Massachusetts Institute of Technology
Department of Nuclear Engineering
Advanced Reactor Technology Pebble Bed Project

Recent Predictions on NPR Capsules by Integrated Fuel Performance Model

Jing Wang
Advisors: Prof. R. Ballinger & Prof. S. Yip
Sponsor: Idaho National Engineering Lab.
July 19, 2002

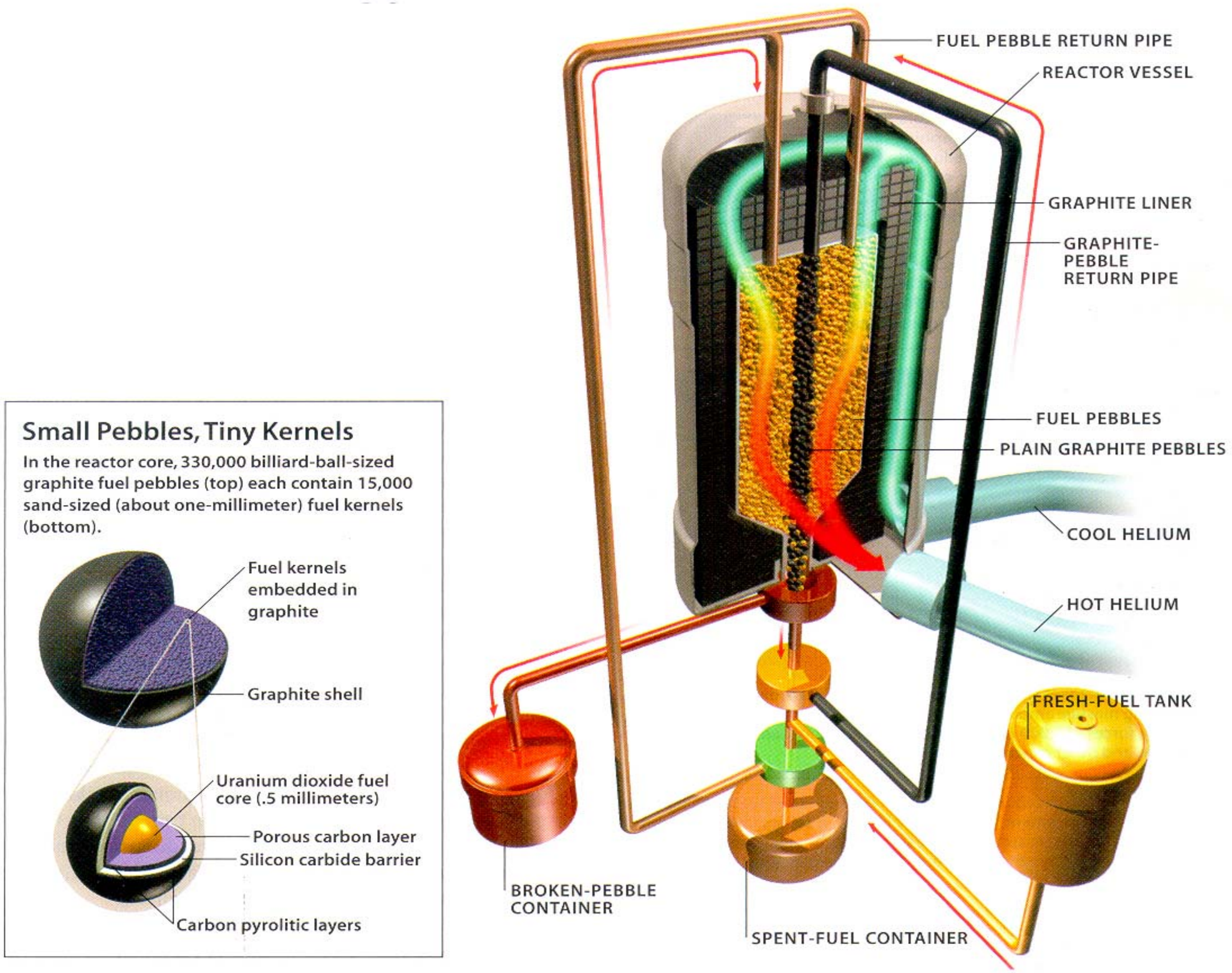
MIT Nuclear Engineering Department

Outline

- ☐ Overview of Integrated Fuel Performance Model
- ☐ Predictions on NPR Capsules

Integrated Fuel Performance Model

Pebble Bed Reactor and TRISO Fuel

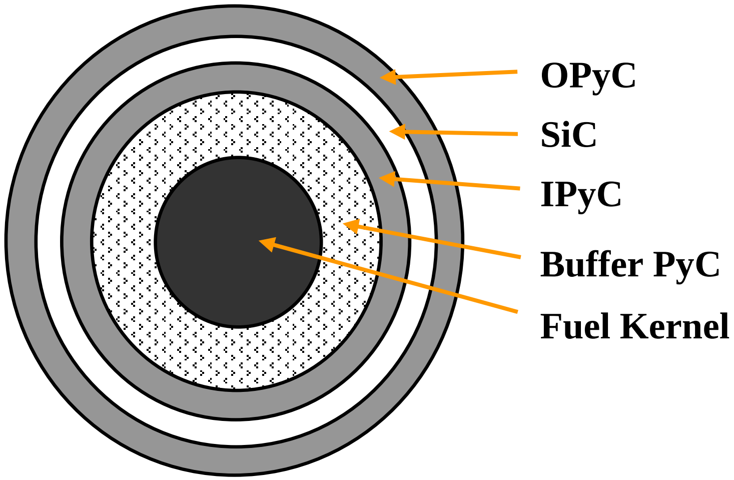


Small Pebbles, Tiny Kernels

In the reactor core, 330,000 billiard-ball-sized graphite fuel pebbles (top) each contain 15,000 sand-sized (about one-millimeter) fuel kernels (bottom).

