INL/MIS-23-72711-Revision-0

Accurate Dosimetry for Future Advanced Reactor Deployment and Operation

May 2023

William E Windes

Changing the World's Energy Future

Idaho National Laboratory

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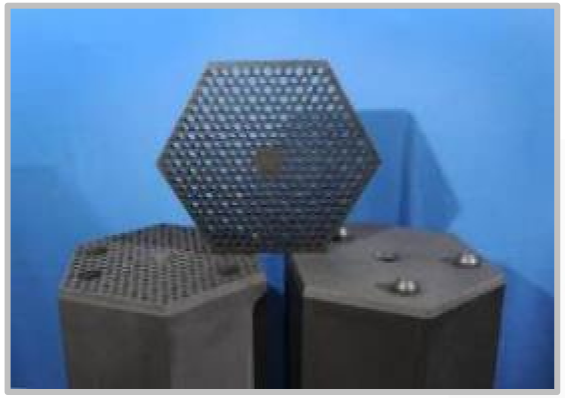
École Polytechnique Fédérale de Lausanne (EPFL)
Lausanne, Switzerland
21-26 May 2023

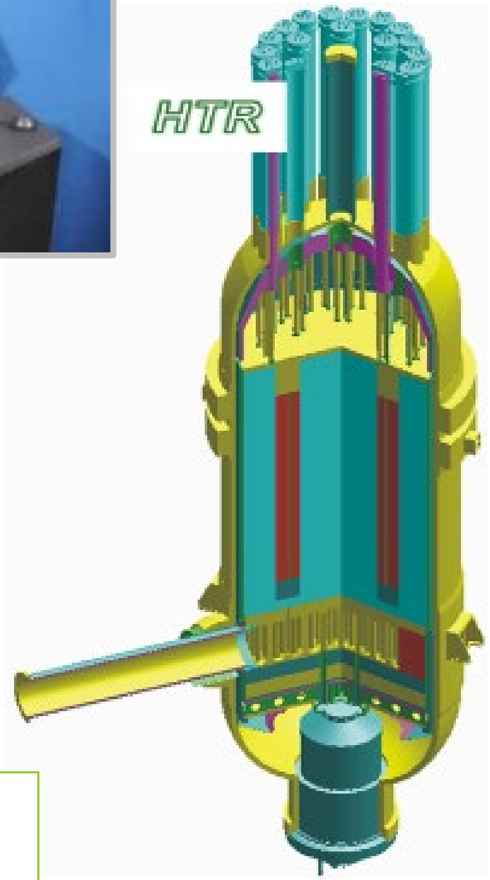
Accurate Dosimetry for Future Advanced Reactor Deployment and Operation

A customer's perspective

William Windes, PhD
Idaho National Laboratory
Directorate Fellow

Discussion Points





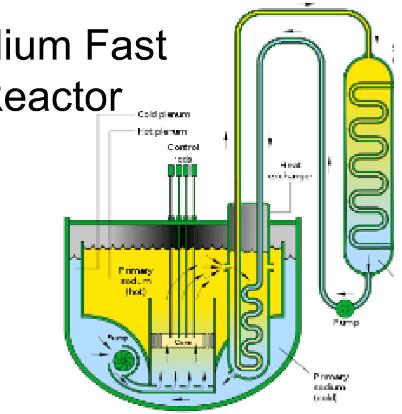
- The Nuclear Renaissance
  - Why you should be interested in this topic
- A practical example
  - Advanced Graphite Creep (AGC)
  - Importance of dosimetry to the experiment
  - Importance of dosimetry to reactor deployment
- Dosimetry's role in advance reactor operations
  - How dosimetry will be used for material lifetime predictions
  - The challenge of dosimetry in future designs

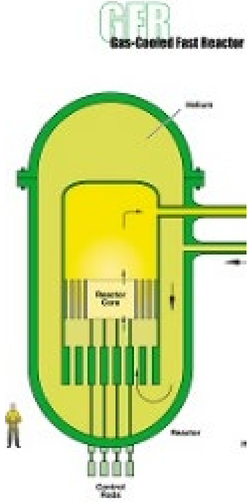
The Nuclear Renaissance

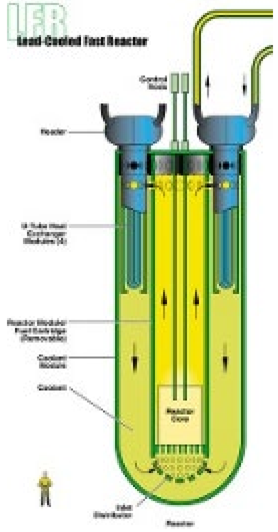
(Since about 2001) the term nuclear renaissance has been used to refer to a possible nuclear power industry revival:

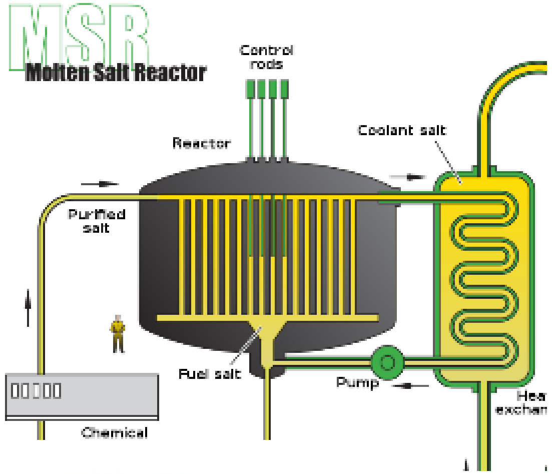
- Rising fossil fuel prices
- Limiting greenhouse gas emission

Sodium Fast Reactor



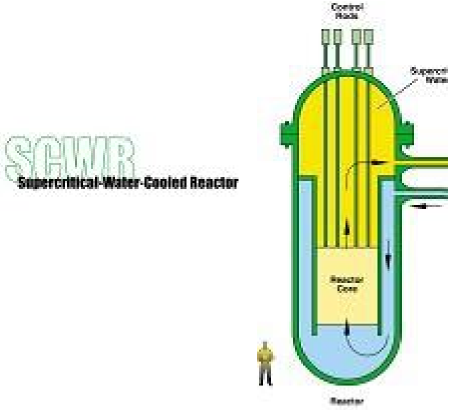


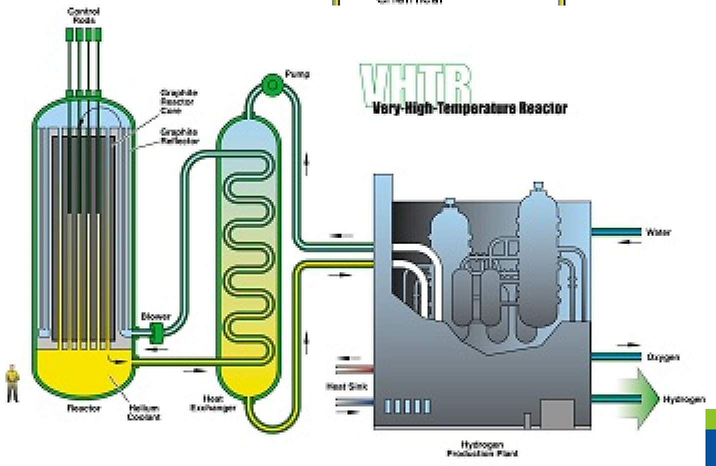




Generation IV reactor designs

- Inherently & Passively safe
  - Natural shutdown and cooling from design
- New designs = new uses
  - Process heat
  - Small modular designs
  - Variety of coolants and fuels





Nuclear Renaissance is here, now

- What started in year 2000 as government funded R&D projects has evolved into numerous commercial enterprises
- **Things are moving fast!!**

More than 70 SMR and microreactors projects worldwide under development

Land Based Water Cooled Reactors

CAREM	SMART	RUTA-70	DHR400
ACP100	UNITHERM	NuScale	RITM-200
CAP200	VK-300	mPOWER	NUWARD
IRIS	KARAT-45	W-SMR	BWRX-300
DMS	KARAT-100	SMR-160	HAPPY200
IMR	ELENA	UK-SMR	CANDU SMR

