Nuclear Design and Analysis of the NIST Replacement Reactor

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National Institute of Standards and Technology
U.S. Department of Commerce

CHRNS
CENTER FOR HIGH RESOLUTION NEUTRON SCATTERING

Talk Overview

NIST

What this talk will cover:

Introduce Replacement Reactor project

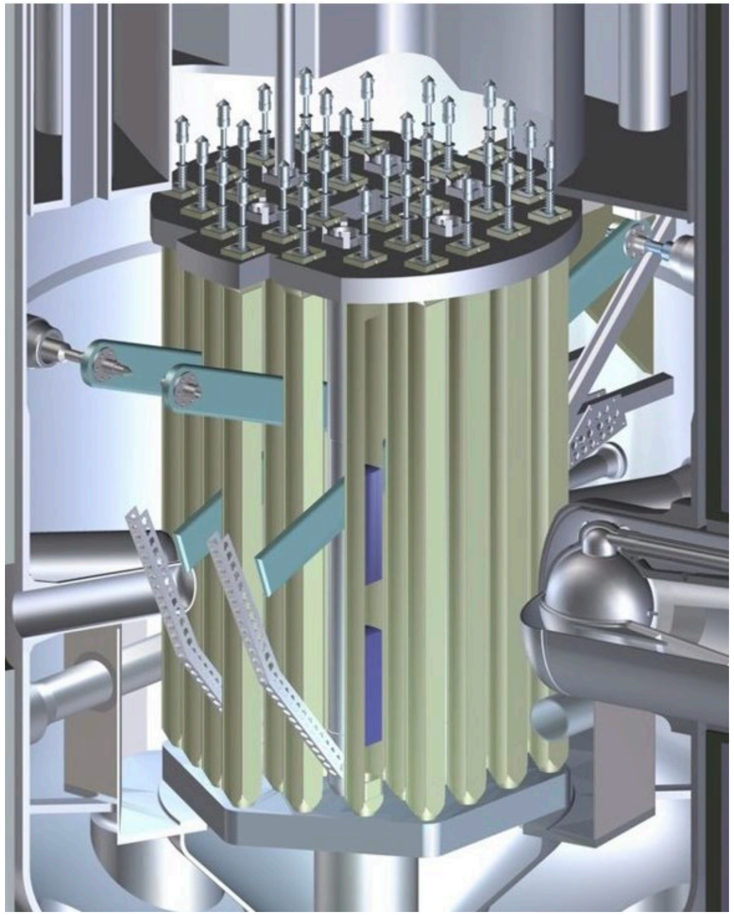
Discuss series of standard reactor physics calculations that characterize reactor performance

Calculation	Significance
Control blade calibration	How does reactor power change as control blades are withdrawn?
Control blade heat expansion	How does the heat from reactor power affect control blade physical properties?
Moderator dump	In an emergency, how much heavy water must be dumped for the reactor to shutdown?
Reactivity coefficients	How does heat affect reactor power over time?

Goal of talk:

Not for everyone to understand all the technical details, but to learn **why** and **how** we calculate certain reactor parameters to determine performance and safety.

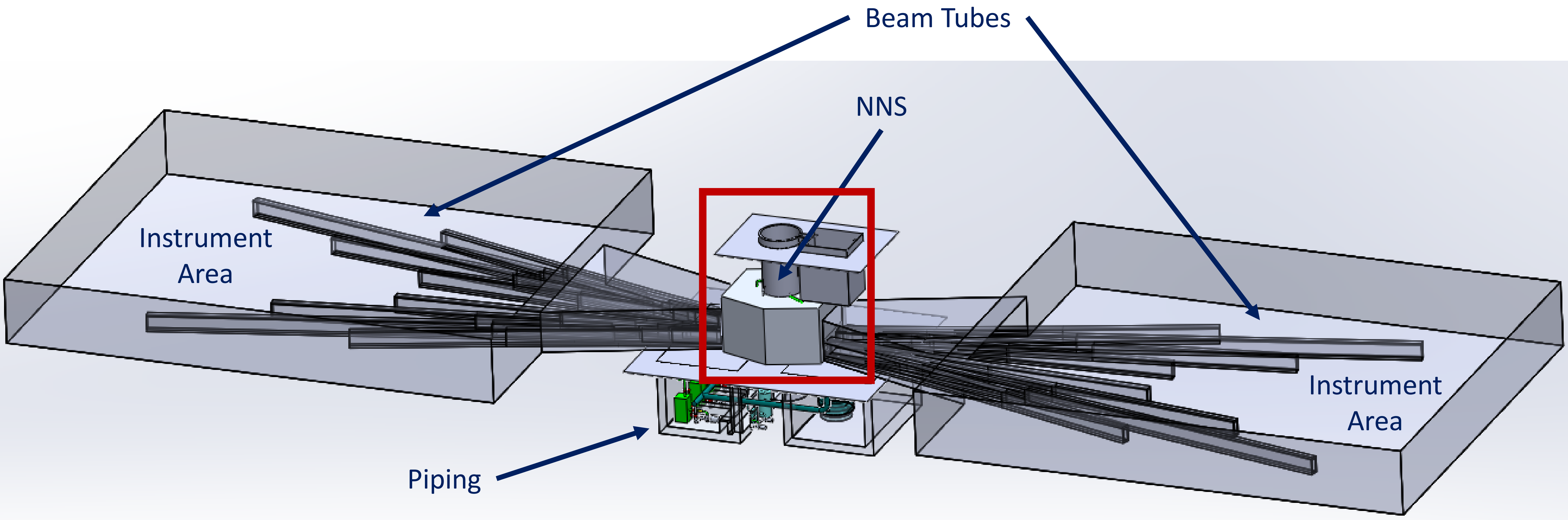
Need for a New Neutron Source



National Bureau of Standards Reactor (NBSR)

