Interesting Nuclear Things with Bob at Idaho Falls

UTK Nuclear Engineering Department Seminar

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Center for Advanced Energy Studies
@TheDoctorRAB

23 October 2019

THE UNIVERSITY OF TENNESSEE KNOXVILLE

No outline slide

Who is Bob?

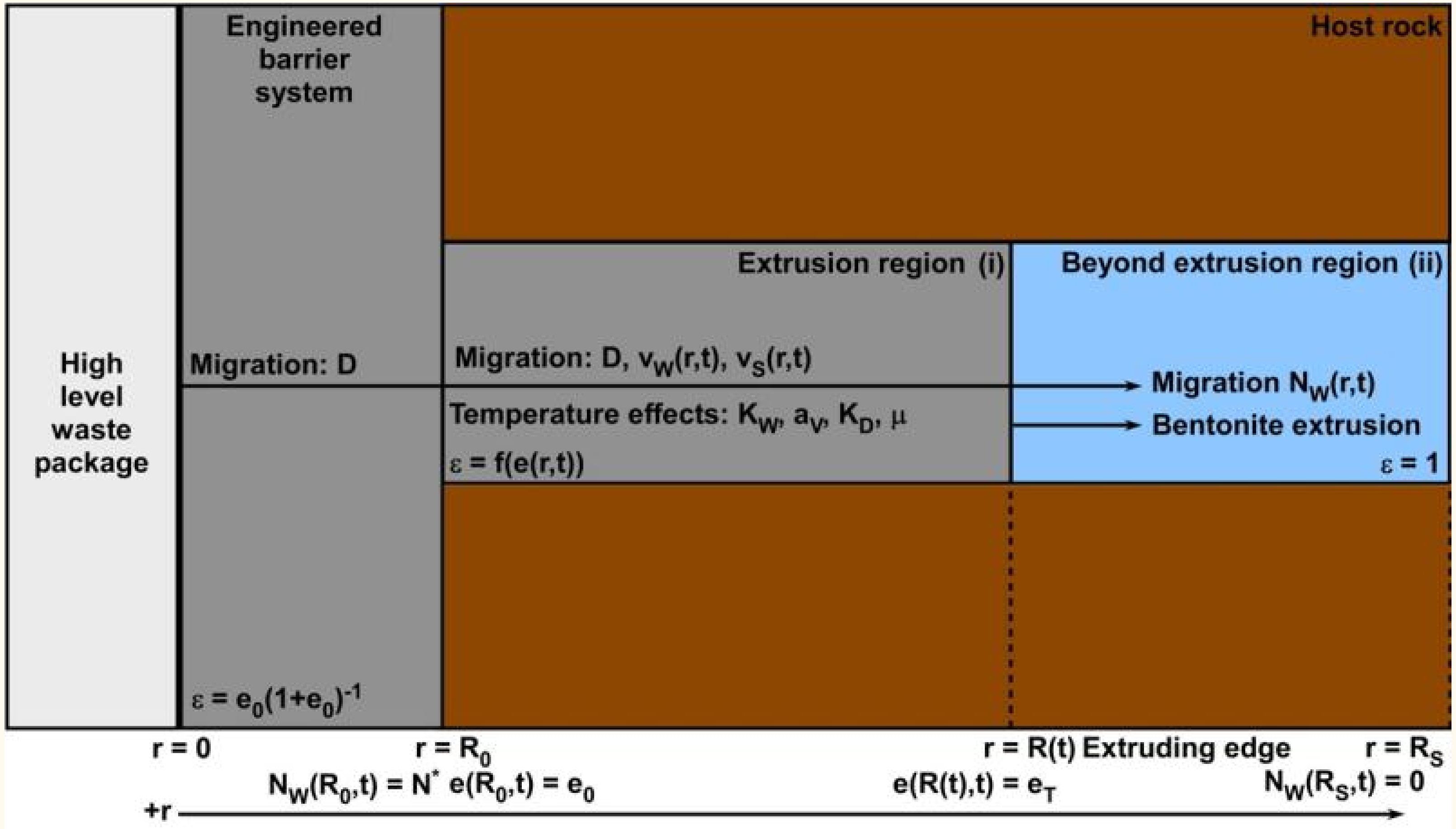
I grew up in Rhode Island

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



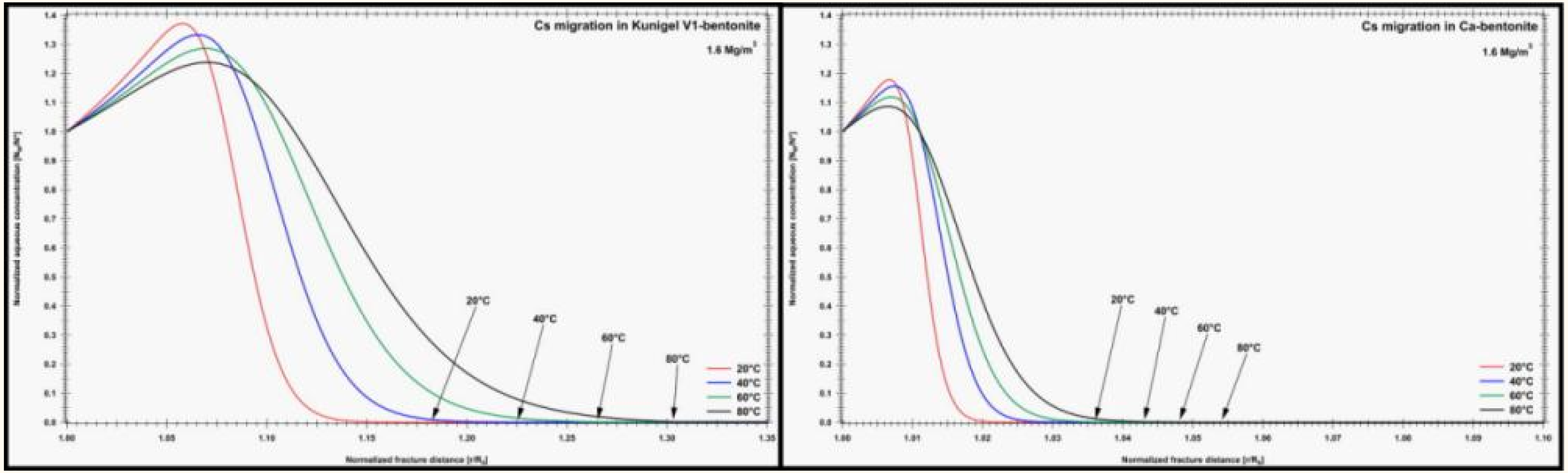
It was a lot of math (even if it doesn't look like it)

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

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

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

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


IDAHO
State Map
CANADA
WASHINGTON
MONTANA
OREGON
NEVADA
UTAH
WYOMING
Eastport
Bonners Ferry
Sandpoint
Hayden
Post Falls
Coeur d' Alene
Kellogg
Plummer
Wallace
St.Maries
Potlatch
Moscow
Lewiston
Orofino
Craigmont
Kamiah
Cottonwood
Grangeville
New Meadows
McCall
Cambridge
Cascade
Weiser
Payette
Emmett
Caldwell
Meridian
Nampa
BOISE
Gibbonsville
Salmon
Challis
Stanley
Mackay
Dubois
Ashton
Hailey
Sun Valley
Arco
Rexburg
Roberts
Rigby
Mountain Home
Bliss
Gooding
Glenns Ferry
Jerome
Shoshone
Moreland
Idaho Falls
Swan Valley
Blackfoot
Buhl
Twin Falls
Rupert
American Falls
Pocatello
Rogerson
Burley
Mc Cammon
Soda Springs
Malta
Downey
Malad City
Montpelier
Preston
LEGEND
Intl. Boundary
Interstate Highway
State Highway
US Federal Highway
Railway Line
State Boundary
State Capital
Major Town
Other Town
Map not to Scale
Copyright © 2015 www.mapsofworld.com
(Updated on 19th May, 2015)

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 UIdaho 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' (*old*) 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

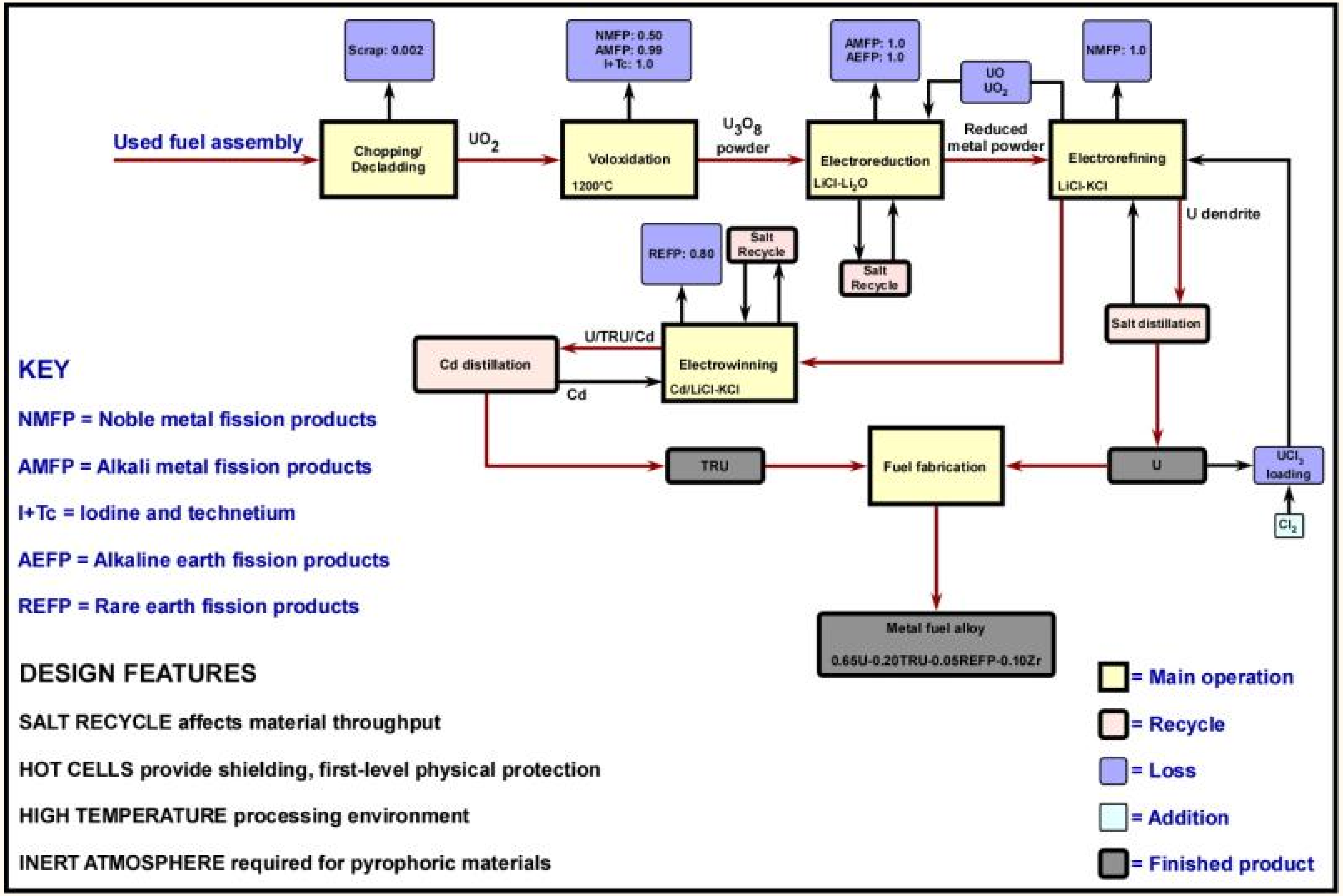
Proliferation resistance
Develop functional components to facility design

