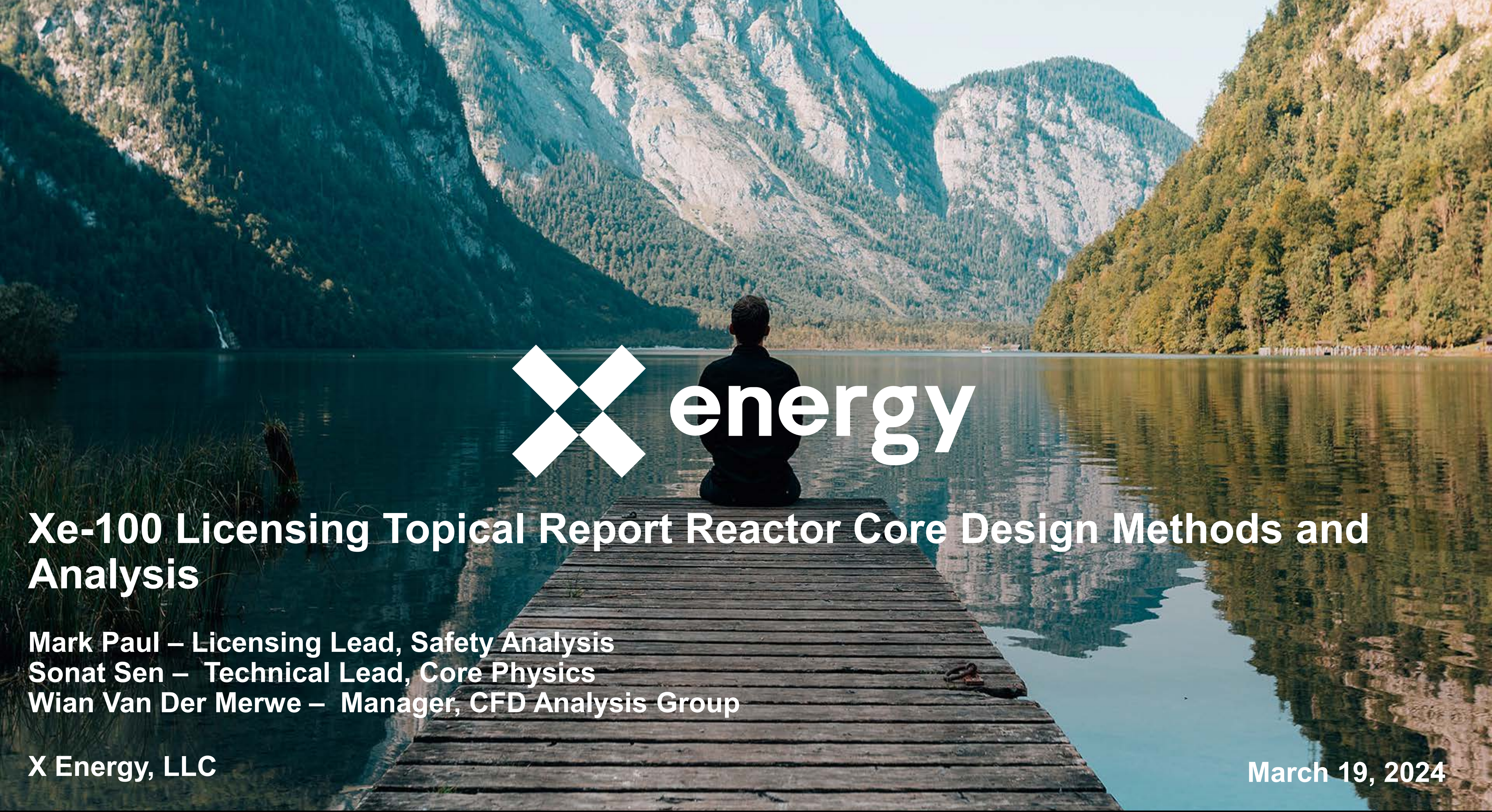

Xe-100 Licensing Topical Report Reactor Core Design Methods and Analysis

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March 19, 2024

Department of Energy Acknowledgement and Disclaimer

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Agenda & Objectives

Agenda:

- Introductions
  - Presentation
    - Xe-100 design basics
    - Core modeling via VSOP
    - Pebble flow modeling via STAR-CCM+
    - Typical results – reactivity coefficients and power distribution
  - Conclusions and Next Steps
  - Q and A
- Closing comments

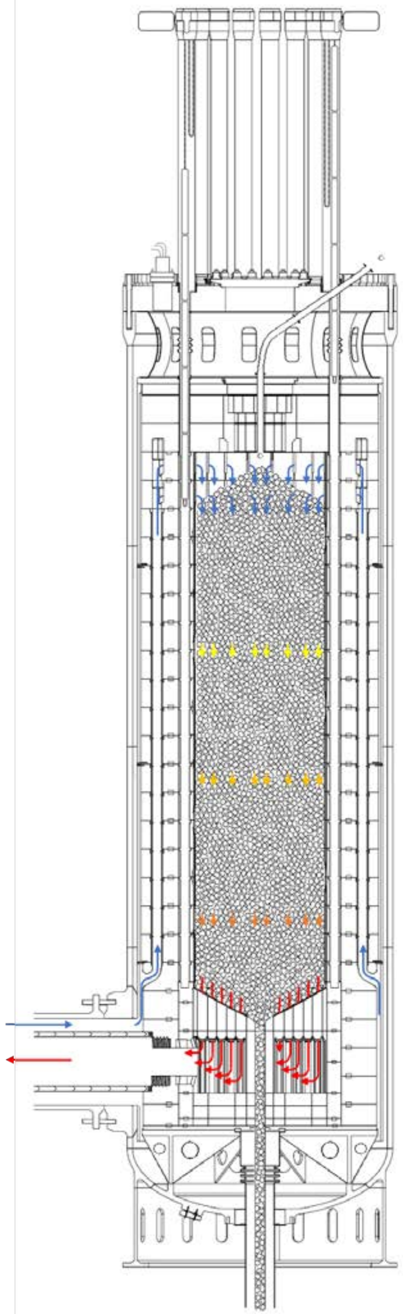
Objectives:

- Provide a preview of X-energy Licensing Topical Report "Reactor Core Design Methods and Analysis"
  - The LTR will be used to support future safety analysis reports for prospective Xe-100 licensing activities under 10 CFR parts 50 and 52, and possibly a future 10 CFR 53.
- Present
  - Xe-100 reactor characteristics
  - Methods and codes used to model the Xe-100 reactor core