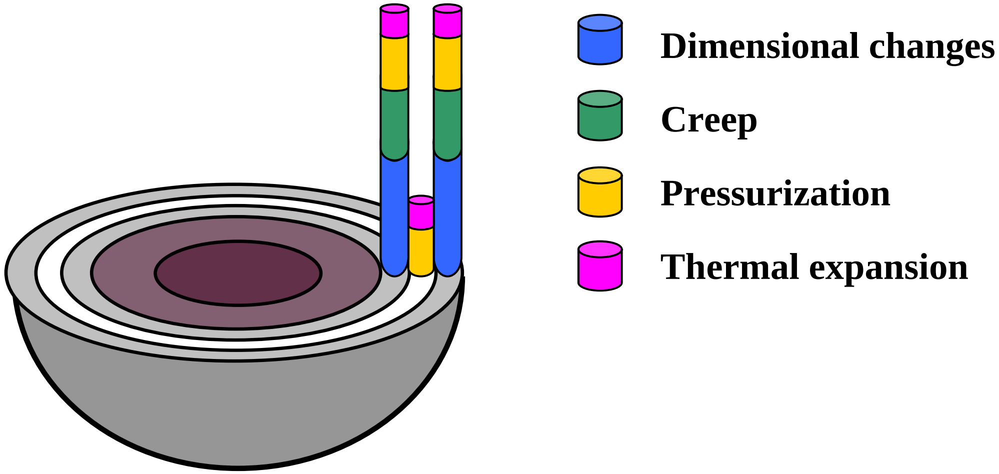
Modules in the Integrated Model

- Fission gas release model
- Thermal model
- Mechanical analysis
- Chemical analysis
- Fuel failure model
- Simulation of refueling in the reactor core



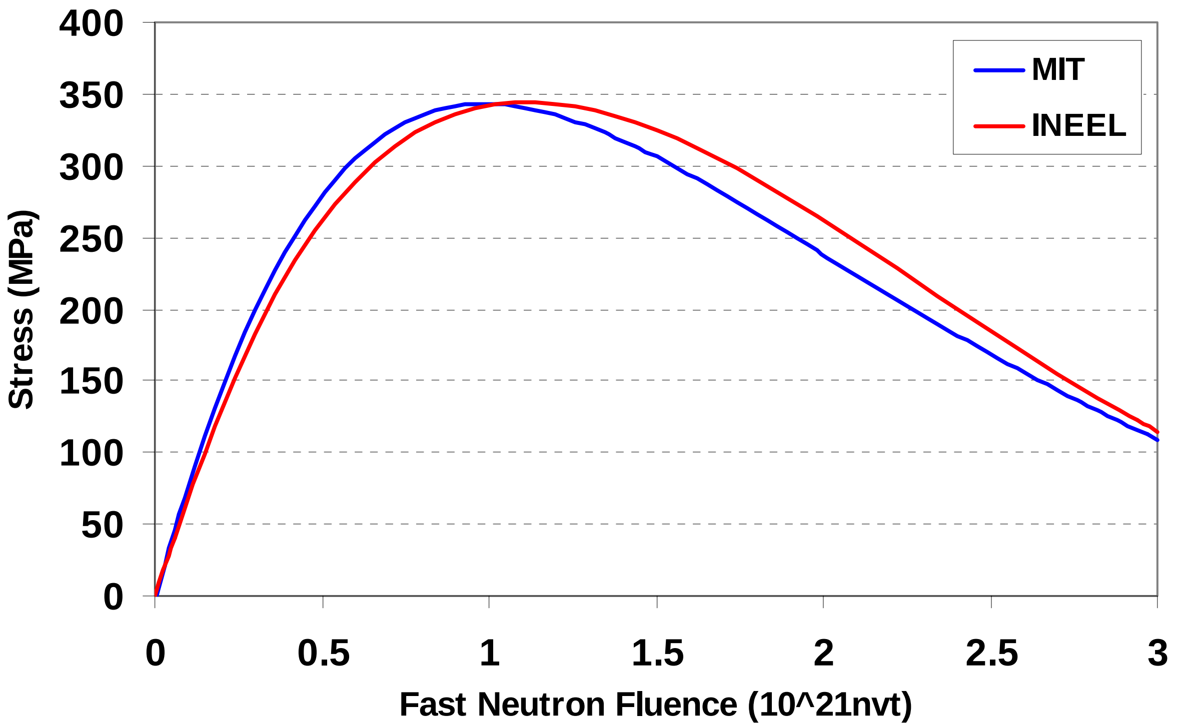
Mechanical Analysis

- **System: IPyC/SiC/OPyC**
- **Methods: Analytical or Finite Element**
- **Viscoelastic Model**
- **Mechanical behavior**
  - **irradiation-induced dimensional changes (PyC)**
  - **irradiation-induced creep (PyC)**
  - **pressurization from fission gases**
  - **thermal expansion**



Stress contributors to IPyC/SiC/OPyC

Benchmarking Stress Calculations on NPR Type Fuel



Stresses in isotropic IPyC under constant temperature 1032°C

Weibull Strength Theory

$$P_f = 1 - e^{-\int (\sigma / \sigma_0)^m \, dV}$$

σ_0 – characteristic strength (MPa.meter$^{3/m}$)