Physical protection
Take advantage of inherent design features

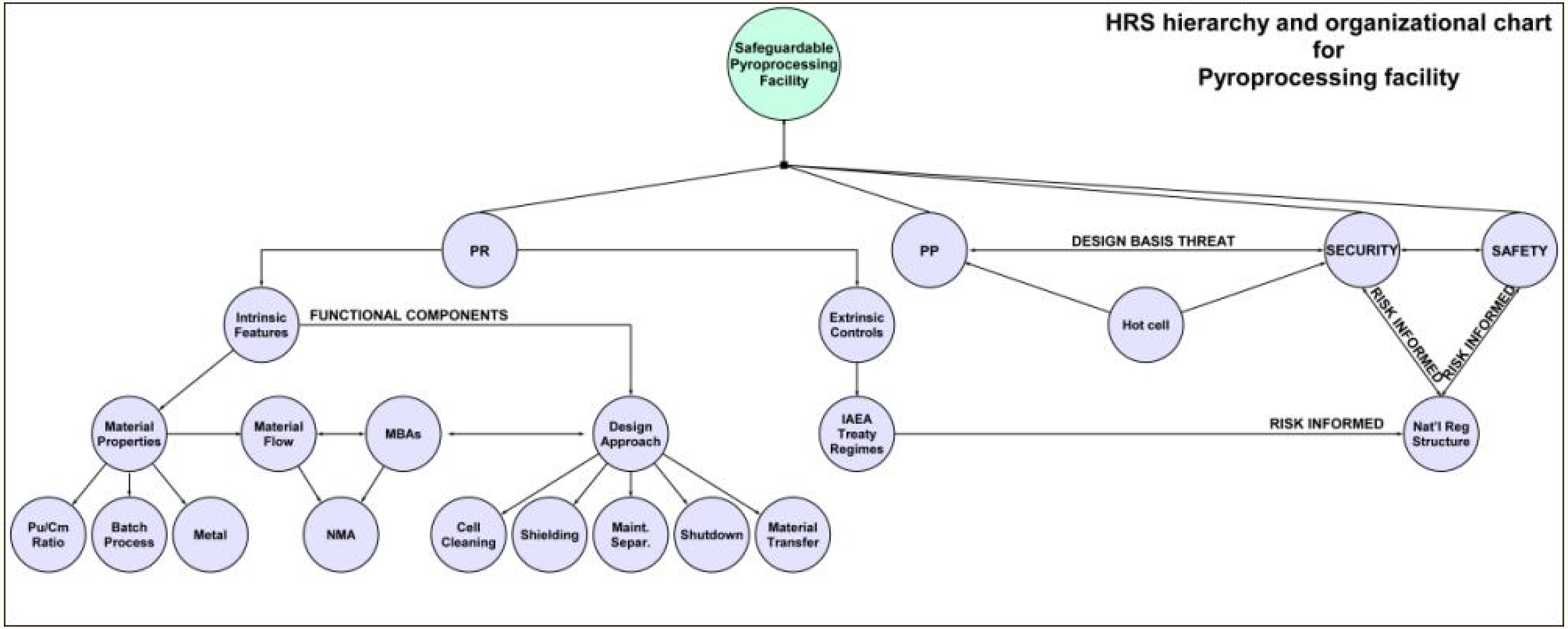
Systems assessment = Safeguardability quantification
Risk-informed approach

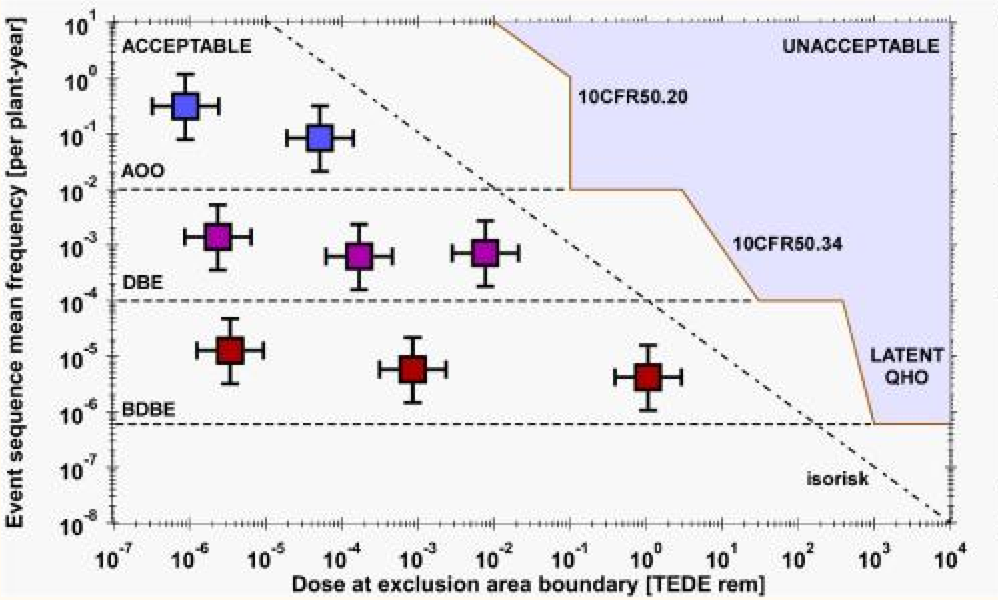
Time may have passed me by, but I still want to develop it

Long-term goals for HRS

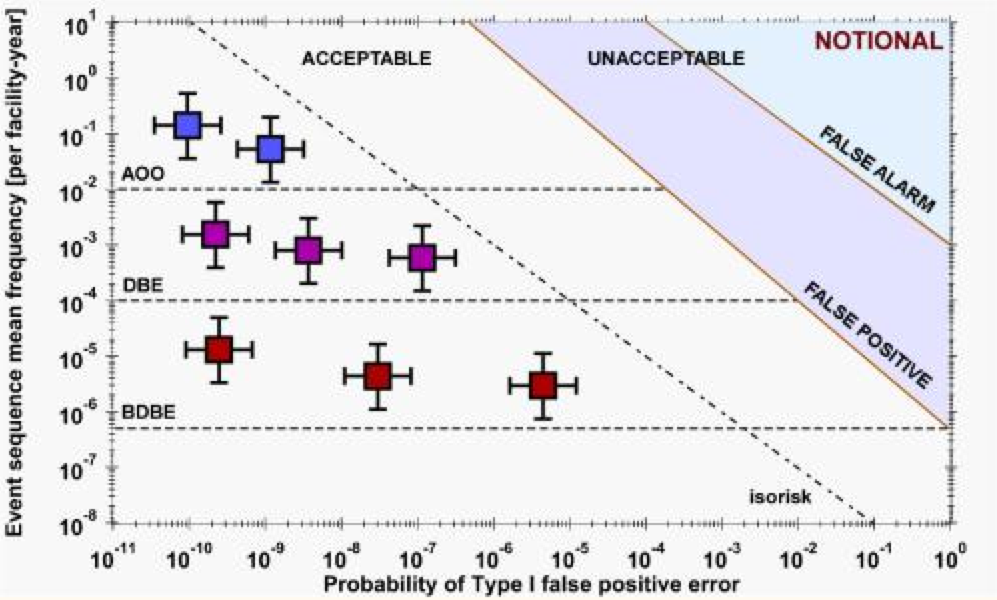


Scrap: 0.002
NMFP: 0.50
AMFP: 0.99
I+Tc: 1.0
AMFP: 1.0
AEFP: 1.0
UO
UO_2
NMFP: 1.0
Used fuel assembly
Chopping/ Decladding
UO_2
Voloxidation
1200°C
U_3O_8 powder
Electroreduction
$LiCl-Li_2O$
Reduced metal powder
Electrorefining
LiCl-KCl
U dendrite
Salt Recycle
REFP: 0.80
Salt Recycle
Salt distillation
U/TRU/Cd
Cd distillation
Electrowinning
Cd/LiCl-KCl
Cd
KEY
NMFP = Noble metal fission products
AMFP = Alkali metal fission products
I+Tc = Iodine and technetium
AEFP = Alkaline earth fission products
REFP = Rare earth fission products
TRU
Fuel fabrication
U
UCl_3 loading
Cl_2
Metal fuel alloy
0.65U-0.20TRU-0.05REFP-0.10Zr
DESIGN FEATURES
SALT RECYCLE affects material throughput
HOT CELLS provide shielding, first-level physical protection
HIGH TEMPERATURE processing environment
INERT ATMOSPHERE required for pyrophoric materials
= Main operation
= Recycle
= Loss
= Addition
= Finished product


HRS hierarchy and organizational chart
for
Pyroprocessing facility
Safeguardable Pyroprocessing Facility
PR
PP
SECURITY
SAFETY
DESIGN BASIS THREAT
Intrinsic Features
FUNCTIONAL COMPONENTS
Extrinsic Controls
Hot cell
RISK INFORMED
RISK INFORMED
Material Properties
Material Flow
MBAs
Design Approach
IAEA Treaty Regimes
RISK INFORMED
Nat'l Reg Structure
Pu/Cm Ratio
Batch Process
Metal
NMA
Cell Cleaning
Shielding
Maint. Separ.
Shutdown
Material Transfer



