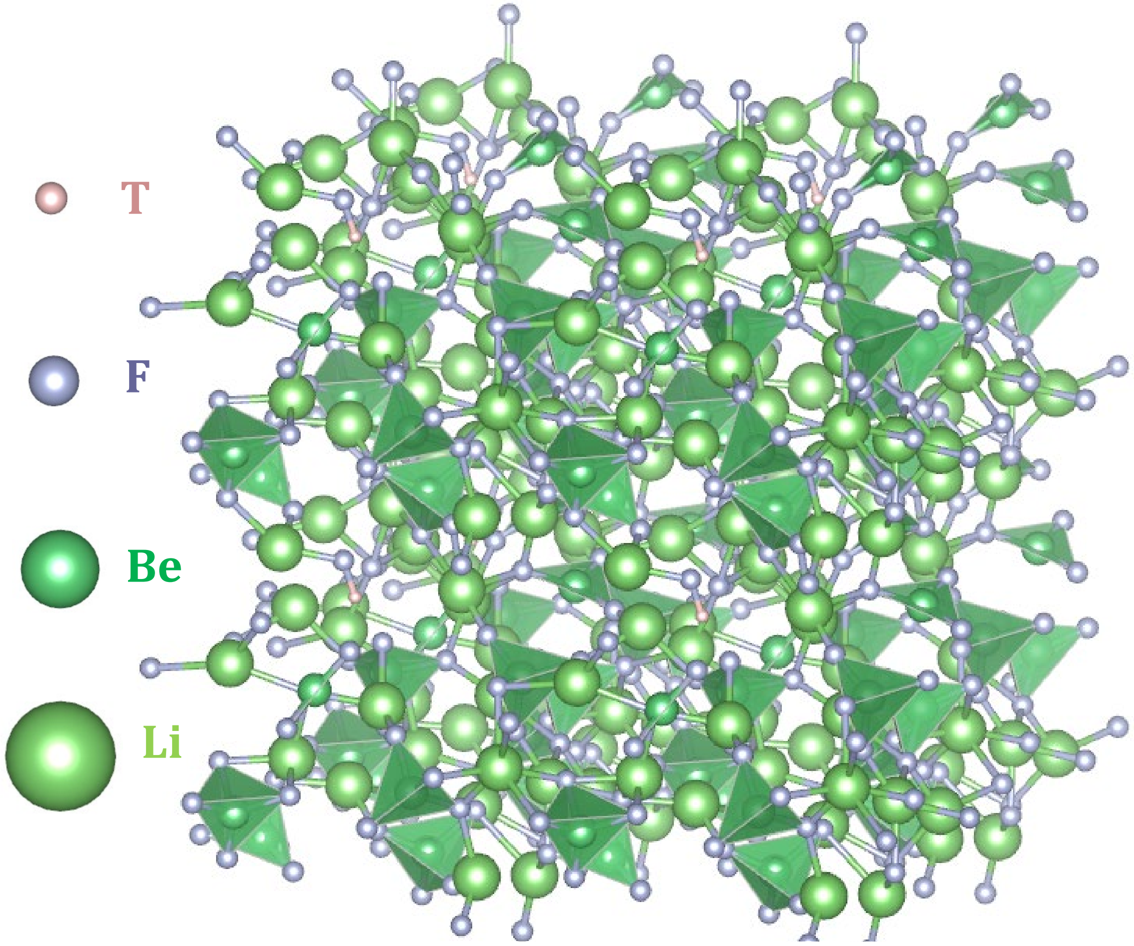
- Initial private funding > $ 100 million
- Three stage development
  - Large magnet development and demonstration: 3 years
  - Sparc: fusion physics demo following five years
  - ARC with flibe blanket
- **Massive technology overlap with all salt systems: fission and fusion**

C. Forsberg et. a., “Fusion Blankets and Fluoride-salt-cooled High-Temperature Reactors with Flibe Salt Coolant: Common Challenges, Tritium Control, and Opportunities for Synergistic Development Strategies between Fission, Fusion and Solar Salt Technologies”, *Nuclear Technology* (Published on line Dec 2019) https://doi.org/10.1080/00295450.2019.1691400

MIT Theory and Individual Effects Experiments on Salts

Recent Advances in First Principle Calculations Enable Prediction of Salt Properties

- Predict density, bulk modulus, expansion coefficient, diffusion.
- Accurately predict structure and chemistry including structure property relationship of tritium in flibe and flinak
- Developed fast robust neural network interatomic potential for Flibe and other salts in a variety of conditions and atomic configurations

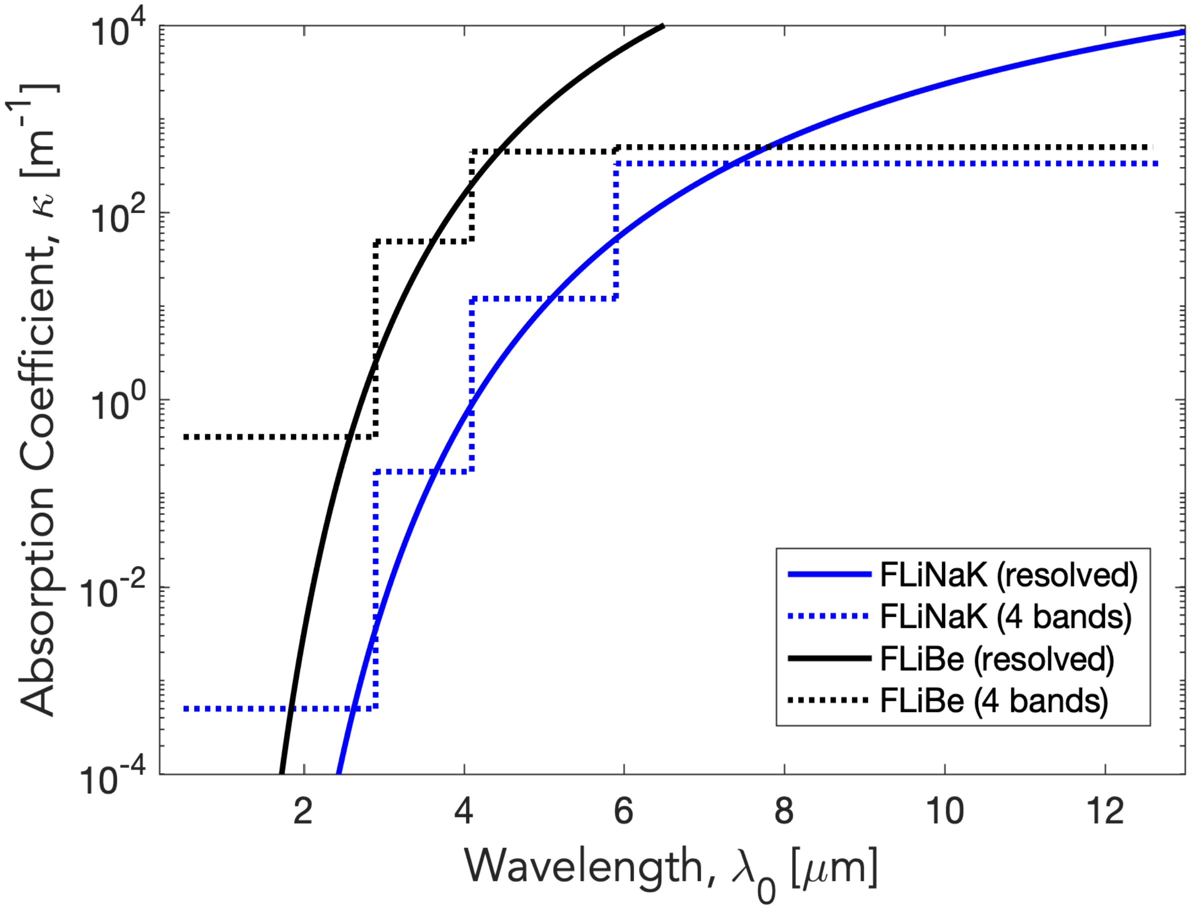


$LiF\text{-}BeF_2 + TF / T_2$

S. Lam, Accelerated Atomistic prediction of structure, dynamics and material properties in molten salts, MIT PhD Thesis, 2020

