LEU Fission Plate Design for Order-of-Magnitude Enhancement of UCN Density at LANL

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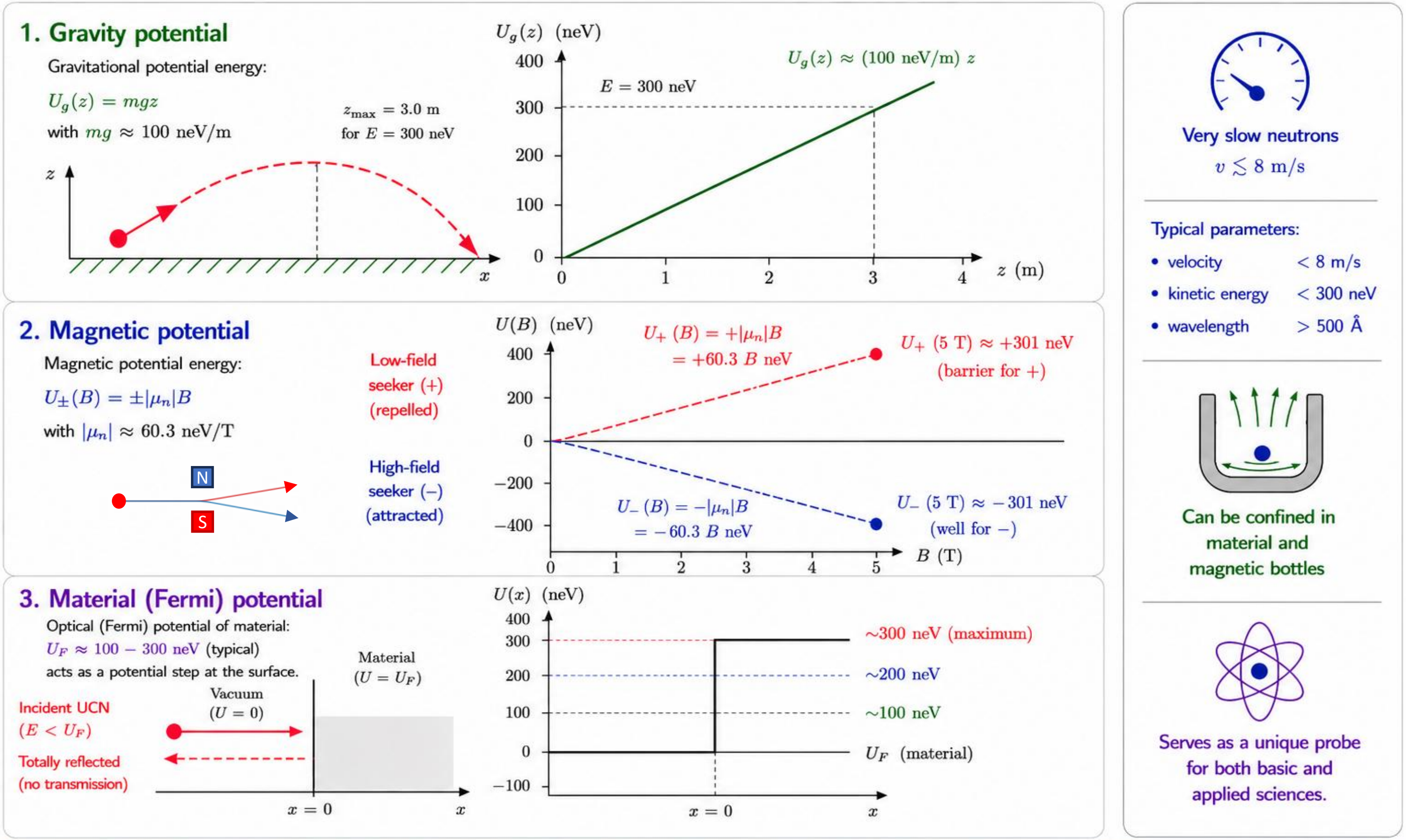
Ultracold Neutrons (UCN)



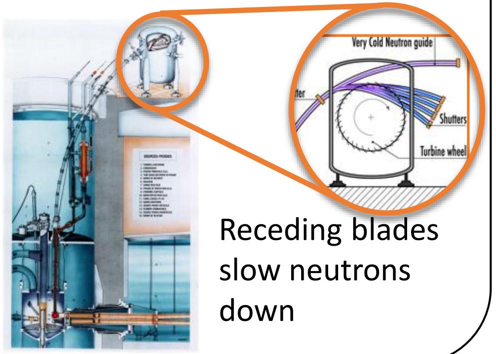
UCN energies ($\lesssim 300$ neV) are comparable to gravitational (~100 neV/m), magnetic (~60 neV/T), and material (~100–300 neV) potentials.
These unusually low energies make UCN sensitive to gravity, magnetic fields, and material surfaces, providing a unique probe for fundamental and applied science.

How are UCN produced?