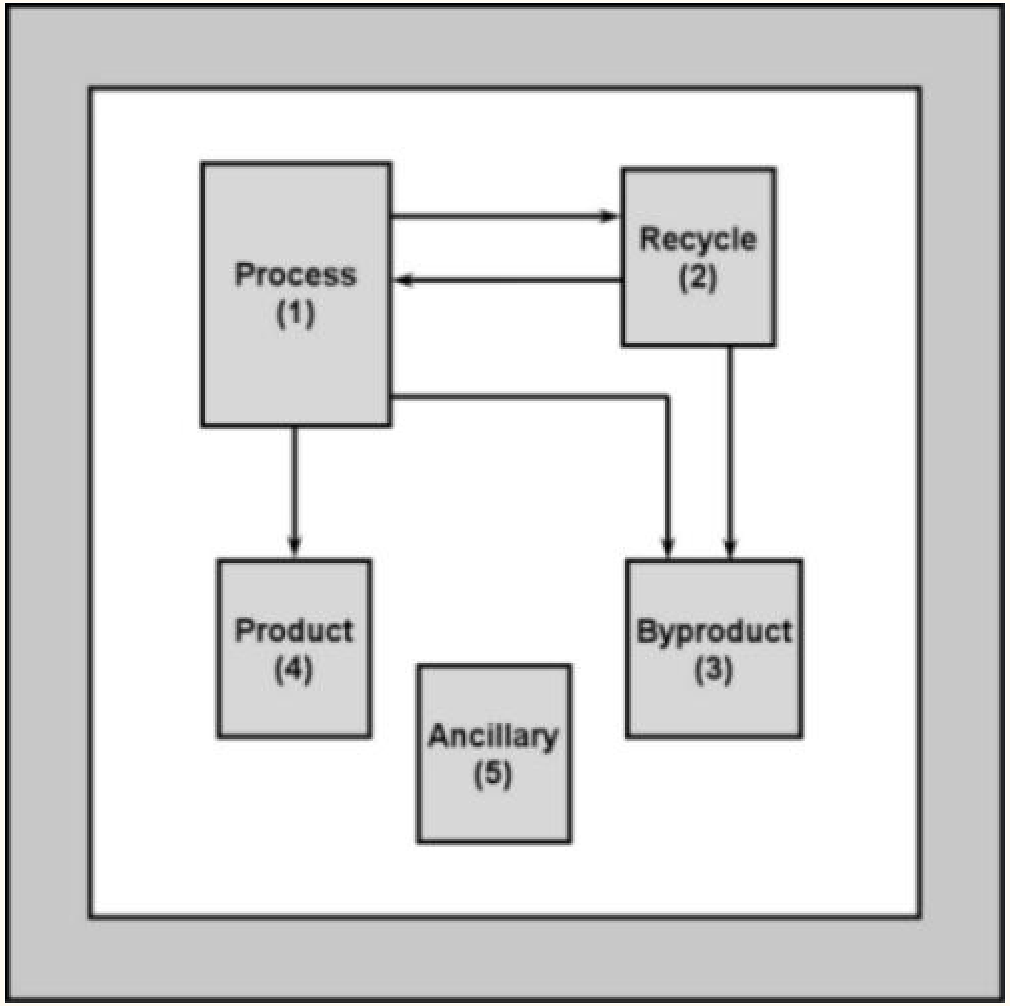
ACCEPTABLE
UNACCEPTABLE
10CFR50.20
10CFR50.34
LATENT
QHO
AOO
DBE
BDBE
isorisk
Event sequence mean frequency [per plant-year]
Dose at exclusion area boundary [TEDE rem]



ACCEPTABLE
UNACCEPTABLE
NOTIONAL
FALSE ALARM
FALSE POSITIVE
AOO
DBE
BDBE
isorisk
Event sequence mean frequency [per facility-year]
Probability of Type I false positive error

Modeling framework

Generalize system processes



Key

(1) Process activity
(2) In-situ recycle

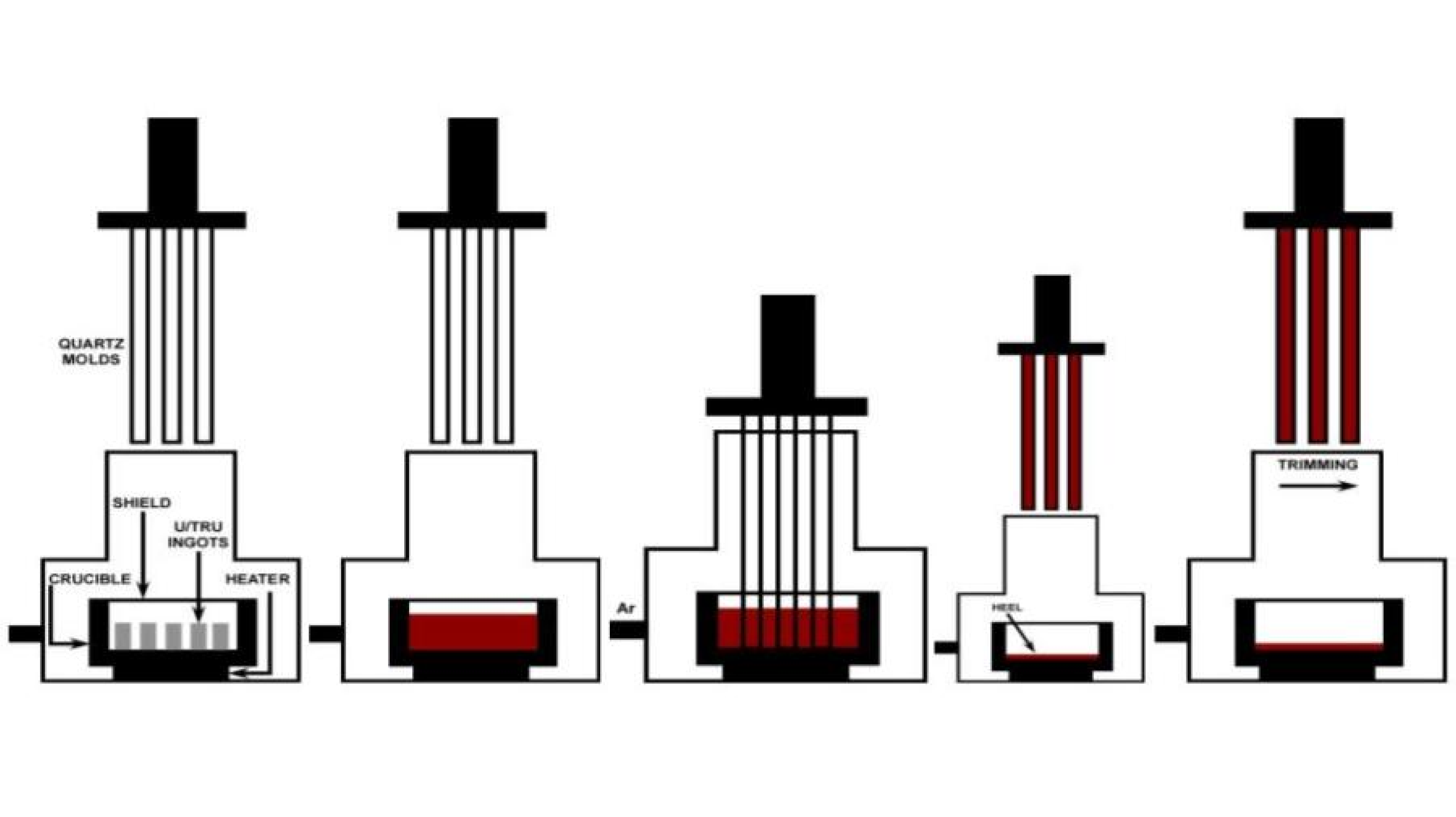
(3) Byproduct
(3a) Waste
(3b) Recycle at head-end

(4) The actual product

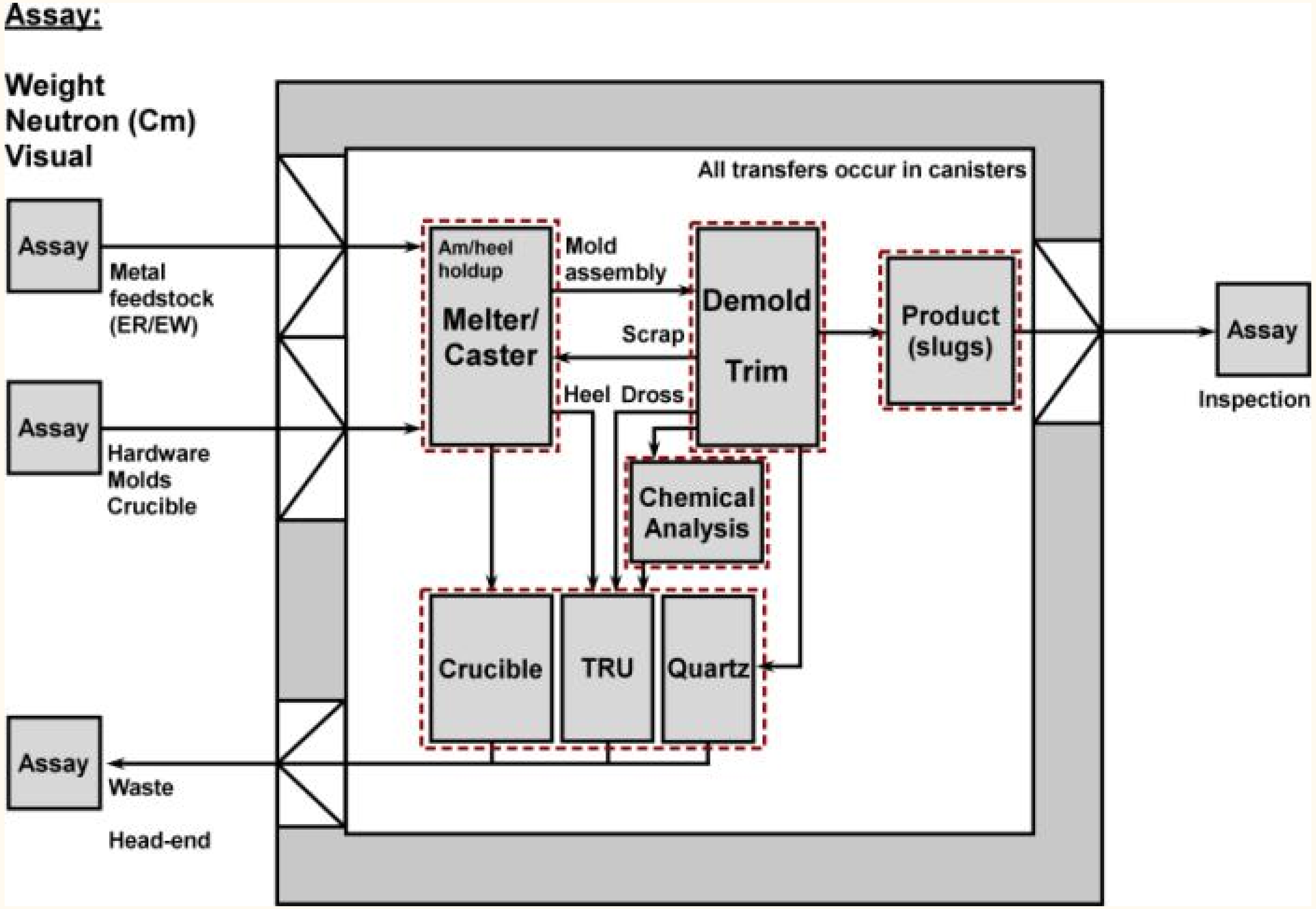
(5) Testing
(5a) Destructive assay
(5b) Chemical analysis
(5c) Quality assurance testing

