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Dynamic System Simulation of Fissile Solution Systems

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Introduction

Dynamic System Simulation (DSS) utilizes state-variables described by differential or difference equations to model system evolution. DSS techniques have been applied to develop a family of models to examine the time-dependent operational behavior of fissile solution systems. The base, or generic model, predicts the behavior of an aqueous homogeneous reactor (AHR), configured with a single cooling loop, operating at atmospheric pressure. A model specific for SUPO (Super Power), a uranium solution fueled AHR that operated at Los Alamos National Laboratory from 1951 to 1974, tailored from the generic model demonstrated close correlation with experimental data for steady-state operation[1]. SUPO is considered the benchmark for steady-state AHR operation.

Subsequently specific models were tailored from the generic model for a variety of historical reactors including KEWB (Kinetics Experiments Water Boiler) “A-2” and “B-5” cores and Silene, which is considered the benchmark for AHR pulse operations. These models demonstrated DSS techniques could reliably be extended to different core geometries (SUPO and KEWB “A-2” were spherical; KEWB “B-5” and Silene cylindrical)[2]. This family of models also shows close correlation with experimental data in all modes of fissile solution system operation including pulse, free evolution, and steady-state. System response due to rate and amplitude of reactivity insertion closely matches experimental data.

This report describes additional extensions of this family of models to include a wider design space for fissile solution systems. Pressurized cores, cooling schemes involving multiple cooling loops of various geometries, and accelerator-driven sub-critical system concepts are modeled.

Pressurized Cores

The Homogenous Reactor Experiments (HRE) conducted at Oak Ridge National Laboratory in the 1950’s was directed at evaluating the concept of using an AHR to generate electric power. Since efficient power conversion requires high temperatures, designers were driven to pressurized core configurations to elevate the fuel boiling point. Suppression of radiolytic gas void, a byproduct of core pressurization, also allowed for higher power and temperatures.

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[1] “A Generic System Model for a Fissile Solution Fueled Assembly”, LA-UR-13-22033, Kimpland, Robert H. & Klein, Steven K., 2013

[2] “A Generic System Model for A Fissile Solution Fueled Assembly”, LA-UR-13-28572 – Part II, Kimpland, Robert H. & Klein, Steven K., 2013

Changes in fuel and coolant temperature of an AHR operating at atmospheric pressure do not significantly impact operating parameters. However, for pressurized systems such as HRE-1 that nominally operated at 68 atmospheres this is not the case. Developing a specific system model for HRE requires consideration of the variation of physical parameters with pressure, temperature, and salt concentration. Modifications to the generic system model for pressurized cores include:

- Thermal conductivity of water varied with coolant temperature
- Thermal conductivity of fuel varied with boundary layer temperature and uranium concentration
- Boiling point of fuel varied with plenum pressure
- Plenum pressure varied to balance core pressure
- Prandtl number of fuel varied with boundary layer temperature
- Prandtl number of coolant varied with temperature
- Isobaric compressibility of fuel varied with bulk fuel temperature
- Isobaric compressibility of boundary layer varied with layer temperature
- Expansion coefficient of boundary layer varied with temperature
- Kinematic viscosity of boundary layer varied with temperature
- Specific heat of fuel varied with bulk fuel temperature
- Specific heat of boundary layer varied with temperature
- Specific heat of coolant varied with temperature
- Fuel density varied with bulk fuel density
- Thermal diffusivity of fuel varied with bulk fuel density
- Radiolytic gas bubble transit time varied with pressure and kinematic viscosity of fuel
- Specific gas volume varied with pressure
- Radiolytic gas threshold set by temperature, pressure, and uranium concentration
- Boundary layer thickness varied with density and dynamic viscosity

Table 1 presents steady-state experimental data and results of applying system models V1 (basic version) and V2 (pressurized core version) to model a $1.90 reactivity insertion.

