ENCLOSURE 2
ATTACHMENT 8

SHINE MEDICAL TECHNOLOGIES, INC.

SHINE MEDICAL TECHNOLOGIES, INC. APPLICATION FOR CONSTRUCTION PERMIT RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

LA-UR-14-28684
STABILITY OF FISSILE SOLUTION SYSTEMS

8 pages follow

Stability of Fissile Solution Systems

Los Alamos National Laboratory
Advanced Nuclear Technology Group (NEN-2)
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Introduction

Dynamic system simulation (DSS) models of a variety of fissile solution systems have been developed. References 1 through 3 describe the preparation and application of these models to historic aqueous homogeneous reactors (AHR). Close agreement is obtained between theoretical treatment using DSS techniques and experimental data. Reference 4 extended this treatment to sub-critical, accelerator-driven systems. The kinetic behavior of these systems is governed by reactivity feedback mechanisms driven by fluid density changes arising from fuel heating and radiolytic gas generation. This behavior is the subject of DSS modeling. Here we consider linear stability analysis by developing transfer functions for these systems and, using the output of DSS models, suggest expected response to small deviations from equilibrium.

Space-Independent Kinetic Equations

As discussed in Reference 1, the space-independent behavior of a fissile solution system may be described by the following set of coupled equations:

$$\frac{dN}{dt} = \frac{\beta}{\Lambda}\left[(R-1)N + \sum_{j=1}^{m} f_j D_j\right] + \frac{Q_s}{n_0} \tag{1}$$

And

$$\frac{dD_j}{dt} = \lambda_j\left(N - D_j\right) \qquad \text{j=1, 2,…, m} \tag{2}$$

$$R = R_0(t) + (\alpha T + \varphi V) \tag{3}$$

Equation 1 governs the normalized prompt neutron population in the fissile solution, while the set of equations represented by Equation 2 track the normalized delayed neutron population. R is the reactivity of the system and Qs represents an external neutron source.

Temperature and radiolytic gas void in the fissile solution are governed by expressions given in equations 4 and 5.

$$\frac{dT}{dt} + \gamma T = K[P - P_0] \tag{4}$$

$$\frac{dV}{dt} + \sigma V = G[P - P_0] \tag{5}$$

Reference 5 presented the analysis of a transfer function for an AHR showing that for deviations from steady-state power, P_0, such that $\delta P(t)/P_0 << 1$, ($\delta P(t)=P(t)-P_0$) the system of equations 1 through 5 may be linearized and a general transfer function developed. This allows examinations of power fluctuations arising from variations in R_0 or Q_s.

Transfer Function and Stability Analysis

Applying the prescription given above the set of equations 1 through 5 may be linearized. Retention of the source term, Q_s, results in the steady-state reactivity, R_0, appearing explicitly in the transfer function:

$$G_p(i\omega;\ P_0) = \left[(i\omega l^* - R_0) + \sum_{j=1}^{m} j\omega\left(\frac{f_j}{i\omega+\lambda_j}\right) - \left(\frac{\bar{K}}{i\omega+\gamma}\right) - \left(\frac{\bar{G}}{i\omega+\sigma}\right)\right]^{-1} \quad (6)$$

Where $l^* = \frac{\Lambda}{\beta}$, $\bar{K} = K\alpha P_0, and\ \bar{G} = G\varphi P_0$

In the absence of Q_s the reactivity term is absent and the transfer function is identical to that presented in Reference 5 where results of applying Equation 6 in such cases are presented in the form of Bode and Nyquist plots. Data utilized in that analysis was that obtained from operation of the LOPO (LOw POwer) AHR that operated at Los Alamos National Laboratory (LANL) in the 1940's. The results of this analysis may be summarized as follows:

- For large enough P_0 a resonance occurs in the transfer function indicating that for such P_0 the reactor is less than critically damped in the linear approximation. Hence, in such cases the transient solution contains a damped oscillatory term with an angular frequency at which a resonance occurs;
- If α and φ are both negative, as is the case with uranium fissile solution systems, the non-linear transient solution also contains a critically damped term. Therefore, no infinite resonance can occur.

