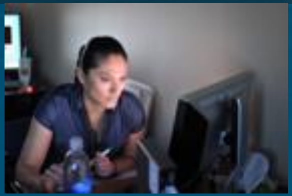
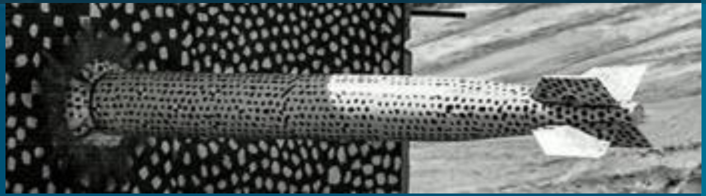
Fluid Fuel Point Reactor Kinetics Equation Modeling for MSR in MELCOR





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PRESENTED BY

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Overview

Delayed neutrons and reactor kinetics

Point reactor kinetics equations

- Formulations (standard and fluid)
- Initialization (fluid)
- “Perfect control system” model (fluid)
- Auxiliary quantities

Input structures for fluid-fuel reactors and MSRE input model

Validation against ORNL MSRE zero-power flow coast-down experiment

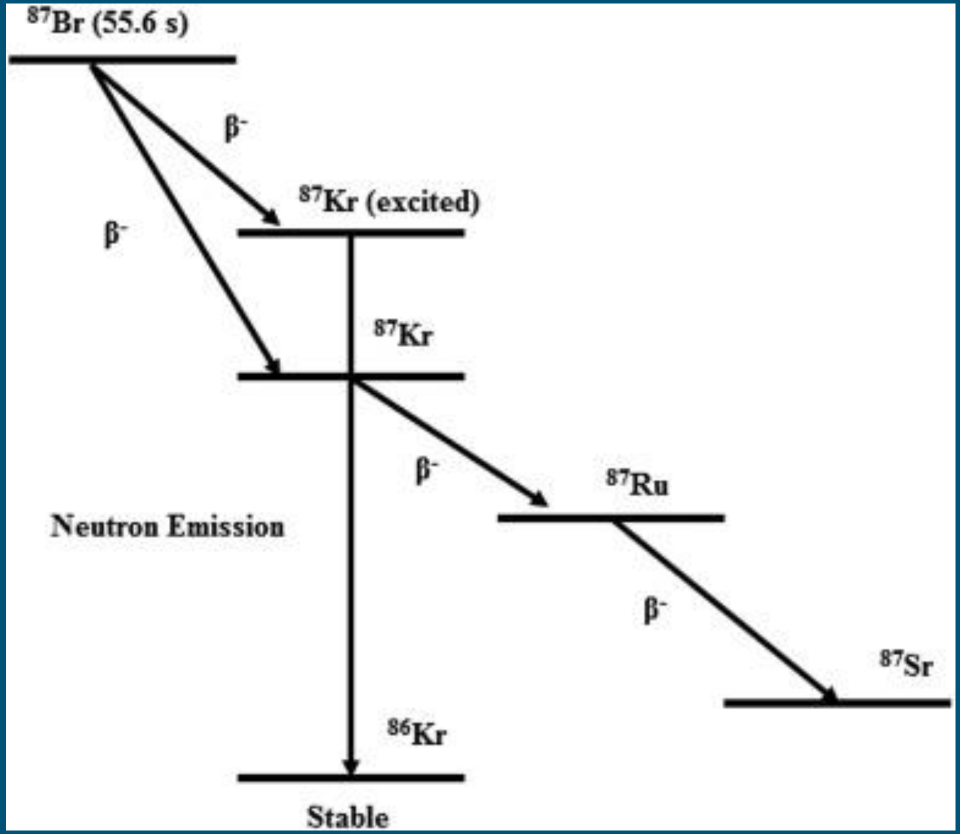
Conclusions

Delayed Neutrons and Reactor Kinetics

Time-dependent neutron population (kinetics) plus system feedback mechanisms (dynamics)

