VERSATILE TEST REACTOR (VTR) OVERVIEW

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U.S. DEPARTMENT OF ENERGY

VTR Mission, Goal, and Objectives

Mission

The mission of the Versatile Test Reactor (VTR) program is to provide leading edge capability for accelerated testing and qualification of advanced fuels and materials enabling the U.S. to regain and sustain technology leadership in the area of advanced reactor systems.

Goal

Enable a fast spectrum Versatile Test Reactor that can begin operations by 2026.

Objectives

-- Execute an efficient approach to development of a conceptual design, cost and schedule estimate, and acquisition approach that would enable a positive decision (CD-1) in 2020 towards 2026 operational startup for the new fast spectrum test reactor.

-- Engage with the NRC to inform licensing of future advanced reactor designs.

-- **Utilize international engagement and collaborations to enhance experiment capability development.**

-- **Utilize strong industry, university, and laboratory engagement and interaction to ensure optimal design and experiment capabilities.**

Background

The Need For a New Test Reactor

- Established through a series of independent surveys of the potential U.S. user community (industry, DOE programs) resulting in a NEAC report ("Assessment of Missions and Requirements for a new U.S. Test Reactor" February, 2017) submitted to and accepted by the full NEAC Committee.
- The report states that *"The Ad Hoc NEAC subcommittee recommends that DOE-NE proceed immediately with pre-conceptual planning activities to support a new test reactor (including cost and schedule estimates)."*
- *After the 2018 Omnibus bill was approved, the VTR kick off meeting was held on April 12th, 2018, consisting of DOE-NE headquarter staff, laboratory team members and executive management.*
- So far, from the discussions with users, the laboratories have established:
  - Draft generic requirements
  - Some specific requirements
  - Draft R&D Plan

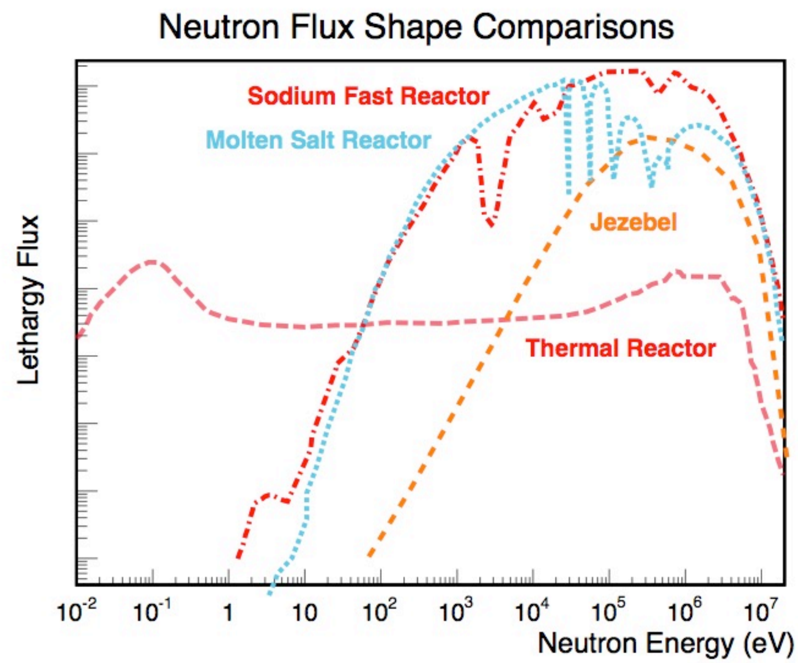
Development of Advanced Reactors is the Primary Driver

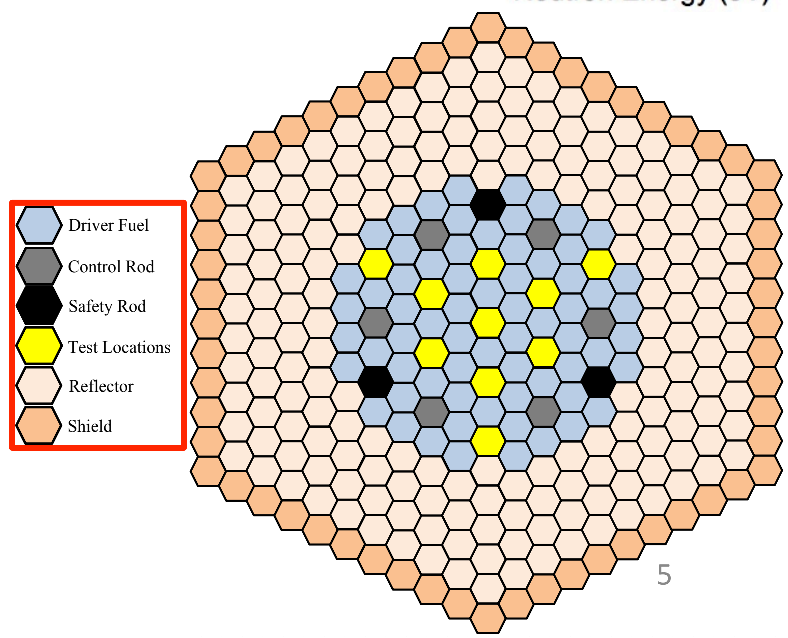
Requires A Source of Fast Neutrons

- Sodium cooled reactors need innovative technology development to reduce capital, operations, and fuel-cycle costs for the next generation of sodium-cooled fast reactors.
  - Higher burn-up fuels
  - Metallic fuels without sodium bonding
  - Materials that can sustain much higher dpa (up to 400 dpa!!)
- Lead, lead-bismuth eutectic, gas, molten salt fast reactor designs being pursued by industry rely on new fuel and material types.
  - Commercial viability and licensing requires considerably more data
- For sustaining the existing fleet and long-term commercial advanced reactor operations, a test reactor is needed for continuous technology improvements.
  - We are still conducting tests for LWR fuels and materials in test reactors, and a fast reactor accelerates materials testing.
  - It took decades to go from 60% to 90+% availability in LWRs partly because of continuous improvements in fuels and materials.
- Access to fast spectrum irradiation capabilities is limited globally (only exists in Russian Federation today).

