Enclosure 1

Presentation Materials for the September 8, 2021 ACRS Meeting

(Non-Proprietary)

KP-FHR Fuel Performance Methodology Topical Report

KAIROS POWER

ACRS FULL COMMITTEE MEETING

SEPTEMBER 8, 2021

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Topical Report Contents

- Introduction
- Fuel Behavior (including PIRT analysis)
- Fuel Modeling
- Verification and Validation / Uncertainty Quantification
- KP-BISON Code
- Fuel Performance Analysis Methodology

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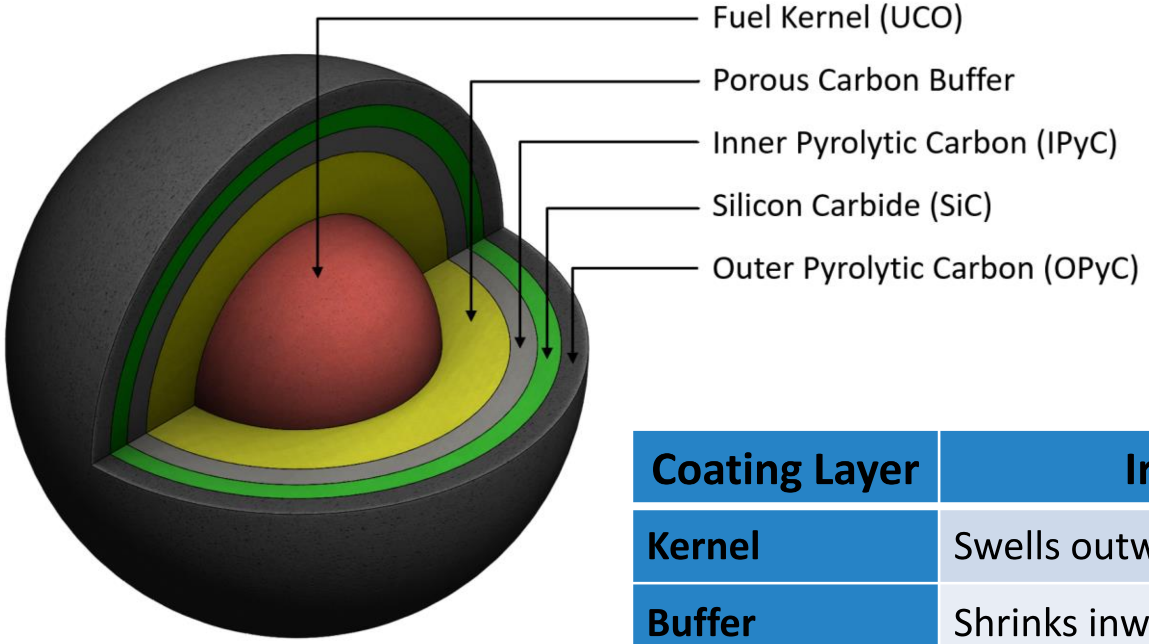
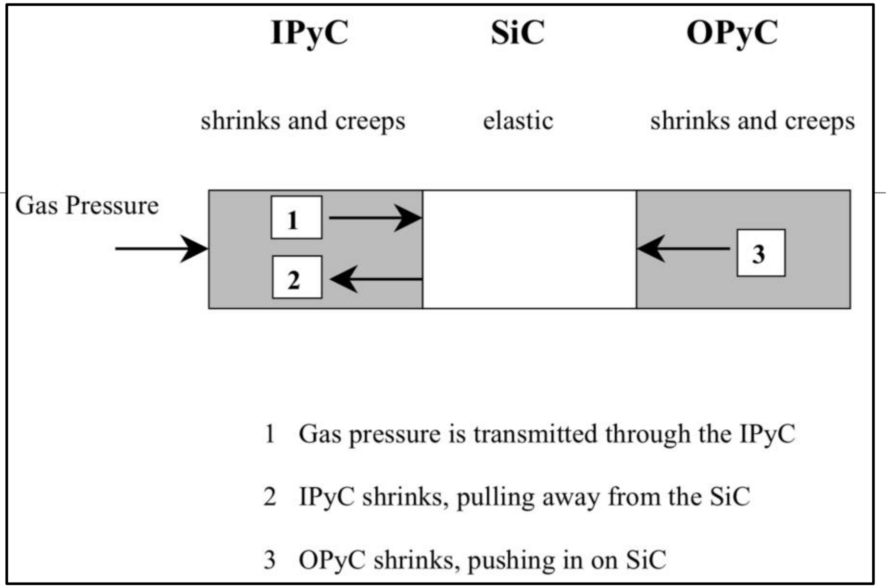
UCO TRISO Fuel Behavior