Micro Reactors

IHTR	MMR-5
IMSBR	MMR-10
eVinci	AURORA
U-Battery	MoveluX

Fast Reactors

4S	W-LFR	SSTAR LFR
BREST-OD-300	SEALER	URANUS
SVBR-100	LFR-AS-200	ARC100
EM^2	LFR-TL-X	

High Temperature Gas-cooled Reactors

HTR-PM	MHR-100	XE-100	HTTR-30
DPP-200	PBMR-400	A-HTR 100	HTR-10
GT-MHR	HTMR-100	MMR	RDE
MHR-T	SC-HTGR	GTHTR300	StarCore

Marine Based Water Cooled Reactors

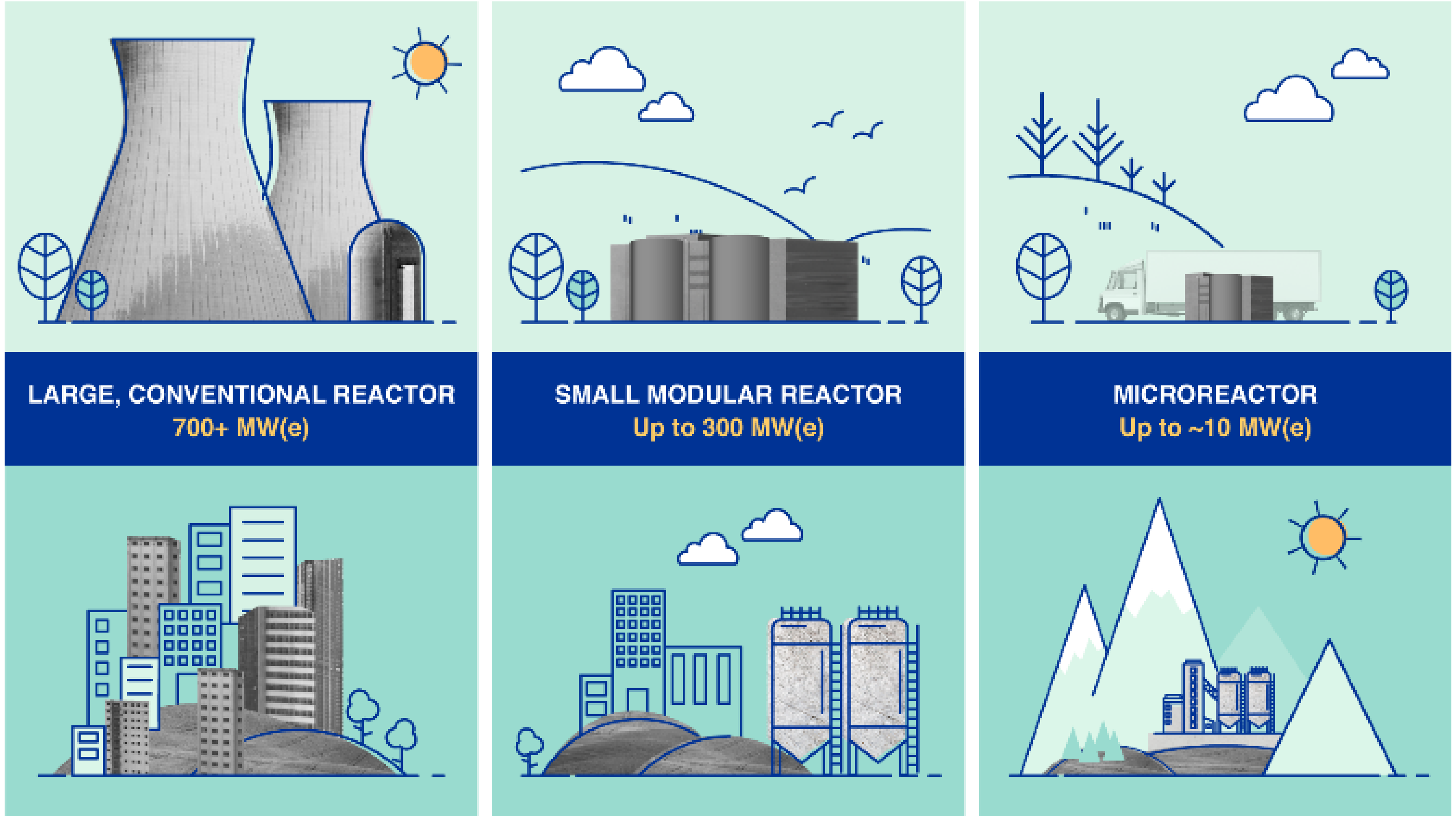
ACPR50S	VBER-300
KLT-40S	ABV-6E
RITM-200M	SHELF

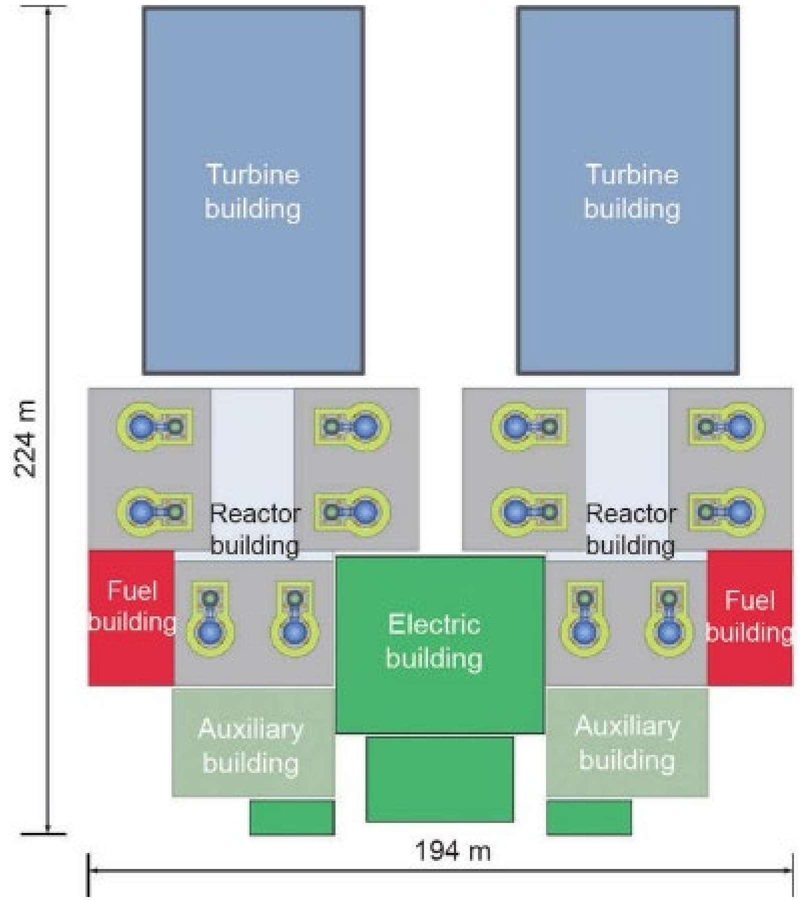
Molten Salt Reactor

IMSR	SSR-WB	CA WB
CMSR	SSR-TS	KP-FHR
THORCON	LFTR REACTOR	MCSFR
FUJI ITMSF	MK1 PB-FHR	

https://aris.iaea.org/

Small Modular Reactors (SMRs)





2 × 600 MWe HTR-PM multi-modules plant:
Same physical size as 1,200 MWe LWR

Left: https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs
Right: “The Shandong Shidao Bay 200 MWe High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation”

Features of Small Modular Reactors (SMRs)

Simplification by Modularization and System Integration

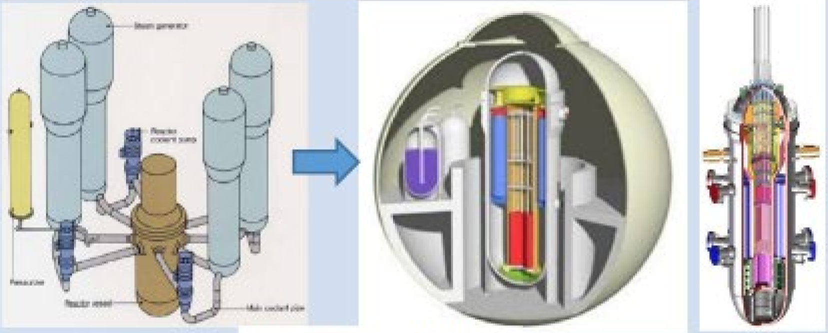


Image courtesy of IRIS 7 .

Multi-module Plant Layout Configuration

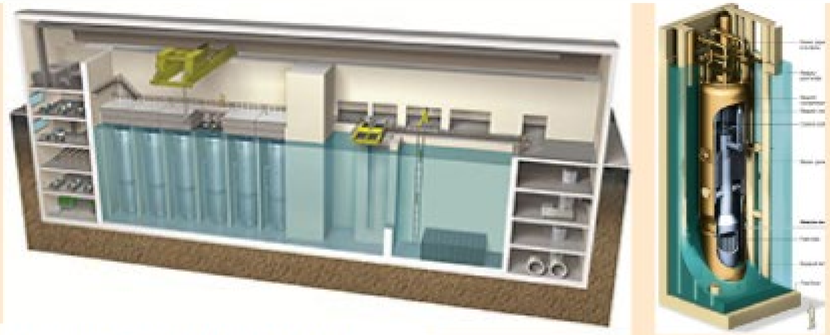


Image courtesy of NuScale Power Inc.

