LA-UR-96- - 1 4 9 8

CONF-9605176--2

Title:

Preliminary Results of GODIVA-IV Prompt Burst Modeling

RECEIVED

MAY 31 1996

OSTI

Author(s):

R. H. Kimpland

Submitted to:

Nuclear Criticality Technology Safety Project
(NCTSP) Workshop
Gaithersburg Hilton Hotel
Gaithersburg, Maryland
May 14-15, 1996

MASTER

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Form No. 836 R5
ST 2629 10/91

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Preliminary Results of GODIVA-IV Prompt Burst Modeling

Robert Kimpland

I. INTRODUCTION

A computer model, which simulates the dynamic behavior of the GODIVA-IV fast (neutron) burst reactor, has been developed at the Los Alamos Critical Experiments Facility (LACEF). This model combines the neutron point kinetics equations with an equation of state, energy, momentum, and continuity equations for uranium metal, through fuel expansion reactivity feedback coefficients. The results of the computer model have been compared with experimental data from GODIVA-IV prompt bursts.

The goal of this work is a better understanding of the basic physics of GODIVA-IV prompt bursts. In particular, a better understanding of inertial effects and dynamic reactivity feedback caused by thermal expansion. Inertial effects are large transient mechanical stresses and accelerations that are produced in fuel materials during sufficiently large exponential power bursts. These stresses are caused by a "lag" in the thermal expansion of the fuel material. Fission energy is deposited into the fuel at a rate greater than normal (temperature following) thermal expansion can accommodate, as a result, mechanical stresses are generated in the fuel material.¹ These stresses cause a rapid acceleration of the fuel material, which leads to fuel material redistribution, expansion, and vibration.

Prompt bursts in GODIVA-IV are quenched by the negative reactivity effects of fuel expansion. As the fuel expands, its density decreases and neutron leakage increases. The burst yield is significantly affected by inertial effects, however, because of the "delay" in fuel expansion.² Figure 1 shows the actual power pulse for a \$1.03 GODIVA-IV prompt burst. The

familiar bell-shaped power pulse is generated for a burst of this size, indicating that normal thermal expansion is occurring. In this range of burst operation (a few cents above prompt critical or less), the burst yield increases linearly with excess reactivity above prompt critical. This behavior is described analytically by the Nordheim-Fuchs model of fast burst reactors.³ However, at some point (greater than a few cents above prompt critical), the burst yield increases more than linearly with excess reactivity. In this range of burst operation, the neutron kinetics, and therefore the fuel heating, are so energetic that the negative reactivity feedback of fuel expansion cannot quench the burst as effectively as in the case of smaller bursts. The fuel expansion and reactivity feedback are said to be "delayed" in this range of operation, because these effects can no longer "keep up" with the neutron kinetics. Figure 2 shows the actual power pulse of a \$1.10 GODIVA-IV prompt burst. The power pulse exhibits a noticeable asymmetry, the trailing side of the pulse falls more rapidly than it rises. This behavior is caused by transient mechanical stresses generated in the fuel material during the burst. These stresses produced a rapid acceleration of the fuel material, which lead to rapid fuel expansion. As a result, large negative reactivity feedback causes the power to fall off rapidly after the peak.

II. THEORY

The GODIVA-IV prompt burst reactor consists of six interlocking fuel rings clamped together with three steel C-clamps. Each ring has a 7-in. outer diameter and a 3.5-in. inner diameter. The total height of the six rings is 6-in.. The central cavity is filled with fuel pieces mounted on a central stainless steel mandrel. A small gap on the order of 10 to 20 mils exists between the central fuel pieces and the fuel rings. The fuel consists of a 1.5-wt% molybdenum-

uranium (93.5% enriched) alloy. The total mass of fuel in the core is approximately 65.4 kg. Because of the relatively complex structure of GODIVA-IV, separate neutronic and hydrodynamic models of the reactor have been developed.

Neutronic Model

A neutronic analysis has been performed to determine the dynamic reactivity feedback coefficients associated with fuel expansion. The two-dimensional neutron transport code TWODANT, was used to calculate the change in reactivity with small changes in fuel density, at various locations within the fuel.⁴ Figure 3 shows a diagram of the GODIVA-IV neutronic model. The model consists of a center fuel piece, surrounding a steel core, and the fuel ring stack, which is separated from the center by a small gap. The fuel is split up into 7 radial zones or concentric cylinders, two zones in the central fuel piece and 5 zones in the fuel rings. The density of each zone is then decreased one at a time by a small amount, while the zone boundaries are adjusted to conserve mass. Based on results produced by the hydrodynamic portion of the computer model, zones 1,2,5,6, and 7 are assumed to expand outward, and zones 3 and 4 are assumed to expand inward, filling the gap. The change in reactivity from the base case is calculated for each zone, and a reactivity feedback coefficient is obtained. Table 1 summarizes the results of this analysis.