Delayed neutron (DN) emission from DN precursor (DNP) decay is a primary governor of dynamic response

- Solid fuel –DNP's stay and hence DN's contribute to economy
- Fluid fuel – DNP's move (ex-core) and lost DN's impact economy

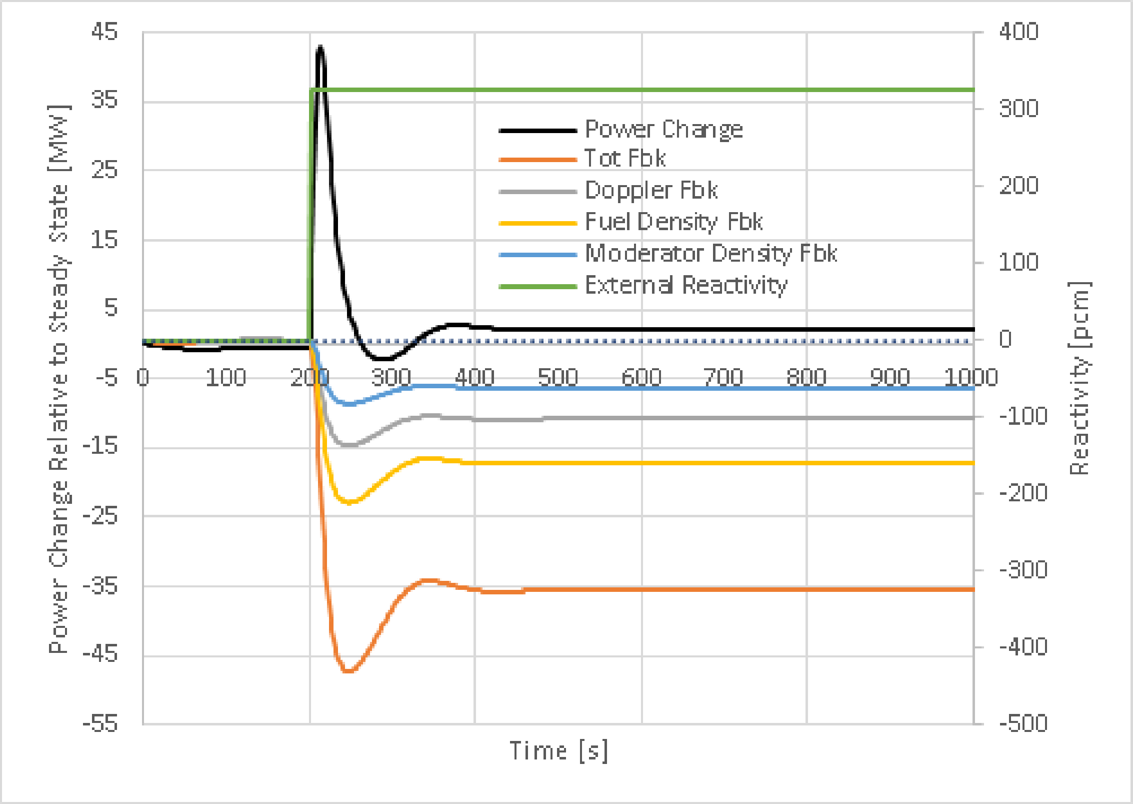


DNP grouping helps with analyses (group decay, abundance)

Process of DNP advection with flowing fuel is DNP "drift"

Cannot neglect the kinetic/dynamic implications of DNP "drift"

Standard Point Reactor Kinetics Equations



Textbook Six DNP group PRKE's

$$\frac{dP}{dt} = \left(\frac{\rho - \beta}{\Lambda}\right) P + \sum_{i=1}^{6} \lambda_i Y_i + S_0$$

$$\frac{dY_i}{dt} = \left(\frac{\beta_i}{\Lambda}\right) P - \lambda_i C_i, \qquad for\ i = 1 \ldots 6$$

DNP drift

- Leads to lower effective DN fraction,
- Looks like a negative reactivity insertion, and
- Introduces a "reactivity bias" barrier to criticality for a given flow

