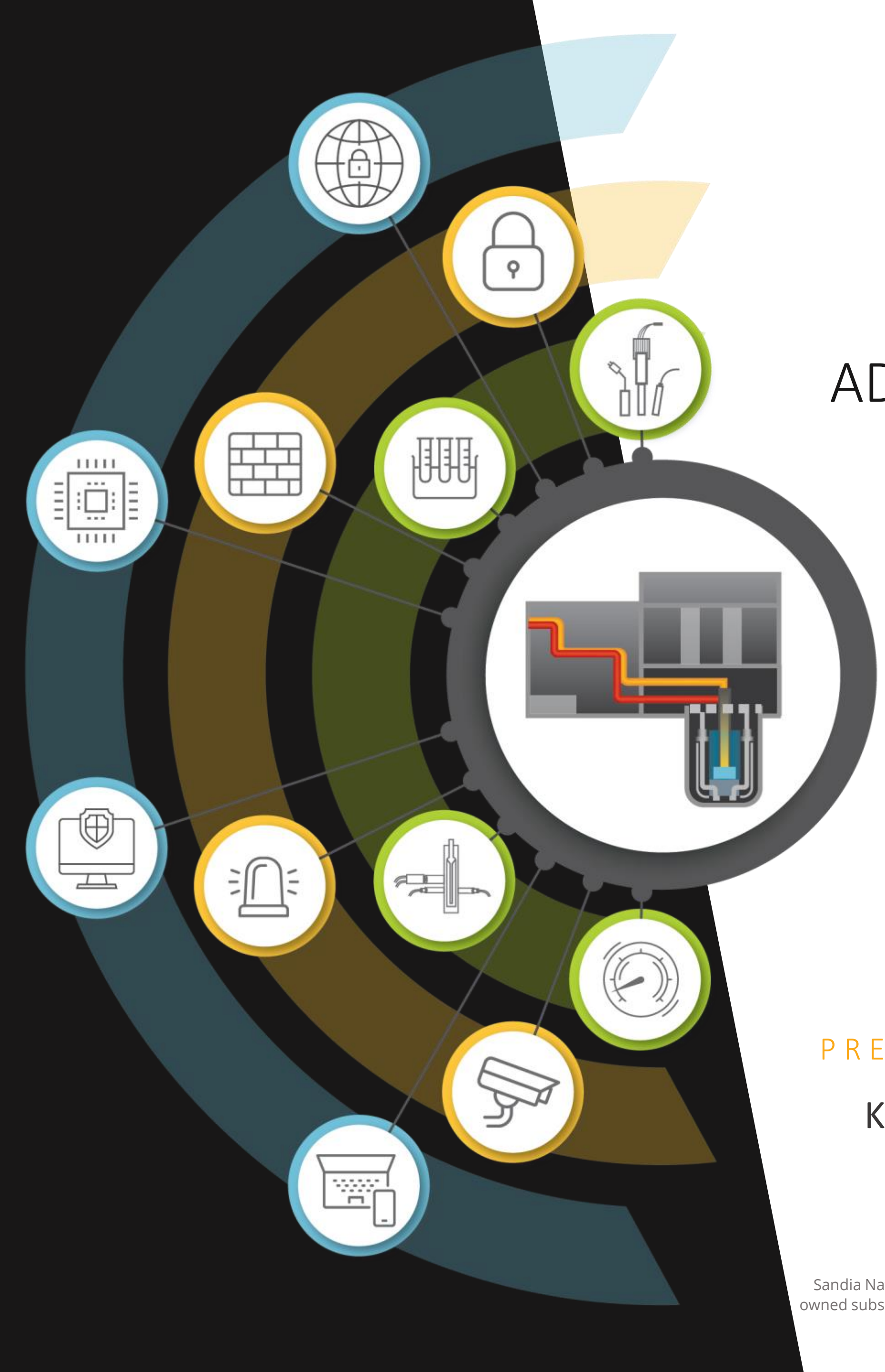


ADVANCED REACTOR SAFEGUARDS & SECURITY

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

PRESENTED BY

Karen Vierow Kirkland (Texas A&M University)

May 14-16, 2024

Info Release ID 1744857

Presentation Overview

- Project Goals and Objectives
- Project Motivation and Background
- Technical Approach
- Conclusions and Future Work
- Deliverables

Acknowledgements

- FY21 Consolidated Innovative Nuclear Research Award
- Award No.: DE-NE0009135
- Period of Performance: 10/01/2021 – 09/30/2023
- Co-authors
  - Shaheen Dewji, Jeffrey Wang (Georgia Institute of Technology)
  - Thomas Freyman (Texas A&M University)
- Collaborators
  - Alan Evans, Chris Faucett, Steven Horowitz (Sandia National Laboratories)

Presentation Overview

- Project goals
  - 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.

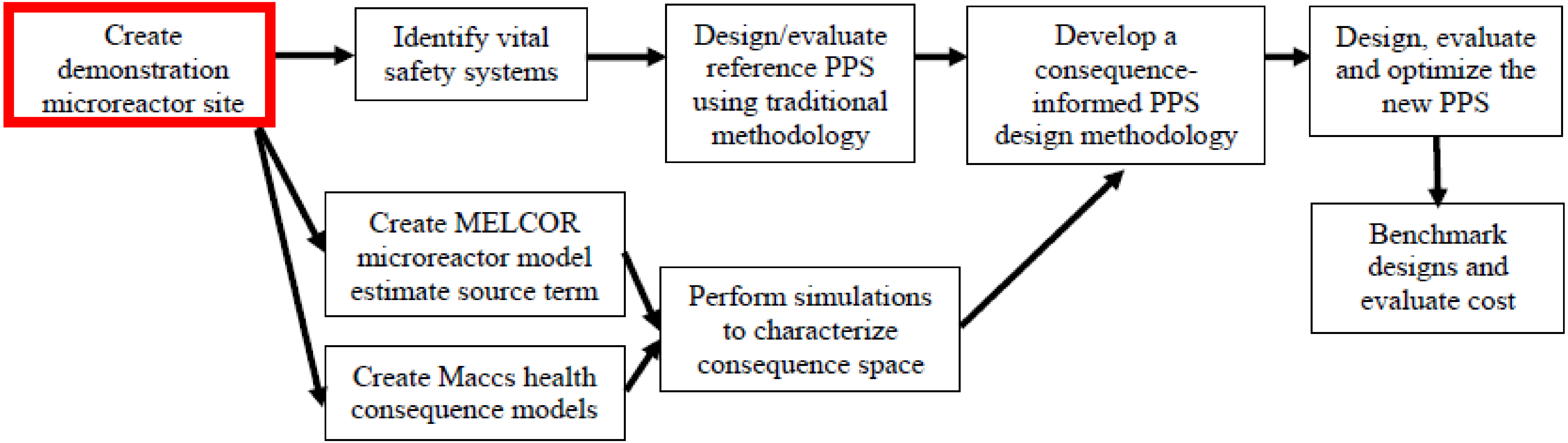
Project Motivation and Background

- Key technological contribution
  - The coupling of consequence modeling with security design in an integrated safety-security framework
  - ***This work is novel in that it uses a consequence-informed approach to PPS design.***

Project Motivation and Background

- The new PPS design methodology:
  - Phase 1: Determination of Desired PPS Characteristics and Facility Design
  - Phase 2: Facility Consequence Modeling, and
  - Phase 3: Consequence-Based PPS Design.
- This new methodology
  - provides a means for cost-reductions of future builds
  - maintains the security of reactors and
  - promotes the NRC's efforts to credit safety features of advanced reactors through proposed amendments to current physical security regulations.

