



Interesting Nuclear Things with Bob at Idaho Falls

UTK Nuclear Engineering Department Seminar

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Center for Advanced Energy Studies
@TheDoctorRAB  

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No outline slide

Who is Bob?

I grew up in Rhode Island

BS (ME/NE) and MS (CE/EnvE) at Worcester Polytechnical Institute

Open pool 10 kW reactor

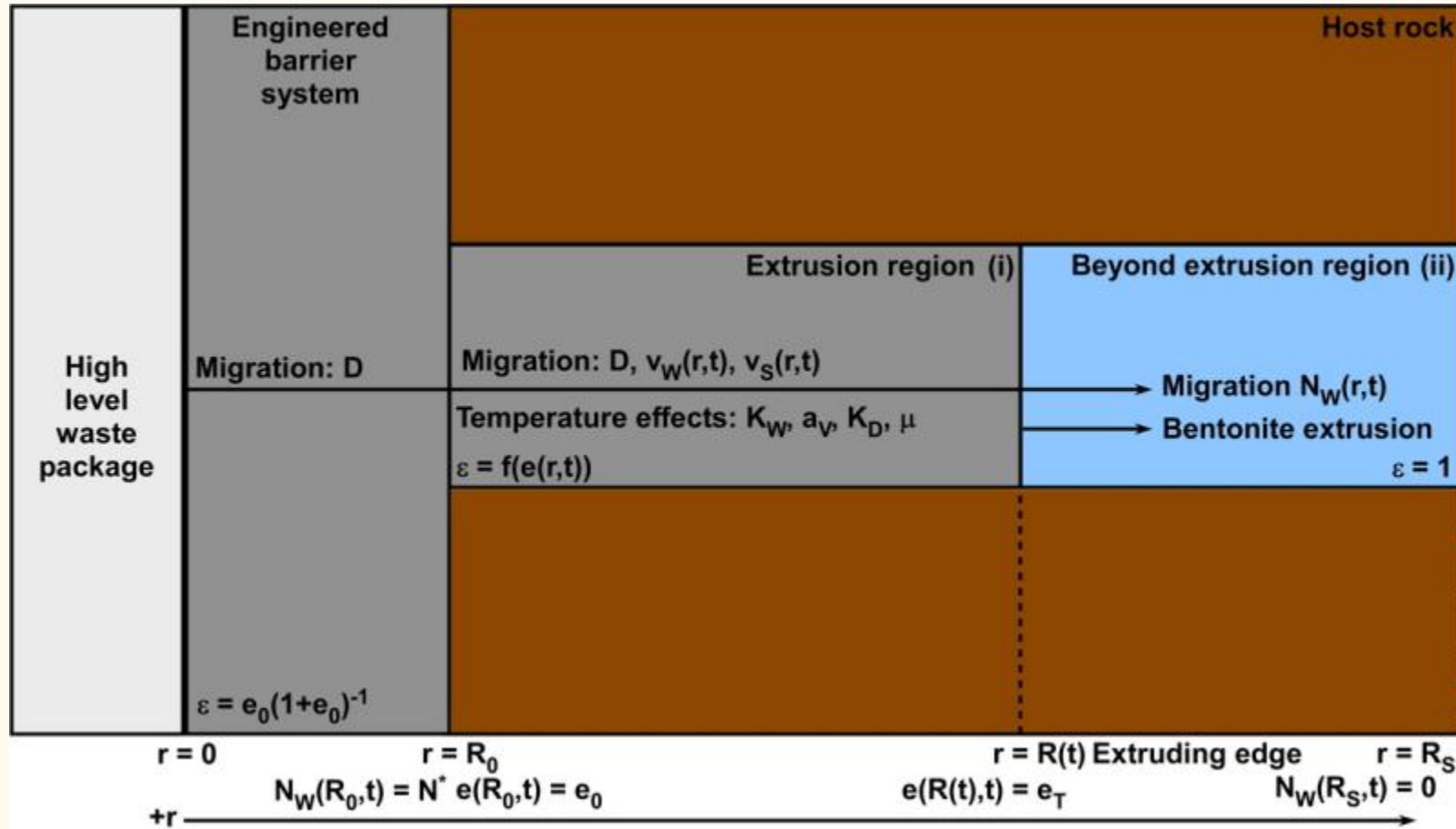
Capstone - PLC programming for real time operational data [1]

MS - Characterization of radioactivity in the environment by total energy

Assistant Radiation Officer (1996-9)

Senior Reactor Operator (1994-9)

My dissertation focused on radionuclide transport modeling coupled with bentonite extrusion



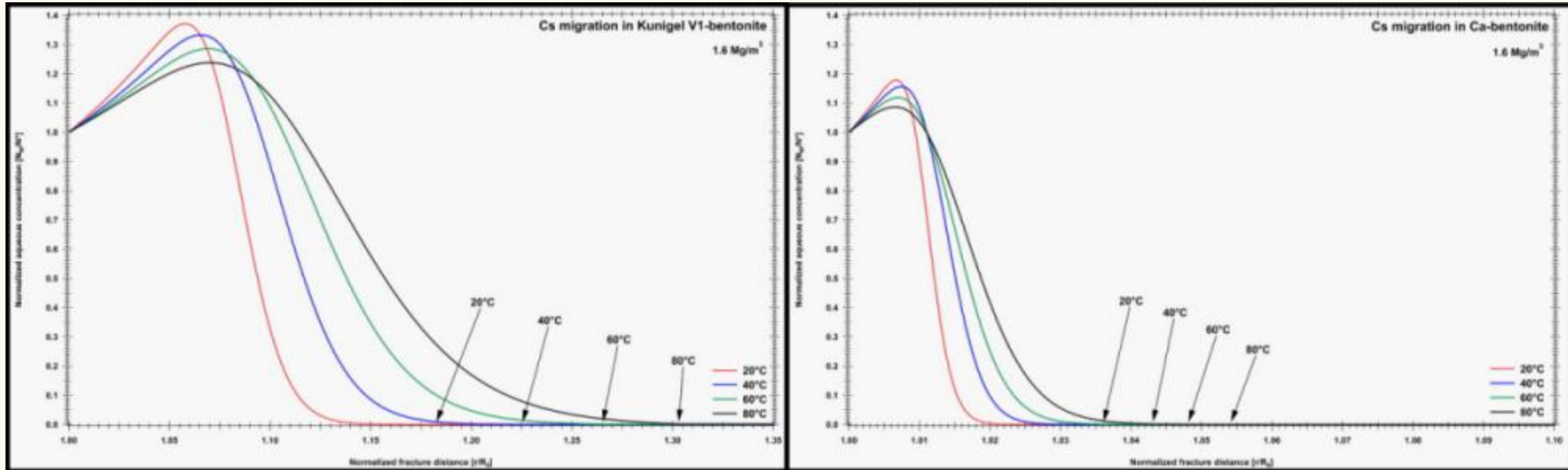
It was a lot of math (even if it doesn't look like it)

$$\frac{\partial}{\partial t}[(\epsilon + \sigma K)N] + \frac{1}{r} \frac{\partial}{\partial r} [r \epsilon v_w (1 - K)N] - \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial}{\partial r} (\epsilon D N) \right] = 0$$

$$\frac{1}{(1 + e)^2} \frac{\partial e}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (D_V(e) r \frac{\partial e}{\partial r})$$

$$\frac{dR_T}{dt} = 2D_V(e) \frac{\partial e}{\partial r} \Big|_{R_T}$$

But I made some #fancy graphs



Main takeaway

Highly sorbing radionuclides could be confined to extrusion region

On to current times

UI at Idaho Falls is an interesting situation

Nontraditional is probably the best term

Main campus 550 miles

Technically, only 3 NE faculty though a lot of 'affiliates'

It's challenging but difficult because I can do what I want

No one currently at Associate level

Resources can be limited



Some fun UI highlights to date

1. Asked if I knew Katy Huff in my interview presentation
2. ANS student section adviser - two campuses - Second in Glasstone 2018
3. Active in local section - delivered over 2000 smoke detectors and counting
4. EC on Fuel Cycle and Nonproliferation Divisions
5. Scenic drive to main campus
6. State of Idaho Department of Commerce funding with Japanese company
7. NASA *EPSCoR* grant for Am RTG fuel
8. No NEUPs yet because Steve and Jamie beat me down
9. Nuclear cybersecurity WG with Prof. Michael Haney in CS
10. Published with multiple CS faculty
11. Affiliate of Boise State Energy Policy Institute
12. Coordinator for new decommissioning and fuel management certificate
13. WSC and NuScale (awarded to Idaho not CAES) simulators
14. Tweet upside down
15. State of Idaho PE license, Faculty Restricted

#Fancy nuclear cybersecurity technical session and panel at ANS Winter with Jamie

What about students?

We have a mix of 'traditional' and 'nontraditional' (*o/d*) students
Can have a learning curve when coming back to school after a long time

INL educational contract and Joint Appointments (VPR Janet Nelson)

1. Kelley Verner - PhD candidate - ANS SSC chair - U-Mo fuel with *INL subcontract*
2. Jieun Lee - MS - pyroprocessing safeguards - Texas A&M for PhD
3. Emma Redfoot - MS - hybrid systems - Oklo
4. Malachi Tolman - MEng - BISON - Sandia - also INL subcontract
5. Seth Dustin - MS - AM RTG - NNSA Fellow - Los Alamos
6. John Peterson - MS - microreactor design - Atomic Alchemy Idaho Falls startup

There are other nontraditional students working with me on SMR fuel cycle analysis, back-end management, PID controls, unmanned space travel

Selected research pathways

(with many pictures)

Safeguardability

Safeguards-by-design

Started at UC-Berkeley with Per Peterson, Joonhong Ahn, KAERI

At UCB - developed a holistic, top-down methodology

Commercial pyroprocessing facility example system

Intended to apply to other nuclear materials facilities

Proliferation resistance

Develop functional components to facility design

Physical protection

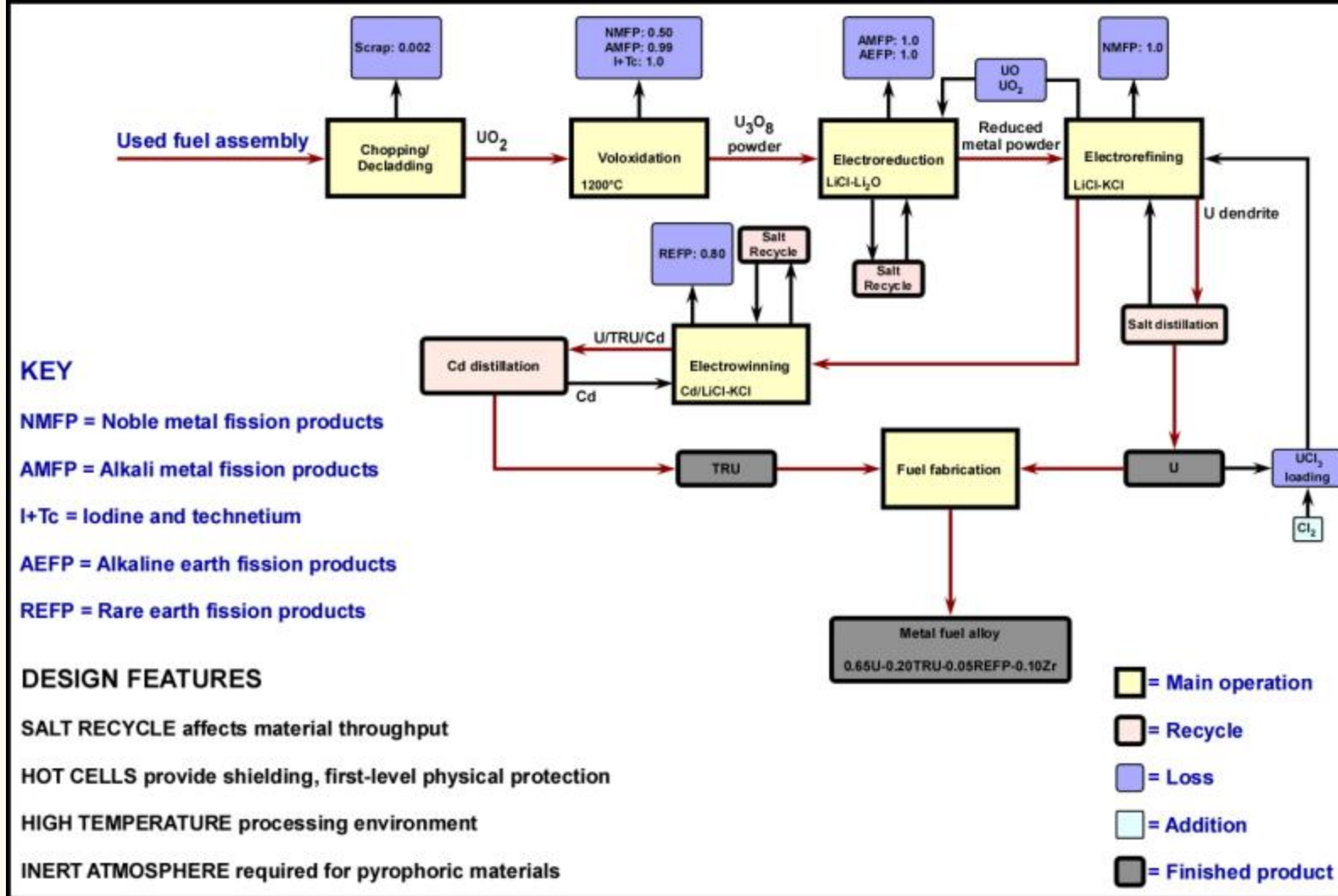
Take advantage of inherent design features