The presence of the gap between the fuel rings and the center fuel piece has a significant affect on the reactivity feedback. The zones that expand outward, and move fuel away from the center, produce a negative reactivity insertion. The zones that expand inward, and move fuel toward the center of the core, produce a positive reactivity insertion. Based on these calculations,

it has been assumed that the reactivity feedback produced by zones 1-4 will most likely cancel out. Zones 5-7 will most likely be the main contributors to reactivity feedback during a burst.

To calculate the power of a GODIVA-IV prompt burst as a function of time, the neutron point kinetics equations are used. These equations in normalized form are given by

$$\frac{dN}{dt} = \frac{\beta}{\Lambda} \left[(R-1)N + \sum_{i=1}^6 \frac{\beta_i}{\beta} D_i \right] \quad (1)$$

and

$$\frac{dD_i}{dt} = \lambda_i (N - D_i) \quad (2)$$

where N is the relative fission power, R is the reactivity of the reactor in dollars, Λ is the mean generation time, D_i is the relative precursor power of the i^{th} group, and β_i and λ_i are the standard delayed neutron parameters. The power of the reactor n , in Megawatts, is given by $n = n_o N$, where n_o is the initial power of the reactor. The reactivity of the reactor is given by

$$R = R_o + \sum_{i=5}^7 \phi_{\text{zone } i} \Delta \rho_{\text{zone } i} \quad (3)$$

where R_o is the initial reactivity step, $\phi_{\text{zone } i}$ is the fuel expansion reactivity feedback coefficient for zone i (given in Table 1), and $\rho_{\text{zone } i}$ is the fuel density of zone i . Based on a Rossi- α measurement, β/Λ is given the value $8.5 \times 10^5 \text{s}^{-1}$.

Hydrodynamic Model

The presence of the gap between the fuel rings and the center fuel pieces isolates the fuel rings mechanically. They are allowed to expand freely, both inward and outward radially. It has been assumed that the steel C-clamps, which hold the stack of rings together, restrict most of the

axial expansion along the top and bottom surfaces of the stack. Figure 4 shows a diagram of the hydrodynamic model for GODIVA-IV. The model consists of a hollow cylinder of fuel, which has been broken up into 40 regions, 8 axial mesh points and 5 radial (the radial zones are equal to the neutronic model's radial zones). Each region has its own equation of state, energy, momentum and continuity equations.

An equation of state for uranium metal may be written as follows

$$\frac{dP}{dt} = \frac{\alpha}{\kappa} \frac{dT}{dt} + \frac{1}{\rho \kappa} \frac{d\rho}{dt} \quad (4)$$

where P is condensed phase pressure, T is temperature, ρ is density, α is the isobaric compressibility of uranium metal ($4.456 \times 10^{-5} \text{ K}^{-1}$), and κ is the isothermal compressibility of uranium metal ($1.856 \times 10^{-5} \text{ MPa}^{-1}$).⁵ The rate at which the metal density changes with time may be written as

$$\frac{\partial \rho}{\partial t} = -\rho \left[\frac{\partial U_z}{\partial z} + \frac{1}{r} \frac{\partial (r U_r)}{\partial r} \right] \quad (5)$$

where U_z and U_r are the axial and radial velocities of the fuel, respectively. To obtain these velocities, a simplified version of the Navier-Stokes equations is used. In cylindrical coordinates, these equations may be written as

$$\rho \frac{\partial U_z}{\partial t} = -\frac{\partial P}{\partial z} \quad (6)$$

and

$$\underline{(7)} \quad \rho \frac{\partial U_r}{\partial t} = - \frac{\partial P}{\partial r}.$$

An energy equation for the reactor may be written as

$$\rho C_p \frac{\partial T}{\partial t} = \frac{n}{V} f(r,z) \quad (8)$$

where C_p is the specific heat of uranium metal (1.403×10^4 MJ/kg°C), V is the volume of the fuel, and $f(r,z)$ is a function describing the spatial distribution of the fission power in the reactor. It has been assumed that the work done by the metal and heat transfer are negligible during the prompt bursts of interest.

The hydrodynamic model presented above, has been solved numerically with the use of a dynamic system simulator.⁶ These simulations track fuel temperature, density, pressure, displacement, and velocity as a function of time and position. The hydrodynamic model is coupled with the neutron point kinetics model through the fuel expansion reactivity feedback coefficients given in equation 3. Thus, the combined hydrodynamic and neutronic models can simulate self-limiting prompt bursts in GODIVA-IV.

III. RESULTS

The change in fuel temperature at the thermal couple location and the full width at half maximum for several GODIVA-IV prompt bursts have been measured. The model has been used to simulate these prompt bursts, in order to determine the accuracy of the model. Table 2 shows a comparison between the model's results and the experimental data. The maximum relative error between the model's fuel temperature change and the experimental data is 29%, which occurs

for the \$1.072 burst. The maximum relative error between the model's FWHM and the experimental data is 17%, which occurred for the \$1.031 burst. Based on these results, the model appears to be adequately coupling hydrodynamics and neutronics.

