Risk-informed Consequence-Driven Physical Protection System Optimization for Microreactor Sites

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Presentation Overview

- Project Goals and Objectives
- Project Hypothesis
- Technical Approach
- Results
- Project Outcomes and Impacts (Conclusions)

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Presentation Overview

- FY21 Consolidated Innovative Nuclear Research Award
- Award No.: DE-NE0009135
- Period of Performance: 10/01/2021 – 09/30/2023
- Technical Work Scope Identification:
  - CT-4
  - ADVANCED AND SMALL MODULAR REACTOR MATERIALS ACCOUNTANCY AND PHYSICAL PROTECTION
  - "New and novel PPS approaches are also needed that can drastically reduce either up-front or operational security costs for the life of the reactor. Proposals should focus on regulatory needs and describe how the proposed work addresses those needs for the advanced reactors."

Project Goals and Objectives

- Project goals (and why the project matters to vendors)
  - Enable a more appropriately-sized Physical Protection System (PPS) for advanced reactor designs while maintaining constant or reducing the risk associated with future reactors; and
  - Pursue reduced security costs for the life of the reactor to increase the cost-competitiveness of safe and secure nuclear power generation.
- Anticipated key technological contribution
  - The coupling of consequence modeling with security design in an integrated safety-security framework

Project Hypothesis

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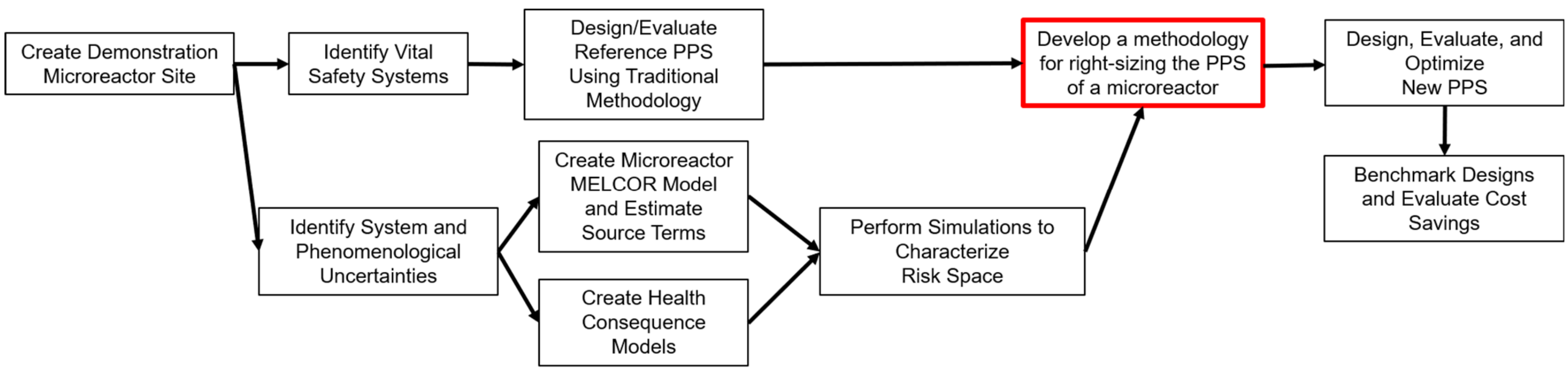
- The hypothesis:
  - The enhanced safety of advanced non-LWR and microreactor designs sufficiently reduces the consequence space of sabotage events such that the PPS footprint (upfront and operational) may be reduced to generate cost savings without sacrificing security or safety.

Technical Approach – Task Flow

Develop and demonstrate a new consequence-informed approach on a reference microreactor site



Recent Developments in Advanced Reactor Security Licensing

- Currently, to license a commercial nuclear power facility an applicant has two options, 10 CFR 50 and 10 CFR 52
- Regardless of the licensing path chosen, security at the facility is governed by 10 CFR 73
- 10 CFR 73 defines two design basis threats (DBTs)
  - Sabotage DBT
  - Theft DBT
- NRC is currently developing two rulings with significant impact on the operational requirements, design, and implementation of Physical Protection Systems (PPS) at new advanced commercial nuclear power facilities

NOTE: These statements reference proposed rulings from NRC which are subject to change during the rulemaking process

Recent Developments in Advanced Reactor Security Licensing

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Alternative Physical Security Requirements (APSR):[1]

- Creates new PPS requirements for any ***advanced*** commercial power reactor design undergoing licensing through 10 CFR 50 or 10 CFR 52
- Advanced reactor is defined as a light water SMR or *any* non-LWR design (traditional large LWRs do not qualify)
- Proposes technology-inclusive PPS objective to "prevent a significant release of radionuclides from any source"
- Allows for ***off-site*** response force, ***off-site*** SAS, and SAS to be considered a non-vital are
- Codified in the proposed 10 CFR 73.55(s)