Underground construction for enhanced security and seismic

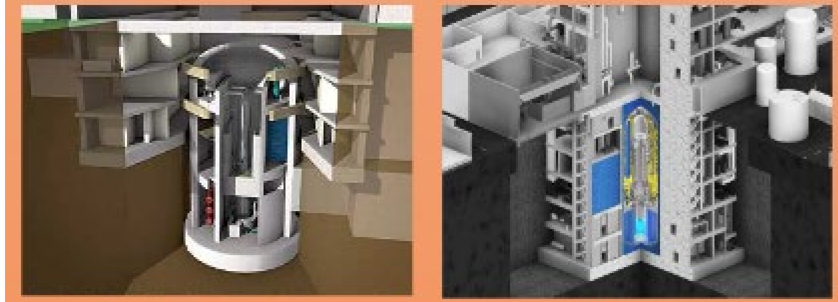


Image courtesy of BWX Technology, Inc.

Enhanced Safety Performance through Passive System

- Enhanced severe accident features
- Passive containment cooling system
- Pressure suppression containment

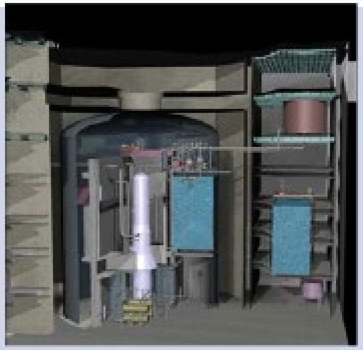


Image courtesy of BWX Technology, Inc.

Slide credit: Frederik Reitsma (GIF Webinar: Overview of SMR Technology Development, July 2020)

Some recent developments

Dow, X-energy to drive carbon emissions reductions through deployment of advanced small modular nuclear power

- Dow and X-energy collaborate on intent to provide process heat and power at one of Dow's U.S. Gulf Coast facilities by ~2030
- Dow is first manufacturer to announce intention to develop small ... ar technology options
- ... take a minority equity stake in X-energy

Kairos Power, Los Alamos collaborate to make TRISO fuel 09/12/2022
TRISO fuel pebbles for the Hermes demonstration reactor will be produced at the New Mexico lab's Low Enriched Fuel Fabrication Facility (LEFFF) under a newly announced agreement. This is the first nuclear iteration in Kairos Power's "rapid iterative approach" to nuclear fuel development as well as the first nuclear fuel development campaign for LEFFF.

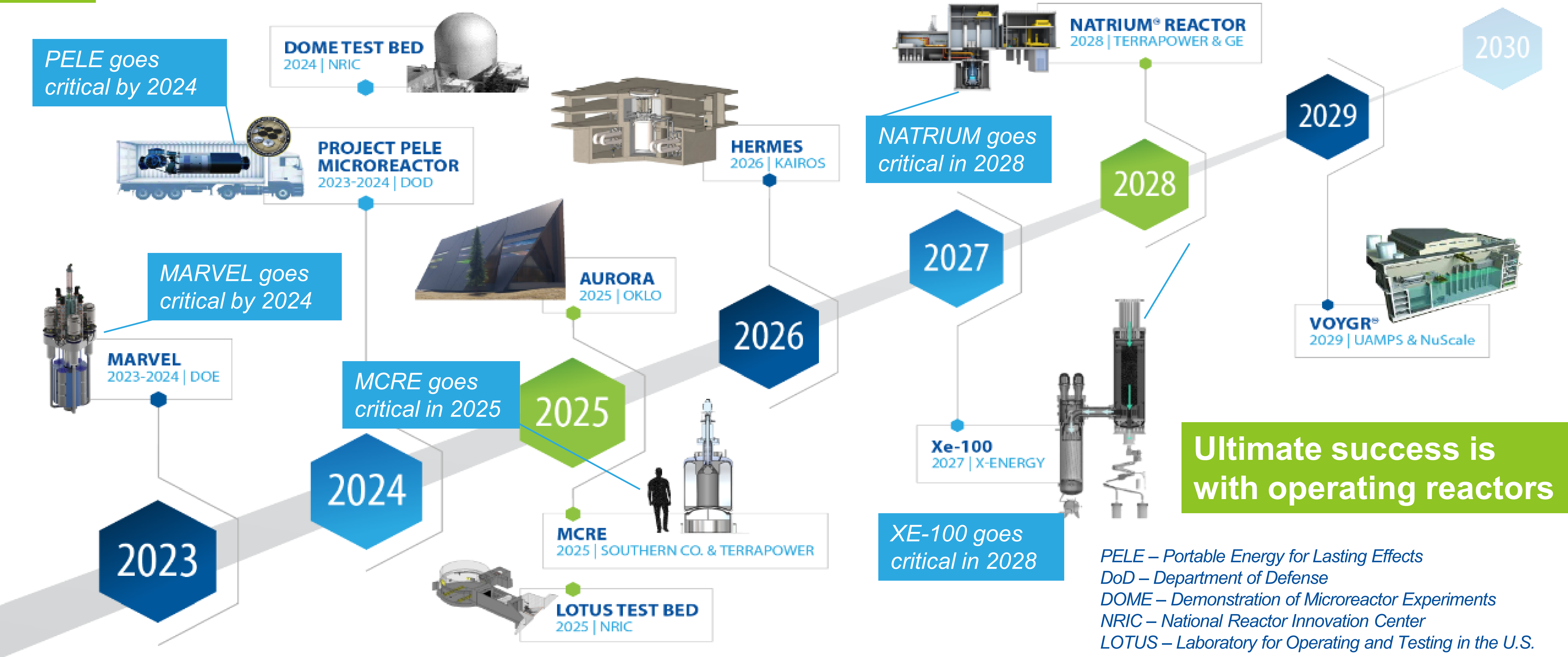
eVinci™ Microreactor Team Closes Out 2022 with Milestone Achievement
January 27, 2023
The microreactor team last month submitted two important topical reports to the Nuclear Regulatory Commission, and 24 white papers during 2022, on critical aspects of the technology and design

APRIL 28, 2022

NASA Selects USNC Advanced Technologies for Ultra-High Temperature Component Testing Facility

Proposed Infrastructure First to Combine Mechanical and Ultra-High Temperature Evaluations

USA Advanced reactor deployment (before 2030)

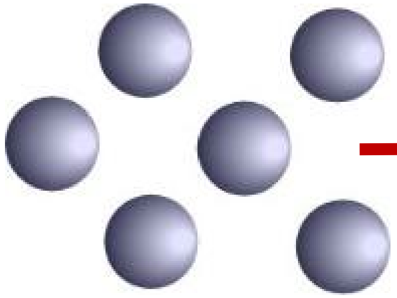


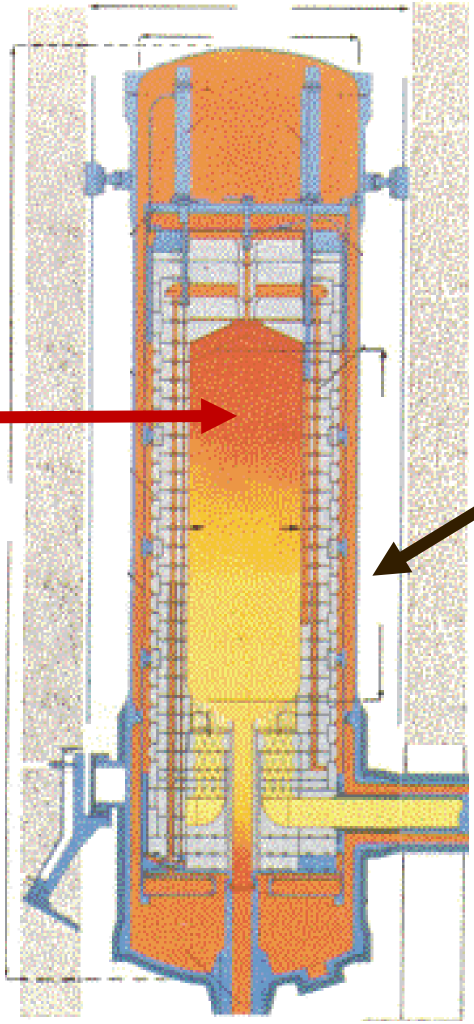
Ultimate success is with operating reactors

PELE – Portable Energy for Lasting Effects
DoD – Department of Defense
DOME – Demonstration of Microreactor Experiments
NRIC – National Reactor Innovation Center
LOTUS – Laboratory for Operating and Testing in the U.S.

