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Title: Extensions to Dynamic System Simulation of Fissile Solution Systems

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Extensions to Dynamic System Simulation of Fissile Solution Systems

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Introduction

Previous reports have documented the results of applying dynamic system simulation (DSS) techniques to model a variety of fissile solution systems. The SUPO (Super Power) aqueous homogeneous reactor (AHR) was chosen as the benchmark for comparison of model results to experimental data for steady-state operation.[1] Subsequently, DSS was applied to additional AHR to verify results obtained for SUPO and extend modeling to prompt critical excursions, ramp reactivity insertions of various magnitudes and rate, and boiling operations in SILENE and KEWB (Kinetic Experiment Water Boiler).[2] Additional models for pressurized cores (HRE: Homogeneous Reactor Experiment), annular core geometries, and accelerator-driven subcritical systems (ADAHR) were developed and results reported.[3] The focus of each of these models is core dynamics; neutron kinetics, thermal hydraulics, radiolytic gas generation and transport are coupled to examine the time-based evolution of these systems from start-up through transition to steady-state. A common characteristic of these models is the assumption that (a) core cooling system inlet temperature and flow and (b) plenum gas inlet pressure and flow are held constant; no external (to core) component operations that may result in dynamic change to these parameters are considered. This report discusses extension of models to include explicit reference to cooling structures and radiolytic gas handling. The accelerator-driven subcritical generic system model described in References 3 and 4 is used as a basis for this extension.

Generic Accelerator-Driven Subcritical System

The basic ADAHR model includes subsystems expected to be present in any implementation of this technology. These include:

- A DT (deuterium-tritium) accelerator that produces 14 MeV neutrons in a gas bottle located in the central region of the system;
- A multiplier, likely consisting of natural uranium, to increase the overall flux of neutrons in the system;
- A vessel containing fissile solution of uranium in the neutron field produced in the multiplier.

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

[2] A Generic System Model for a Fissile Solution Fueled Assembly – Part II, LA-UR-13-28572, Kimpland, Robert H, and Klein, Steven K, January, 2014

[3] Dynamic System Simulation of Fissile Solution Systems, LA-UR-14-22490, Kimpland, Robert H, Klein, Steven K, and Roybal, Marsha M, April 2014.

As noted above, previous models considered only cooling of the solution-containing vessel and radiolytic gas generation and transport therein. Necessary cooling for the tritium gas target for the accelerator and the multiplier was not included in the model; cooling elements and radiolytic gas handling external to the vessel were not considered.

Cooling Loop and Radiolytic Gas Handling Model Extensions

The present model extends previous ones through explicit addition of the following:

- Cooling of the gas bottle and multiplier;
- External piping to and from the cooling structures to heat exchangers
- Radiolytic gas handling

Overall cooling is segmented into two separate loops; one services the gas bottle and multiplier while the other loop services the in-vessel cooling structures. Both have independent shell-type heat exchangers and necessary piping to and from the heat generating system elements. These structures are contained in the overall system model as a core cooling sub-model.

A reflecting pool is included in the gas bottle/multiplier cooling loop. It is assumed that the gas bottle and multiplier coolant dumps into the reflecting pool. Further, it is assumed that one multiplier cooling structure also cools the gas bottle while the second cools only the multiplier.

In a similar manner, the radiolytic gas handling system accepts fission fragment generated gas in the vessel and transported to the solution surface to escape into the plenum. This gas is assumed to be molecular hydrogen (H_2) and oxygen (O_2) in the quantities determined by experiments on historical AHR. Gas composition, quantity, enthalpy, and pressure are generated from the previous basic system model.

Major gas handling components included in the model extension include a demister, heat exchanger, heaters, re-combiner, and condenser along with necessary piping; thus the loop from molecular gas to water in liquid form is included in this extension. Continuity of constituents in the plenum cover gas, product gases from the core, energy (adiabatic) and water makeup is maintained. The following assumptions are made:

- Adiabatic, incompressible single-phase flow;
- Pressure range in plenum from 80 – 110 kPa;
- Core gas temperature range of 30 – 80C;
- Fission power range for gas generation and water makeup of 25 – 150 kW

Thermal Extensions

Temperature of the multiplier, TM, is given by:

$$\frac{d}{dt}TM = AKM * (PCF * PF * (ENP - EN0)) - \gamma_{M1} * (TM - TMW1) - \gamma_{M2} * (TM - TMW2)$$