Neutron turbine

A. Steyerl (TUM/ILL 1985)

~50 cm^{-3}



Receding blades slow neutrons down

Superthermal Process

No thermal equilibrium between the neutron "gas" and the scattering system

Neutrons lose energy by creating phonons in the "converter" (down-scattering)

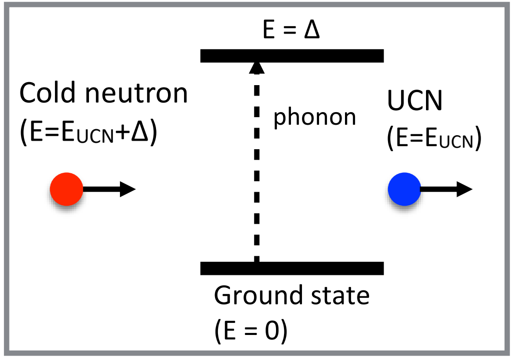
"Up-scattering" is suppressed by the Boltzmann factor

$$\sigma_{up} = \frac{E_{UCN} + \Delta}{E_{UCN}} e^{-\frac{\Delta}{kT}} \sigma_{down}$$

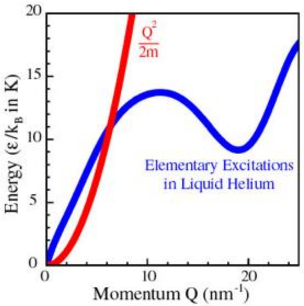
$$\Rightarrow \text{For } \Delta \gg kT \gg E_{UCN}, \quad \sigma_{up} \ll \sigma_{down}$$

(Golub, Richardson & Lamoreaux, 1991)

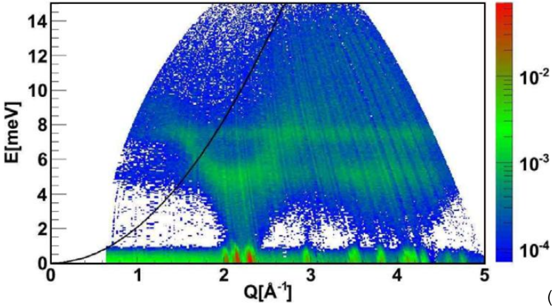
Down-scattering



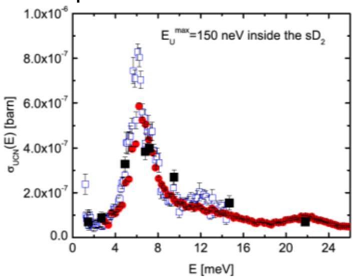
LHe



SD_2 S(Q,E): map pf phonon densities



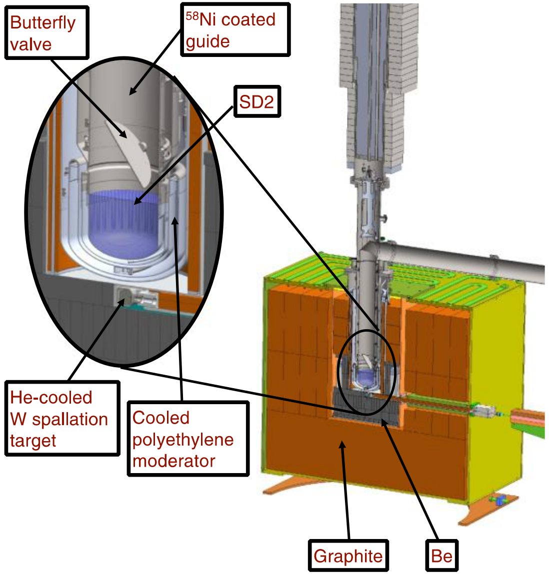
UCN production cross section in SD_2



(Frei et al (2010) EPL)