Relatively lower DN emission in core as core DNP inventory decreases

Relatively higher DN emission in core as core DNP inventory increases

Fuel flow (e.g. as driven by fuel pump) has direct reactivity implications

Fluid Fuel Point Reactor Kinetics Equations – Formulation

$$\frac{dP(t)}{dt} = \left(\frac{\rho(t) - \bar{\beta}}{\Lambda}\right)P(t) + \sum_{i=1}^{6} \lambda_i C_i^C + S_0$$

$$\frac{dC_i^C(t)}{dt} = \overset{A}{\left(\frac{\beta_i}{\Lambda}\right)P(t)} - \overset{B}{\left(\lambda_i + {}^{1}/_{\tau_C}\right)C_i^C(t)} + \overset{C}{\left(\frac{V_L}{\tau_L V_C}\right)C_i^L(t - \tau_L)}, \qquad for\ i = 1 \ldots 6$$

$$\frac{dC_i^L(t)}{dt} = \overset{D}{\left(\frac{V_C}{\tau_C V_L}\right)C_i^C(t)} - \overset{E}{\left(\lambda_i + {}^{1}/_{\tau_L}\right)C_i^L(t)}, \qquad for\ i = 1 \ldots 6$$

$$\bar{\beta} = \beta - \left(\frac{\Lambda}{P(t)}\right)\sum_{i=1}^{6} \lambda_i C_i^L(t)$$

- **A** – In-Vessel DNP gain by fission
- **B** – In-Vessel DNP loss by decay, flow
- **C** – In-Vessel DNP gain by Ex-Vessel DNP flow
- **D** – Ex-Vessel DNP gain by In-Vessel DNP flow
- **E** – Ex-Vessel DNP loss by decay, flow

Where:

$P(t)$= Thermal power due to fission 0

C_i^C= delayed neutron precursor group i inventory/concentration in-core

C_i^L= delayed neutron precursor group i inventory/concentration ex-core

S_0= Thermal power generation rate due to neutron source

$\rho(t) = \frac{k-1}{k}$= Reactivity for k the effective multiplication factor

$\bar{\beta}$= Effective delayed neutron fraction

β= Delayed neutron fraction (static, in absence of drift effects)

$\Lambda = {}^{1}/_{\nu V \Sigma_f}$= Neutron generation time

$\tau_{C/L} = {}^{M_{C/L}}/_{\dot{m}}$ = Residence time of precursors (core, loop, respectively)

$V_{C/L}$= Fluid volume (core, loop, respectively)

λ_i= Decay constant of delayed neutron precursor group i

Fluid Fuel Point Reactor Kinetics Equations – Steady State Initialization

Assume critical at some power and steady flow

Assume no feedback or control reactivity

Time derivatives of dependent variables are zero (steady)

Given P_0, derive initial values for:

- All DNP variables by cohort
- Bias reactivity
- Effective DN fraction

These are initial conditions for FFPRKE model

Under these assumptions, the steady form of the FFPRK equations is:

$$\frac{dP(0)}{dt} = 0 = \left(\frac{\Delta\rho_0 - \bar{\beta}(0)}{\Lambda}\right)P_0 + \sum_{i=1}^{6}\lambda_i C_{i,0}^C = \left(\frac{\Delta\rho_0 - \beta + \beta_{lost}(0)}{\Lambda}\right)P_0 + \sum_{i=1}^{6}\lambda_i C_{i,0}^C$$

$$\frac{dC_i^C(0)}{dt} = 0 = \left(\frac{\beta_i}{\Lambda}\right)P_0 - \left(\lambda_i + {}^2/_{\tau_C}\right)C_{i,0}^C + \left(\frac{V_L}{V_C}\right)\left(\lambda_i + {}^2/_{\tau_L}\right)C_{i,0}^L, \qquad i = 1 \dots 6$$

$$\frac{dC_i^L(0)}{dt} = 0 = \left(\frac{V_C}{\tau_C V_L}\right)C_{i,0}^C - \left(\lambda_i + {}^1/_{\tau_L}\right)C_{i,0}^L, \qquad i = 1 \dots 6$$