Where:

- AKM is the inverse heat capacity of the multiplier (AKM = 1/MM/CPM where MM is the mass of the multiplier in kg and CPM is the specific heat of the multiplier in MJ/kg/sec)
- PCF is the power conversion factor from the accelerator source strength in neutrons/second; PF is the partition factor for the multiplier power
- ENP is the fission power of the system from the point reactor kinetics model
- EN0 the initial power of the system
- γ_{M1} and γ_{M2} are the overall heat transfer coefficients for multiplier to wall in ($MJ/m^2/°C$)
- TMW1 and TMW2 are the multiplier wall temperatures in °C of lumps 1 and 2, respectively

As can be seen from the structure of this equation the temperature of multiplier is treated as a two-lump model.

Tritium gas tank heat output to each half lump in MJ is developed from typical values related to accelerator source strength. These values are identified as the variables ACCH1 and ACCH2. In addition, the multiplier cooling loop requires the following set of variables:

- $TCM1IN$ and $TCM2IN$ – Multiplier coolant temperature for lumps 1 and 2 (°C);
- γ_{C1} and γ_{C2} – Overall heat transfer coefficients from multiplier wall to coolant ($MJ/m^2/°C$);
- $MMC1$ and $MMC2$ – Multiplier coolant mass (kg);
- $CPCM$ – Specific heat of coolant (MJ/kg/°C);
- $TCM11$ and $TCM12$ – Temperature of multiplier coolant half lump (°C) ;
- $WCM1$ and $WCM2$ – Multiplier coolant mass flow rates (kg/sec);
- $MMW1$ and $MMW2$ – Multiplier wall mass (kg);
- $CPMW$ – Specific heat of multiplier wall (MJ/kg/C).

Note that the inverse heat capacities of the multiplier coolant are:

$AKMC1 = 2 * \frac{CPCM}{MMC1}$ and $AKMC2 = 2 * \frac{CPCM}{MMC2}$.

With these designations the following expressions for the multiplier coolant may be written:

$$\frac{d}{dt}TMW1 = \frac{CPMW}{MMW1} * (\gamma_{M1} * (TM - TMW1) - \gamma_{C1} * (TMW1 - TCM11))$$

$$\frac{d}{dt}TMW2 = \frac{CPMW}{MMW2} * (\gamma_{M2} * (TM - TMW2) - \gamma_{C2} * (TMW2 - TCM21))$$

$$\frac{d}{dt}TCM11 = AKMC1 * \left(ACCH1 + 0.5 * \gamma_{C1} * (TMW1 - TCM11)\right) * \frac{WCM1}{MMC1} * (TCM1IN - TCM11)$$

$$\frac{d}{dt}TCM12 = AKMC1 * \left(ACCH2 + 0.5 * \gamma_{C1} * (TMW1 - TCM11)\right) * \frac{WCM1}{MMC1} * (TCM11 - TCM12)$$

$$\frac{d}{dt}TCM21 = AKMC2 * 0.5 * \gamma_{C2} * (TMW2 - TCM21) * \frac{WCM2}{MMC2} * (TCM2IN - TCM21)$$

$$\frac{d}{dt}TCM22 = AKMC2 * 0.5 * \gamma_{C2} * (TMW2 - TCM21) * \frac{WCM2}{MMC2} * (TCM21 - TCM22)$$

The reflecting pool temperature changes with the two multiplier cooling structures that pass heated water from the gas bottle and multiplier coolant into the pool; hence, the pool temperature, TPOOL, changes dynamically according to the following expressions:

$$\frac{d}{dt}TPOOL = AKPL * WCPL * CPPL * (TPLIN - TPOOL)$$

Where $AKPL$=CPPL/MPL is the inverse heat capacity of the coolant in the pool; (CPPL is the specific heat of the coolant in the pool in MJ/kg/°C; MPL is the mass of coolant in the pool). WCPL is the mass flow rate of coolant into the pool in kg/sec from the two multiplier cooling loops; (WCPL=WCM1+WCM2); and, TPLIN is the inlet temperature of coolant into the pool.

The Heat Exchanger model involves piping between the core, the tube side and the shell side; both primary and secondary segments are modeled.