SUPO (SUper POwer), a descendent of LOPO, operated at LANL for 23 years from 1951 until 1974. During that period it accumulated approximately 600,000 kwh of operation. SUPO is considered the benchmark system for AHR performance. In Reference 6 the stability of SUPO is analyzed by utilizing experimental data from SUPO operations to develop a simulation model. This model exhibited no sustained reactivity oscillations and predicted mild core thermo physical response during transients due to large thermal inertia of the solution fuel and the rapid reactivity feedback of the radiolytic gas.

Figures 1 and 2 provide Bode amplitude and phase shift diagrams for SUPO using the transfer function in Equation 6 with values obtained from the DSS model for SUPO as identified in references 1 through 3.

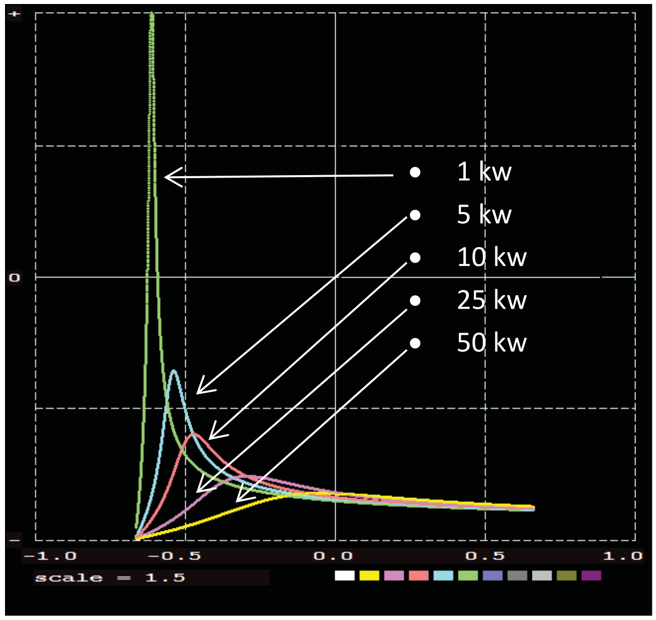

Figure 1 Bode Amplitude Plot for SUPO

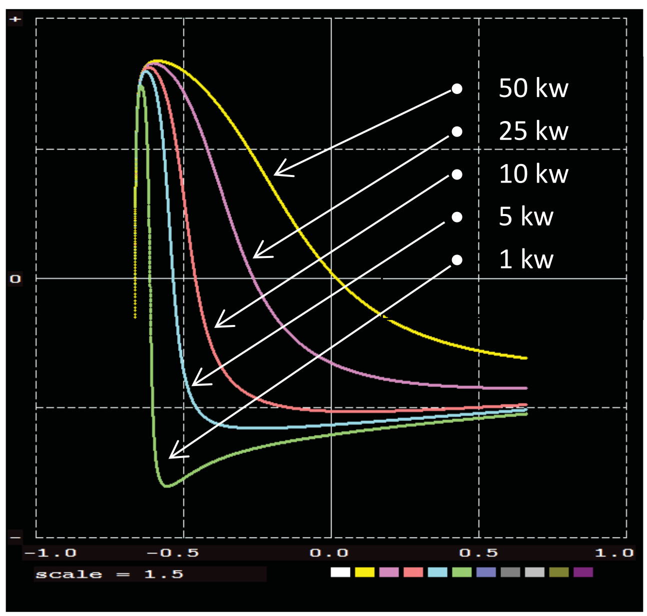

Figure 2 Bode Phase Shift Plot for SUPO

The relative behavior of SUPO given here and LOPO given in Reference 5 is the same:

- Resonances occur in amplitude plots with both reactors showing resonances at approximately the same frequencies (~0.01 – 0.1 radians/sec) at high power. SUPO exhibits resonances for low power. All are damped;
- Amplitude damping is greater the higher the fission power; (in this sense higher power systems are increasingly stable);
- Phase shifts increase with power.

Figures 3 and 4 provide Nyquist plots for SUPO. Here only the terminal region approaching $\omega = 0.1$ is shown. Figure 3 is a large scale view. The contours are closed by the arc at$-\infty$. Figure 4 is a detail view

of the contours near +1. Since there are no unstable closed loops stability may be claimed as in Reference 5 and the conclusions of that reference apply.