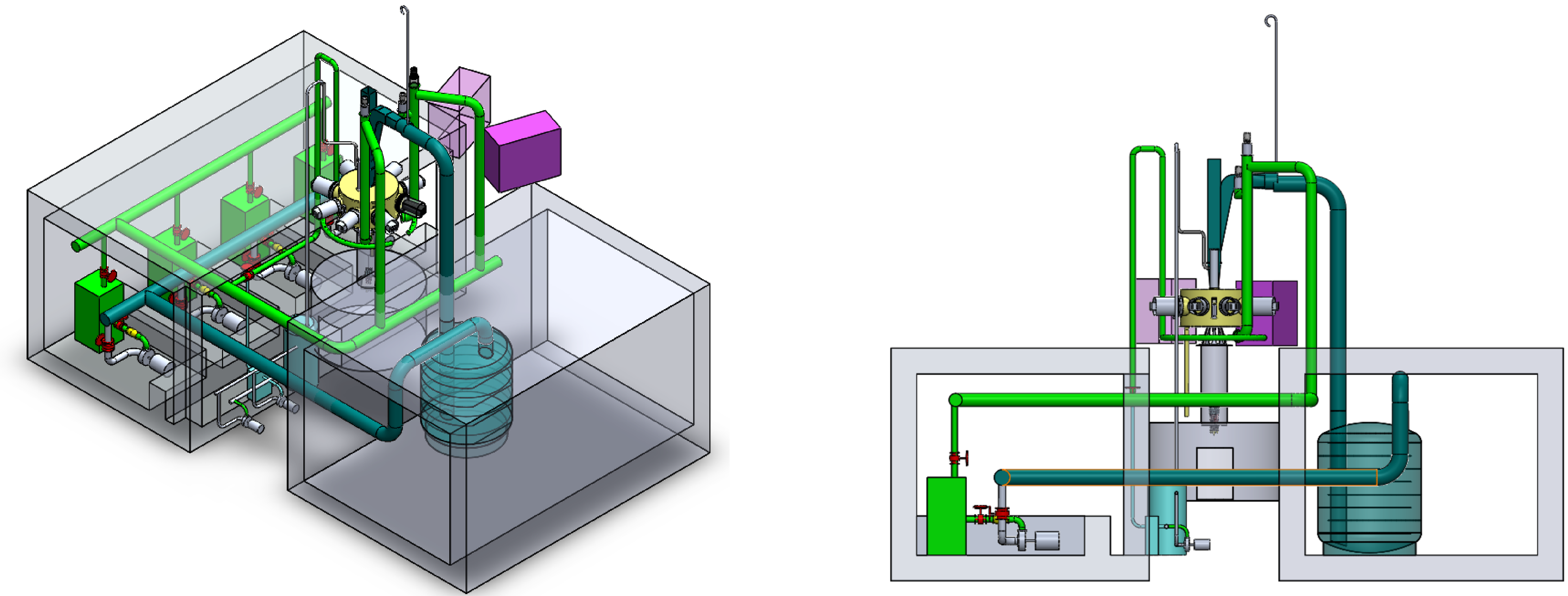
- Research reactors produce neutrons for unique experiments, e.g.
    - Measure element compositions
    - Examine stress fractures at atomic levels
    - Map behaviors of very strong magnets
- Our current source of neutrons (NBSR) has been active since 1967--over 50 years!
- A new neutron source (NNS) allows
    - Easier maintenance
    - More operating time
    - More instruments
    - = More experiments!