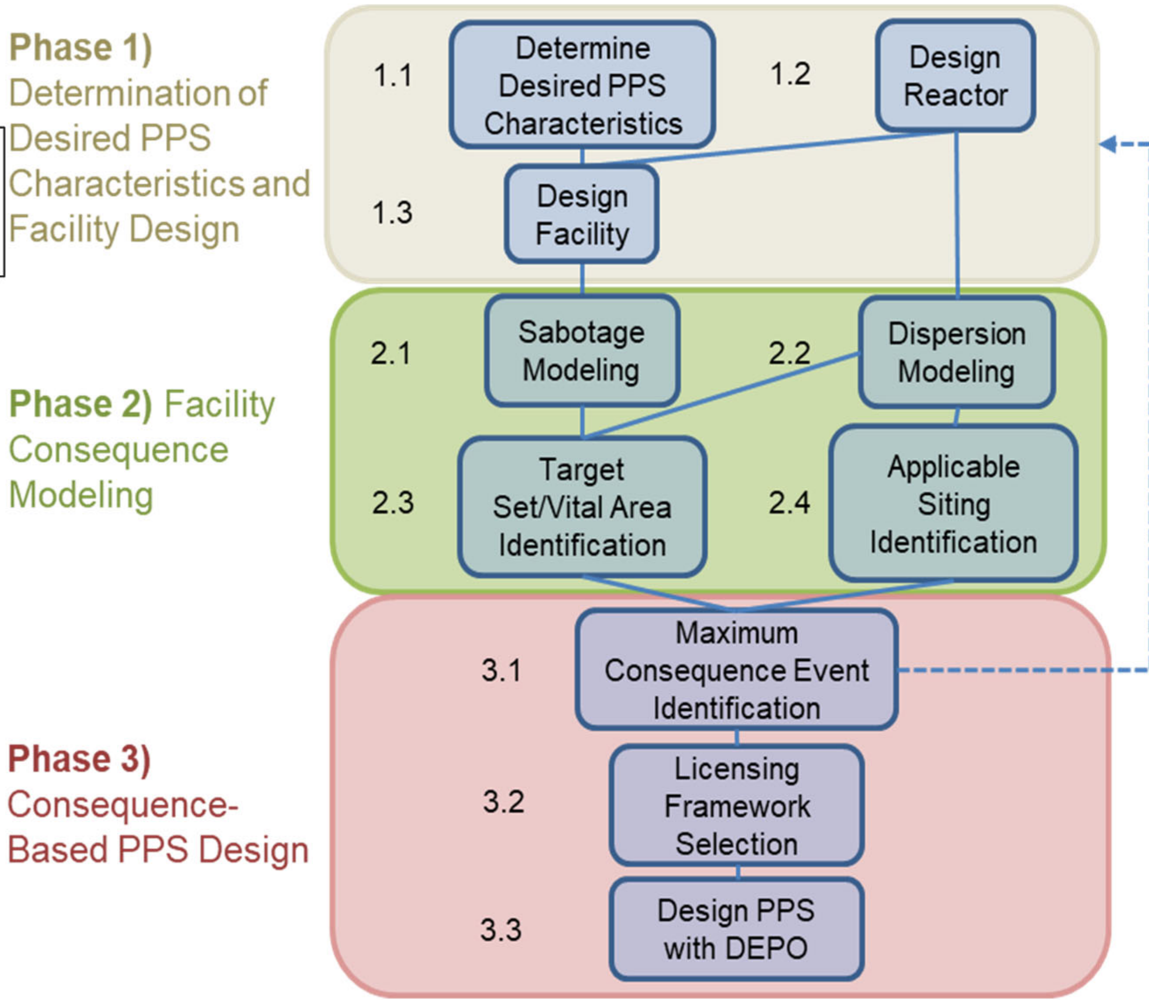
10 CFR 53:[2]

- Creates entirely new licensing pathway for *any commercial power* reactor design
- Off-site dose consequences codified in proposed 53.210(a) and (b) (same as those in 10 CFR 50 and 52 licensing paths)
- Replaces previous security regulations with proposed sections 73.100, 73.110, and 73.120 regarding physical and cyber security
- 73.100 focuses on PPS requirements to stop the sabotage DBT, does **NOT** specifically reference off-site dose values from 53.210
- **73.100 does not outline stringent requirements on CAS, SAS, or on-site response force size**

1. U.S. Nuclear Regulatory Commission "Rulemaking: Alternative Physical Security Requirements for Advanced Reactors," 2022 https://www.regulations.gov/document/NRC-2017-0227-0036
2. U.S. Nuclear Regulatory Commission, Consolidated Part 53 Preliminary Proposed Rule Language, 2022 https://www.nrc.gov/docs/ML2212/ML22125A000.pdf

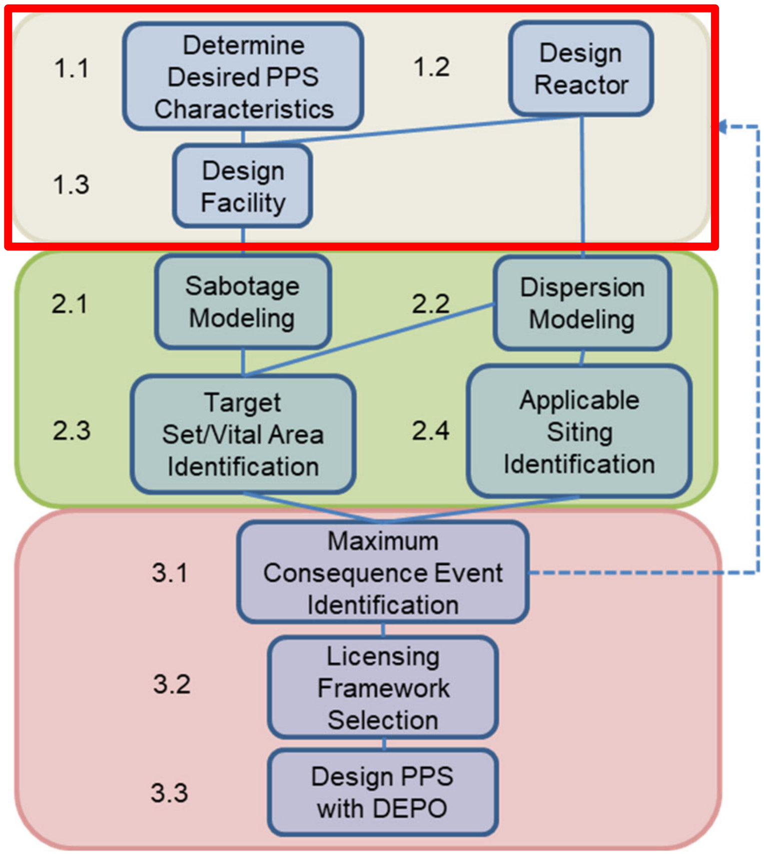
New Methodology

NOTE: Steps at equal elevations in the chart may be completed concurrently to save on development time



If design fails to meet necessary off-site consequence objectives for desired PPS goals, a redesign of reactor, SSCs, or changing of desired PPS goals may be necessary

Phase 1: Determination of Desired PPS Characteristics and Facility Design



1.1 Determine Desired PPS Characteristics

- Identify key desirable PPS characteristics
- Think of: On or off-site response force, who the response force, response force size, SAS location, CAS and SAS staffing