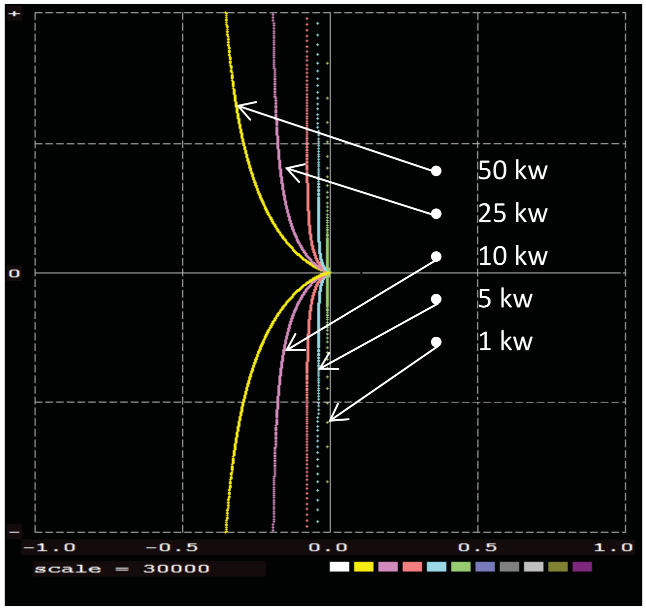

Figure 3 Nyquist Trajectories for SUPO

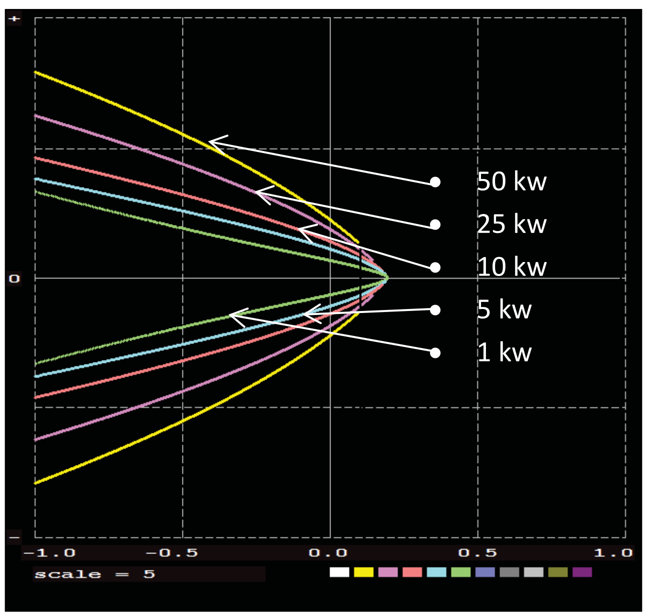

Figure 4 Details of Nyquist Trajectories Near +1

Reference 4 presented a DSS for a sub-critical accelerator-driven system. Power dependency on the external source is described as are examples of perturbations from steady-state reactivity (such as may occur from off-normal behavior in the gas loop) and an oscillating source.

Figure 5 illustrates the response of a sub-critical accelerator-driven system operating at steady-state to step reactivity (R_0) insertion. Figure 6 illustrates the response to oscillation in the source Q_s.