Proposal NNS



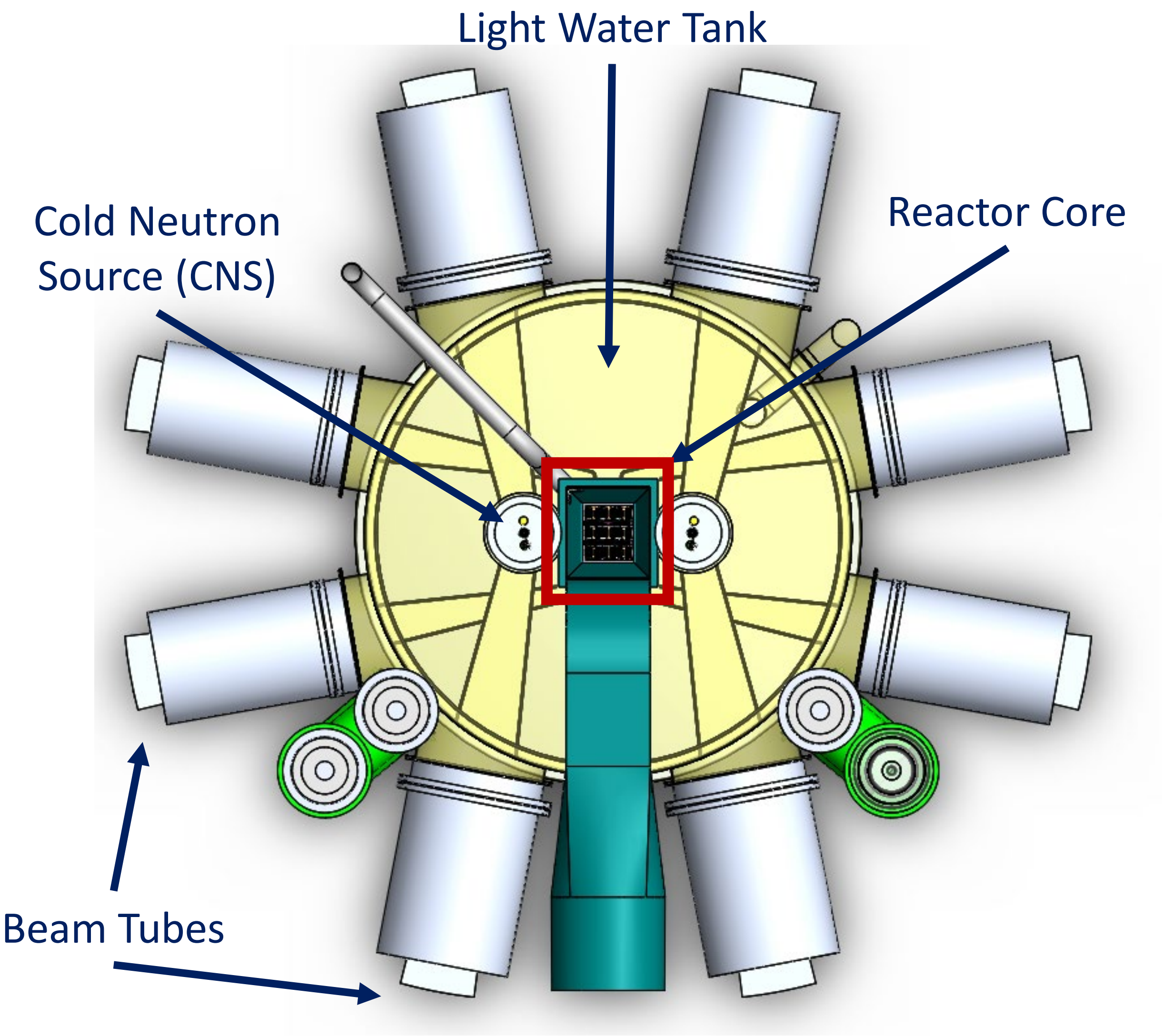
Proposal New Neutron Source (NNS) Site

Proposal NNS



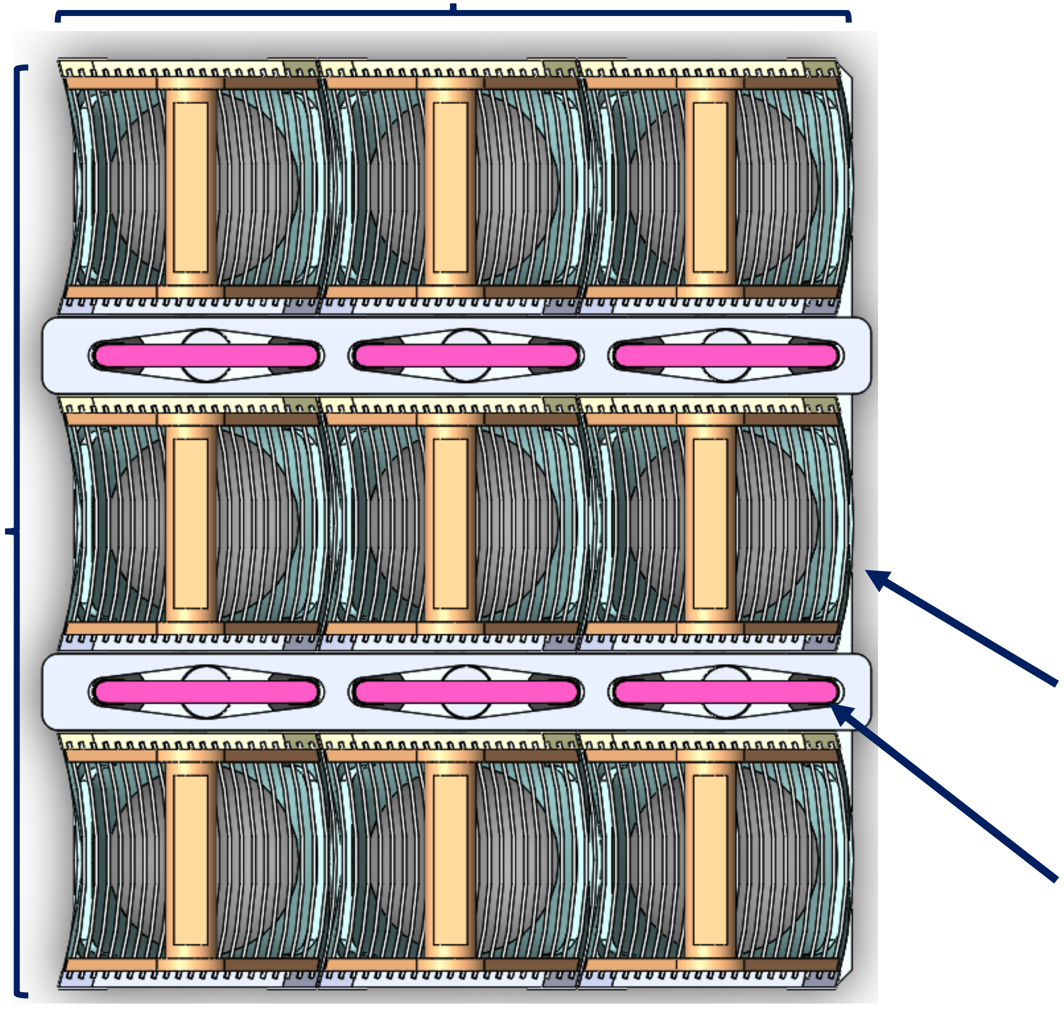
Primary System and Core

Proposal NNS



- Updated cold neutron sources
- More beam tubes
- More room for new instruments

Reactor Core



Basic Core Characteristics

- 9 Fuel Assemblies (U-10Mo)
  - Produce neutrons through fission
  - Curved plates for structural robustness
- 6 Control Blades (hafnium)
  - Control rate of fission by absorbing neutrons when blade is inserted in core

NBSR and NNS Comparison

NBSR

- 20 MW
- D2O coolant
- Closed vessel
- HEU fuel
- 30 fuel assemblies
- 38.5 day cycle
- 1 instrument hall

NNS

- 20 MW
- H2O coolant (Lower cost)
- Open pool (Easier maintenance)
- LEU fuel (New requirement)
- 9 fuel assemblies
- 50 day cycle (More op time)
- 2 instrument halls

