ANALYSIS OF PROMPT EXCURSIONS IN SIMPLE SYSTEMS.

W. R. Stratton and T. H. Colvin

The motivation for the study which I will describe this afternoon was the desire or necessity to make relatively accurate estimates of nuclear accidents that a fast reactor might experience during its lifetime. Estimates of the so-called "maximum credible accident" have been made by various people. In particular Drs. Bethe and Tait have made estimates for the reactor at Dounreay, Scotland, and N.D.A. personnel have made similar calculations for the Detroit-Edison reactor. It was our hope that by developing a somewhat different calculation that could be coded for the fast digital computers at Los Alamos, we could make some progress toward understanding the various parameters that are used to describe these conceptual accidents.

After this study was started it became obvious that the reactor accident problem was too complicated to be solved at once. We needed some carefully controlled experiments in, hopefully, a simple system that we could use to test our theory or calculations. In other words, we felt the need to be able to solve a somewhat more restricted problem before attacking the more difficult one of reactor accidents.

The simple system which we have studied to test the calculation is that of the LASL's Lady Godiva. Before I describe the calculation we use, it is worthwhile reviewing what Lady Godiva is, and the prompt burst program she experienced.

Godiva is a bare, highly-enriched uranium metal assembly which is fabricated in three sections that go together to form a sphere. The first slide illustrates Godiva in the disassembled state. The total mass of the system is about 55 kg

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and the U^{235} content is not quite 94%. The system is normally assembled by remote control, and any experiments are monitored by appropriate counters, detectors, and closed circuit television.

Godiva was originally made in order to find, accurately, the delayed and prompt critical masses of unreflected, enriched uranium in the form of a sphere. By delayed critical mass we mean that mass such that a neutron flux existing in the assembly is just maintained -- neither increasing nor decreasing. To maintain this situation the assembly must call upon all neutrons from fission -- the delayed fraction as well as prompt neutrons. The prompt critical mass is defined as that mass such that a neutron flux can be maintained by calling upon the prompt neutrons only. Since delayed neutrons are still present, the neutron level at prompt critical steadily increases with a period of about 1 millisecond. That is, a flux will increase by a factor of e in every millisecond. The surface mass that one has to add to Godiva to change her behavior from delayed to prompt is about 1270 grams. Addition of more mass will make her super prompt critical, and the effect of delayed neutrons is trivial. For example, addition of 200 grams over that of the prompt critical mass results in a period of about $6\mu\text{sec}$.

One more definition will be of use. The interval between delayed critical and prompt critical is usually defined as an interval of reactivity -- often referred to as one dollar of reactivity. It is a more general concept than an increment of surface mass. For example, the change in reactivity from delayed to prompt behavior could have been accomplished by adding a neutron reflector or increasing the average density by eliminating parting planes, and partially filled holes. For the bare Godiva, reactivity is linear with added surface mass.

The prompt bursts are manufactured by assembling the three pieces of metal with a control rod adjusted such that the system is just below delayed critical. A booster slug of metal is then fired into the center section by means of an air gun. This slug of enriched uranium is worth slightly more than a dollar in reactivity, making the system super prompt critical by a few cents. A burst develops very shortly thereafter.

Very briefly, these controlled bursts develop in the following manner. The neutron level, and consequently fission energy, rises exponentially with periods or e-folding times of from about 10 to 350 microseconds. This continues until thermal expansion caused by the fission energy reduces the reactivity below prompt critical, and the neutron flux and fission rate drop about as fast as they rose a few μ sec before. About this time the system is "scrammed" by automatically separating the three pieces of metal.

The second slide illustrates a composite picture of several bursts. The measured fission rate is plotted against time. The period or e-folding time of the neutron flux of each burst is indicated to the right of the peak.

Each burst was followed by use of scintillation detectors activated by the leakage flux of neutrons. The output of these counters were displayed on an oscilloscope and automatically photographed. The fission yield of each burst was obtained by measuring the induced activity in a sulfur pallet attached to the surface of Godiva. This in turn was related to fissions in Godiva by separate experiments.