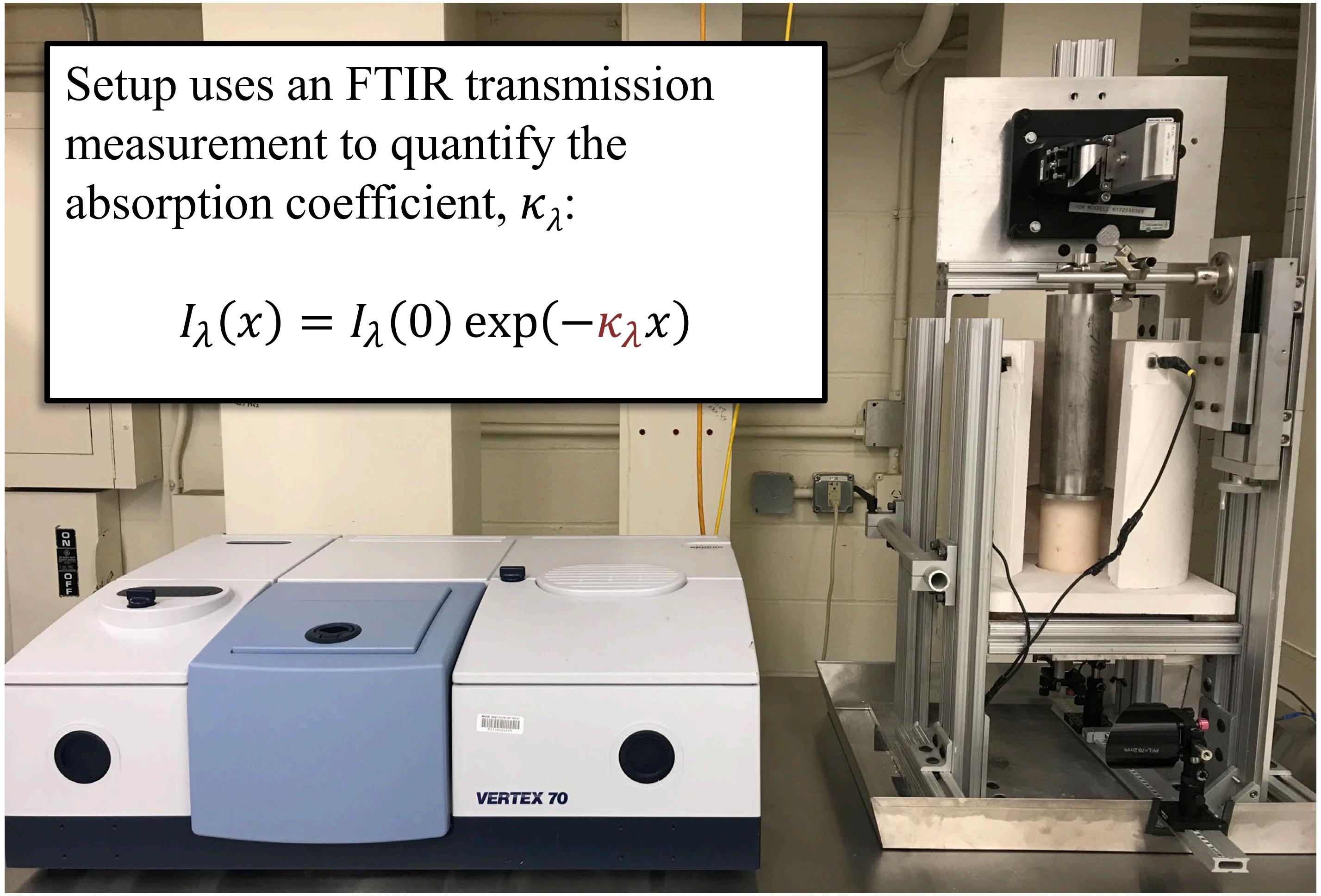
MIT has Developed Better Computational Fluid Dynamic Design Tools to Enable Efficient Calculation of Radiative Heat Transfer

- Salts are semi-transparent
- Radiative heat transport becomes an important heat transfer mechanism between 600 and 700°C because it increases as the temperature to the forth power
- High cost to accurately calculate heat transfer
- Developed improved CFD methodology



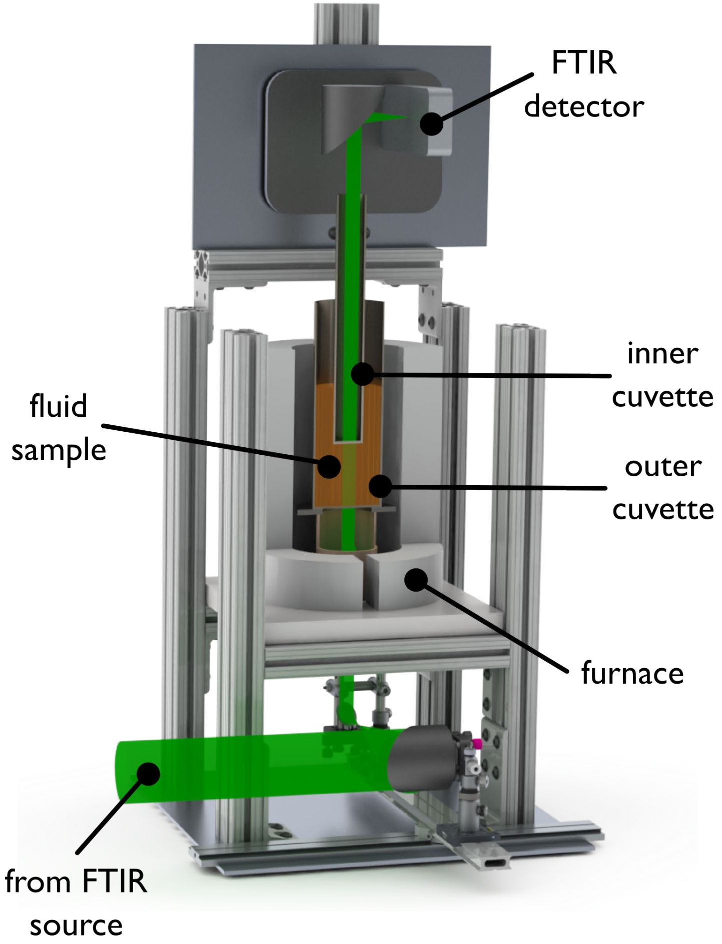
C. Coyle et al., "Advancing Radiative Heat Transfer Modeling in High-Temperature Liquid Salts", Nuclear Science and Engineering, 782-792, 13 March 2020 (on line) https://doi.org/10.1080/00295639.2020.17239

An Experimental Apparatus Has Been Designed to Measure High-resolution Optical Property Data for CFD Model Input



Setup uses an FTIR transmission measurement to quantify the absorption coefficient, κ_λ:

$$I_\lambda(x) = I_\lambda(0)\exp(-\kappa_\lambda x)$$

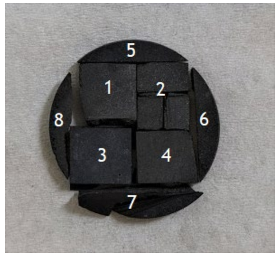


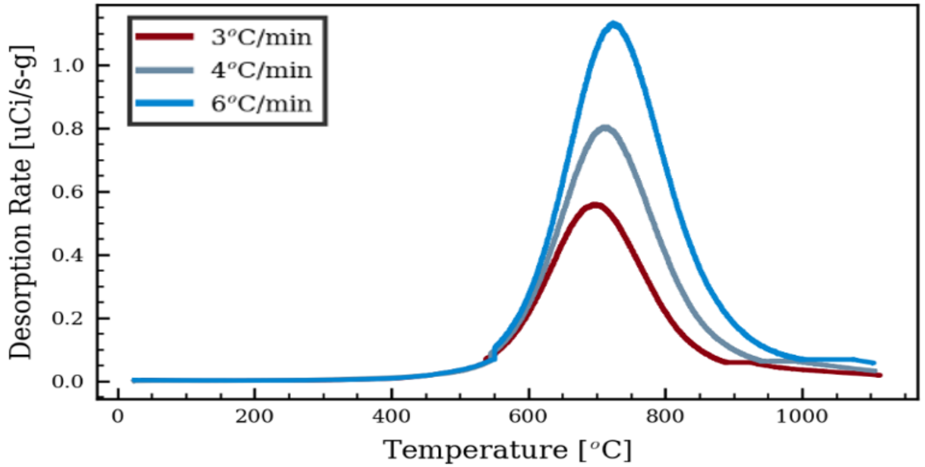
MIT Has (1) Irradiated Graphite In Flibe Salt, (2) Measured Tritium Distribution in Carbon to Understand Tritium Uptake and (3) Updated Modeling of Tritium In FHRs

- Thermal desorption system designed for tritium analysis of graphites irradiated in Flibe
- Measurements: ^{3}H inventory and desorption vs. temp.; ^{3}H chemical forms; Desorption activation energy; Effect of H_2 in desorption furnace

FS-1

IG-110U Sample





FHR Region	^{3}H Release
Heat Exchanger	53.6%
Core Pebbles	26.3%
Hot Leg	8.9%
Reactor Vessel	4.8%
Cold Leg	4.2%
Reflector	1.9%
Off-Gas	0.3%