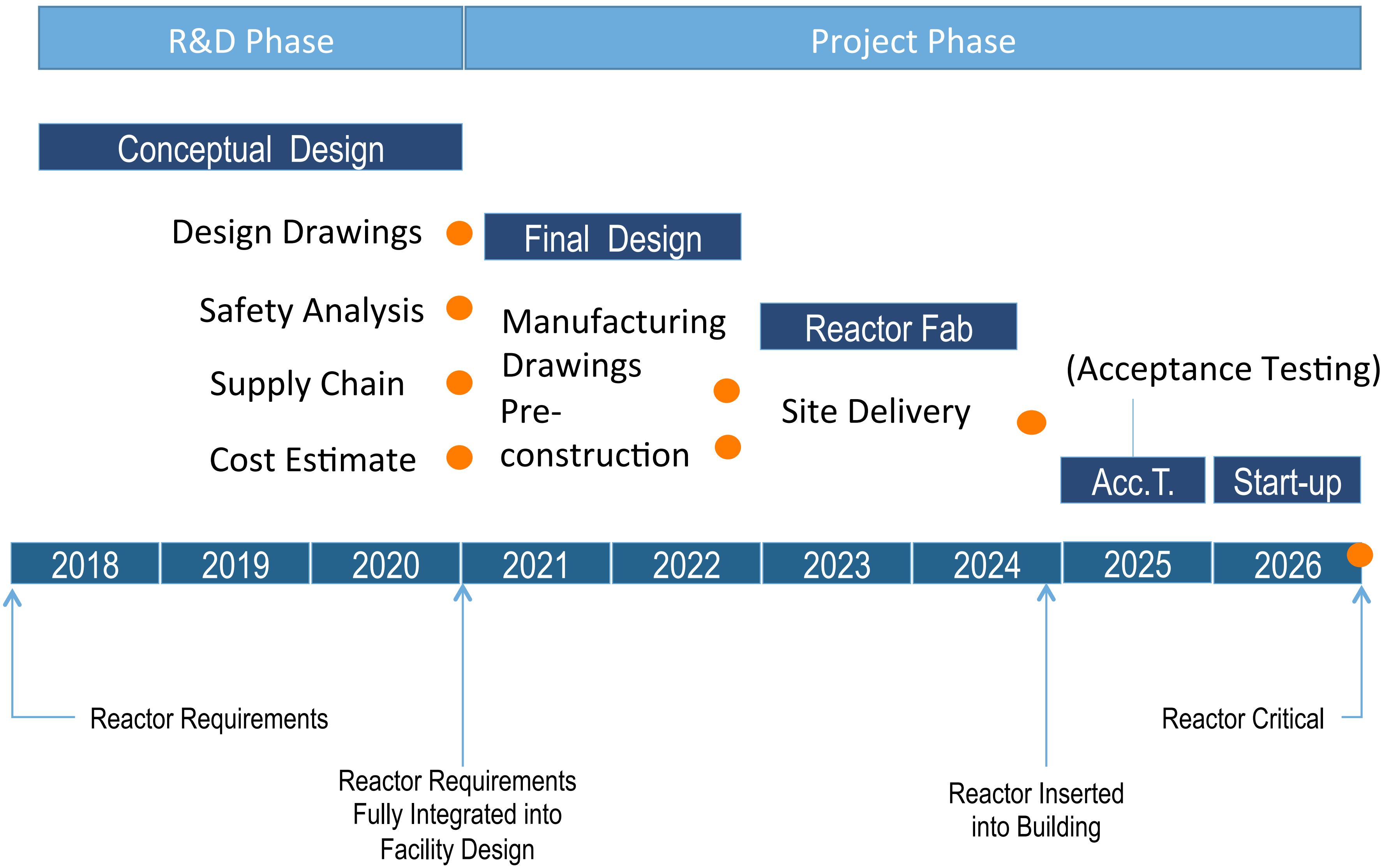
Draft requirements/assumptions of VTR

1. Be capable of running experiments representative of typical fast reactors *(Candidate Coolants: Na, Lead, LBE, Gas, Molten Salt)*
2. Fast flux of approximately **4E15 n/cm²s**, with prototypical spectrum (≤300MW$_{th}$)
3. Load factor: as large as possible *(maximize dpa/year to > 30 dpa/year)*
4. Ability to perform large number of experiments simultaneously
5. Effective testing height ≤ 1 m
6. Baseline design - metallic driver fuel **(5%LEU-20Pu[RG]-10Zr)**
7. **Provide flexibility for novel experimental techniques**