LANSCE UCN Source

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

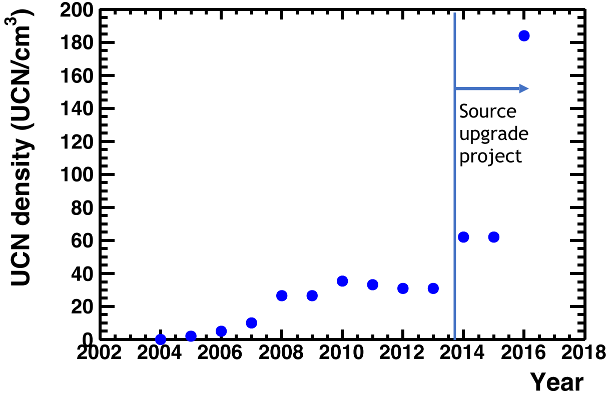


Spallation neutrons from W target
K.E. ~ 2 MeV

Thermal neutrons in Be and graphite moderator
K.E. ~ 25 meV

Cold neutrons in polyethylene cold moderator
K.E. ~ 6 meV

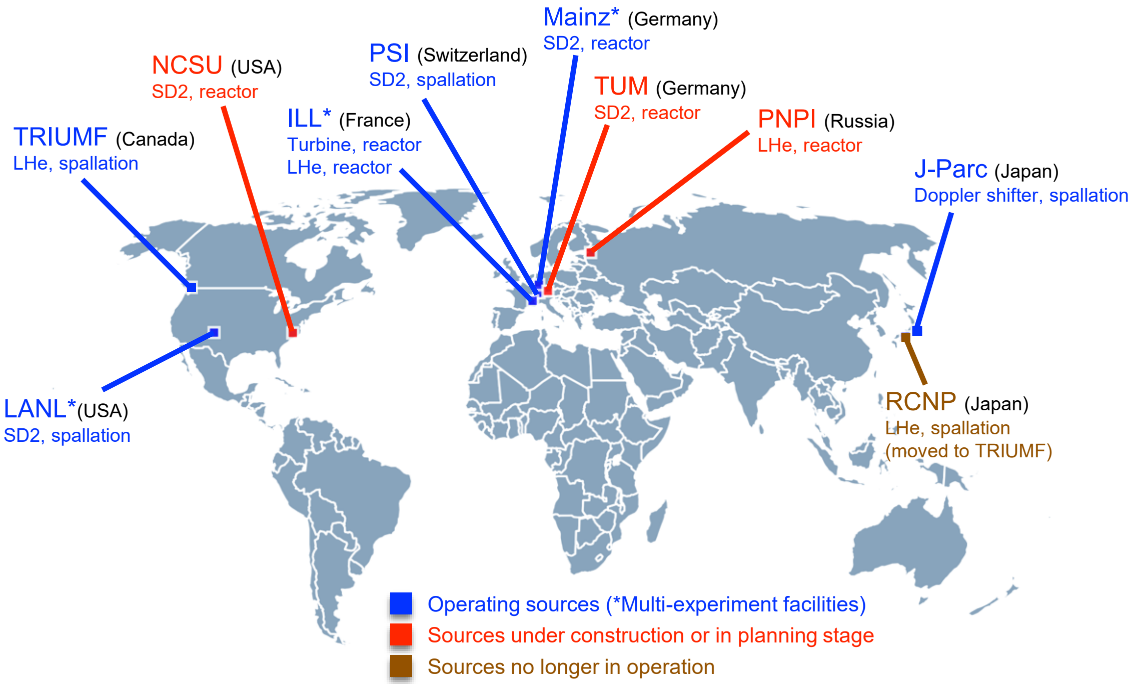
Ultracold neutrons in SD2 converter
K.E. ~ 100 neV



LDRD funded upgrade of the UCN source (FY14-17) more than quadrupled the UCN output by:
1) increasing the average beam current and
2) optimizing for CN moderation and UCN transport, making it the world's best UCN source.
[Ito et al. PRC 97, 012501(R) (2018).]

Poly transport, C. M. Lavelle, C. Y. Liu, M. B. Stone, NIM A 711, 166 (2013).
SD2 transport, J. R. Granada, Eur. Phys. Lett. 86, 66007 (2009).

UCN sources around the world



Why (Low) Enriched Uranium?

6 meV neutrons for UCN production
0.025 eV thermal neutron energy
2 MeV average fission neutron energy

Ideal process: fission fast neutrons and preserve thermal and cold neutrons, however material mass requirements prevent this

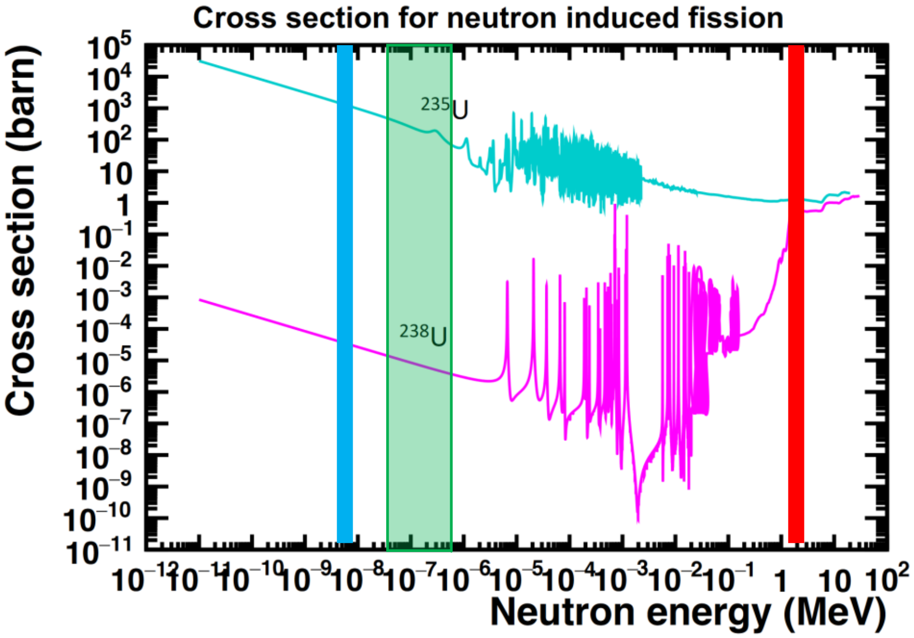
Mean free path for fission

Thickness of material required:

- Fast neutrons
  - 40 cm in DU
  - 20 cm in U-235
- Thermal neutrons
  - 0.02 cm in U-235
  - 0.1 cm in 20% LEU

Can create fission neutrons from thermal neutrons, but not reasonably well from fast neutrons