Table 1: SUPO Data & System Model Results

Version	**kW**	**Fuel ºC**	**% Void**	**Exit Coolant ºC**
Experimental Data	25	75	Unknown	35
System Model V1	22.83	69.23	1.50	30.27
System Model V2	24.9	64.18	2.09	32.45

Considerable experimental data is available for Silene. Comparison of experimental data and system model V1 and V2 results are presented below in Tables 2 through 5. As with SUPO reasonable agreement between experimental data and either model is evident. The following terminology is used in these tables to define the operational modes:

- Pulse: $\Delta k \geq\!> \beta$; reactivity insertion rate approximately $20.00/second
- Slow Kinetics: $\Delta k \leq \beta$; reactivity insertion rate approximately $0.03/second

- Free Evolution: reactivity insertion rate approximately $0.20/second
- Boiling: Δk $\geq$ $5.00; reactivity insertion rate approximately $0.40/second

Table 2: Silene Pulse Operations					
Exp #	**Δk($)**	**Peak Fission Rate**	**Fissions Integrated to Peak**	**Fissions Integrated to Equilibrium**	**Equilibrium Temp °C**
S2-258	1.32	7.10E+17	1.80E+16	8.80E+16	48.70
Model V1		8.51E+17	2.15E+16	1.94E+17	61.15
Model V2		1.06E+18	2.36E+16	1.85E+17	52.15
S3-258	1.84	4.90E+18	5.40E+16	1.42E+17	56.10
Model V1		1.03E+18	2.66E+16	2.66E+17	75.24
Model V2		1.29E+18	3.11E+16	2.40E+17	60.98
S3-300	2.31	1.10E+19	6.60E+17	1.80E+17	62.20
Model V1		1.18E+18	2.93E+16	2.70E+17	76.67
Model V2		1.48E+18	3.24E+16	2.72E+17	67.85
S2-259	2.60	1.70E+19	8.20E+16	2.10E+17	68.00
Model V1		1.20E+18	2.89E+16	2.82E+17	76.33
Model V2		1.50E+18	3.21E+16	2.86E+17	67.82
S3-259	2.86	2.10E+19	7.90E+16	2.10E+17	71.80
Model V1		1.14E+18	2.84E+16	2.84E+17	76.60
Model V2		1.43E+18	3.13E+16	3.06E+17	72.99
S1-346	2.96	2.50E+19	9.80E+16	2.90E+17	74.00
Model V1		1.11E+18	2.32E+16	3.08E+17	81.73
Model V2		1.40E+18	3.10E+16	3.08E+17	72.16

Table 3: Silene Slow Kinetics Operations					
Exp #	**Δk($)**	**Peak Fission Rate**	**Fissions Integrated to Peak**	**Fissions Integrated to Equilibrium**	**Equilibrium Temp °C**
LE3-214	0.49	1.20E+15	1.80E+16	6.30E+16	32.50
Model V1		1.30E+15	2.02E+16	8.01E+16	36.51
Model V2		1.61E+15	2.51E+16	9.92E+16	36.58
S1-300	0.51	1.30E+15	2.20E+16	6.00E+16	35.90
Model V1		1.23E+15	1.85E+16	7.03E+16	36.83
Model V2		1.46E+15	2.15E+16	8.34E+16	36.90
S1-329	0.98	8.40E+15	1.60E+16	6.00E+16	38.00
Model V1		1.68E+16	7.81E+15	1.01E+17	42.81
Model V2		2.08E+16	9.76E+15	1.23E+17	42.66
S2-346	0.88	8.70E+15	1.70E+16	6.40E+16	38.00
Model V1		9.31E+15	1.58E+16	1.16E+17	44.52
Model V2		1.15E+16	1.95E+16	1.33E+17	42.74
S2-300	0.97	1.70E+16	1.30E+16	7.00E+16	43.40
Model V1		1.79E+16	9.91E+15	1.34E+17	50.61

Model V2		2.21E+16	1.14E+16	1.54E+17	48.58
S1-258	0.98	1.90E+16	9.90E+15	7.70E+16	42.80
Model V1		1.73E+16	7.93E+15	1.20E+17	46.89
Model V2		2.14E+16	9.13E+15	1.43E+17	46.11