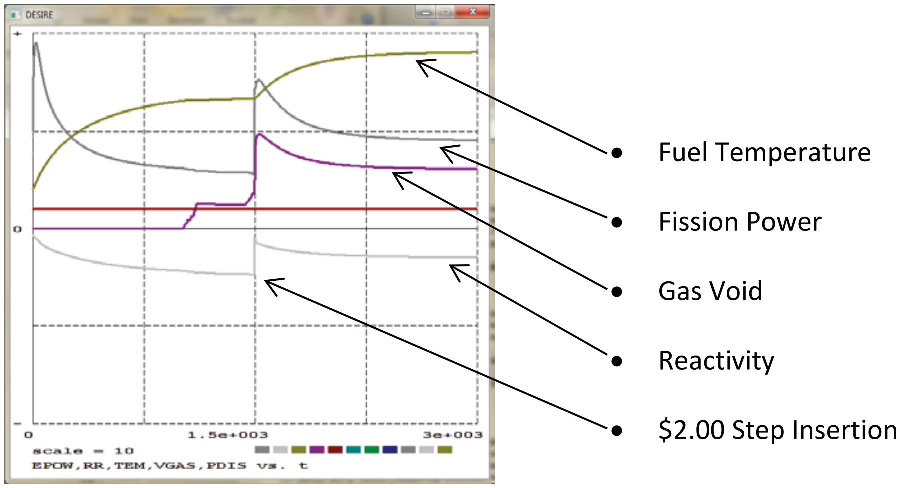

Figure 5 System Responses to a Step Reactivity Insertion

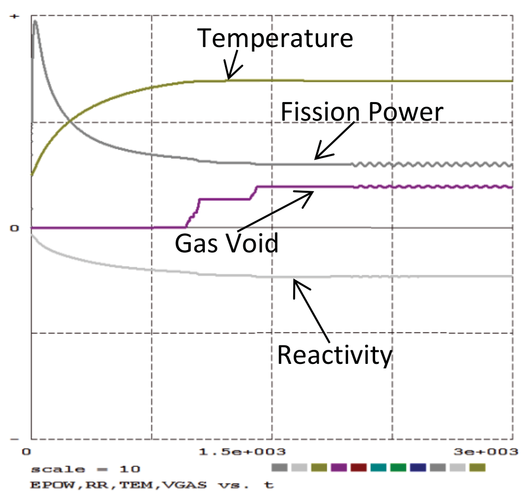

Figure 6 System Responses to Accelerator Output Oscillation

In Figure 5 the rapid damping of the step increase can be seen with the result that a new steady-state is reached. This would be the case regardless of the source of the reactivity step (control rods, clogged plenum, increased flow or decreased temperature of coolant). Figure 6 illustrates that an oscillating source results in a similar oscillation in the fission power. In either case reaction to bounded excursions are similarly bounded.

If we apply the general transfer function in Equation 6 to an accelerator-driven sub-critical system the following Bode and Nyquist plots are obtained. The DSS for such a system described in Reference 4 was utilized to obtain steady-state power and other parameters needed in Equation 6; Figures 7 through 10 presents the results.