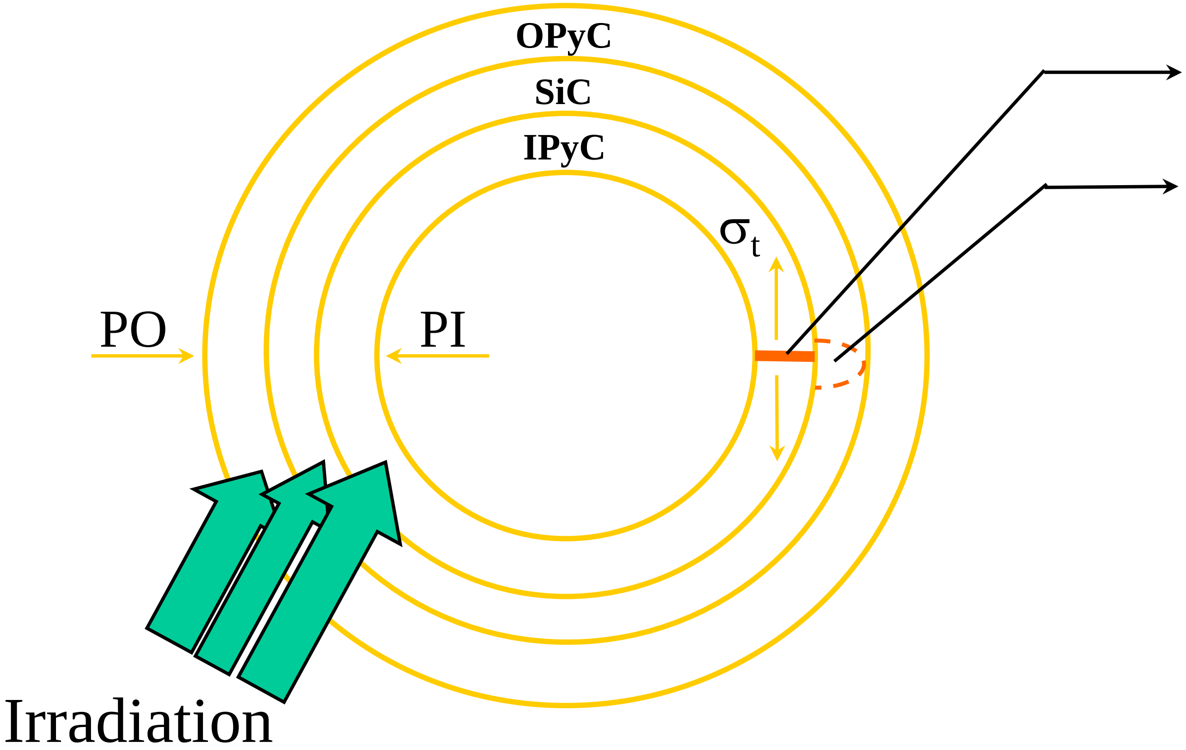
m – Weibull modulus

$$P_f = 1 - e^{-\left(\bar{\sigma} / \sigma_{mf}\right)^m}$$

σ_{mf} – mean fracture strength (MPa)