Solving for DNP cohorts:

$$C_{i,0}^C = \alpha_i P_0, \qquad i = 1 \dots 6$$

$$C_{i,0}^L = \gamma_i \alpha_i P_0 = \gamma_i C_{i,0}^C, \qquad i = 1 \dots 6$$

$$\gamma_i = \left(\frac{V_C}{\tau_C V_L}\right)\Big/\left(\lambda_i + {}^1/_{\tau_L}\right), \qquad i = 1 \dots 6$$

$$\alpha_i = \left(\frac{\beta_i}{\Lambda}\right)\Big/\left[\left(\lambda_i + {}^2/_{\tau_C}\right) - \gamma_i\left(\left(\frac{V_L}{V_C}\right)\left(\lambda_i + {}^2/_{\tau_L}\right)\right)\right], \qquad i = 1 \dots 6$$

Solving for the bias reactivity and the time-zero effective delayed neutron fraction:

$$\Delta\rho_0 = \beta - \Lambda\sum_{i=1}^{6}\lambda_i\alpha_i(1+\gamma_i)$$

$$\bar{\beta}(0) = \beta - \beta_{lost}(0) = \beta - \Lambda\sum_{i=1}^{6}\lambda_i\gamma_i\alpha_i$$

Fluid Fuel Point Reactor Kinetics Equations – "Perfect" Control System

Given the set of FFPRK equations and assuming some arbitrary change in fuel flow, an equation can be derived for the time-dependent reactivity intervention of a "perfect control system" that counteracts flow reactivity effects and preserves system criticality. Initially, the reactor is critical with some bias reactivity $\Delta\rho_0$ at some power P_0 with some fuel flow characterized by fluid volumes and core/loop transit times. Assuming the time derivative of reactor power stays at zero and substituting the static and lost delayed neutron fractions for the effective delayed neutron fraction:

$$\left(\frac{\Lambda}{P_0}\right)\frac{dP(t)}{dt} = 0 = \Delta\rho_0 + \rho_{fb}(t) + \rho_{cr}(t) - \beta + \left(\frac{\Lambda}{P_0}\right)\sum_{i=1}^{6}\lambda_i\left(C_i^C(t) + C_i^L(t)\right) \tag{20}$$

Then, solving for the value of $\rho_{cr}(t)$ assuming no feedback reactivity:

$$\rho_{cr}(t) = \left(\frac{\Lambda}{P_0}\right)\left(\sum_{i=1}^{6}\lambda_i\left(\left(C_{i,0}^C - C_i^C(t)\right) + \left(C_{i,0}^L - C_i^L(t)\right)\right)\right) \tag{21}$$

As time goes on and as the FFPRK model is being solved, an external control reactivity following this prescription will hold reactor power approximately constant despite DNP drift due to flow changes. The situation is more complicated if temperature feedback is involved, but for a zero-power flow reactivity transient this result proves particularly useful.

Fluid Fuel Point Reactor Kinetics Equations – Auxiliary Quantities

Gross characteristics of core and loop flow are leveraged in FFPRKE source terms to describe drift

- Transit times approximate the time required for flow to traverse the core and the balance of the loop
- Fluid volumes of the entire core and loop

$$V_C = \sum_{j=1}^{N_C} V_j$$

$$V_L = \sum_{j=1}^{N_L} V_j$$

$$\tau_C = \frac{1}{V_C} \sum_{j=1}^{N_C} (vAV)_j$$

$$\tau_L = \frac{1}{V_L} \sum_{j=1}^{N_L} (vAV)_j$$

"core" quantities consist of a sum over all CV's identified as belonging to the core

"loop" quantities consist of a sum over all CV's identified as belonging to the balance of the flow loop (ex-core)