Fuel fabrication process

Injection casting assumed to fabricate metal fuel slugs



Understand how material flow affects design



Key

(1) Injection casting

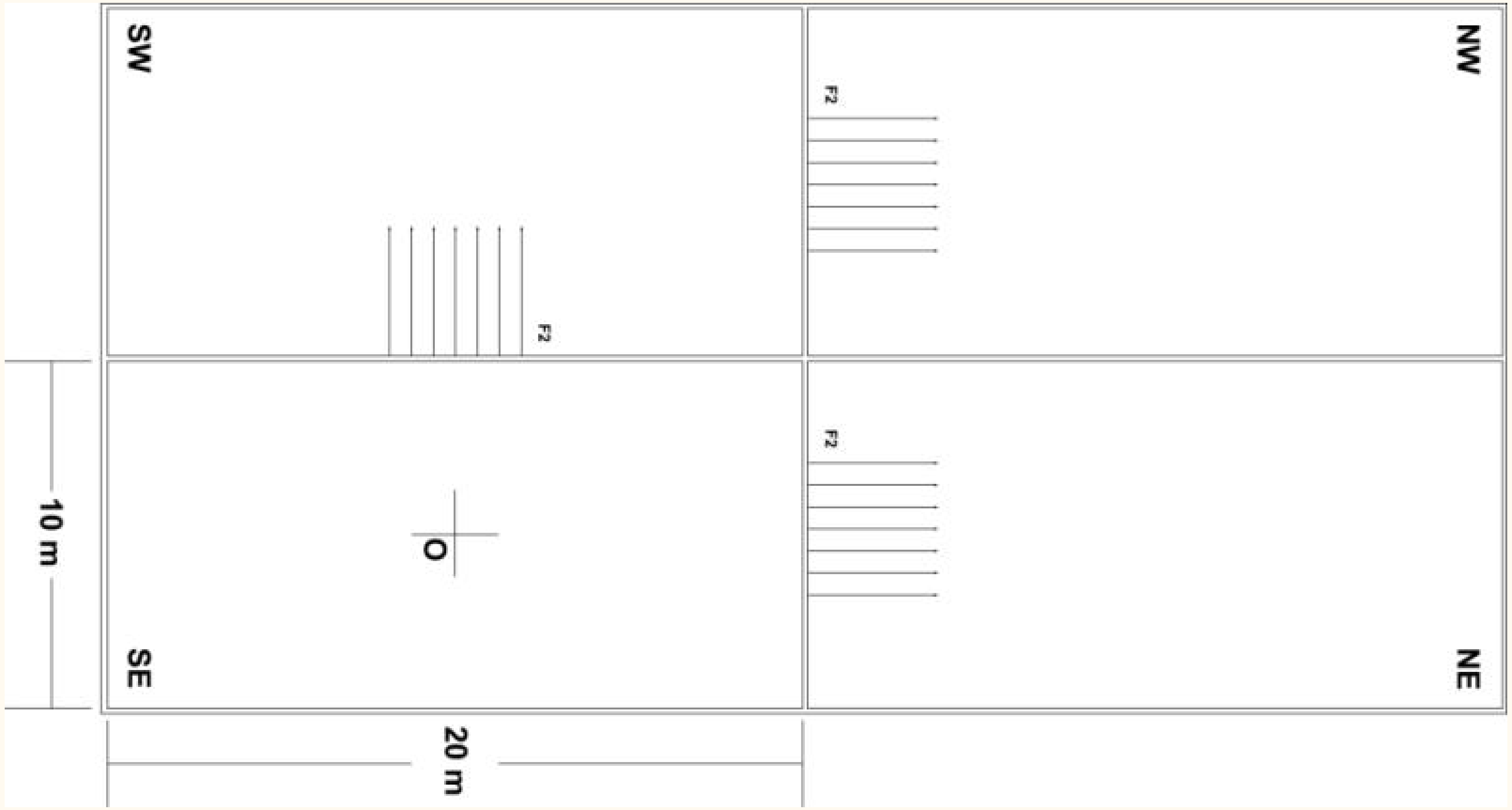
(2) Scrap

(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

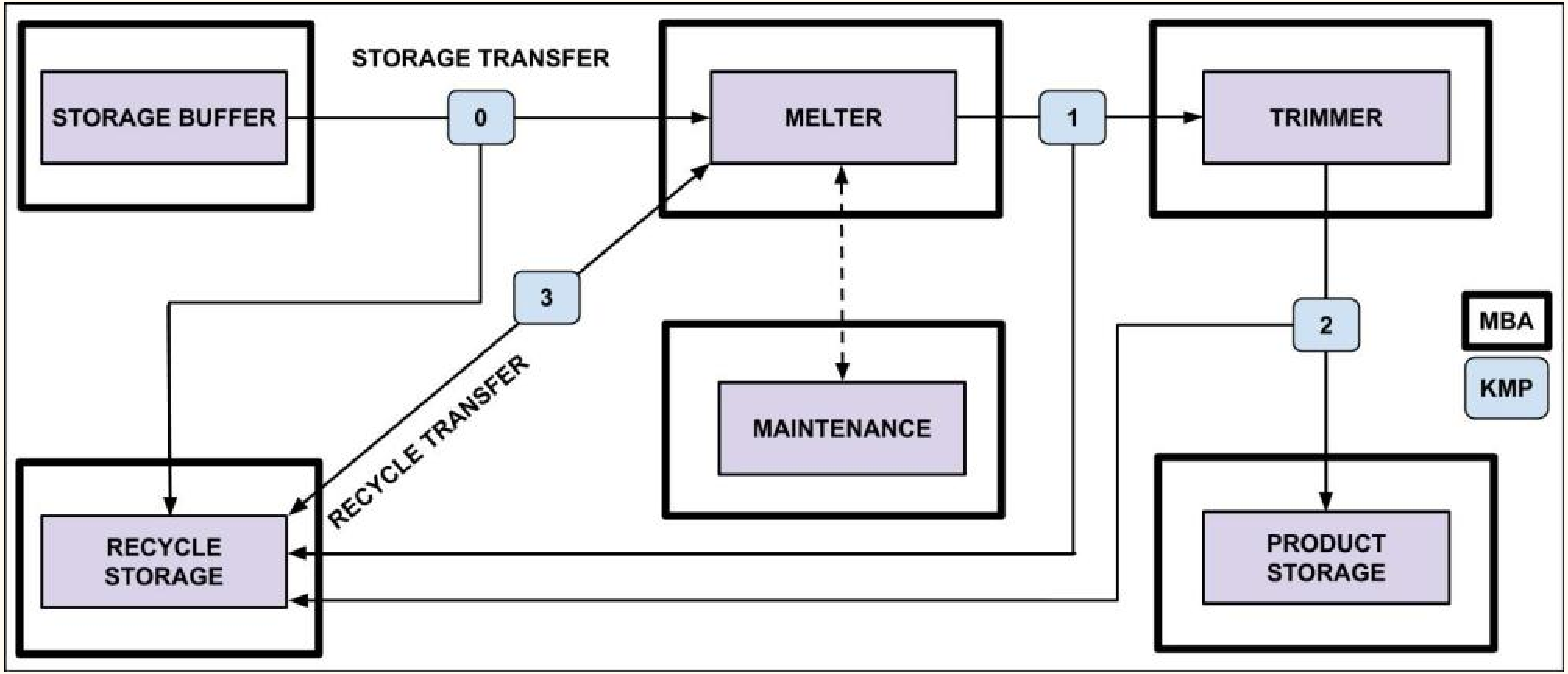
SDEF - Cm-244 watt spectrum

TRU processing states are not self-protecting under IAEA standard

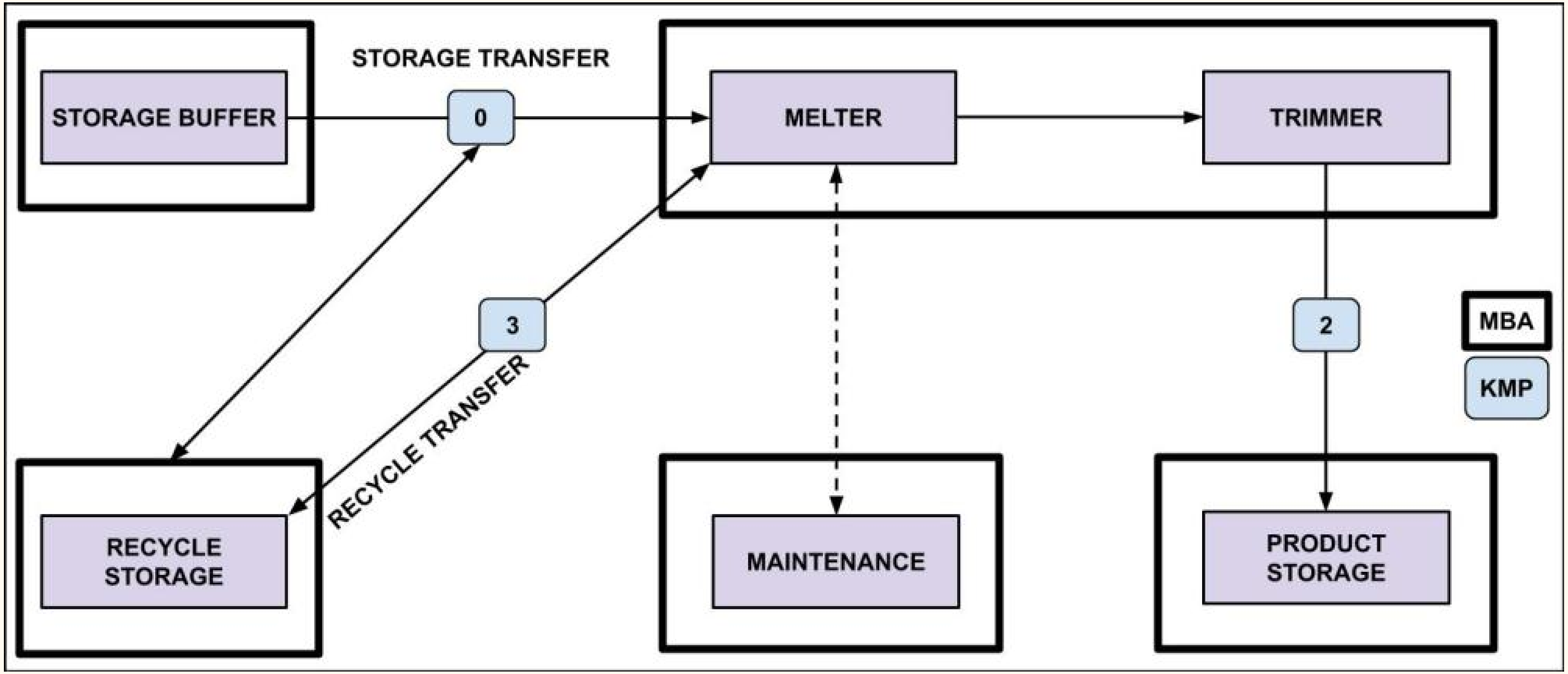
Wall thickness on par with other analogues (less than $10 \mu Sv/h$)
Average 30 cm - 45 cm thickness concrete