- Updated system-level transport model based on TRIDENT (Stempien, MIT 2015)
- Implemented new method for calculating tritium transport and trapping in graphite

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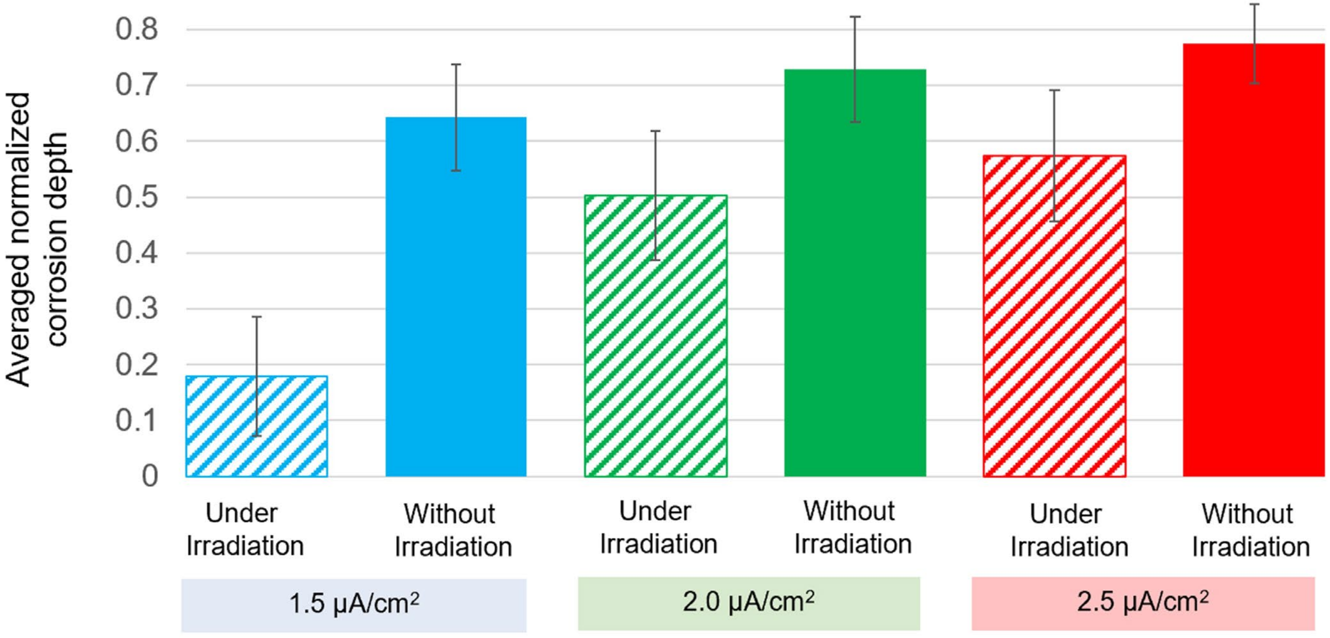
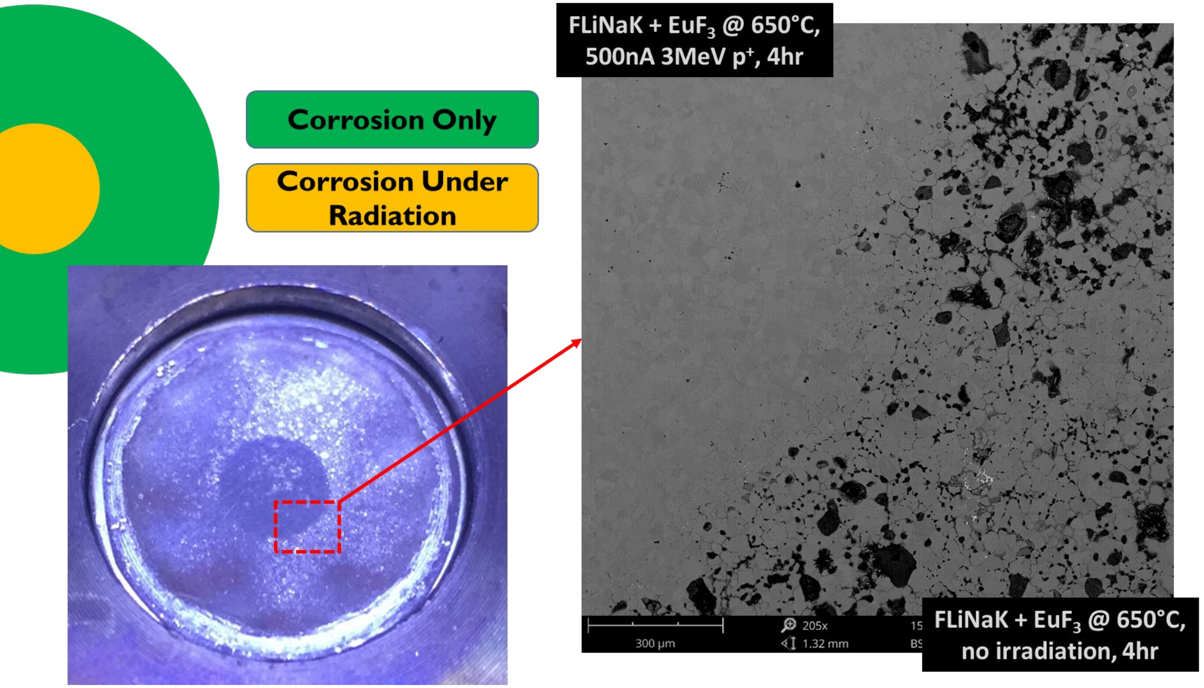
K. Dolan, Tritium Retention in Nuclear Graphite, System-Level Transport, and Management Strategies for the Fluoride-Salt-Cooled High-Temperature Reactor, PhD Thesis, 2020

MIT: Discovery of Irradiation Decelerated Corrosion

- Coupled effects of corrosion and irradiation largely unknown
- Corrosion rates with radiation (stripped) and without irradiation (color)





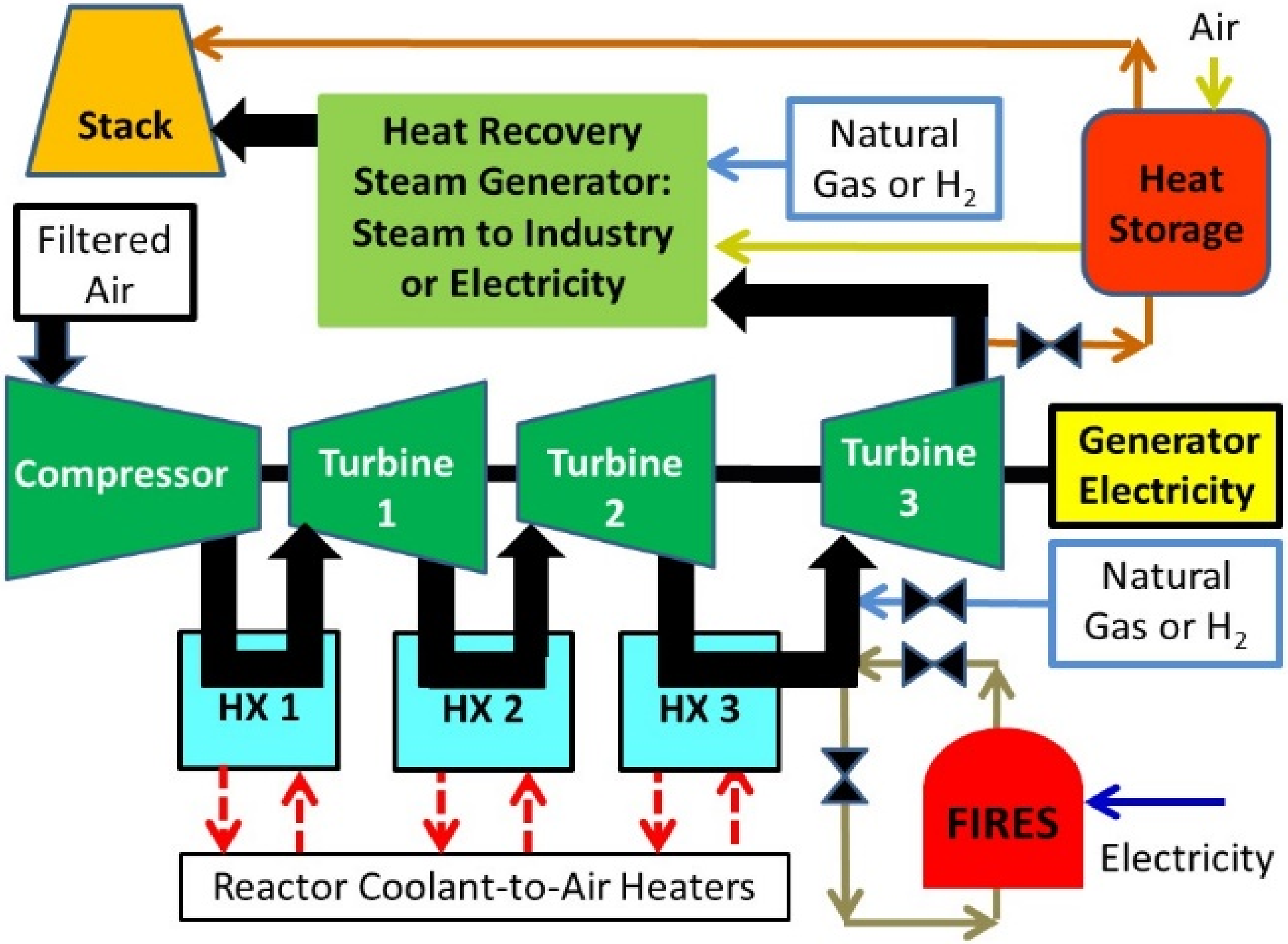
- Prof. Short's group discovered that radiation damage induces *self-healing*, slowing corrosion in molten salts
- Agrees with radiation diffusion theory