(Very) High Temperature Reactor (HTR)

(Graphite)
Fuel Pebbles

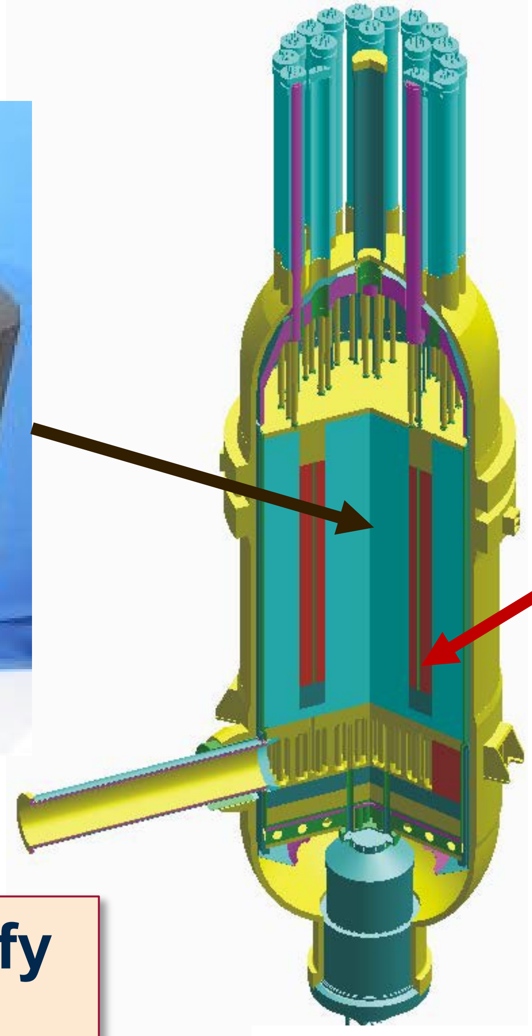




Pebble Bed

Graphite Core

How do we qualify the core components?

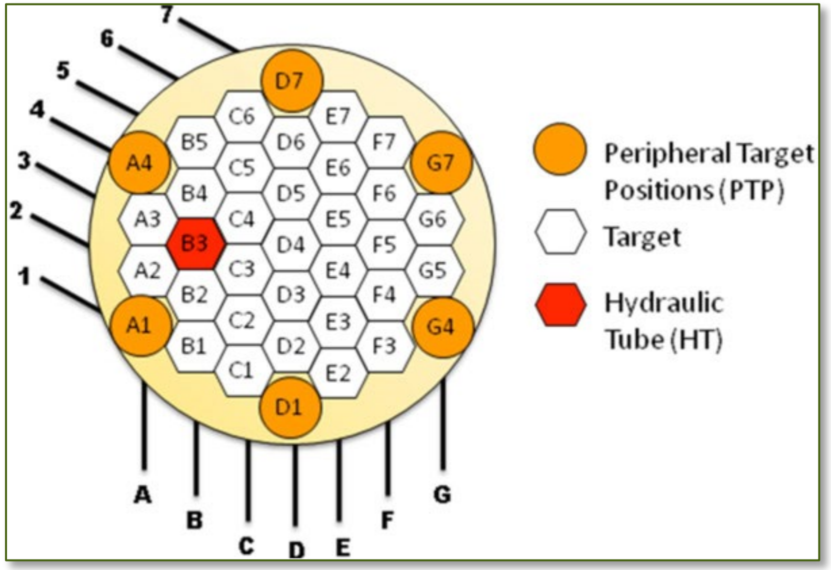


Prismatic

Graphite Fuel Element

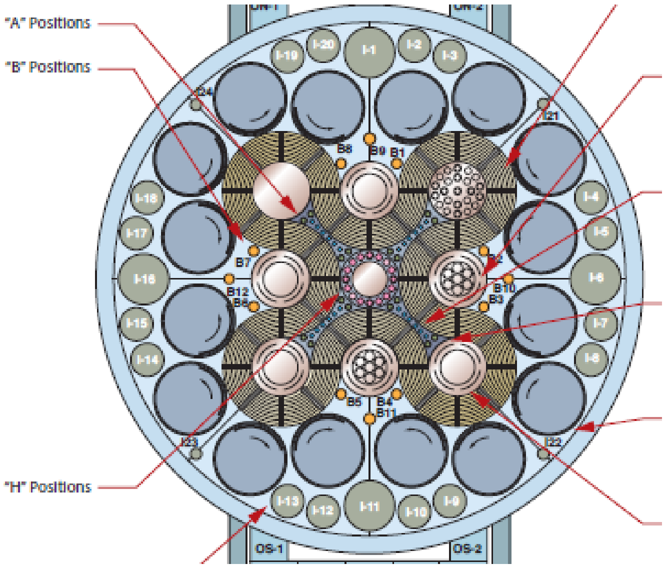
Qualification through MTR experiments

HFIR



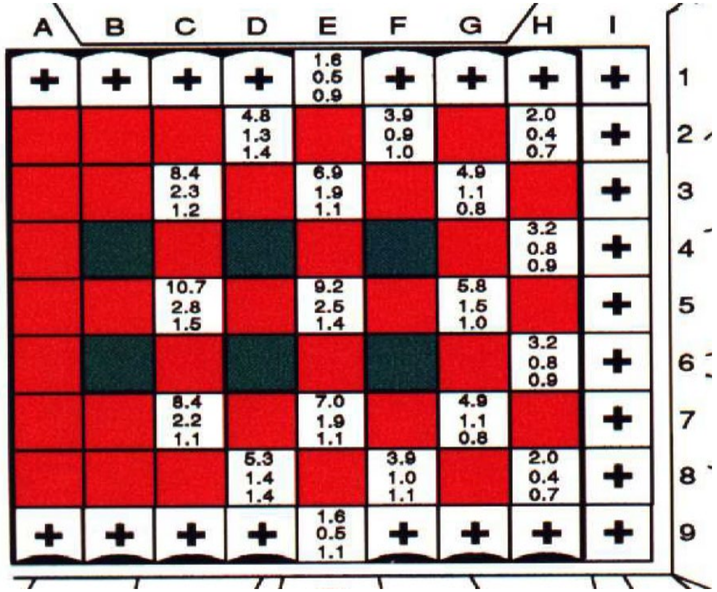
- *LWR: U-Al*
- *61cm (24inch) height*
- *30 target positions (2 can be instrumented).*
- *6 peripheral target positions*
- *Rabbit*
- ***Nominal diameter ~ 1.8cm (5/8")***

ATR



- *LWR: U-Al*
- *123cm (48inch) height*
- *9 flux traps, 68 core positions*
  - *Instrumented > 0.625*
- *Rabbit*
- ***Diameters range:***
  - *1.6cm (0.625")*
  - *2.2cm (0.875")*
  - *13.5cm (5.375")*

HFR (Petten)



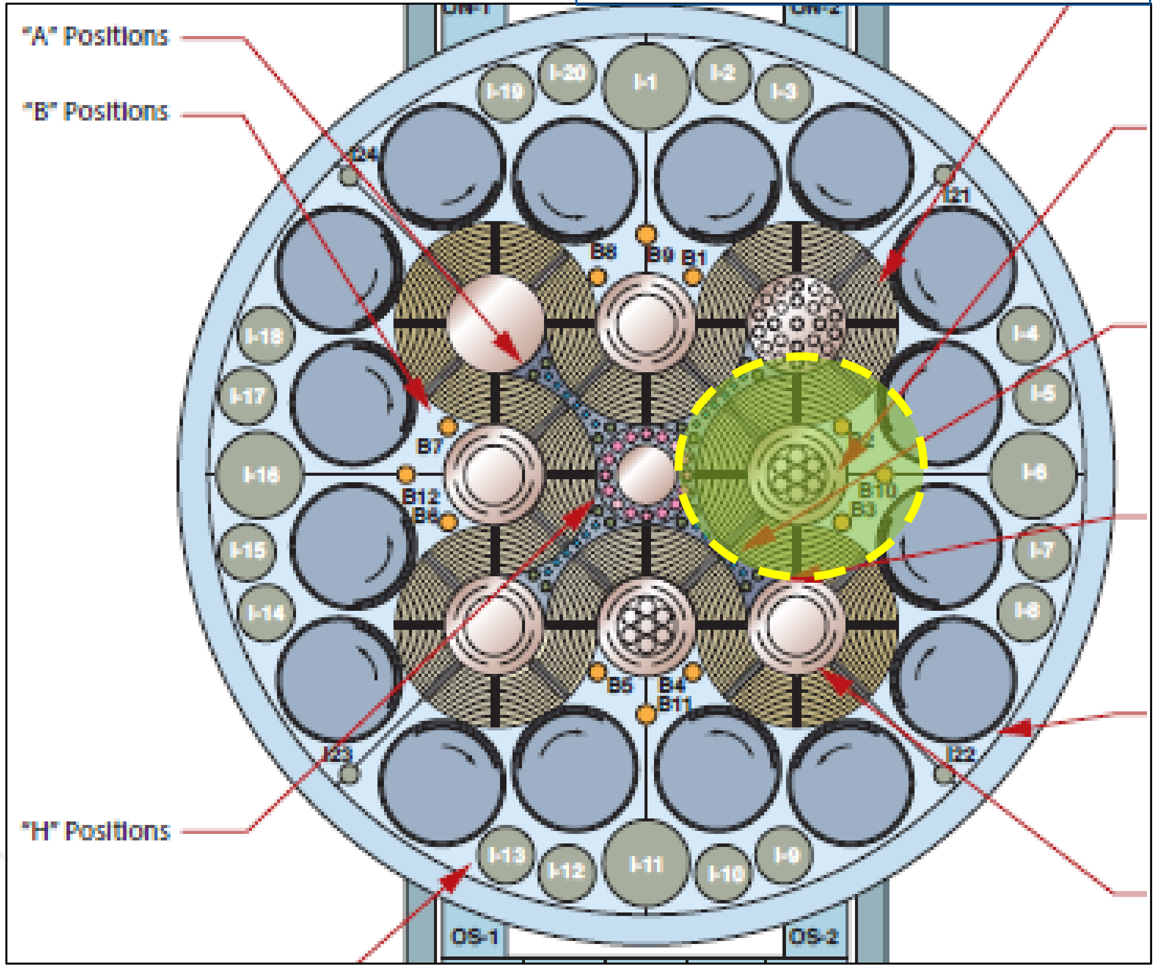
- *LWR: U-Al / U-Si*
- *60cm (24inch) height*
- *17 experimental positions*
- *Rabbit*
- ***Nominal diameter ~ 8.3cm²***