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

$$\Phi^{-1}(1-\alpha) + \Phi^{-1}(1-\beta) = \frac{SQ}{\sigma}$$

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 $1 - \beta$

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

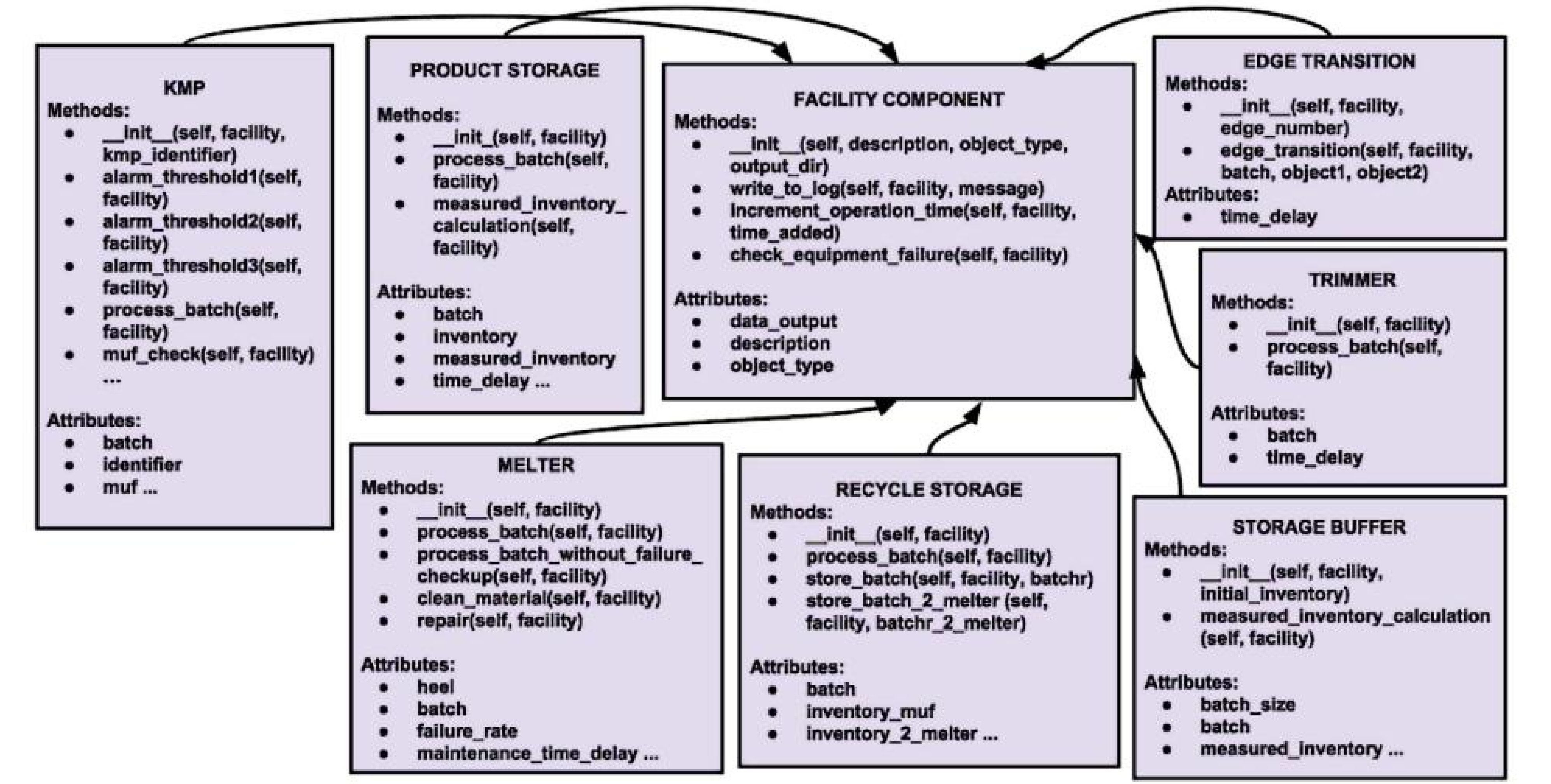


Fig. 4. Other than subclasses for sub-processes in the fuel fabrication process, the key measurement point class and the edge transition class also inherit functionalities from the facility component class. Major methods and attributes for each class are described above.

Total material processed

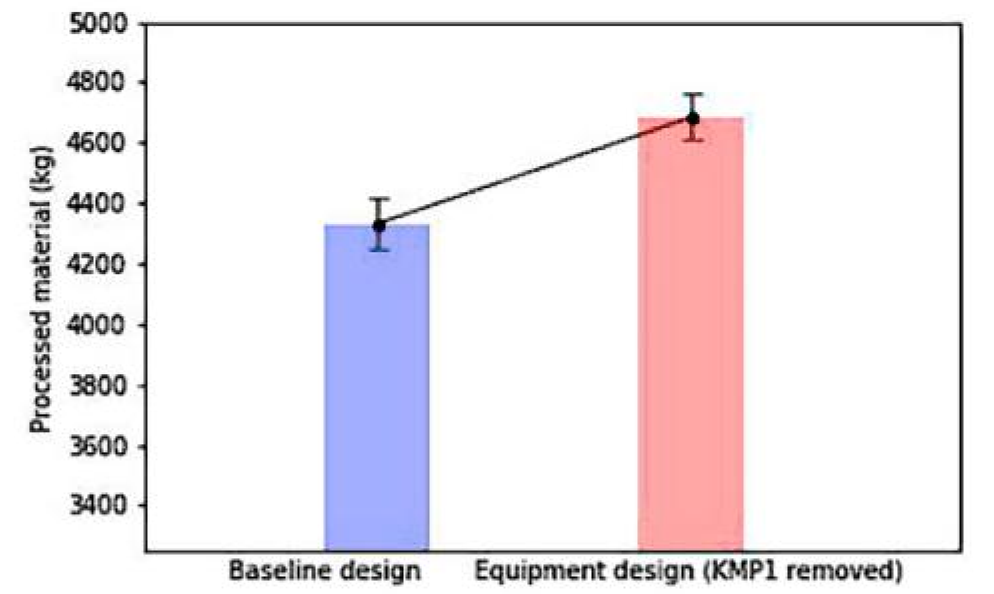


Fig. 9.1. The baseline design processed the product of 4332 ± 81.8 kg while the equipment design processed 4684 ± 75.5 kg. Equipment design could process 350 kg more compared to the baseline design with the same false alarm probability of 5% at each KMP.

Total campaigns completed

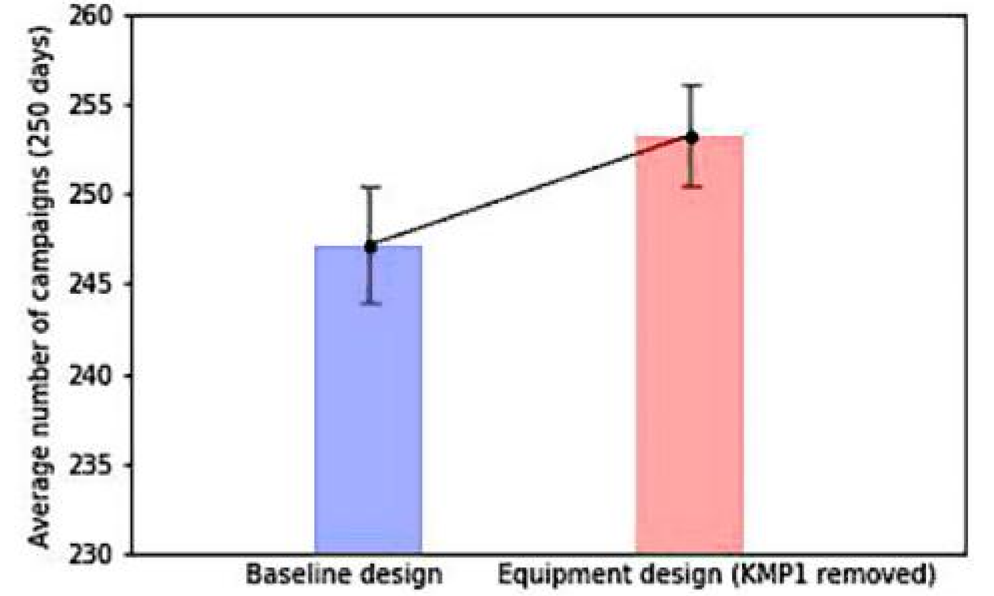


Fig. 9.2. The average number of campaigns is 247 ± 3.2 for the baseline design while for the equipment design it is 253 ± 2.8.