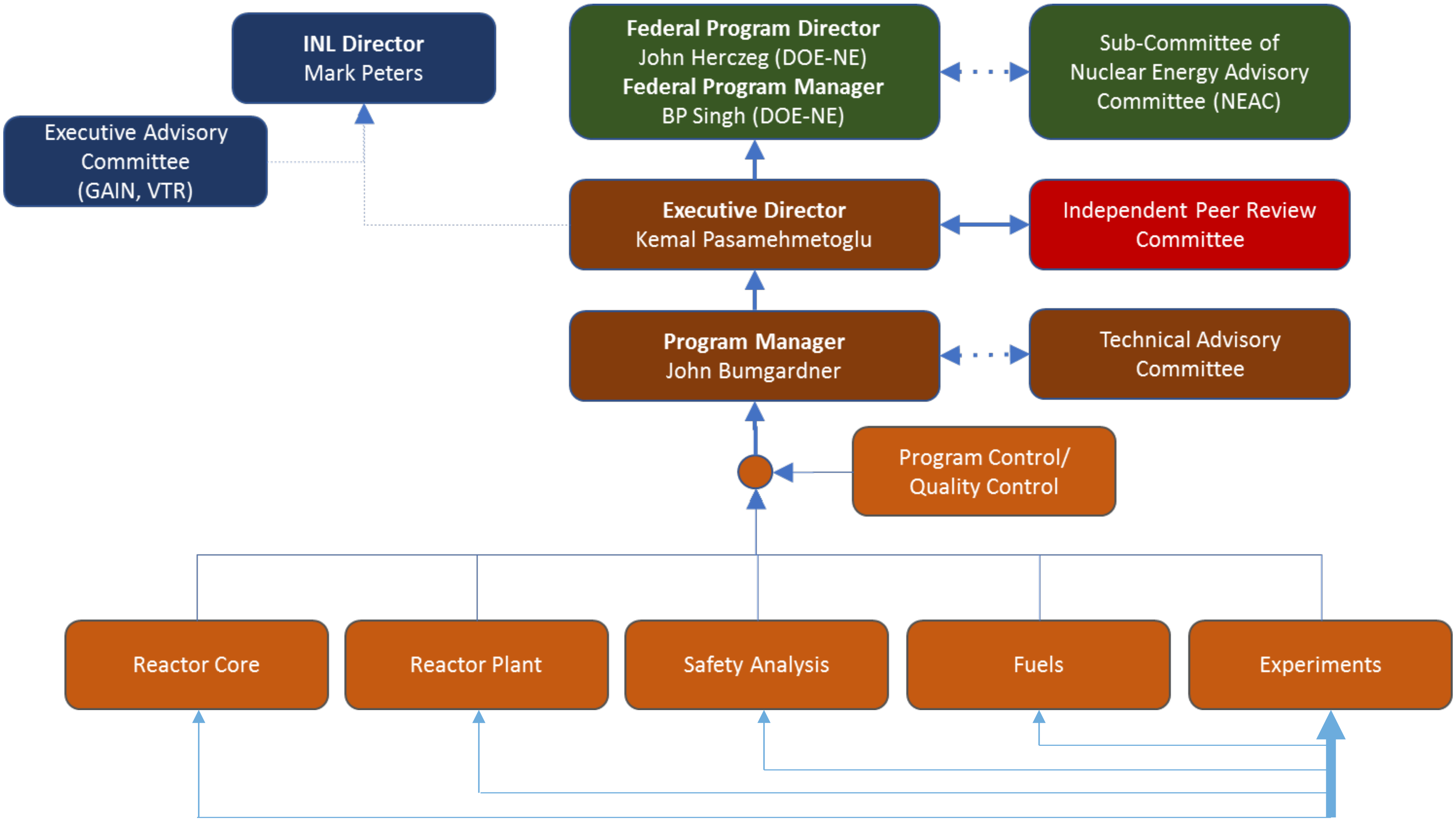


Reactor Timeline* – Complex iterative process, high rigor



* Assumes timely and adequate Congressional appropriations based on CBO estimates

VTR Program Organization



The VTR is an essential tool for supporting a new generation of high-value nuclear experiments, testing and validation

VTR Experimental Program Development

The goal of the VTR Experimental Program is to maximize experimental outcomes by:

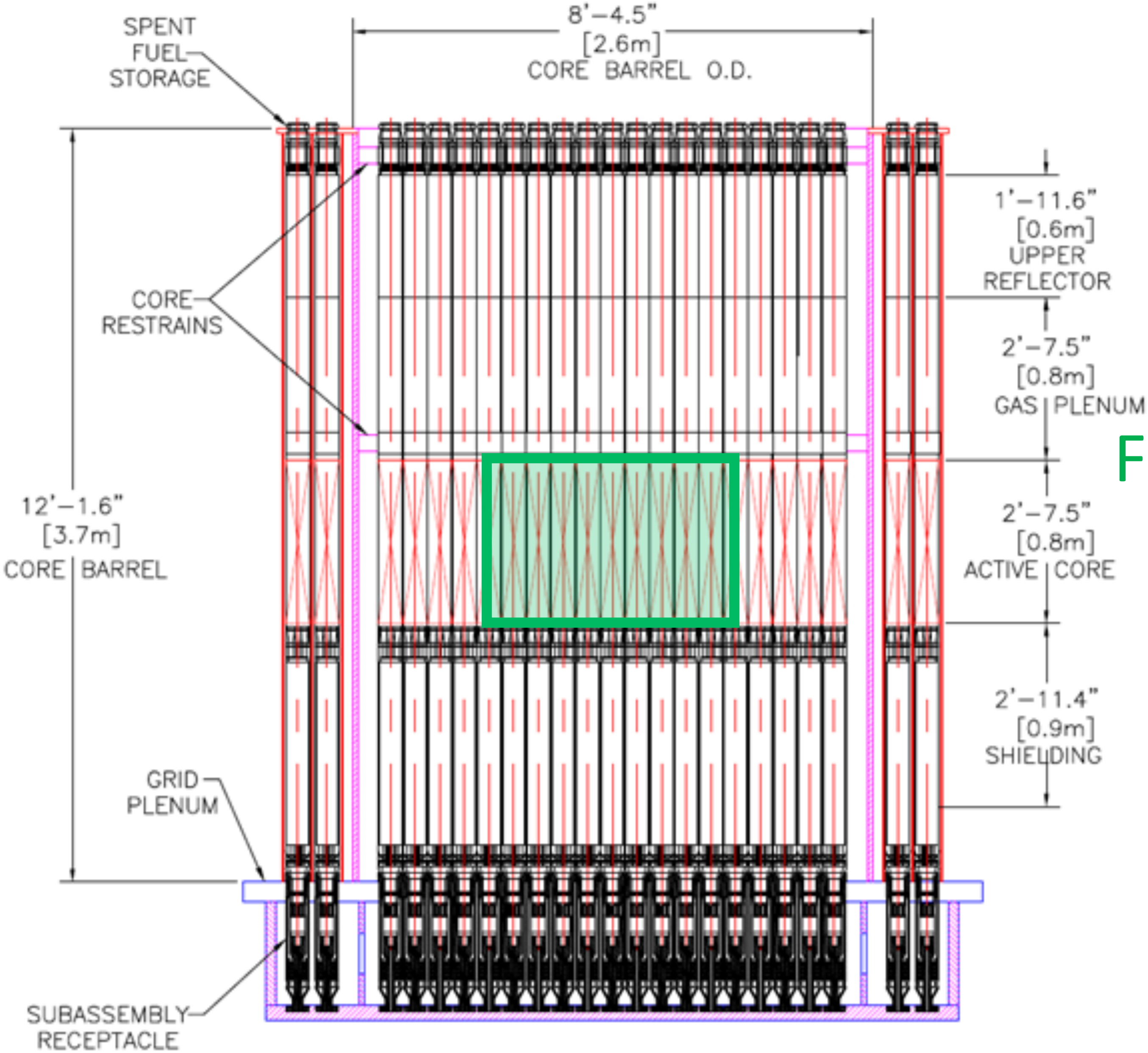
- Providing a broad array of experimental capabilities
  - physics, materials, fuels, sensors, validation and novel experiments
- Providing the most accurate and precise experimental boundary conditions and validation opportunities as possible
  - Science-based Engineering Learning Layer is being developed
    - I&C data + licensed codes have O(10%) uncertainties, which have a time dependence, and propagate into final experimental outcomes
    - Local experimental instrumentation is often used to increase local fidelity but are not used to inform licensing codes (frozen)
    - Some of the most precise measurements of local conditions are not carried out in real- or near real-time (post irradiation examination)