NEUTRON INTERACTIONS

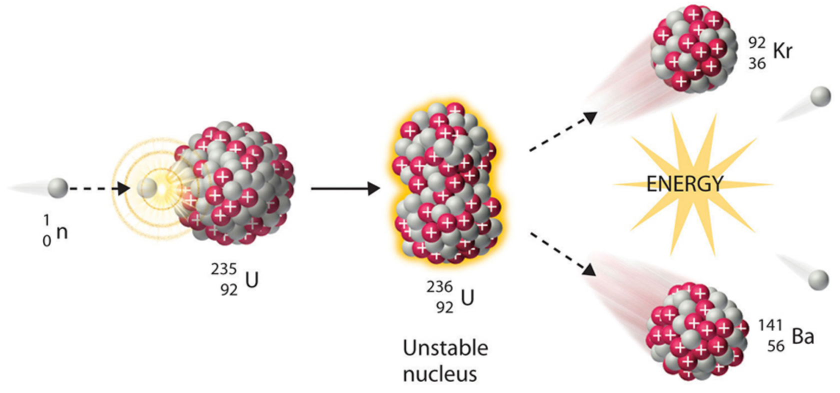
FISSION

Fission is a process in which a nucleus splits into two smaller nuclei. Nuclear reactors use **induced fission**, where neutrons bombard a heavy radioisotope, like U-235, producing an unstable, compound nucleus that then fissions.

About 2.4 neutrons and 200 MeV are produced per fission event.

Fission is a probabilistic event, where there exists a non-unitary probability of inducing fission.

Spontaneous fission events also occur, where a heavy radioisotope fissions without an incident particle but in negligible amounts.



Biff the Trainee says…

U-235 fission produces fission products, energy, and 2 neutrons.

NEUTRON INTERACTIONS

NEUTRON ENERGY SPECTRUM AT 20 C

CLASSIFICATION	ENERGY (eV)
cold	0.0-0.025
thermal	0.025
epithermal	0.025-0.4
intermediate	0.4-1 MeV
fast	1-20 MeV

The kinetic energy of a particle is proportional to the temperature of its surroundings. Thermal neutrons are called "thermal" because they are in equilibrium with the thermal motion of the surroundings. So, these energies are relative to surrounding temperature.

Uranium needs thermal neutrons to fission

Fissioning uranium releases fast neutrons

To sustain fission, these fast neutrons need to be slowed down to thermal energies.

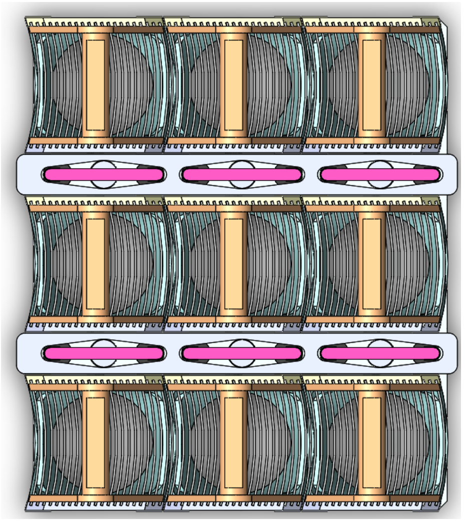
Biff the Trainee says...

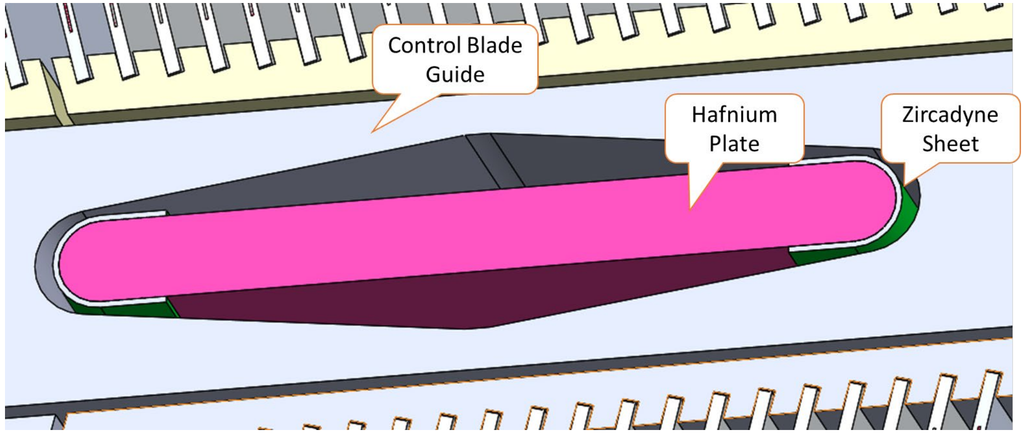
Fission *requires* thermal neutrons but *produces* fast neutrons.

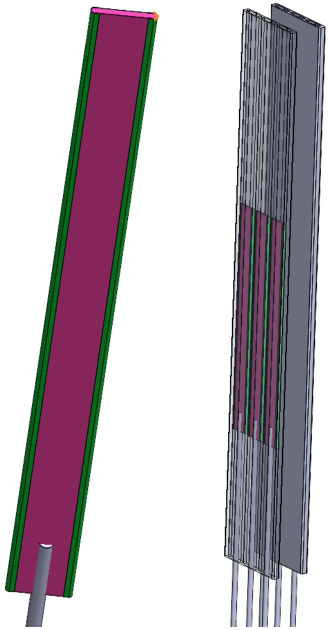
Control Blade Calibration

What is a Control Blade?