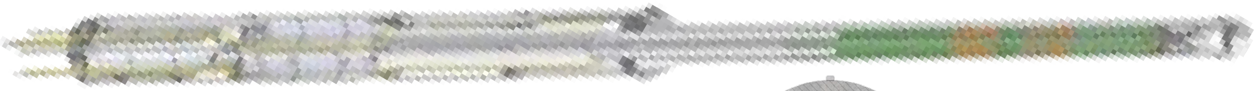
Advanced Graphite Creep (AGC) Experiment

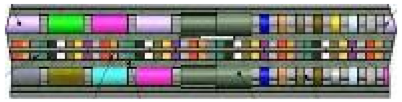
ATR
- *123cm (48inch) height*
- *9 flux traps, 68 core positions*
- ***East Flux Trap:***
    - *13.5cm (5.375”)*

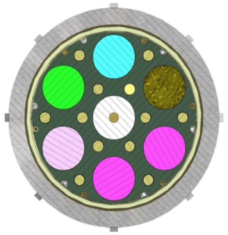
***AGC:** (East Flux Trap)*
- *Height: 123cm (48inch)*
- *Diameter: 8.26 cm (3.250”)*
- *Graphite body holding ~450 specimens*
- *Neutron Flux: n/cm^2-s:*
    - *4.4x10^{14} thermal*
    - *9.7x10^{13} fast (E <0.1 MeV)*
- *Mechanical load : 13.8, 17.2, 20.7 Mpa*
    - *Top specimens loaded*
    - *Lower specimens unloaded*