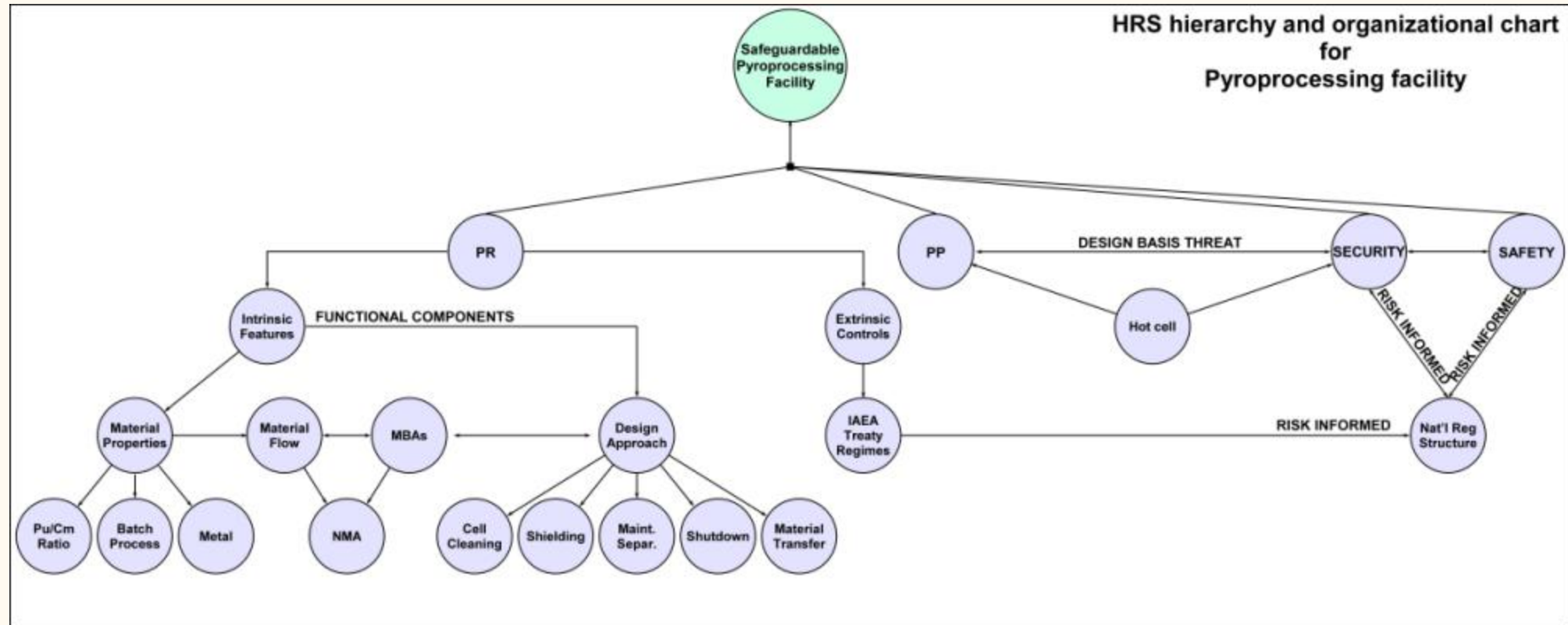
Systems assessment = Safeguardability quantification

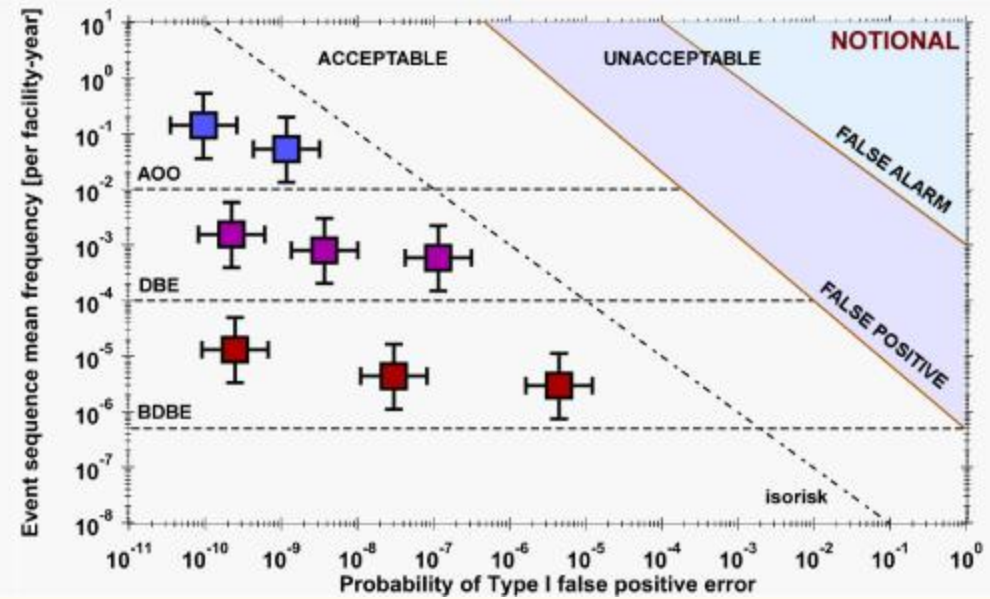
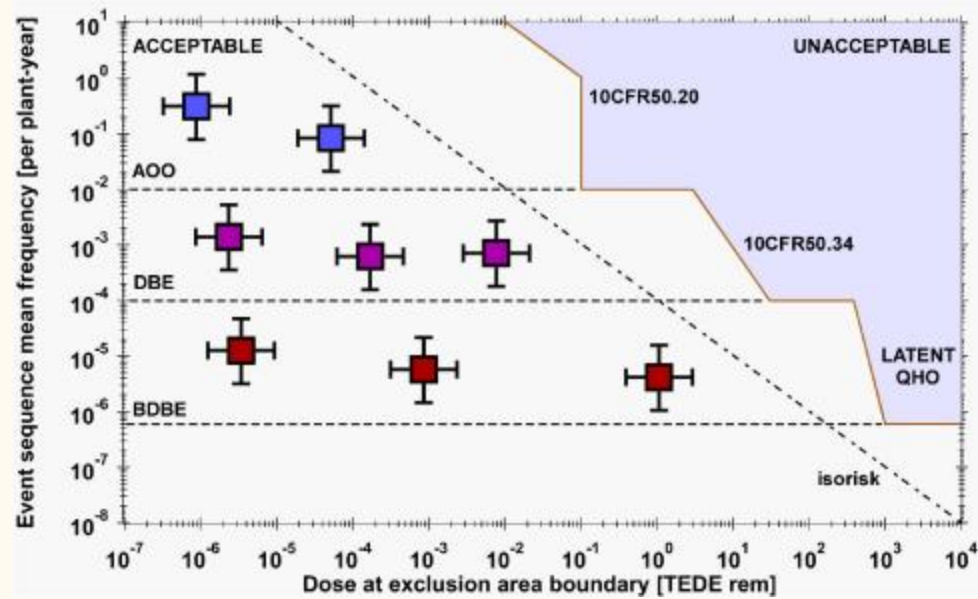
Risk-informed approach