Coating Layer	Irradiation Behavior	Observation
Kernel	Swells outward	Pushes buffer outward
Buffer	Shrinks inward	Pulls IPyC inward if not debonded
IPyC / OPyC	Shrink early during irradiation and then start swelling later in irradiation as fast neutron fluence accumulates Dimensional changes are anisotropic	Swelling starts radially at moderate fast neutron fluence levels and tangentially at higher fast neutron fluence levels
SiC	Elastic behavior	PyC shrinkage provides compressive stress Fission gas pressure causes tensile stress

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UCO TRISO Fuel Behavior – Failure Mechanisms

Key failure mechanisms identified in TRISO fuel

- Pressure vessel failure of spherical or aspherical particles resulting in the failure of all three coating layers
- Cracking of the IPyC layer leading to SiC failure
- Partial debonding of the IPyC from the SiC leading to SiC failure
- Kernel migration towards the SiC layer and its subsequent failure
- Chemical attack of the SiC layer by fission products or CO leading to its failure
- Thermal decomposition of the SiC layer at high temperatures
- Buffer fracture leading to cracking of undebonded IPyC

KP-BISON models failure mechanisms relevant to UCO fuel under KP-FHR irradiation conditions with the purpose of predicting the potential failure of the SiC layer and the release of fission products.

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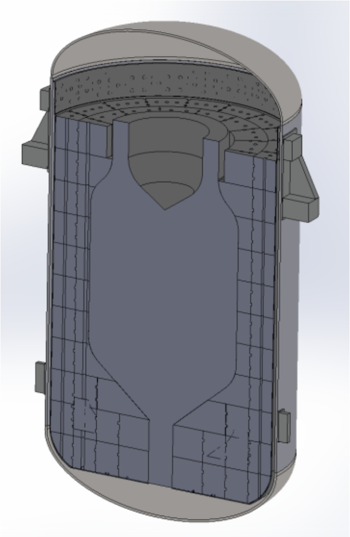
UCO TRISO Fuel Performance Modeling – KP-BISON

Kairos Power

Idaho National Laboratory

NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

UCO TRISO Model in BISON



- Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)
- UCO TRISO Fuel

BISON

MOOSE
Multiphysics Object-Oriented Simulation Environment

Engineering-scale nuclear fuel performance code

- Finite-element modeling of LWR, TRISO, and metal fuels in 1D-spherical, 2D-axisymmetric, and 3D geometries
- Fully-coupled thermodynamics and species diffusion equations
- Steady and transient reactor operations

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UCO TRISO Fuel Performance Modeling – KP-BISON

KP-BISON was chosen as Fuel Performance Code by Kairos Power

- Computational benefits from the MOOSE (Multiphysics Object-Oriented Simulation Environment) framework
- Leverage of extensive development effort by INL (Idaho National Laboratory) and NEAMS (Nuclear Energy Advanced Modeling & Simulation Program)
- Level of development and maturity of BISON code
  - Co-development KP-INL
  - FOA award DE-NE0008854 *Modeling and Simulation Development Pathways to Accelerating KP-FHR Licensing*
- Efficient support from development and maintenance team ("BISON Team") at INL

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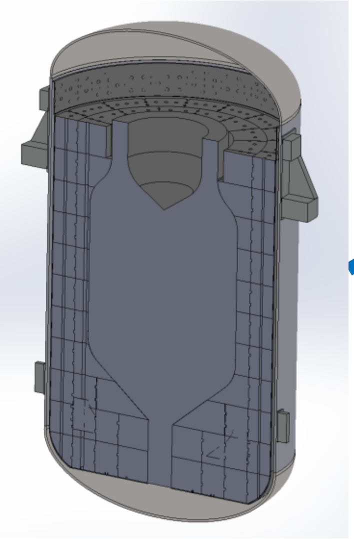
KP-BISON – Inputs & Outputs

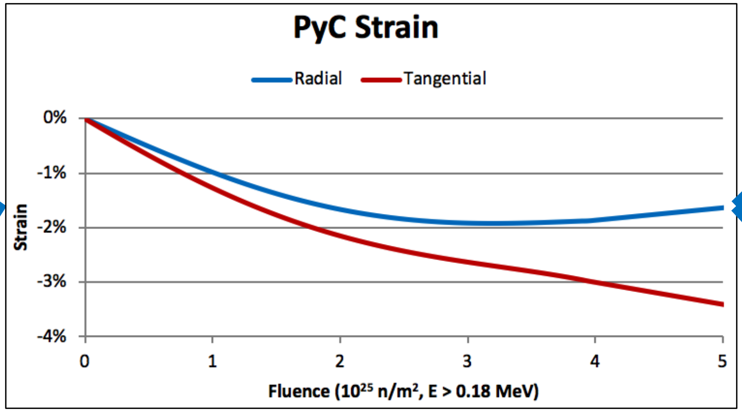
Geometry
- radius, thickness, etc.