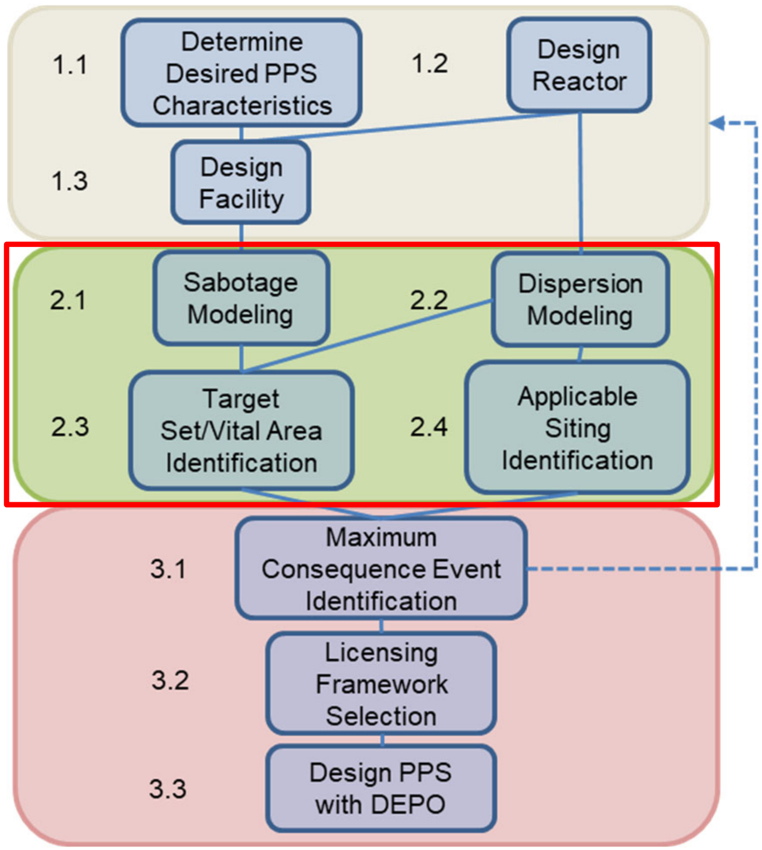
1.2 Design Reactor

- Identify desired reactor thermal, electric power output
- Determine fuel type, design, and composition
- Select number of desired units at a site
- ***Quantify fuel radionuclide concentrations/masses at varying levels of burnup throughout reactor life***

1.3 Design Facility

- Create a site-specific layout and floor plans of entire Protected Area (PA) incorporating all considerations identified in 1.1 and 1.2

Phase 2: Facility Consequence Modeling



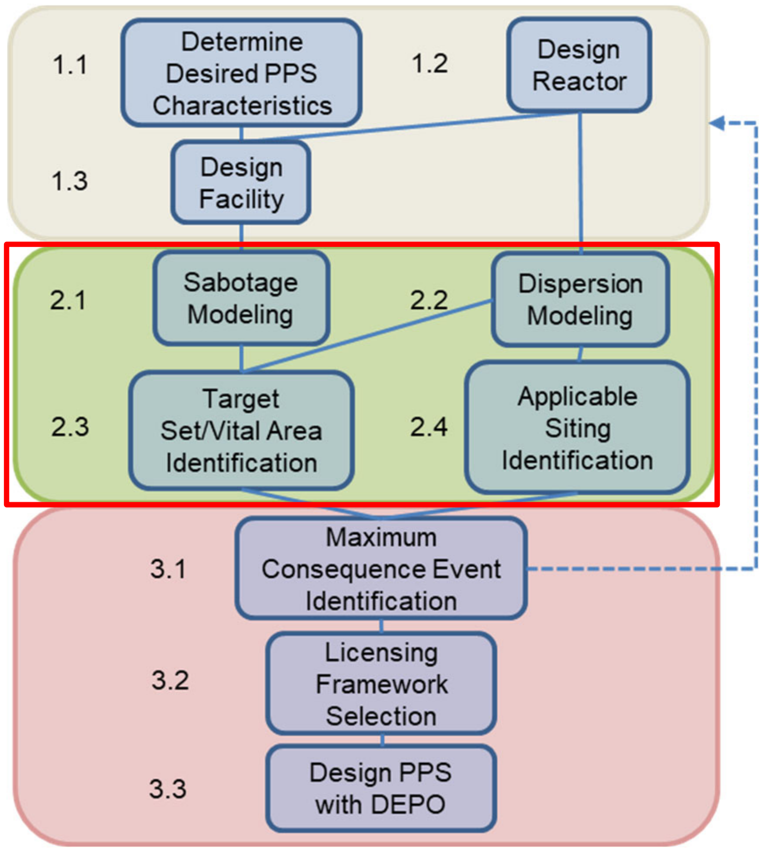
2.1 Sabotage Modeling

- While conducting traditional DBA analysis, simultaneously model physics-based sabotage actions the DBT may conduct at the facility
- Use off-site dose rate ranges calculated by dispersion modeling to quantify consequence of each source-term generated by system-level modeling of DBT actions

2.2 Dispersion Modeling

- Incrementally model releases of core inventories at "worst" possible burnup time and "worst" weather conditions
- Determine percentage of total core inventory released, percentage of core chemical species released, and which concurrent weather conditions would result in off-site dose limits that violate the licensing regulations. This is the ***Maximum Limiting Consequence Source Term (MLCS)***
- Identify radionuclides of most importance for off-site dose to general public for specific reactor/fuel type