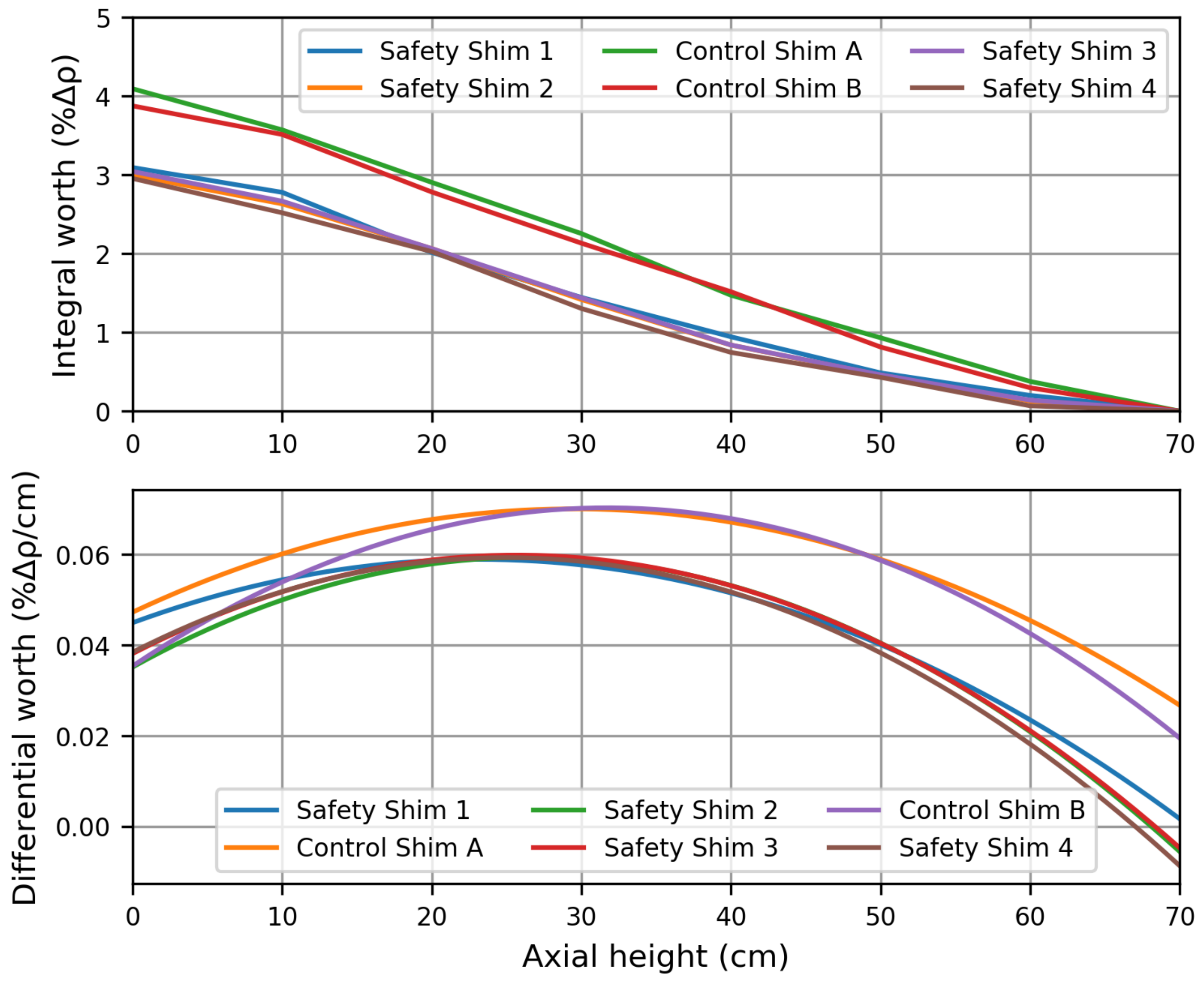
Six control blades (70 cm tall, 7 cm wide, 0.7 cm thick) made of halfnium plates control reactor power. When they are fully inserted, the reactor is shutdown. When fully withdrawn– full power.







Control Blade Calibration



What is a Control Blade Calibration?

Essentially, measure how much reactor power changes from blade movement

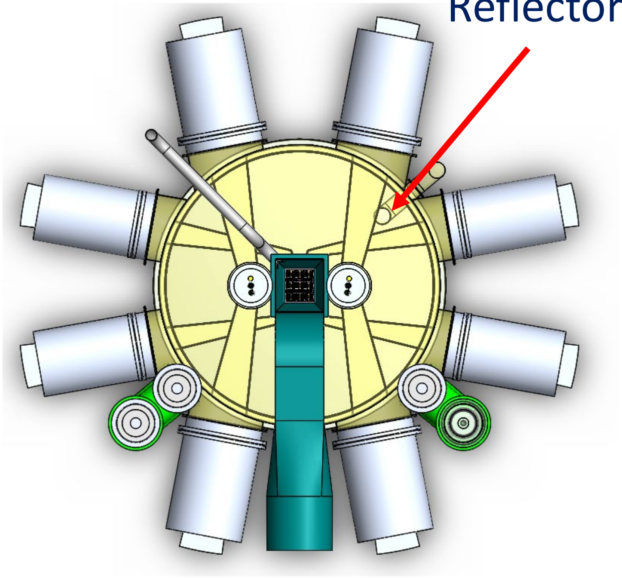
Observations

- Control blades in the middle of the core are "worth" more because they affect a larger amount of neutron flux