Time may have passed me by, but I still want to develop it

Long-term goals for HRS



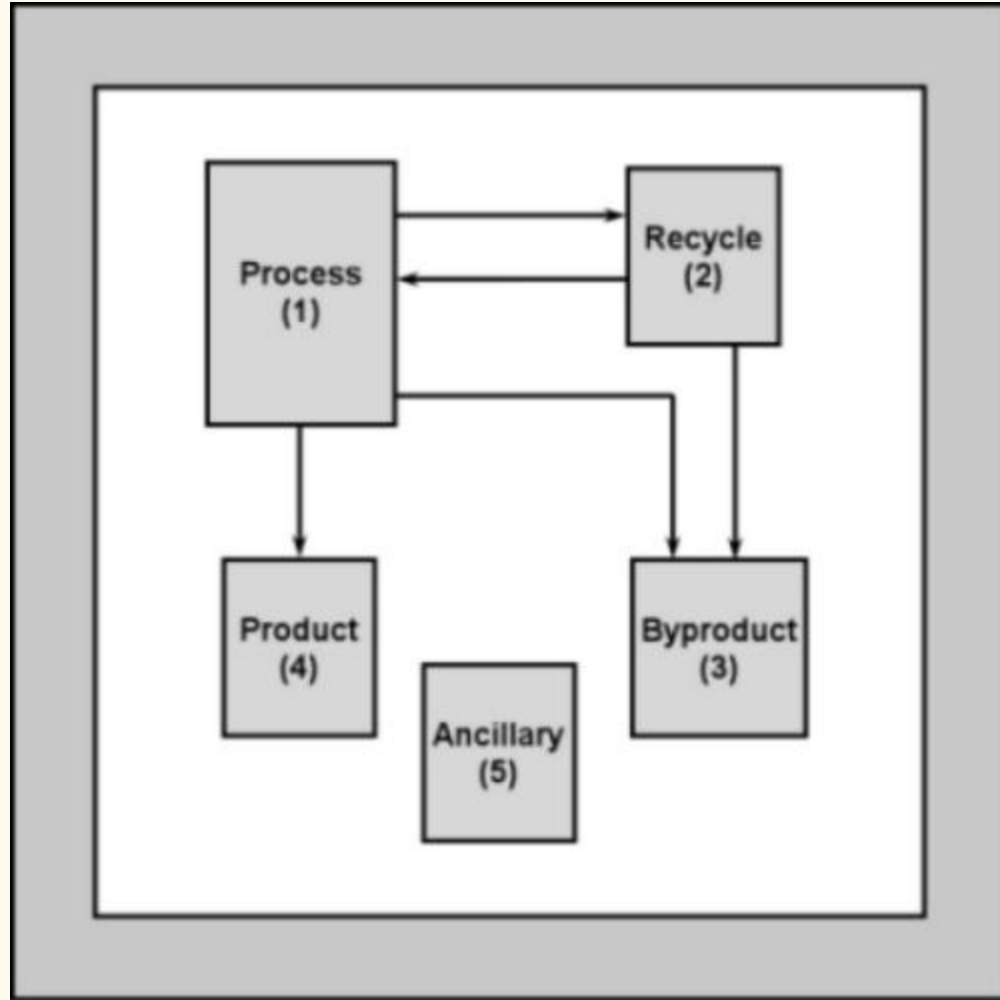




Modeling framework

Generalize system processes

Key



(1) Process activity

(2) In-situ recycle

(3) Byproduct

(3a) Waste

(3b) Recycle at head-end

(4) The actual product

(5) Testing

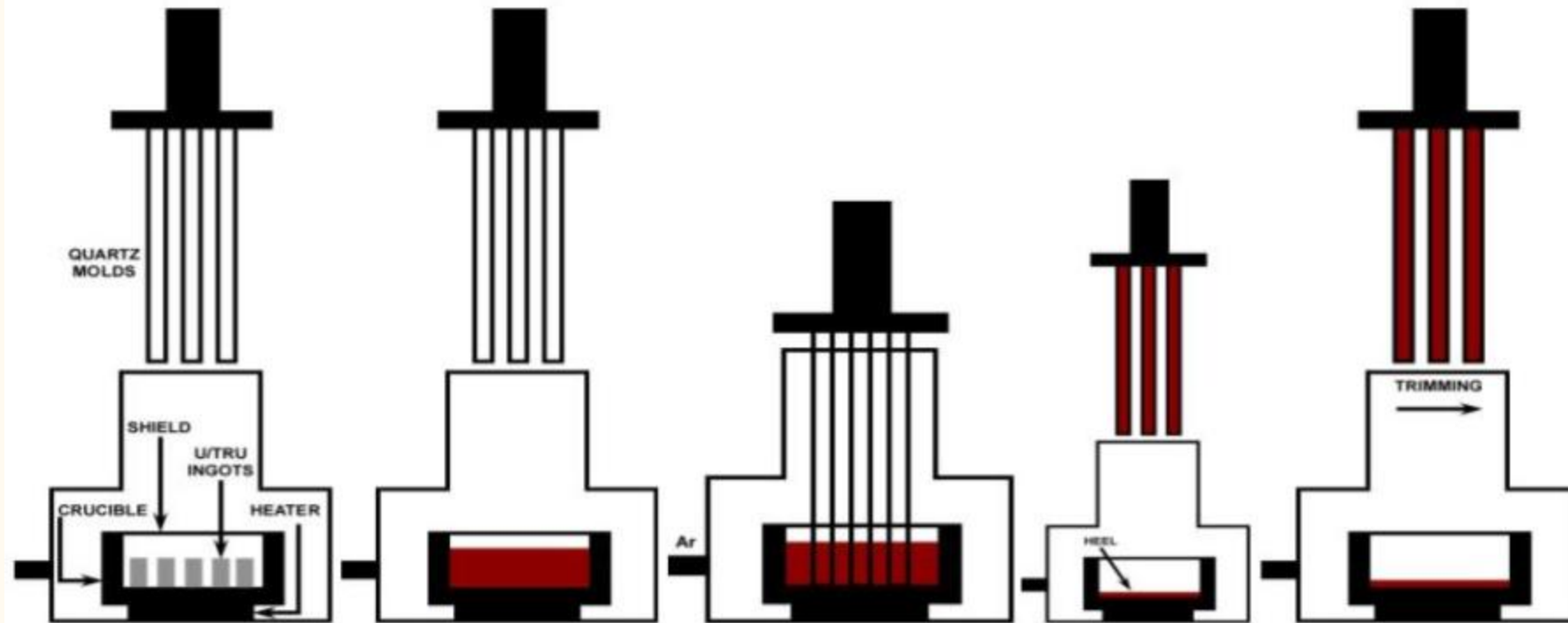
(5a) Destructive assay

(5b) Chemical analysis

(5c) Quality assurance testing

Fuel fabrication process

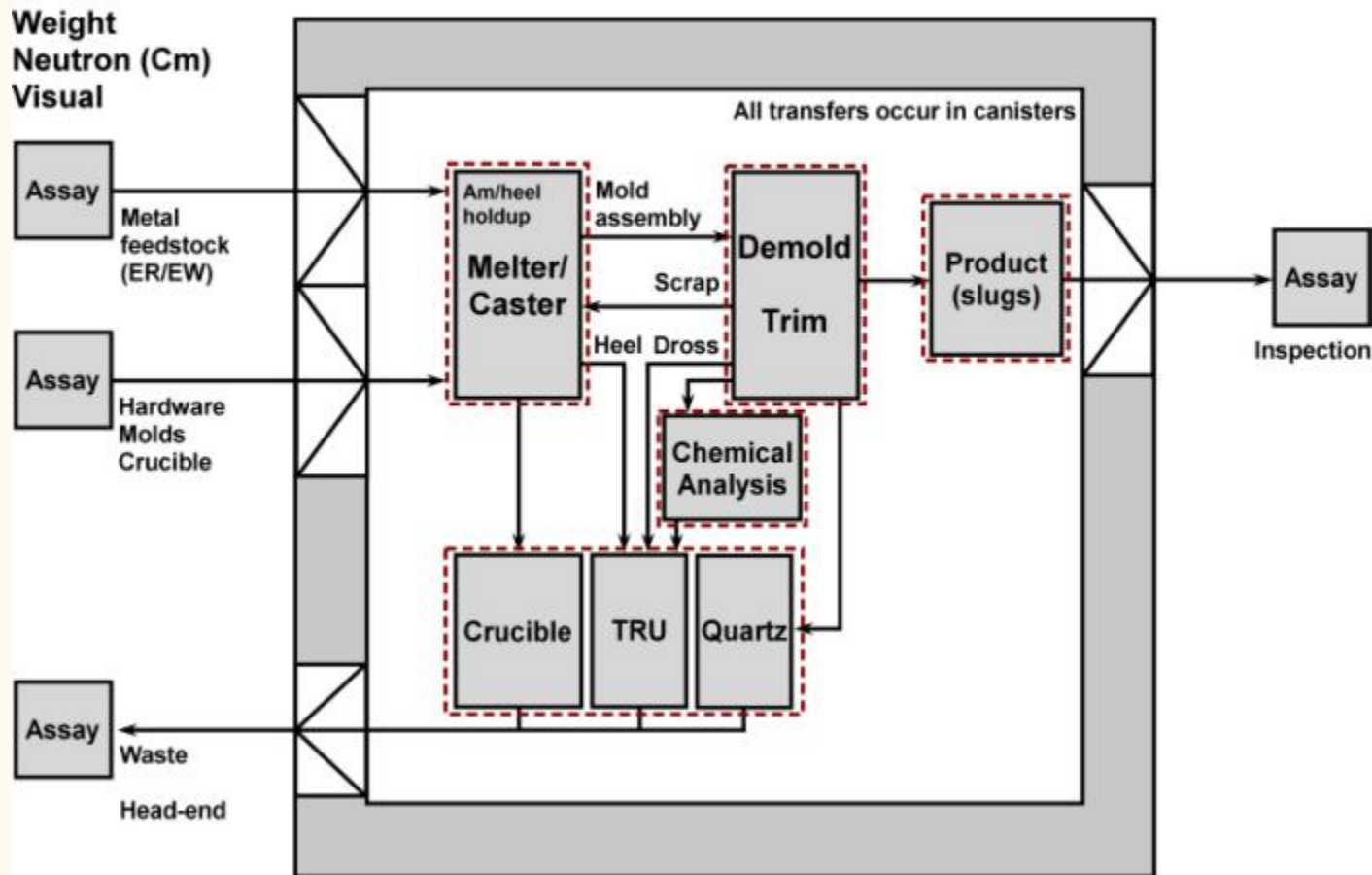
Injection casting assumed to fabricate metal fuel slugs



Understand how material flow affects design

Key

Assay:



(1) Injection casting

(2) Scrap

(3) TRU (heel)

(3a) Crucible

(3b) Quartz

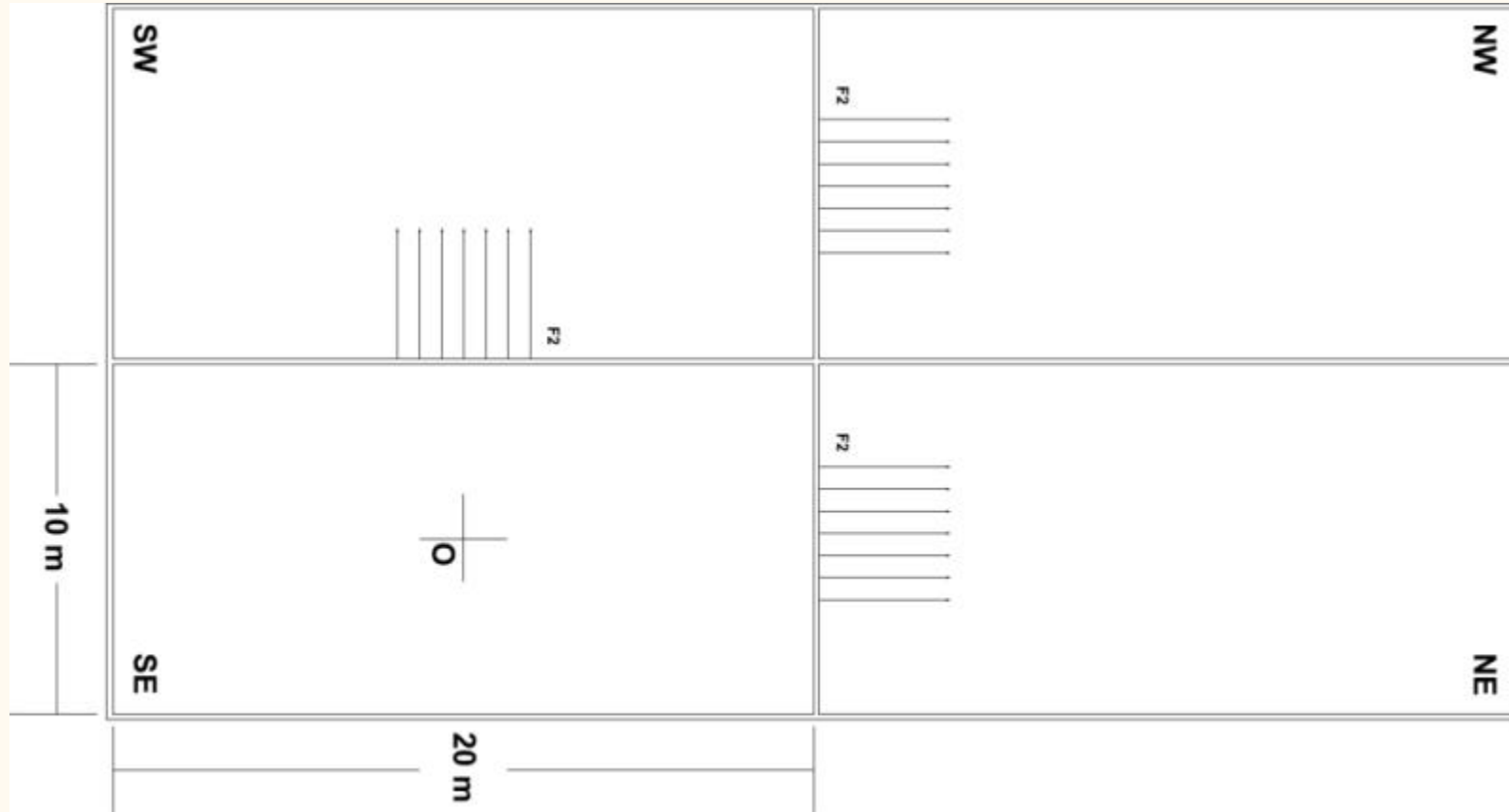
(4) Fuel slugs

(5) Testing (5a) DA

(5b) Chemical analysis

(5c) Other QA

Part 1 - Use of MCNP to estimate wall thickness



Will TRU processing state affect safeguardability?