Phase 2: Facility Consequence Modeling



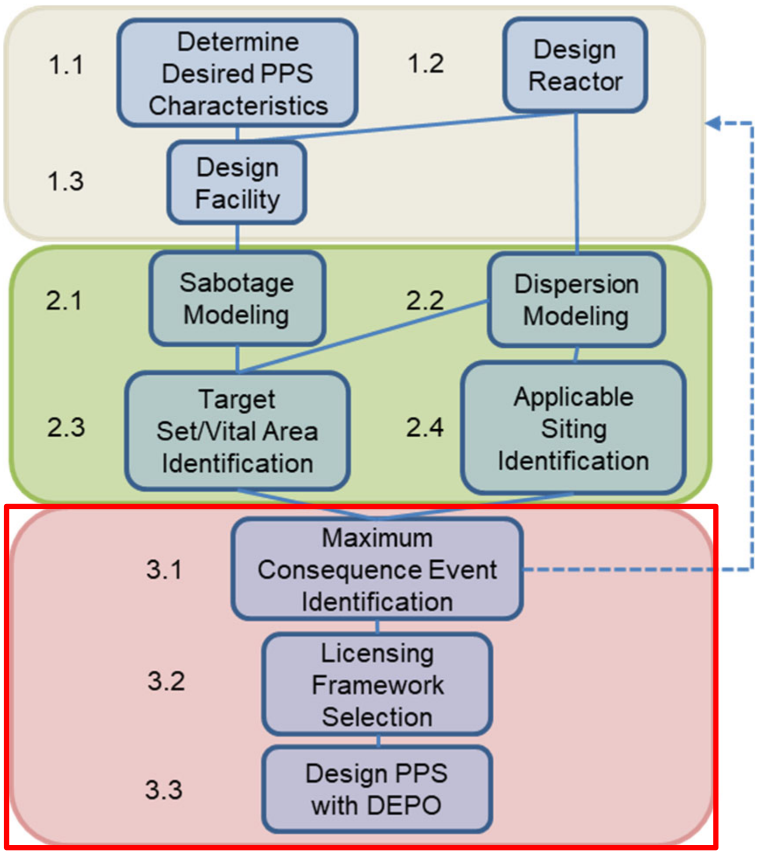
2.3 Target Set/Vital Area Identification

- Combining generated source-terms and off-site dose calculations, determine total consequence related to any potential target-set the DBT may target
- Use results to determine which components are safety and security significant and must be protected within Vital Areas

2.4 Applicable Siting Identification

- All potential licensing pathways utilize the same off-site dose consequence values:
  - 25 rem Total Effective Dose Equivalent (TEDE) at site boundary over course of 25 rem
  - 25 rem TEDE at low population zone boundary over course of entire accident
- Utilize dispersion modeling generated off-site dose values to determine where low population zone boundary can be located for given reactor design

Phase 3: PPS Design



3.1 Maximum Consequence Event Identification

- Identify which action conducted by the DBT, in conjunction with relevant necessary weather conditions, would cause highest dose to public at both site boundary and low population zone. Refer to as ***Maximum Consequence Event (MCE)***.
- Check if value of MCE is above or below the calculated MLCS in 2.2
- If MCE exceeds the MLCS, return to Phase 1 to re-design reactor, SSCs, or adjust desired PPS design characteristics

3.2 Licensing Framework Decision

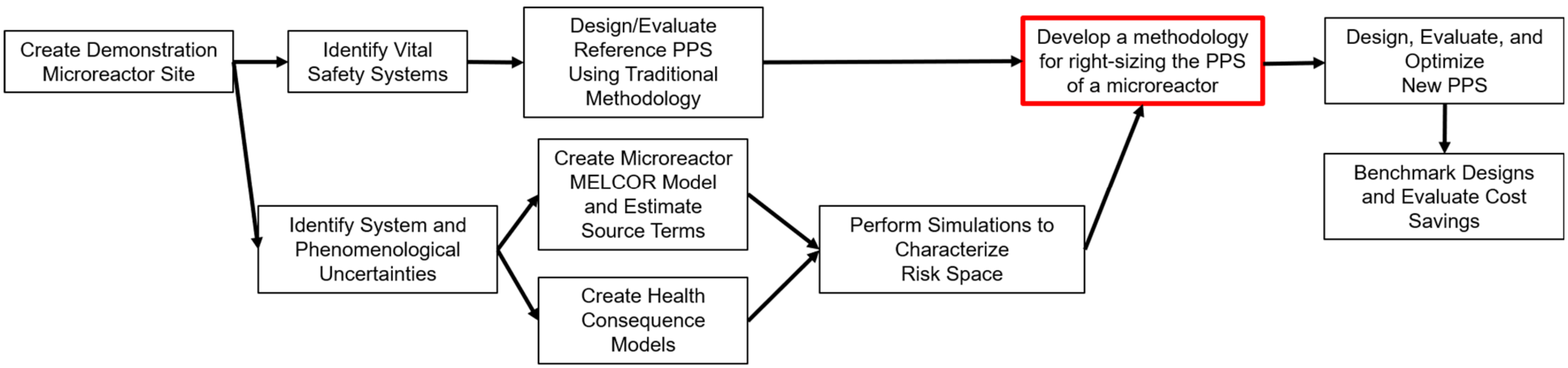
- Determine which licensing framework to use incorporating all information and desired objectives for reactor facility