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

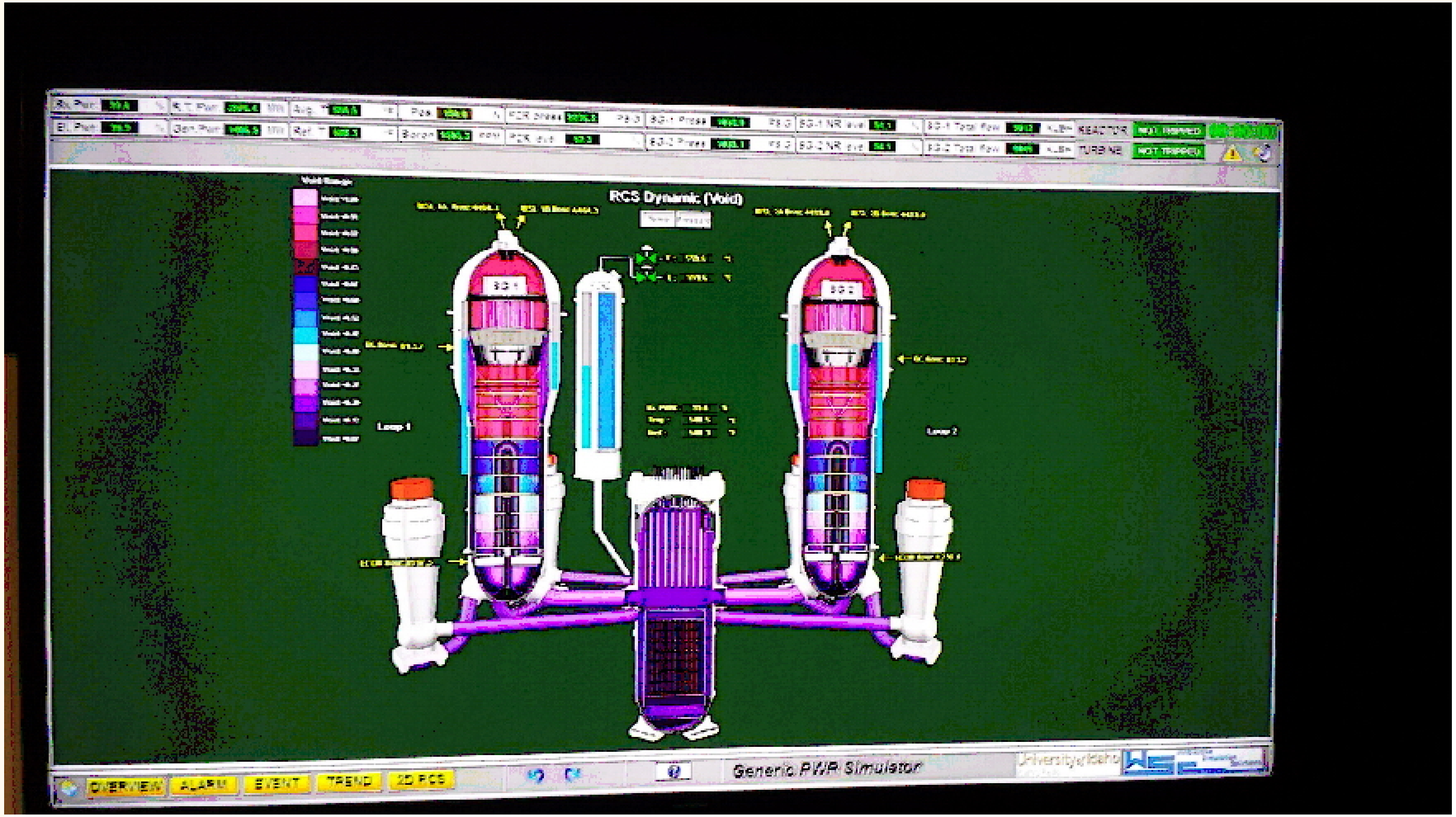
Full HAZOP

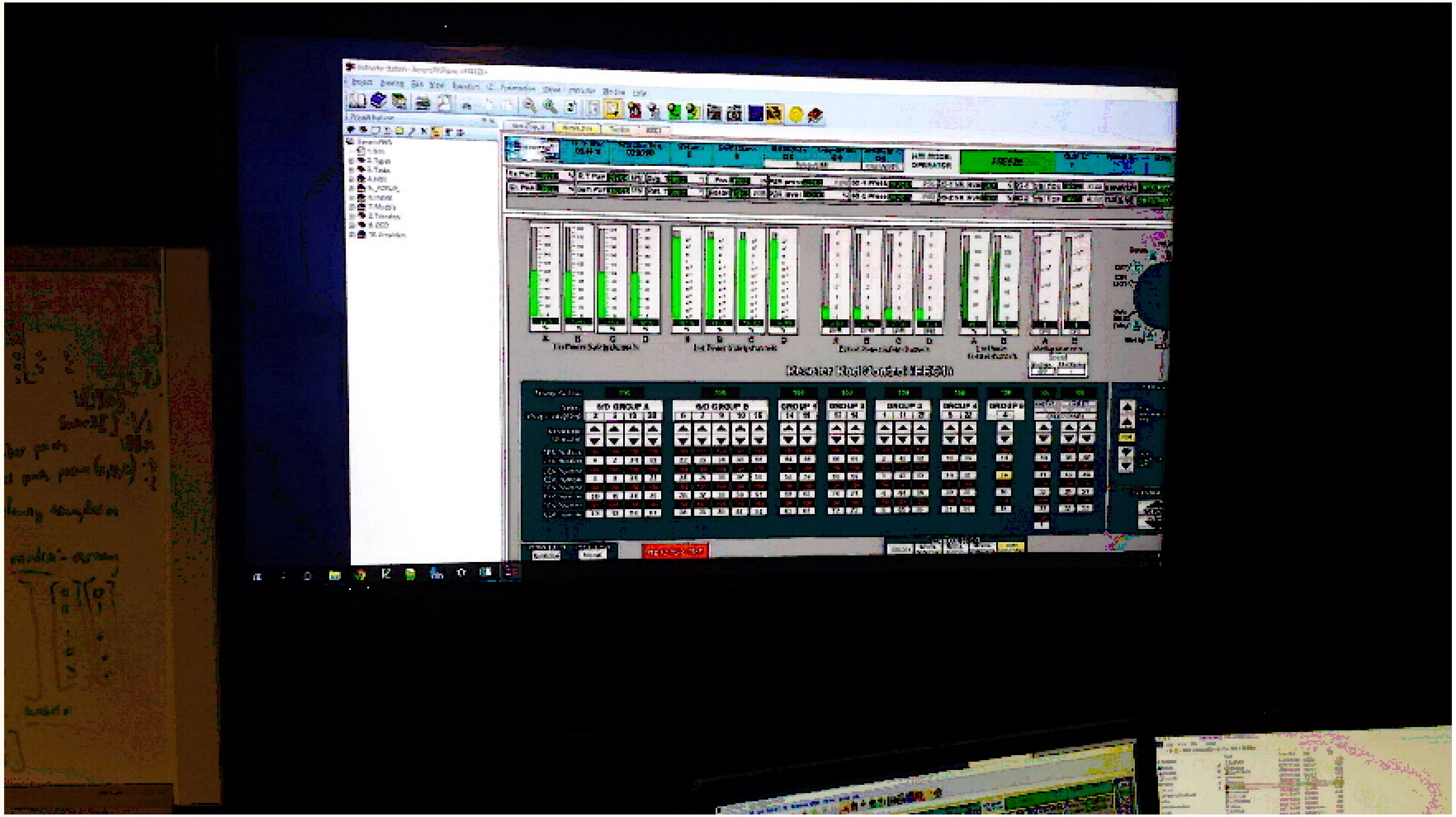
University of Idaho-Idaho Falls Nuclear Cybersecurity Working Group

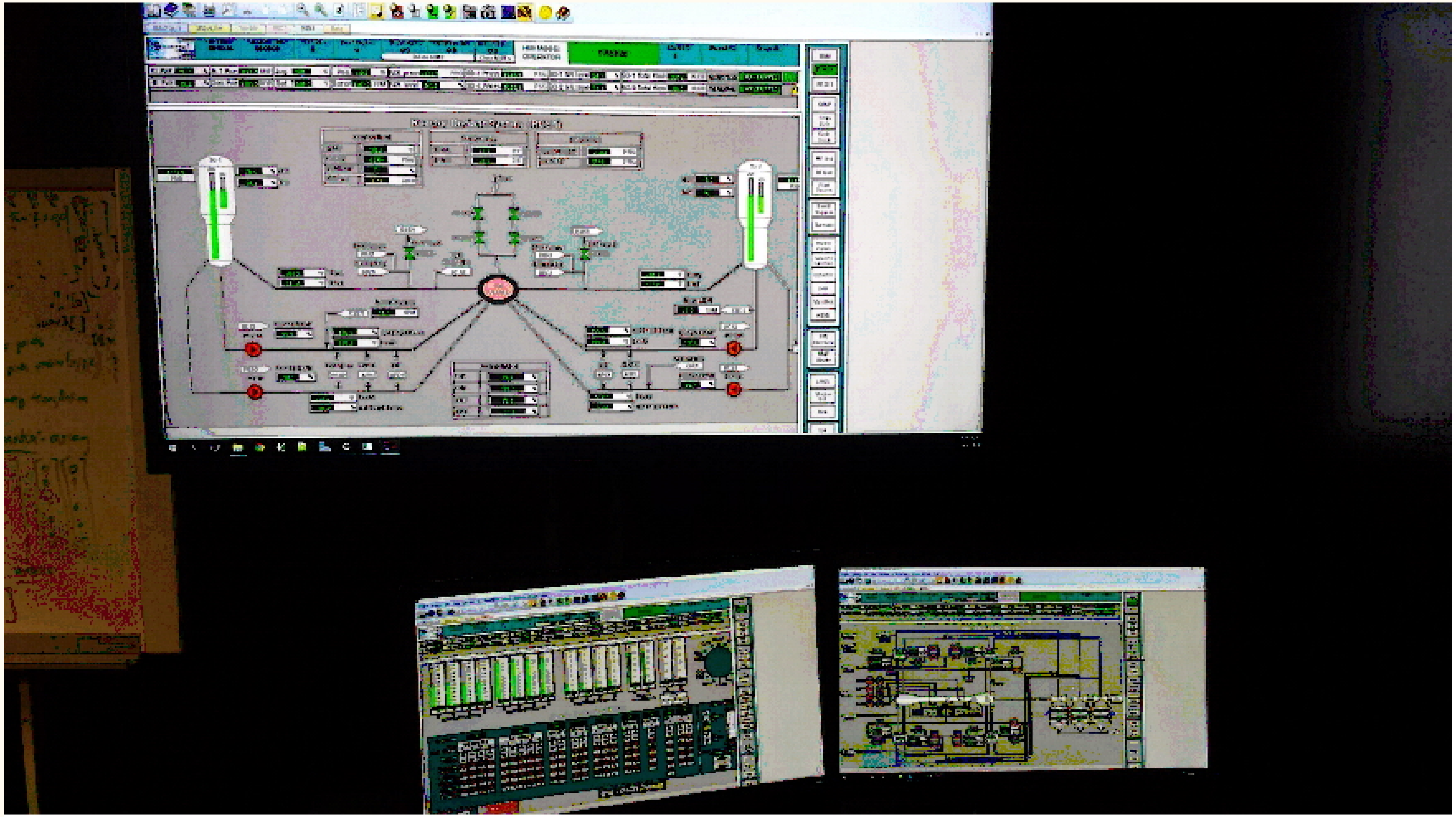
We (i.e. me) acquired the Western Services Corp PWR simulator