Piping from the core to the heat exchanger requires four variables:

- TP2 is the input temperature into the tube side in °C;
- MP2 is the mass of coolant in the pipe in kg;
- WCHE is the total primary mass flow rate in kg/sec. (for the solution vessel coolant loop WCHE=WC+WC2+WC3 where WC, WC2, and WC3 are the mass flow rates for each of the three in-solution cooling structure; for the multiplier and gas bottle cooling heat exchanger the sum of the two flow rates WCM1 and WCM2 are used);
- TP2IN is the average primary coolant vessel outlet temperature in °C.

With these definitions the heat exchanger primary inlet temperature may be cast as:

$$\frac{d}{dt}TP2 = \frac{WCHE}{MP2} * (TP2IN - TP2)$$

On the tube side with the identification of:

- MTT as the total mass of the tube side coolant lump (kg);
- γ_1 as the overall heat transfer coefficient tube side to tube (MW/°C);
- TT as the temperature of the tube in °C;
- TT1 and TT2 as the temperatures of the first and second half lumps in °C;
- CPC as the coolant specific heat of the coolant in the tube side (MJ/kg/°C).

The following expressions then apply:

$$\frac{d}{dt}TT1 = 2 * \frac{WCHE}{MTT} * (TP2 - TT1) - \frac{\gamma_1 * CPC}{MTT} * (TT1 - TT)$$

$$\frac{d}{dt}TT2 = 2 * \frac{WCHE}{MTT} * (TT1 - TT2) - \frac{\gamma_1 * CPC}{MTT} * (TT1 - TT)$$

So that the temperature of coolant entering the core, TC1IN, may be expressed as:

$$\frac{d}{dt}TC1IN = \frac{WCHE}{MP1} * (TT1 - TC1IN)$$

Where, MP1 is the mass of cooling in the pipe from the heat exchanger to the vessel in kg.

TT is as yet undefined. To determine its value a shell side model is required. As before the following definitions apply:

- TS1IN is the temperature of the secondary coolant in °C;
- WCS is the secondary side coolant mass flow rate in kg/sec;
- MSS is the total mass of secondary coolant lump in kg;
- γ_2 and γ_3 the overall heat transfer coefficients of the tube to shell side and shell side to shell in MW/°C;
- TS1 and TS2 the temperature of shell side coolant lump in °C;
- MT is the mass of the tube in kg;
- MS the mass of the shell in kg;
- CPT the specific heat of the tube in MJ/°C/kg;
- CPS the specific heat of the shell in MJ/°C/kg.

Then it may be written that:

$$\frac{d}{dt}TS1 = 2 * \frac{WCS}{MSS} * (TS1IN - TS1) + \gamma_2 * \frac{CPC}{MSS} * (TT - TS1) - \gamma_3 * \frac{CPC}{MSS} * (TS1 - TS)$$

$$\frac{d}{dt}TS2 = 2 * \frac{WCS}{MSS} * (TS1 - TS2) + \gamma_2 * \frac{CPC}{MSS} * (TT - TS1) - \gamma_3 * \frac{CPC}{MSS} * (TS1 - TS)$$

Where,

$$\frac{d}{dt}TT = \gamma_1 * \frac{CPT}{MT} * (TT1 - TT) - \gamma_2 * \frac{CPT}{MT} * (TT - TS1)$$

$$\frac{d}{dt}TS = \gamma_3 * \frac{CPS}{MS} * (TS1 - TS)$$

This completes the model description for the heat exchanger handling the vessel cooling. That for the heat exchanger handling the multiplier and gas bottle cooling is the same with the appropriate use of inlet temperatures and flow rates from those structures.

Radiolytic Gas Handling Extension

The radiolytic gas flow loop (GFL) starts with the plenum outlet and ends with the plenum inlet. Three gases are included in the GFL: air, which flows through the entire GFL, H_2 and O_2, which flow from the GFL inlet to the H_2/O_2 removal station.

The primary components of the GFL are as follows:

1. Piping: Straight pipe sections, bends, and valves.
2. Blower (compressor): Moves volume of gas with moderate to substantial increase in pressure.
3. Heat Exchangers: Each heat exchanger, *i*, will have heat input $\dot{Q}_i$ as well as an associated pressure drop, or head loss, on the gas side. Liquid water cooling or heating is assumed on the other side of the heat exchanger. There will be a heat exchanger for each gas-capture resin bed and one downstream from the H_2/O_2 removal system that sets the temperature of the cover gas before it exits the GFL and enters the plenum.
4. Gas-capture Resin Beds: In series to remove gases present in trace amounts such as iodine or xenon. Additional heating or cooling may be required at the resin beds, depending on the technology and design of these components.
5. H_2/O_2 Removal System: Consisting of a re-combiner and condenser. The re-combiner removes H_2 and O_2 from the gas mixture, producing water as a gas. The condenser serves to convert the water gas into liquid and remove the water from the GFL to the H_2O holding tank. These components will both have an associated head (pressure) loss. There will be heat added to the system in the re-combiner, proportional to the water production. The condenser is in essence a heat exchanger that removes the heat from the gas flow and moves the condensed water to the holding tank. There is at least one additional stage where the gas flows through a bed of desiccant to further reduce the relative humidity. Instead of desiccant the system may employ flow plates with a gas-separating membranes and dry hot gas flowing on the other side of the membrane.

The energy balance in the GFL treated as a single phase incompressible gas mixture may be expressed as follows.

$$\sum_i \dot{Q}_i + \dot{m}_{mix}\left[u + \frac{p}{\rho} + \alpha\frac{v^2}{2} + gz\right]_{1=GFL-in}$$
$$= \sum_i \dot{W}_i + \dot{m}_{CG}\left[u + \frac{p}{\rho} + \alpha\frac{v^2}{2} + gz\right]_{2=GFL-out}$$
$$+ \dot{m}_i \sum_i HeadLosses_i + \dot{m}_{H2-O2}\left[u + \frac{p}{\rho} + \alpha\frac{v^2}{2} + gz\right]_{3=Condenser-out}$$

Where

- u is the internal energy (can be expressed as enthalpy: $h = u + \frac{p}{\rho}$)
- p is the pressure
- ρ is density

- v is the average fluid velocity at the cross section (α=1 for turbulent flow, Reynolds number > 4000, which will be the case for most pipe flows in this sort of system; or α=2 for laminar flow, Reynolds number <2300, which would be the case for very small pipes in heat exchangers)
- g is the gravitational constant
- z is the head height

In general, mass flow rate may be expressed as $\frac{dm}{dt} = \rho v A$, where the area A is based on piping.

The ideal gas law, $p_i v = m_i R_i T_i$, applies with Dalton's Law for partial pressure, $p = \sum_i p_i$.

Care must be exercised when specifying mass flow in the above equations. The mass flow will either be $\dot{m}_{mix}$ for mixture (GFL inlet) or $\dot{m}_{CG}$ for the cover gas only (GFL outlet). For the major portion of the GFL from the plenum to the re-combiner and condenser there is a mixture of cover gas, H_2 and O_2. However, from the condenser back to the plenum there is only the cover gas since the H_2 and O_2 have been recombined and removed from the stream. For head losses of major components the appropriate mass flow rate must be specified. Later design stages will incorporate optimal order of the specific stages/components of the GFL, based on the operating requirements of individual components, such as operating temperature and humidity.

Piping – The following treatment is for straight pipe sections, bends, and valves. Head loss due to piping in heat exchanges is treated separately.

Head losses may be categorized as major or minor. Major head losses are due to friction in straight pipe sections. Minor head losses, also termed local, arise from pressure drop at bends, valves and similar structures. For a GFL all major and minor head losses are summed around the loop.

Major head losses sum those for each straight pipe section in the GFL and may be expressed as:

$$\sum h_{major\_piping} = \sum \left(f\frac{L}{D}\right)_{piping} \frac{v^2}{2}$$

where L is the length of the pipe section, D is the hydraulic diameter, v the average fluid velocity in the section, and f is the friction factor.

The friction factor is dependent on whether the flow in the pipe is laminar or turbulent. For this treatment if the Reynolds number, Re, for the flow is greater than 4000 the flow is characterized as turbulent. Flow is deemed laminar if Re < 2300. For values 2300 < Re < 4000 flow is called intermediate and is treated as a weighted combination of the two correlations.

For turbulent flow (Re > 4000), $f = f\left[\frac{\epsilon}{D}, Re\right]$, where ε is a coefficient related to pipe wall roughness. This functional relationship for f may be determined from the Moody diagram that presents experimental values for fully developed flow in circular pipes.

More conveniently, f may be approximated by the following relationship:

$$f = \left[1.14 - 2log\left(\frac{\epsilon}{D} + \frac{9.35}{Re\sqrt{f}}\right)\right]^{-2}$$

For laminar flow (Re < 2300): $f = \frac{64}{Re}$.