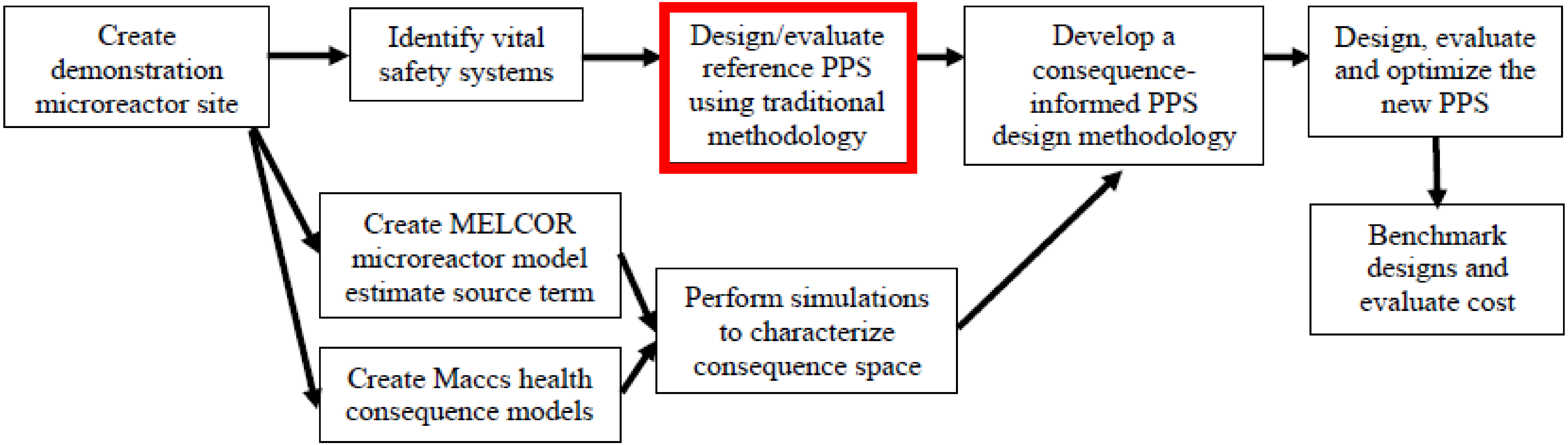
Technical Approach – Task Flow



Creation of notional microreactor site

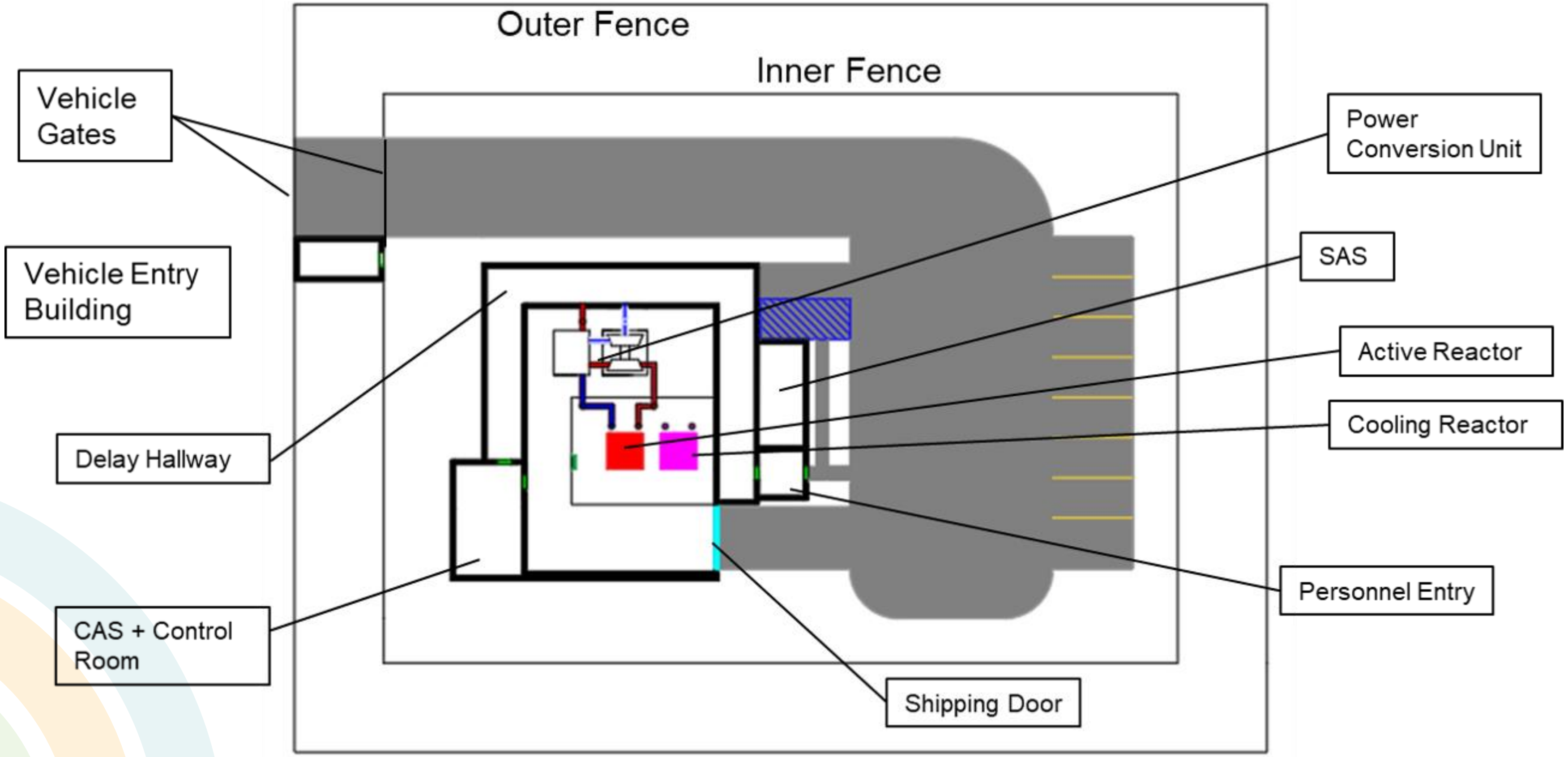
- Reference microreactor design
  - The INL Design A Special Purpose Reactor (SPR) [Sterbentz et al., 2018]
  - The MELCOR severe accident code was used for safety modeling.
- Notional microreactor site design for security modeling
  - The microreactor itself
  - A power conversion system
  - Any required supporting systems as determined by reactor subject matter experts, and
  - A control building.