Table 4: Silene Free Evolution Operations					
Exp #	**Δk($)**	**Peak Fission Rate**	**Fissions Integrated to Peak**	**Fissions Integrated to Equilibrium**	**Equilibrium Temp °C**
LE1-362	2.96	2.00E+16	9.60E+15	2.90E+17	72.00
Model V1		3.94E+17	1.60E+16	3.16E+17	81.31
Model V2		4.97E+17	1.78E+16	3.21E+17	71.72
LE2-362	2.96	1.80E+17	1.20E+16	2.60E+17	70.00
Model V1		4.61E+17	1.72E+16	2.88E+17	76.03
Model V2		5.81E+17	1.90E+16	3.41E+17	75.07
LE1-258	3.42	1.80E+17	1.10E+16	3.00E+17	83.10
Model V1		4.11E+17	1.53E+16	3.31E+17	81.79
Model V2		5.18E+17	1.69E+16	3.59E+17	75.89
LE1-273	3.55	1.70E+17	1.10E+16	3.00E+17	84.00
Model V1		4.11E+17	1.53E+16	3.28E+17	82.11
Model V2		5.17E+17	1.69E+16	3.67E+17	77.95

Table 5: Silene Boiling Operations					
Exp #	**Δk($)**	**Peak Fission Rate**	**Fissions Integrated to Peak**	**Fissions Integrated to Equilibrium**	**Equilibrium Temp °C**
LE1-175	5.00	4.20E+17	1.70E+17	Unreported	Unreported
Model V1		4.28E+17	1.56E+16	3.74E+17	84.57
Model V2		5.44E+17	1.72E+16	5.34E+17	91.45
LE1-176	5.20	4.50E+17	1.80E+16	Unreported	Unreported
Model V1		4.71E+17	1.74E+16	4.22E+17	85.04
Model V2		5.94E+17	1.92E+16	6.29E+17	94.46
LE2-176	6.00	4.10E+17	1.70E+16	Unreported	Unreported
Model V1		5.81E+17	2.18E+16	4.82E+17	83.48
Model V2		7.32E+17	2.41E+16	8.22E+17	100.00
LE2-343	6.40	3.80E+17	1.60E+16	Unreported	Unreported
Model V1		5.69E+17	2.16E+16	4.51E+17	83.98
Model V2		7.17E+17	2.39E+16	7.74E+17	99.54
LE1-281	7.20	4.20E+17	1.70E+16	Unreported	Unreported
Model V1		5.22E+17	1.82E+16	5.02E+17	88.21
Model V2		6.57E+17	1.99E+16	7.94E+17	97.93

Version 2 of the system model was tailored to the Homogeneous Reactor Experiment (HRE-1). Experimental data shows that HRE-1 produced 1,000 kW at a core pressure of 1,000 psi (68 atm) while just below the boiling point of water at that pressure (277 ^{o}C). Version 2 of the System Model estimates 919 kW under those conditions.

Core Cooling

The large negative reactivity feedback due to temperature characteristic of all AHRs means that removal of fission generated heat in the solution fuel is a major design requirement. Early AHRs like SUPO and KEWB “A-2” were relatively small spheres with less than 20 liters of highly enriched uranium solution. Both cores were water cooled with 0.25” o.d. stainless steel coils comprising approximately 5% of fuel volume. Coolant flow rates reported for these AHRs matched criteria for turbulent flow. Therefore, the cooling sub-model of the initial DSS generic model for incorporated a Dittus-Boelter treatment for forced convective heat transfer from tube wall to cold coolant. Natural convective treatment is used from the hot fuel to the tube wall. Since in both SUPO and KEWB “A-2” the majority of the coolant tube length was coiled normal to the vertical axis of the reaction vessel, the natural convection treatment is for an isothermal horizontal cylinder.

Since KEWB “B-5” and Silene cores were only air cooled on the exterior of the reaction vessel, cooling was “switched off” in the model for these cores.