3.3 Design PPS with DEPO

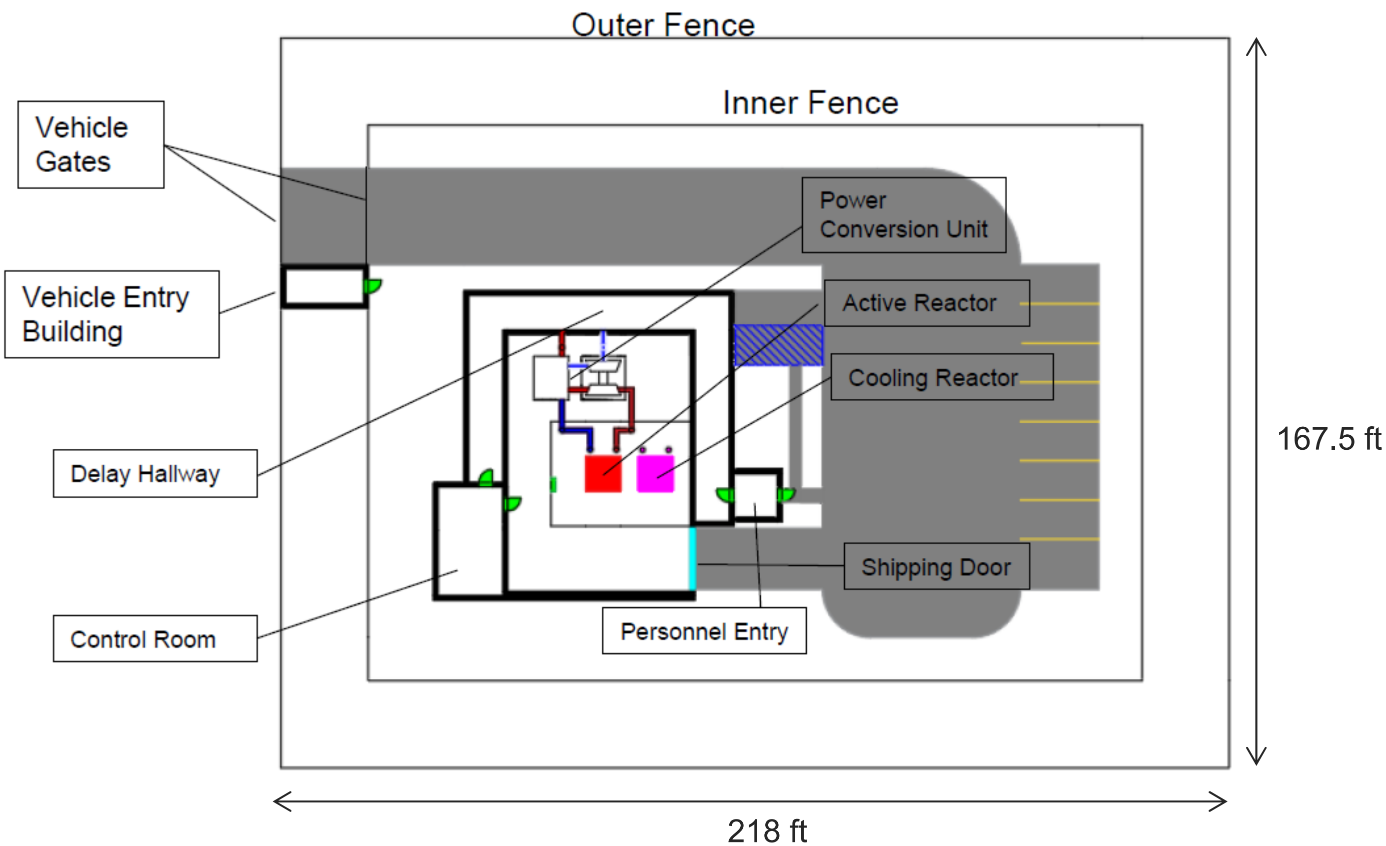
- Utilize traditional DEPO method to design PPS which meets necessary requirements from chosen licensing path

Technical Approach – Task Flow

Develop and demonstrate a new consequence-informed approach on a reference microreactor site



Creation of Demonstration Microreactor Site - Facility Design for INL Design A Special Purpose Reactor (SPR)



Top-down view of proposed SPR facility

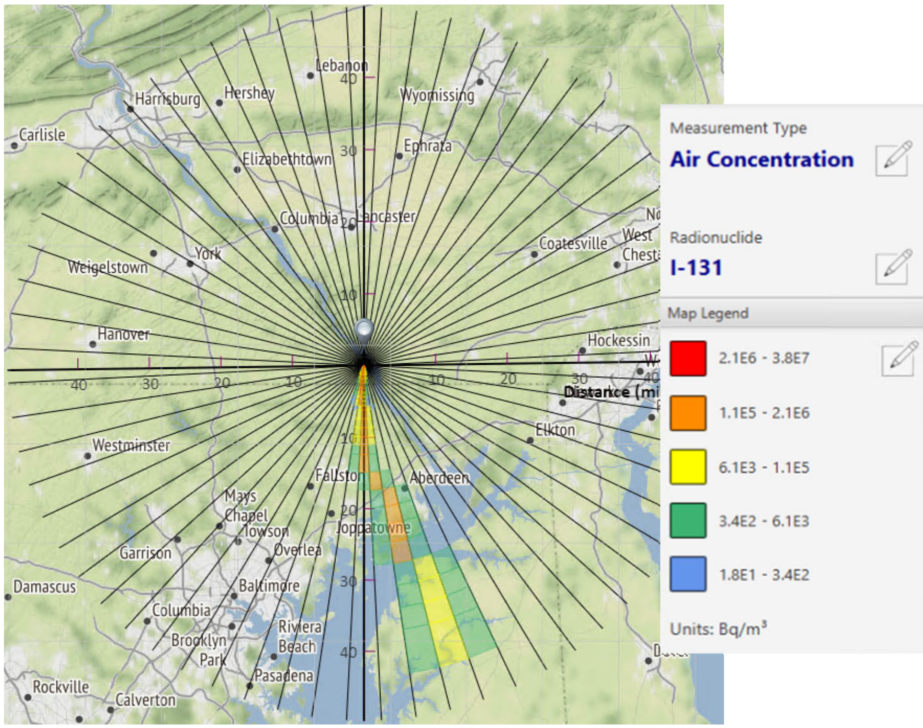
Create Microreactor MELCOR Model and Estimate Source Terms

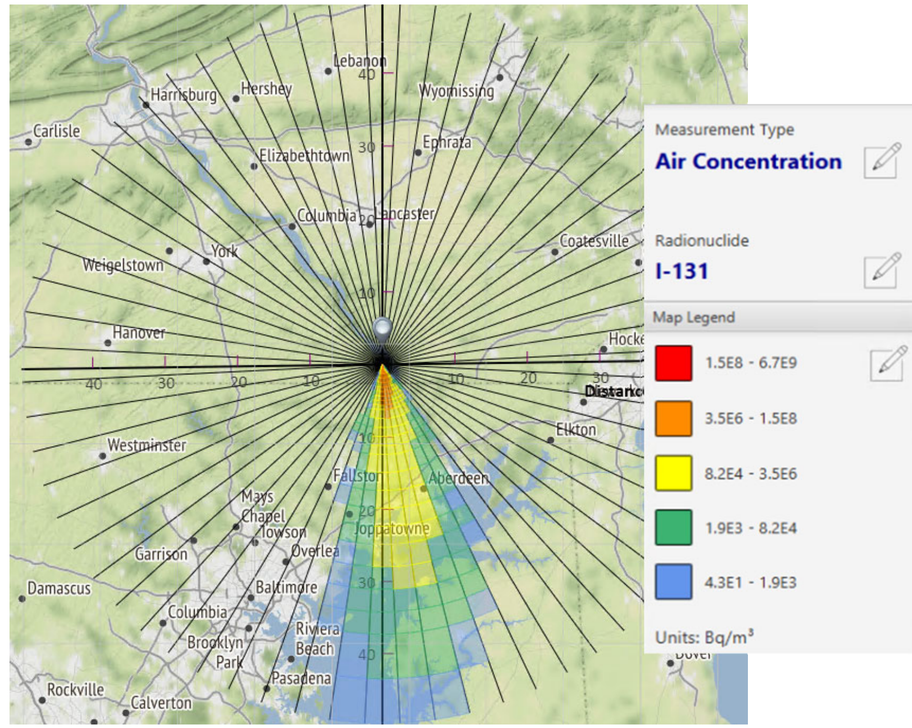
- MELCOR analysis indicated small radionuclide releases from the SPR facility based on adversary induced transients in the Transient Over Power scenario
- Results indicated low off-site consequence from adversary actions