Two variables are present on this slide to which I will refer later. These are the maximum fission rate for each burst and the width in time of the burst at one-half maximum value. Note that the maximum rate changes by a

factor of about 1000 when the period changes by a factor of only 30 from 11.6 μ sec to 350 μ sec. The width of the peak gets progressively smaller as the period decreases, although this is seen less clearly because of the logarithmic plotting. The peak power level of the 11.6 μ sec burst is rather astounding. It is about 8000 megawatts. Fortunately, it doesn't last long.

The third slide illustrates the total fission yield of several bursts as a function of reciprocal period. The burst gets more violent as the period decreases, or reciprocal period increases. The reciprocal period is commonly known as the "alpha" of the system. The prompt alpha is directly proportional to excess reactivity over prompt critical. Note on this slide that at low alphas the burst is linearly related to alpha, but at higher values the burst yield increases much faster. This breakaway from a linear dependence on reactivity is a most important feature of the experiments. We feel that it must be understood before calculations can be made on more complex systems.

These last two slides summarize the experimental information that we will attempt to match theoretically. We will attempt to match the burst yield, the maximum rate, and burst width.

The calculation that we have been using is one designed for a fast digital computer. It is conceptually possible to do it by hand, but in practice, impossible. In a general way it involves stepwise integration of various quantities in space and in time.

To be specific, we imagine Godiva to be a perfect sphere of enriched uranium of normal density, without, of course, the existing parting planes, partly filled holes, etc. We further imagine this sphere to be made up of several concentric spherical shells or mass points, as they are commonly called. The number of these

hypothetical shells including the innermost sphere is usually 10, but this is a variable at our disposal. It depends on the complexity of the problem. Each shell may be imagined to be characterized by 2 radii, a density, and various nuclear constants. In Godiva the nuclear constants and densities for each shell are initially identical, but for more complicated situations this may not be the case.

Slide 4 represents a somewhat simplified flow diagram or schematic of the calculation. Each box is meant to represent a given portion of the code. In a general way we are trying to match experimental results (in this case, those of Godiva) by numerically integrating differential expressions in space and time. The process is necessarily cyclical. I will try to show how this is done. Suppose we start at the box labeled fission energy generation. At this point in the code the fission energy rate is calculated for each mass point. Each of these fission rates is integrated in time, stepwise, by multiplying by a small increment in time. The space integration for fission energy generated in this time increment is merely a sum over mass points. These small increments in fission energy alter the temperature of each mass point through a heat capacity and by allowing each mass point to work thermodynamically on its neighbors. These temperatures lead directly to a new pressure gradient from which accelerations of each of the radii can be calculated. These can be integrated stepwise in time to give velocities, which in turn lead to new radii. Given a new configuration we turn to the neutronics portion of the code which gives us a new neutron multiplication or alpha, and a new flux distribution. We are now back to the starting point, but advanced a small increment in time; the procedure is repeated exactly as before, but with very slightly different variables.

This type calculation is not entirely new. I think where it differs from previous work is in the cycle including pressures, accelerations, and velocities calculated for small increments of time and many mass points. I have seen calculations described which essentially go from temperatures to radii, or to a new configuration by use of the coefficient of expansion. Including pressures, accelerations, and velocities allow non-equilibrium situations to develop. That is, one can find situations where pressures build up faster than velocities can expand the mass to a new equilibrium state. The inertia of matter is such that it can be moved only so fast.

A typical calculation representing a Godiva prompt burst would indicate a burst time from a low neutron flux level through a maximum and down to a low flux level again of about $120/\mu\text{seconds}$. A time increment of $1/4/\mu\text{sec}$ was used. We therefore repeated this cyclical procedure 480 times in this problem. The advantages of a fast digital computer are fairly obvious.