Since AHRs of current interest may utilize multiple cooling loops of different geometries than the cooling coils in historic cores the DSS models have been extended to address these modifications. Cooling structure geometries included in Version 3 of the DSS Generic System Model include in fuel vertical tubes and annular channels at the edges of the reaction vessel. Both natural and forced convection heat transfer correlations have been tailored to cooling structure geometry. In addition the model includes recognition of laminar versus turbulent flow for forced convection and applies the appropriate treatment. Finally, models may incorporate up to three cooling loops in any of these configurations. Energy balance is incorporated for each loop to verify computational accuracy.

The actual physical cooling system for SUPO incorporated three identical coils of 0.25” o.d. stainless steel tubing. Versions 1 and 2 of the AHR system models treated the system as a single coil of the proper length and surface area with the results discussed above. The initial effort in extending these models to handle multiple cooling loops was to split the single loop treatment for SUPO into the three identical physical loops and compare results with experimental data and previous models. Results using the same $1.90 slow ramp reactivity insertion as with Versions 1 & 2 are: fission power 24.77 kW; fuel temperature 73.07 °C; void percent 1.47%; and, coolant exit temperature 32.45 ^{o}C. These values compare favorably with those shown in Table 1.

Figure 1 shows a top view of an annular core AHR (ACAHR) with edge cooling in annular channels.

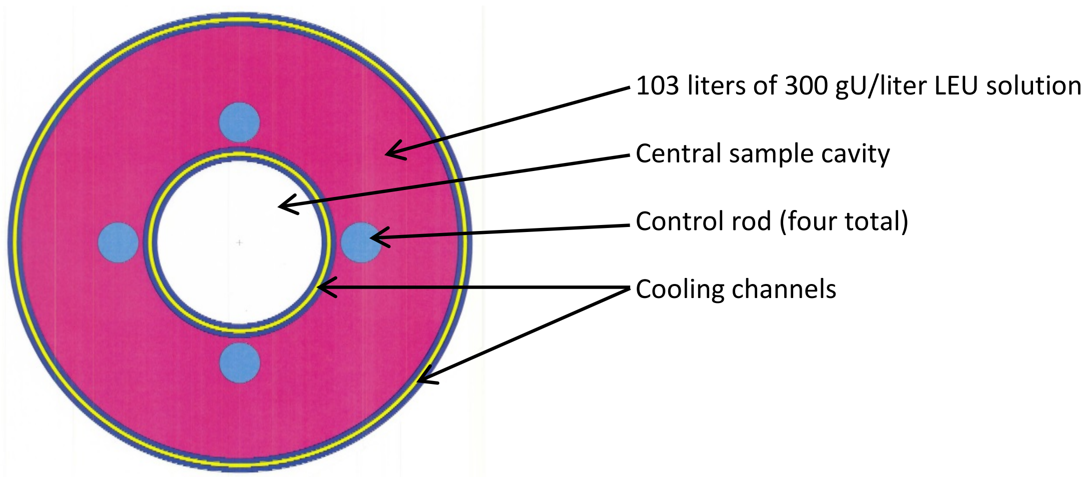

Figure 1: Annular Core AHR with Cooling Channels

This configuration is used for evaluating the performance of a two-loop annular cooled system model. The two cooling channels are assumed to have approximately the same thickness. The coolant flow is distributed proportionally to the cross sectional areas of the two annuli. Note that the example is unreflected, as with KEWB "B-5" and Silene, this core can operate with approximately $5.00 excess reactivity in either a steady-state or pulse mode. Each of the two previous generations of system model, V1 and V2 have been modified to handle multiple cooling configurations designated V3a1 and V3a2 respectively. Table 6 presents the results for ramp and step reactivity insertions.