Weiyue Zhou et al. *NIMB*, **440**, 54 (2019) Weiyue Zhou et al. *Nat. Commun.*, **11**:3430 (2020).

MIT Systems Studies and Integrate Effects Testing

Developing Power Cycles to Couple to Salt Reactors

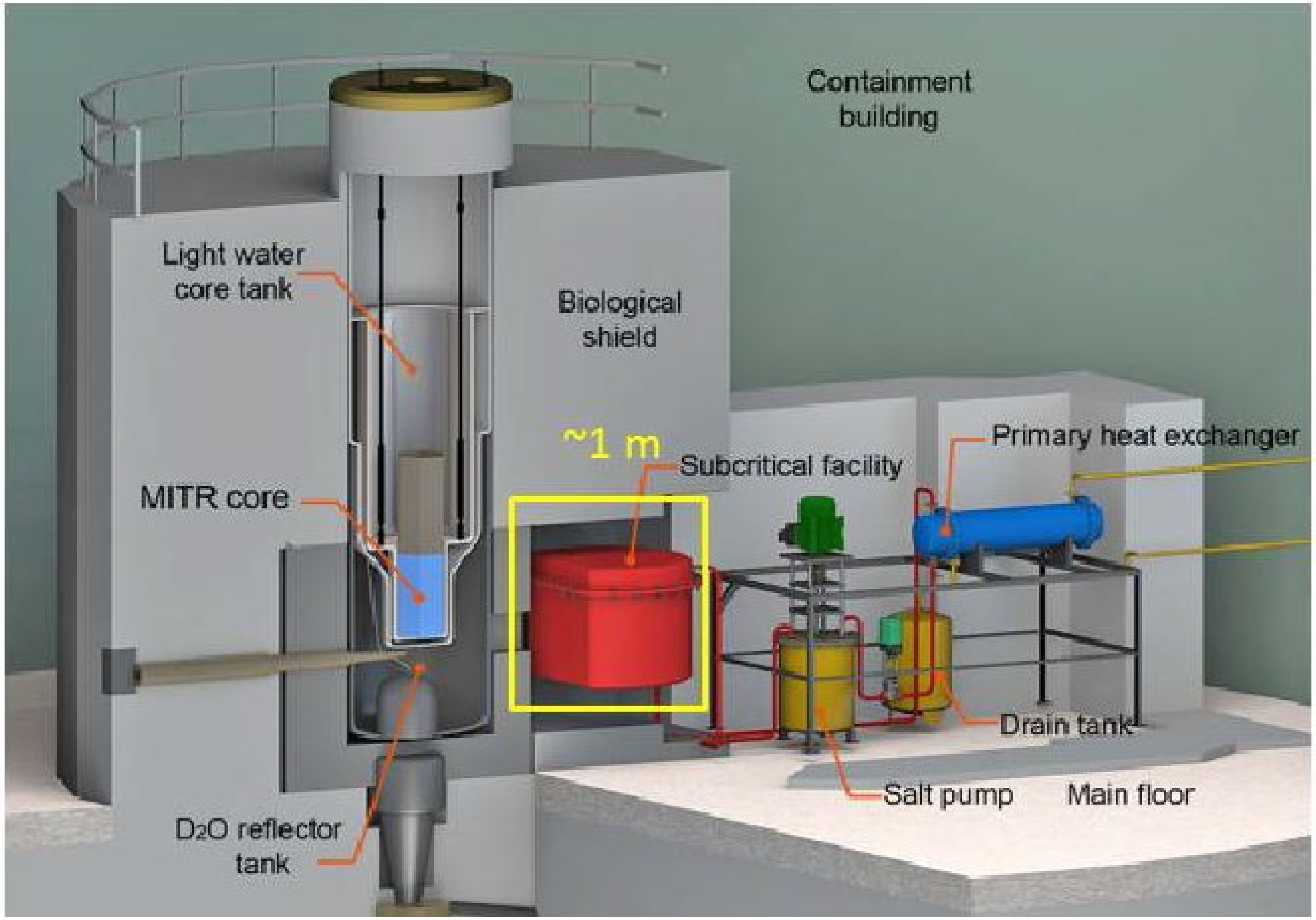
- First MSR (Aircraft Nuclear Propulsion) designed to couple to jet engine
- Nuclear Air-Brayton Cycle (NACC) with heat storage
  - Base-load reactor
  - Variable output to grid to maximize revenue
  - Thermodynamic peaking cycle with combustible fuel to electricity >70% efficient



C. W. Forsberg, P. J. McDaniel, and B. Zohuri, B., 2020. "Nuclear Air-Brayton Power Cycles with Thermodynamic Topping Cycles, Assured Peaking Capacity and Heat Storage for Variable Electricity and Heat," *Nuclear Technology*. https://doi.org/10.1080/00295450.2020.1785793

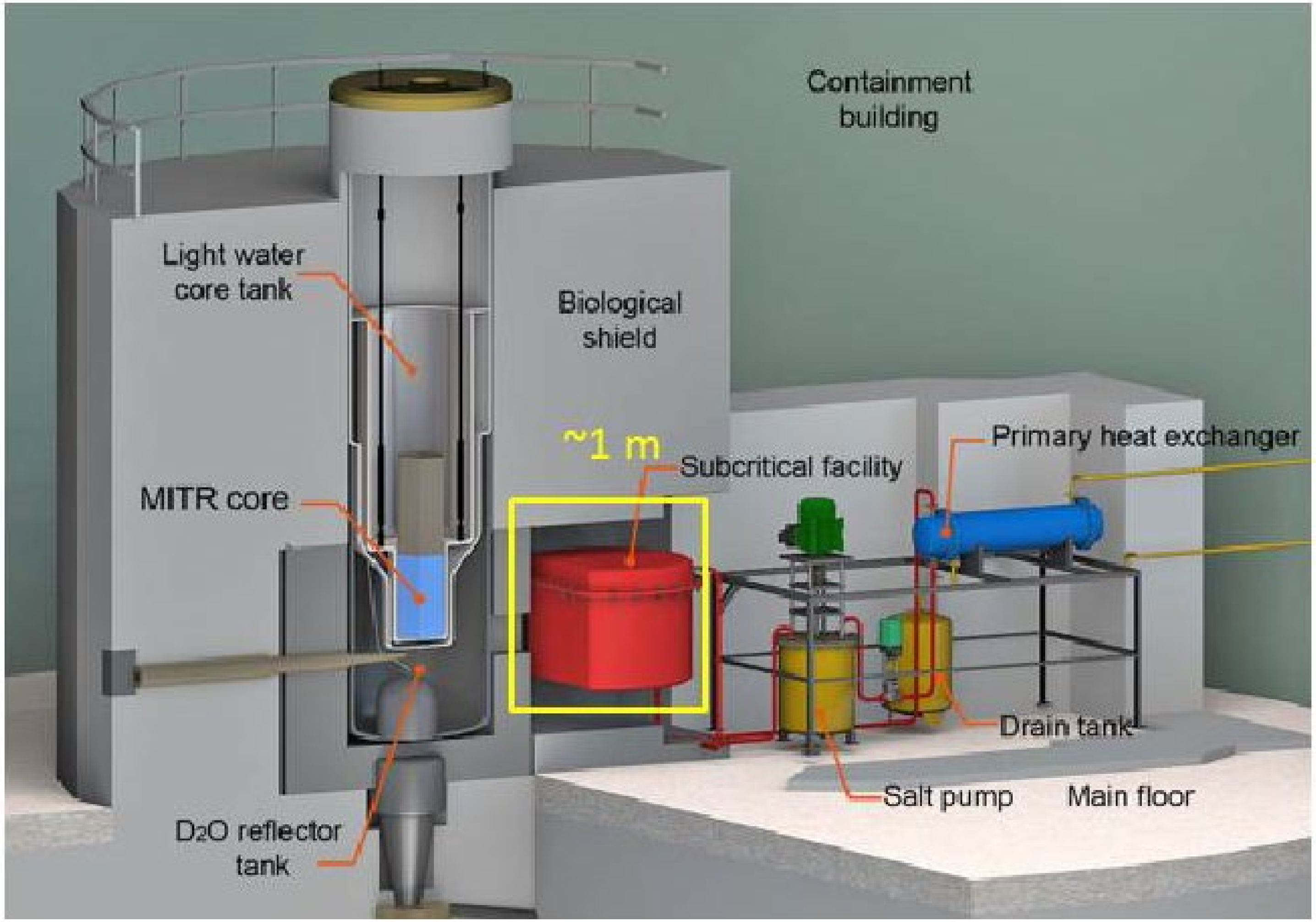
MIT Has Initiated Construction of Salt Loop at MIT Reactor