1 - ERD metal+salt

1a - ERD metal

2 - U+TRU+salt

3 - TRU+salt

3a - TRU+Cd

4 - U/TRU alloy

SDEF - Cm-244 watt spectrum

TRU processing states are not self-protecting under IAEA standard

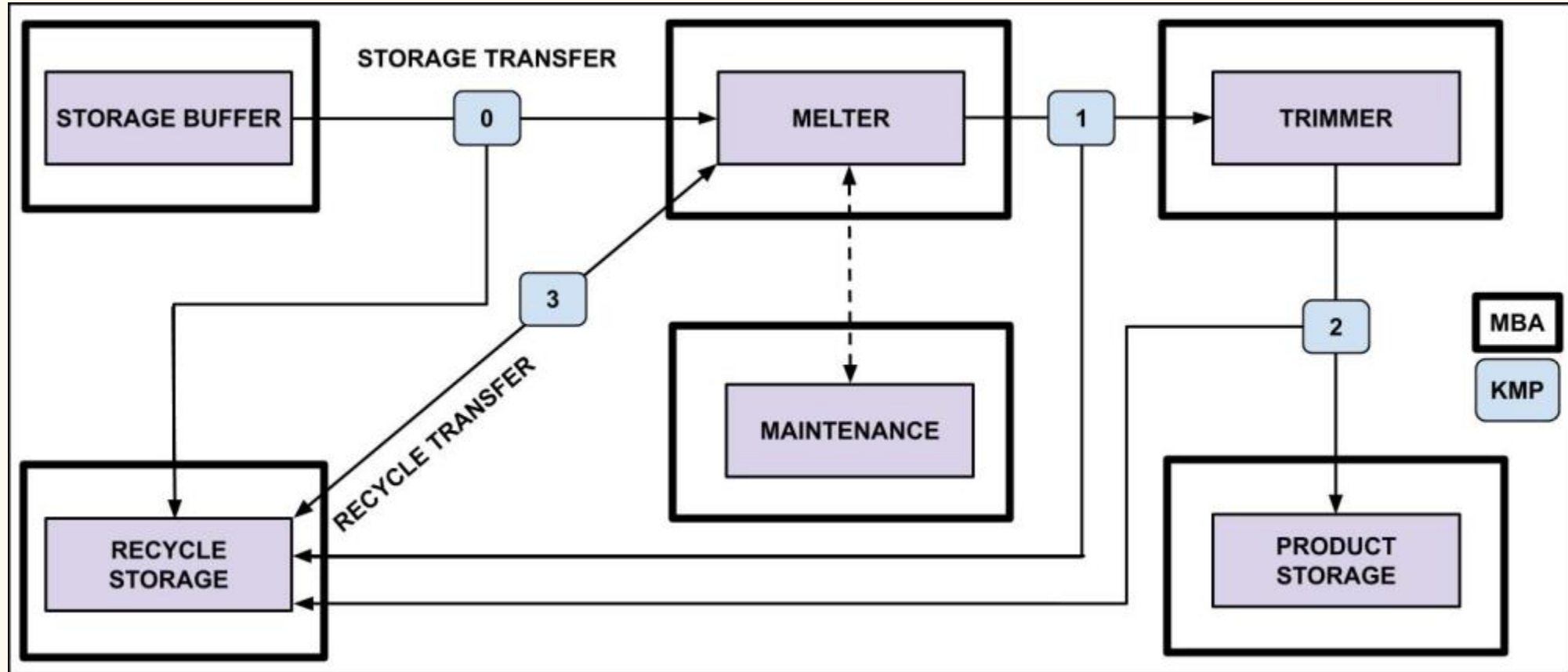
Wall thickness on par with other analogues (less than 10 /)

Average 30 cm - 45 cm thickness concrete

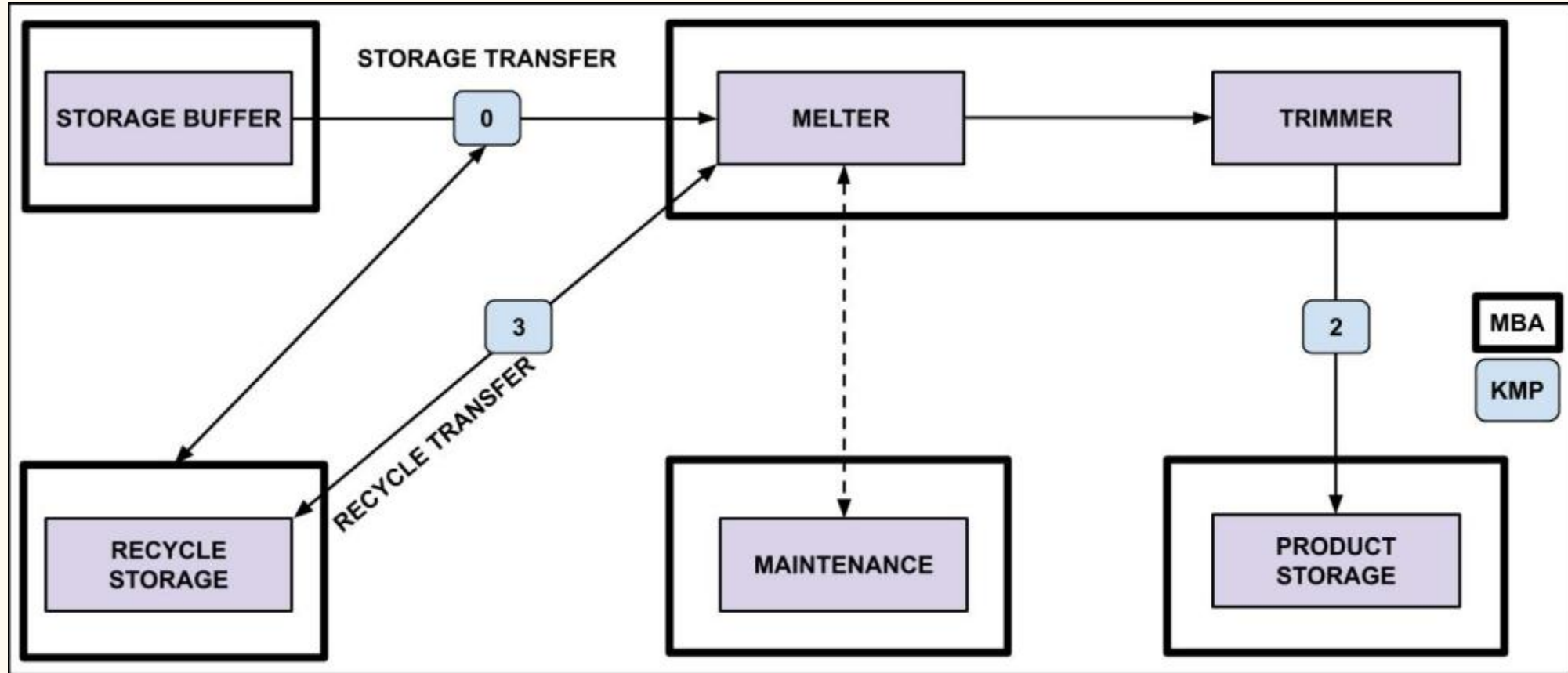
Maintenance, storage buffers located in proximity to process cells

Material transfer paths and facility footprint reduced

Part 2 - Apply discrete event simulation to facility design



Discrete event simulation describes state changes of system variables over time



Discrete event simulation lends itself well to object oriented programming

This is what I think is the key to safeguards-by-design

Jieun revamped the code

Model flow of Pu for each processing state; different times, batch size

Determine materials accounting due to operation, failure, maintenance

Connect to Type I error

$$\Phi^{-1}(1 - \alpha) + \Phi^{-1}(1 - \beta) = \text{---}$$

What can discrete simulation say about safeguardability (in terms of design)?

Results showed material flow not a function of equipment failure

Safeguardability shown as a function of material flow and design

For these proposed designs, operational goals are not affected - equal campaigns

SEID less than 2.4 kg for varying 1 —

First build that showed designs can be evaluated quantitatively

Jieun then added error propagation and increased accounting

First build calculated inventory difference at end of campaign

Now, at end of every material balance area/unit process

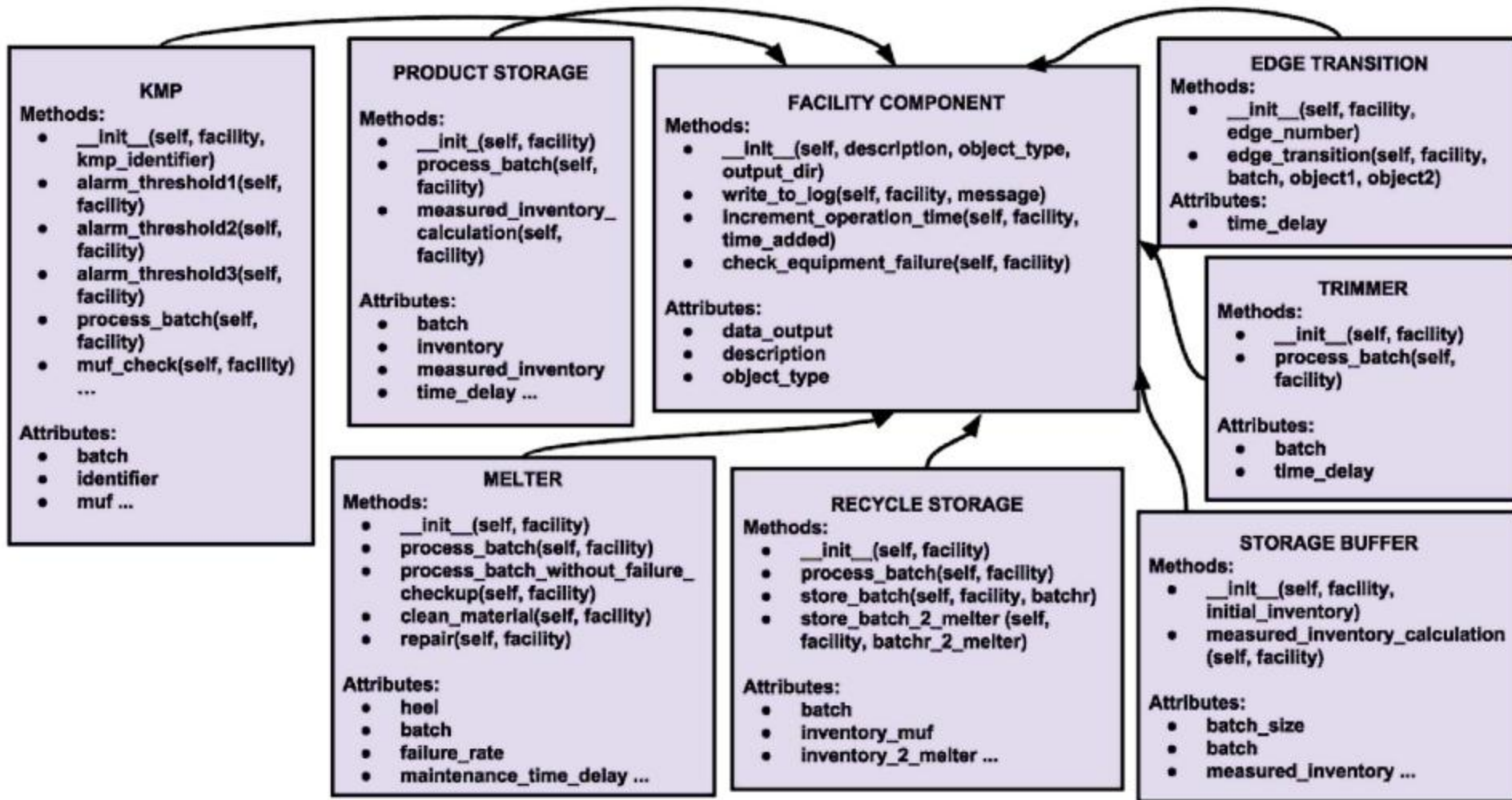


Fig. 4. Other than subclasses for sub-processes in the fuel fabrication process, the key measurement point class and the edge transition class also inherit functionalities from the facility component class. Major methods and attributes for each class are described above.