Resort to control volume averaged notions of flow path phasic (pool) flows

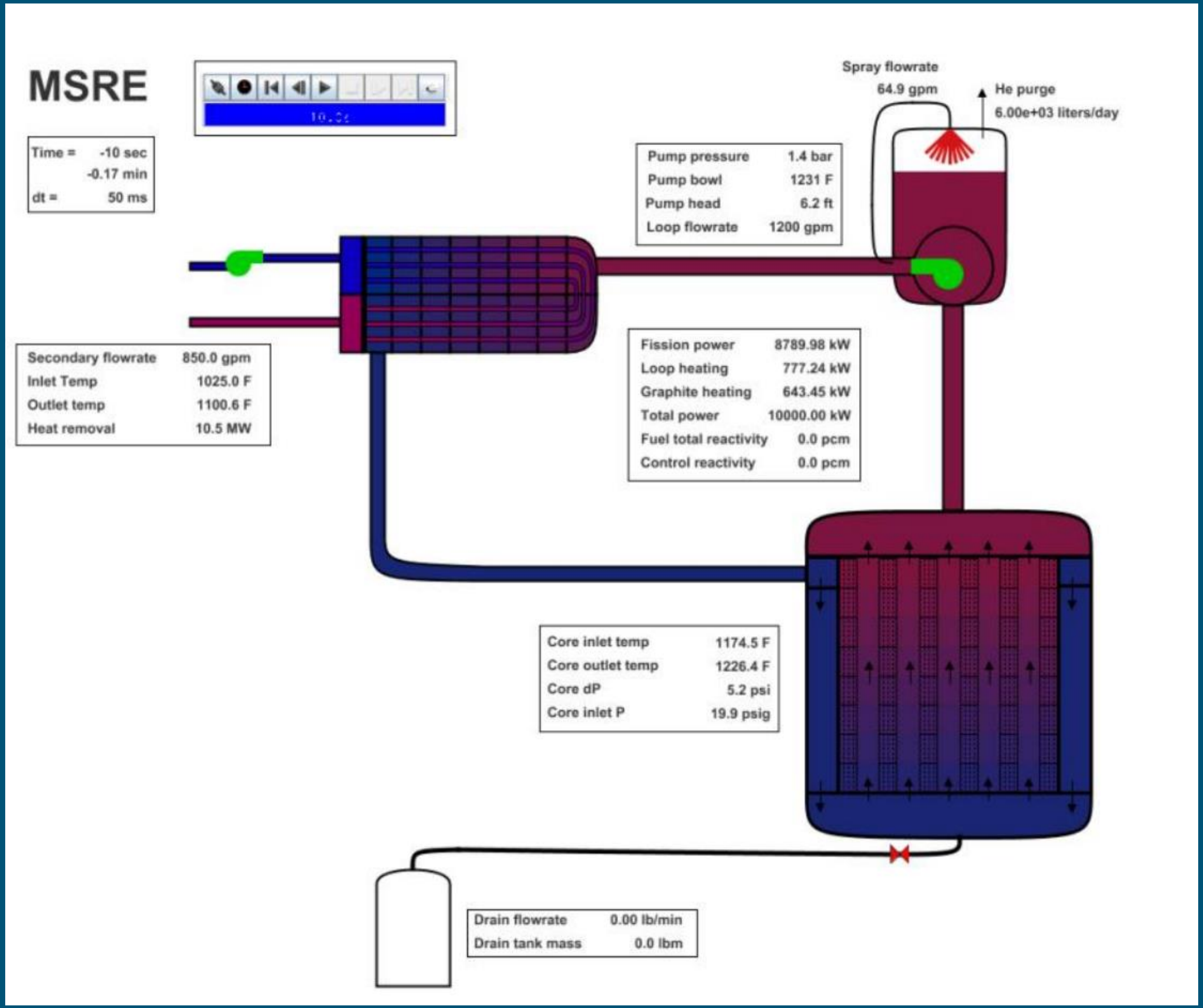
Fluid Fuel Reactor Input Structures

Fluid fueled “cores” are affected in MELCOR without resorting to the COR package (all through CVH)

- Designate the “core” and “loop” CV types to associate CV definitions with the primary loop
- Designate a power distribution for “core” CVs
- Configure PKM parameters (timing, feedback, external reactivity, etc.)