Technical Approach – Task Flow



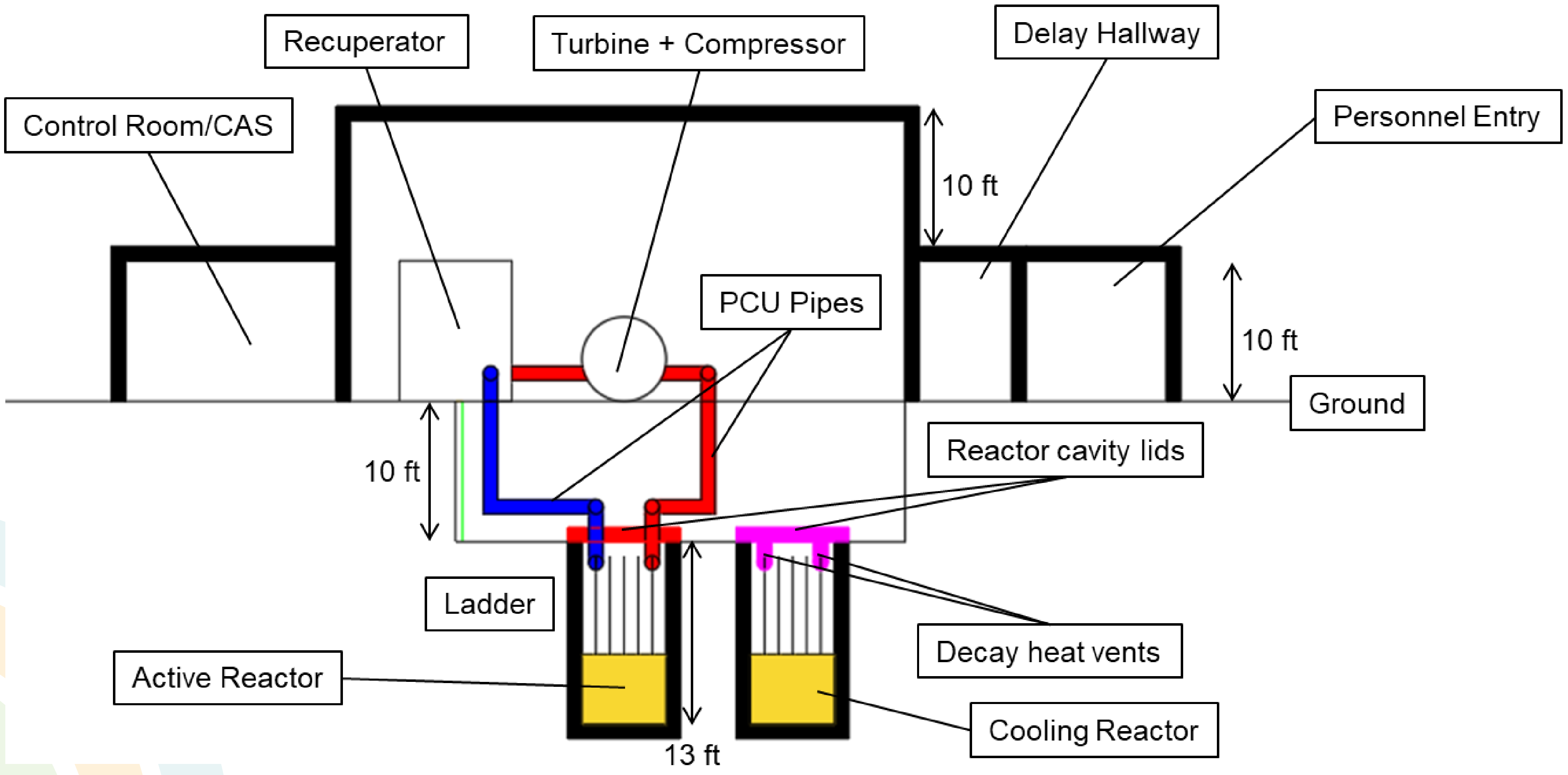
Design and evaluation of notional PPS using traditional DEPO methodology

- A PPS has been designed using the DEPO methodology.



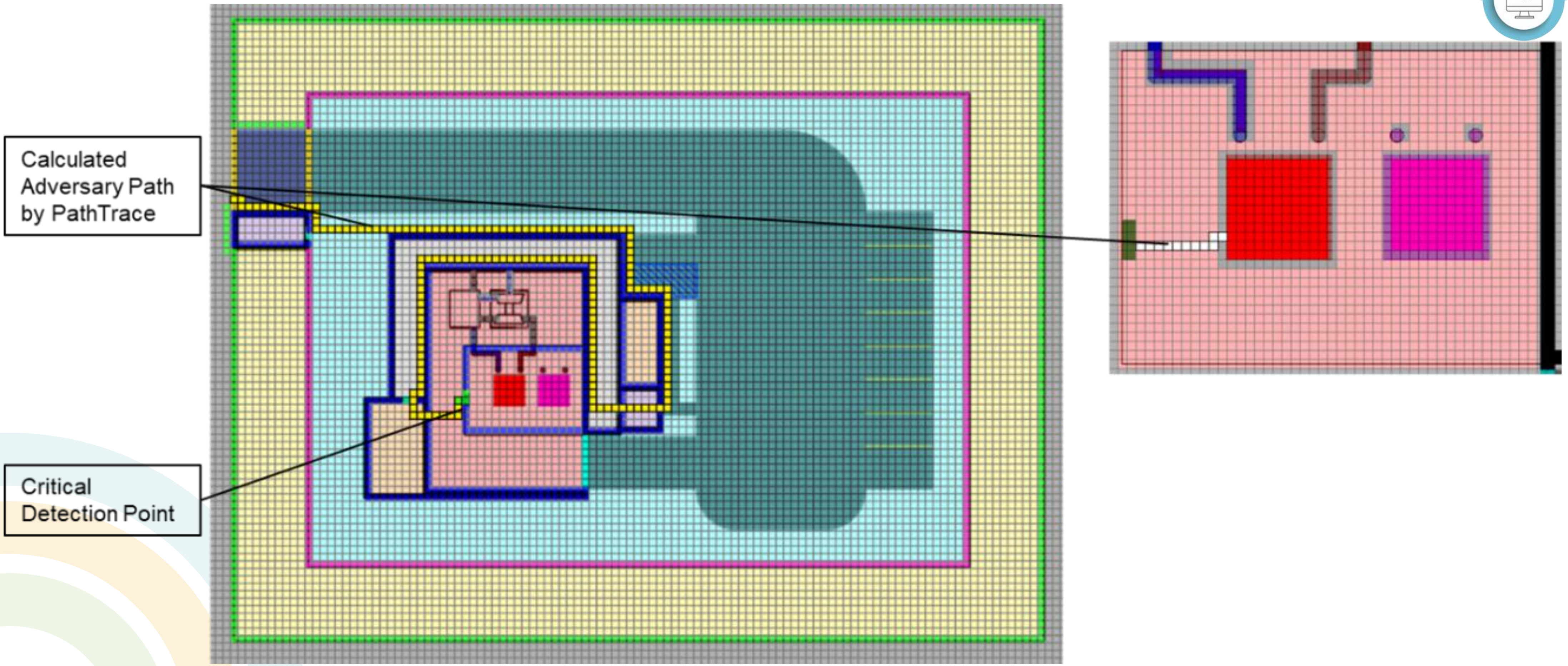
Top-down view of INL Design A SPR facility design for PPS modeling

Design and evaluation of notional PPS using traditional DEPO methodology



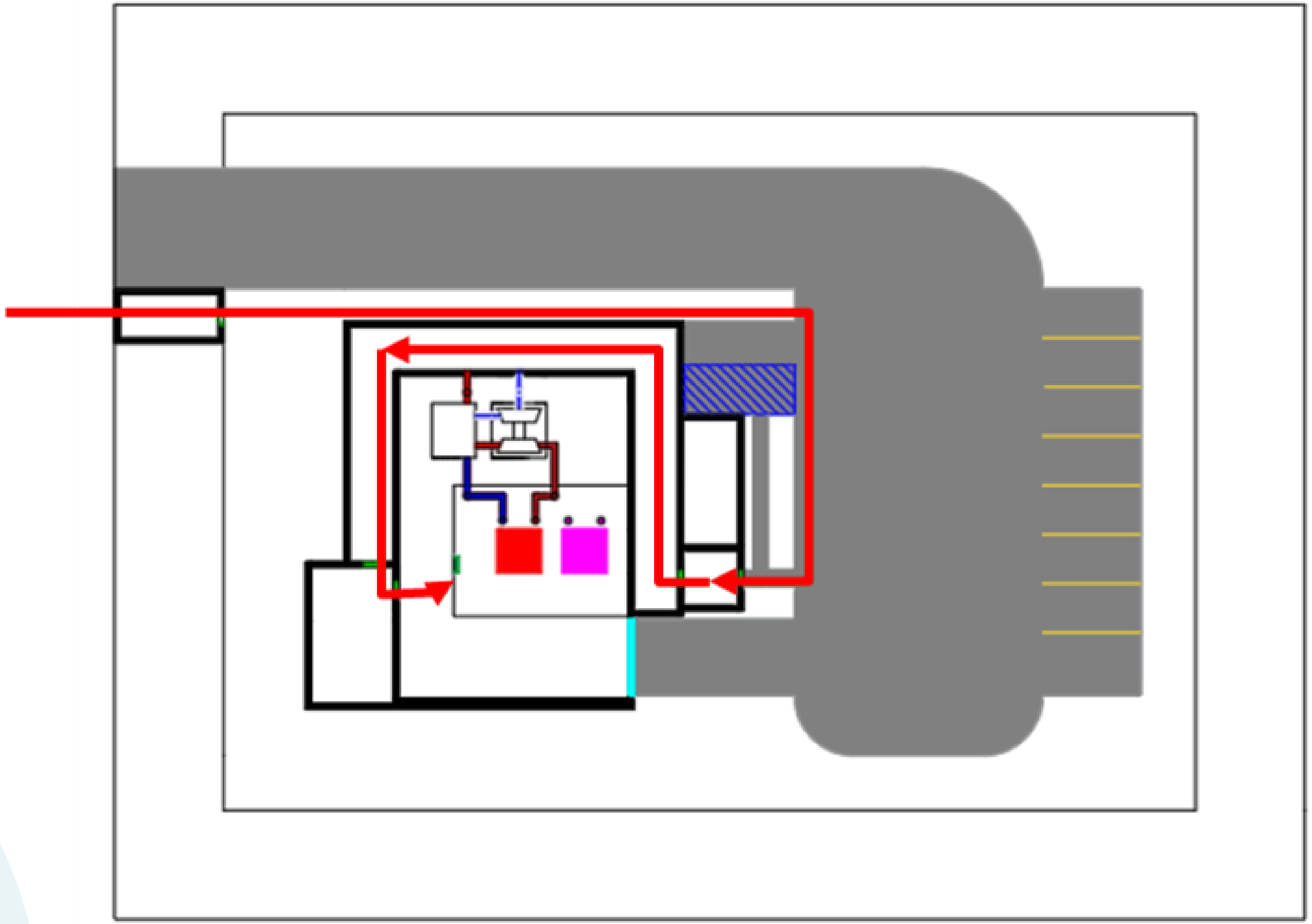
Side view of the INL Design A SPR facility design for PPS modeling