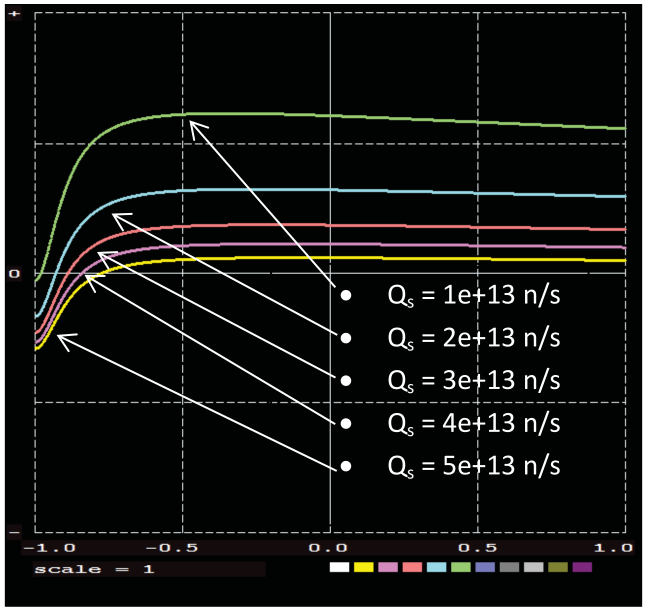

Figure 7 Bode Amplitude Plot for an Accelerator-Driven System

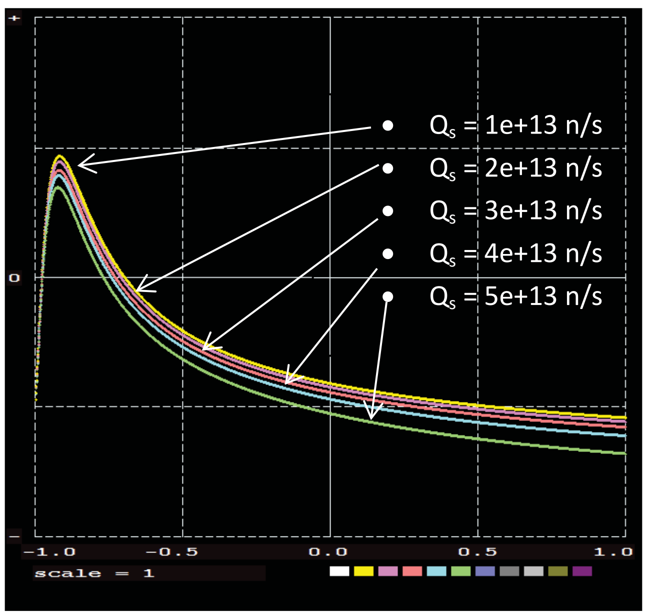

Figure 8 Bode Phase Plot for an Accelerator-Driven System

The close grouping of both the amplitude and phase shift plots for the accelerator-driven sub-critical system shows that there is little dependency on the stability characteristics of the system over this range of neutron source values. Fundamentally, this is an expression of the low power density (~0.3 – 0.5 kw/liter) as compared to AHR that generally operate in the 1.5 – 3.0 kw/liter range.

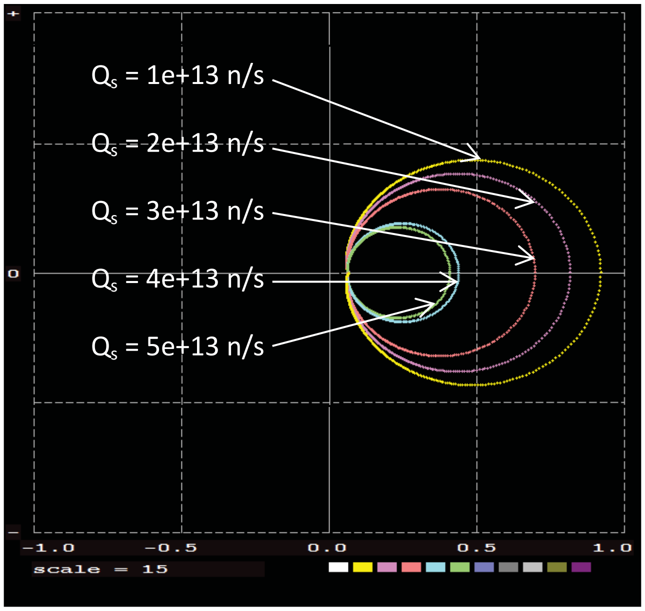

Figure 9 Nyquist Plot for Accelerator-Driven System

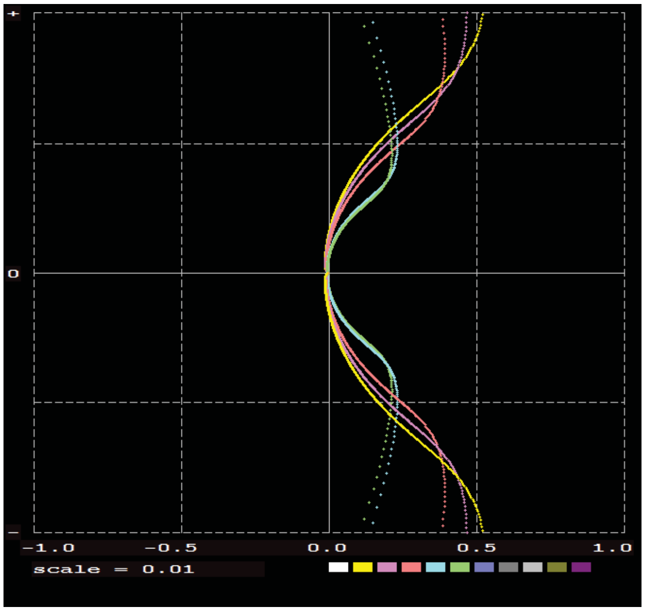

Figure 10 Details of Nyquist Plot for Accelerator-Driven System Near +1

As can be seen from these figures the general stability characteristics of a sub-critical accelerator-driven system mimic that of the fissile solution reactor:

- Resonances of the transfer function decrease with increasing power while phase shift increases;
- The plot of the characteristic equation (Nyquist) meets stability criteria;
- These systems exhibit high stability across a wide range of source strengths.

Conclusions

A general transfer function applicable to both AHR and subcritical accelerator-driven systems has been presented. Analysis of the results of applying the transfer function to both classes of systems employing fissile solution fuel allows the general conclusions:

- These systems are unconditionally stable in the linear approximation;
- For negative reactivity feedback in temperature and radiolytic gas void, as is the case with uranium fissile solution systems, non-linear stability criteria is met;
- In general it may be concluded that no bounded reactivity or source strength excursion can result in an unbounded response.

References

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