Table 6: Results of a $5.00 insertion into an Annular Core AHR

Parameter	V3a1	V3a2
Steady-State Power (kW)	111.20	91.27
Fuel Temperature (°C)	82.82	91.38
Gas Void (%)	2.08	1.59
Step Insertion Power (kW)	217,745	239,789

Figure 2 shows the output trace from V3a1 ramp insertion. The x-axis is time in seconds while the y-axis is normalized to display the time evolution of each parameter on the same graph. The behavior shown is typical of that previously presented in references 1 & 2. A sharp initial power peak is followed by a sharp decline as fuel heats. Subsequently there is a dynamic transition region as radiolytic gas becomes saturated in the core. Once the full ramp insertion is completed, the core settles into steady-state operation.

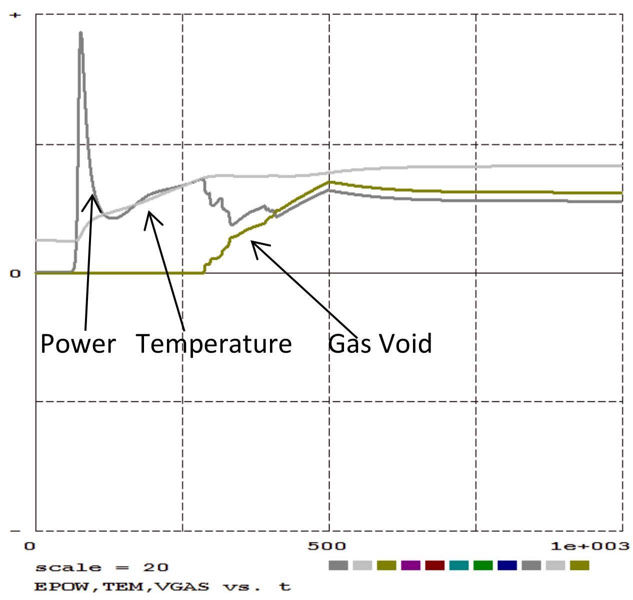

Figure 2: System Model Trace of $5.00 Ramp Insertion into ACAHR

Accelerator-Driven Systems

Fissile solution systems driven by accelerators are designed to operate in a sub-critical configuration. The typical geometry of these systems has the accelerator-driven neutron source placed in the center region of the core; hence, they are essentially an annular core system. The performance of these systems has been modeled by adding a neutron source to the neutron kinetics sub-model of versions 3a1 and 3a2 of the system model.

Figure 3 illustrates a generic configuration of an accelerator-driven sub-critical assembly. Note that three cooling loops are present; two are the inner and outer annular channels as in the ACAHR above, while a third loop consisting of 12 vertical tubes evenly spaced around the fuel annulus is present.

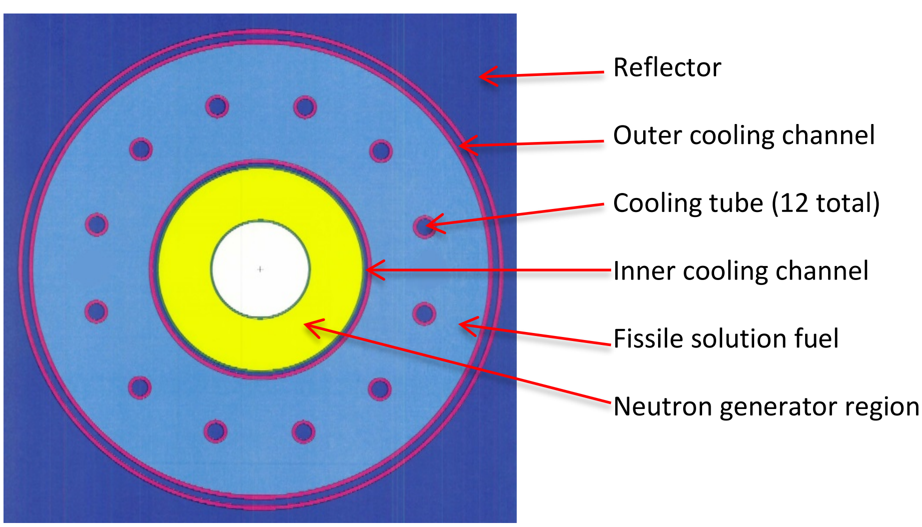

Figure 3: Notional Accelerator-Driven Sub-Critical Assembly

Table 7 compares results of operation of this notional system as estimated by the DSS system models Versions V3b1 and V3b2. As in the previous example version V3b1 is an extended basic generic model and V3b2 incorporates the changes to handle pressurized cores. Due to the low void fraction pressurizing this core would not be considered a viable option to increase fission power. Version V3b2 with a core pressure of 1,000 psi (68 atm) estimates 66.64 kW, confirming this hypothesis.