Design and evaluation of notional PPS using traditional DEPO methodology



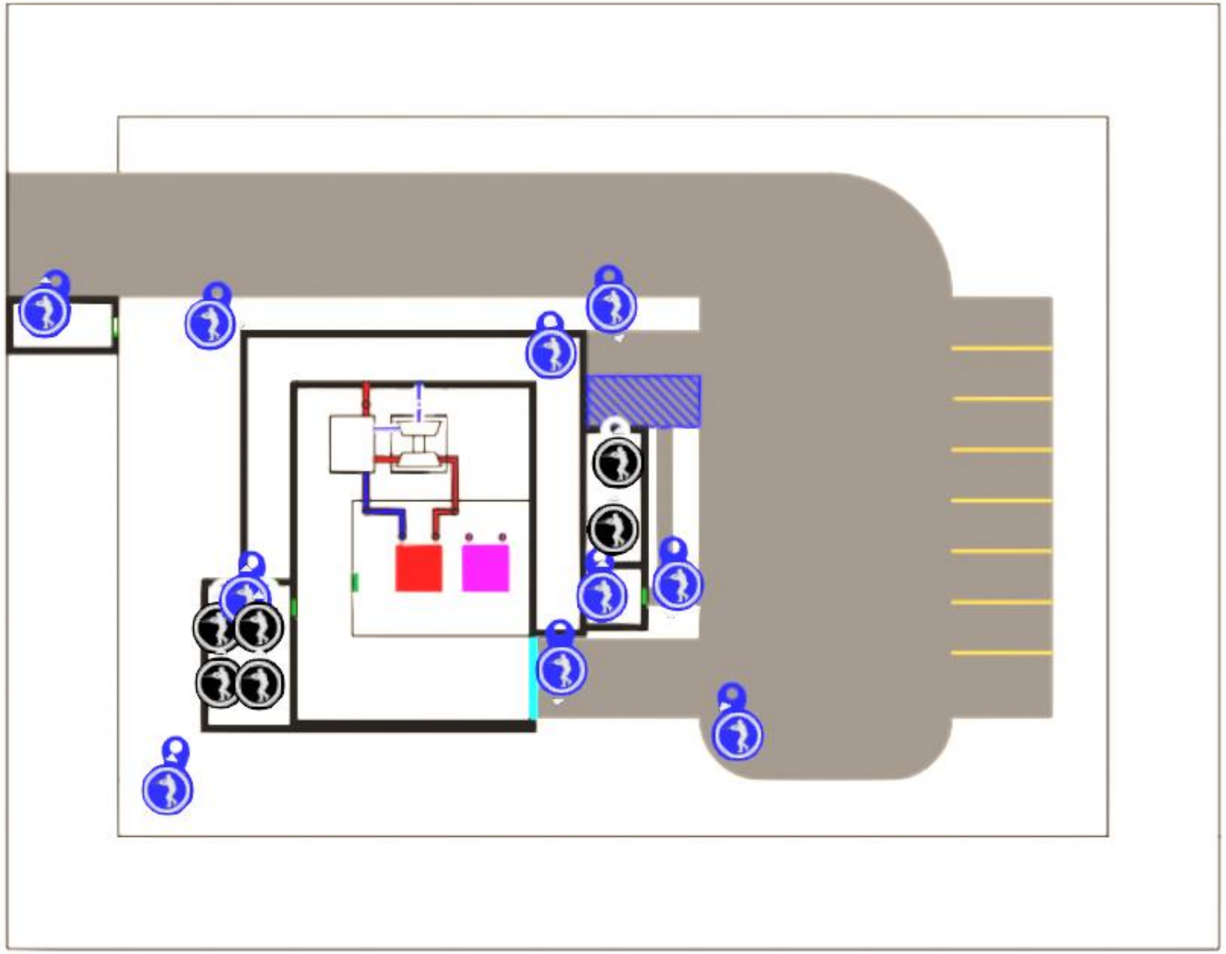
PathTrace model of adversary attack targeting the reactor units