Reflector Dump

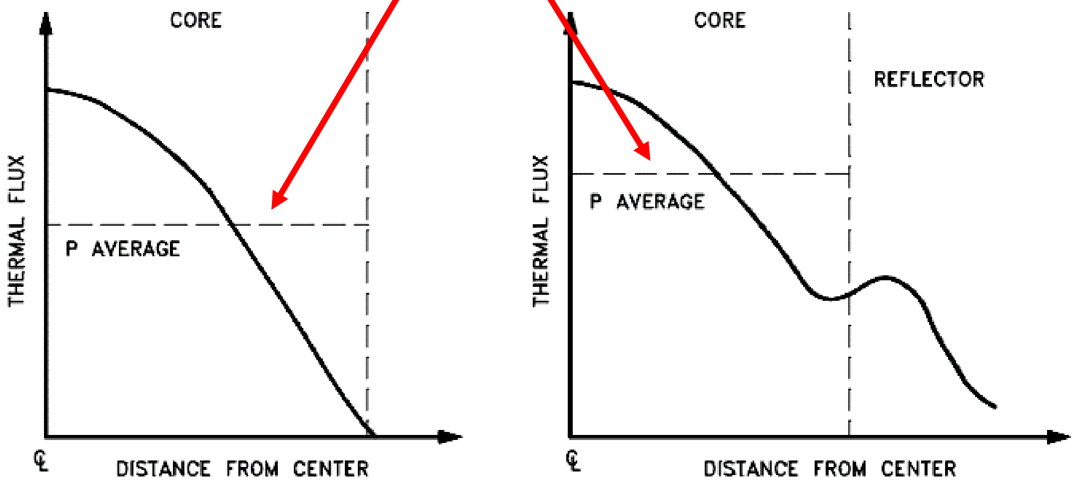
- **Reflector** (NNS: heavy water) bounces neutrons back into the core, reducing neutron leakage
- Should be non-fissionable and have high scattering/low absorption cross sections
- Evenly-distributed flux allows a higher average power and more predictable temps and burnup