Given the aggressive schedule, one focus of the Experimental R&D program is to identify requirements that impact the VTR design

IBD Power Monitoring System

- Stable, independent power monitoring system for VTR Learning Layer
  - <2% "power" measurement precision for ~300MW-day
  - <0.5% systematic uncertainty over ~30GW-days (single 100 day cycle)
  - Long term stability (30+ years)
- VTR R&D funding awarded to GIT, Yale, & IIT for IBD trade study
  - The objective is to develop and design a VTR specific ex-core power measurement system based on Inverse Beta Decay (IBD) detector technologies. A VTR power monitor capable of daily 2%-level precision measurements, or better, is envisioned. The system will be designed for operation well outside the reactor vessel in environmental conditions that cannot lead to sensor degradation or drift, thus providing a precise, reliable and independent reactor power history over the entire VTR program timescale. Integration of the IBD power monitor data into the VTR analytics system will provide independent and foundational support in minimizing experimental systematic uncertainties associated with the reconstructed power of a pool-type sodium fast reactor.

VTR Core Assembly – Elevation view

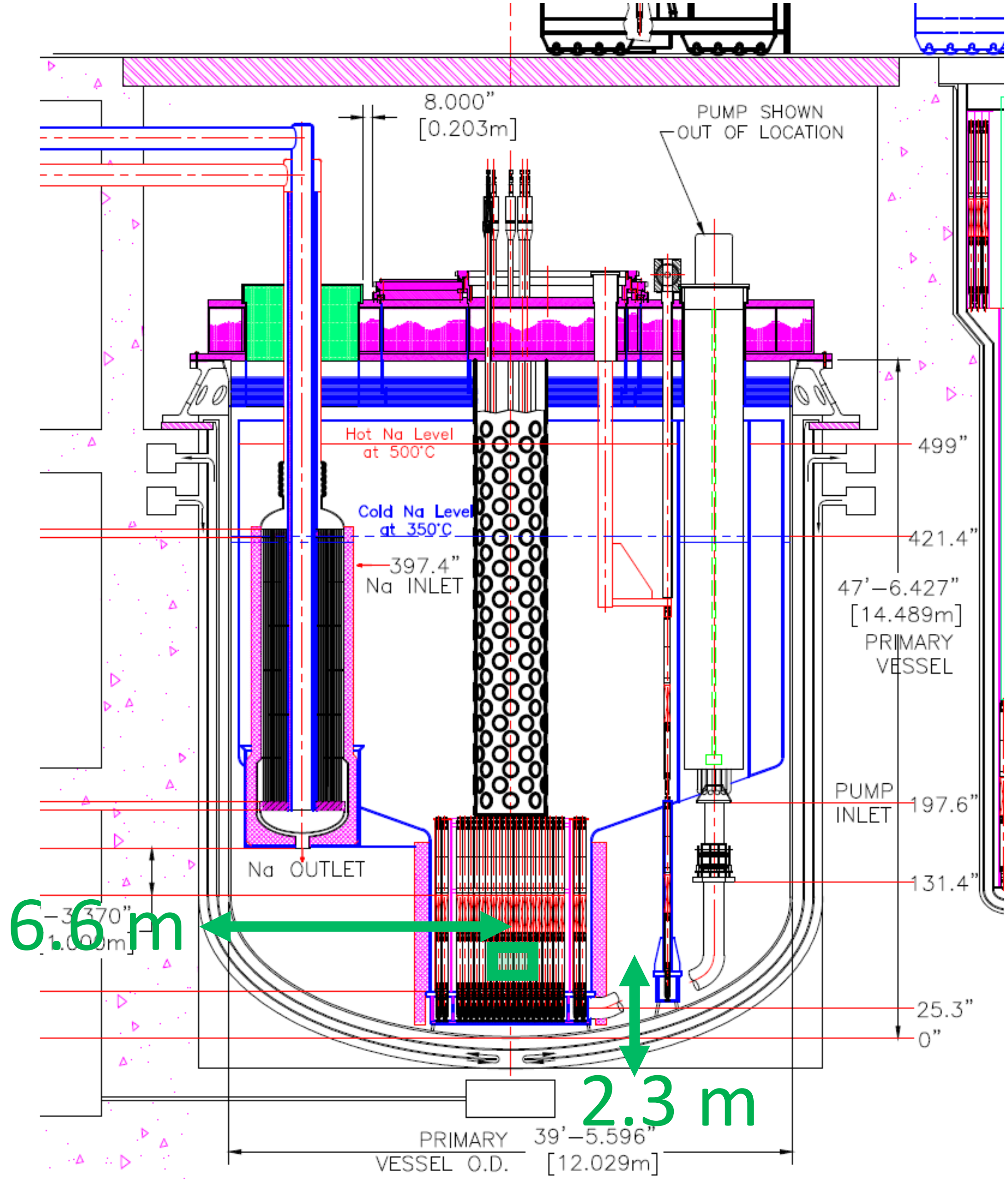


Fueled Region
0.8m high
1.2m wide

Predecisional Draft

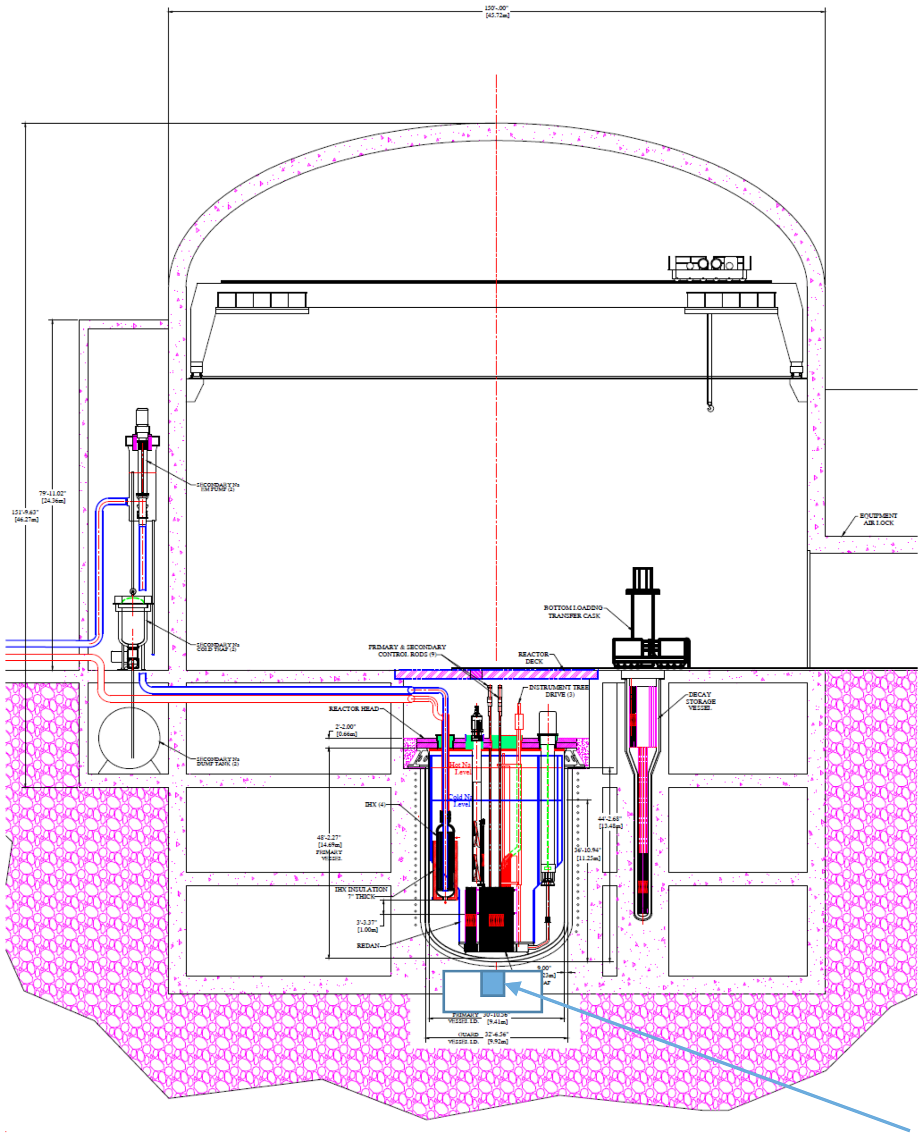
VTR Reactor Initial Layout– Elevation View

- The VTR will be a pool-type sodium reactor. The initial layout is a 12m diameter and 12.7m deep molten sodium pool.
- Core is bottom mounted in the vessel:
  - 2.3m from bottom of external vessel to horizontal fuel centerline
  - 6.6m from side of external vessel to vertical fuel centerline



Predecisional Draft

Hypothetical VTR Reactor with IBD Monitor – Elevation View



Potential
IBD Detector

Predecisional Draft

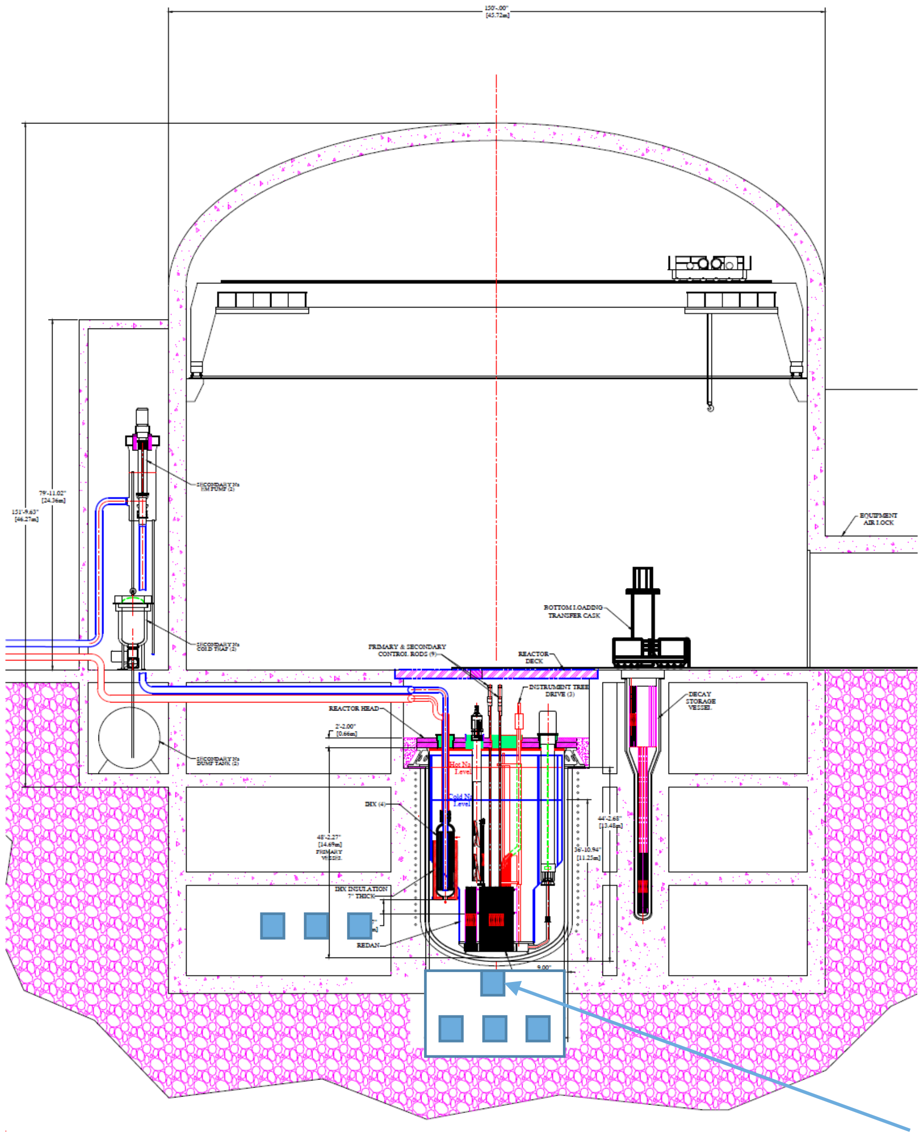
Relative VTR Isotopic Fission Rates

- Sodium cooled 5%LEU-20Pu_{RG}-10Zr metallic fuel
- 99.8% of fissions occur in five isotopes:

ISOTOPE		BOEC	EOEC	(relative change)
• U235	:	13.2%	12.8%	-3.7%
• U238	:	12.6%	12.7%	1.5%
• Pu239	:	61.8%	61.8%	0.02%
• Pu240	:	8.2%	8.4%	2.2%
• Pu241	:	3.7%	3.8%	2.3%
• Pu242	:	0.3%	0.3%	2.5%