applicable when microscopic cracks prevail

Fracture Mechanics Based Failure Model

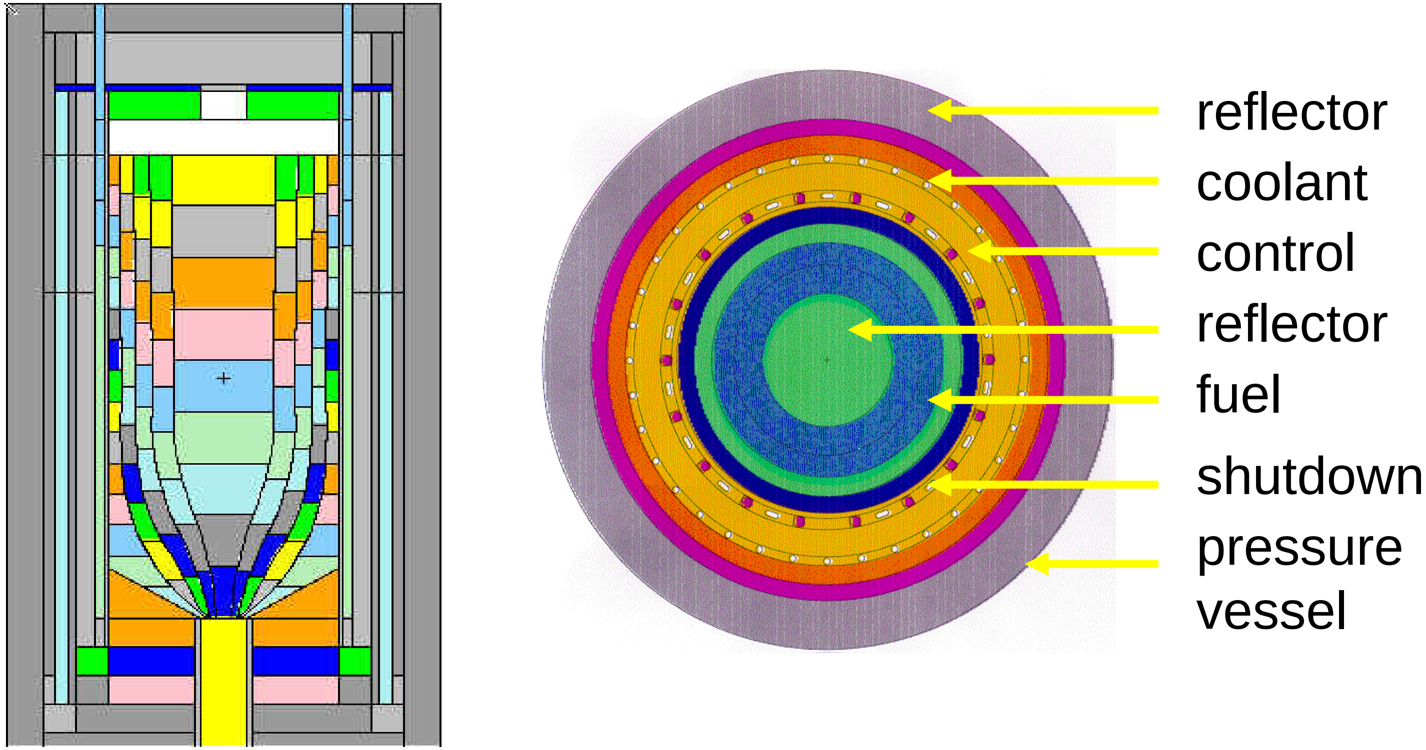


$$K_I(IPyC) = y\sigma_t\sqrt{\pi a}$$

$$K_{IC}(SiC)$$

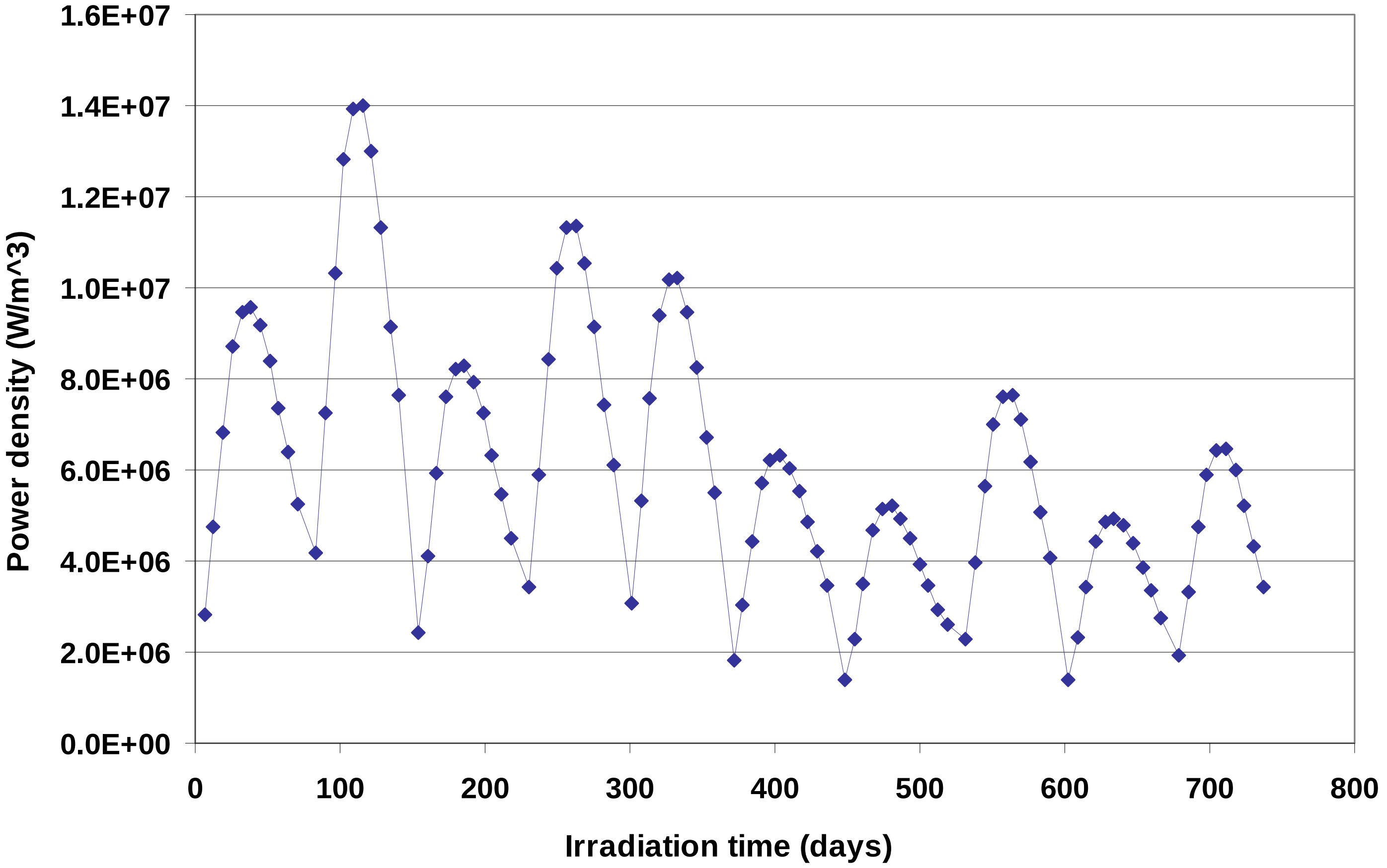
applied when macroscopic crack presents

Simulation of Refueling through Non-isothermal MPBR Core



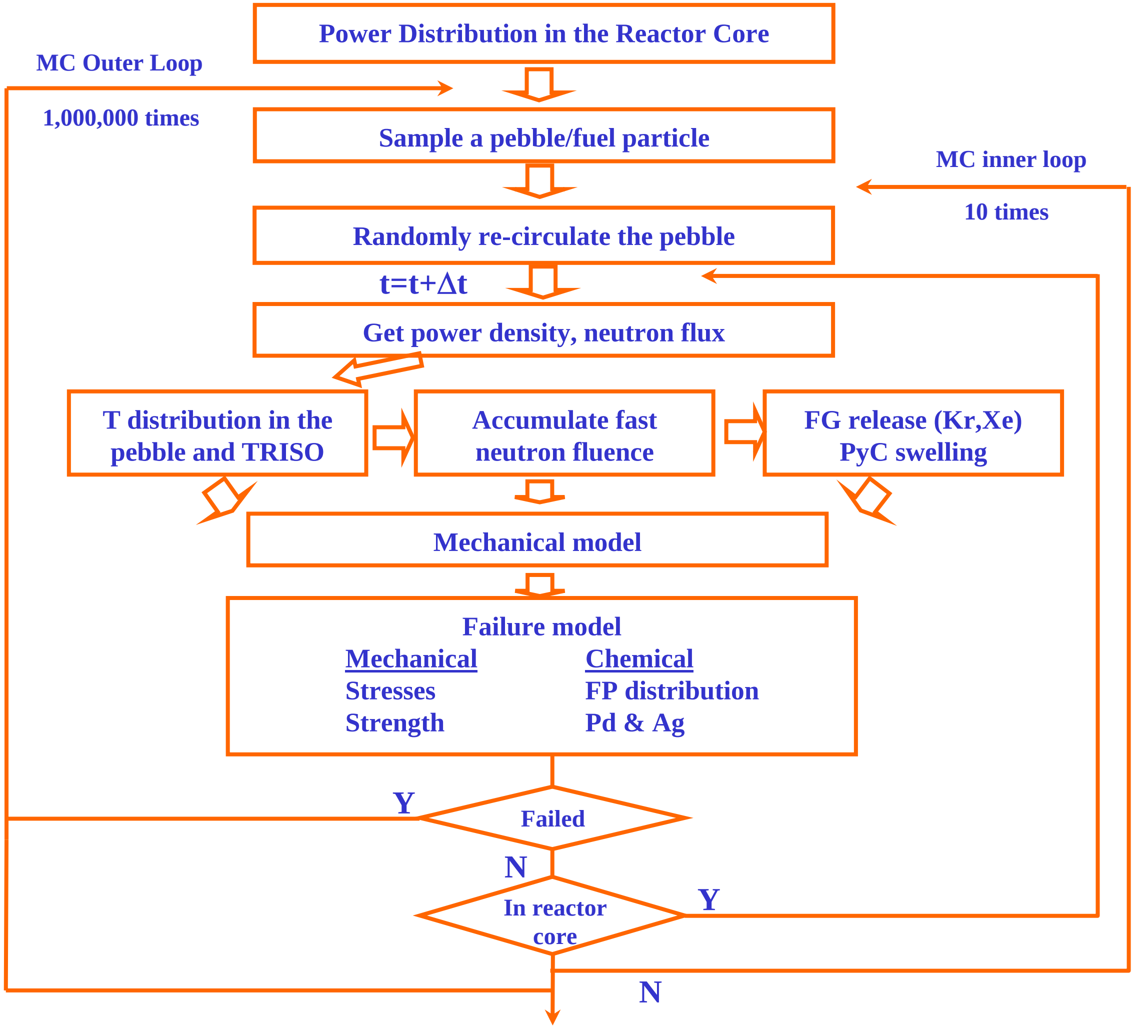
VSOP Model of MPBR core

Simulation of Refueling - cont'd



A typical power history of a pebble in MPBR core

Integrated Fuel Performance Model



Power Distribution in the Reactor Core

MC Outer Loop