- MIT reactor: 6 Megawatts
- Forced circulation salt loop, heat and cool
  - High-temperature
  - Fully instrumented
  - 3-year project (DOE IRP)
- Partners
  - North Carolina State University
  - U. of California at Berkeley
  - ORNL



Salt Loop Has Multiple Goals

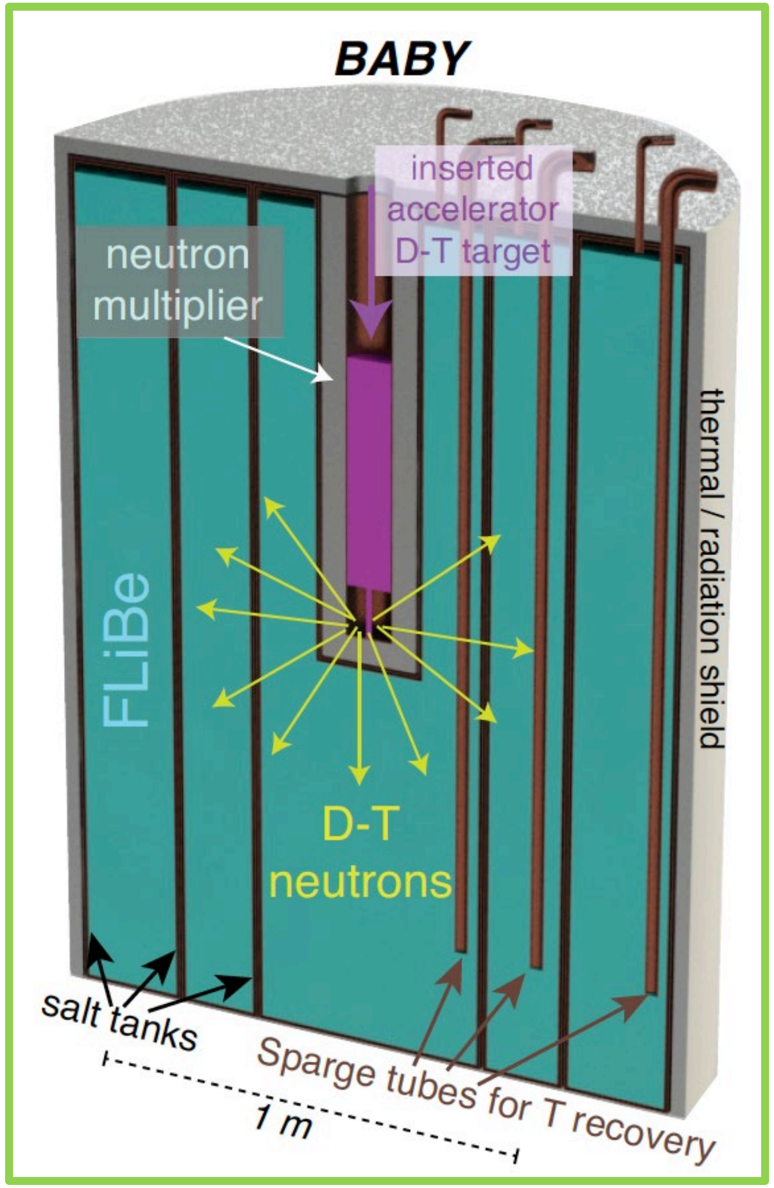
- Learning curve for future loops at ATR, VTR and university reactors
- Sequence
  - Clean salt
  - Salt with fissile materials
- Strong interaction with private industry, national laboratories and universities



MIT Has Started Design of a Flibe Fusion Blanket Experiment:

BABY: *Building A Better Yield Blanket*

- Motivation
  - Blanket technology is at a low TRL
  - **No experimental demonstrations of global Tritium Breeding Ratio>1 in a representative blanket prototype for any fusion blanket**
  - Proof-of-concept for ARC blanket using a modular, phased approach with TBR>1
- Design
  - Accelerator creates fusion neutrons
  - High energy neutrons produce tritium
  - Measure total tritium production