- Relatively stable isotopic fission ratios during a 100-day irradiation cycle for equilibrium core (100 days on/ 20 days off)
- VTR operations will nominally not include load following – a steady power decrease of ~2% through each cycle (burnup)

Hypothetical VTR Reactor with IBD monitor and neutrino detector testing hall(s)

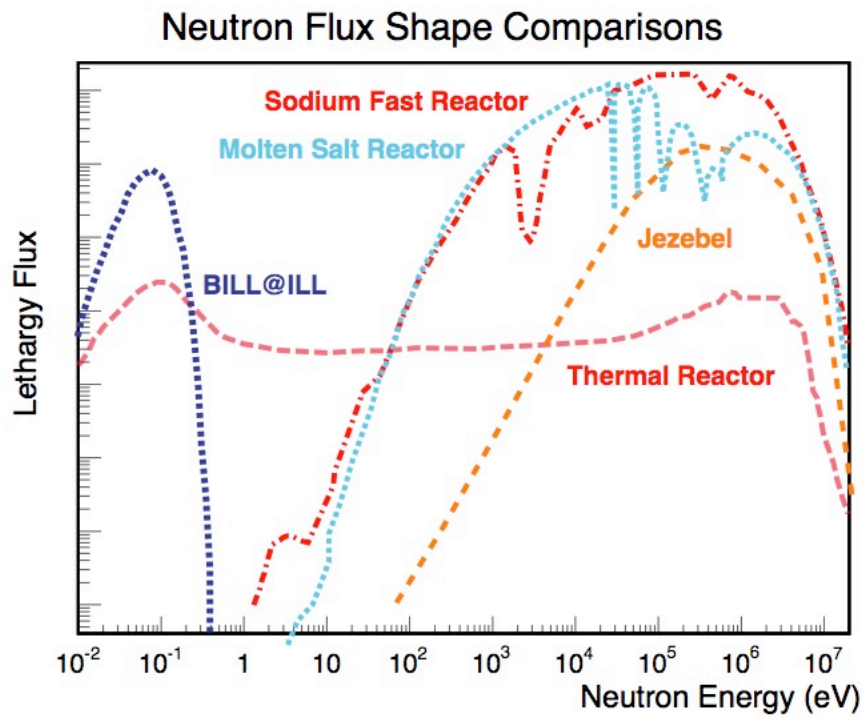


Potential IBD Detector

Predecisional Draft

Potential VTR nuclear data support for reactor υ_e effort

- At least three sets of measurements are particularly relevant to VTR υ_e efforts:
  - Direct measurements of reactor υ_e line shapes
    - Inverse beta decay detector + HEU shape (PROSPECT) +others
  - Measurements of fission product yields
    - VTR rabbit system + ICP-MS
  - Measurements of electron emission following fission
    - VTR beta spectroscopy system



Predecisional Draft

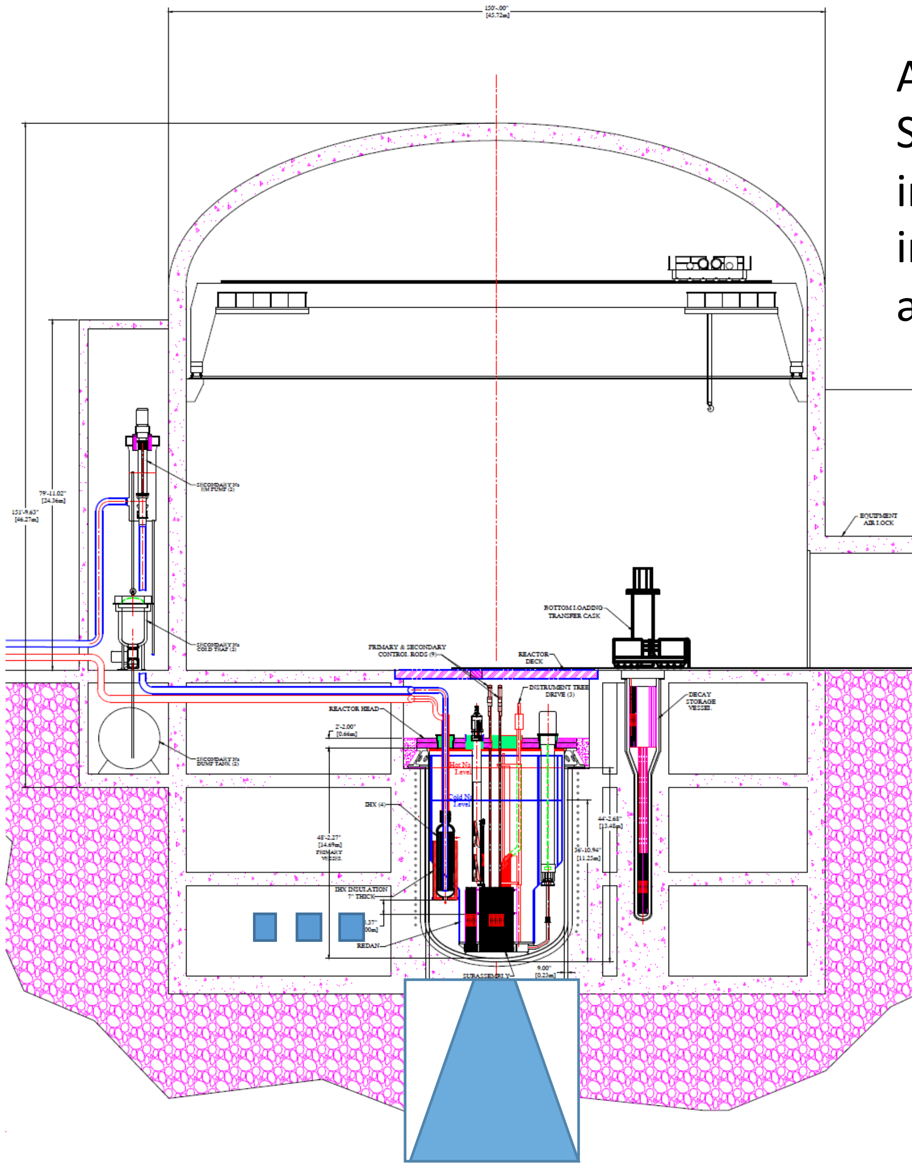
Hypothetical VTR with L^2-compensated IBD experiment and testing/development hall