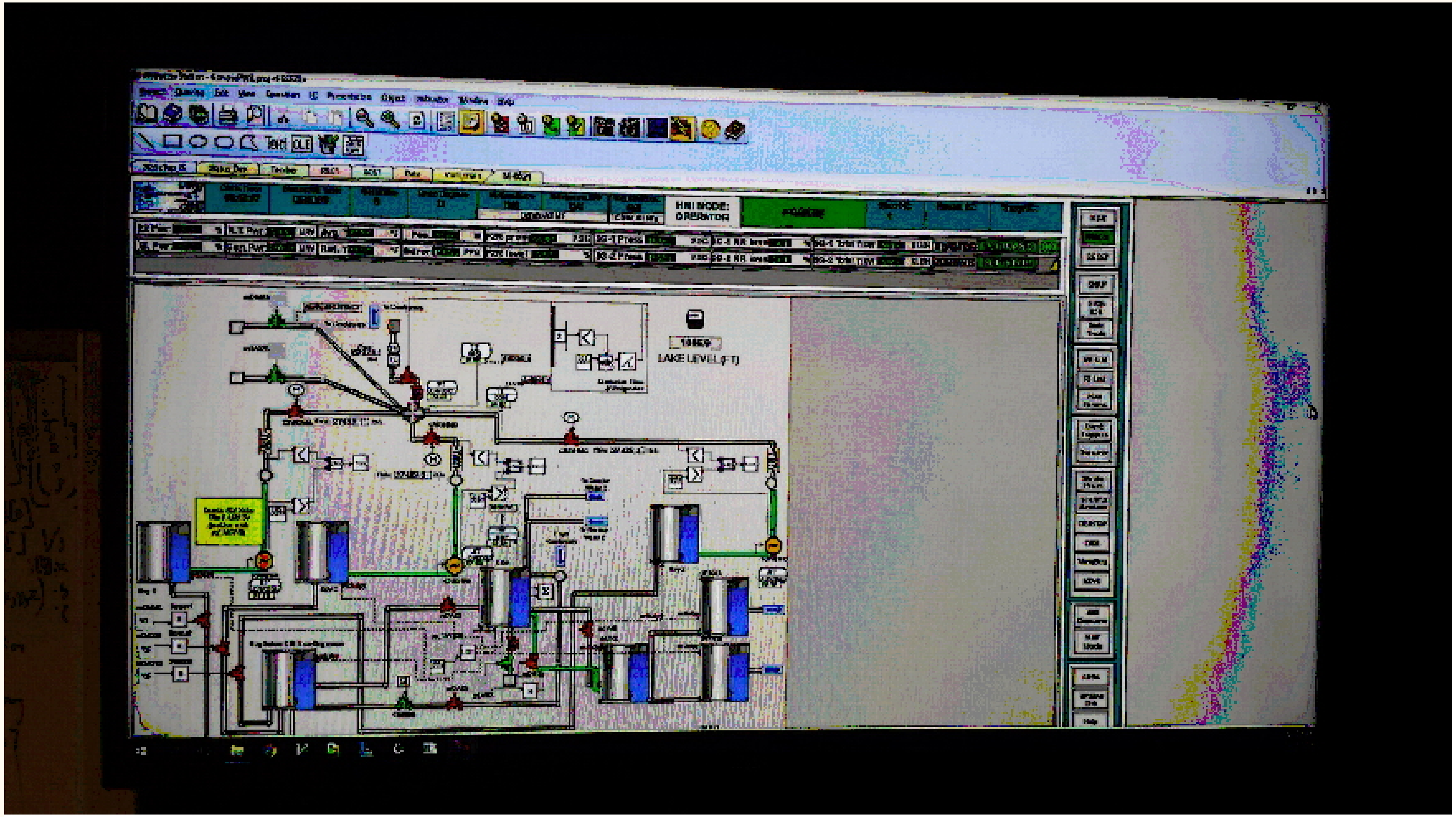
Modeling
I&C
Thermal hydraulics
Electrical generation and distribution systems
Human factors
Logic/control system testing

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


RCS Dynamic (Void)
Loop 1
Loop 2
REACTOR
TURBINE
NOT TRIPPED
NOT TRIPPED
OVERVIEW
ALARM
EVENT
TREND
2D RCS
Generic PWR Simulator






HMI MODE:
OPERATOR
LAKE LEVEL(FT)

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

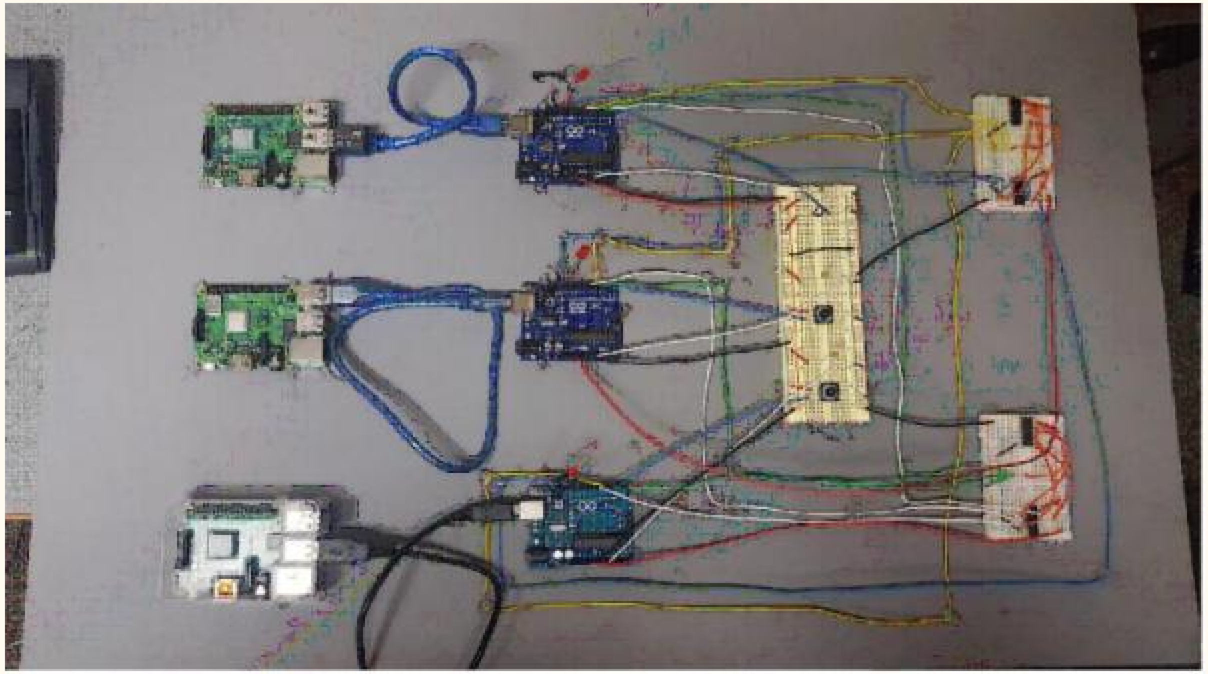
Means that common cause or cascading type 'failures' (attacks) increase risk

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 UIdaho, Boise State, Sakae

Sakae has unique aluminum casting capabilities

We proposed an intermediate storage cask of borated aluminum

UIdaho - Neutrons, heat removal, regulations

Boise St - Materials science - solid solution of B_4C and Al

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 ORIGEN for burnup and depletion

Thanks to Steve Skutnik for help

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

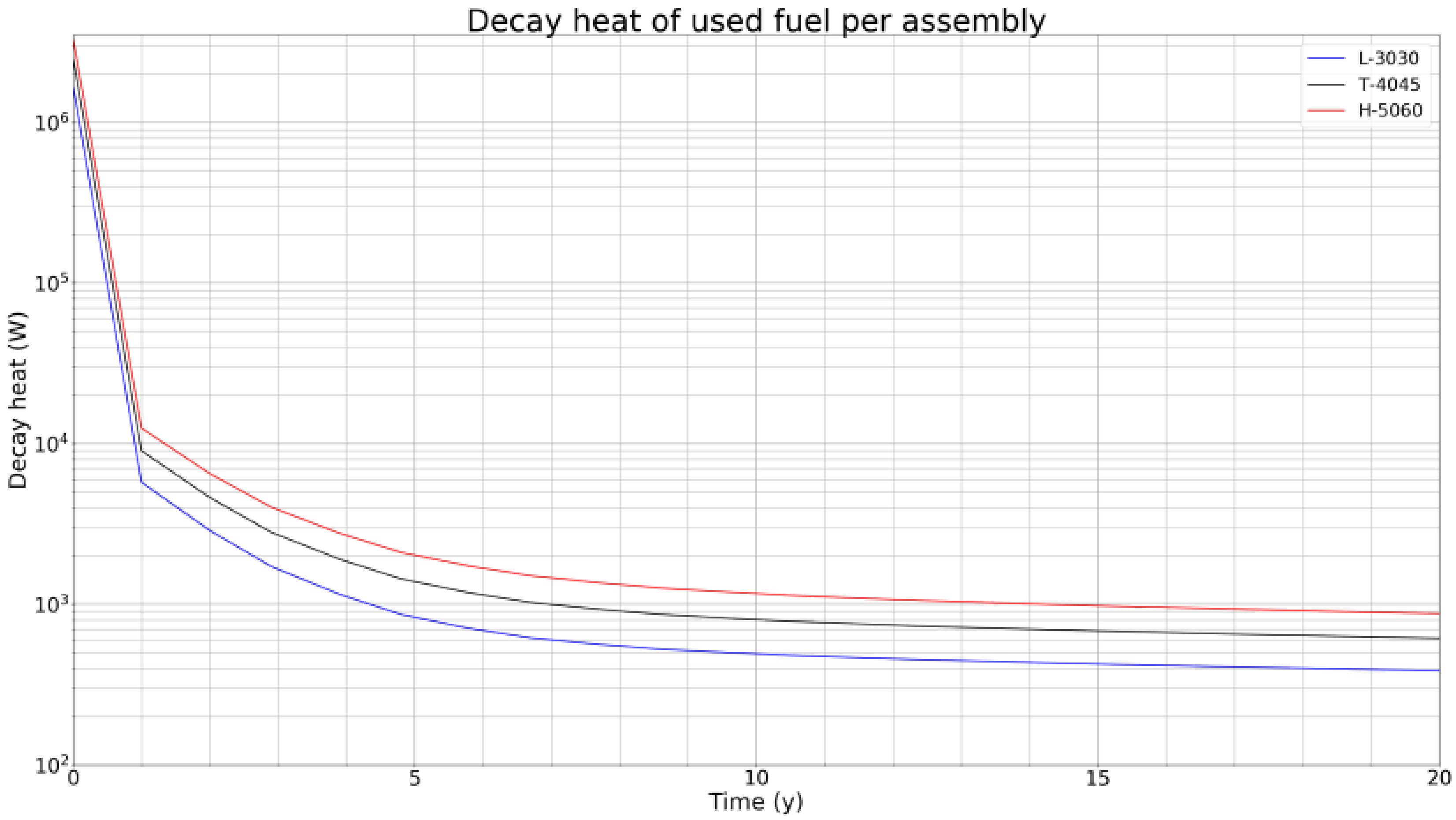
Based on literature review

(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


Decay heat of used fuel per assembly
L-3030
T-4045
H-5060
Decay heat (W)
10^6
10^5
10^4
10^3
10^2
0
5
10
15
20
Time (y)