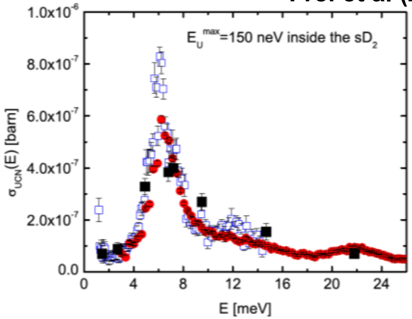
Need U-235 to increase fission rate in compact space and reduce material budget



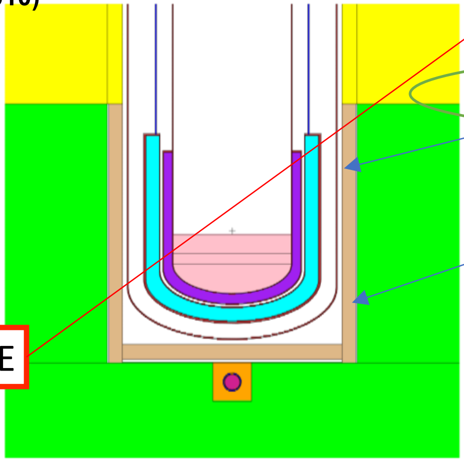
LEU Boosted Source / Thermal Moderators

Material	Thermal MFP (cm)	Thermal Abs (cm)	1 MeV MFP (cm)	1 MeV Abs (cm)	UCN prod (/319 UCN/cm³/μC)	Ave Heat SD_2 (/6.5 W)	Prod Gain/ Heat Gain
CH_2	0.37	37	2.2	(>10 m)	3.0	2.8	1.1
H_20	0.46	45	1.8	(>10 m)	6.7	5.6	1.2
Be	0.26	167	0.51	556	3.5	4.5	0.7
C	2.1	3333	4.1	(>1 m)	1.4	1.4	1.0

Frei et al (2010)