L ≈ 4-17m
A=1m^2 @L=5m
M_T^{scint} ≈ 66 tonnes

υ_e detection rate
≈ 20/cm$_L$/day
≈ 2000/cm$_L$/cycle
≈ 7.2x10^6/year

For 15cm thick layers
(80 layers total)
≈ 30k υ_e/layer/cycle
σ_L^{det} ≈ 4.3cm

L resolution from core
(not a point source)
(includes flux shape)
δ_L^{core} ≈ 21cm



After 9 cycles (3 years)
Statistical uncertainties
in 125 keV bins have little
impact on sensitivity
assuming S/B>3

$$\sigma_L = 0.21/L \oplus 0.043$$

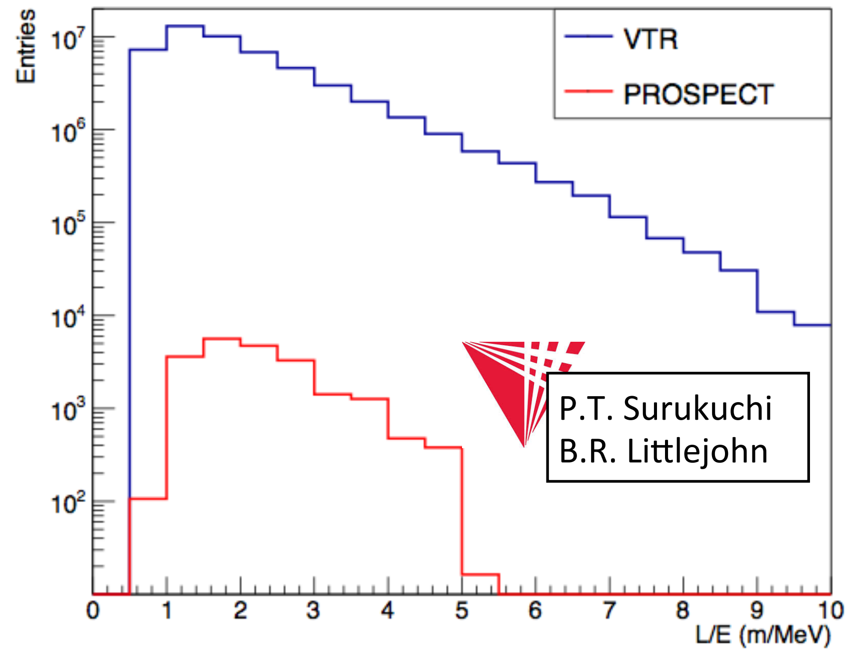
$$\sigma_E = 0.045/\sqrt{E}$$

Predecisional Draft

Estimated L/E Coverage for Sterile Antineutrino Search at VTR

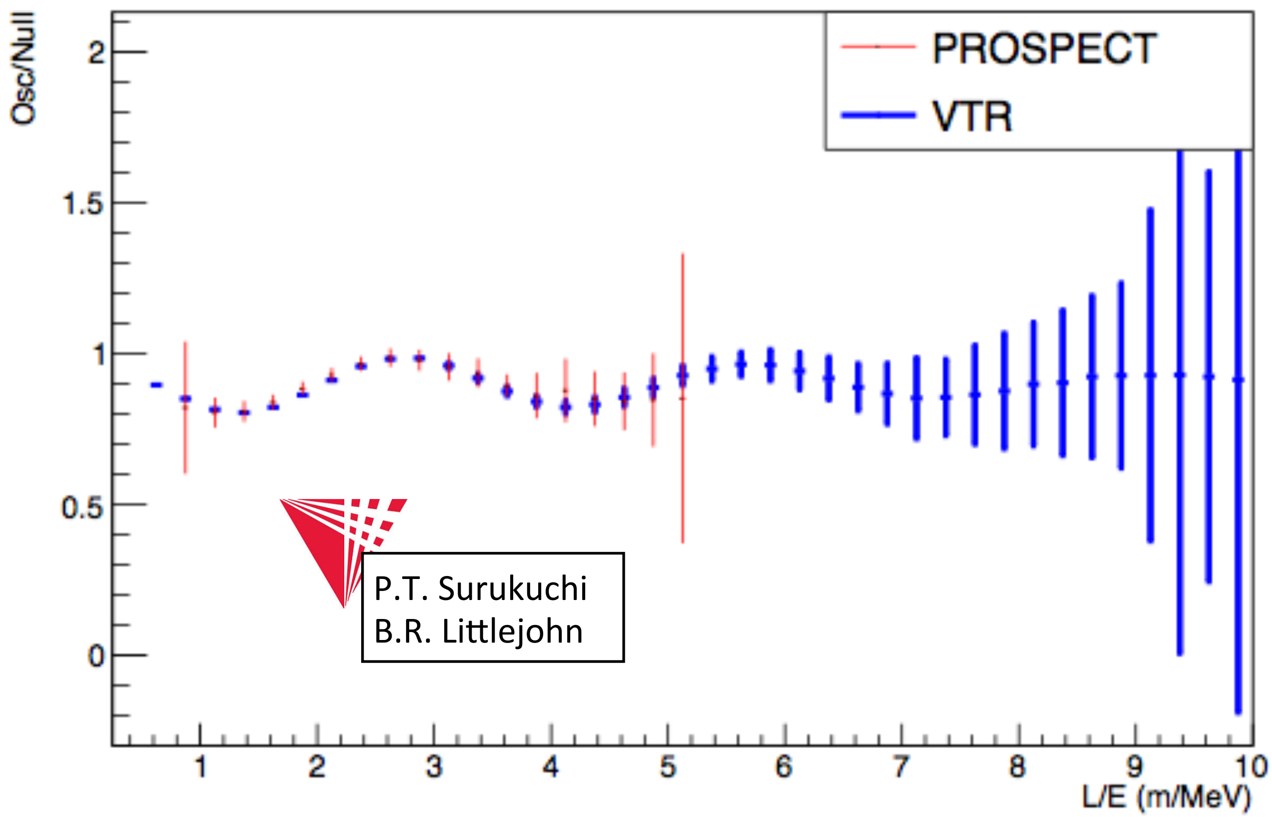
Inputs and Assumptions

- **Detector :**
  - 2 m x 2 m x 13 m (52 tonnes)
  - Baseline: 4-17 m
  - 95 x 18 15 cm x 15 cm segments
- **Reactor :**
  - 0.4 m wide and 0.5 m high
  - 100 MW power
- 10 years running
- S:B = 1:3
- Assumed 'best' (center) PROSPECT segment energy response for all segments
- Assumed uncertainties:
  - Signal and cosmic background statistics
  - PROSPECT IBD energy response uncertainty (nonlinearity, scaling, resolution), treated as uncorrelated between each segment
  - 2% segment-uncorrelated IBD rate uncertainty