Total material processed

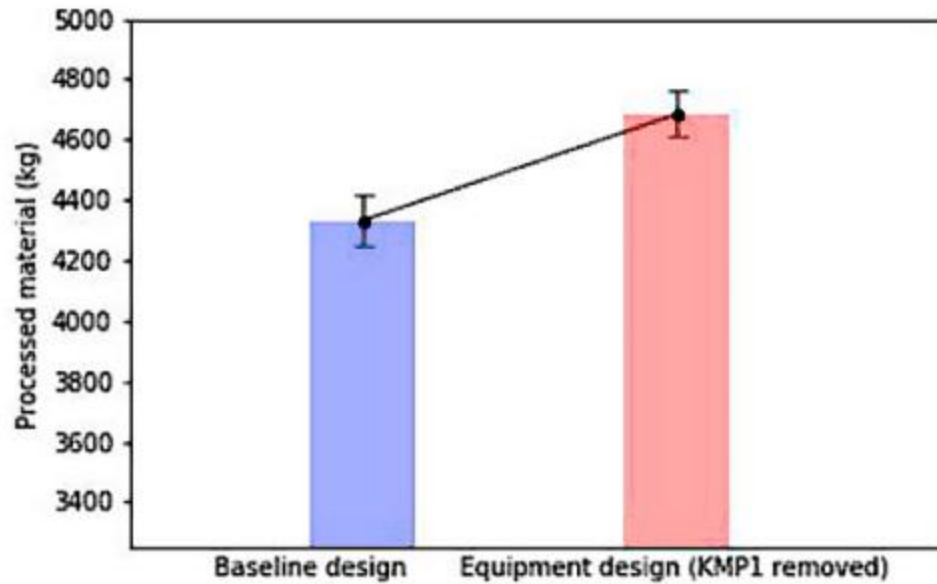


Fig. 9.1. The baseline design processed the product of 4332 ± 81.8 kg while the equipment design processed 4684 ± 75.5 kg. Equipment design could process 350 kg more compared to the baseline design with the same false alarm probability of 5% at each KMP.

Total campaigns completed

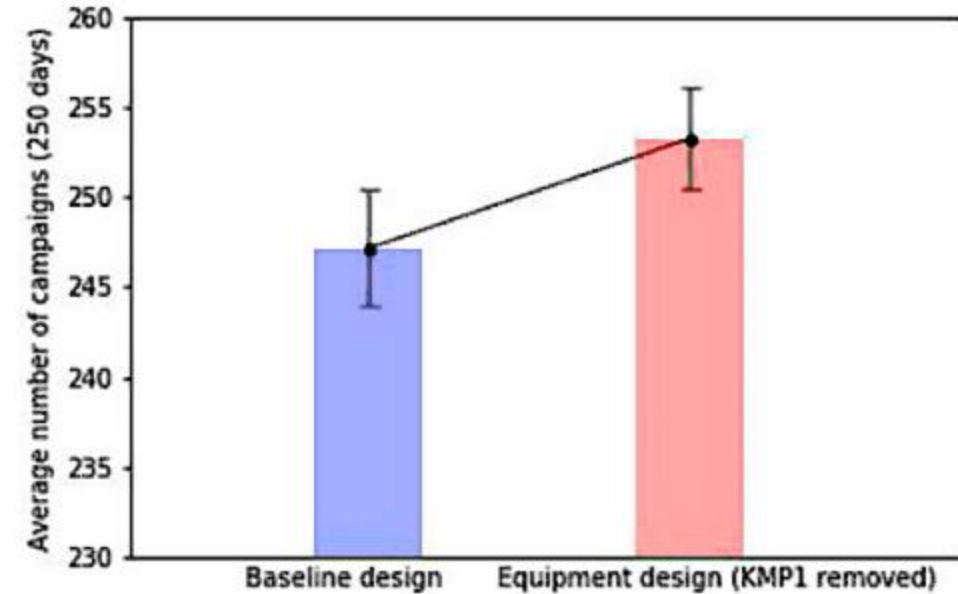


Fig. 9.2. The average number of campaigns is 247 ± 3.2 for the baseline design while for the equipment design it is 253 ± 2.8 .

We also performed a hazard operability analysis

Specialized form of risk assessment

Process flow diagrams developed for -

1. Voloxidation
2. Electroreduction, electrorefining, electrowinning
3. Ar atmosphere control system

Operational deviation analysis within the context of safeguard-by-design

Different hot cells for electroreduction and electrorefining (different salts)

Because low pressure possible salt leak could ruin materials accounting

Really forces you to understand systems at a very deep level

Actually really interesting to do

Table 2

HAZOP Table for voloxidation (Deviation = Parameter + Guideword).

Guideword	Deviation	Possible causes	Consequences	Protection methods
Parameter: Pressure				
More of	High pressure	Excess hot gas in the machine (fission gas product buildup) from: Stuck valve, Fast air flow, High RPM speed of the motor for the folding mesh, High power piston vibrator	Machinery rupture, Explosion/fire, Fission gas release	Safety relief valve, Valve actuation, Installation of the flowmeters, Periodic checkup of motors, Manual control of electric motors for rotating the folding mesh and running the piston vibrator, Use of proper materials for the equipment or the piping systems, which are designed to withstand high pressure (steel)
Less of	Low pressure	Malfunctioning valves, Low air flow, Low RPM speed of the motor for the folding mesh, Low power piston vibrator	Low efficiency of oxidation (No severe accidents)	Pressure gauge installation, Valve repair, Flowmeter installation, Motor repair
None of	No pressure	No oxidation from: No air gas flow (gas supply line rupture), No feed (malfunctioning hatch valve)	No yellowcake production	Flowmeter repair, Installation of backup loop for the gas supply line, Valve actuation
Parameter: Gas flow				
More of	High flow	Flowmeter malfunction	Fast flowmeter wear-out, High oxidation efficiency can build many gaseous fission products in the system, Fuel powders may escape (Yoo et al., 2008)	Frequent flowmeter calibration, Flowmeter repair
Less of	Low flow	Small pipe leaks, Pipe rupture, Valve partial opening	Low oxidation efficiency	Pipe repair, Valve actuation

Safeguardability - what capabilities are needed?