1,000,000 times

Sample a pebble/fuel particle

MC inner loop

10 times

Randomly re-circulate the pebble

$t=t+\Delta t$

Get power density, neutron flux

T distribution in the pebble and TRISO

Accumulate fast neutron fluence

FG release (Kr,Xe)
PyC swelling

Mechanical model

Failure model

Mechanical	Chemical
Stresses	FP distribution
Strength	Pd & Ag

Failed

Y

N

In reactor core

Y

N

Monte Carlo outer loop:

Samples fuel particle statistical characteristics

MC inner loop:

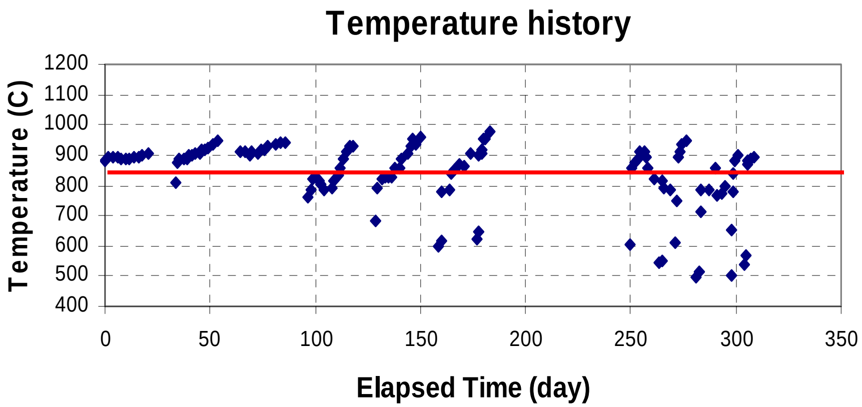
Implements refueling scheme in reactor core