$$P_{UCN} = \rho_{SD}\int \Phi_{CN}(E)\sigma_{UCN}(E)dE$$



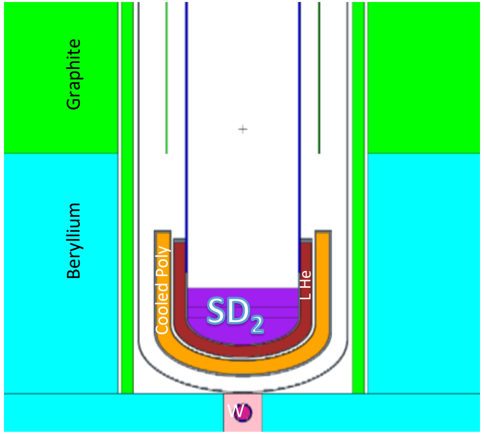
Thermal Moderator – 1.79 cm wall

LEU Shell – 2.1 mm wall / 16.5cm radius

Current Source – Graphite Shell – 2 cm wall
319 UCN/cm³/μC and 6.5 W

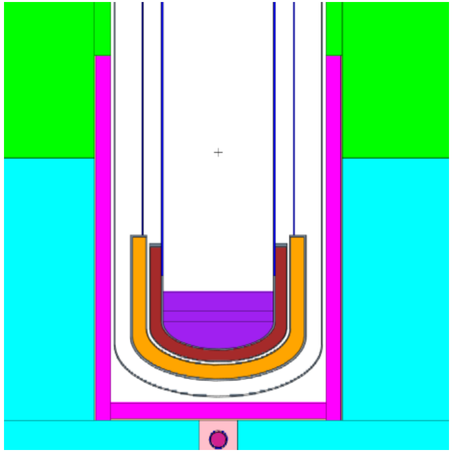
MCNP Modeling: Improvements and Gains

Existing Source



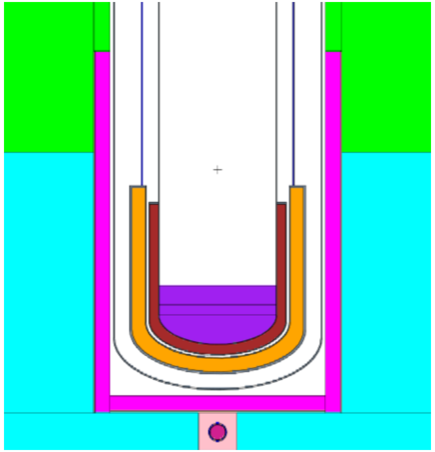
7.5X

LEU Fission Plate



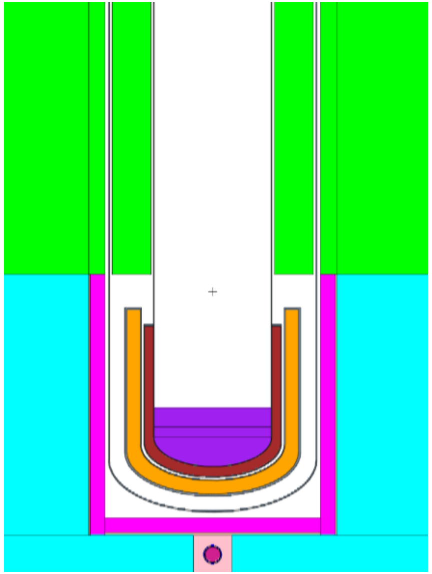
10X

Fission Plate + Taller Cold Source



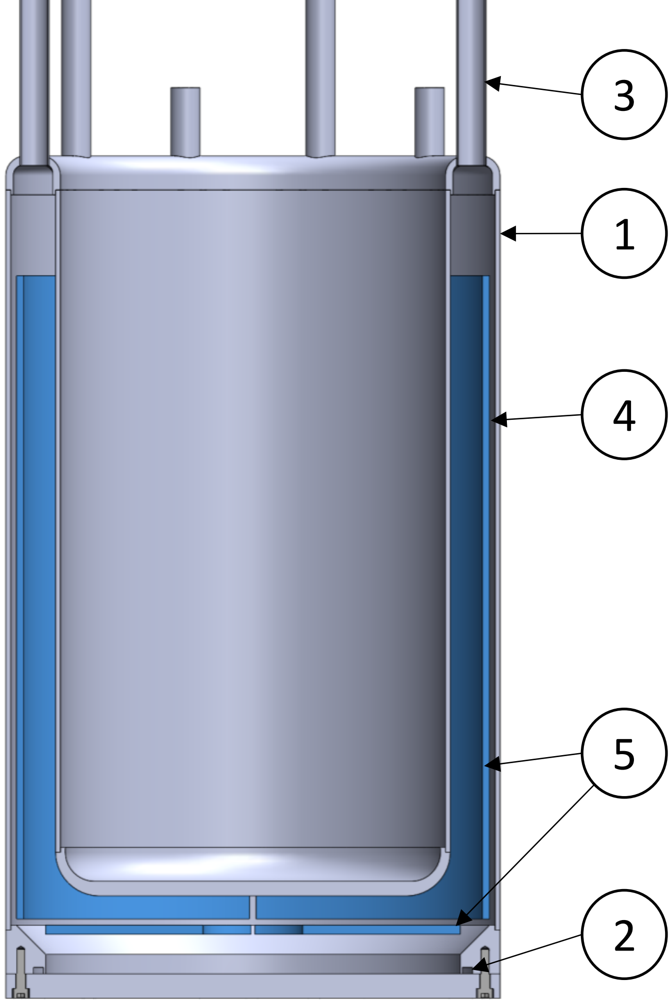
15X

Fission Plate + Taller Cold Source + Graphite in Cryostat Neck



From Concept to Design

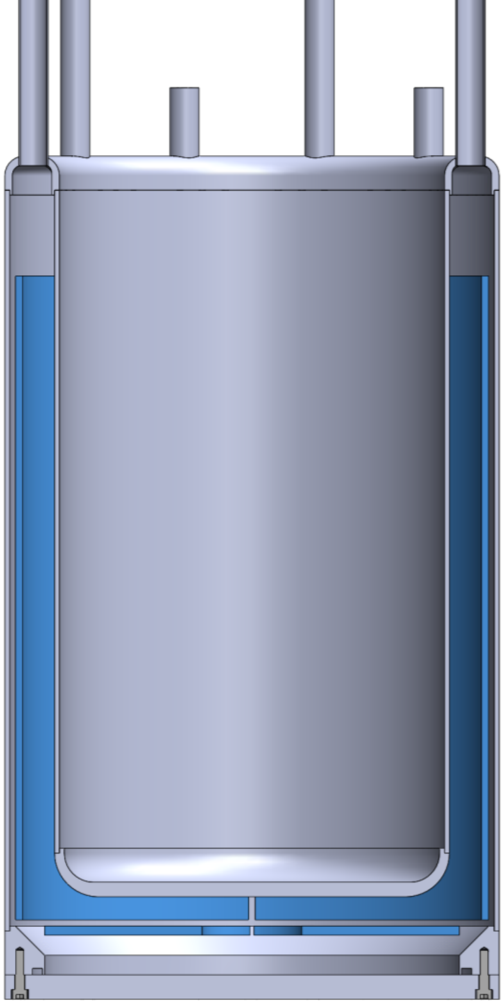
- Sized to fit inside space of existing graphite cylinder
- ① Detailed for compatibility with ASME BPV Sec VIII and manufacturability
- ② Metal O-Ring seal for ease of assembly
- ③ Inlet and Outlets sized for fluid flow
- ④ Flow requirements and water channels based on coolant needs
- ⑤ LEU geometry based on manufacturability, encapsulation requirements, and neutron moderation thickness
- Aiming for useable life of 10 years