MACCS FLOW PATH - RADIONUCLIDE MASS DISTRIBUTION IN KG

CLASS	Total	maccs_fp	maccs_fp2
XE	4.576E-04	9.234E-05	3.653E-04
CS	4.486E-05	1.043E-05	3.443E-05
BA	4.945E-08	1.175E-08	3.770E-08
I	0.000E+00	0.000E+00	0.000E+00
TE	1.301E-05	3.146E-06	9.862E-06
RU	3.944E-08	9.241E-09	3.020E-08
MO	1.119E-06	2.643E-07	8.547E-07
CE	3.147E-11	7.773E-12	2.370E-11
LA	8.984E-12	2.250E-12	6.734E-12
UO2	4.780E-05	9.311E-06	3.849E-05
CD	3.056E-07	7.665E-08	2.289E-07
AG	2.914E-07	7.195E-08	2.194E-07
BO2	0.000E+00	0.000E+00	0.000E+00
H2O	0.000E+00	0.000E+00	0.000E+00
CON	0.000E+00	0.000E+00	0.000E+00
CSI	1.554E-05	3.682E-06	1.185E-05
CSM	1.677E-04	4.172E-05	1.259E-04

Creation of Health Consequence Models



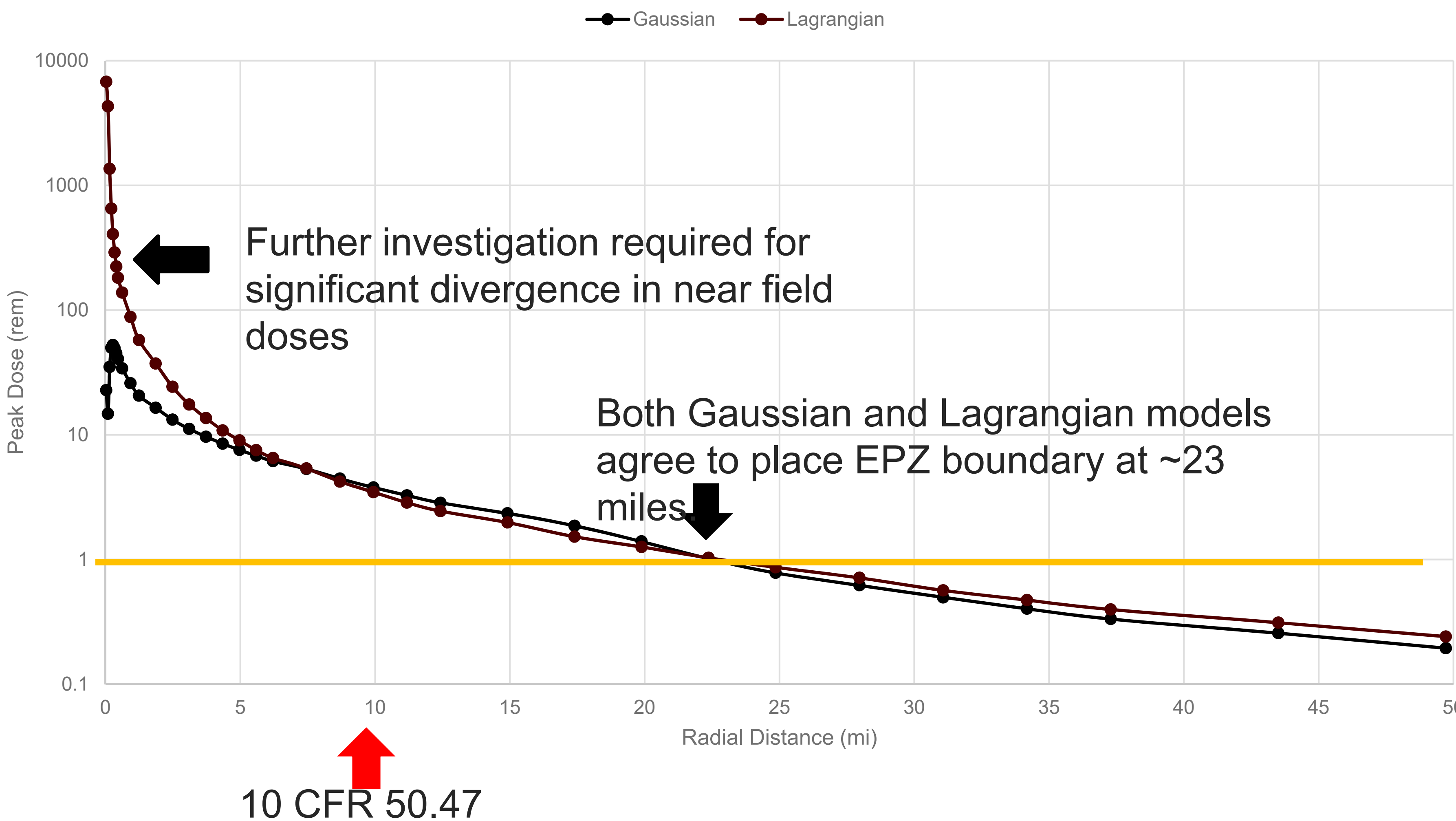


Gaussian at +24H

Lagrangian at +24H

Visual Representation of Gaussian and Lagrangian Distributions for Simulations of a Selected Peach Bottom BWR Scenario (not the heat pipe microreactor otherwise modeled in this project)