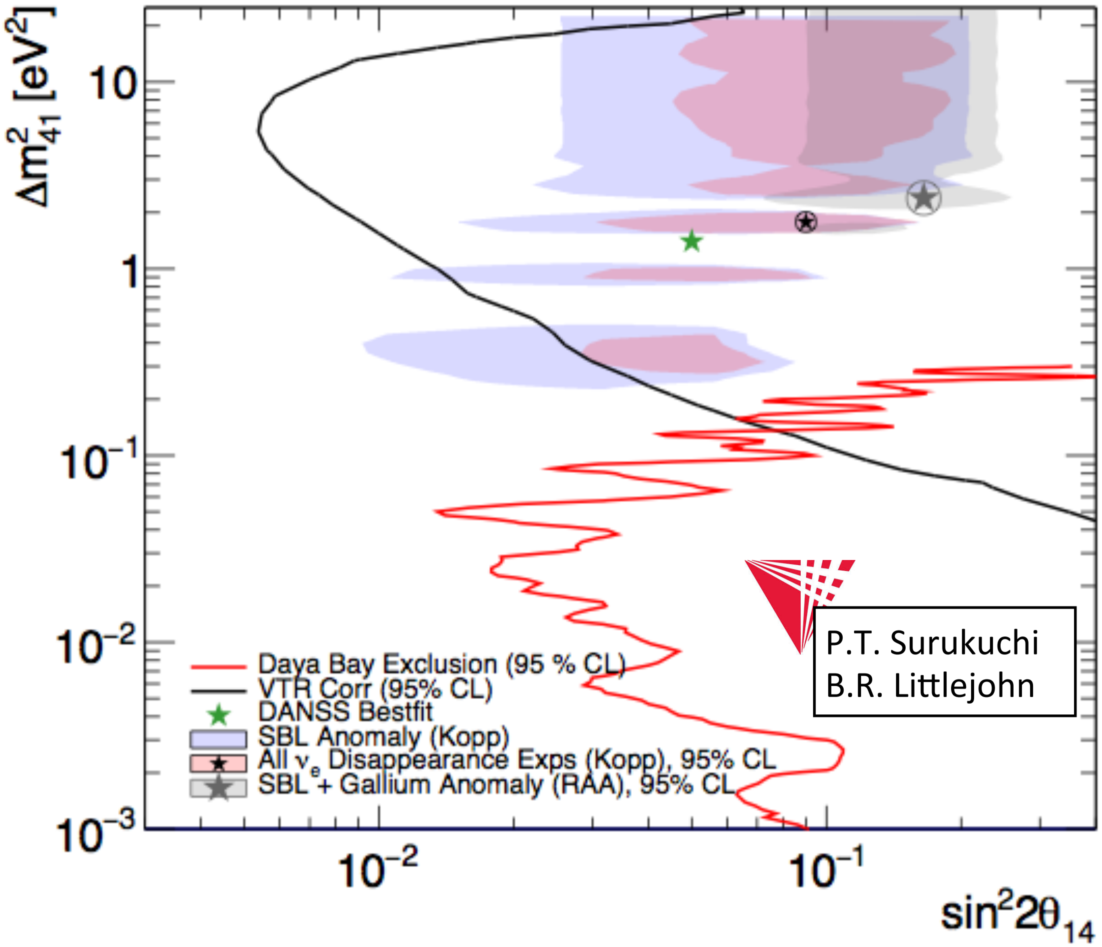
- Curves show the L/E stats current PROSPECT result (https://arxiv.org/abs/1806.02784)
- L/E coverage shows VTR detector's ability to cover very wide Δm^2 range
- VTR rates shown in comparison with the PROSPECT event rates

Estimated Oscillation Sensitivity at VTR



- Curves show the L/E stats current PROSPECT result (https://arxiv.org/abs/1806.02784)
- L/E coverage ~twice as wide as PROSPECT
- A good situation for addressing a wide coverage of 3+1, or 3+2, or osc + neutrino decay, or other non-standard oscillatory patterns

Estimated 3+1 Sensitivity at VTR



- VTR detector covers the entire Kopp region at 95% CL
- No variation observed in 100 MW vs 300 MW because systematics dominate when the statistics are so high

Summary

- VTR R&D Phase is underway with goal to go critical in 2026
- Initial VTR Core Design
  - Fast flux, high power ≤300MW_{th}
  - Compact – 0.8m x 1.2m
  - Bottom mounted core provides ~4m minimum υ_e baseline
  - Large stable Pu vector – 74% of fissions
- VTR Scientific Surveillance Layer
  - Comprehensive data and analytics layer
    - Open HDF5-based storage with Python notebook workflow
  - Need a non-degrading (30 year) fission following monitor with:
    - Precision of <2% per full-power day
    - Precision of <0.5% for 100 full-power days (one run cycle)

Summary

VTR = υ_eTR

- Neutrino physics support (fundamental physics, nuclear physics, advanced detector development, safeguards)
  - Unique υ_e source
    - High-power (compact) core, relatively stable fission fractions
    - Pu fuel (advanced fuel cycle and safeguards phase space)
    - Fast neutron spectrum (advanced reactor, safeguards, nuclear data phase space)
  - Research reactor environment
    - 100 days on – 20 days off
    - Experiment design possibilities (up to 10% of fuel can be replaced)

Many opportunities exist but time is short!

Nuclear Physics at VTR

- Many scientific opportunities exist! What do we need to maximize the scientific impact of VTR?
- Imagine that the VTR is being built for YOU
  - What would you like to see in the design to accommodate important experiments?
    - Added surveillance instrumentation for validation (beyond nominal plant and I&C instrumentation)
    - Experimental access/interface requirements
      - Rabbit(s), thimble(s), beam line(s), beta spectrometer, isotope production, etc..
    - Post irradiation infrastructure
      - On-site capabilities
  - What is the value/impact of the extended measurement capabilities?
    - Need to work with sponsors to insure success

Many opportunities exist but time is short!

Questions?

Clean. Reliable. **Nuclear.**

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