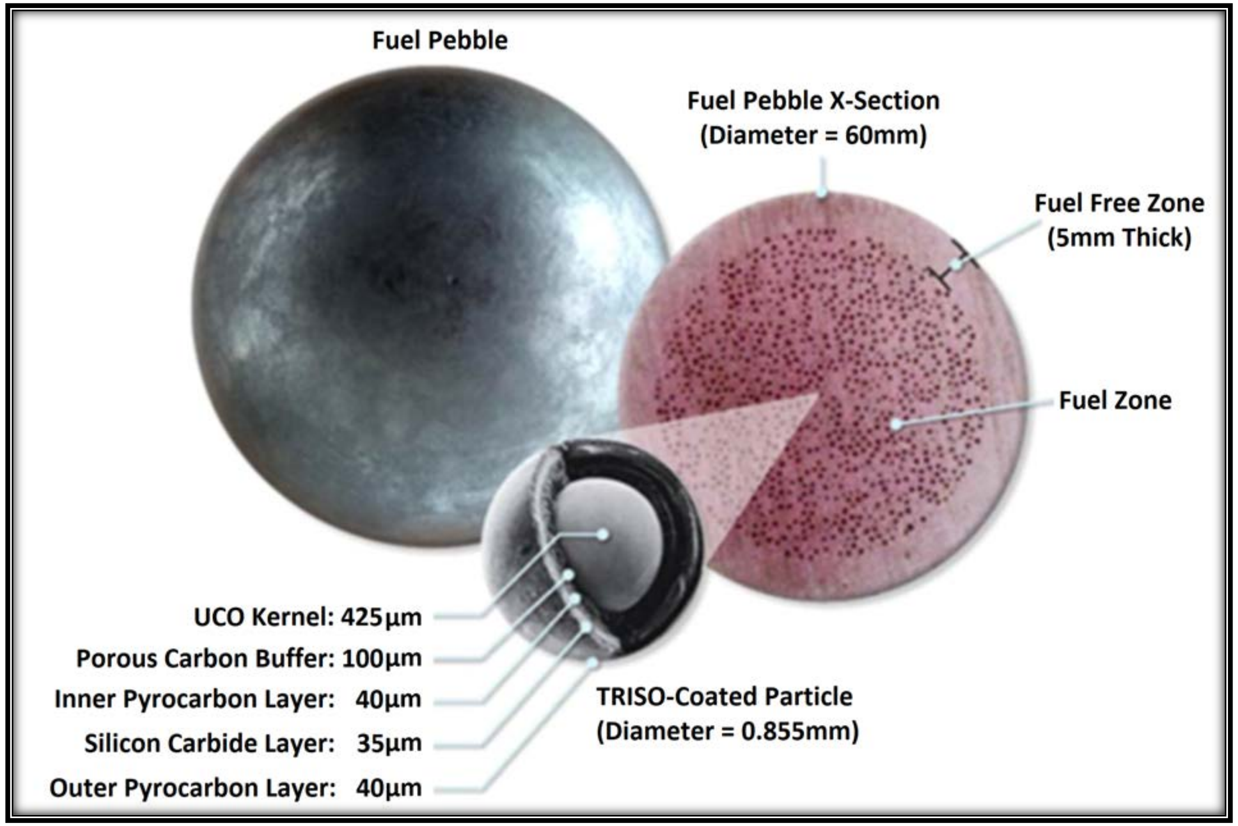
Xe-100 Overview

X-energy is developing the Xe-100, a 200 MWt, 80 MWe high-temperature gas-cooled reactor (HTGR). The reactor core is a pebble bed design.

- The Xe-100 will be used to produce high-temperature steam for:
  - Electricity
  - Industrial processes
- Core: Approximately 220,000 spherical pebbles
- Fuel:
  - Each pebble contains approximately 19,000 TRISO fuel particles
  - U-235 enrichment up to 15.5 weight percent
  - Fuel is in UCO form
- Coolant: Helium
  - Nominal core inlet/outlet temperatures: 260/750°C



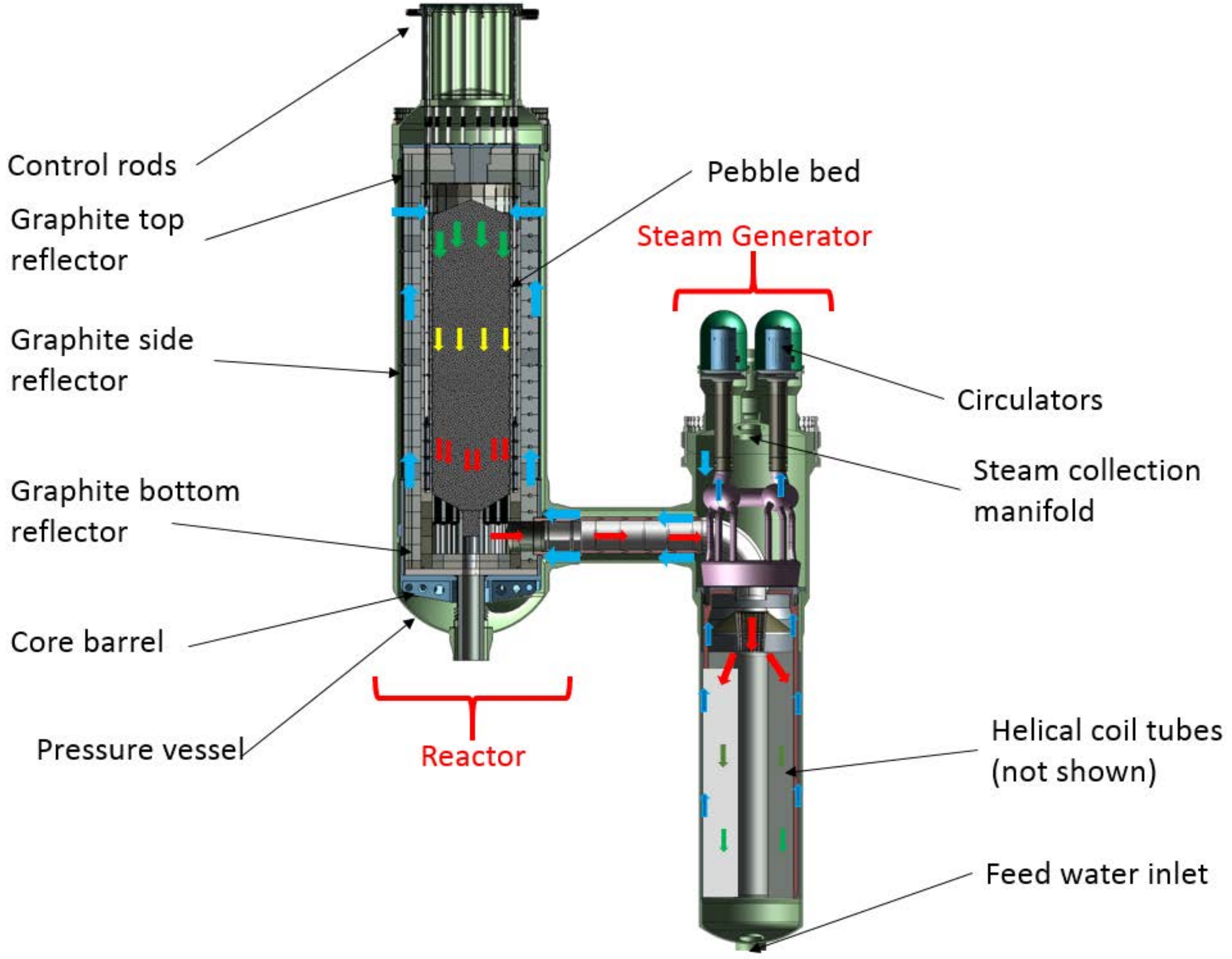
Xe-100 Fuel Particle and Pebble



TRISO – TRistructural ISOtropic

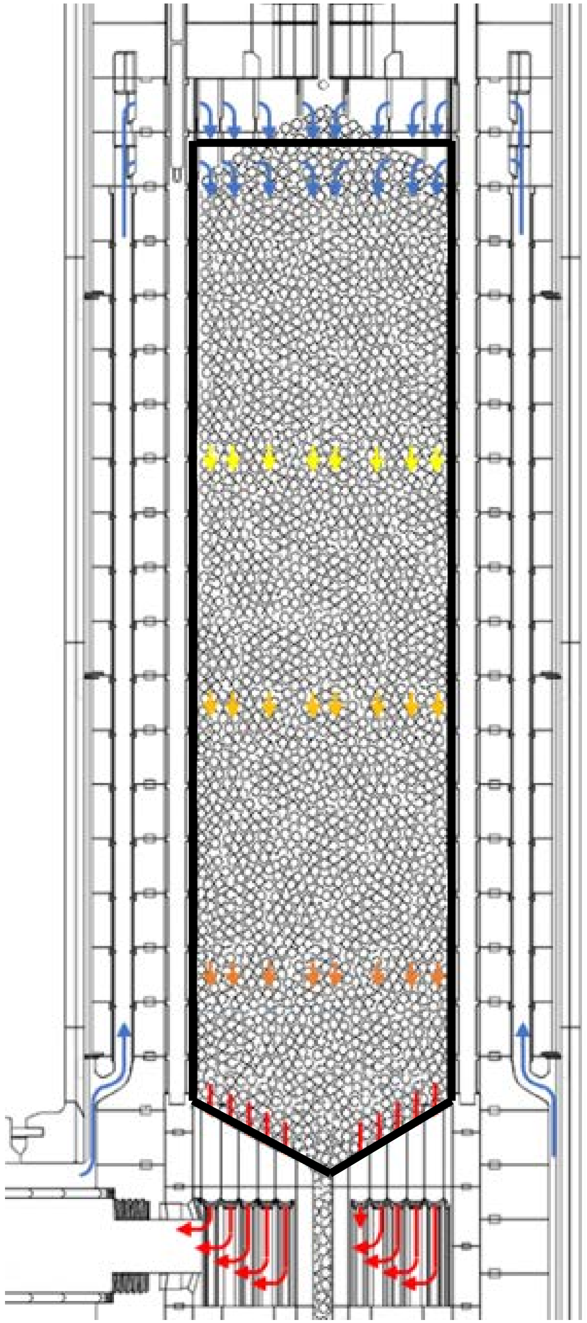
The DOE describes TRISO particles as "The most robust nuclear fuel on the planet."