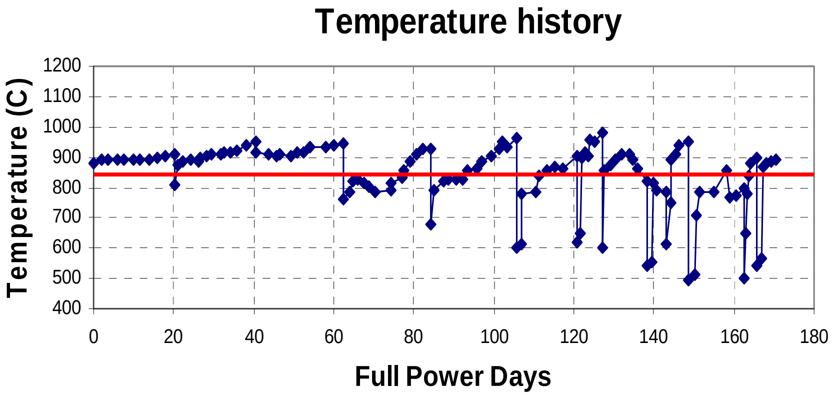
Predictions on NPR capsules

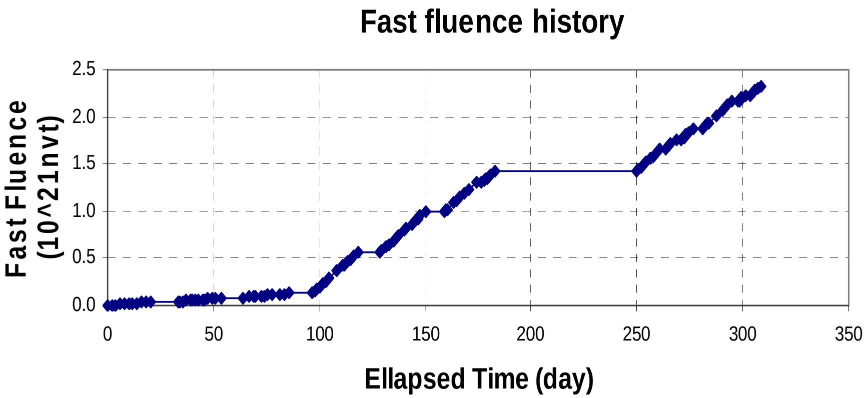
Typical NPR Particle Parameters

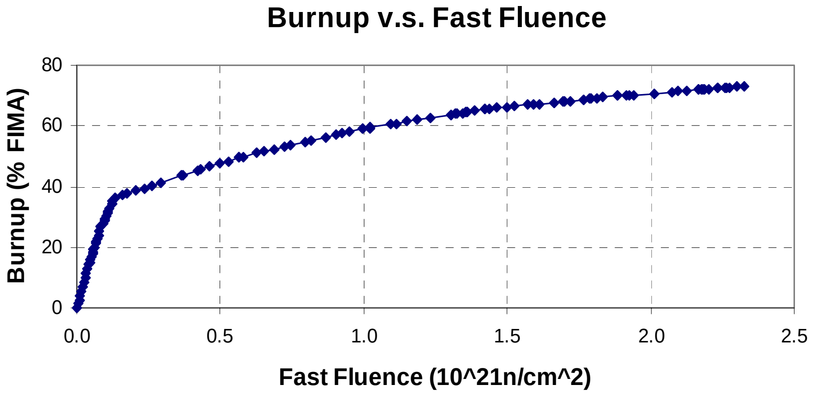
	Mean Value	Std. Deviation	Distr. Type
Kernel Diameter (μm)	195	5.20	Triangular
Buffer Thickness (μm)	100	10.2	Triangular
IPyC Thickness (μm)	53	3.68	Triangular
SiC Thickness (μm)	35	3.12	Triangular
OPyC Thickness (μm)	43	4.01	Triangular
Fuel Density (g/cm^3)	10.52	0.01	Triangular
Buffer Density (g/cm^3)	0.9577	0.05	Triangular
IPyC σ_0 (MPa.meter$^{3/m}$)	24.4	9.5 (modulus)	Weibull
OPyC σ_0 (MPa.meter$^{3/m}$)	20.1	9.5 (modulus)	Weibull
SiC σ_0 (MPa.meter$^{3/m}$)	9.64	6.0 (modulus)	Weibull
SiC K_{IC} (MPa. μm$^{1/2}$)	3300	530	Triangular

Example of Compact Irradiation History









NPR-1 A8

Fuel Failure Predictions

Irradiation Conditions

Fuel Compact ID	Fast Fluence (10^{25} n/m^2)	Irradiation Temp. (°C)	Burnup (%FIMA)
NPR-2 A4	3.8	746	79
NPR-1 A5	3.8	987	79
NPR-1 A8	2.4	845	72
NPR-1A A9	1.9	1052	64

IPyC Layer *

	% Failed	95% Conf. Interval (%)	INEEL Calc.	MIT Calc.
NPR-2 A4	65	$54<p<76$	100	99.6
NPR-1 A5	31	$17<p<47$	100	26.6
NPR-1 A8	6	$2<p<16$	100	60.7
NPR-1A A9	18	$5<p<42$	100	23.9

SiC Layer *

	% Failed	95% Conf. Interval (%)	INEEL Calc.	MIT Calc.
NPR-2 A4	3	$2<p<6$	8.2	13.9
NPR-1 A5	0.6	$0<p<3$	1.6	0.358
NPR-1 A8	0	$0<p<2$	4.9	2.74
NPR-1A A9	1	$0<p<5$	0.9	0.492

(*: layer failure is considered as a through wall crack as measured by PIE.)