Design and evaluation of notional PPS using traditional DEPO methodology



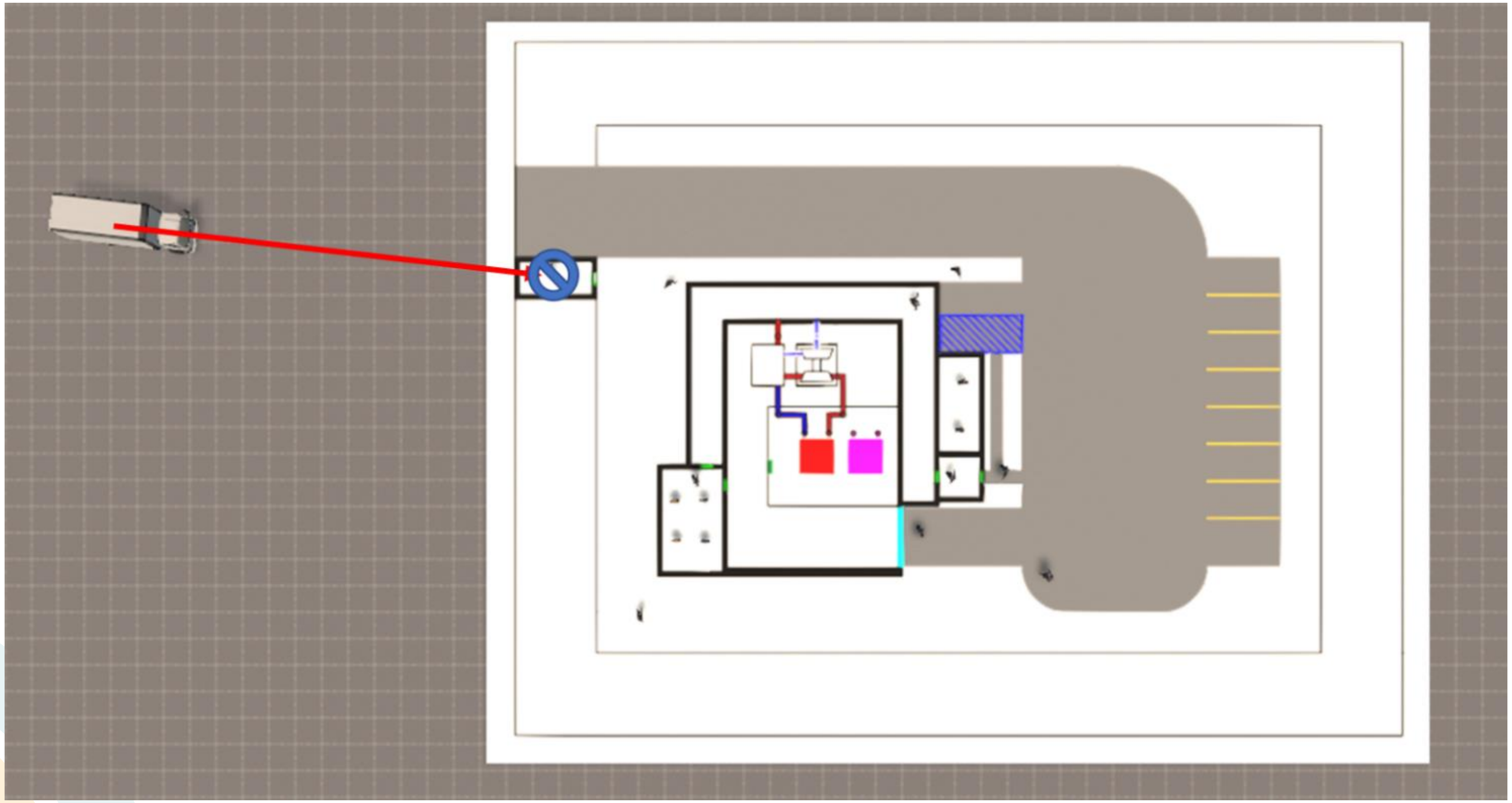
Adversary path simulated in SCRIBE 3D

Design and evaluation of notional PPS using traditional DEPO methodology



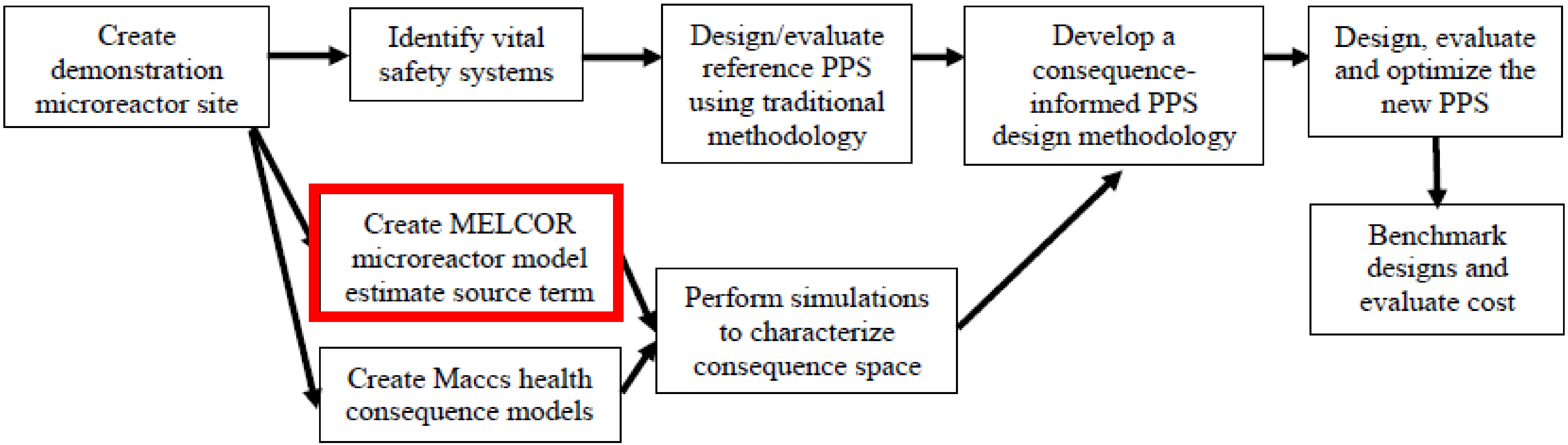
Initial positions of armed (blue) and unarmed (black) employees at facility

Design and evaluation of notional PPS using traditional DEPO methodology



Beginning of Scenario 1 showing vehicle movement and elimination of vehicle entry building guard

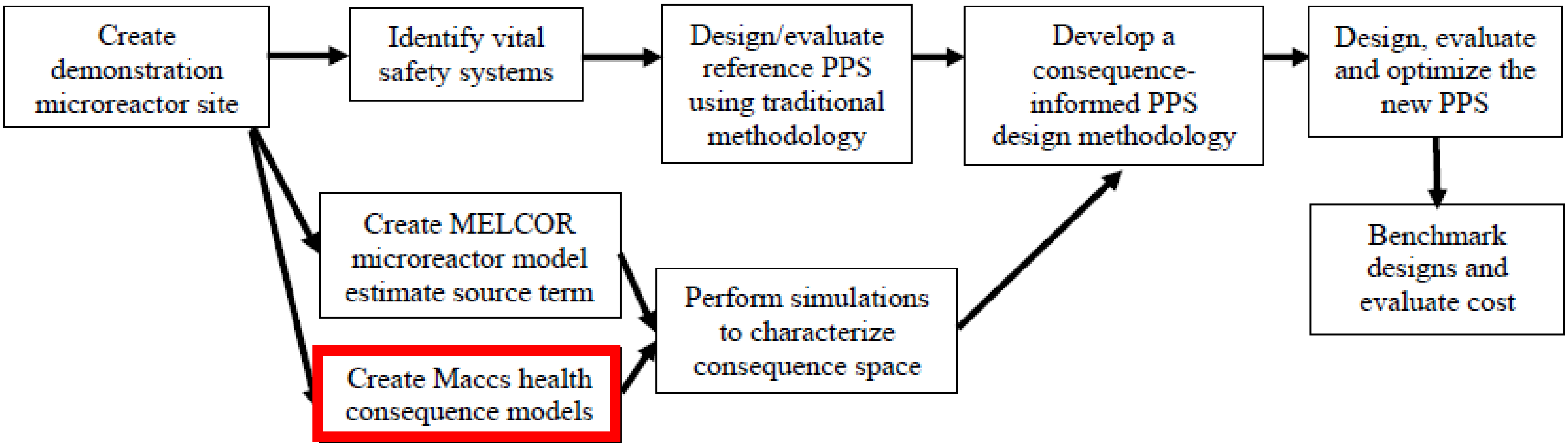
Technical Approach – Task Flow



MELCOR Microreactor Model

- MELCOR Model of the SPR Heat Pipe Reactor [Wagner et al., 2022]
- Calculation of Source Terms
  - Following the SPR Design A accident analysis conducted by SNL
    - Modeling conducted to determine largest credible source term by sabotage DBT.
    - Differences from previous analysis conducted by SNL:
      - A security event was assumed instead of an accident scenario
      - A security event provides the potential for more elaborate reactor transients than traditional accident analysis.

Technical Approach – Task Flow



Health Consequence Modeling

- Atmospheric transport and dispersion (ATD) modeling provided the consequence modeling.
  - Utilized the MELCOR source term information from the previous task.
  - The Maccs tool adopted, enabling the integration of ATD models with health physics models for radioactive releases.