Xe-100 Reactor and Steam Generator



Physical Components Modeled

- Modeled:
  - Cylindrical pebble bed region
  - Lower conic region
  - Control and Shutdown rods
  - Graphite reflectors
  - Coolant channels in the reflector
  - Coolant inlet and outlet channels in the reflector are represented
- Not modeled:
  - Defueling chute



Xe-100 Reactor Core Characteristics

The Xe-100 core configuration is:

- Non-stationary: pebbles move down slowly through the core multiple times until they reach the target discharge burnup
- Heterogeneous:
  - Pebbles from different passes
  - Nature of the fuel:
    - The fuel particles dispersed in the matrix inside the pebbles
    - The arrangement of pebbles within the core
- The pebble bed continuously evolves from an early startup (initial commissioning) phase to a statistically steady burnup equilibrium condition

Xe-100 Reactor Core Modeling

Neutronic analyses of the Xe-100 core:

- Non-stationary – The modeling tracks changes in fuel as it passes down through the core
- Double-heterogeneity of TRISO particles and pebbles is modeled
- Evolving core is explicitly modeled:
  - From graphite only in the core →
  - Combination of graphite, LEU and HALEU →
  - Equilibrium HALEU core

X-energy Applications of the Reactor Core Model

- Reactor core steady-state design analysis
- 100% nominal full power equilibrium core analysis
- Initial start-up and running-in analysis
- Low power operation
- Load follow maneuvers
- Reactivity control system requirements (for example, shutdown margins)
- Provides input parameters to support the safety analysis
- Other operational transients (for example, slow transients that do not require modeling of the delayed neutrons)
- Tool for validation purposes and to perform research and development in aspects that involve, for example, advanced fuel cycle behavior

Reactor Core Design Analysis and Methods – Computer Codes

VSOP

Comprehensive numerical simulation of an HTGR with spherical fuel pebbles:

- Provides both neutronics and thermal-hydraulics modelling capabilities
- Qualified via commercial grade dedication

AND

STAR-CCM+

Computational Fluid Dynamics (CFD) simulations:

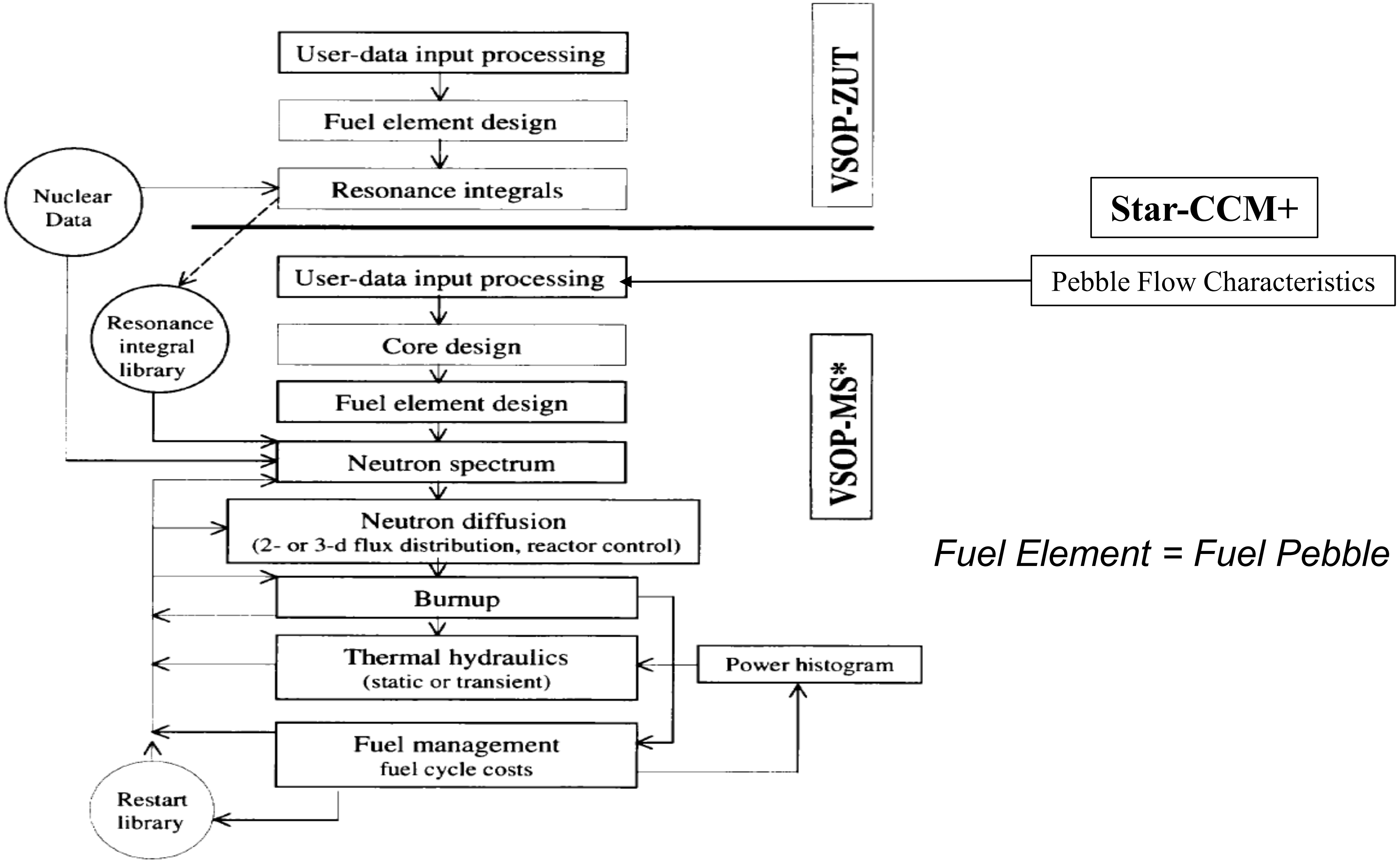
- Models pebble flow characteristics through the core
- Provides an input into the VSOP code
- Developed under an acceptable Quality Assurance Program

VSOP

VSOP models:

- Processing of cross-sections
- Set-up of the reactor geometry and the fuel element
- Neutron spectrum evaluation
- Neutron diffusion calculation
- Fuel burnup
- Fuel movement through the core
- Thermal-hydraulic feedback mechanisms
  - Neutronic model calculates the power distribution
  - Results in fuel and moderator temperatures change
  - Feeds back to the neutronics calculation

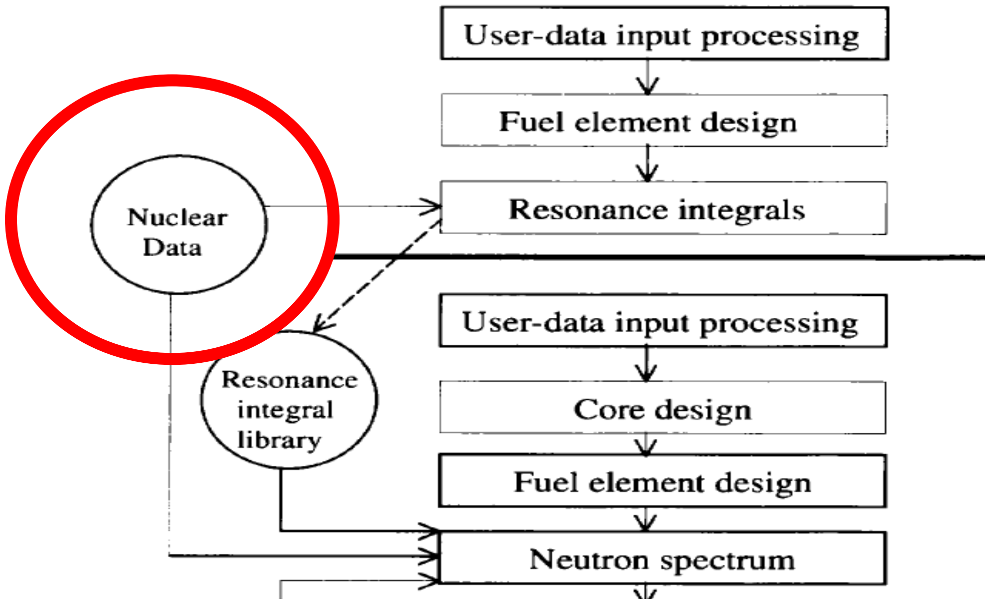
VSOP Program Flow



Fuel Element = Fuel Pebble

VSOP Nuclear Data (Cross Section Libraries)