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

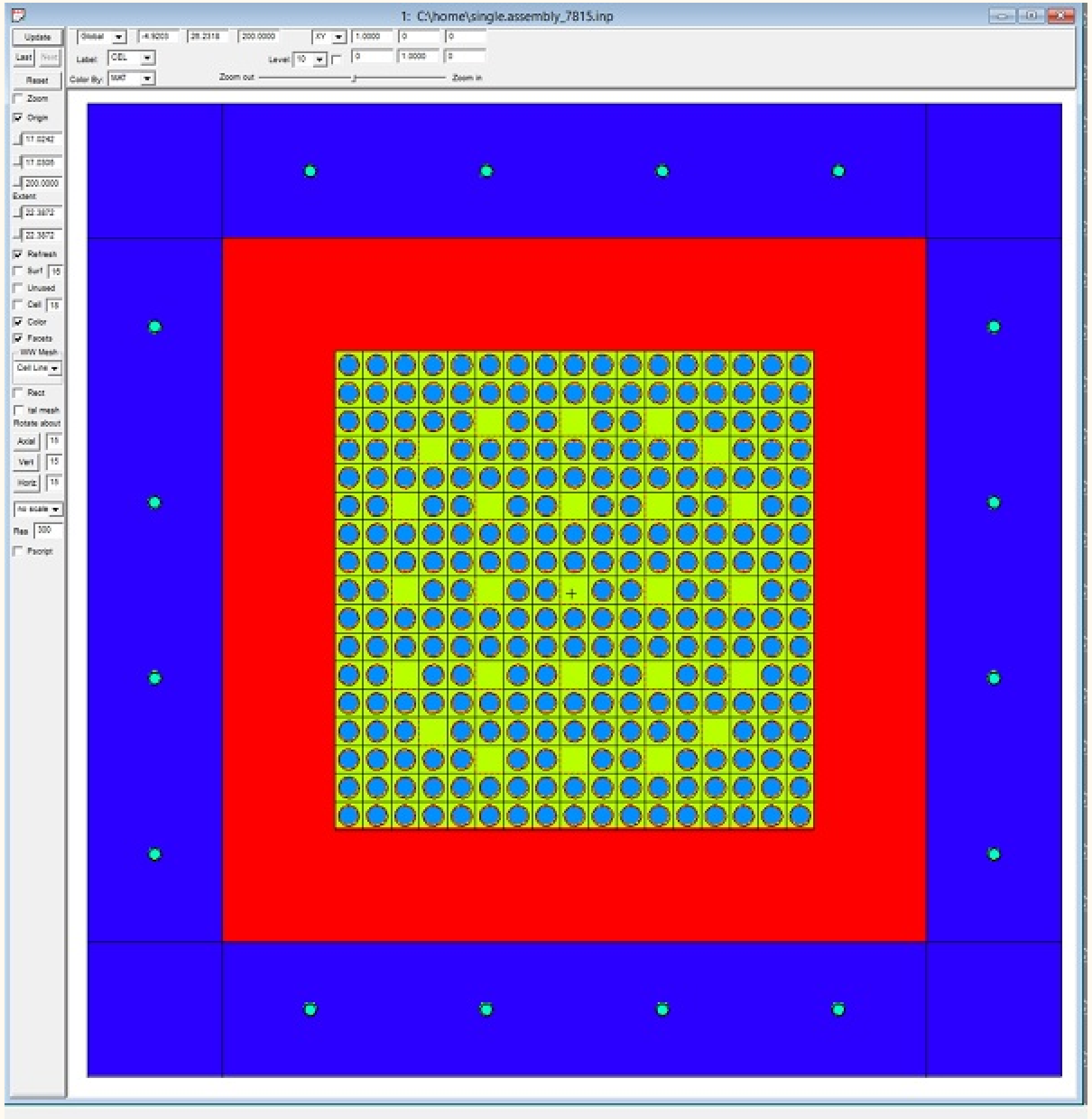
B_4C - 10, 30, 50, 70, 90 wt% in Al per plate thickness

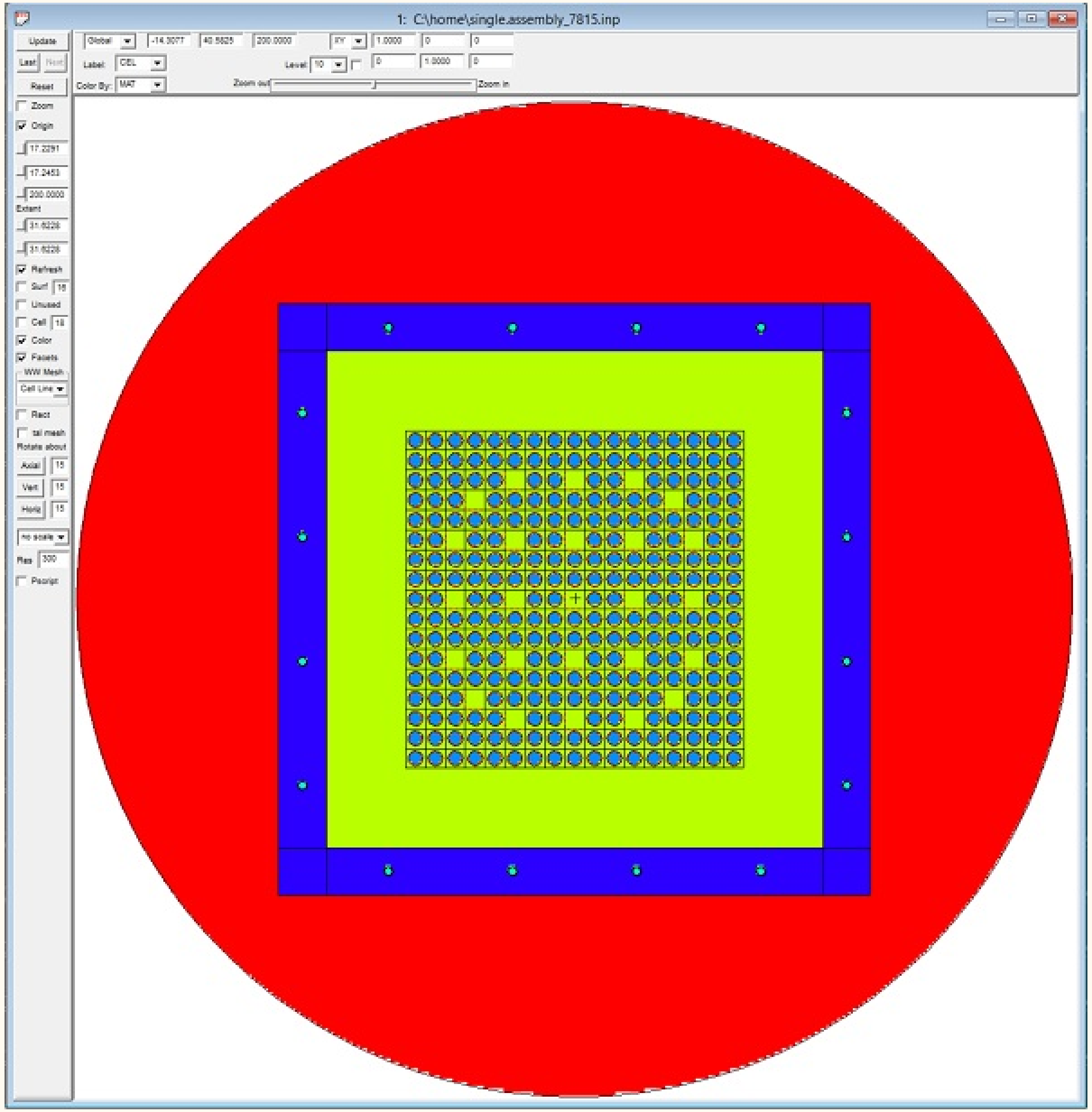
^{10}B loading in B_4C - 5, 10, 25, 50, 75 wt%

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 $10\mu Sv/h$


1: C:\home\single.assembly_7815.inp


1: C:\home\single.assembly_7815.inp

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

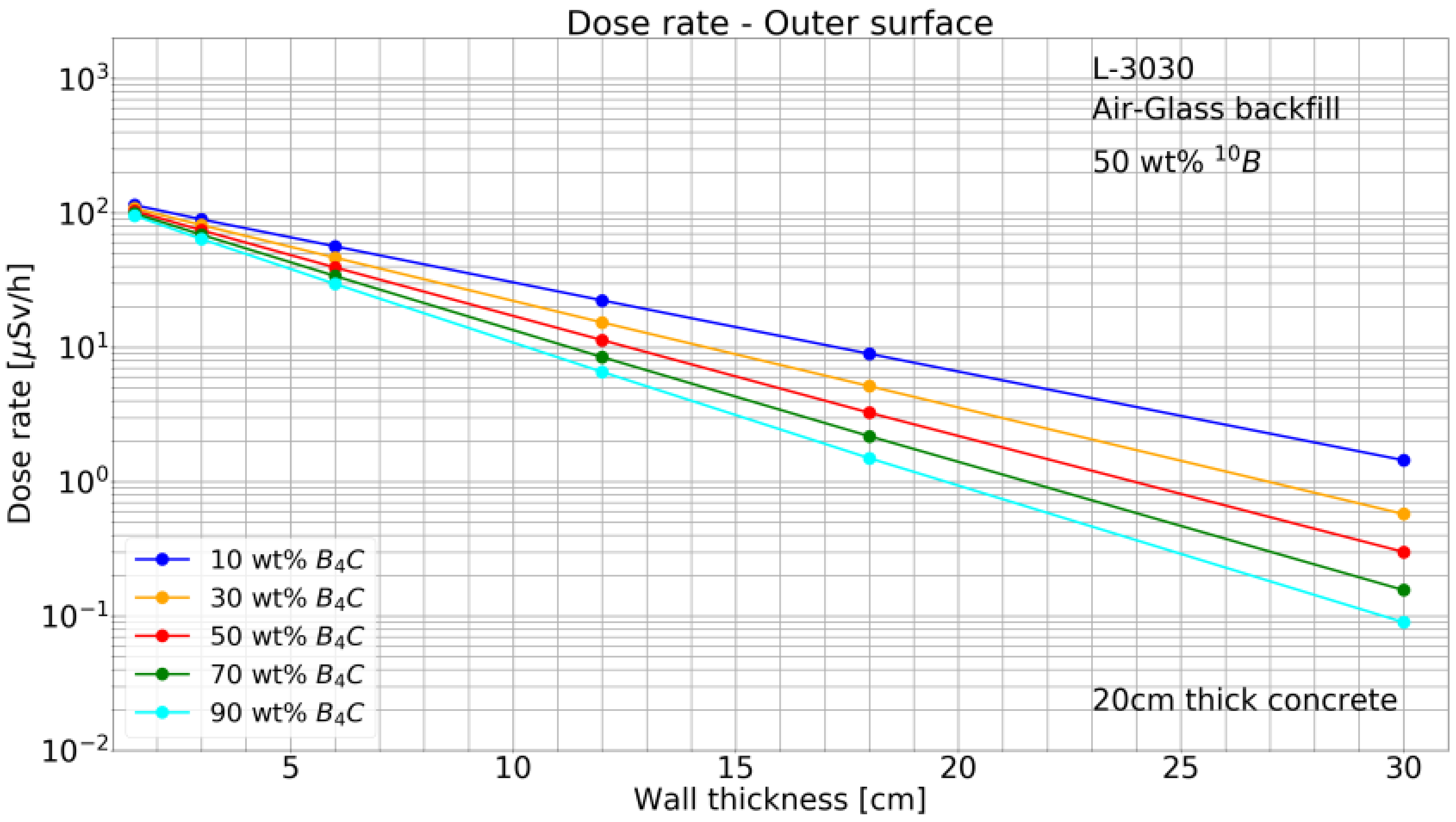
SDEF card - 5 source points per rod (POS)

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


Dose rate - Outer surface
L-3030
Air-Glass backfill
50 wt% ^{10}B
20cm thick concrete
Dose rate [μSv/h]
Wall thickness [cm]
10 wt% B_4C
30 wt% B_4C
50 wt% B_4C
70 wt% B_4C
90 wt% B_4C

What do the results mean for design?

I don't know the cost of ^{10}B

Sakae needs to figure out limits of plate casting

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

12 wt% B_4C 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).

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