Someone who can and likes to code
I feel like Diogenes over here

Verification, benchmarking of the current model form

Funding

Development of a GUI

Which we have capabilities for already

Waste stream characterization for safeguards termination

Figure of merit to quantify proliferation risk

Full HAZOP

University of Idaho-Idaho Falls Nuclear Cybersecurity Working Group

We (i.e. me) acquired the Western Services Corp PWR simulator

Modeling

I&C

Thermal hydraulics

Electrical generation and distribution systems

Human factors

Logic/control system testing

Features

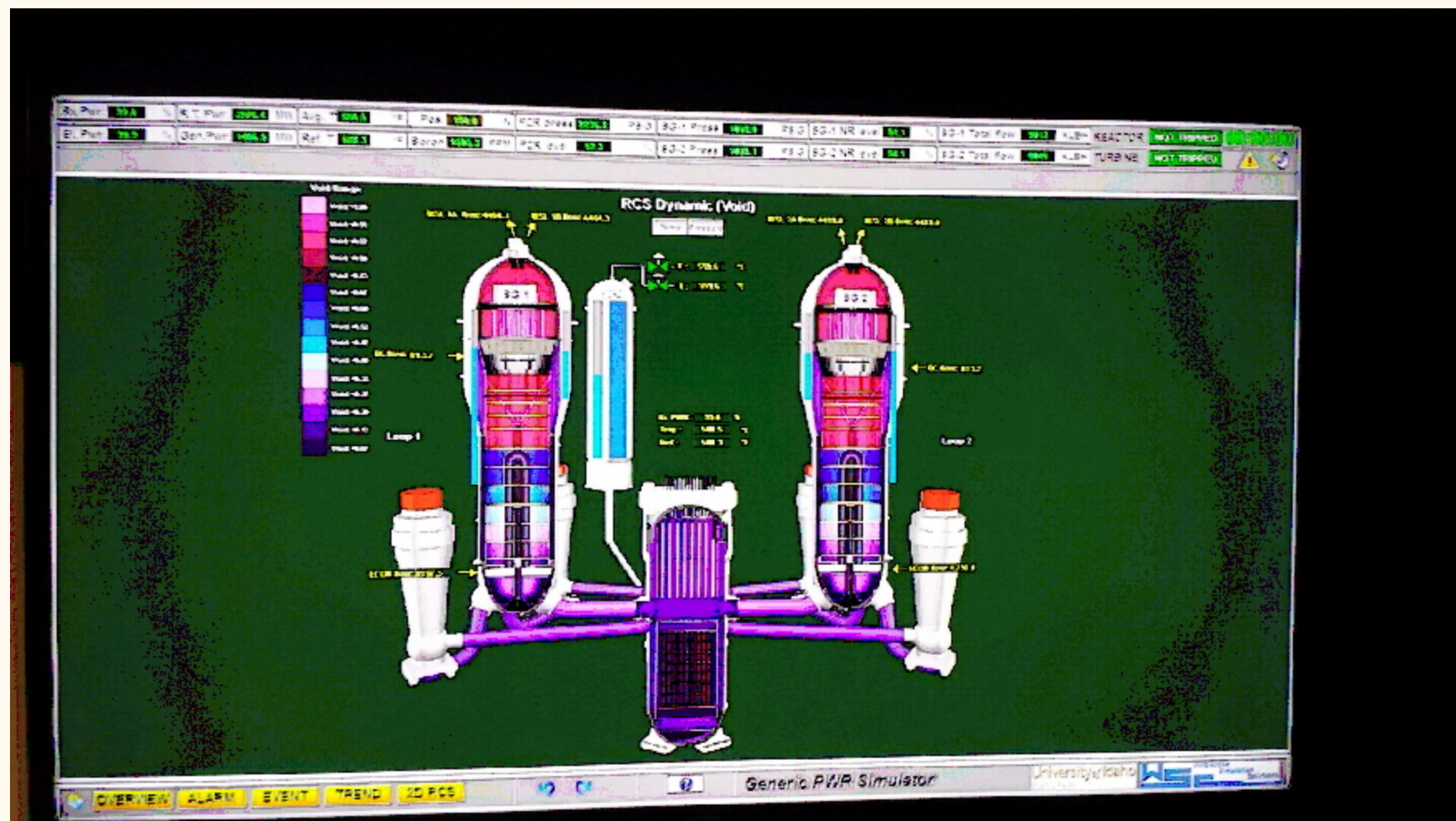
Two loop design, similar to the APR1400

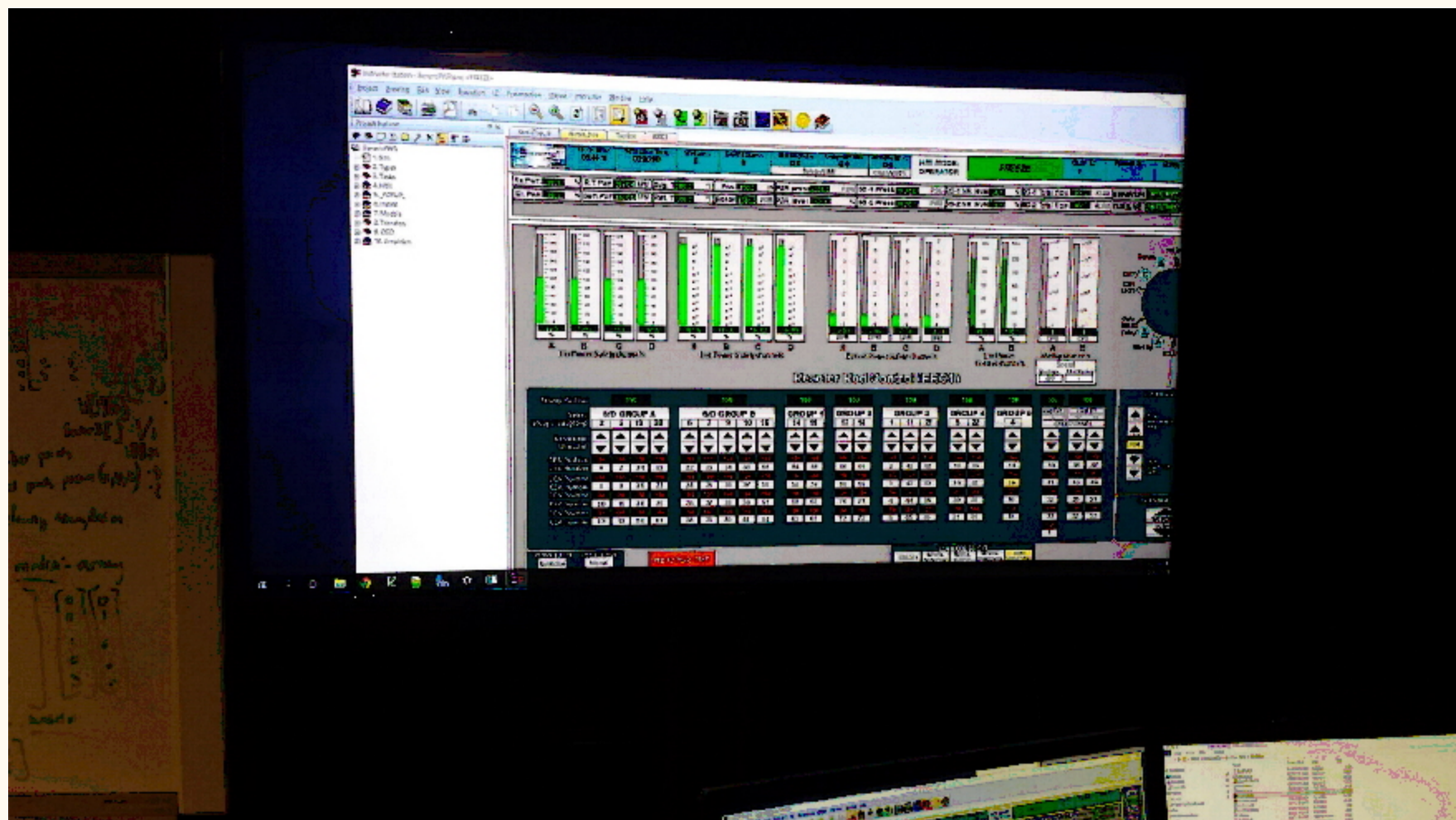
75 graphic control screens

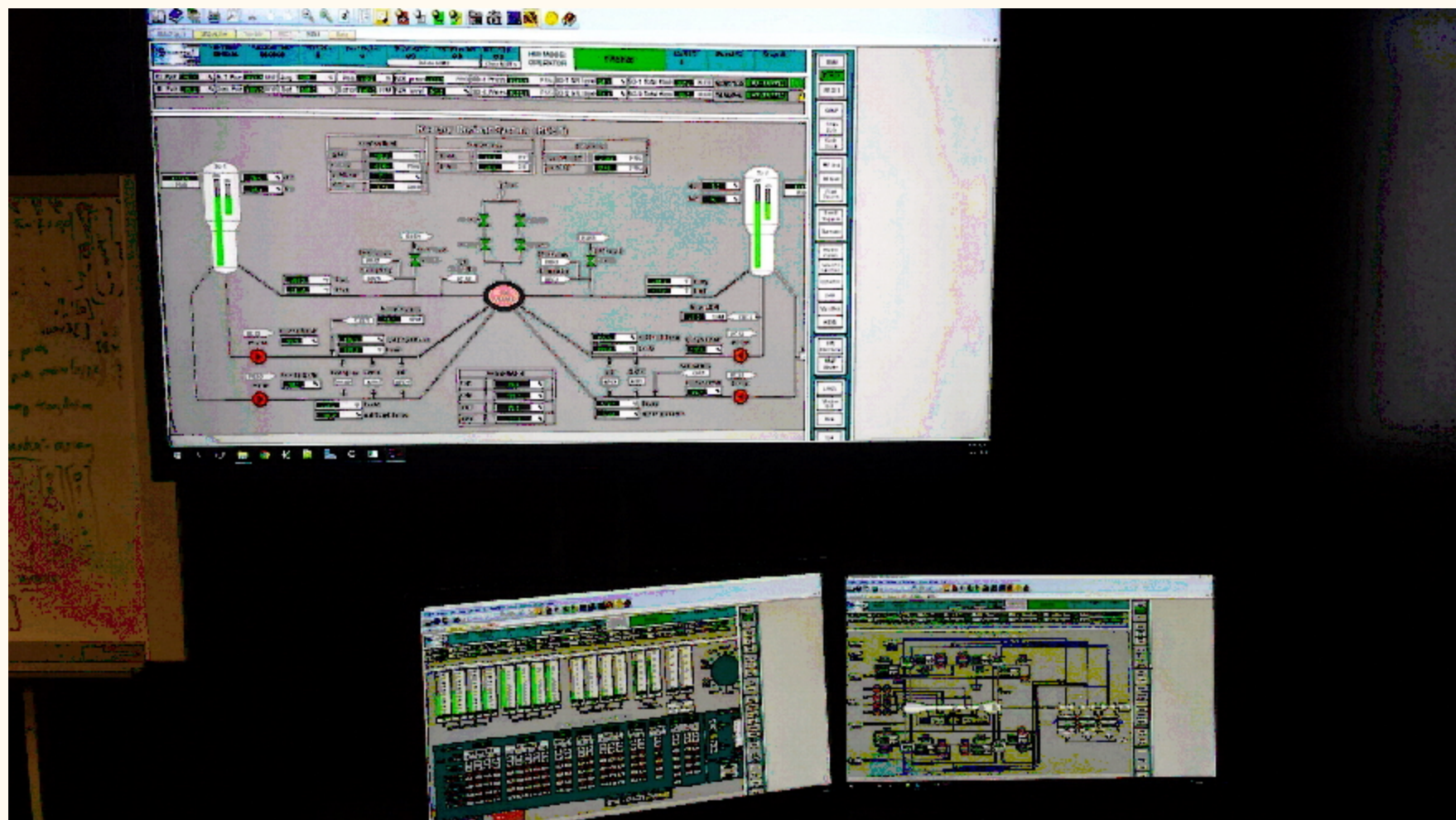
Full-featured trending system to monitor multiple transients Developers license allows for cybersecurity incidents to be coded and input into simulator

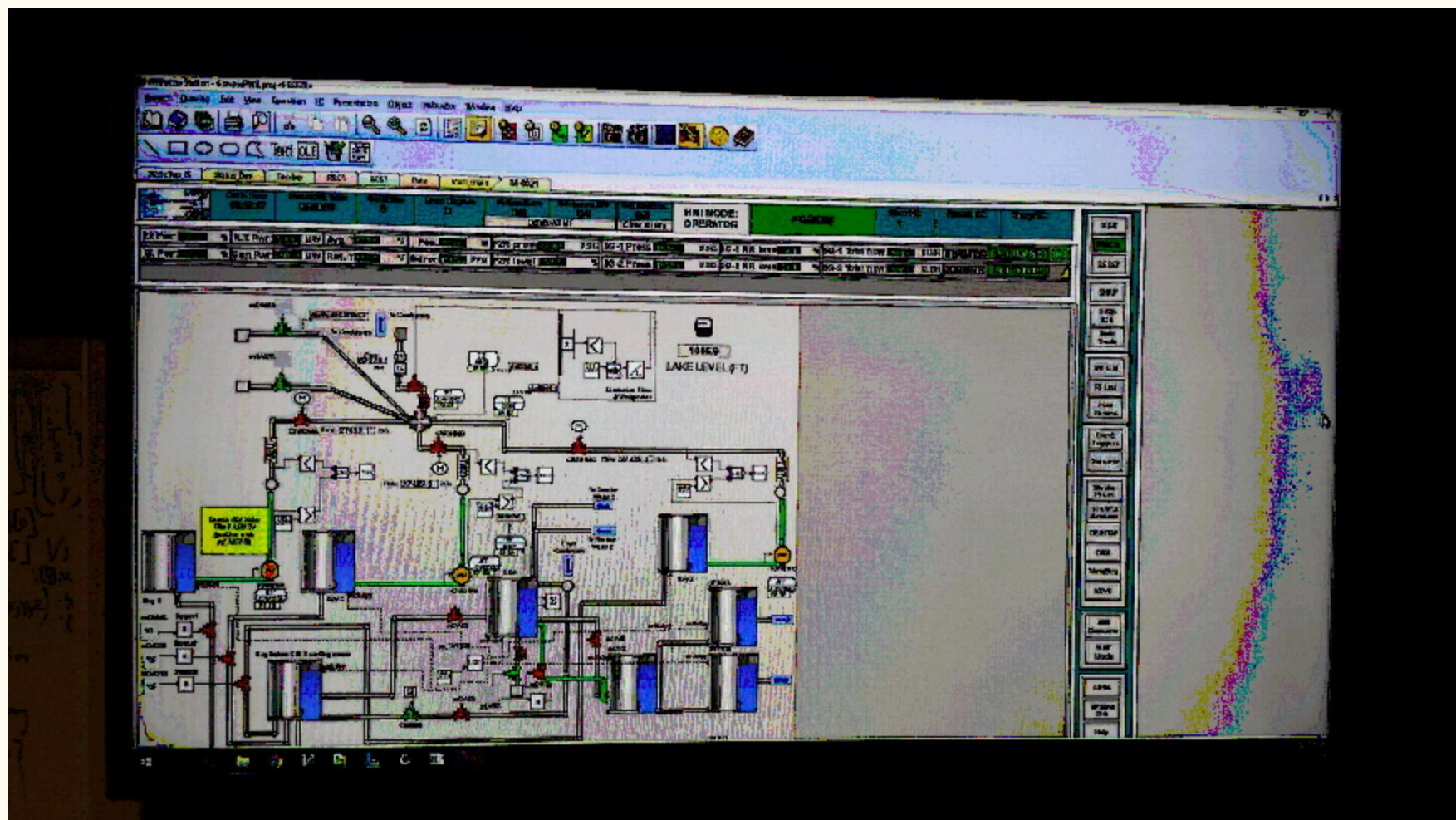
Housed in the Applied Visualization Laboratory at CAES

Source code









How can cyber vulnerabilities be integrated into traditional risk assessment?

Cyberattacks against critical energy infrastructure have gone from possible to eventual to actual

Plant modernization -----> digitization

Not just control panel

NRC wants stronger cybersecurity at plants but doesn't really know what that looks like

Emerging field with a lot of latitude to develop solutions

(That is what I say when reviewers argue with me)

Cyberattacks will act on many vectors

That means one type of attack can be used for multiple systems

We take the position that actually 'hacking the reactor' is unlikely

Forcing operator to trip or vent steam will cost a lot of money

There will also be a lot of down time to investigate the attack

Losses of several million dollars per year

I&C systems must be resilient to cyber domain threats, and guide operators with clear, prioritized information to make distinctions between safety events and cyber-based instrument manipulation

We reviewed past cyber events at nuclear installations

Davis-Besse, Browns Ferry, Hatch

Other non nuclear events - Ukraine, SF muni (they hacked it to actually run on time)

Commonalities

Insufficient cybersecurity features

Unintentional circumvention of facility security measures

Unknowing insider participation

These were not hacks - deficiencies in effective security policies

What happens when there is a directed attack?

We need a modernized definition of risk

Cyberattacks are deliberate - frequency is 1

Risk associated with digitization related to the strength of their defenses and their connectivity with other systems

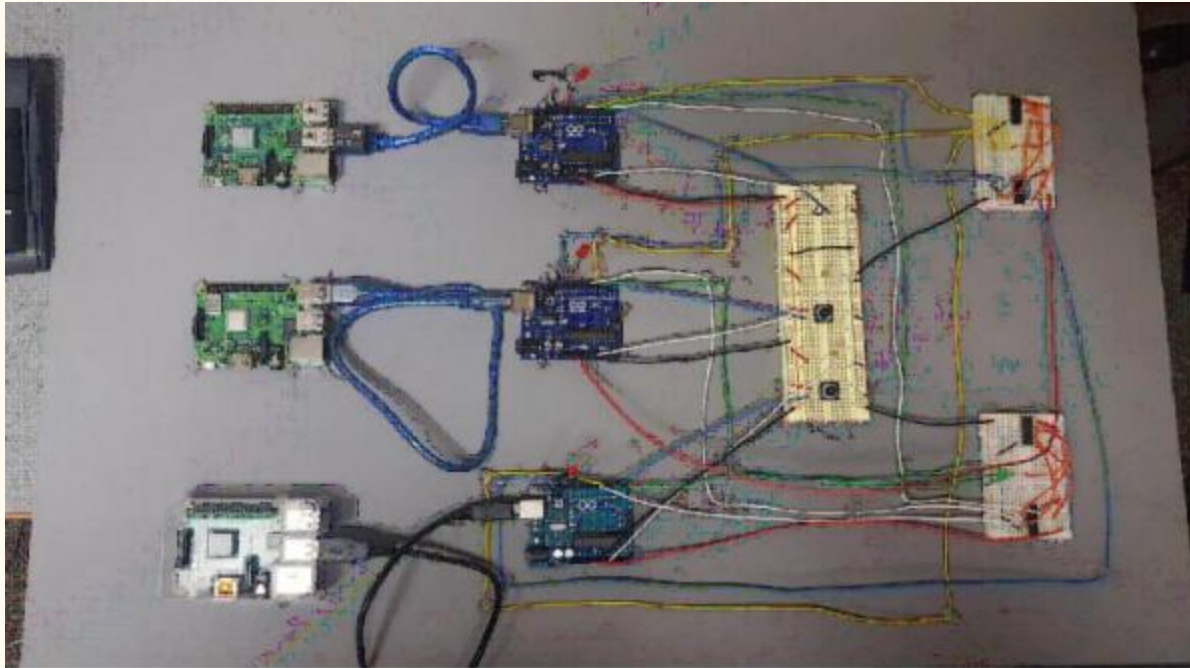
Means that common cause or cascading type 'failures' (attacks) increase risk

Traditional PRA kind of breaks down at this point

Solutions still should be within a performance based (vendor agnostic) context

We also modeled a man in the middle attack for a plant

Boron monitoring system setpoint



Showed 2 out of 3 circuit could mitigate the attack

Cybersecurity - what capabilities are needed?