Advanced Test Reactor
Idaho National Laboratory



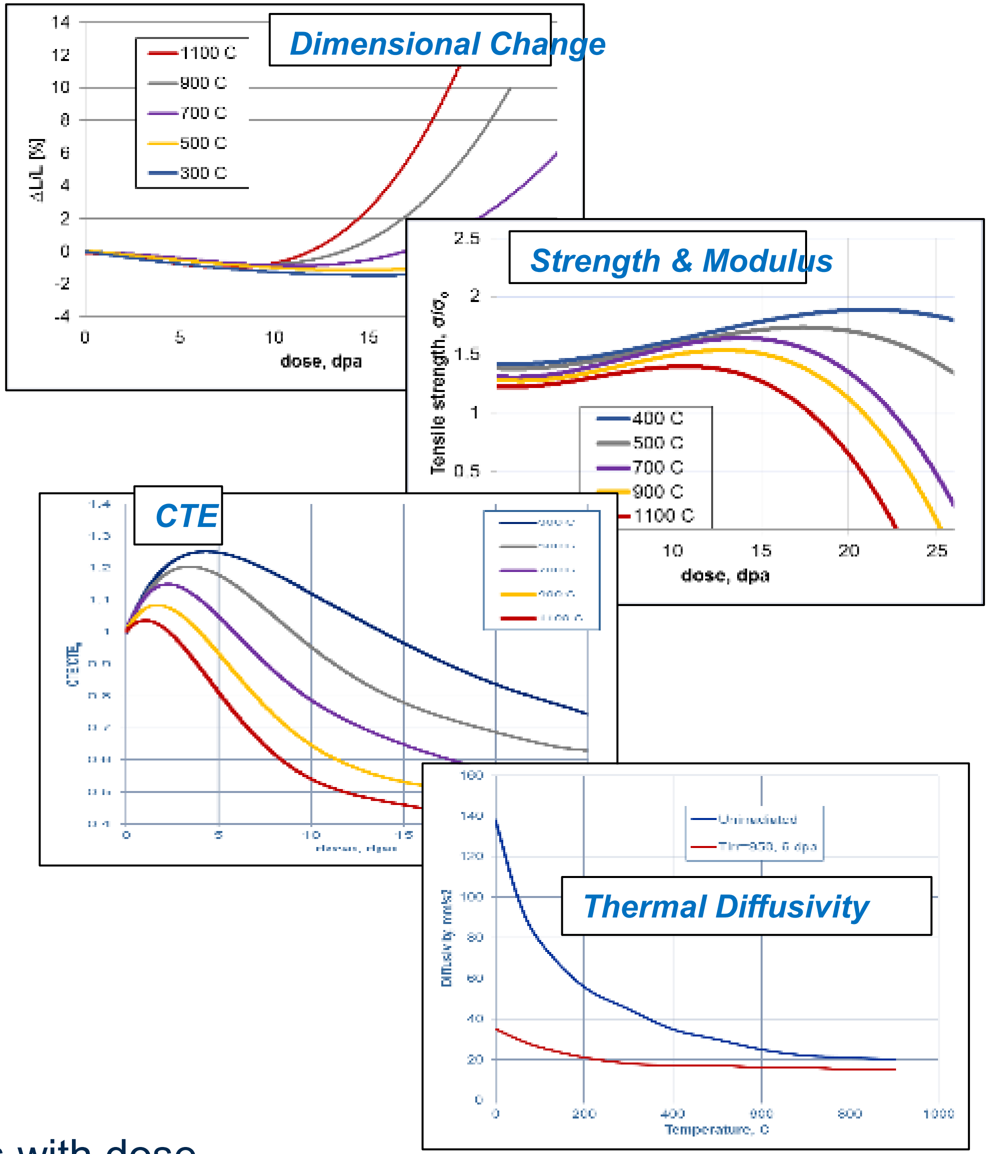




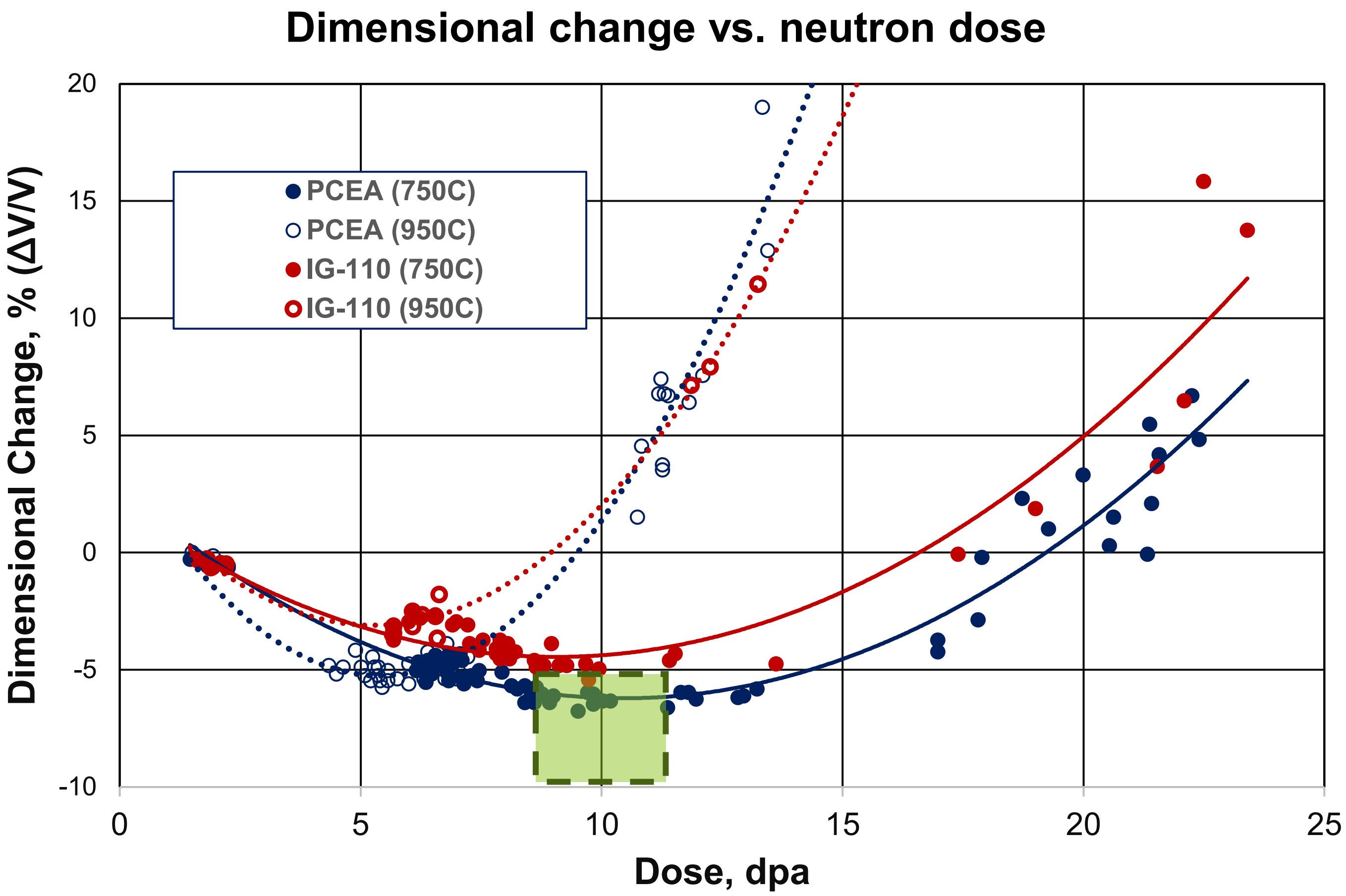


What are we looking for? Irradiated

- Significant changes occur during normal operation:
  - Dimensional change
    - ***Turnaround*** *dose is key parameter*
    - *Highly temperature dependent*
  - Density
    - *Graphite gets denser with irradiation until* ***Turnaround*** *dose*
    - *After* ***Turnaround*** *density decreases (volumetric expansion)*
    - *Formation of microcracks (molten salt consideration)*
  - Strength and modulus
    - *Graphite gets stronger with irradiation …*
    - *Until* ***Turnaround*** *dose is achieved. It then decreases*
  - Coefficient of thermal expansion
    - *Initial increase but then reduces before* ***Turnaround***
    - *CTE is why properties are so temperature dependent*
  - Thermal conductivity
    - *Decreases almost immediately to ~30% of unirradiated values*
    - *At temperatures it is same as unirradiated conductivity*
  - Oxidation rate
    - Increases approximately 2-3 times over unirradiated rates. Increases with dose
- Significant changes **do not** typically occur in the following properties:
  - Neutron moderation, specific heat capacity, or emissivity



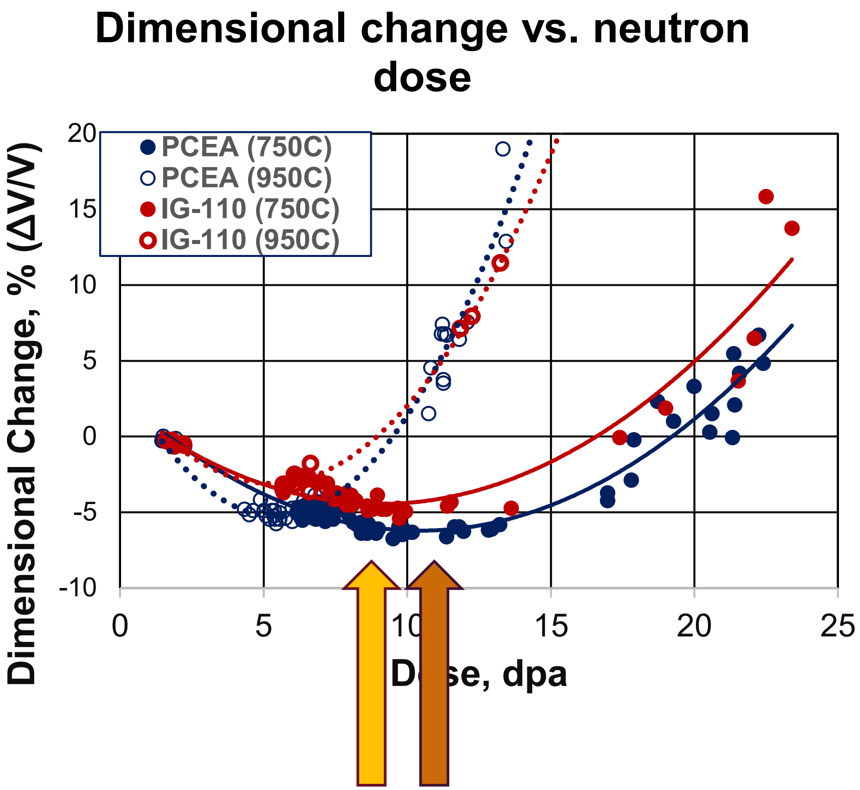
Turnaround dose – critical parameter



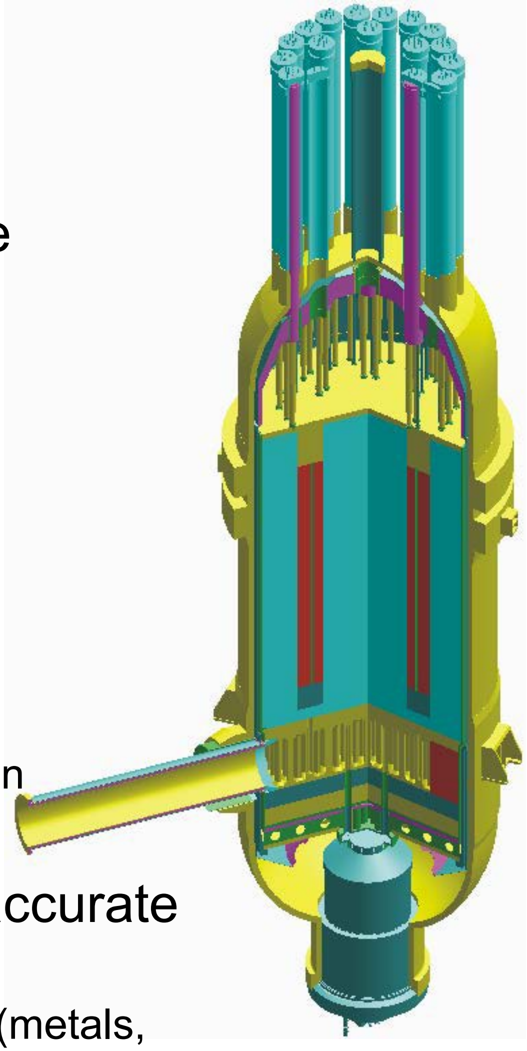
- Turnaround dose plays critical role
  - Need accurate turnaround dose.
  - Therefore need accurate dosimetry.
- What is the dose measurement error?
  - 0% (every neutron in reactor)
  - Better estimates:
    - 5 - 6%
    - 10-15%
    - 20 - 30%
- Worked to improve this error
  - Uncertainty Quotient (UQ) Tool
  - ATR uncertainty ~7-8% error
  - Other MTRs ~ 5% error
- What does this mean?
  - Turnaround of 10 dpa(displacements per atom)
  - dpa range of $\rightarrow$ 9.2 – 10.8 dpa

From: M.C.R. Heijna, S. de Groot, J.A. Vreeling, "Comparison of irradiation behaviour of HTR graphite grades", Journal of Nuclear Materials 492 (2017) 148e156

What does this mean inside a Reactor (HTR)



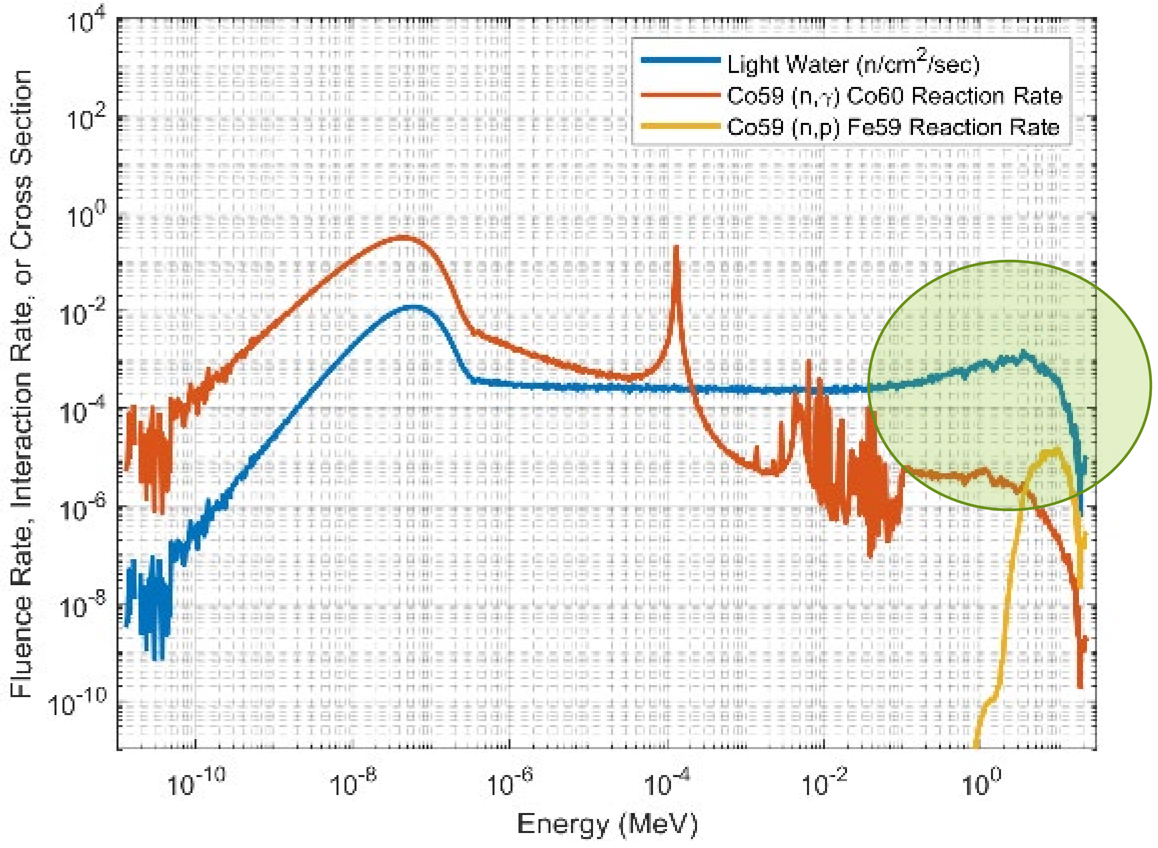
- Dose rates to calculate component lifetime
  - Large reactors
    - ***~ 0.5 – 0.75 dpa per year***
  - Small reactors
    - ***~ 0.25 – 0.5 dpa per year***
  - Micro reactors
    - ***?? (Variable)***
- So, if error is +/- 8%
  - Components could be removed 2+ years too soon
  - Or they could be in reactor 2+ years too long
- Absolutely critical that experiments have accurate dose measurements
  - All irradiated materials have same requirements (metals, ceramics, composites, and graphite)
  - Required for licensing
  - Needed to predict behavior of safety envelope