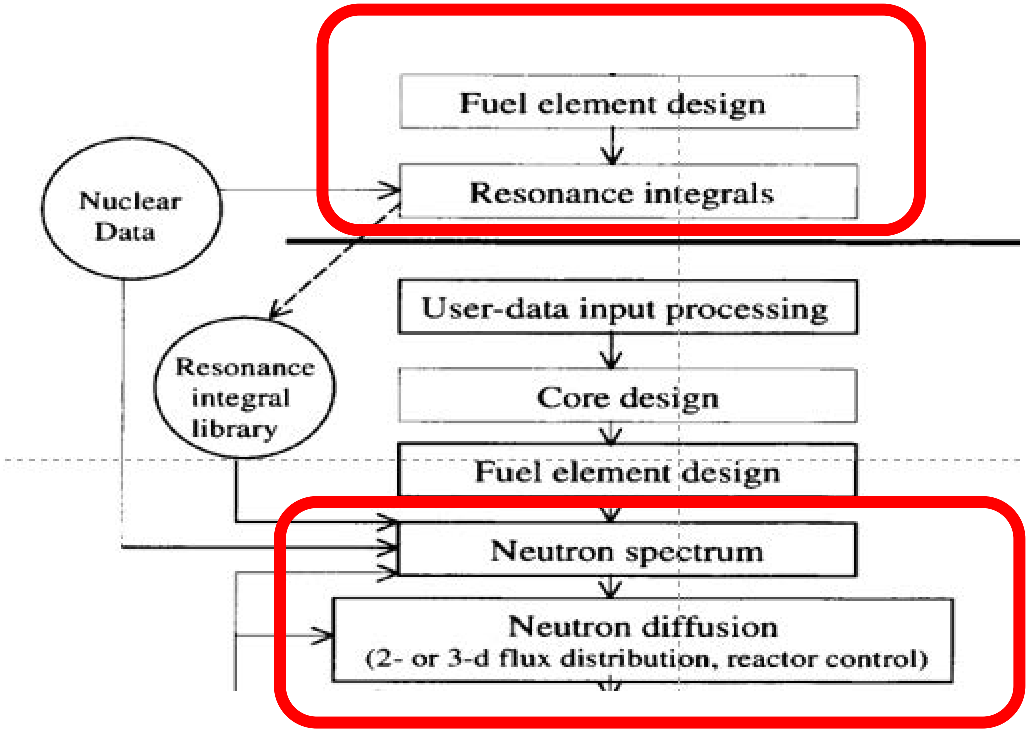
- Two libraries to encompass the entire neutron energy range:
  - A 68-energy group structure ranging from 10 Mev to 0.414 eV
  - A thermal library with a 30-energy group structure ranging from 2.05 eV to 10^{-5} eV
- The libraries contain 190 isotopes with their corresponding cross-sections
- 28 of the 190 are heavy metal isotopes including Th, Pr, U, Np, Pu, Am, Cm
- The thermal library contains thermal scattering kernels for graphite, hydrogen and oxygen at various temperatures



VSOP Neutronics Analysis

VSOP calculates two other data sets as input to the neutronics calculations:

- Resonance integrals:
  - For Th-232, U-238, Pu-240, and Pu-242
  - Calculated for each of the 68 energy groups
- Neutron Escape Probabilities

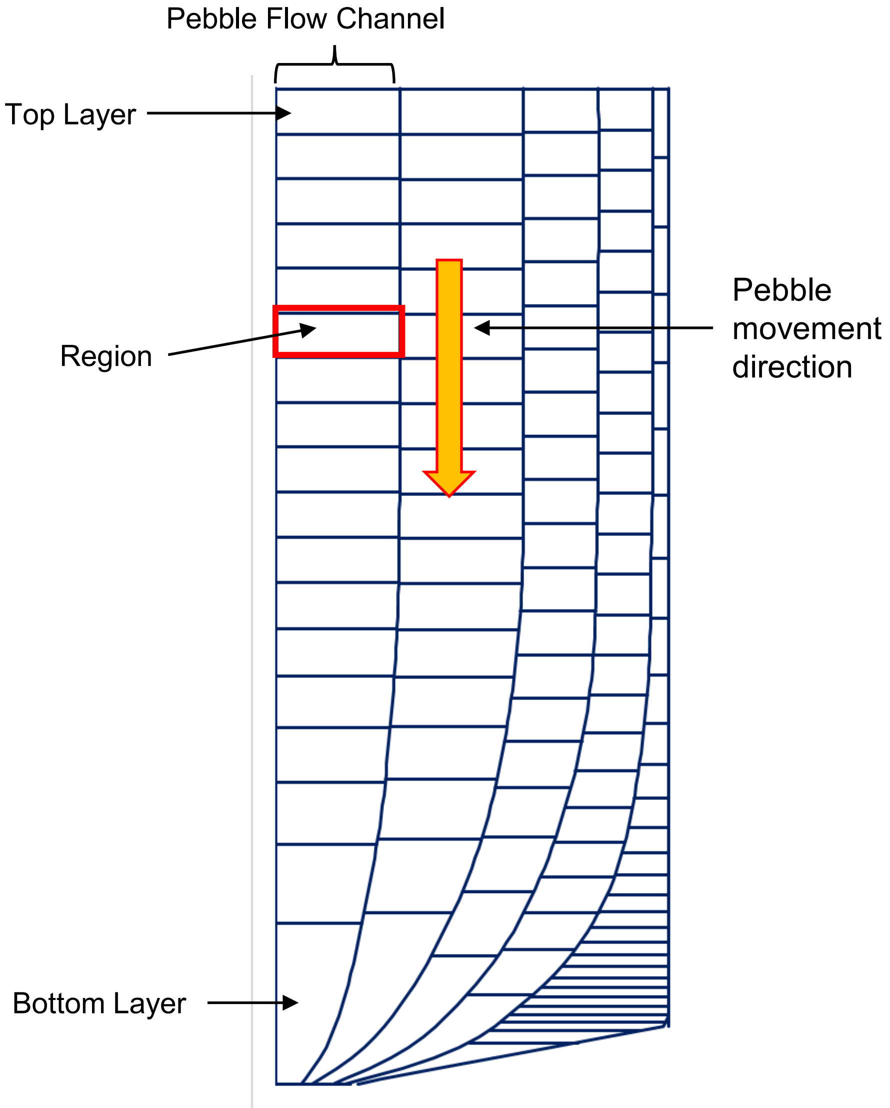


The Xe-100 VSOP model uses 4-group diffusion theory:

- A thermal energy group
- Two epithermal groups
- A fast energy group

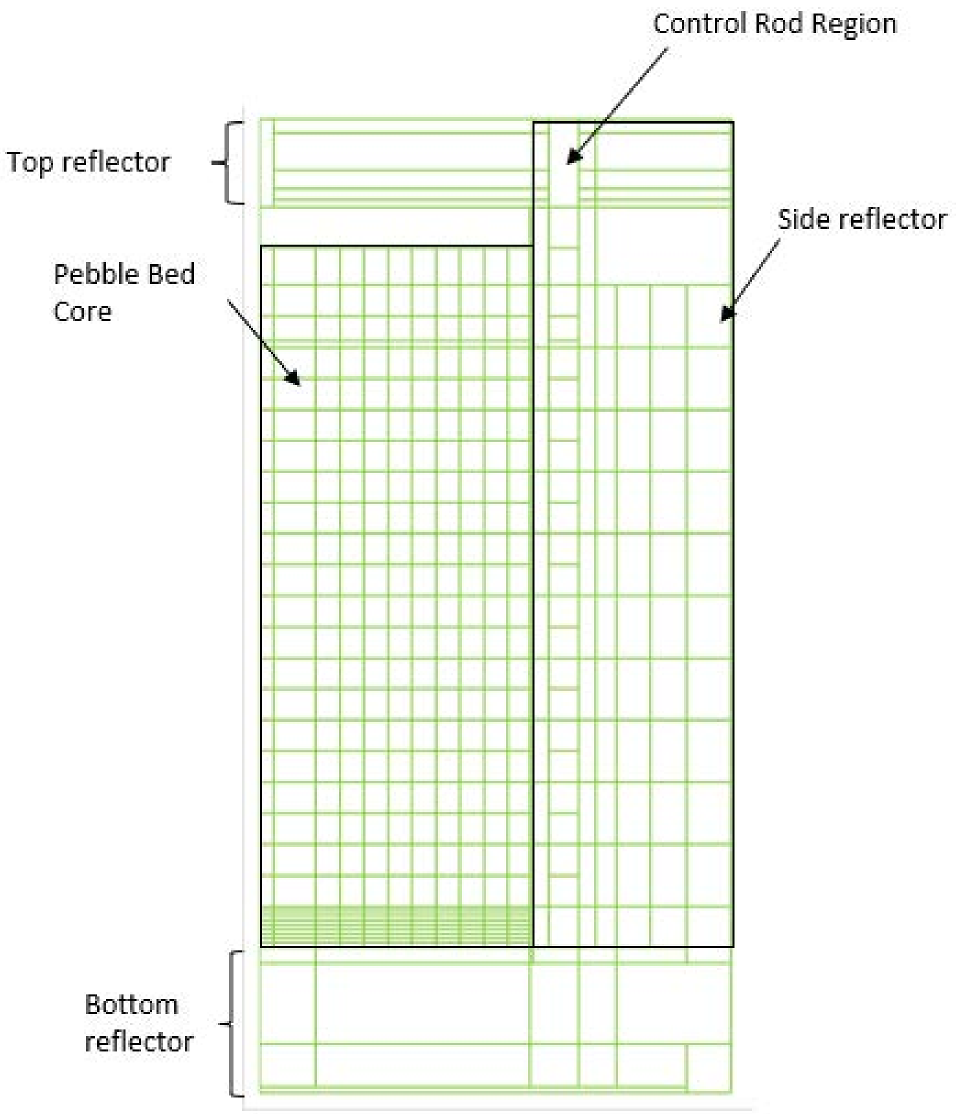
Core Design Using VSOP

- Two-dimensional modeling (RZ)
- 5 radial pebble flow channels
- Each channel is subdivided into equal-volume sub-units called “layers” or “regions”, to simulate the effect of the pebble axial flow velocities in each channel
- Each “region” contains information for pebbles from different passes in non-physical containers called “batches”
- The simulation provides batch-wise data for:
  - Burnup
  - Fluence
  - Fuel shuffling
  - Decay heat production



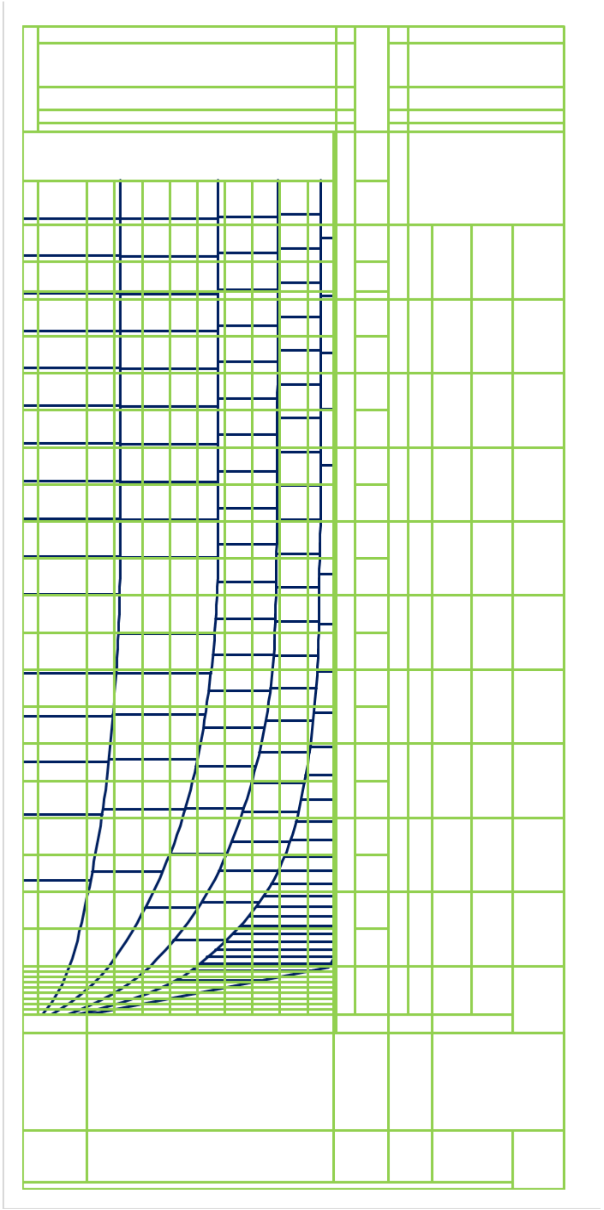
Core Design Using VSOP

- The neutronic and thermal-hydraulic mesh represents a finer mesh for the solution of the neutron diffusion and heat transport (conduction, convection and radiation)
- Neutronic mesh includes:
  - Core
  - Graphite reflectors at the top, bottom, and sides
  - Helium space at the top of the core
- Thermal-hydraulic mesh adds to that:
  - Core barrel at the top and bottom
  - Reactor cavity at the right boundary
- Simulation provides mesh-wise data for neutron flux, power and temperatures (coolant and solid)



Core Design Using VSOP

- The flow channel and region configuration are superimposed on a neutronic mesh. The model:
  - Assigns material composition to each region (therefore each mesh node) of the pebble bed core
    - Composition of regions changes with time
  - Outside of the core, the mesh unit comprises a predefined reactor material such as graphite reflectors, void regions, etc.
    - Composition is fixed
- Neutron flux, power, and temperatures are mapped back to flow channel and region configuration

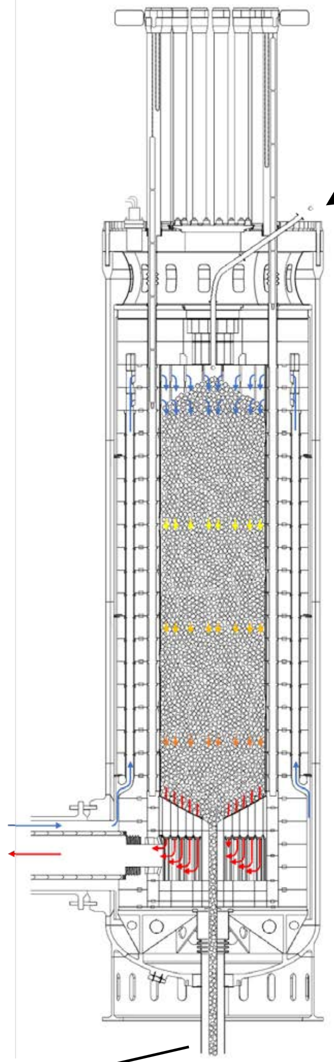


Pebble Flow Physical Process

- Fuel pebbles are introduced at the top of the core and move downward through the core until they exit at the bottom through the defuel chute
- Burnup is then determined by the gamma spectrum

Each pebble is either:

  - Sent to spent fuel storage
  - Returned to the top of the core
  - A fuel pebble will pass on average six times through the core