Someone who can and likes to code

Funding

Replicating past cyberattacks into WSC simulator

Development of new envelope of attacks as a design basis

I&C design and testing

Situational awareness (which is a human factors issue)

Interface with INL HSSL (with Ron, Katya et al.)

Idaho Global Entrepreneurial Mission
State of Idaho Department of Commerce
Used fuel cask with Sakae Casting, LLC (Ibaraki)

IGEM funds products to market

Collaboration with Uldaho, Boise State, Sakae

Sakae has unique aluminum casting capabilities

We proposed an intermediate storage cask of borated aluminum

Uldaho - Neutrons, heat removal, regulations

Boise St - Materials science - solid solution of ^{238}Pu and

IGEM is a typical proposal process

Everyone gets up in your business

Present to the IGEM council and they vote on it

We argue some used fuel pools filling up

Assemblies need several years cooling before transfer to standard dry casks

Understand that some are transferred sooner - not necessarily internationally

Design a cask pool and dry storage

I did the market research (IGEM requirement)

Turns out hard numbers on used fuel pool capacities were really hard to find

Active NPP nations that are once through and not phasing out

For the most part, Europe doesn't seem to be a potential market

Most Asian countries lack robust dry storage

United States could go either way

I used ORIGIN for burnup and depletion

Thanks to Steve Skutnik for help

Divided the cases in to low burnup, typical burnup, high burnup

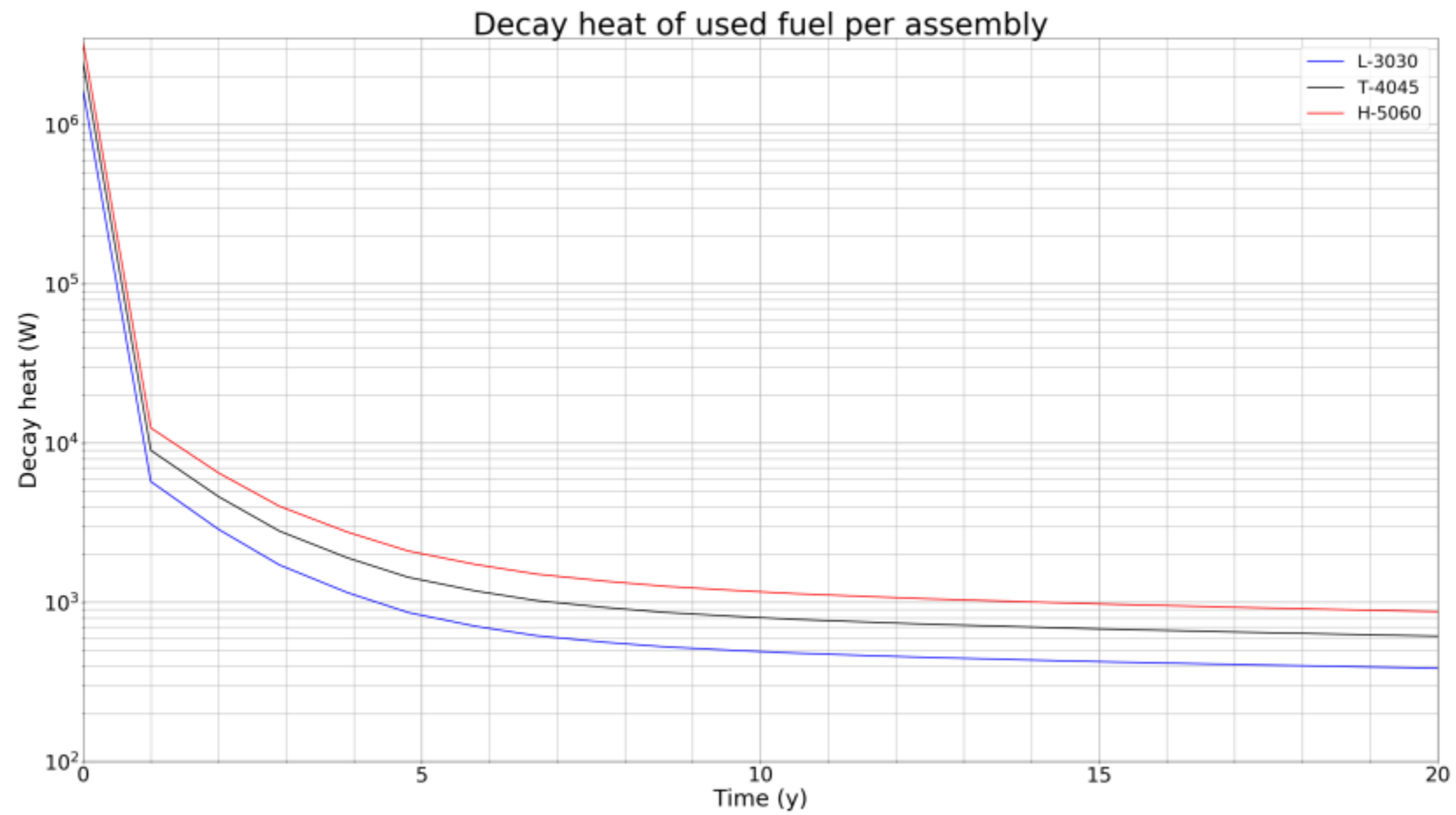
Based on literature review

(Read - N-XXYY - X.X% and YY GWD/MTU)

L-3030, T-4045, H-5060

Westinghouse 17x17 PWR

515 day cycle length and pool cooling (decay) from discharge out to 20 years



Then I ran many many many MCNP simulations for dose rate

I decided that the cask probably would only be useful for older fuel (20 y)

ORIGEN shows Cm-244 to be dominant emitter across the board (SDEF)

Plate thickness - 1.5, 3, 6, 12, 18, 30 cm

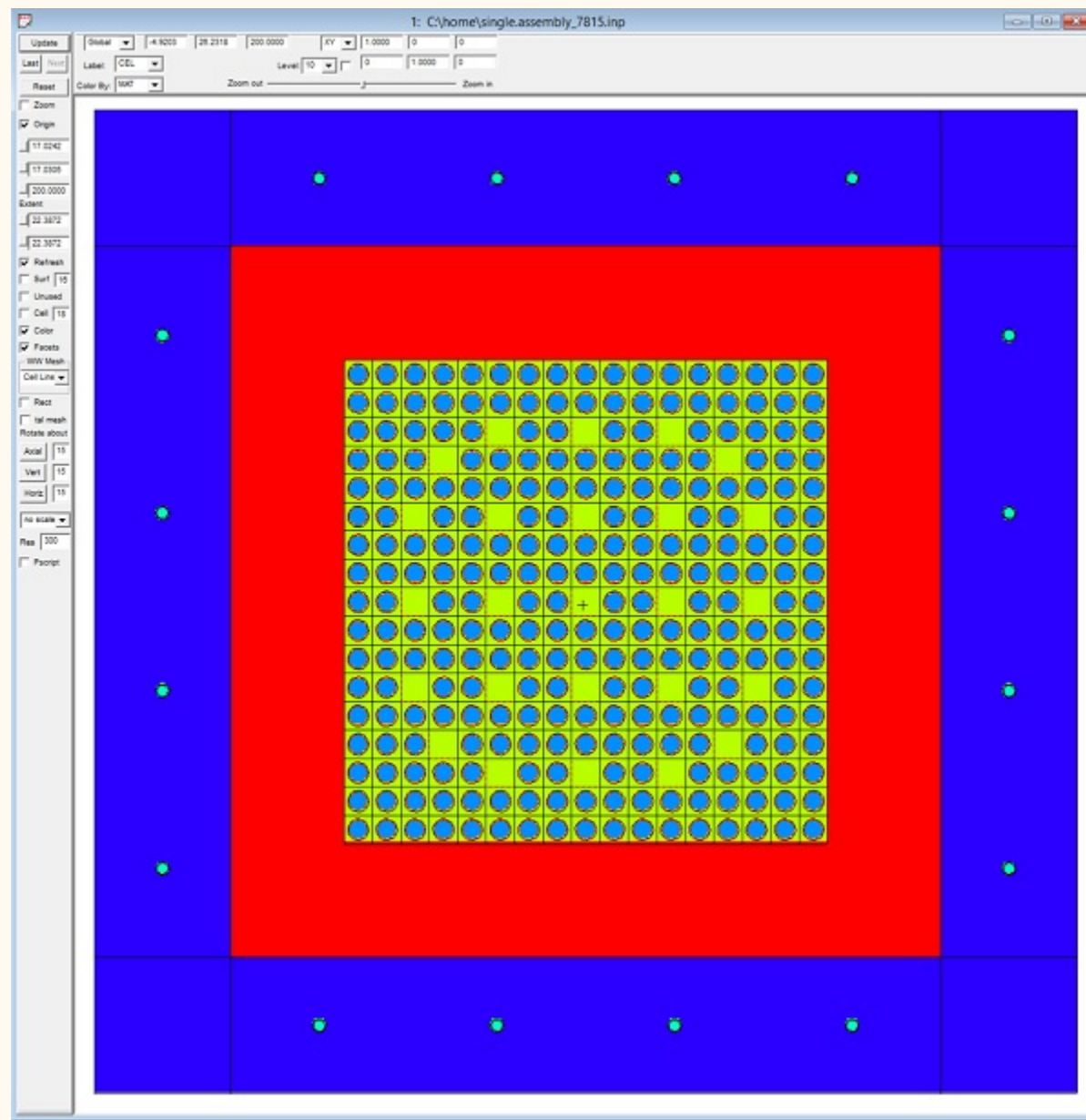
$^{244}_{94}$ - 10, 30, 50, 70, 90 wt% in Al per plate thickness