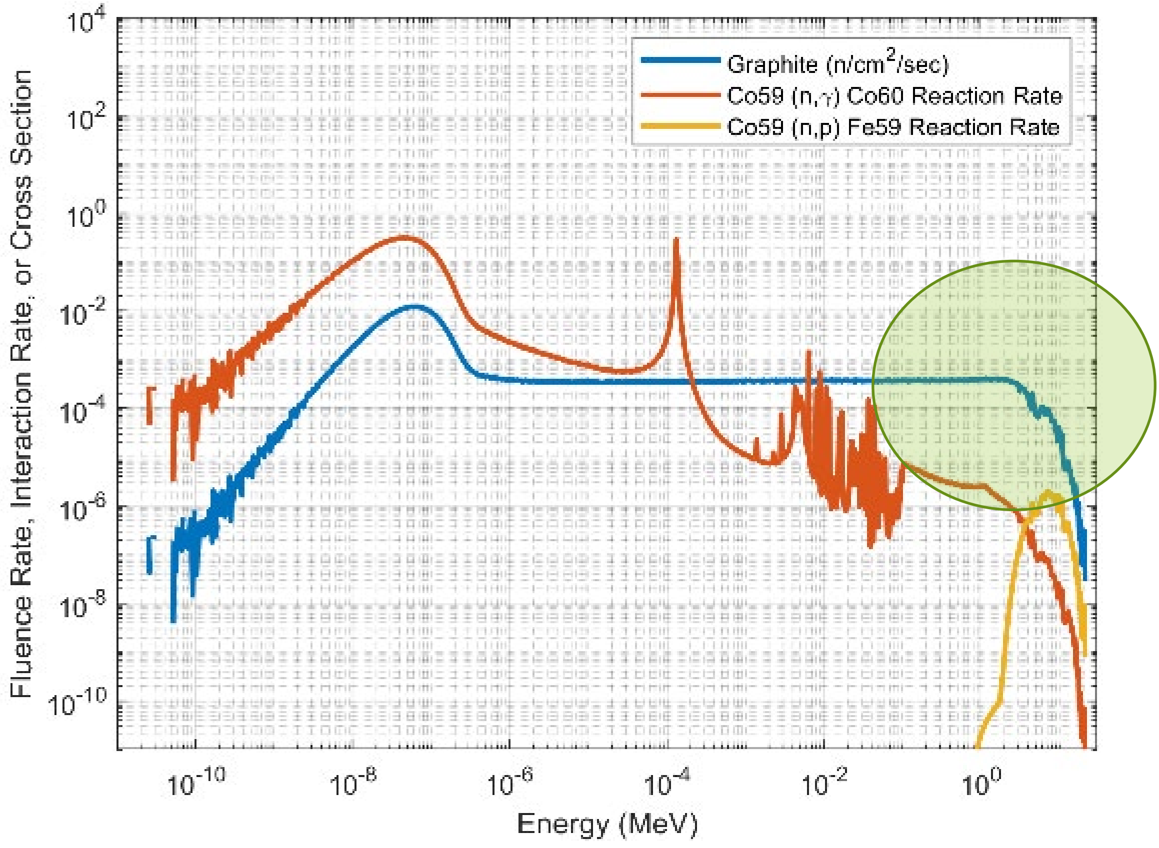


Dosimetry uncertainties exacerbate the problem

Graphite vs Light Water reactor spectrum

- There are differences depending upon the reactor design





Work to be discussed by Dr. T. Holschuh on Tuesday (thomas.holschuh@inl.gov)

Dosimetry uncertainties exacerbate the problem

Getting the right measurements

- AGC experiment completely redesigned the flux wire package
  - ***Ni, Fe, Ti (Basic package)***
- Improved package
  - ***Ni, Fe, Ti, Mn, Cu, Ag***
- Better captures the spectrum for AGC

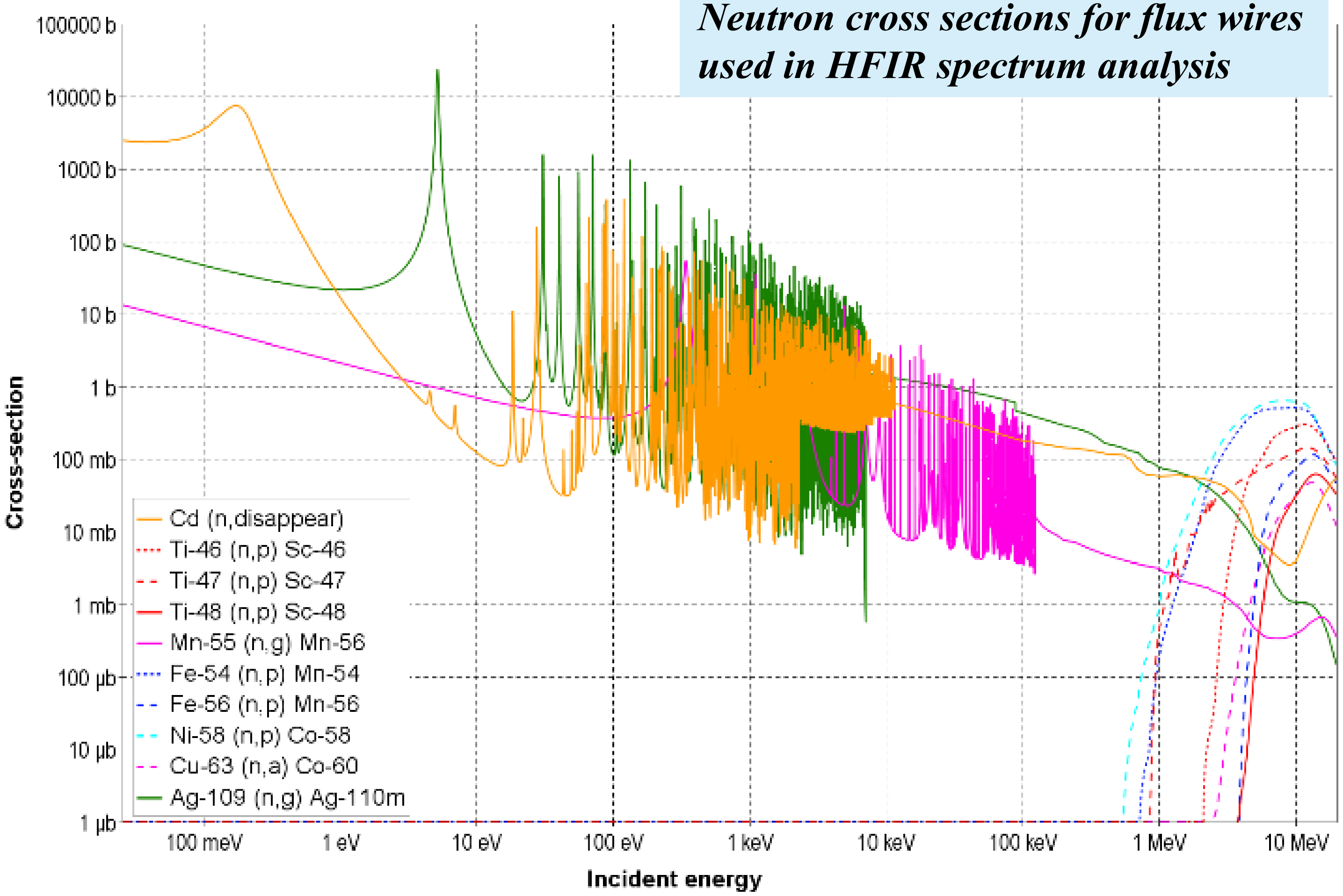
The point:

- While the dosimetry errors are minor for the LWR test reactors they add up
  - *10% turnaround dose error:*
    - ***Replacing core too early***
    - ***Outside safety envelope***

And this is for thermal designs:

- *Fast, sodium, molten salt, liquid fuel, etc. ➔ much more difficult to match*

Neutron cross sections for flux wires used in HFIR spectrum analysis



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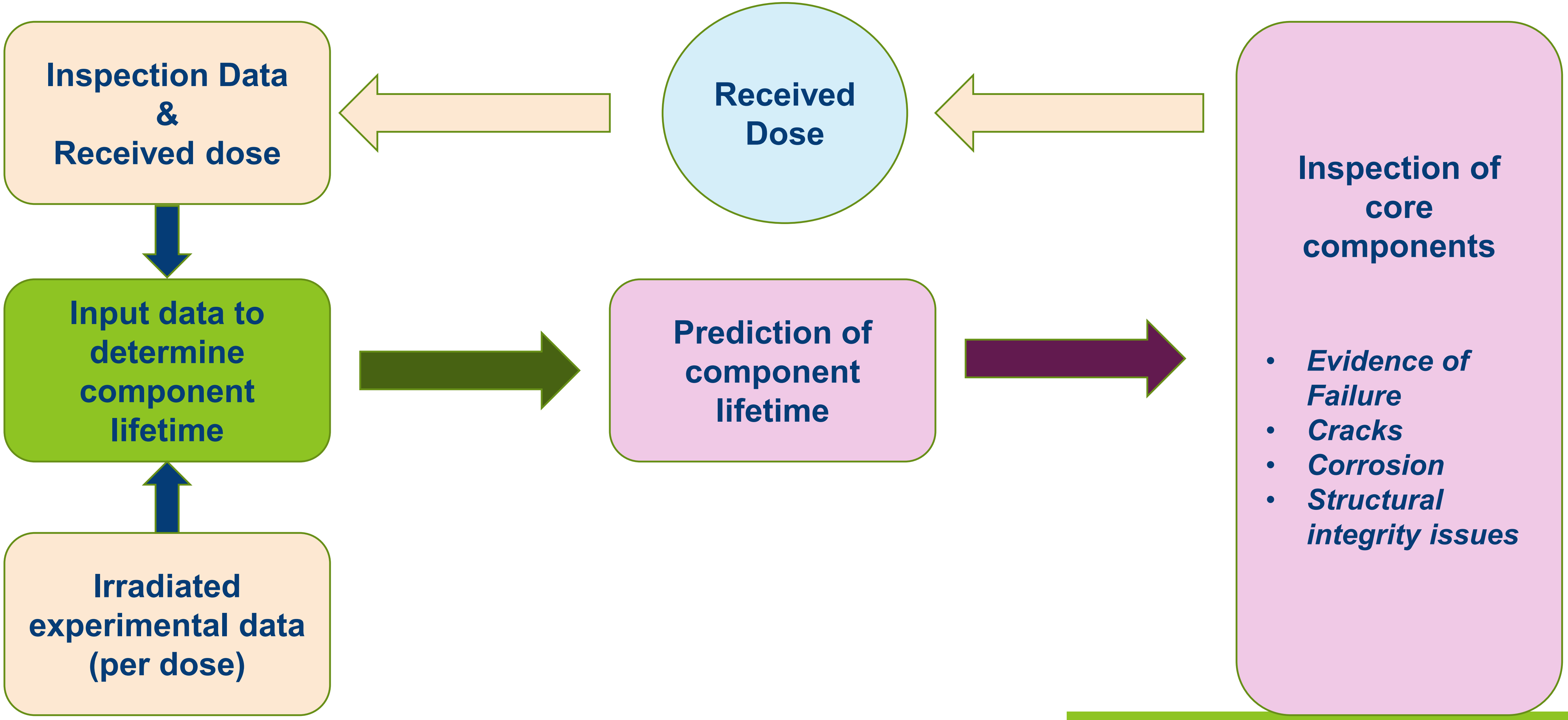
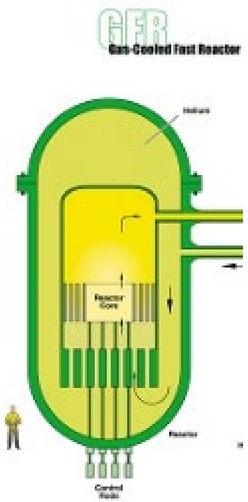
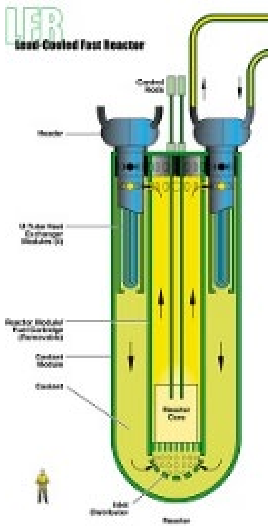
Operational dosimetry requirements

This is how component lifetime will be estimated

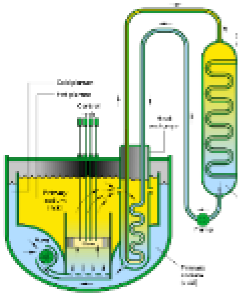


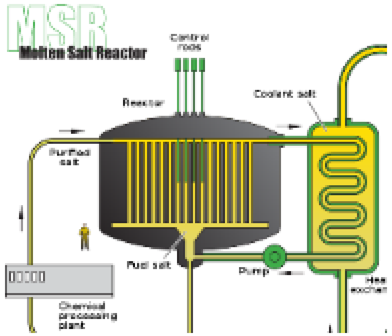
New dosimetry techniques within advanced designs

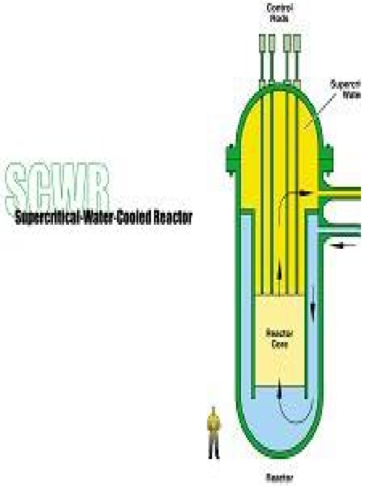


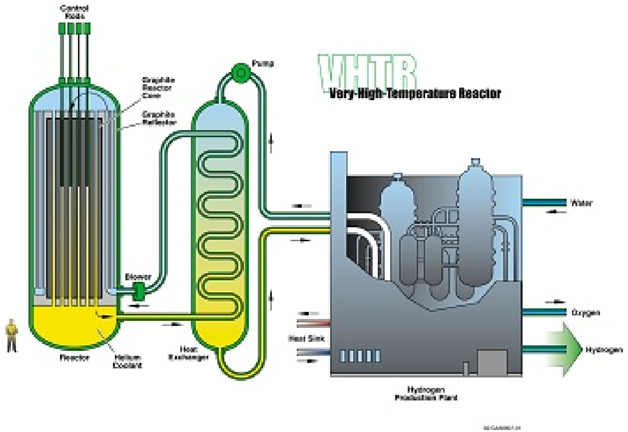


Sodium Fast Reactor









- New dosimetry techniques needed for challenging environments of new advanced reactors:
  - Solid cores
    - ***Solid graphite & composite cores***
  - Corrosive molten salts, lead, sodium, supercritical water
  - 1000°C temperatures
  - Fueled molten salts, carbide fuel
- Compact designs:
  - Micro-reactors
  - Heat pipes
  - Continuous fueling
- You need to begin to collaborate with material scientists
  - They need your help!

Conclusions

- Nuclear renaissance is here
  - Multiple Advanced Reactor designs being built world-wide
  - New reactor materials need to be qualified for irradiation applications
- Irradiated materials qualified as a function of received dose
  - Light water, U-Al test reactors used to qualify new materials
  - Material property changes per n/cm^2-s
  - Component lifetimes calculated by received dose
- Material Scientists need accurate dosimetry to predict accurate lifetime dose
  - Accurate spectrum
    - *Both in MTR and in designed advanced reactor environment*
  - Correct measurement technique (Flux wires)
  - Other MTRs ~ 5% error
- Need new dosimetry techniques for new reactor designs
  - Challenging core environments that we have never experienced before
  - Please start discussions with material scientists now

A few references

- https://www.energy.gov/ne/articles/5-advanced-reactor-designs-watch-2030
- https://gain.inl.gov/SitePages/Home.aspx
- https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs
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- https://www.energy.gov/ne/downloads/infographic-what-nuclear-microreactor-0
- https://www.terrapower.com/natrium-demo-kemmerer-Wyoming/
- https://www.energy.gov/ne/advanced-reactor-demonstration-program
- https://event.asme.org/CARD-2023
- https://nric.inl.gov/

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