Table 7: System Model Results for a Notional Accelerator-Driven Assembly

Parameter	V3b1	V3b2
Steady-State Power (kW)	71.31	65.10
Fuel Temperature (°C)	60.18	67.01
Gas Void (%)	0.81	0.54
Inner Channel Outlet Temperature (°C)	22.78	23.03
Cooling Tubes Outlet Temperature (°C)	22.56	21.75
Outlet Channel Outlet Temperature (°C)	21.40	21.27

Figure 4 is a system model trace of the first 150 seconds of startup of the notional accelerator-driven system. Notice that when the accelerator starts operation the reactivity of the system starts declining as the fuel temperature rises. It is a distinguishing characteristic of sub-critical accelerator-driven systems that in the absence of other external influences the reactivity of the system is always lower when the accelerator is functioning than when it is not.

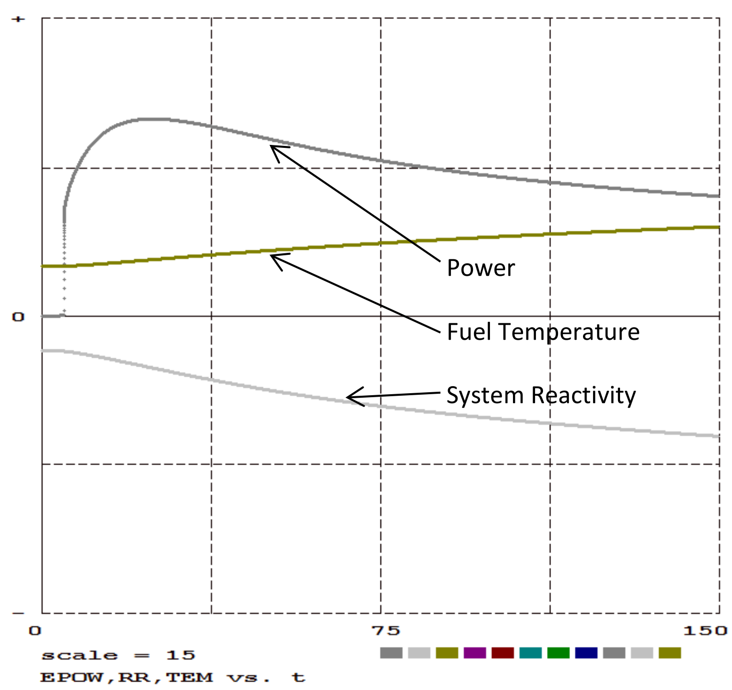

Figure 4: System Model Results for a Sub-Critical Accelerator-Driven System

It must be noted that these results are only theoretical since no such system has ever been constructed and operated; however, the close agreement between experimental data on historical AHR and DSS model results does lend some confidence in these estimates.

Summary

Dynamic System Simulation has been applied to model fissile solution systems including aqueous homogeneous reactors (AHR) and accelerator-driven sub-critical systems. The basic model with a single cooling loop exhibits close agreement with experimental data. Extensions of this basic model include modifications to vary the physical constants of cooling water and fuel with temperature, pressure, and uranium concentration. These modifications exhibit close correlation with the basic version but allows modeling of pressurized cores. More complex cooling structures and multiple cooling loops are addressed with additional model extensions that can handle pressurized or unpressurized configurations. Finally these models have been extended to estimate performance of accelerator-driven subcritical assemblies configured with multiple cooling loops of differing geometries.

These models demonstrate the power of Dynamic System Simulation as a technique to examine the time-dependent behavior of complex systems.