Reflector tank of pure heavy water

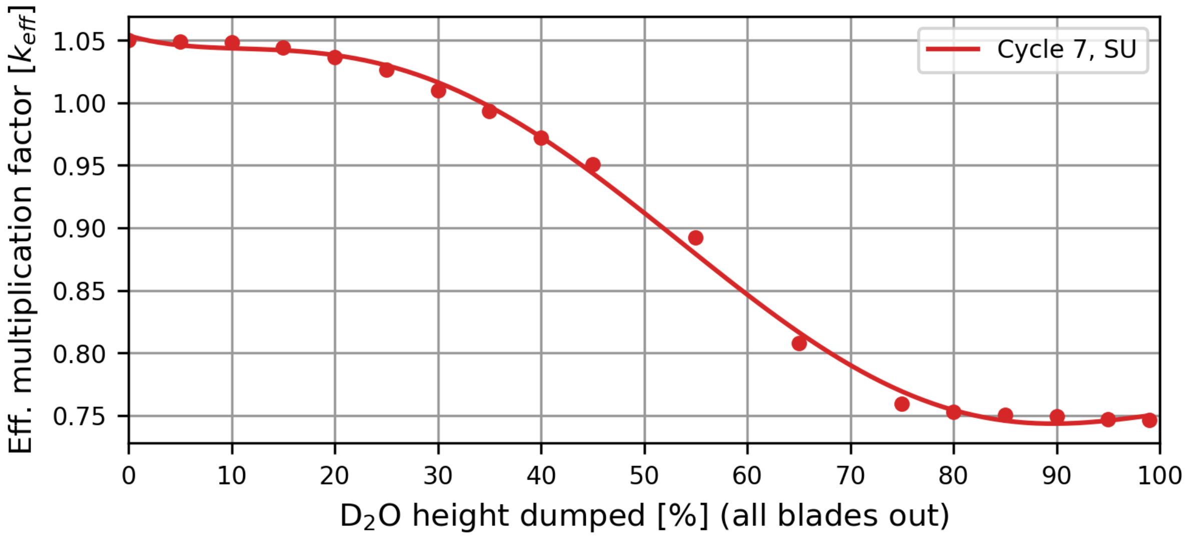


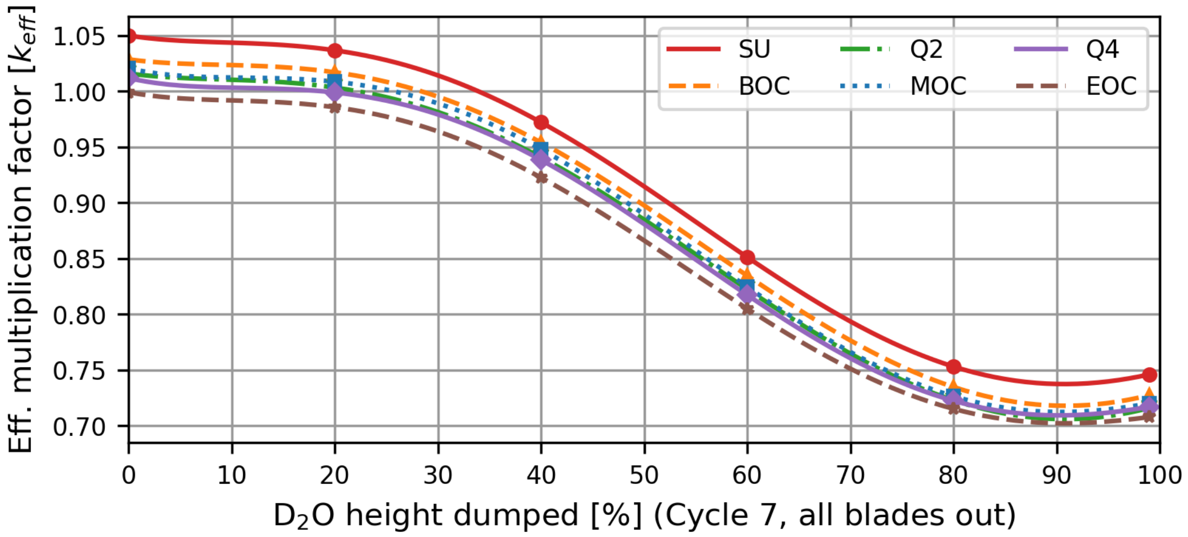
get elevation view

Higher avg power with reflector to contain neutrons



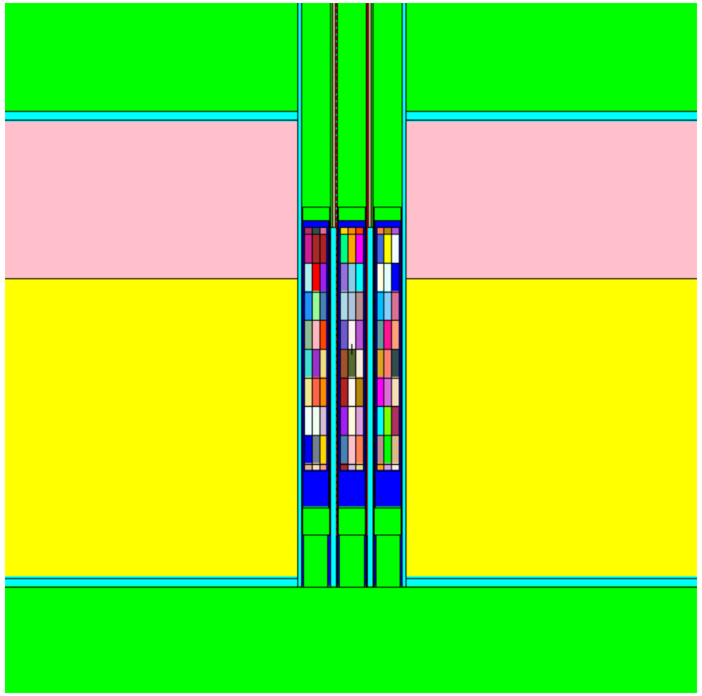
Reflector Dump





Observations

- Reactor is most reactive at startup (SU)
- At least 35% of the heavy water reflector must be dumped for the reactor to be subcritical



Reflector with 35% dumped by noble gas, elevation view

Reactivity Coefficients

Types of Reactivity Coefficients	How is reactor power affected when…
Moderator temperature coefficient	When fission heats up light water moderator
Void coefficient	If air gets mixed in with light water moderator
Fuel temperature coefficient	When fuel elements heat up
Mixing coefficient	If the heavy water reflector and light water moderator accidentally mix

MODERATOR

Fission neutrons are produced with energies of about 2 MeV.

Thermalization is the process of reducing the energy of a neutron to the thermal region (~0.025 eV at 20 C).

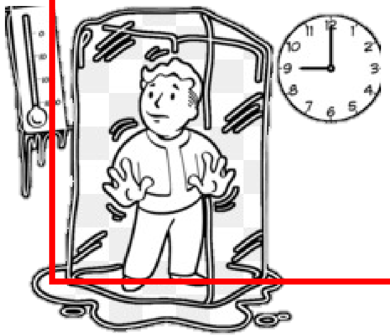
A moderator is used to thermalize neutrons.

A good moderator reduces neutron speeds in as few collisions as possible without absorbing them. This requires a large scattering and small absorption cross sections with large energy loss per collision. In most fission reactors, a good reflector is a good moderator.

The energy absorbed by a moderator (ξ) is measured in units of lethargy (u), where:

$$\xi = -\ln (E_i/E_f)$$

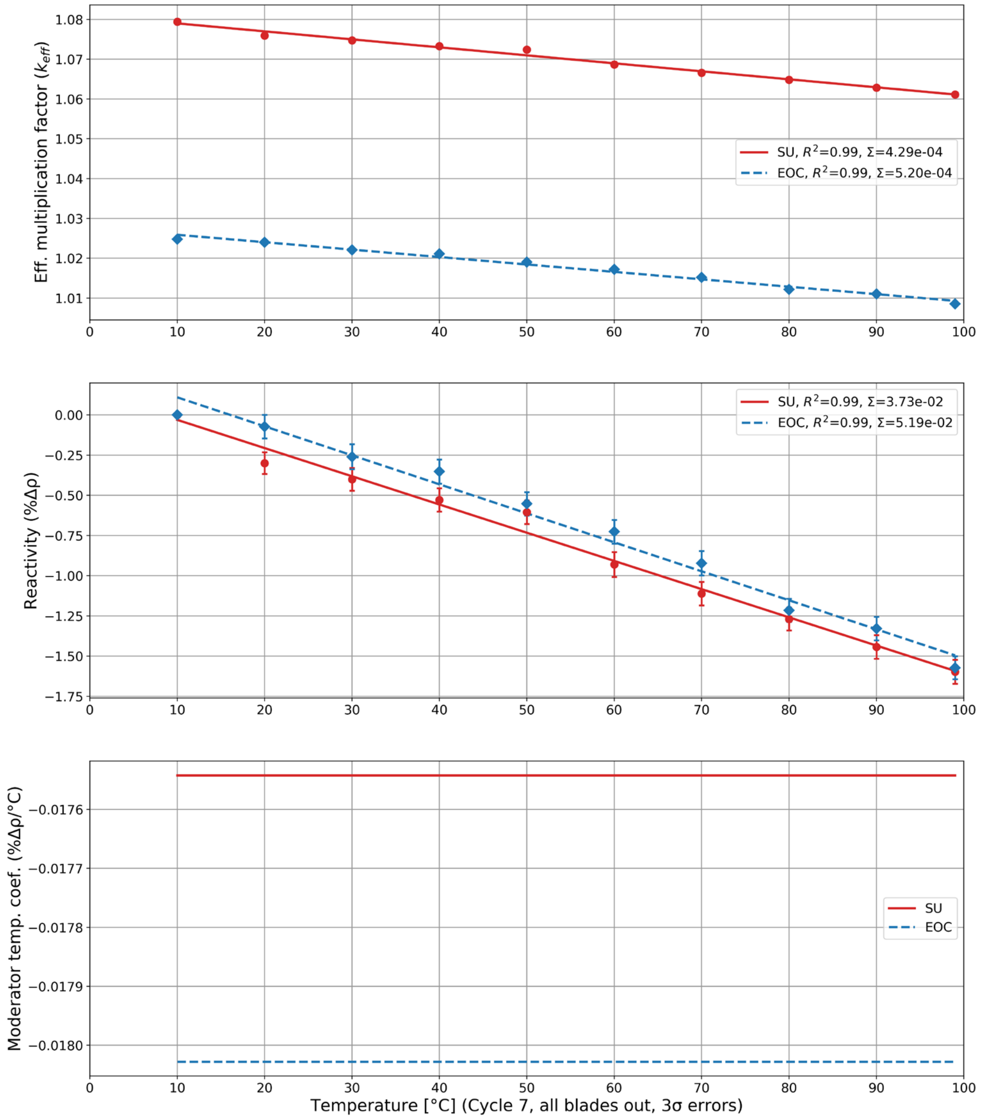
Our moderator reduces 2 MeV fast neutrons to 0.025 eV thermal neutrons by absorbing 99.999999% of the initial energy. By the formula, this is a lethargy of 18.4 u.