Systematic Study on NPR-1 Capsule

NPR-1 R/B of Selected Fission Gases

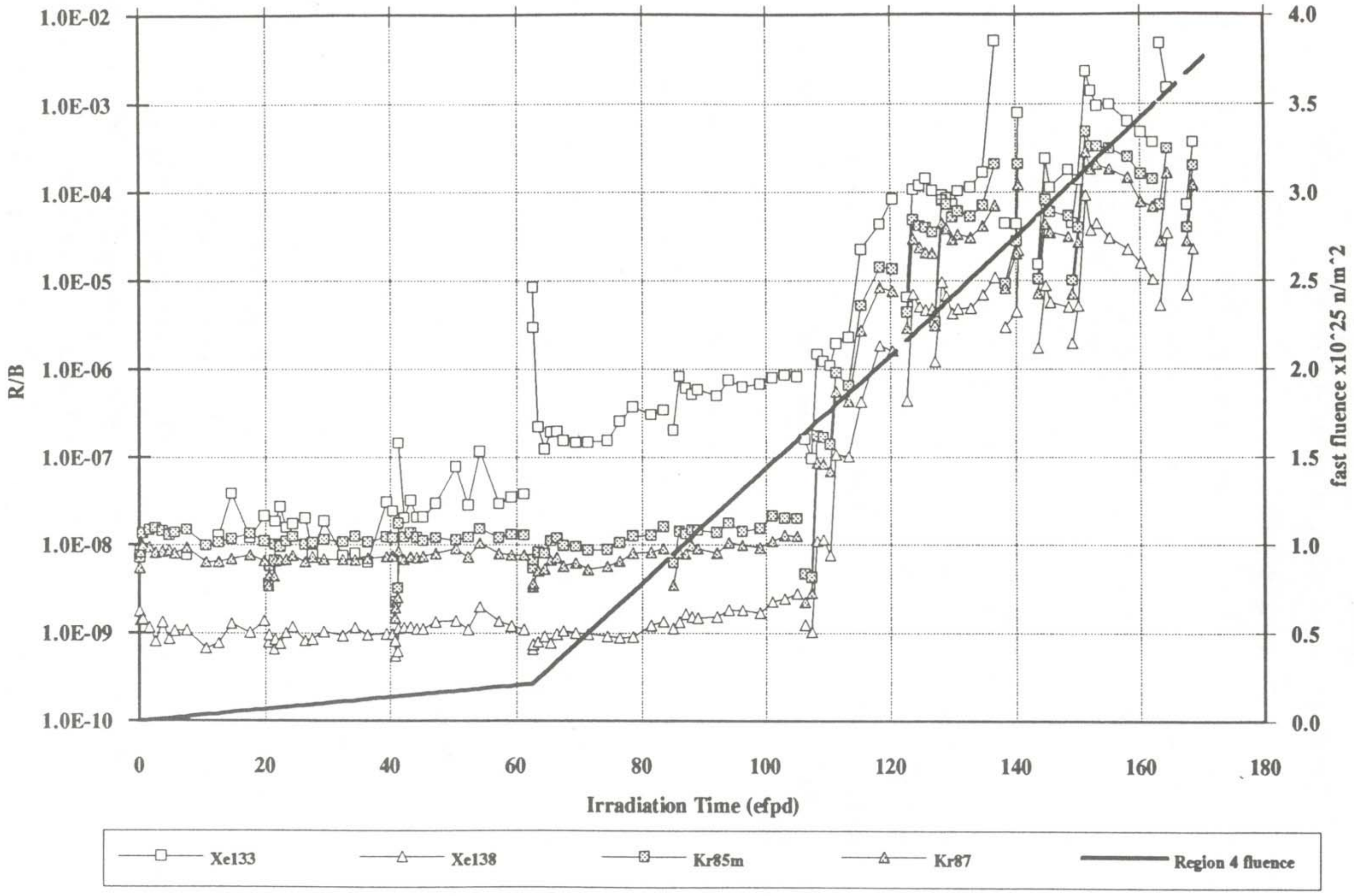


Figure 4.4-2. NPR 1 R/B of selected fission gases and estimated region 4 compact fast fluence as a function of efpd.

Irr. Conditions for NPR-1 Compacts

Compact ID	A1	A2	A3	A4	A5	A6	A7	A8
EOL Fluence (10^{21}n/cm^2)	2.4	3.0	3.5	3.8	3.8	3.5	3.0	2.4
EOL Burnup (% FIMA)	74.0	77.0	78.5	79.0	79.0	78.5	77.0	74.0
Avg. Irr. T (C)	874	1050	1036	993	987	1001	1003	845
EFPD (Day)	170.0							
Irradiation Time (Day)	308.3							

Prediction of Failures /w Real Irr. History

Compact ID	A1	A2	A3	A4	A5	A6	A7	A8
IPyC Failure	47.38%	6.440%	14.99%	33.54%	26.61%	24.43%	15.64%	60.70%
OPyC Failure	3.87%	0.262%	0.461%	1.91%	1.14%	1.00%	0.548%	6.13%
Particle Failure	1.61%	0.0001%	0.025%	0.857%	0.358%	0.272%	0.068%	2.74%