Creation of Health Consequence Models



Combined Mean Peak Dose Distribution for Peach Bottom BWR Scenario

Perform Simulations to Characterize Risk Space

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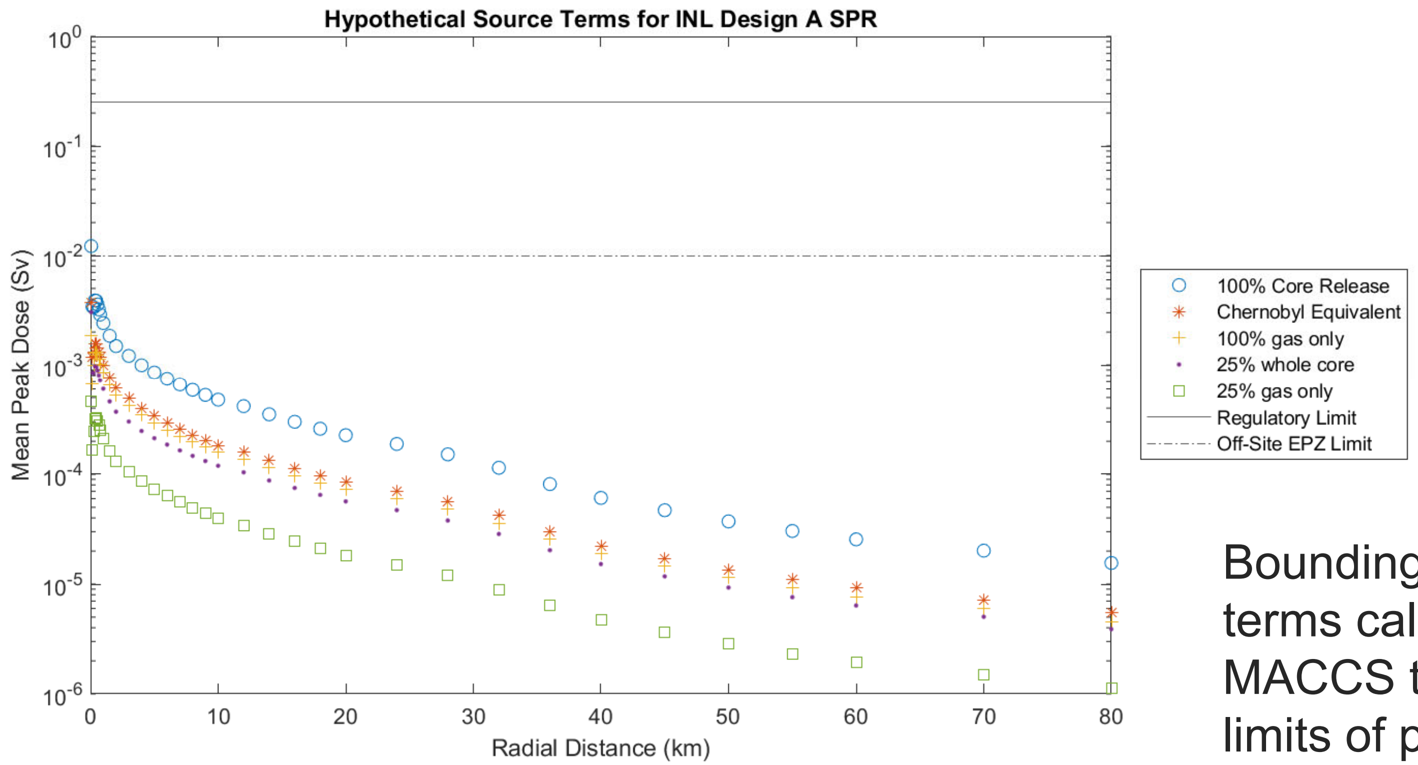
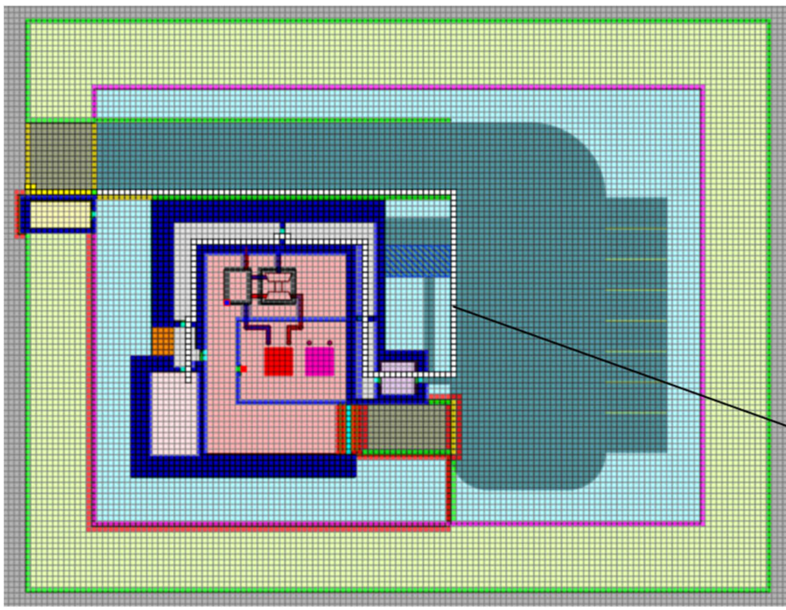


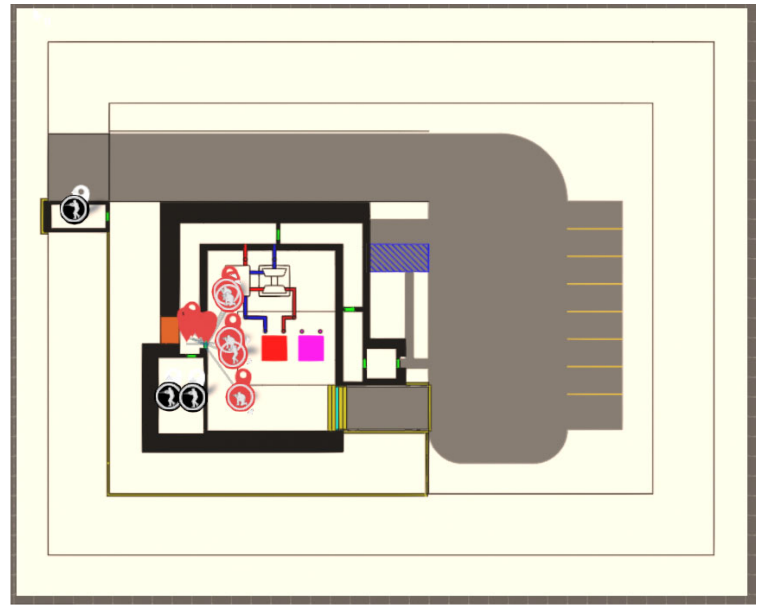
Bounding case source-terms calculated from MACCS to show upper limits of potential off-site consequence (Wang 2023)