Biff the Trainee says…

Our water moderator slows down fast fission neutrons to thermal neutrons, which allows us to sustain fission.

Moderator Temperature Coefficient



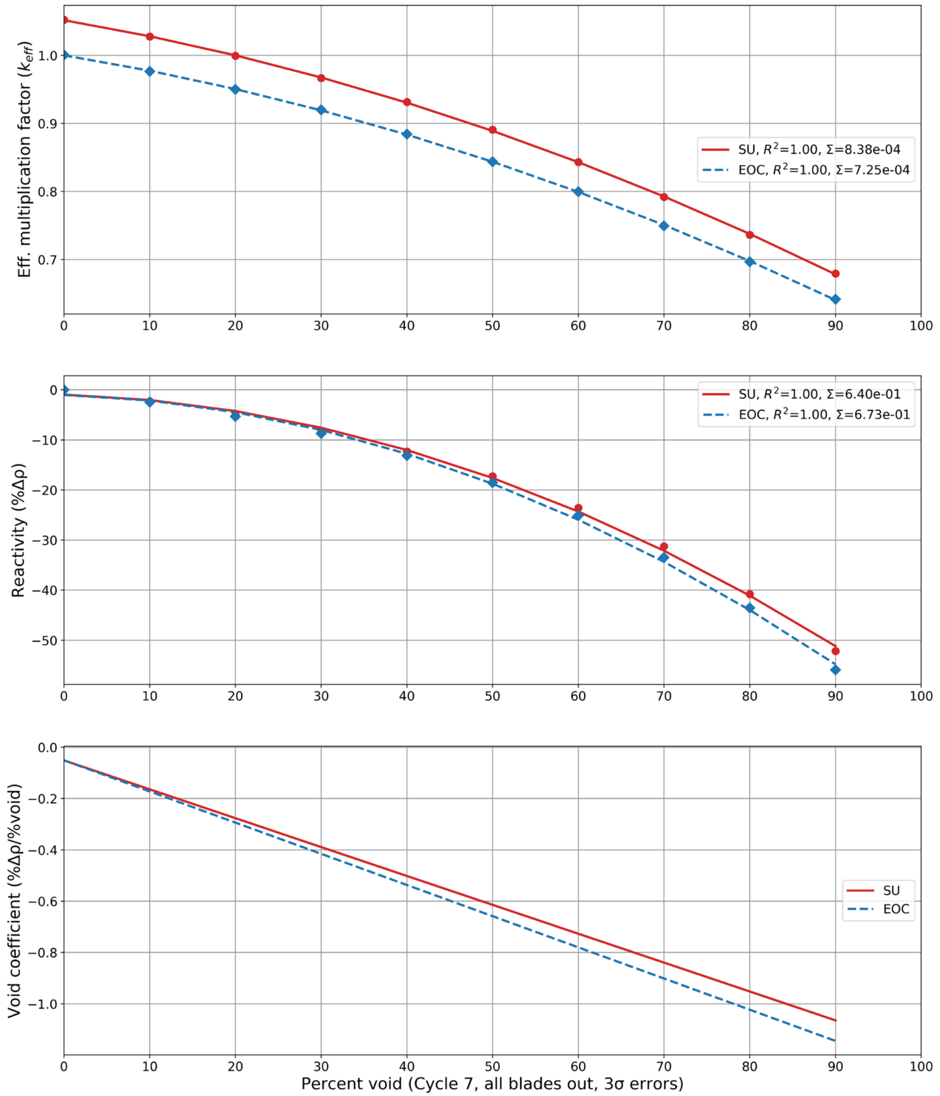
Mechanism

- Water heats up due to thermal energy from fission
- Temperature goes up, density goes down
- Lower density = less effective water molecules in given volume
- Less water molecules = less neutrons causing fission

Observations

- Different cycle states are differently affected by changes in moderator temperature (startup vs. end-of-cycle)
- Moderator temperature coefficient is constant over all temperatures

Void Coefficient



Observations

- Calculates reactor power as a function of constant temperature but decreasing density
- Might be an issue if water is boiled, equipment added to pool, or new beam lines are added (all reducing effective water density)
- 0% void = pure water, 100% void = pure air

Observations

- Different cycle states are differently affected by changes in void (startup vs. end-of-cycle)
- Not expected to be a problem for the NNS

Summary

What we've learned:

Calculation	Conclusion
control blade calibration	Helps us predict how much reactor power changes as we move control blades
control blade heat expansion	How does the heat from reactor power affect control blade physical properties?
moderator dump	In an emergency, about 35% of our heavy water needs to be dumped for a shutdown
moderator temperature coefficient	As light water heats up during operation, it becomes less effective at facilitating fission
void coefficient	Any bubbles or air pockets in the core significantly decreases reactor power

Overall takeaways:

- Plans for a new reactor are underway (on House of Rep. floor for funding soon)
- New reactor will have more instruments, operate longer, be cheaper to maintain long-term
- Series of nuclear calculations help predict reactor performance and safety