CVH Record	Description
CV_FLUIDFUEL	Identify the “core” CV type and the “loop” CV type
CV_FISPOWDIST	Specify a reactor power spatial shape distribution across all “core” CVs
CV_FLUIDFUELPKM01	Specify FFPKM start time and initial steady power
CV_FLUIDFUELPKM02	Specify external reactivity and any external neutron source
CV_FLUIDFUELPKM03	Configure reactivity feedback options

MSRE Input Model



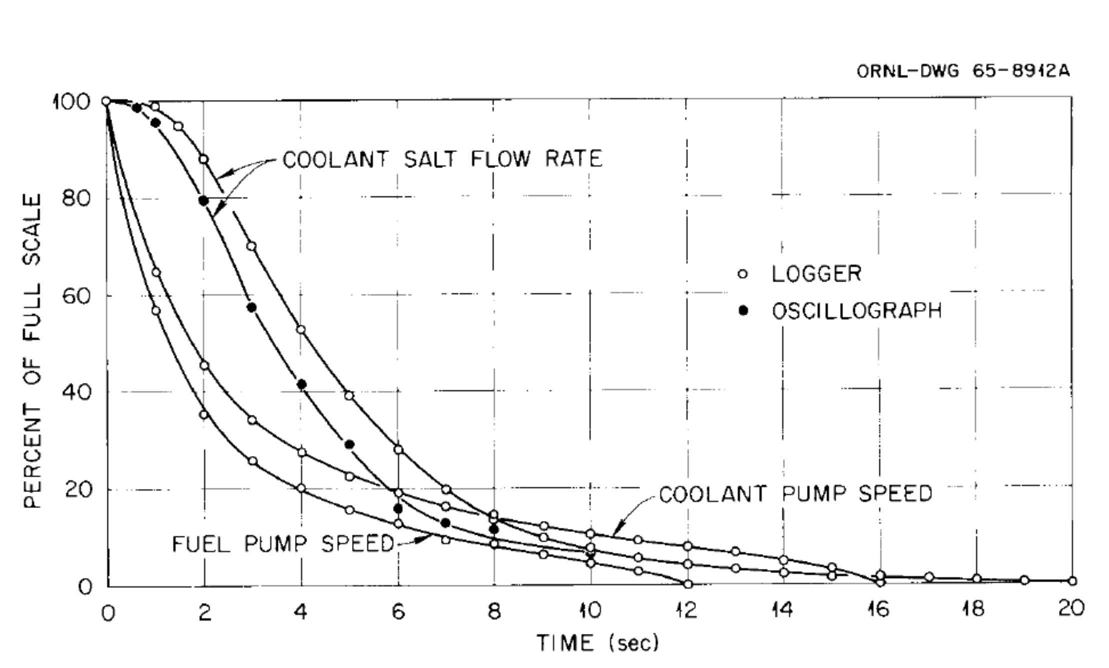
ORNL MSRE Zero-Power Flow Coast-Down Experimental Benchmark