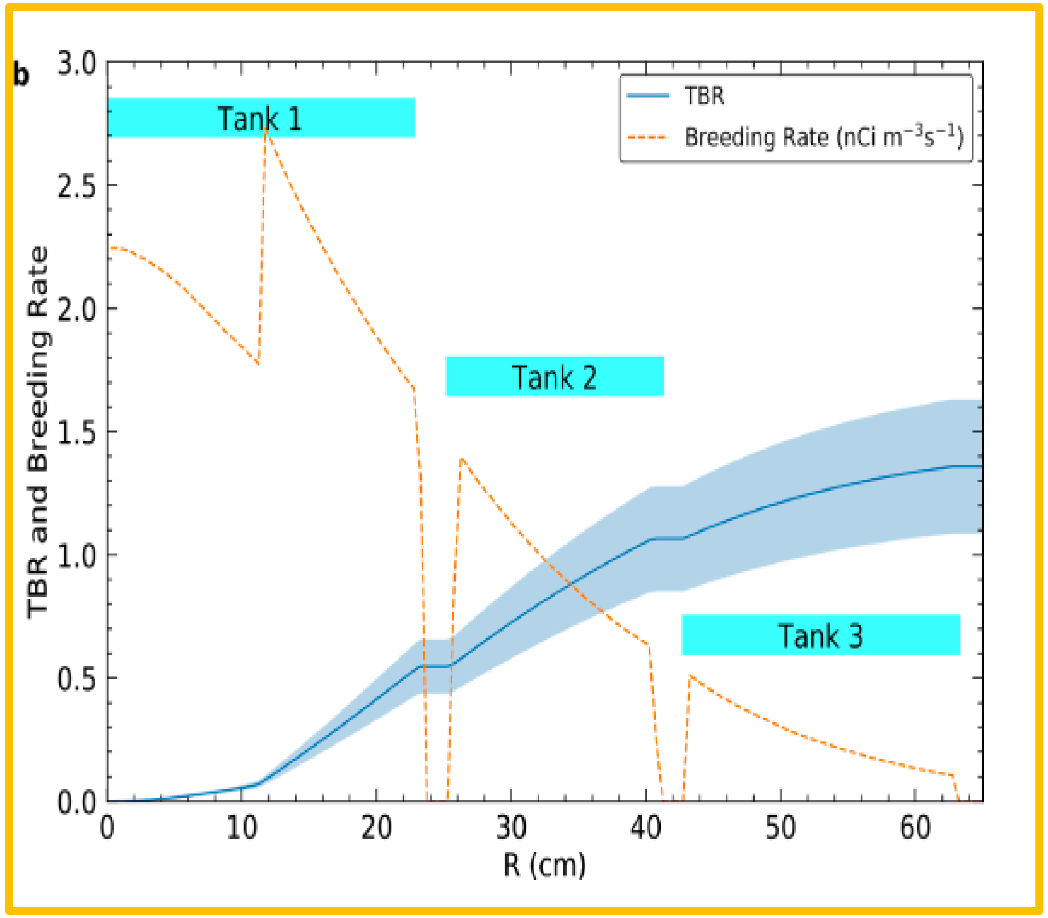


C. Sorenson

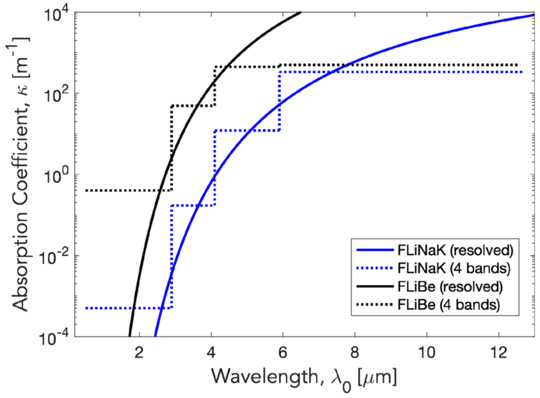
Massachusetts Institute of Technology

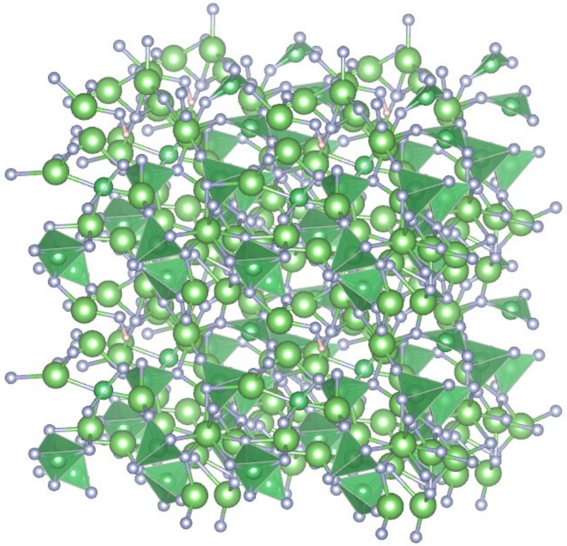
MIT Fusion BABY Experiment To Use a Phased Development Strategy to Demonstrate Breeding

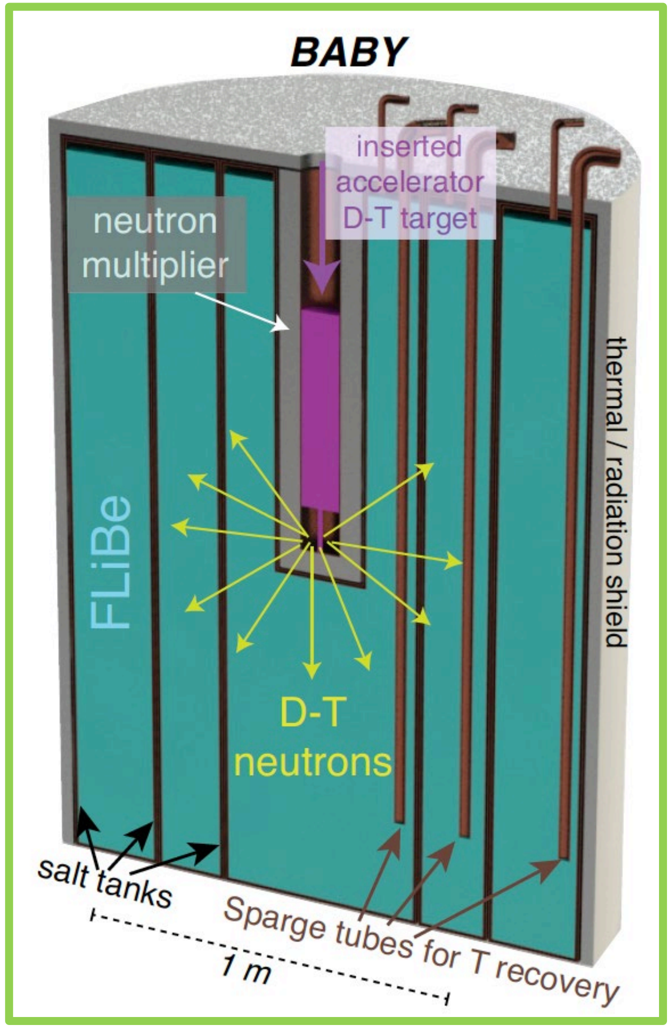
- Tank 1: achieve TBR ~0.5, demonstrate feasibility of approach (2021)
- Add Tanks 2-3: achieve global TBR ~1.4 (2022)
- Team
  - MIT: D. Whyte, S. Ferry, E. Peterson, C. Sorenson, K. Woller
  - INL, ORNL, SRNL

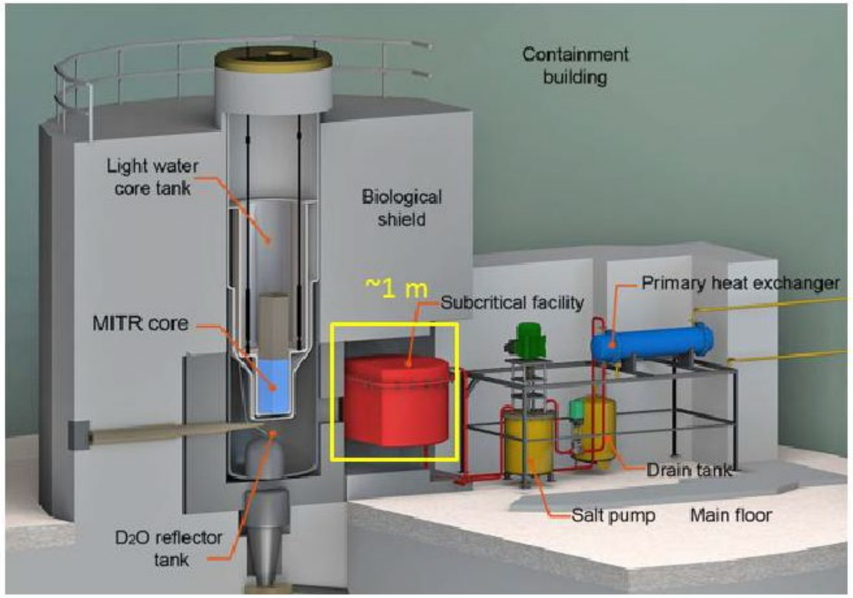


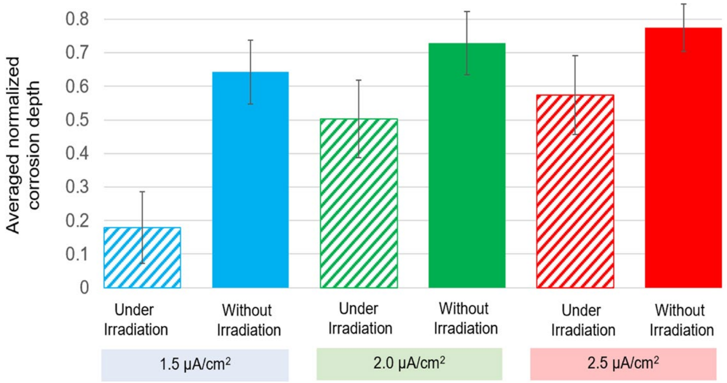
Questions


Absorption Coefficient, κ [m^{-1}]
10^4
10^2
10^0
10^{-2}
10^{-4}
Wavelength, λ_0 [μm]
2
4
6
8
10
12
FLiNaK (resolved)
FLiNaK (4 bands)
FLiBe (resolved)
FLiBe (4 bands)




BABY
inserted accelerator D-T target
neutron multiplier
FLiBe
thermal / radiation shield
D-T neutrons
salt tanks
Sparge tubes for T recovery
1 m


Containment building
Light water core tank
Biological shield
~1 m
Subcritical facility
Primary heat exchanger
MITR core
Drain tank
Salt pump
Main floor
D2O reflector tank

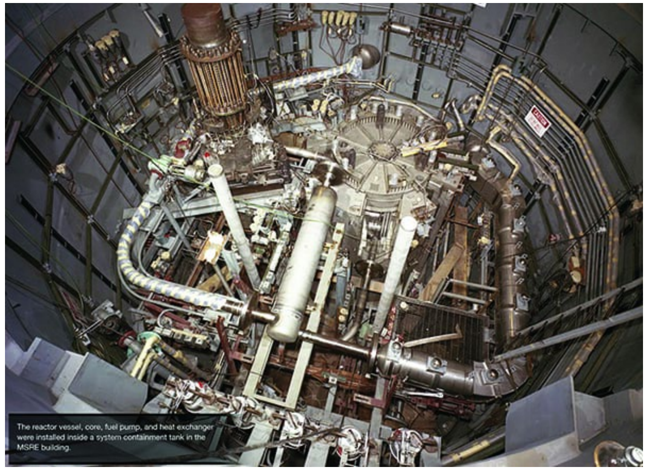

Averaged normalized corrosion depth
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Under Irradiation
Without Irradiation
Under Irradiation
Without Irradiation
Under Irradiation
Without Irradiation
1.5 μA/cm²
2.0 μA/cm²
2.5 μA/cm²

Biography: Charles Forsberg

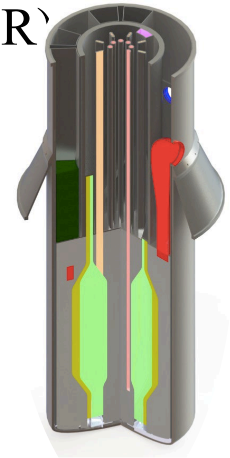
Dr. Charles Forsberg research areas include Fluoride-salt-cooled High-Temperature Reactors (FHRs) and utility-scale heat storage including Firebrick Resistance-Heated Energy Storage (FIRES). He teaches at MIT the fuel cycle and nuclear chemical engineering classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory where he was one of three originators of the FHR. At MIT he is the PI to build a salt loop in the MIT reactor—the first reactor salt loop in 40 years in the U.S. Dr. Forsberg leads a team developing an integrated development plan for fusion reactors with salt blankets. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a Director of the ANS.. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 12 patents and published over 300 papers.