Design, Evaluate and Optimize New PPS

Example of PathTrace analysis

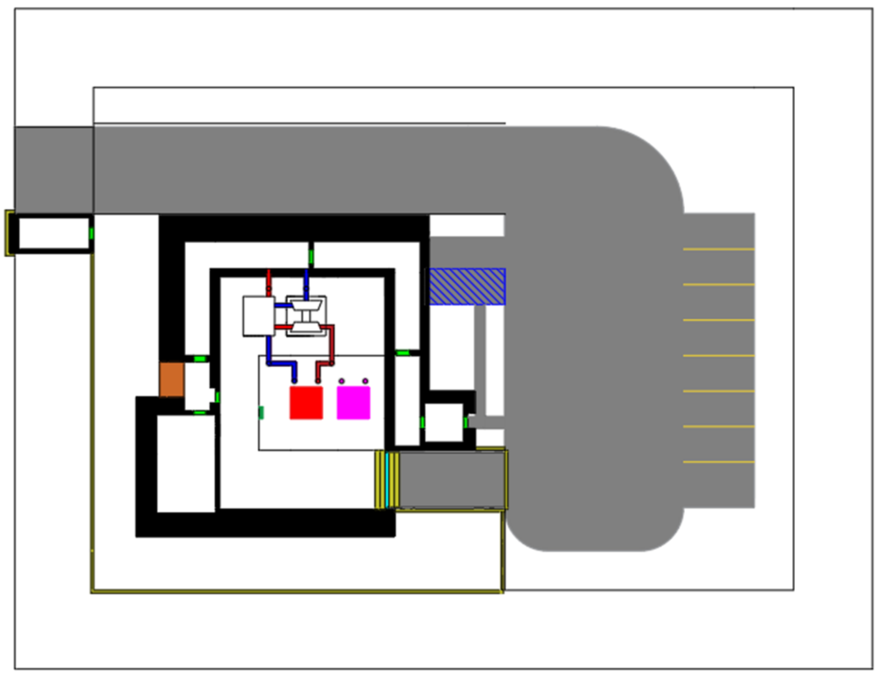


Adversary Path using Quickest Path option

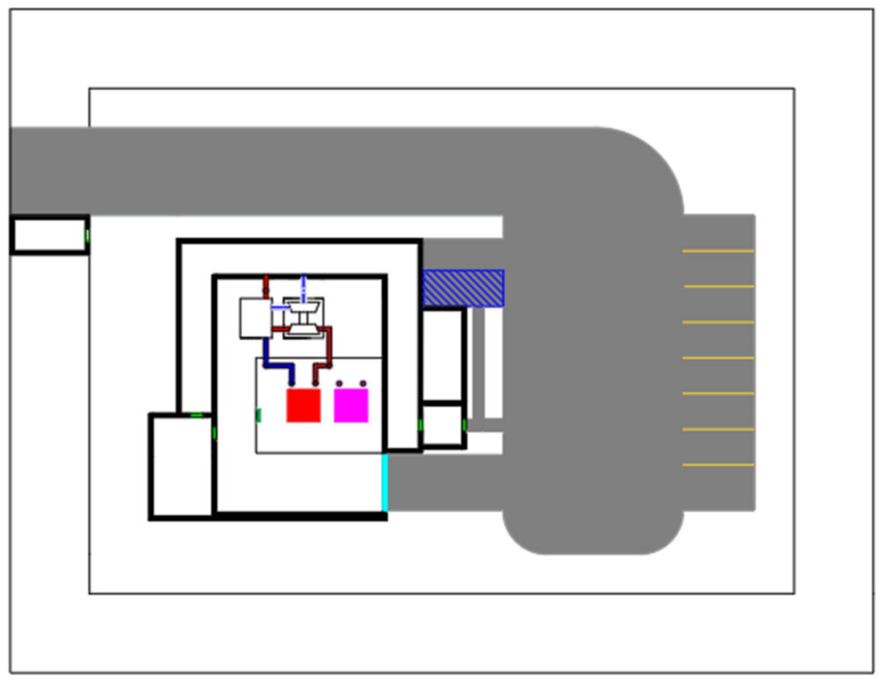


Example of Scribe3D analysis

Design, Evaluate and Optimize New PPS



Methodology designed facility allowing off-site response force



Facility designed facility assuming traditional 10 CFR 73 regulations

Benchmark Designs and Evaluate Cost Savings

- The success of the methodology was evaluated by a comparison of the footprints and costs of a PPS designed following the new methodology against the PPS designed following the traditional methodology.
- Application of the methodology to a hypothetical microreactor site demonstrated low off-site consequence using conservative modeling assumptions for source term and PPS design.
- The resulting facility and PPS design showed that an increase in physical barriers and delay elements were necessary to allow for off-site response, in comparison to a facility designed assuming standard 10 CFR 73 security regulations.
- However, the increase in capital cost for more delay elements were more than offset by the significantly reduced staffing and operational cost.

Project Outcomes and Impacts

- This project provides the following outcomes and impacts:
  - a flexible methodology for PPS design optimization that will reduce upfront and operational security costs
  - justification for incorporating consequence analysis into physical security regulations
  - a means to define the level of consequences for reactors which is based on an integrated analysis of security and safety effects.
- Impact (and why the project matters to AR utilities/owners/vendors)
  - provides a means for cost-reductions of future builds,
  - maintains or possibly increases the security of reactors and
  - promote the NRC's efforts to credit safety features of advanced reactors through proposed amendments to current physical security regulations.