Prediction of Failures /w Ideal Irr. History

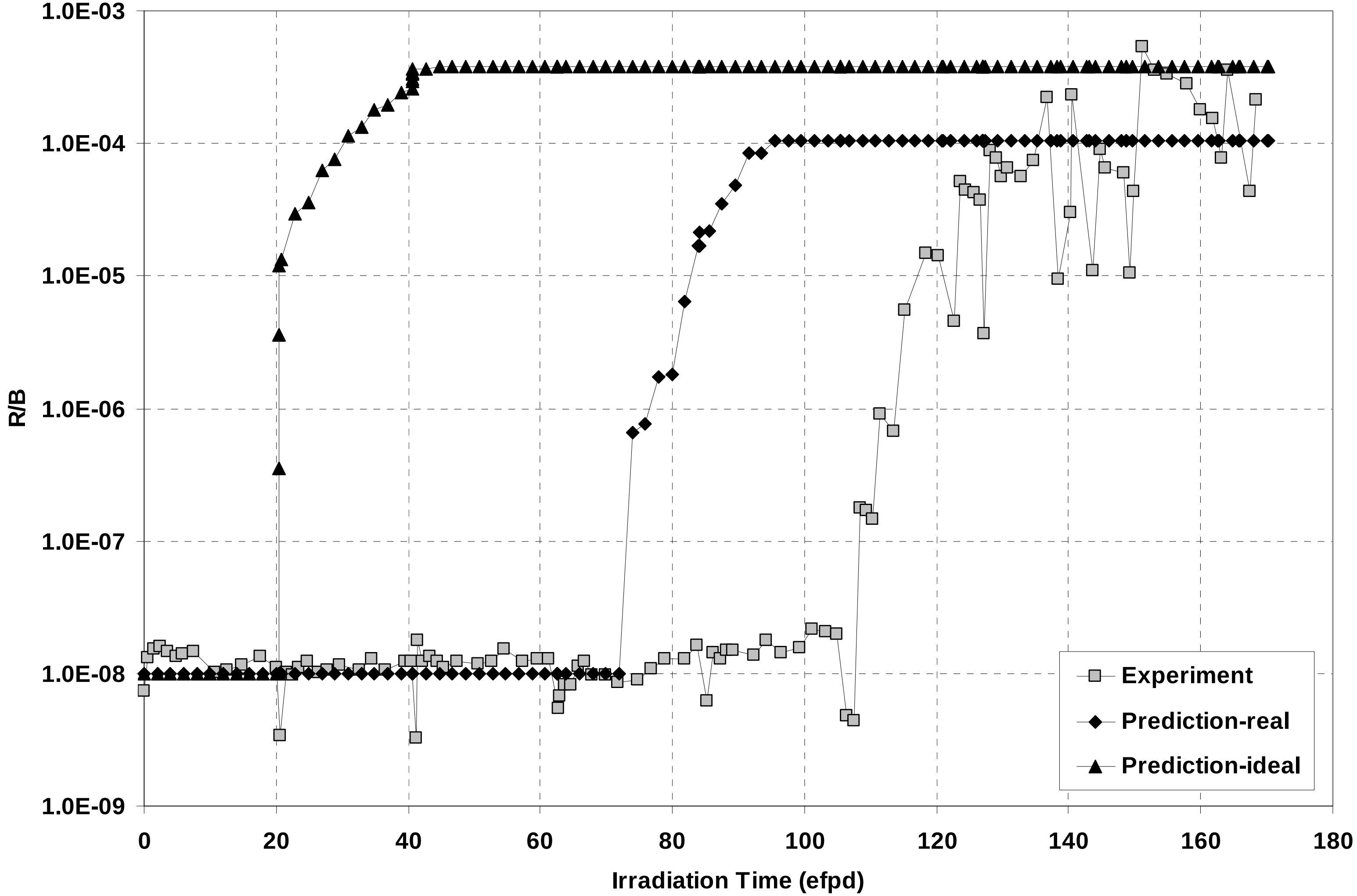
Compact ID	A1	A2	A3	A4	A5	A6	A7	A8
IPyC Failure	84.24%	16.71%	19.42%	33.85%	36.26%	30.26%	29.06%	91.71%
OPyC Failure	13.1%	0.436%	0.549%	1.564%	1.85%	1.23%	1.11%	16.3%
Particle Failure	8.32%	0.038%	0.074%	0.613%	0.790%	0.400%	0.337%	9.64%

Overall Failure of NPR-1 Capsule

	Irradiation Test	Prediction (Real Irr. History)	Prediction (Ideal Irr. History)
No. Particles Contained	77500	77500	77500
No. Failed Particles	625 (a)	656	2384
Failure Probability	0.806%	0.846%	3.076%
Peak Fluence at Initial Failure (10^{21}n/cm^2)	1.7	0.587	0.071
Peak Burnup at Initial Failure (% FIMA)	72%	59%	24%
EFPD at Initial Failure	108	73.9	20.45
Peak Temperature at Initial Failure (C)	1123	1025	1086

(a): From readings of the Kr^{85m} R/B

Kr^{85m} R/B of NPR-1 Capsule



Path Forward

- ❑ Develop Advanced Failure Model
  - Follows PyC Cracking & Stress Distribution after initial PyC failure
- ❑ Develop and Incorporate Chemistry Model
  - INEEL Inputs
  - FP Migration Experimental Results
  - Pd Interaction Results
  - Other Input