The neutronic calculation we use is the so-called Serber-Wilson one velocity approximation. It is valid for a system in which the neutron spectrum is fast, and does not change in time appreciably. If an appreciable portion of the flux is moderated, a more complicated method must be used.

To summarize, then, the computer calculates the fission rate for each mass point, as a function of time, at the same time changing the configuration incrementally through temperatures, pressures, accelerations, velocities and radii. The computer is programmed to print certain of the variables at various times and in general we can follow whatever variable we wish in both space and time throughout the problem.

To match the experimental results of the prompt burst program, the Serber-Wilson portion of the code was forced to give back a prompt neutron

alpha of zero for the prompt critical mass, and the delayed neutron Rossi alpha measured at the LASL for the delayed critical mass. This was done by assuming small variations in the nuclear constants used in the Serber-Wilson calculation. These same constants were then used throughout the entire study of the Godiva experiments. To obtain various alphas or reactivities above prompt critical, slightly different masses were entered as input conditions. The problems were started by assuming a neutron flux level greater than zero, but small enough that calculated internal temperatures were no different than room temperature. Several problems were run in and beyond the reactivity region covered by the Godiva experiments.

The fifth slide compares the experimental and calculated prompt burst fissions as a function of reactivity. We have, incidentally, taken prompt critical as zero reactivity, purely for convenience. The agreement is quite satisfactory at the higher reactivities. In particular we can catch the break from a linear dependence on reactivity quite accurately. At very high reactivities, the yield is proportional to the reactivity cubed. We tend to underestimate the yield at low reactivities. The principal reason, we think, involves reflected neutrons from the ground even though the system was suspended about twenty feet in the air for these experiments.

The sixth slide illustrates our agreement with the maximum fission rate as recorded during the experiments. The plot is again against reactivity. This maximum rate changes many factors of ten over the range of experiments and so logarithmic plotting is necessary. Here again we underestimate at low reactivities, but in this case, overestimate at the high reactivities, but not seriously.

The seventh slide is intended to compare our estimate of the burst shape with the experimental values. The width, as you recollect, is the spread in time of the burst at one-half its maximum value. It should be a fairly easy quantity to measure. In order to avoid logarithmic scales again this quantity is multiplied by alpha, the reciprocal period — experimentally a precise quantity. The width is inversely proportional to alpha, so their product should be nearly constant. The abscissa is alpha per μsec (in units of reciprocal μsec) which for Godiva is numerically practically the same as reactivity. We can see here there is at least one reason why the burst yield is calculated to be low near prompt critical. We underestimate the width of the burst as well as the maximum rate. As I mentioned before, it is thought that reflected neutrons cause most of the rise in the experimental data. At higher reactivities we also underestimate the burst width. However, the previous slide indicated that in this reactivity region we overestimate the maximum rate. Apparently, the two errors, neither of which is large, cancel each other to result in the correct burst yield. This effect at the higher reactivities is thought to result from the effects of Godiva being made in pieces, each of which can adjust to a temperature rise easier than can a large homogeneous sphere. We have set up one calculation which is a relatively crude attempt to allow for this with the result that we can recover about half the difference between experimental and calculated values at the higher reactivities. The error in burst width is now about 10% and hardly a matter for concern.

To summarize, the present calculation can follow quite satisfactorily a prompt burst of the Lady Godiva assembly. The burst yield, maximum rates and widths come out correctly within reasonable errors. In particular the code can

predict quite accurately that point where the burst yield deviates from a linear dependence on reactivity and commences to depend on the square and finally the cube of the reactivity.

This agreement encouraged us to extend the calculation to other LASL critical assemblies to see if one can discover general and fairly simple laws or rules that can be used to describe their behavior.

Critical mass measurements have been made at the LASL for unreflected, enriched assemblies of 53.6% U^{235} and 29% U^{235} . The critical masses of these assemblies are about 140 kg and 383 kg, respectively. At another extreme, critical measurements have been made for Topsy, which was a highly enriched uranium sphere reflected by about nine inches of normal uranium -- effectively an infinite reflector. The critical mass of the core of Topsy was not quite 18 kg.