Liquid-salts are so hot right now

Molten Salt Reactors

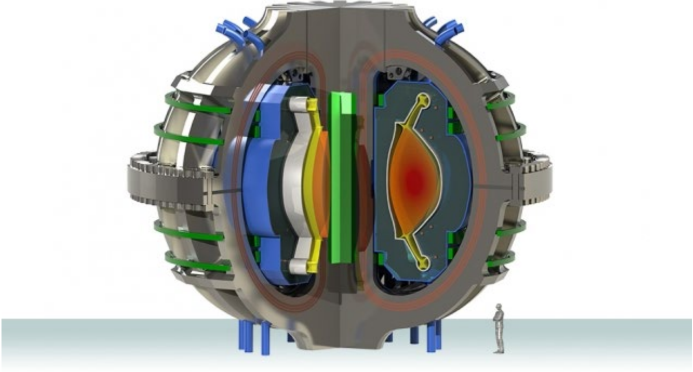


Salt-Cooled Reactors (PB-FHR)



Coolant	**Avg. Temp. of Delivered Heat (˚C)**
Water	280
Sodium	500
Helium	550
Salt	650

Compact, Fusion Reactors (ARC)



Concentrated Solar Power

Salts of interest:

Fluorides:	FLiNaK, FLiBe, Many others
Chlorides:	(Na-K-Mg)Cl (Na-U-X)Cl
Nitrates:	$NaNO_3$-KNO_3

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- Thermal desorption system designed for tritium analysis of graphites irradiated in Flibe
- Measurements: Tritium inventory and desorption vs. temperature; Tritium chemical forms; Desorption activation energy; Effect of H_2 in desorption furnace

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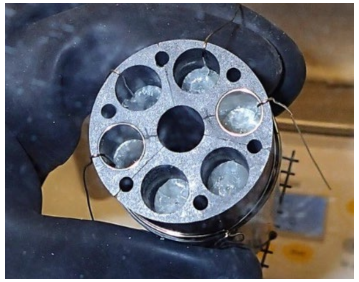
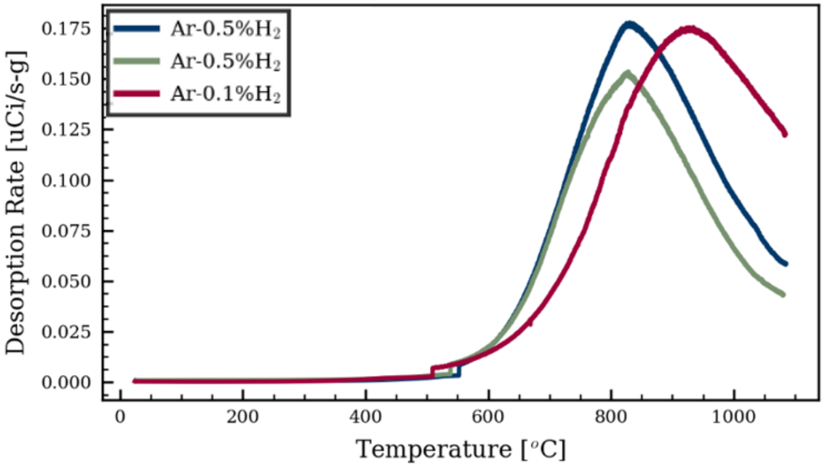


IG-110U Crucible



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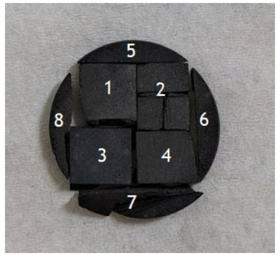
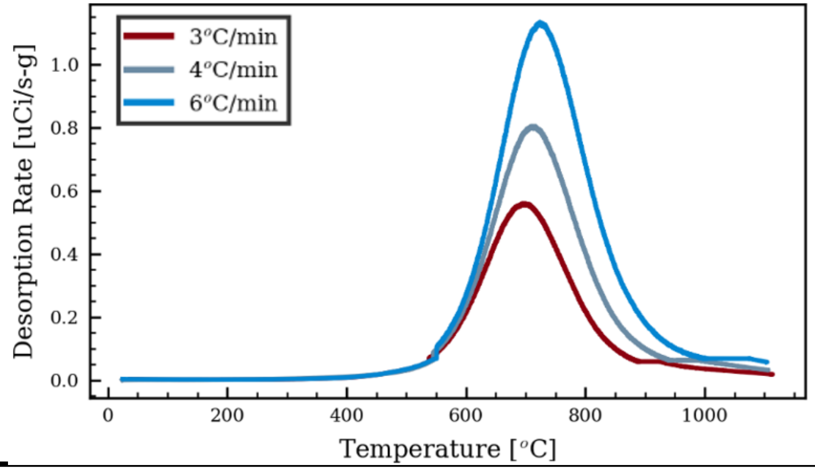
IG-110U Sample





K. Dolan, Tritium Retention in Nuclear Graphite, System-Level Transport, and Management Strategies for the Fluoride-Salt-Cooled High-Temperature Reactor, PhD Thesis, 2020

Updated Modeling of Tritium Distribution in FHRs

- Updated system-level transport model based on TRIDENT (Stempien, MIT 2015)
- Added additional FHR regions: hot leg, cold leg, reactor vessel, reactor cover gas
- Implemented new method for calculating tritium transport and trapping in graphite