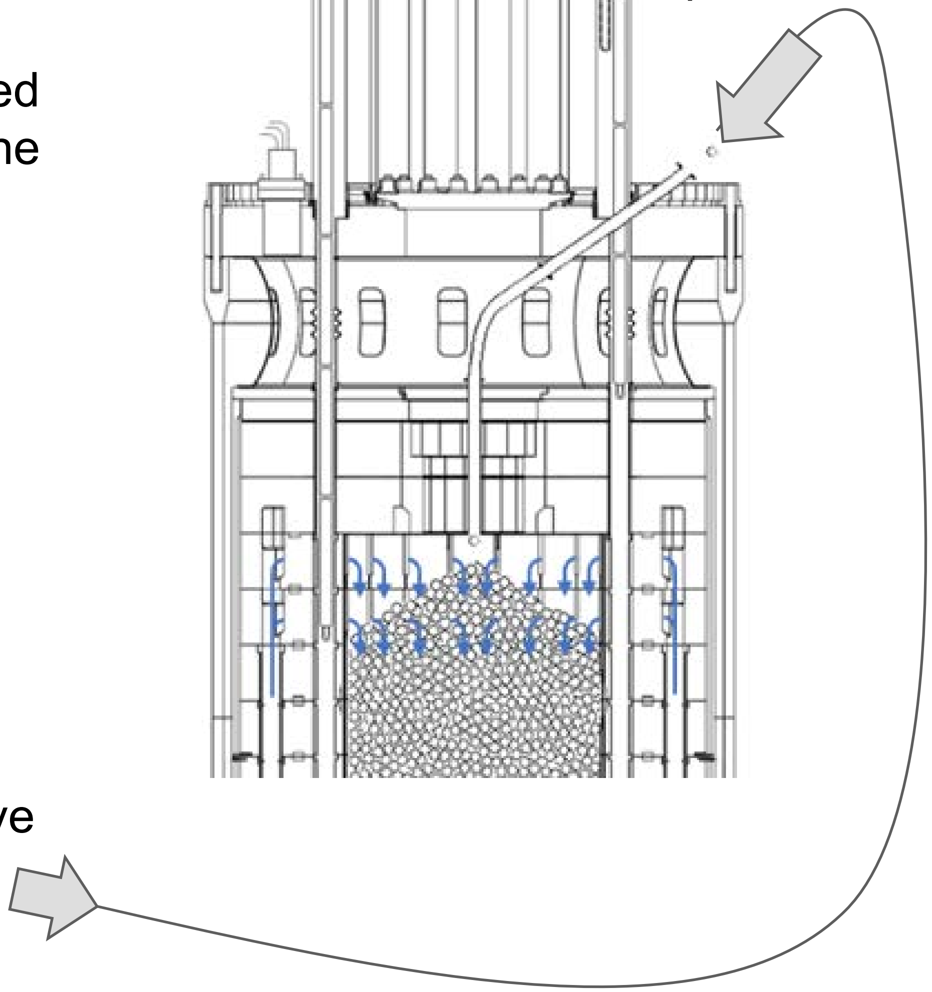


Pebble Flow in the Model

Single fuel loading location introduces a stochastic behavior (random placement) for the pebbles loaded to the core.

- Stochastic behavior is modeled by volume-weighted mixing of the pebbles removed from the bottom of the core (1) before they are loaded at the top (2)
- Mixing is done in terms of:
  - Isotopic content
  - Burnup
  - Fast fluence

(2) Returning pebbles



(1) Volume-weighted mixing of pebbles that have passed through the core

VSOP Calculations Supporting Safety Analysis

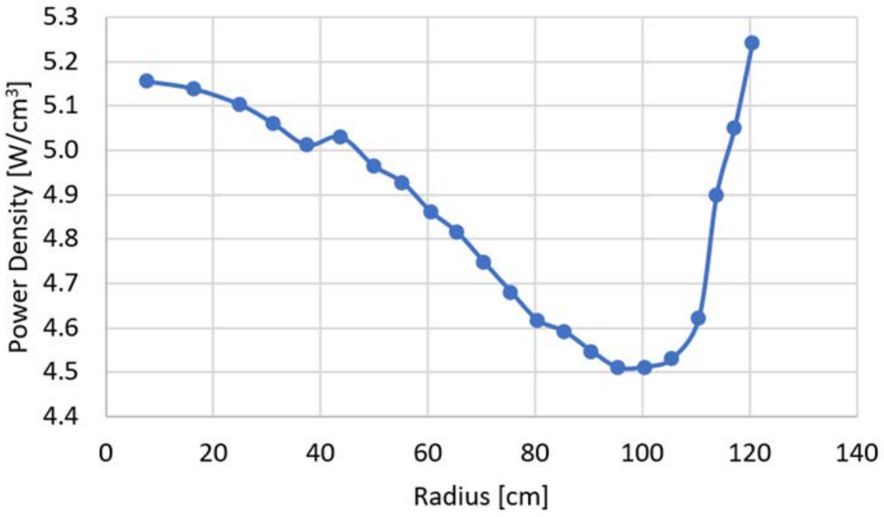
- Reactivity coefficients:
  - Fuel temperature coefficient
  - Moderator temperature coefficient
  - Reflector temperature coefficient
- Xenon feedback coefficients
- Control and shutdown element worth:
  - Integral worth
  - Differential worth
- Power distribution:
  - Peaking factor
  - Axial and radial power profile
- Kinetics parameters:
  - Delayed neutron fractions
  - Delayed neutron decay constants
  - Neutron mean generation time

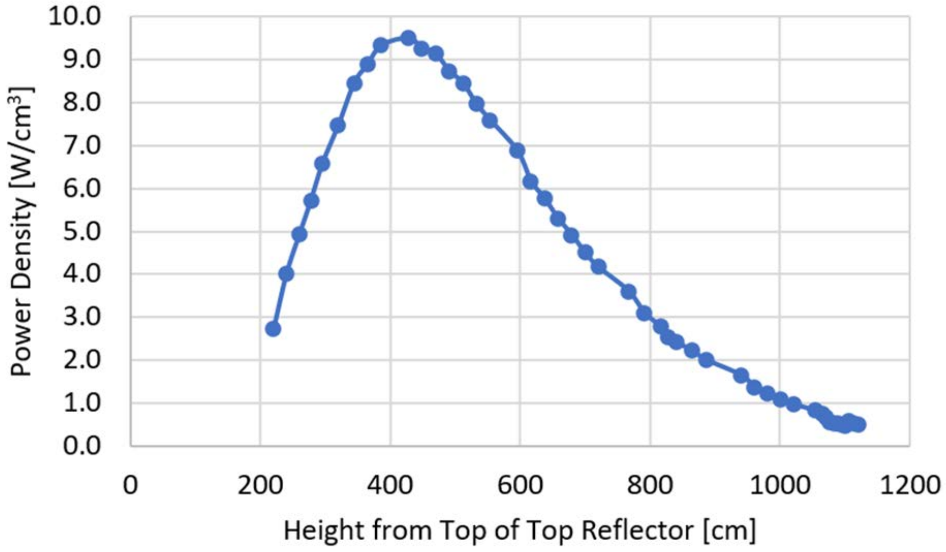
Typical Core Physics Results

Temperature Coefficients at 100% power

Fuel Temp. [°C]	Fuel Temp. Coefficient [pcm/°C]	Moderator Temp. [°C]	Moderator Temp. Coefficient [pcm/°C]	Reflector Temp. [°C]	Reflector Temp. Coefficient [pcm/°C]
662	-3.80	645	-1.62	329	2.50

Average Power Density Profiles – radial and axial





Reactor Core Design Analysis and Methods – Computer Codes

STAR-CCM+

Computational Fluid Dynamics (CFD) simulations:

- Models pebble flow characteristics through the core
- Constitutes an input into the VSOP code system
- Developed under an acceptable Quality Assurance Program