A series of calculations were made for these assemblies in a manner exactly the same as was done for the Lady Godiva. Different nuclear constants were required to force agreement with critical measurements, and different masses were inserted as input conditions, but otherwise no changes were made. In this manner we obtained a series of burst yields for various reactivities for each assembly. These results are displayed on the eighth slide. We have plotted on this slide the total fissions per gram of uranium -- U^{235} plus U^{238} -- versus reactivity above prompt critical in dollars. The curves are remarkably similar. Even at reactivities of about 50 cents the burst yield per gram of the 29% assembly is less than a factor of two lower than Godiva. The mass, however, is over seven times that of Godiva. For the same reactivity the total burst is, of course, much larger for the heavier assemblies.

The curve representing Topsy was obtained by calculating the fissions in the core and dividing by the core mass. Lady Godiva and Topsy represent two extremes in reflecting material; Godiva has none, and Topsy has, effectively, an infinite amount. One can imagine a family of curves falling between those for Godiva and Topsy representing intermediate reflector thicknesses.

Note that at reactivities somewhat less than 10 cents, the yield of all assemblies is linear with reactivity. To show this more clearly, the data are replotted on the ninth slide. The ordinate on this slide is fissions per gram per dollar. It has no special significance except to emphasize the linear portion of these burst curves and emphasize the break from the linear dependence on reactivity. The curve representing Topsy seems to break at about 10 cents, definitely a higher reactivity than that for the break in the unclad assemblies. The linear portion of these burst curves represent something of more than academic interest. During these low reactivity bursts the assemblies are very nearly in thermal equilibrium. It is clear that an explosion can not occur if an assembly is in equilibrium.

A quantity of some interest that can be obtained from these calculations is the energy that the system puts into motion of the material -- the kinetic energy. We feel that this is a far better measure of the explosive power of a burst than is the total energy release. A good example is the prompt burst of 1.2×10^{17} fissions that damaged the original Godiva assembly last February. The period of this burst (as calculated) was about $4.5 \mu\text{sec}$ and the total energy release was equivalent to 1.8 lbs. high explosive. It was about 21 cents over prompt critical. The individual sections of Godiva were warped and oxidized so badly that a new assembly has been made. However, only one piece, the booster

slug, was ruptured and very little actual damage was done. The calculated kinetic energy was only 1-1/2% of the 1.8 lbs. total or less than 1/2 ounce H.E. equivalent. The powder contained in a half dozen rifle shells could have caused as much damage. The answer is, of course, that most of the energy created merely heated the system and little excess was left over to cause damage. The maximum internal temperatures (as calculated) during the burst were only about 60°C short of the melting temperature of uranium. Photographs of the main components after the incident suggest that the material did reach a semi-plastic state.

For each of the assemblies studied we can follow the generation of kinetic energy as a function of time as well as the fission energy versus time. For bursts at low reactivities (less than about 10 cents), we can watch the kinetic energy rise to a maximum, and drop again to zero as tensions develop in the metal that stop the motion. At very high reactivities, the metal is certain to burst apart since the maximum tensions develop as the third power of the reactivity.

The tenth slide shows how the ratio, kinetic energy divided by total energy release, varies with reactivity for these assemblies. In each case we have taken the maximum kinetic energy calculated during the problem for this plot. Thus, for metal assemblies the ratio should be zero for reactivities less than about 10 cents, but if the system were liquid or, in general, had no cohesive properties, the ratio should be about as shown. The ratio is a most rapidly varying function of reactivity.

The results obtained for the Topsy assembly are definitely less than those for the unreflected systems. Some large part of this difference is stored in the reflector as compressive energy.

It is now possible to consider how we would attempt to represent the dynamics of a fast reactor. We must first construct a spherical analogue of the reactor as our computational scheme is set for this geometry. There are two ways we can do this fairly easily, neither one of which is entirely satisfactory.