Fuel characteristics
- composition, densities, etc.

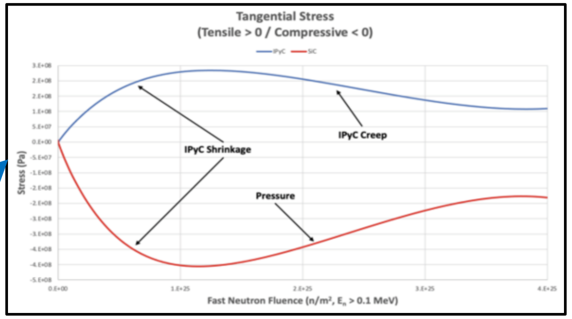
Variation in as-fabricated properties



Irradiation conditions
- Fission rate density
- Fast fluence
- Coolant temperature



Material properties implemented in KP-BISON



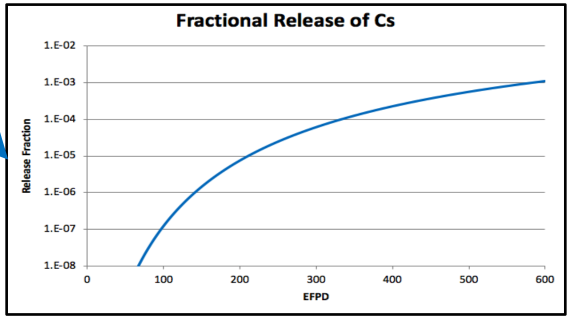
Fuel temperature, fission gas pressure, displacements, stress

⇩

Figures of Merit (FOMs)

Failure probability

Fission product release



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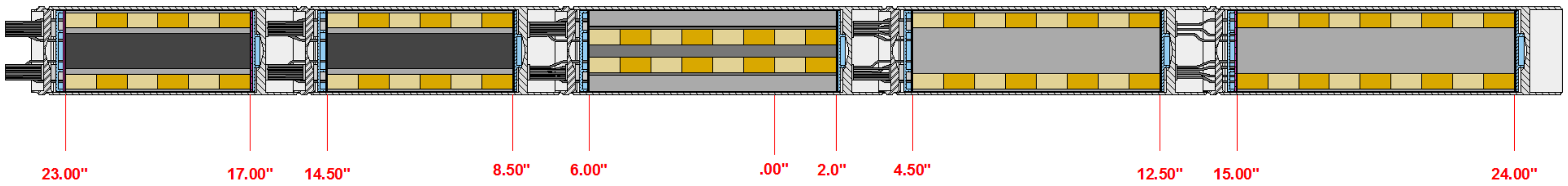
KP-BISON – Fuel Properties

Leverage of extensive DOE effort in the development and qualification of UCO TRISO fuel (AGR Program)

KP-FHR UCO TRISO fuel is similar to AGR UCO TRISO fuels

- AGR-2 -> *UCO TRISO-Coated Particle Fuel Performance* - Topical Report EPRI-AR-1(NP)-A
- AGR-5/6/7 -> AGR Program's UCO TRISO fuel qualification and margin tests



AGR-5/6/7 Test Train – Courtesy of AGR Program

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KP-BISON – Material Properties & Physical Models

TRISO Constituents	Material Properties
Kernel Buffer IPyC SiC OPyC	Swelling Elastic modulus Poisson's ratio Irradiation-induced creep Poisson's ratio in creep Irradiation-induced dimensional changes Thermal conductivity Specific heat capacity Thermal expansion Diffusion coefficients

Existing database of material properties and physical models suited to modeling of TRISO fuel behavior and performance

Physical Models	Description
Heat Equation	Thermal state of the particle and temperature profile across the kernel and coating layers
Fission yields	Generation of fission products
Fission gas release	Generation of internal pressure
Internal gas pressure	Stress state of the particle potentially leading to its failure
Palladium penetration	Corrosion of the SiC layer potentially leading to its failure
Release rate over birth rate (R/B) ratio	Indicator of TRISO failure
Fission product transport (Fickian diffusion)	Release of fission products to the coolant

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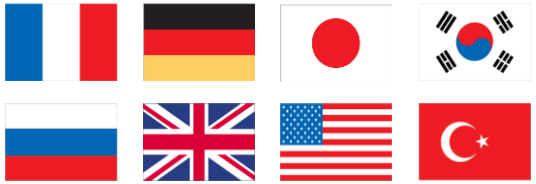
Verification & Validation

INL Benchmark International Data

- Code-to-code comparison with PARFUME
  - Representative cases of KP-FHR
- AGR-1 and AGR-2 PIE and AGR-5/6/7 R/B data
  - Select data within KP-FHR envelope
  - Separate effects
- Additional PIE or R/B data
  - German, Chinese, etc.