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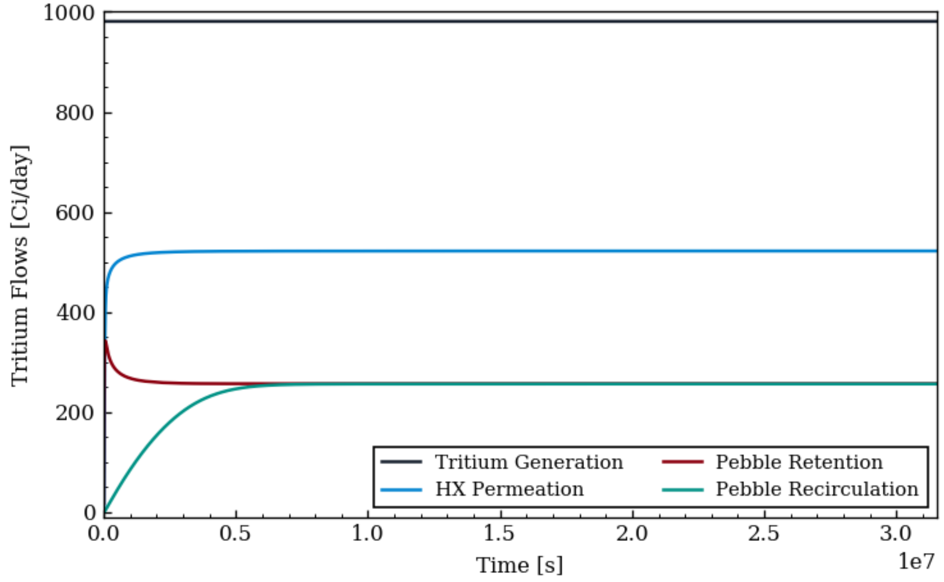
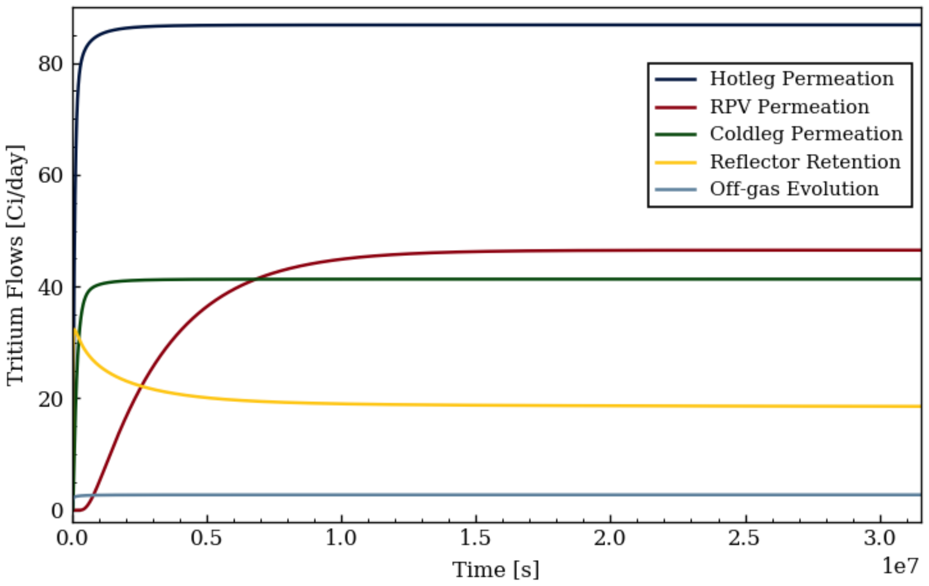
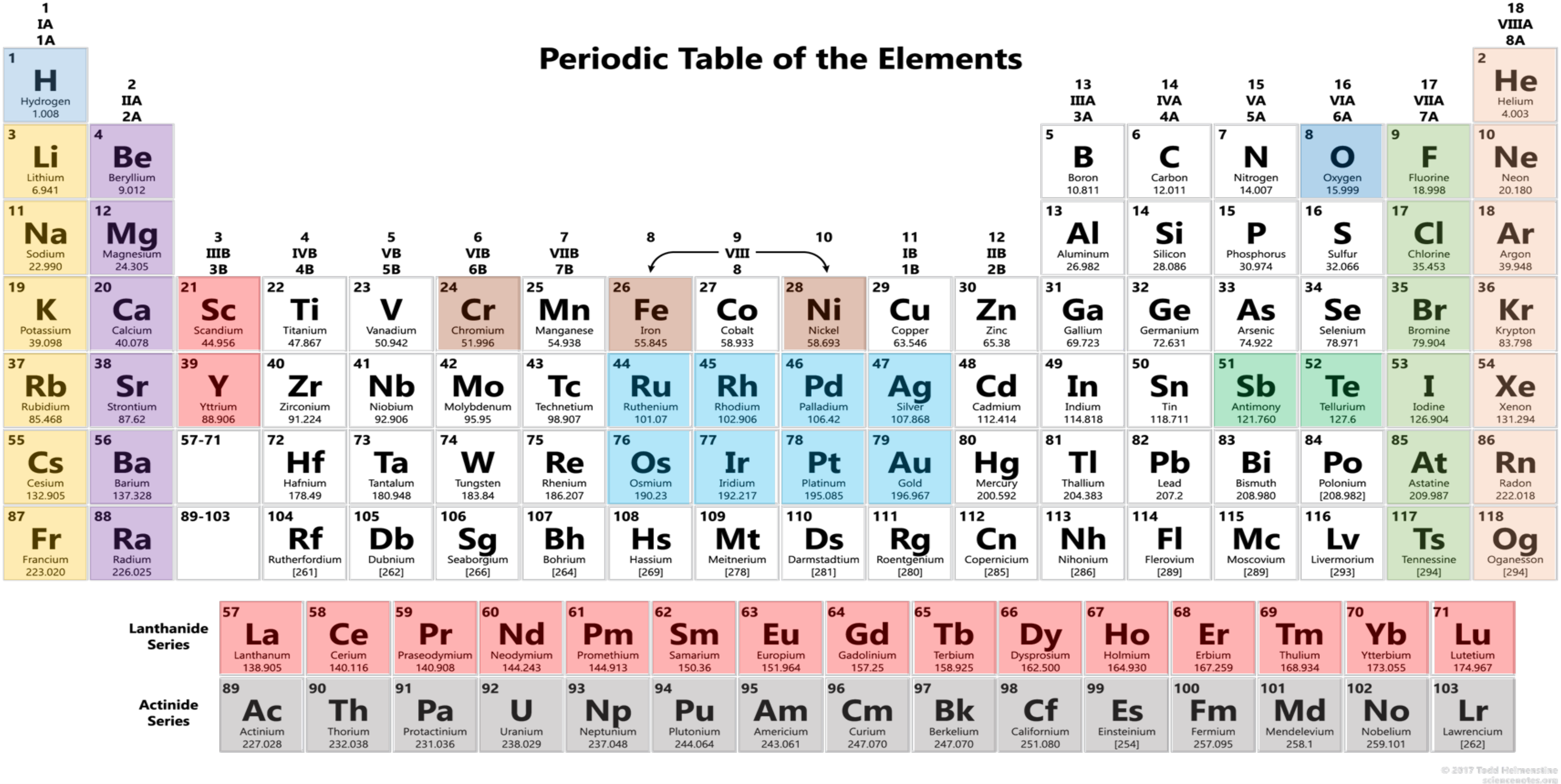




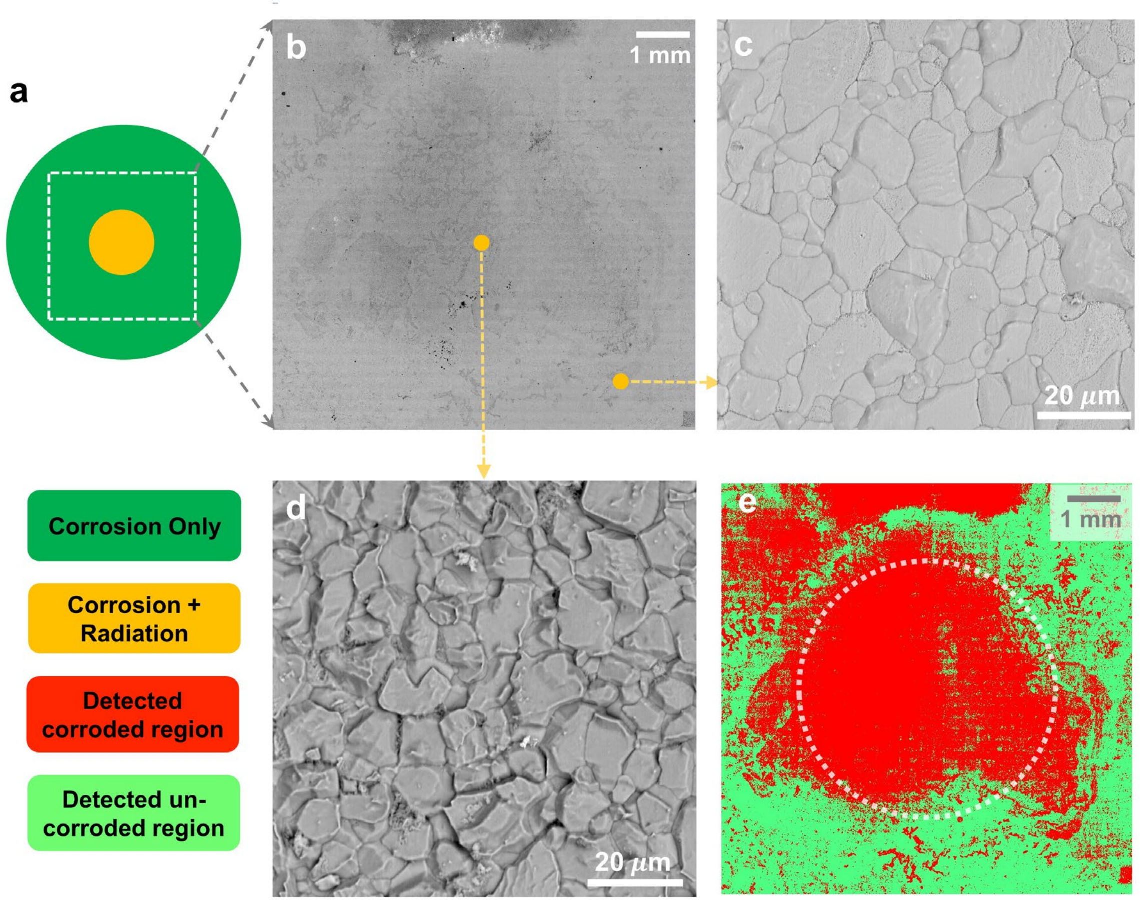
Future work: Non-tritium impurities in molten salt reactors



Periodic Table of the Elements

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]
Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967		
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]		

Proving Radiation Decelerated Corrosion



Machine learning used to auto-identify corroded regions, disproving competing hypotheses

Mechanism proposed and proven to explain effect, predicting prevalence in other systems