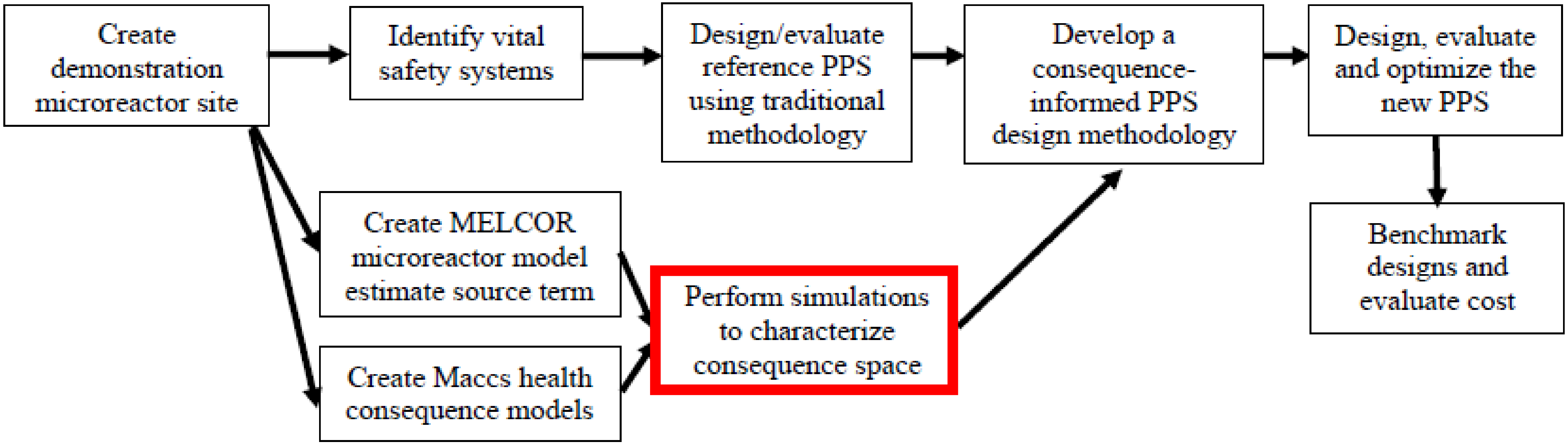
Health Consequence Modeling

- Two approaches within MACCS:
  - Gaussian Straight-Line Plume Segment Model (GPM)
    - Estimates a radionuclide release from a given source with a Gaussian normal distribution along the crosswind plane.
    - Travels with constant initial velocity and direction outward from initial point.
  - HYSPLIT and the Lagrangian Particle in Cell Model (PIC)
    - Predicts movement and dispersion of airborne pollutants and particles.
    - Models a set of particles subject to a random walk in all three dimensions
    - Generates a plume-like shape of estimated dispersion and deposition density for the duration.

Health Consequence Modeling

- Gaussian plume modeling was more successful in predicting near-field dose estimates for the Emergency Planning Zone (EPZ) placement of advanced nuclear reactor designs.
- The results of the Gaussian plume modeling of the SPR were used herein to estimate dose consequences of the reactor facility.