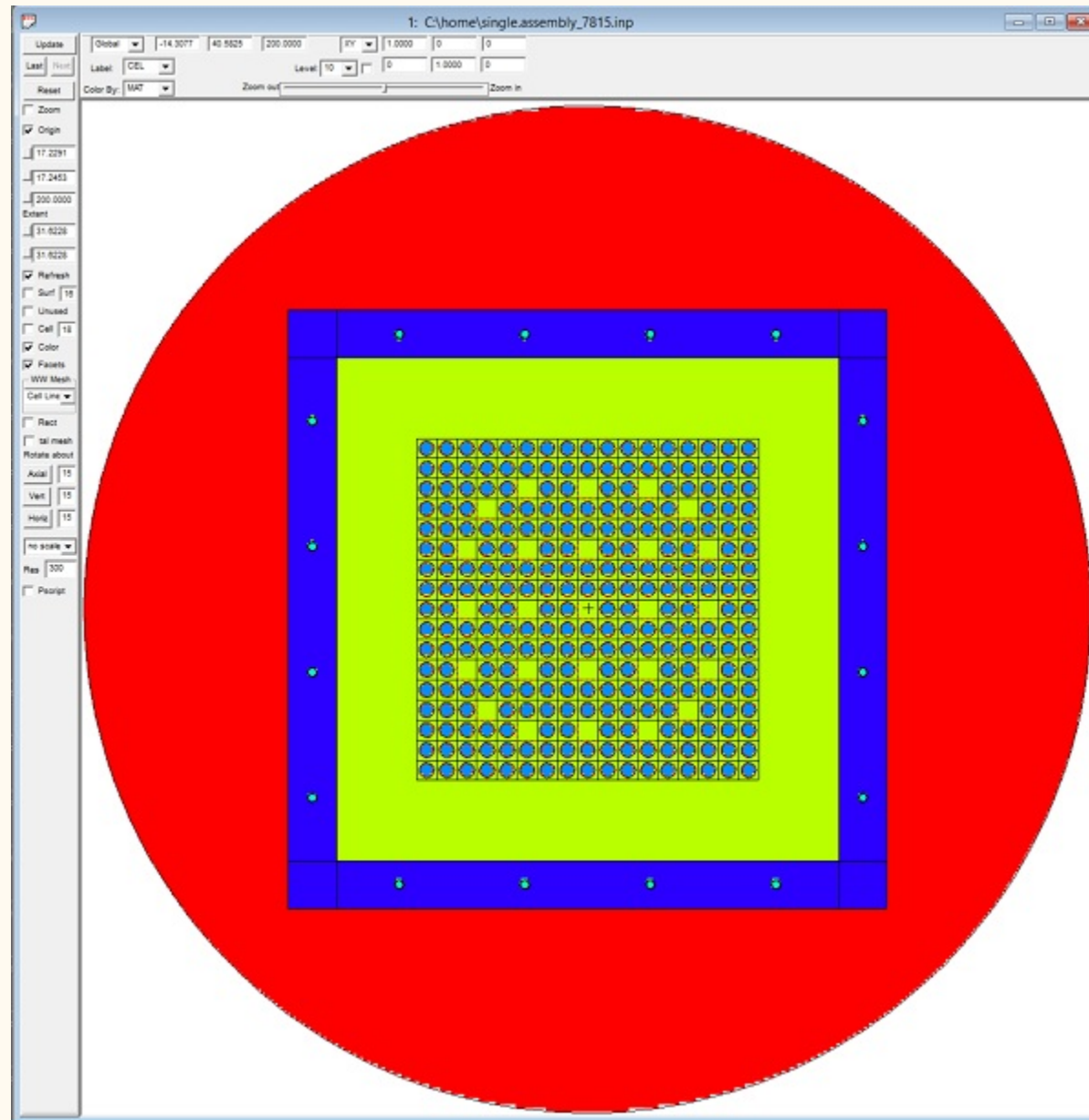
$^{10}_{10}$ loading in $^{244}_{94}$ - 5, 10, 25, 50, 75 wt%

For each enrichment-burnup

Then a second set of simulations emplaced in concrete - 3, 5, 10, 15, 20 cm

Looking for plate thickness for dose rate below 10 /





More MCNP modeling notes for your interest

Backfill - air, water, helium, borosilicate glass

Lattice card 17x17 unit cells - 269 rods - pitch 12.54 mm

Material card taken from ORIGEN output with 1E-08 wt% cutoff

Standard defaults for dose card

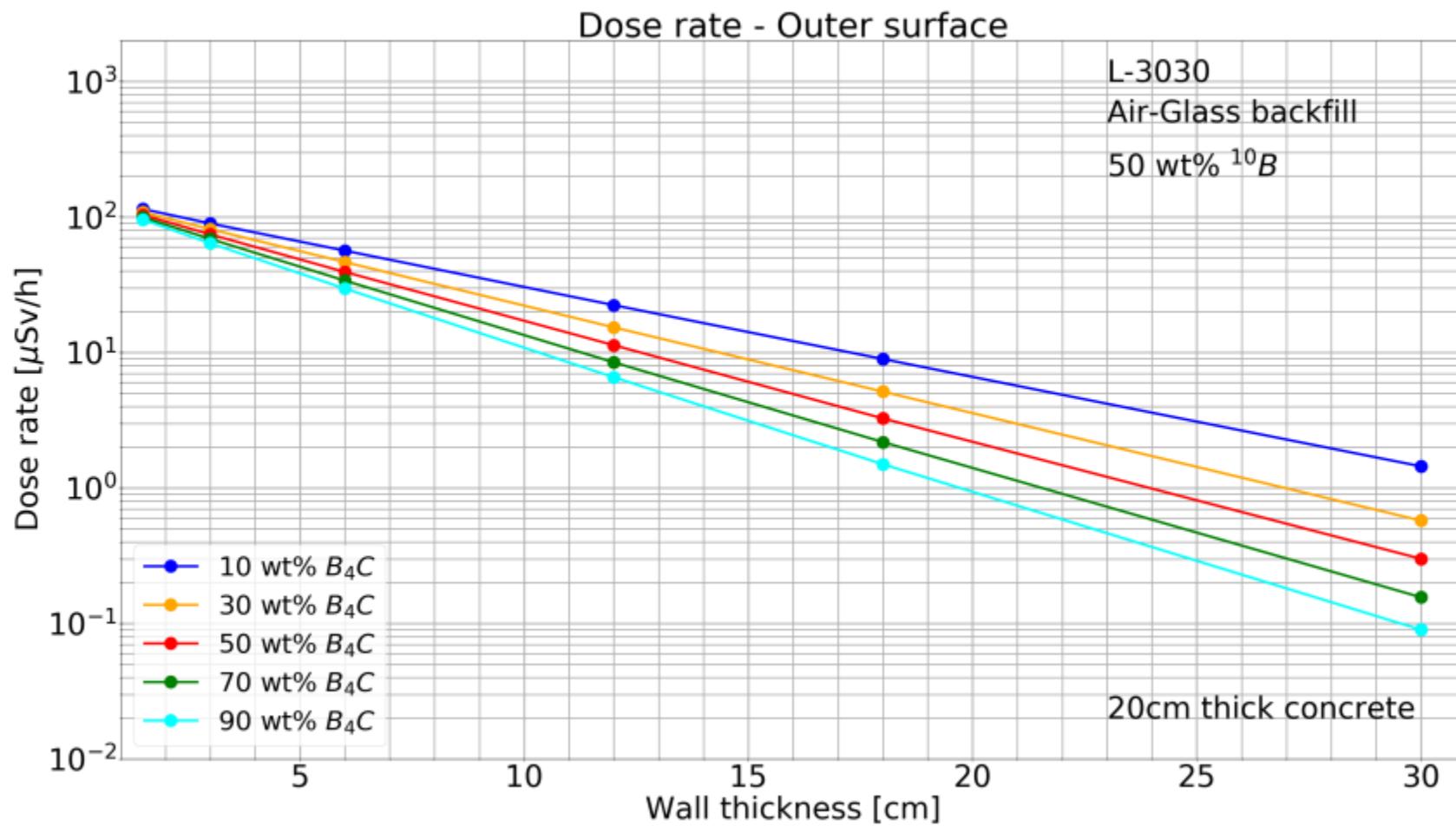
SDEF card - 5 source points per rod (POS)

ERG = Spontaneous Cm fission energy distribution

F2 tally for outward normal on each plate

NPS 2E6 (bare) and 3E6 (container) passed all tests

Equal dose rates off plates - isotropic



What do the results mean for design?

I don't know the cost of ¹⁰

Sakae needs to figure out limits of plate casting

Use of water backfill may be criticality risk if there are multiple casks

12 wt% ₄ constraint for now

High burnup fuel may not be feasible

I suggested NRC certification to enhance marketability

Currently 4 companies have obtained compliance each with different models

NUHOMS, MAGNASTOR, HI-STAR, HI-STORM (51 total)

10CFR72 is the relevant regulation

In short, the regulation is highly performance based

Demonstrate subcriticality, heat removal, occupational safety, etc.

Much of 10CFR72 is devoted to QA, which we can't do at this time

Application for Phase II design under review

Cask design - what capabilities are needed?

MCNP a lot

Cost analysis

Safety analysis

Establishing new quality assurance and quality control

Casting, but that is Sakae

Materials science



Relevant publications

Capstone

Leo M. Bobek, R. A. Borrelli, PLC-based reactivity measurements using inverse point kinetics, Transactions of the American Nuclear Society, 74, Annual meeting of the American Nuclear Society, 16-20 June, 1996, Reno, Nevada.

Ph.D.

R. A. Borrelli, Olivier Thivent, Joonhong Ahn, Parametric studies on confinement of radionuclides in the excavated damaged zone due to bentonite type and temperature change, Physics and Chemistry of the Earth, 65, 32 (2013).

R. A. Borrelli, Olivier Thivent, Joonhong Ahn, Impacts of elevated temperatures on bentonite extrusion and radionuclide transport in the excavated damaged zone, Nuclear Technology, 174(1), 94 (2011).

Relevant publications

Ph.D.

R. A. Borrelli, Joonhong Ahn, Radionuclide transport in a water-saturated planar fracture with bentonite extrusion, *Nuclear Technology*, 164(3), 442 (2008).

R. A. Borrelli, Joonhong Ahn, Numerical modeling of bentonite extrusion and radionuclide migration in a saturated planar fracture, *Physics and Chemistry of the Earth*, 33 S131 (2008).

Relevant publications

Safeguardability

R. A. Borrelli, A high reliability safeguards approach for safeguardability of remotely-handled nuclear facilities: 1. Functional components to system design, Journal of Nuclear Materials Management, XLII(3), 4 (2014).

R. A. Borrelli, A high reliability safeguards approach for safeguardability of remotely-handled nuclear facilities: 2. A risk-informed approach for safeguards, Journal of Nuclear Materials Management, XLII(3), 27 (2014).

Relevant publications

Safeguardability

R. A. Borrelli, J. Ahn, Y. Hwang, Approaches to a practical systems assessment for safeguardability of the advanced nuclear fuel cycle, Nuclear Technology, 197, 248 (2017).

R. A. Borrelli, Functional components for a design strategy: Hot cell shielding in the High Reliability Safeguards methodology, Nuclear Engineering and Design, 305, 18 (2016).

R. A. Borrelli, Use of curium neutron flux from head-end pyroprocessing subsystems for the high reliability safeguards methodology, Nuclear Engineering and Design, 277, 166 (2014).

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J. Lee, M. Tolman, R. A. Borrelli, High reliability safeguards approach to remotely handled nuclear processing facilities: Use of discrete event simulation for material throughput for fuel fabrication, Nuclear Engineering and Design 324, 54 (2017).

J. Lee, A. Shigrekar, R. A. Borrelli, Hazard and operability analysis of a pyroprocessing facility, Nuclear Engineering and Design 348, 131 (2019).

J. Lee, R. A. Borrelli, Sensitivity analysis and application of advanced nuclear accounting methodologies on the high reliability safeguards model: Use of discrete event simulation for material throughput in fuel fabrication, Nuclear Engineering and Design 345, 183 (2019).

Relevant publications

Cybersecurity

J. Peterson, M. Haney, R. A. Borrelli, An overview of methodologies for cyber security vulnerability assessments conducted in nuclear power plants, Nuclear Engineering and Design 346, 75 (2019).

T. MacLean, M. Haney, R. A. Borrelli, Cybersecurity modeling of non-critical nuclear power plant digital instrumentation. Critical Infrastructure Protection XIII, J. Staggs, S. Sheno, eds. Chapter 15, 277.

Relevant publications

IGEM

R. A. Borrelli, Updates on borated aluminum cask design for onsite used fuel storage, Proc., American Nuclear Society Annual Meeting, 09-13 June, 2019, Minneapolis, Minnesota.

R. A. Borrelli, J. S. Dustin, S. Pedersen, B. J. Jaques, Design of a borated aluminum cask design for onsite used fuel storage, Proc., American Nuclear Society Annual Meeting, 17-21 June, 2018 Philadelphia, Pennsylvania.

R. A. Borrelli, M. S. Delligatti, Regulatory licensing pathway for a borated aluminum cask design for onsite used fuel storage, Proc., American Nuclear Society Annual Meeting, 17-21 June, 2018, Philadelphia, Pennsylvania.