Pebble Flow

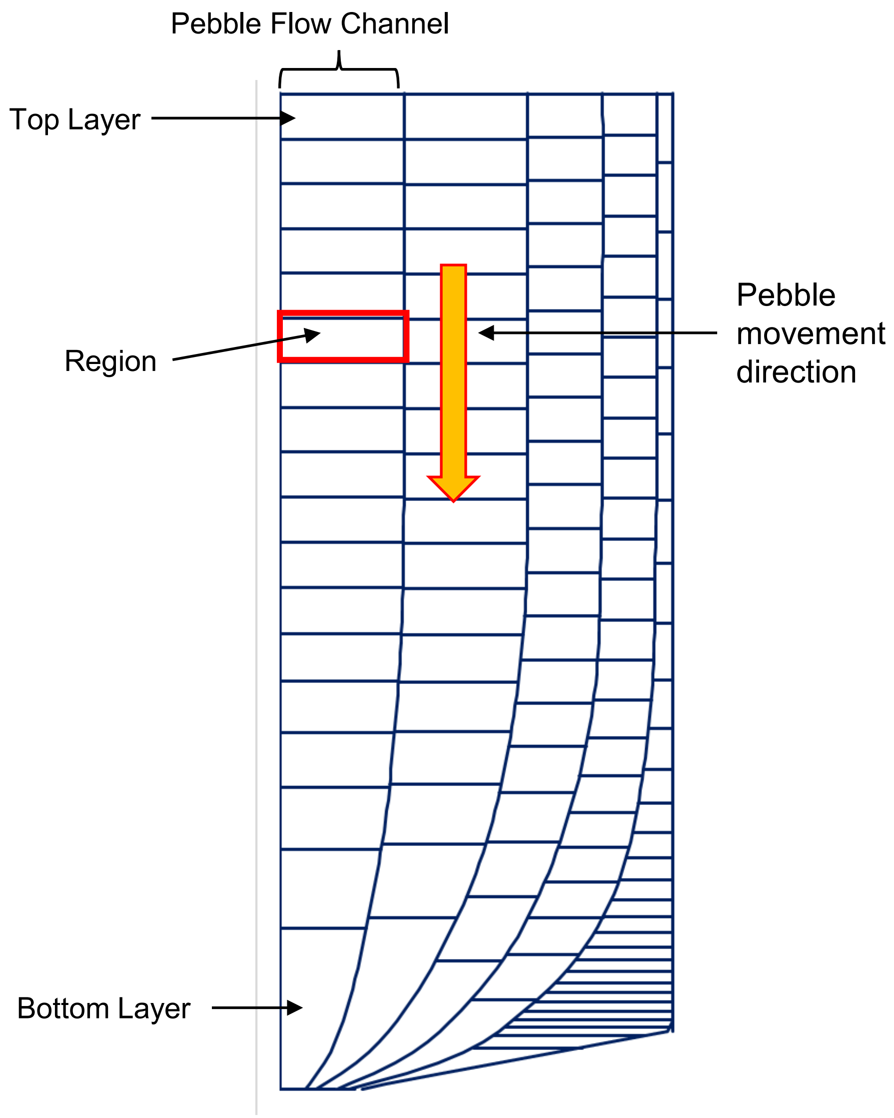
- Pebble flow velocity distribution is strongly influenced by:
  - Conical reflector bottom
  - Wall effects
- Pebble flow modeled in five radial flow channels, within each flow channel:
  - Pebble velocity viewed to be radially independent
  - Velocity in effect therefore means the velocity of the vertical components
  - The continuity equation holds:

$$\boldsymbol{M(r,z) = Q(r,z) \cdot v(r,z) = M(r)}, \quad \textit{where}$$

M = the volume flow

Q = the cross-sectional area

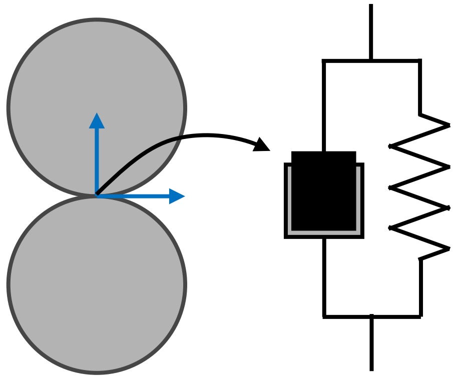
v = vertical velocity components



Pebble Flow

- Pebble movement through the core is influenced by:
  - Core geometry:
    - Modeled explicitly
    - 3-Dimensional CAD models of the core used as base
  - Contacting pebbles:
    - Modeled with spherical discrete elements using Discrete Element Method (DEM)
    - Each pebble has substance and cannot pass through walls or each other
  - Contact characteristics:
    - Friction coefficients
    - Restitution coefficients
    - Rolling resistances

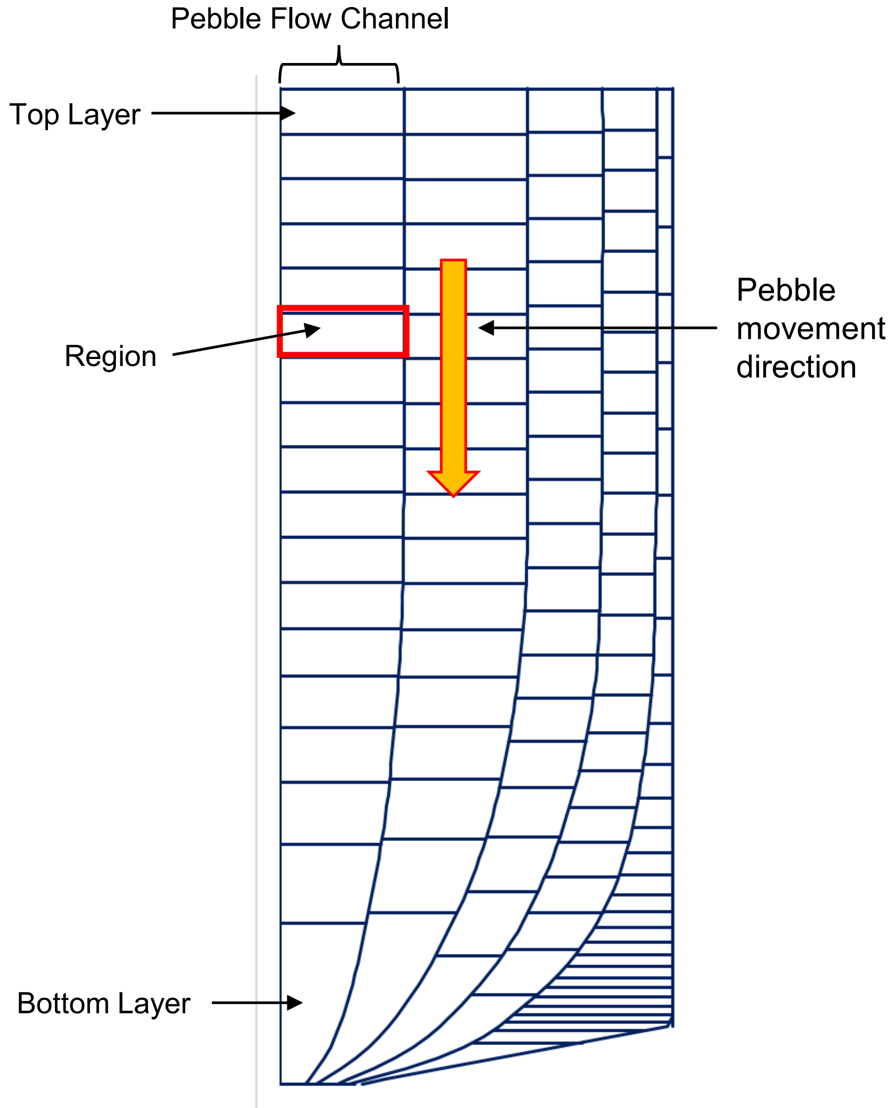
- Hertz-Mindlin contact model:
  - A spring-dashpot DEM contact model
  - Allows for inelastic collisions



- Force-proportional rolling resistance model:
  - Coupled to shapes
  - Spheres have a low resistance to rolling