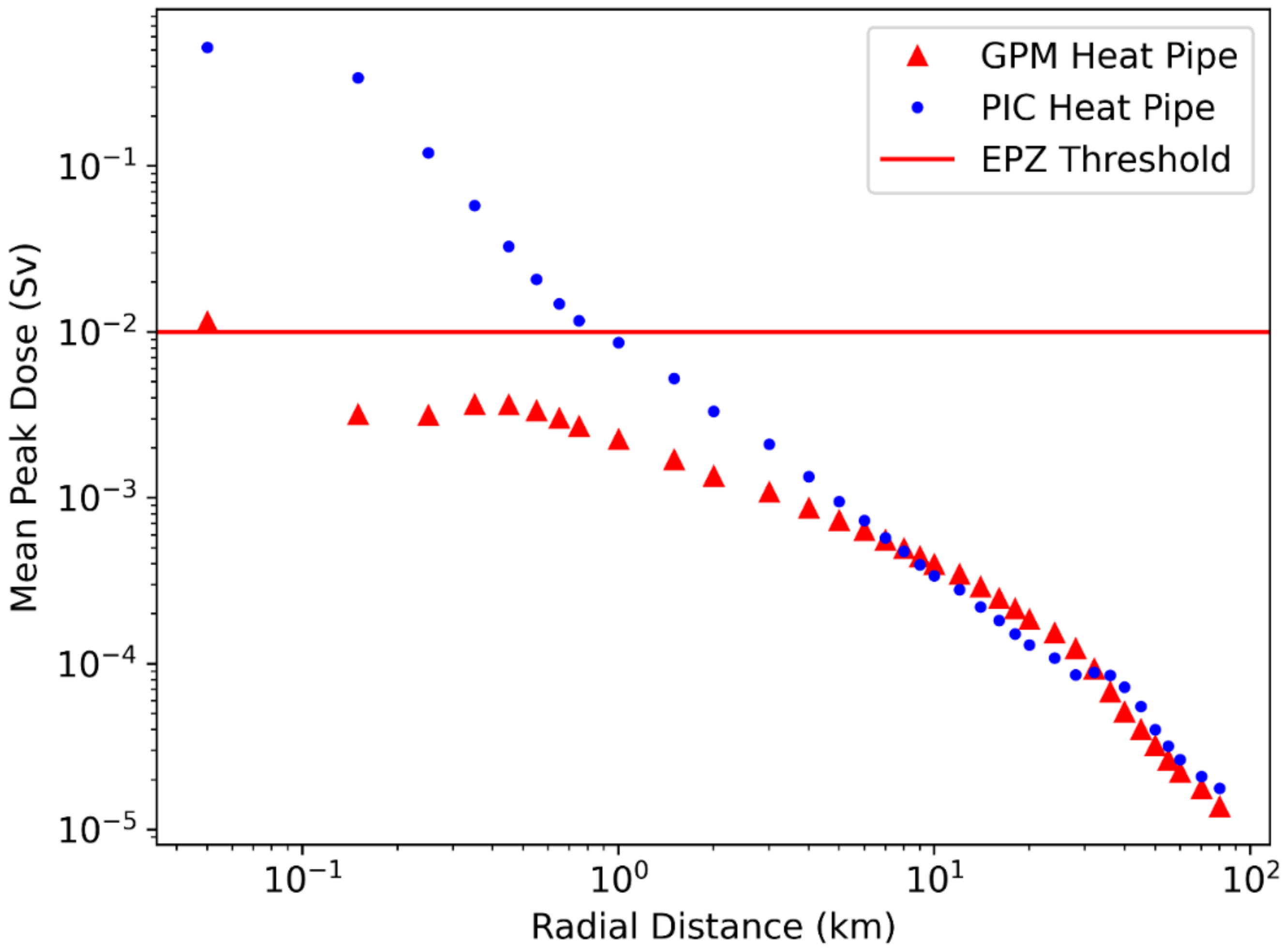
Technical Approach – Task Flow



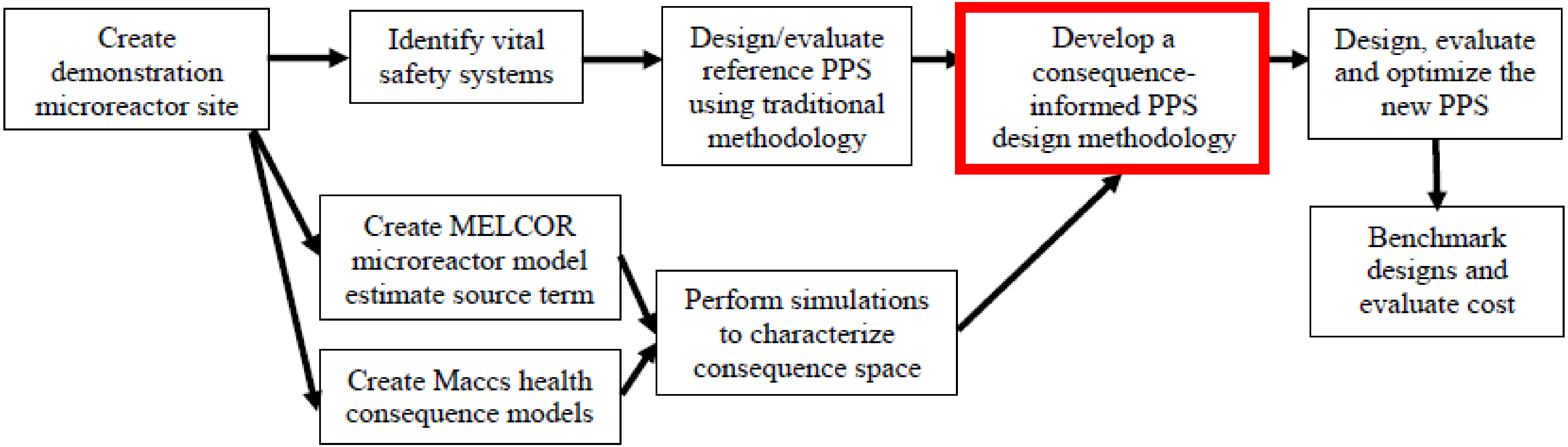
Simulations to Characterize Risk Space

- Simulations were performed to assess consequences for feedback to the PPS design.
- Maccs analyses yielded very small doses from the heat pipe reactor
  - Following even the maximum theoretical 100% release of the core inventory
  - Demonstrating that ***results from Maccs are necessary to define the fundamental technical basis for a scalable EPZ*** of a hypothetical power facility utilizing a single INL Design A SPR heat pipe reactor.
- Under proposed 10 CFR 50.160 and the approved NuScale scalable EPZ,
  - operators of these reactors could apply for a non-standard EPZ radius using the methodology herein with Maccs' GPM atmospheric transport and dispersion simulation.
  - Maccs also provides an alternative simulation method (Lagrangian PIC integration).
  - GPM simulation results are accompanied by an equivalent PIC simulation, which is compared to determine eligibility and consequences of utilizing Lagrangian PIC over GPM to determine EPZ boundaries.

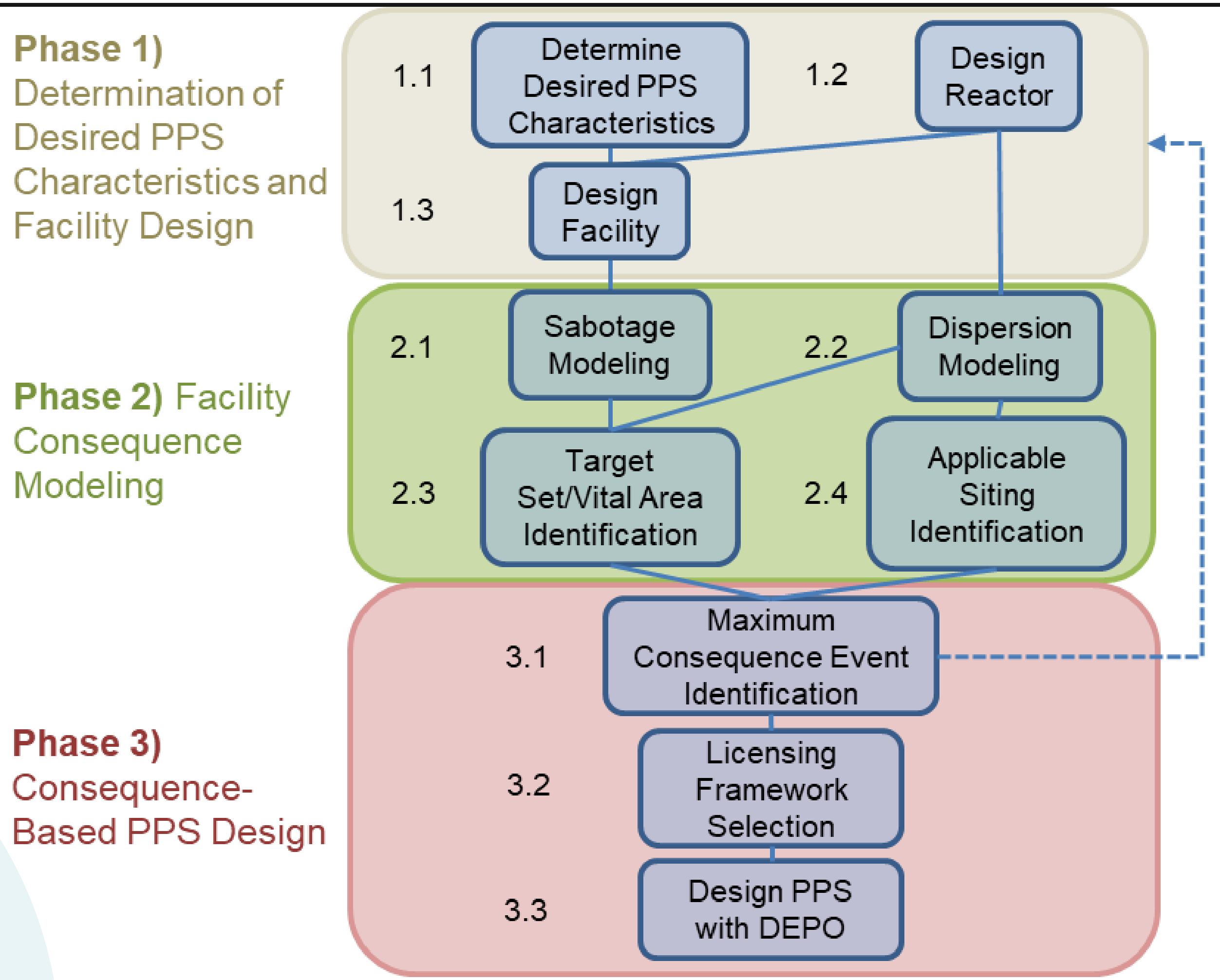
Perform simulations to characterize risk space



Technical Approach – Task Flow

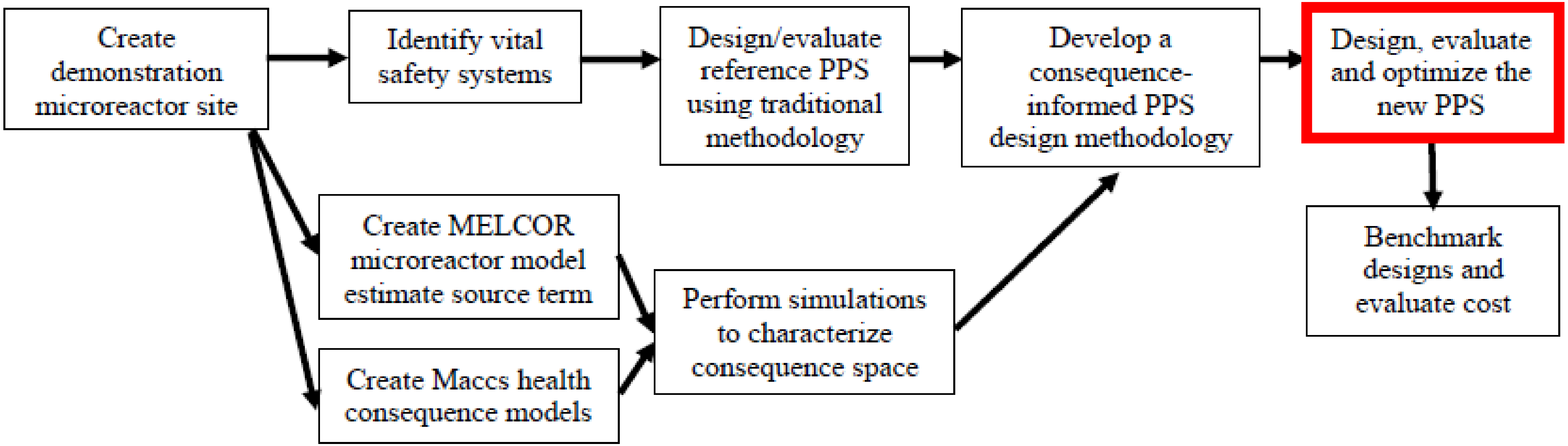


Consequence-Informed PPS Design Methodology



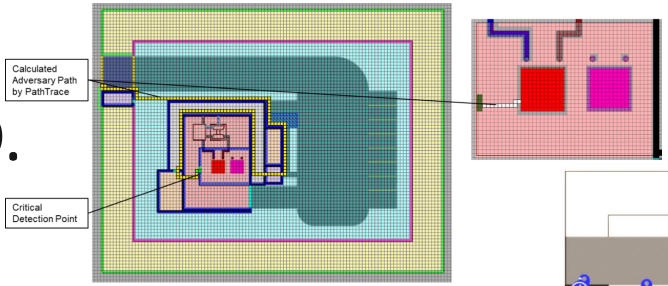
New Consequence-Informed PPS Design Methodology