Los Alamos NATIONAL LABORATORY

Vessel Design

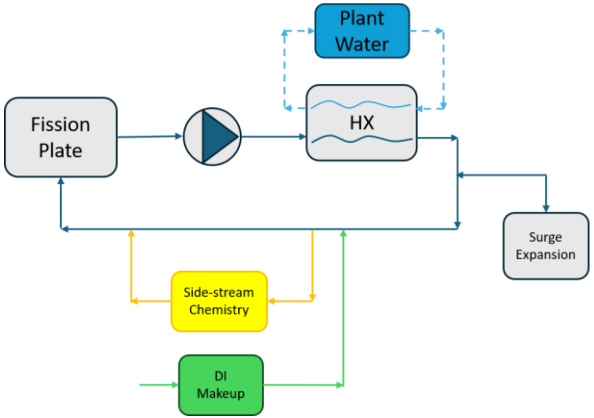
- To circulate water, must pressurize to ~100 psi
- Modest pressure also raises boiling temp
- Design temperature – 150 °C Max
- Materials,
  - must be neutron friendly
  - prefer high strength for thinner walls
  - galvanic compatibility
  - aluminum or zirconium (dehalfinated)
  - Zr2.5Nb alloy preferred
- Construct to Zr705 specs, use nuclear grade alloy
- Cannot find vendor to bid
  - will probably construct in-house
  - sourcing material will be largest bottleneck



LEU Cooling: Concept and CFD checks

Closed Primary Cooling Loop

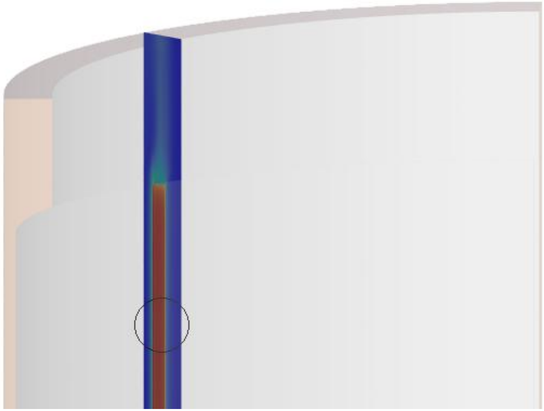
High purity DI water in the primary loop is needed to prevent corrosion. Leak detection in the heat exchanger maintains control over water chemistry and identifies issues before they arise



(grey)	Heat removal path	Designed to accommodate a 200 kW primary loop with additional capacity. 50 – 100 GPM
(yellow)	Water Chemistry path	DI cleanup, mixed-bed resin, filtration, conductivity/pH/flow/DP monitoring 1 – 5 GPM

Preliminary Fluent cooling results

Model provides basis for water coolant design pressure and flow rates with conservative heat loads



Static fluid flow channel surrounding LEU element.

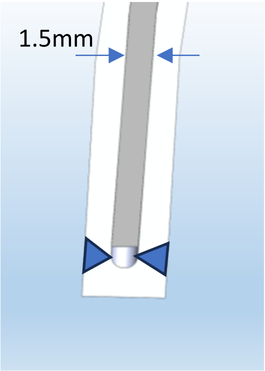
50 GPM bottom to top

140 kW/liter bulk fission heating in LEU

322 K maximum temperature

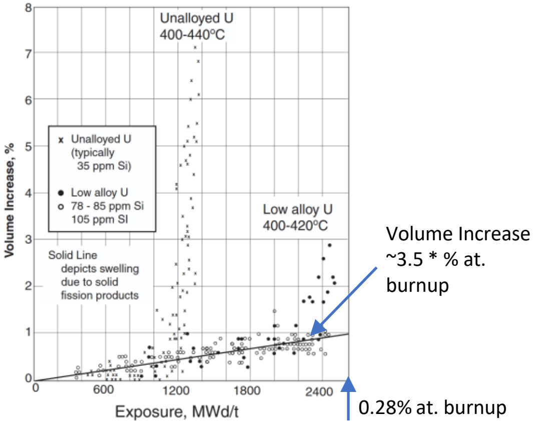
LEU and Encapsulation: Swelling and Aging

Fabrication Plan



Local casting →
co-roll with Zr-2.5Nb →
edge welding (e-beam)→
oversized plenum
backfilled with He

Fission Swelling

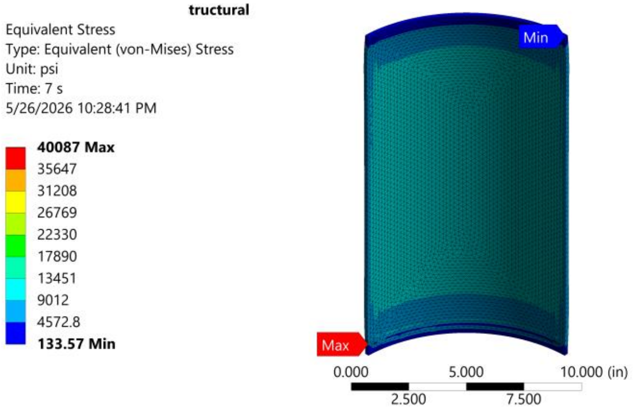


$\Delta V/V \approx 3$ X at. % BU

2.59×10^{19}fissions/cm³/cycle
→ **~0.053 at.% BU → ~0.16% swelling**

10-year / 10-cycle estimate:
2.59×10^{20}fissions/cm³
→ **~0.53 at.% BU → ~1.6% swelling**

ANSYS Model of 7% swelling



With a planned lifecycle of 10 years, a conservative mechanical model of swelling shows stresses below the yield stress of Zr2.5Nb ~ 55 psi

Roy and Sah, *Irradiation Behaviour of Nuclear Fuels*, 1983; McDonell, Caskey, and Angerman, "High-Performance Uranium-Metal Fuels for Savannah River Reactors"; Seshadri, Jokisaari, and Sun, "A Review of Irradiation Damage and Effects in α-Uranium.