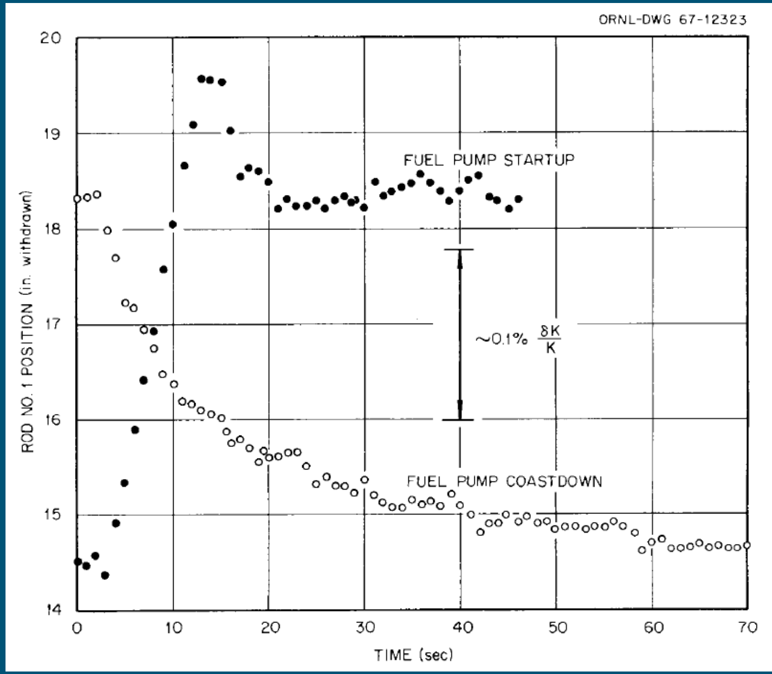
Null transient was checked

- Steady-state MSRE model built, FFPRKE's start governing power at some problem time given initial power
- Verify steady power level (zero reactivity) and a bias reactivity consistent with experimental value
- Good test of input structures, data read/write, output plots, etc.

Zero-power fuel pump coast-down

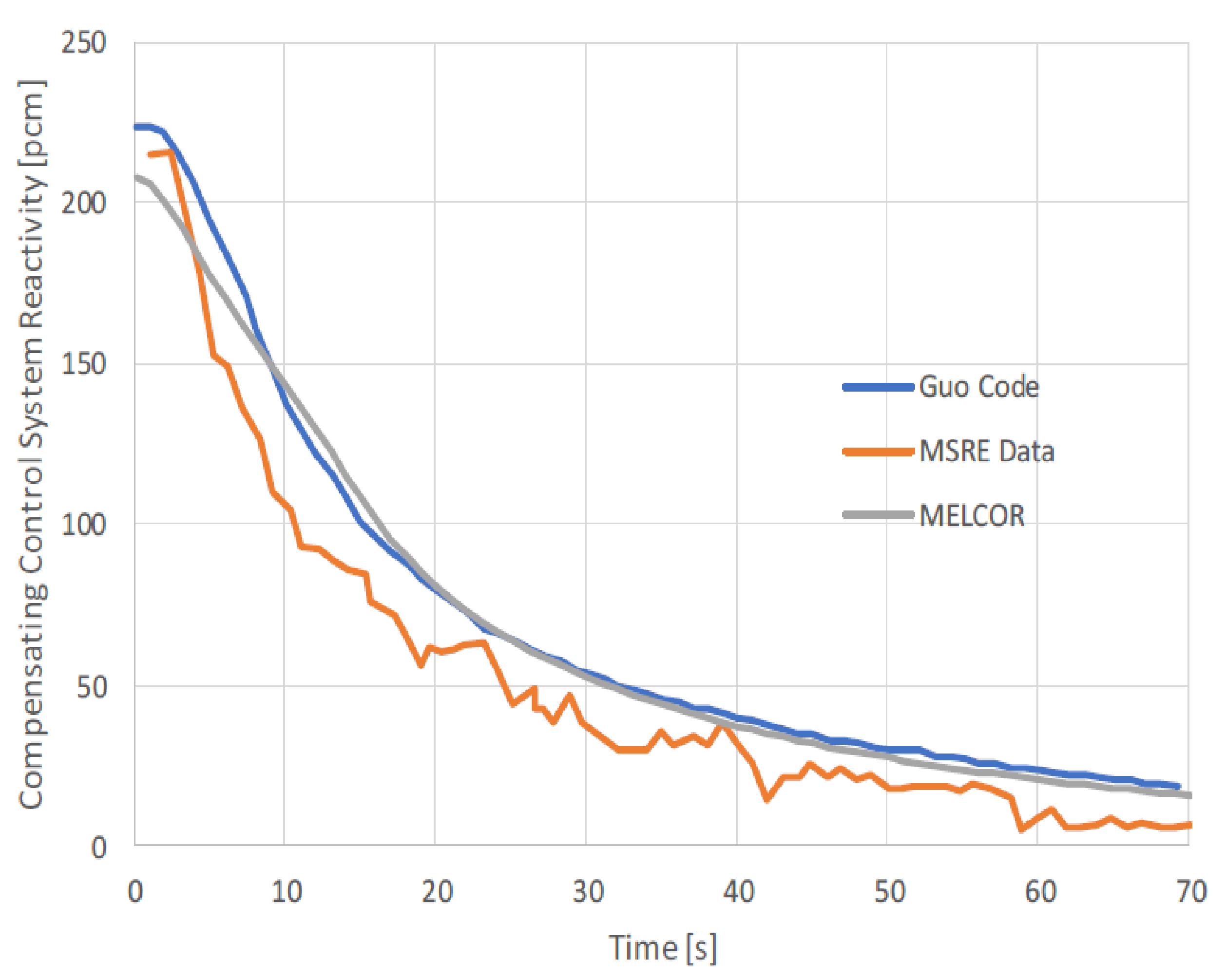
*Fuel circulation worth: 0.212 +/- 0.004 δK/K