Minor, or local, head losses are a function of the specific flow element and its geometry (pipe bend, entrance/exit, valve, flow meter, desiccant bed, etc.); the values for k may be found in various handbooks (e.g. Idelchick). All local losses in the GFL may be lumped into the following expression noting that each element will have its own value of k and the associated velocity v for the given cross sectional area of the element.

$$\sum h_{minor_{pipe-valve}} = \sum k_{local}\frac{v^2}{2}$$

Blower – This component moves the volume of gas along with moderate increase in pressure, which adds energy to the system. The blower work term may be expressed as:

$$\dot{W}_{blower} = FR\left(\frac{m^3}{s}\right)\Delta p_{blower} = \frac{\dot{m}}{\rho}\Delta p_{blower}$$

Where FR is the volumetric flow rate and Δp_{blower} is the pressure rise. Note that this power will be negative denoting input to the fluid. In a scenario where a large increase in pressure is needed (e.g. for large gas flow rates) a compressor is used rather than a blower, with consequence that one must take into account the compressibility of the gas as well as the temperature rise due to compression.

The head, or pressure rise, of the blower, pump, or compressor must be determined for each specific flow rate; however, each device has a characteristic curve, $\Delta p_{blower} \sim - const \cdot FR^2$, thus for a set system head rise will move along the characteristic curve. Variable-speed devices move along multiple characteristic curves.

Heat Exchangers – The heat transfer of the *i*-th exchanger may be expressed as:

$$\dot{Q}_i = \dot{m}_{hot}\left(h_{hot_{in}} - h_{hot_{out}}\right) = \dot{m}_{cold}\left(h_{cold_{out}} - h_{cold_{in}}\right)$$

For constant specific heat values and no phase change this expression may be recast.

$$\dot{Q}_i = \dot{m}_{hot}c_{p_{hot}}\left(T_{hot_{in}} - T_{hot_{out}}\right) = \dot{m}_{cold}c_{p_{cold}}\left(T_{cold_{out}} - T_{cold_{in}}\right)$$

Or with heat capacity rates: $C = \dot{m}c_p$

$$\dot{Q}_i = C_{hot}\left(T_{hot_{in}} - T_{hot_{out}}\right) = C_{hot}\left(T_{cold_{out}} - T_{cold_{in}}\right)$$

Maximum heat transfer may then be defined as $\dot{Q}_{i\_max} = C_{min}\left(T_{hot_{in}} - T_{cold_{out}}\right) = C_{min}\Delta T_{max}$

Where $C_{min} = \min(C_{hot}, C_{cold})$, which is the minimum heat capacity rate.

Define effectiveness as $\epsilon = \frac{\dot{Q}_i}{\dot{Q}_{i\_max}}$

The amount of heat transferred to the gas in a GFL heat exchanger is defined as follows.

$$\dot{Q}_i = U \cdot A \cdot \Delta T_{LM} = NTU \cdot C_{min} \cdot \Delta T_{LM}$$

U is the overall heat transfer coefficient in $\frac{W}{m^2K}$ for a heat exchanger, which depends on the specific design, in particular the mass flow rates of the fluids. A is the area of heat transfer and ΔT_{LM} is the log-mean temperature difference (LMTD): $\Delta T_{LM} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$. Indices 1 and 2 denote inlet/outlet for hot/cold side of the heat exchanger depending on the flow direction and the exchanger design. NTU is the number of transfer units; a dimensionless parameter where$NTU = \frac{U \cdot A}{C_{min}}$. In general, NTU is a function of design, efficiency and the extrema of heat capacity rates: $NTU = NTU\left(H_{x\_type}, \varepsilon, \frac{C_{min}}{C_{max}}\right)$. NTU-ε relations for different types of heat exchangers are tabulated in various places. Below is an example from Table 11.4 of Incropera/Dewitt[4].