Figure 5 shows the model's simulation of \$1.031 prompt burst. The power pulse demonstrates the bell-shaped profile exhibited in Figure 1. The stress curve shows the time behavior of the maximum stress, which was produced along the central radius of the fuel stack. Figure 6 shows the average displacement of the inner and outer radial surfaces of the fuel stack during the \$1.031 burst. These Figures illustrate the behavior of a prompt burst where inertial effects do not occur. The stress curve shows a single compression-tension wave, which subsides immediately. The displacement curves show the fuel expanding with temperature, but without any rapid accelerations.

Figure 7 shows the model's simulation of a \$1.10 prompt burst. The power pulse shows the same kind of asymmetry exhibited in Figure 2. Again, the stress curve shows the maximum stress, which occurred along the central radius of the stack. Figure 8 shows the average displacement of the inner and outer radial surfaces of the stack for the \$1.10 burst. These Figures illustrate the behavior of a prompt burst in which inertial effects do occur. The stress curve shows a continuous compression-tension wave of varying amplitude occurring in the uranium metal. The displacement curves show the inner and outer radial surfaces vibrating. This vibrating or "ringing" is caused by the rapid accelerations produced by the compression-tension waves. The frequency of these radial displacement waves is 19.4 kHz. This same frequency has been observed in all the simulations in which inertial effects occur.

Figure 9 shows the radial distribution of the maximum stresses produced during the \$1.10 burst. These stresses occurred at the half-height position in the fuel stack. The largest stress

occurs along the central radius of the rings, while the minimum stresses occur along the inner and outer radial surfaces. These stresses oscillate with the same frequency as the inner and outer radial surface displacements, however the amplitude of the stress waves varies with time.

IV. CONCLUSION

The dynamic computer model developed to simulate GODIVA-IV prompt bursts adequately predicts the magnitude of power bursts. Also, it demonstrates the characteristic features of prompt bursts in metal assemblies, such as the change in shape of power pulses and the "ringing" of fuel surfaces at the onset of inertial effects. The model will be used to test more sophisticated reactivity feedback coefficients and neutronic-hydrodynamic coupling schemes. It will also be used for a more detailed analysis of inertial effects.

REFERENCES

1. T.E. Wimett, "Dynamics and Power Prediction in Fission Bursts," *Nuclear Science & Engineering*, Vol. 110, pp. 209-236 (1992).
2. T.E. Wimett et al., "Godiva II-An Unmoderated Pulse-Irradiation Reactor," *Nuclear Science & Engineering*, Vol. 8, pp.691-708 (1960).
3. D.L. Hetrick, *Dynamics of Nuclear Reactors*, (University of Chicago Press, Ltd. 1971).
4. Ray E. Alcouff et al., "DANTSYS: A Diffusion Accelerated Neutral Particle Transport Code System," Los Alamos National Laboratory Document, LA-12969-M, (June 1995).
5. D.M. Peterson et al., "PAD: A One-Dimensional Coupled Neutronic-Thermodynamic-Hydrodynamic Computer Code," Los Alamos Scientific Laboratory Report, LA-6540-MS, (December 1976).
6. G.A. Korn, *Interactive Dynamic System Simulation*, (McGraw-Hill, inc. 1989).

Table 1 . Results of neutronic analysis

Location	K_{eff}	ϕ \$(g/cm^3)
Base Case	1.009364	~
Zone 1	1.009326	~
Zone 2	1.009337	~
Zone 3	1.009393	~
Zone 4	1.009459	~
Zone 5	1.009194	-0.666
Zone 6	1.009259	-0.411
Zone 7	1.009319	-0.176

Table 2 Comparison between the model's results and experimental data.

	Model		Exp.	
Burst \$	Fuel ΔT °C	FWHM μ sec.	Fuel ΔT °C	FWHM μ sec.
\$1.031	72	133	68	114
\$1.050	128	79	~	82
\$1.072	194	51	151	50
\$1.092	262	37	230	36
\$1.100	295	33	270	33

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Godiva-IV \$1.03

Figure 1 \$1.03 Godiva-IV Promptburst

Godiva-IV \$1.10

Figure 2 \$1.10 Godiva-IV prompt burst

Godiva-IV Neutronic Model

Figure 3 Neutronic model.

Godiva-IV Hydrodynamic Model

Figure 4 Hydrodynamic model.

Figure 5 Model's simulation of \$1.03 burst.

Figure 6 Surface displacement for 7/1.03 burst.

Figure 7 Model's simulation of #1/10 burst

Figure 8 Surface displacement for #1.10 burst.

Figure 9 Radial distribution of stresses produced during #1.10 burst