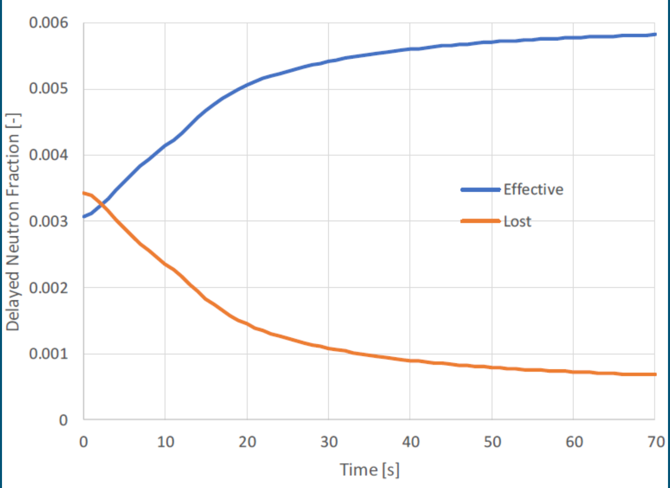


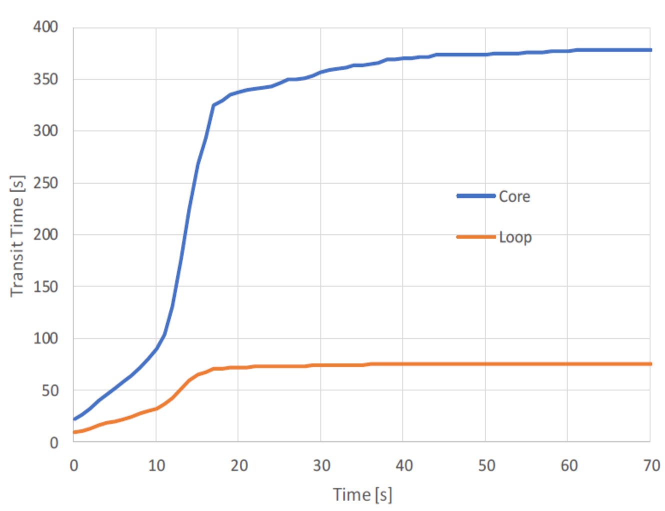


ORNL MSRE Zero-Power Flow Coast-Down Experimental Benchmark

Validation of FFPRKE predictions against experimental data and a separate computer code







Conclusions

To facilitate MELCOR modeling of MSRs, a fluid fuel point reactor kinetics equation model was developed and integrated

An approach consistent with the systems-level MELCOR modeling philosophy was taken

Validation was performed against experimental data from ORNL MSRE

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