Technical Approach – Task Flow

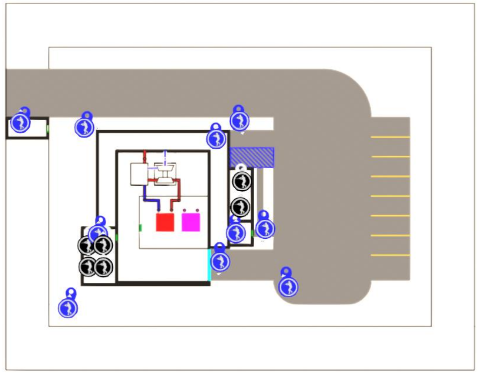


Design, evaluate, and optimize new PPS

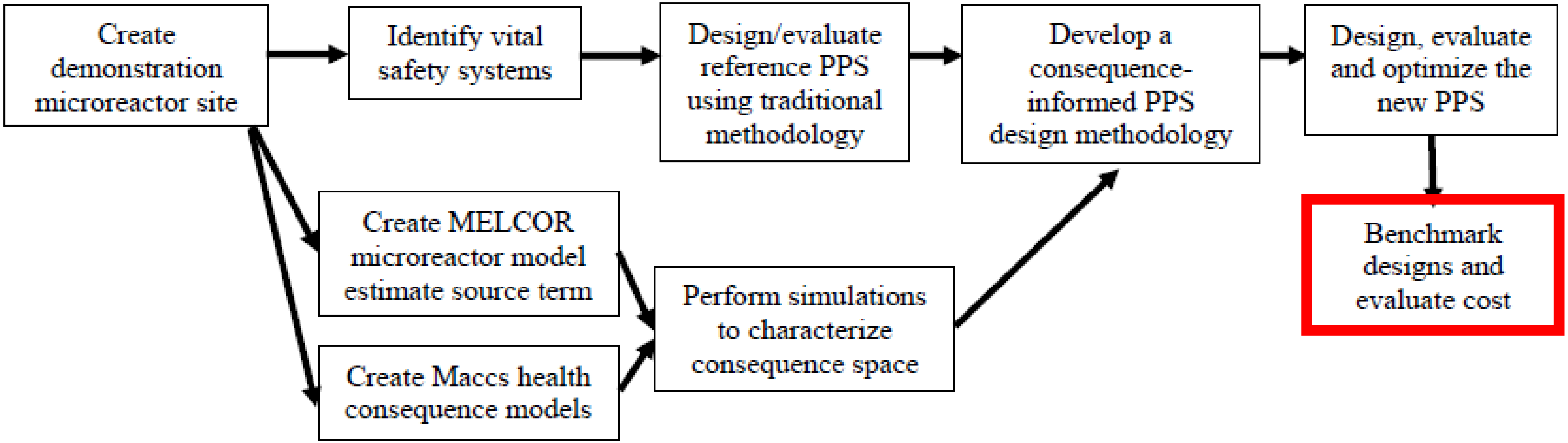
- Iterations of the facility layout and PPS design were conducted with PathTrace.
  - Added increasingly more PPS elements to provide delay
  - Eventually, a layout with sufficient delay to allow for response force arrival was generated.
  - The finalized facility layout was used in SCRIBE 3D to simulate engagements between the response force and adversary.



- Two scenarios were analyzed in SCRIBE 3D.
  - Adversary forces of 5, 6, 7, and 8 adversaries
  - Two different levels of fortification by the adversary



Technical Approach – Task Flow



Benchmark Designs and Evaluate Cost

- Analysis of two separate PPS designs for the same SPR
  - Baseline DEPO design where PPS utilized a fully staffed on-site security force
    - ten armed guards,
    - an on-site Central Alarm Station (CAS), and
    - on-site Secondary Alarm Station (SAS).
  - PPS design generated using the consequence-informed licensing path selection methodology,
    - off-site SAS
    - off-site response force with an estimated response time of 30-minutes.

Benchmark Designs and Evaluate Cost

- The two designs had equal success rates
  - Seven out of eight analyzed scenarios
  - PPS success was achieved via different means.
- DEPO-based design
  - Response force had a near immediate response time upon detection of the adversary.
  - Combined operations and security staffing burden of 80 FTE or 40 FTE/MWe
- PPS design from the consequence-informed licensing path selection methodology
  - Off-site response force had an estimated response time of 30-minutes.
  - Combined operational and security staff of 10 FTE or 5 FTE/MWe
- *This dramatic manpower reduction resulted in a significant cost savings for the PPS designed according to the new methodology.*

Conclusions

- This project has successfully met its goals to:
  - Enable a more appropriately sized 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.
- Novel approach:
  - uses a consequence-informed risk analysis approach to PPS design.
- Key technological contribution:
  - the coupling of consequence modeling with security design in an integrated safety-security framework.

Future Work

- Consideration of multiple reactors on site
  - Maccs can now simultaneous releases
- Analysis of a reactor with a larger core inventory
  - Microreactor has a very small core inventory
  - The value of the new methodologies presented herein would be better demonstrated as more realistic assumptions about the amount of core release could be made.
- Addition of cyber-security, for a safety-security-cyber approach to designing a PPS

Deliverables

- A new methodology for optimized PPS design for microreactor sites
- A new framework for consequence informing security-by-design methods
- A new strategy for right-sizing the PPS of a microreactor and design optimization
- Quarterly progress reports to the sponsor
- Student thesis/dissertation
  - Wang, Jeffrey, Comparison of Atmospheric Dispersion Models for Risk Informed Advanced Reactor Licensing and EPZ Sizing, MS Thesis, Georgia Institute of Technology, August 2023.
  - T. Freyman, The Formulation of a Consequence-Informed Methodology for the Design of Physical Protection Systems at Advanced Commercial Reactor Facilities, Ph.D. Dissertation, May 2024.

Deliverables

- Jeffrey Wang, Shaheen Dewji, "Comparison of Gaussian and Lagrangian Plume Modeling of Doses for Guidance in Microreactor Physical Protection System Design", presentation to the *2022 International Maccs User Group*, Sept. 20, 2022.
- Shaheen Dewji, Karen Kirkland, "Risk-informed Consequence-Driven Physical Protection System Optimization for Microreactor Sites", presentation to Advanced Reactor Safeguards Spring Meeting, Oak Ridge, TN, April 18, 2023.
- J. Wang, D. Clayton, S. Dewji, Risk-Informed Comparison of Atmospheric Plume Models for Dose-Based Advanced Reactor Licensing Siting, proc. of *18th International Probabilistic Safety Assessment and Analysis (PSA 2023)*, July 1, 2023.
- Thomas Freyman, Karen Kirkland, "A Consequence-Informed Licensing Path Selection for the Design of Physical Protection Systems at Commercial Nuclear Power Facilities", *Nuclear Science and Engineering,* 2024.
- Jeffrey Wang, Daniel Clayton, Shaheen Azim Dewji, "Comparison of Atmospheric Radionuclide Dispersion Models for a Risk-Informed Consequence-Driven Advanced Reactor Licensing Framework", *Journal of Environmental Radioactivity*, 2024.