IAEA CRP-6 Benchmark



- Fuel Performance Models During Normal Operation And Operational Transients
  - Verification: cases 1-13
- Fission Product Release Behavior Models Under Accident Conditions
  - Verification: cases 1-5
  - Validation: cases 6-11

Gen-IV Benchmark

- TRISO Fuel Performance Models Under Accident Conditions
  - Select AGR-1, AGR-2, and HFR-EU1bis safety tests
  - Includes code-to-code comparison during normal operation

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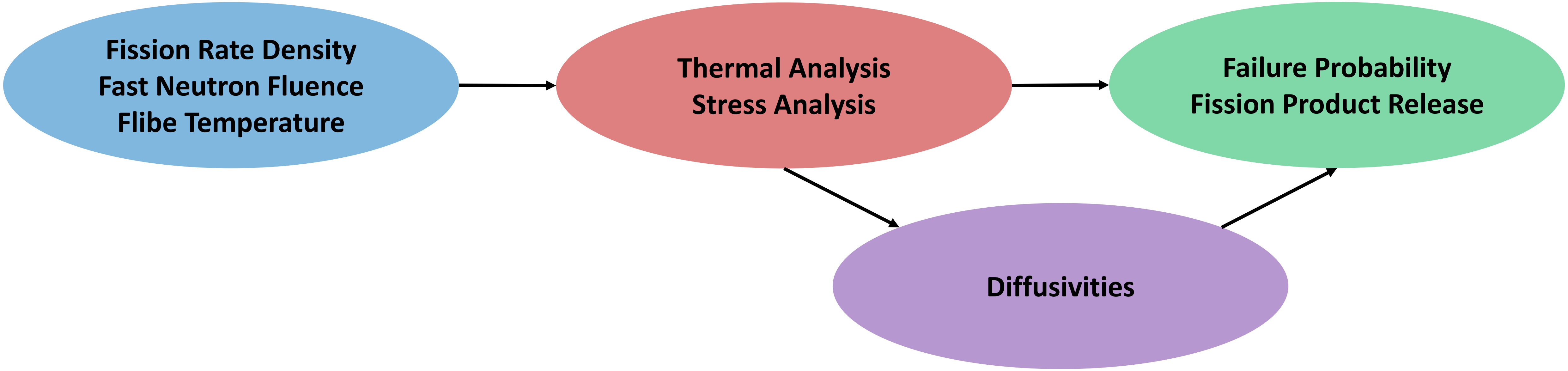
Fuel Performance Analysis Methodology

For each TRISO particle

- Irradiation input parameters
- Thermo-mechanical analysis of the TRISO coating layers
- Evaluation of the failure probability (stress) and fission product release (diffusivities)



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Statistical Treatment

- Particle-to-particle statistical variations in physical dimensions and fuel properties (layer thickness, density, etc.) that arise from the fuel fabrication process.

- Particles in the tails of the statistical distributions are more prone to failure.

⇒ statistical treatment of a large population of particles to compute its overall failure probability.

⇒ Monte Carlo computation scheme implemented in KP-BISON

Property	Specified Mean Value
Kernel diameter (μm)	425 ± 10
Buffer thickness (μm)	100 ± 15
PyC thickness (μm)	40 ± 4
SiC thickness (μm)	35 ± 3
Kernel density (g/cm³)	≥ 10.4
Buffer density (g/cm³)	1.05 ± 0.10
PyC density (g/cm³)	1.90 ± 0.05
SiC density (g/cm³)	≥ 3.19
C/U atomic ratio	0.40 ± 0.10
O/U atomic ratio	1.50 ± 0.20
PyC BAF	≤ 1.045
SiC aspect ratio	1.04