Activation Products: What limits the lifecycle?

Isotope	σ (barns)	Half-Life	Removal	Reactivity Impact
Xe-135	**2,650,000**	**9.14 hours**	**Decay dominates**	**~0.6% (equilibrium)**
Sm-149	40,140	STABLE	Burnup only	~0.4% (equilibrium)
Gd-157	254,000	STABLE	Instant burnout	Trace only
Gd-155	60,900	STABLE	Instant burnout	Trace only
Zr-88*	771,000	83.4 days	Decay dominates	~0.4% (estimated)

*Cross section newly measured (PRL 134, 112702 (2025)) Will evaluate with MCNP when data becomes available

✅ **Neutron poisons are NOT a limitation** – total reactivity impacts ~1.5% of flux

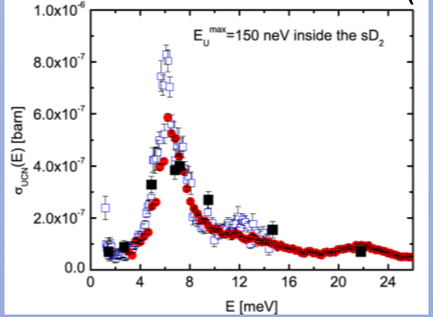
⚠️ **Pu-239 buildup limits you to ~9 cycles** (116 days each) before safety analysis update needed

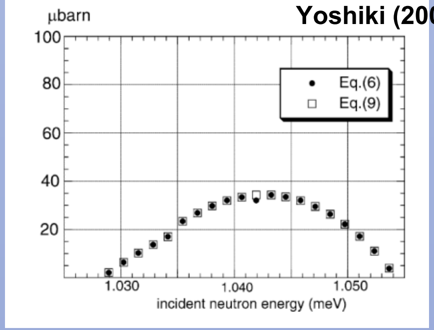
Conclusions

- Design of a fission plate can boost the density of ultracold neutrons by 8-15x
- Material budget ~15-18 kg 20% LEU (in hand)
- We don't plan to irradiate the LEU with proton beam, but spallation neutrons with a rate of ~ 6.5E10 n/(cm^2 sec)
- We prefer LEU metal because LANL knows how to process locally
- This design requires a water moderator that would be used for cooling as well and so we would have to encapsulate the LEU metal
- We prefer Zr2.5Nb for the encapsulation and the water containment because of the low capture cross sections, strength and compatibility with stainless steel
- Water system based on LANSCE target team experience
- A number of engineering calculations (cooling, structural, activations) give confidence it will remain operational for a decade

Backup Slides

SD2 vs LHE

<table>
<tr><th></th><th>SD_2</th><th>LHe</th></tr>
<tr><td>UCN production</td><td>Frei et al (2010)


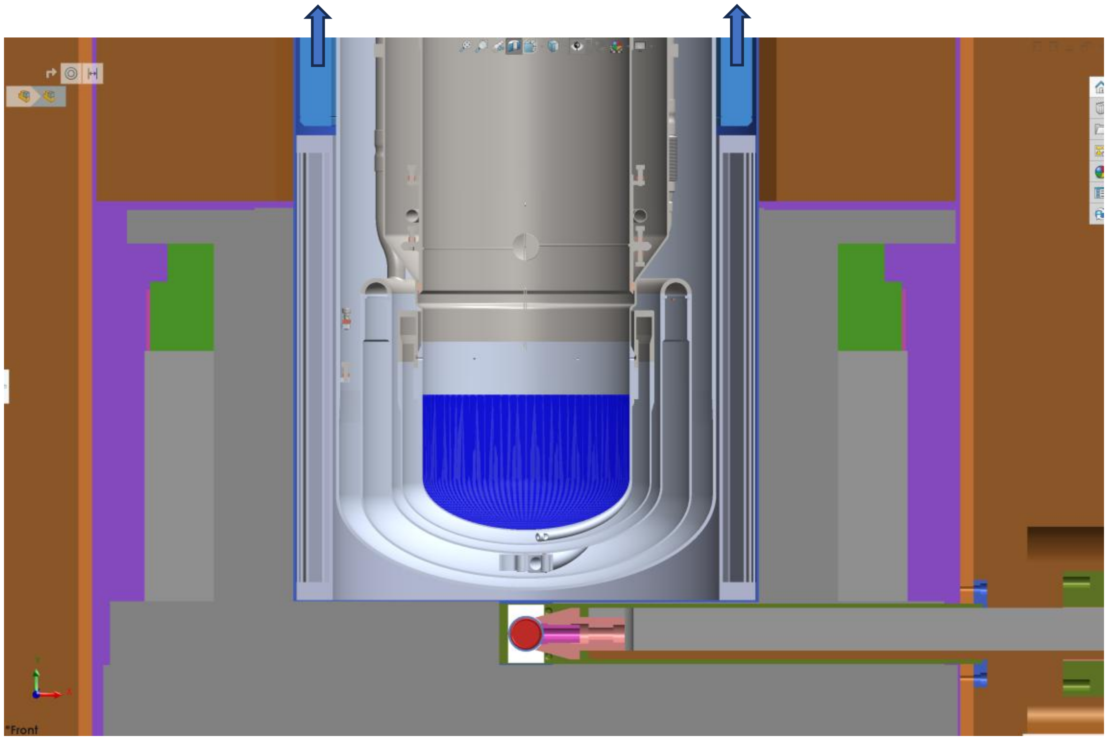
</td><td>Yoshiki (2003)