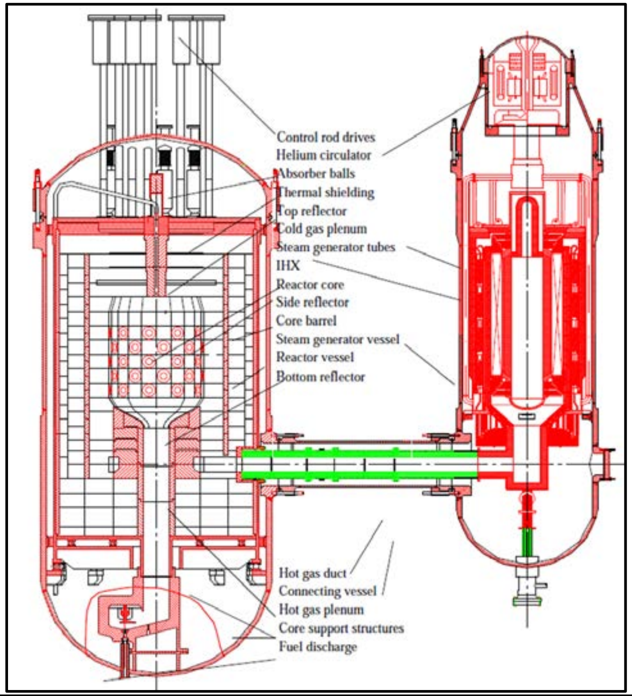
Pebble Flow

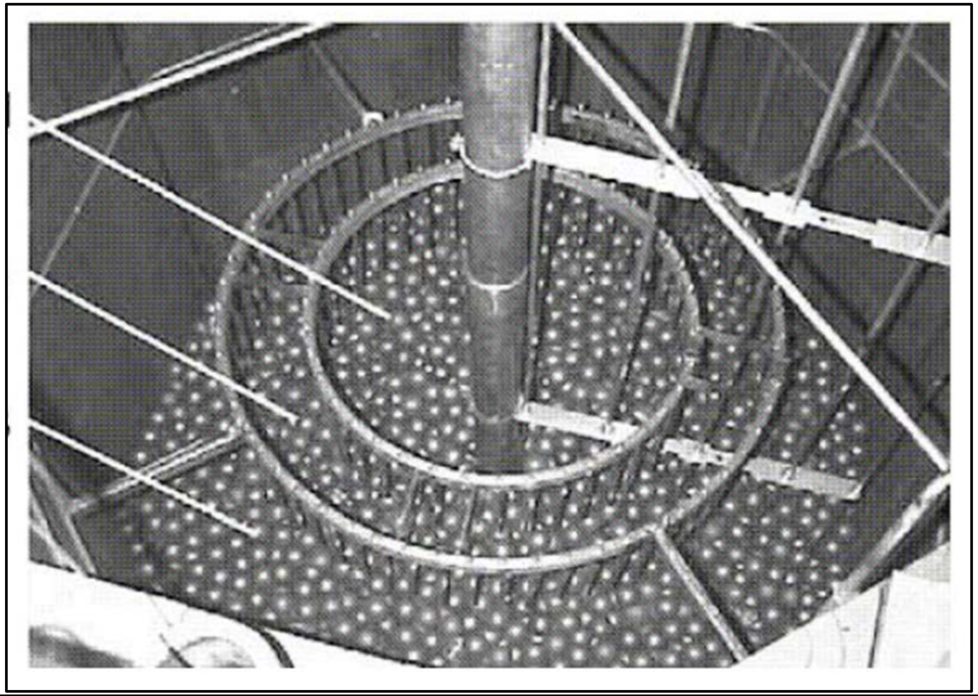
- Pebbles move at different velocities. Pebbles towards the center move faster than those adjacent to the reflector
- Pebble flow affects the core residence time of the pebbles, having a direct impact on burnup and, therefore:
  - Reactivity
  - Power profile
  - Core temperature
  - Decay heat
- **Average** residence time for a fuel pebble is about 3 years and varies somewhat between pebbles
- **Average** discharge burnup is 163 GWd/MTU

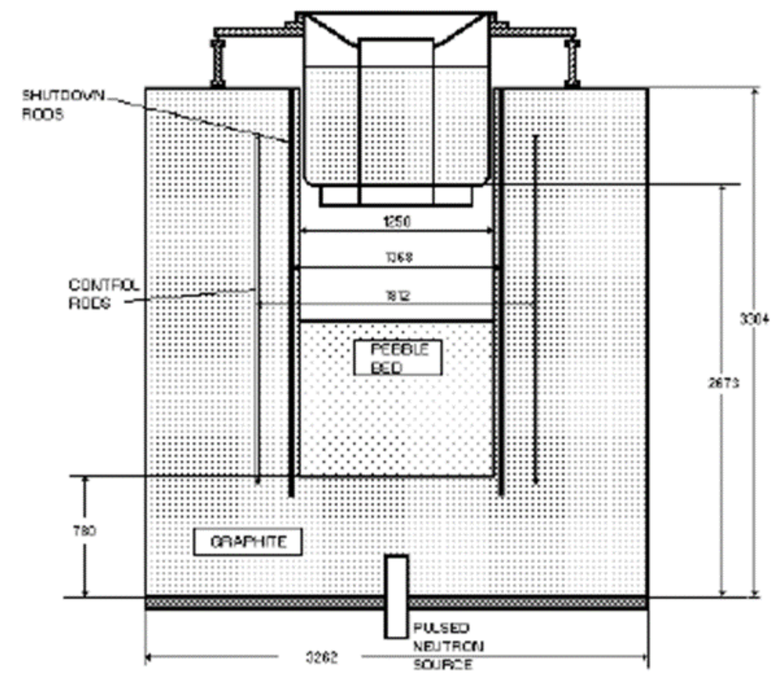


Code Validation | VSOP

- By comparison with experimental data from test facilities that apply to Xe-100 design and code-to-code benchmarks:
  - HTR-10 test reactor
  - ASTRA critical facility
  - HTR-PROTEUS critical experiments

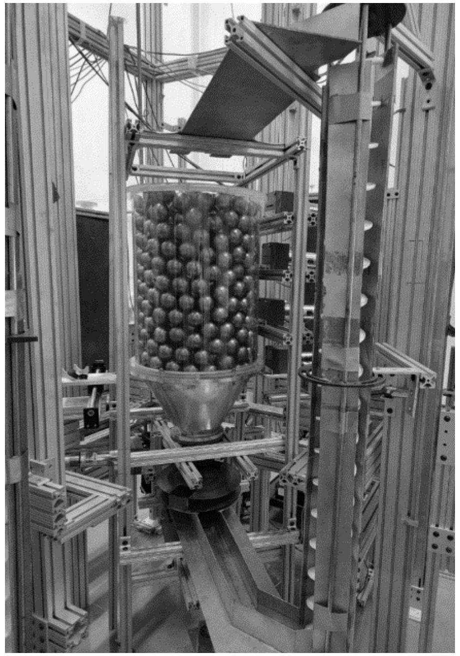


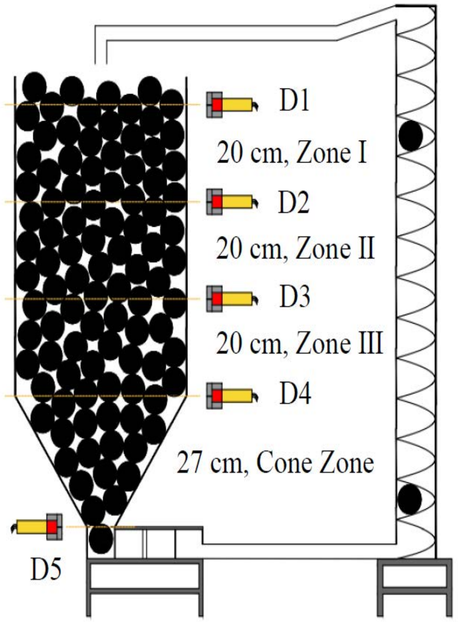




Code Validation | STAR-CCM+

- By comparison with experimental data from a physical model at Missouri University of Science and Technology
- Closest representative experiment of the Xe-100 core in terms of pebble movement
- The data is readily available and, since the experiment is ongoing, additional data can be acquired





Conclusions and Next Steps

X-Energy:

- Complete the validation and verification plans for VSOP and STAR-CCM+ and continue activities in accordance with the plans
- Update the LTR after all validation and verification activities have been completed and coordinate with the NRC staff for review and approval

NRC:

- After the LTR submittal, review for acceptance and approve the Xe-100 reactor core design and analysis methodology and the associated use of computer codes for use in future safety analysis reports (SARs) based on a preliminary Xe-100 design