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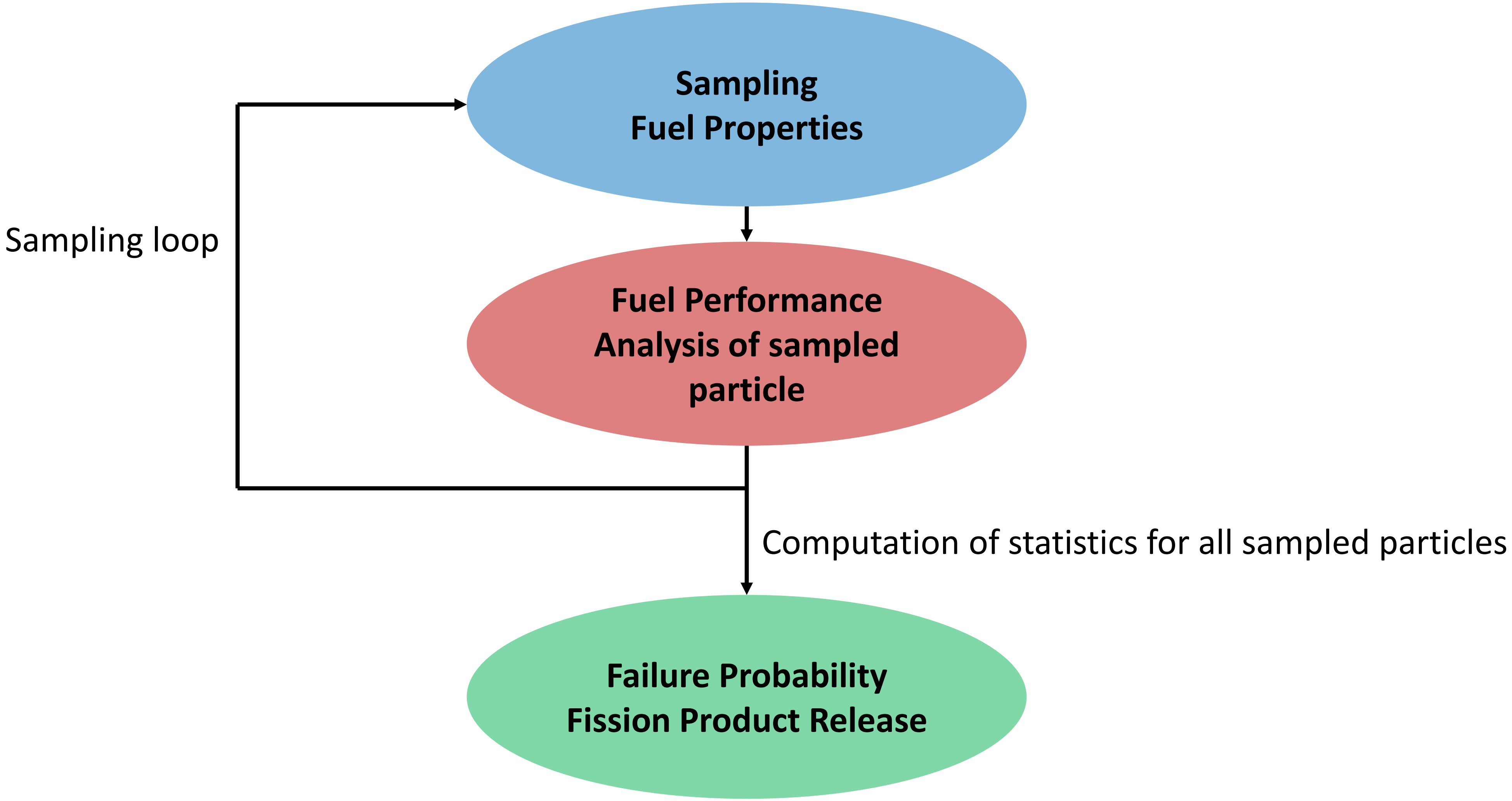
Monte Carlo Calculation Scheme



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Uncertainty Quantification

Uncertainty exists in:

- Operating conditions (i.e., fission rate density, neutron flux, temperature)
- Material properties that define the mechanical state of the TRISO particles and, ultimately, the integrity of the coating layers
- Physical models that determine some of the physical quantities affecting material properties and fission product transport
- Fuel properties (geometrical dimension, density, etc.) that are tailored by fuel fabrication to obtain TRISO particles that adequately perform under irradiation

⇒ sensitivity studies will be conducted to assess the quantitative impact of the variations of these input parameters to the probability of failure of the TRISO particles and subsequent release of fission products.

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Uncertainty Quantification Methodology

A proprietary methodology was developed to ensure that the probability of failure of the TRISO particles and subsequent release of fission products are calculated conservatively.

In particular, the methodology derives one-sided 95/95 tolerance limits on the two FOMs.

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