</td></tr>
<tr><td></td><td colspan="2">$\int\sigma(SD_2)dE \sim 10 \times \int\sigma(LHe)dE$</td></tr>
<tr><td>Up scattering</td><td>τ_{abs} ~ 150 ms at 5 K</td><td>τ_{up}~T^7, and ~1000 s at 0.7 K (multiphonon process)</td></tr>
<tr><td>Nuclear absorption</td><td>τ_{abs} ~ 150 ms</td><td>0</td></tr>
<tr><td>Other losses</td><td>• Absorption by H contamination (τ_{abs}~150 ms at 0.2% HD)
• Up-scattering by para-D2 (τ_{up}~150 ms at 1.0% para)</td><td>Absorption by ^{3}He (τ_{abs}~500 s at X=10^{-10})</td></tr>
</table>

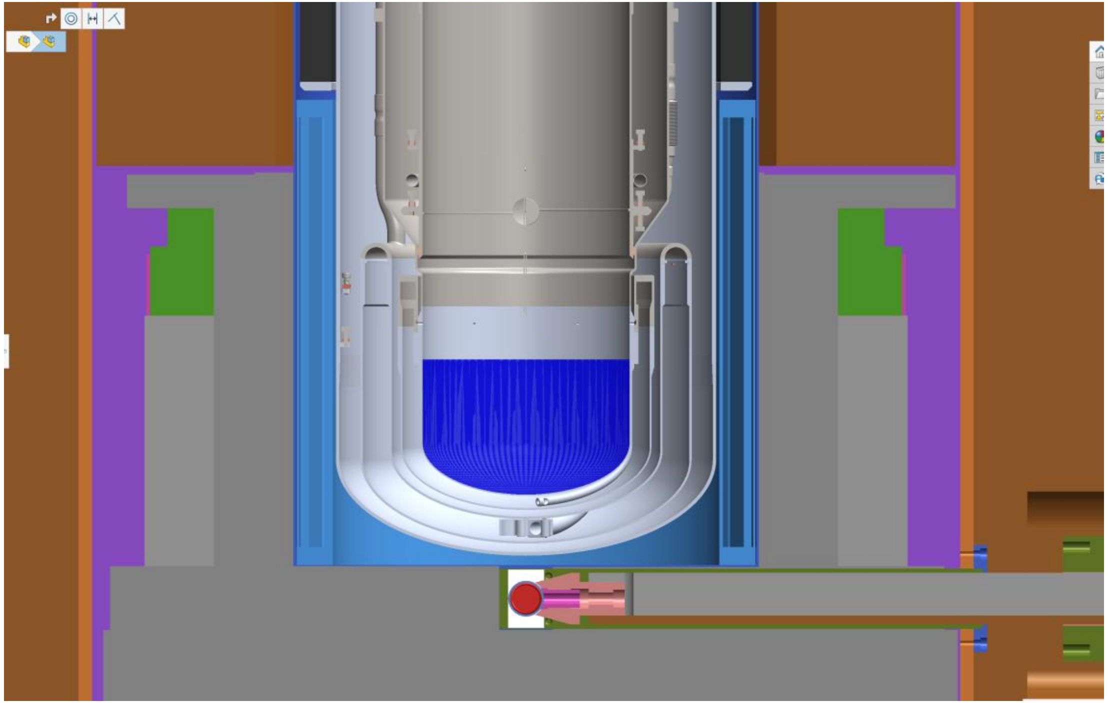
Baseline Fission Plate Design

- Metallic LEU 2mm thick plates lining a cylindrical "paint can" 33 cm ϕ x 34 cm high (825 cc volume)
  - Local facility can fabricate rolled plates of LEU from local stock (roughly 2mm x 150 mm x 300 mm)
- H_2O to fill the space between the LEU and the source cryostat
  - Both functions of moderator and coolant, will model after Target 4 water system.
- Average neutron flux at the device, 6.55E10 n/(cm^2 s)
- 140 kW heating in LEU for beam current of 10 uA (140 W/cc avg.)
- Production of Pu239, 1.2g/116 day average run cycle
  - Expected MAR < 12 PEG, → up to 1257 day useful life (10 accelerator cycles)
- Neutron poison production from CINDER calculations
  - Total reactivity impacts <2% of flux

Retract Graphite Shell, Currently Surrounds Source



Fission Plate Insert



LEU metal outer diameter, Water inside for moderation and cooling