TABLE 11.4 Heat Exchanger NTU Relations

Flow Arrangement	Relation		
Parallel flo	$\text{NTU} = -\frac{\ln[1-\varepsilon(1+C_r)]}{1+C_r}$		(11.28b)
Counterflo	$\text{NTU} = \frac{1}{C_r - 1}\ln\left(\frac{\varepsilon - 1}{\varepsilon C_r - 1}\right)$	$(C_r < 1)$	
	$\text{NTU} = \frac{\varepsilon}{1-\varepsilon}$	$(C_r = 1)$	(11.29b)
Shell-and-tube			
One shell pass (2, 4, . . . tube passes)	$(\text{NTU})_1 = -(1 + C_r^2)^{-1/2}\ln\left(\frac{E-1}{E+1}\right)$		(11.30b)
	$E = \frac{2/\varepsilon_1 - (1+C_r)}{(1+C_r^2)^{1/2}}$		(11.30c)
n shell passes ($2n, 4n,$ . . . tube passes)	Use Equations 11.30b and 11.30c with		
	$\varepsilon_1 = \frac{F-1}{F-C_r}$ $F = \left(\frac{\varepsilon C_r - 1}{\varepsilon - 1}\right)^{1/n}$ $\text{NTU} = n(\text{NTU})_1$		(11.31b, c, d)
Cross-flow (single pass			
C_{max} (mixed), C_{min} (unmixed)	$\text{NTU} = -\ln\left[1 + \left(\frac{1}{C_r}\right)\ln(1-\varepsilon C_r)\right]$		(11.33b)
C_{min} (mixed), C_{max} (unmixed)	$\text{NTU} = -\left(\frac{1}{C_r}\right)\ln[C_r\ln(1-\varepsilon)+1]$		(11.34b)
All exchangers ($C_r = 0$)	$\text{NTU} = -\ln(1-\varepsilon)$		(11.35b)

There will be a head loss associated with each heat exchanger, depending on the type and design. Derivation follows similar steps as for the piping. Considering the internal piping on the gas side, local and average gas velocity in the heat exchange the head loss may be expressed as:

[4] Fundamentals of Heat and Mass Transfer – 5th Edition; Frank P. Incropera and David P. DeWitt;

$$h_{Hx} = \sum \left[\left(f\frac{L}{D} \right) + k \right]_{Hx} \frac{v_{Hx}^2}{2}$$

Gas Capture Resin Beds – Removal of unwanted gases in the GFL is accomplished by use of resin beds in series. It is assumed that mass flow rate is constant throughout since these gases are in trace amounts. The pressure drop through the resin bed is modeled neglecting heat in/out, albeit that these heats may need to be considered at later design stages once the technology for each resin bed is selected. Each module can be approximated as flow through a screen. Head loss will depend on the specific design of a bed. Head loss is then summed over the beds: $\sum h_{resin\_bed} = \sum k_{resin_{system}} \frac{v^2}{2}$.

H_2/O_2 Removal System - consisting of a re-combiner and condenser. The re-combiner removes H_2 and O_2 from the GFL, producing water, which is then converted to the liquid phase by the condenser. The water is then transferred to the holding tank. Both components will have an associated head loss. In general, heat will be added to the system by the re-combiner proportional to water production. The condenser is essentially a heat exchanger, which removes heat from the gas flow.

There is one additional stage where the gas flows through a desiccant bed to further reduce the relative humidity. Instead of the desiccant stage, flow plates with gas separating membrane may be used with dry hot gas flowing on the secondary side of the membrane.

Summary of GFL Model – Revisiting the general expression for the energy balance of the GFL with reference to those just developed for the individual elements results in the following.

$$\sum_i (NTU \cdot C_{min} \cdot \Delta T_{LM})_{Hx\_i} + (NTU \cdot C_{min} \cdot \Delta T_{LM})_{Condenser} + \dot{Q}_{re-combiner}$$

$$+ \dot{m}_{mix} \left[u + \frac{p}{\rho} + \alpha \frac{v^2}{2} + gz \right]_{1=GFL-in}$$

$$= -\frac{\dot{m}_{mix}}{\rho} \Delta p_{blower} + \dot{m}_{CG} \left[u + \frac{p}{\rho} + \alpha \frac{v^2}{2} + gz \right]_{2=GFL-out} + \dot{m}_i \sum_i Head_{Losses_i}$$

$$+ \dot{m}_{H_2-O_2} \left[u + \frac{p}{\rho} + \alpha \frac{v^2}{2} + gz \right]_{3=Condenser-out}$$

Where

$$\sum_i Head_{Losses_i} = \sum h_{major\_piping} + \sum h_{minor_{pipe\_valve}} + \sum h_{resin\_beds} + \sum h_{Hx} + h_{re-combiner} + h_{condenser}$$

Summary

Extensions of the dynamic system simulation (DSS) for a generalized fissile solution system have been developed to include explicit models for cooling and radiolytic gas handling loops. These model extensions may be used to examine the expected performance of a specific system design.