We can (1) distribute the mass uniformly at a low density and assign the material a nonlinear equation of state which simulates heterogeneity, or (2) imagine the mass to be distributed in a series of spherical shells of normal density and normal equation of state. These normal density shells are separated by spherical shells that are essentially voids. This last type problem has been dubbed the name "layer cake."

The first case is similar to the model considered by Bethe and Tait. The generation of fission energy has the characteristic that is generally referred to as threshold. That is, because the core material is at a low density, a given amount of energy must be generated before temperatures are high enough to create positive pressures and initiate disassembly. In general, a threshold tends to increase the severity of a burst.

The second case is somewhat more realistic in that the material is at normal density; in this case there is no threshold.

The idealized reactor that we have considered is assumed to contain 200 kg U^{235} , 400 kg of inert material and a reflector of normal uranium extending for 46 cm. The core volume is 6-1/2 liters. The average density in the core is 9.4 gm/cm^3 .

We have run several problems on this system for the threshold case, and one problem for the layer cake case. These calculations are regarded as studies

more to orient us in this difficult field rather than giving anything resembling definitive answers. The problems were finished very recently and there has not been time to examine the listings in detail.

The threshold problems were started by assuming the core to be at a temperature of about 1100°C , the neutron flux to be at a relatively low level, and all the material in the core in motion at a fixed inward velocity. This could be regarded as our first attempt (quite crude) to mock-up a core collapsing under the force of gravity. This has been done for 3 different velocities corresponding to three different reactivity insertion rates in dollars per second.

We have found that for high reactivity insertion rates, the energy generated over that of the threshold energy is proportional to the $3/4$ power of the rate. At low insertion rates, the excess energy varies more like the cube root of the rate.

The burst energy depends on the rate, of course. For what seems to be a very high rate, say, 3000 dollars per second, the burst energy over threshold might be as high as 2000 lbs. H.E. equivalent. A lower insertion rate, at for example 50 dollars per second, results in a burst over threshold of 120 lbs. H.E. This last incidentally is slightly less than a factor of two of that found by Bethe and Tait.

The one layer cake case we have finished was started by assuming the metal shells to be at normal density, room temperature, and the neutron flux at a relatively low level. Each normal density shell was bounded by void regions. The radii were set into motion inward at a fixed velocity. The reactivity insertion rate corresponded to 35 dollars per second. The total yield was 10.4 lbs. H.E. equivalent, an amount expected of a non-threshold

system like Topsy. This particular problem had 8.3% of the mass of the core concentrated in the central mass point. It is entirely possible that the burst behavior was controlled by these central 50 kilograms, and the assembly was a poor model for a collapsing reactor.

It is worth repeating that these calculations are new; we regard them as orienting studies rather than estimating reactor accidents. The models are relatively specialized; we feel that more can be done in the future.

SUMMARY

To summarize very briefly — we have a calculation, coded for a fast computer, that can fairly accurately match the experimental results obtained from the LASL Lady Godiva prompt burst program. In particular, the code can predict very well the reactivity where the burst yield deviates from a linear dependence on reactivity and commences to rise much more rapidly.

The burst width and maximum rates can be predicted with reasonable accuracy. We have applied the calculation to other simple systems, with the result that there appear to be general rules that one can use to relate the bursts of these systems.

The calculation can predict what fraction of the energy of the system is converted into kinetic energy. It appears that step-function increases of reactivity of about 10 cents or less in homogeneous metal systems develop only a trivial explosive energy.

We have started to extend the method to hypothetical accidents in very idealized reactors. Two general models of reactor cores have been considered. These are (1) a core of low density in which the characteristic of a threshold is important, and (2) a model in which the spherical shells are alternately normal density and void. This portion of the study has been barely started and the numbers quoted should be regarded only as establishing upper and lower limits.

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SIMPLIFIED FLOW DIAGRAM

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