H. D. Lewis

NUCLEAR SCIENCE and ENGINEERING

THE JOURNAL OF THE AMERICAN NUCLEAR SOCIETY

VOLUME 1, NUMBER 2
MAY 1956

ACADEMIC PRESS INC.
PUBLISHERS, NEW YORK 10, N. Y.

VOL. 1, NO. 2, Pages 103-191, May, 1956

NUCLEAR SCIENCE and ENGINEERING

THE JOURNAL OF THE AMERICAN NUCLEAR SOCIETY

VOLUME 1, NUMBER 2, MAY 1956

NUCLEAR SCIENCE AND ENGINEERING: 1, 112–125 (1956)

An Unreflected U-235 Critical Assembly[1]

R. E. PETERSON AND G. A. NEWBY[2]

Los Alamos Scientific Laboratory, Los Alamos, New Mexico

Received November 30, 1955

An unreflected, spherical U^{235} critical assembly has been in operation at the Los Alamos Scientific Laboratory since August, 1951. A remotely controlled mechanical system is used to assemble subcritical components of the sphere, and reactivity is adjusted with U^{235} control rods. The maximum power level during sustained operation is about 1 kw. Investigations with the assembly include studies of the neutron spectrum, observation of the changes of reactivity produced by inserting foreign materials into the assembly, and determination of parameters such as the temperature coefficient of reactivity. In addition, experiments at reactivities above prompt critical have been carried out. The assembly has also been used as a source of short, high-intensity bursts of neutrons in the study of delayed neutrons following fission.

INTRODUCTION

Until 1951, studies of all-metal critical assemblies carried on with the Pajarito Site remotely controlled facilities of the Los Alamos Scientific Laboratory (*1*) were concentrated on configurations of U^{235} surrounded by various reflectors. With these critical assemblies, spatial dependence of fission rates, relations between critical mass and reflector thickness and material, changes in reactivity produced by the introduction of nonfissionable materials into the assemblies, distribution-in-energy of neutrons in the fissionable material, and time-dependent behavior of prompt neutron fission chains were investigated.

An extension of these studies with a bare assembly consisting entirely of fissionable material in a simple geometry seemed desirable, since the number of parameters affecting the interpretation of measurements would be reduced. Accordingly, a nearly spherical and unreflected assembly of uranium, enriched to a U^{235} content of approximately 90%,[3] was constructed. This device, known as "Lady Godiva," was first operated at delayed critical in August, 1951.

This paper deals mainly with details of the design and with parameters of

[1] Work performed under the auspices of the U. S. Atomic Energy Commission.

[2] Present address: School of Engineering, University of California, Berkeley, California.

[3] In subsequent references, the term "uranium" implies material of this enrichment in U^{235}.

importance in the operation of Godiva, and is meant to be descriptive rather than interpretative. Experiments involving use of this critical assembly are mentioned briefly.

DESIGN OBJECTIVES AND CONSTRUCTION

In designing the unreflected U^{235} critical assembly, the objectives were these:

(a) The uranium components should as nearly as possible constitute a sphere, of uniform density and isotopic composition, free from internal voids and from dilution with nonfissionable structural materials.

(b) Major sections, individually subcritical, should be capable of assembly by remotely controlled mechanical devices with such precision that the reactivity of the sphere would be accurately reproduced in successive assembly operations. However, in order to minimize neutron reflection, mechanical supporting systems should be small and light. Accurately reproducible aligning and positioning of the uranium components should, therefore, be effected through the design of the sphere sections themselves rather than by provision of a mechanically precise or rigid assembly device. Design of uranium pieces should be consistent with the mass limitation imposed on uranium casting processes.

(c) The interior parts of the uranium sphere should be accessible to permit the insertion of foils and counters in experiments.

(d) Two systems of reactivity control should be included. A continuously variable control should provide for reactivity adjustment with an accuracy of about 0.01 cent over a total range of perhaps 75 cents. (A *cent* is 1 % of the reactivity increment which changes an assembly operating at delayed critical to one in which the prompt neutrons alone sustain the chain reaction.) A second, coarse system of control to produce successive, equal increments in reactivity by steps of about 5 cents over an 80-cent range, would also be desirable. This system could be used for measuring the linearity of the continuously variable control system as well as for making the gross adjustments to the sphere mass necessary in some experiments.

The way in which the desired features were incorporated into the final Godiva design is indicated in Fig. 1, a view of the uranium components of the critical assembly. It will be noted that the ideal geometry was not achieved, but that instead the assembled parts make up a slightly elongated "sphere." The equatorial diameter of the ball is roughly $6\frac{3}{4}$ in. ($\sim$17 cm) and the average density is slightly less than 19 gm/cm^3.

As indicated in Fig. 1, proper positioning of the sphere sections is effected through the combined action of the alignment cones and the ball-and-socket joints by which the upper and lower sphere sections are attached to the assembly mechanism. A small degree of flexibility in the thin-walled steel tubing members which support the three major sphere components compensates for minor mis-

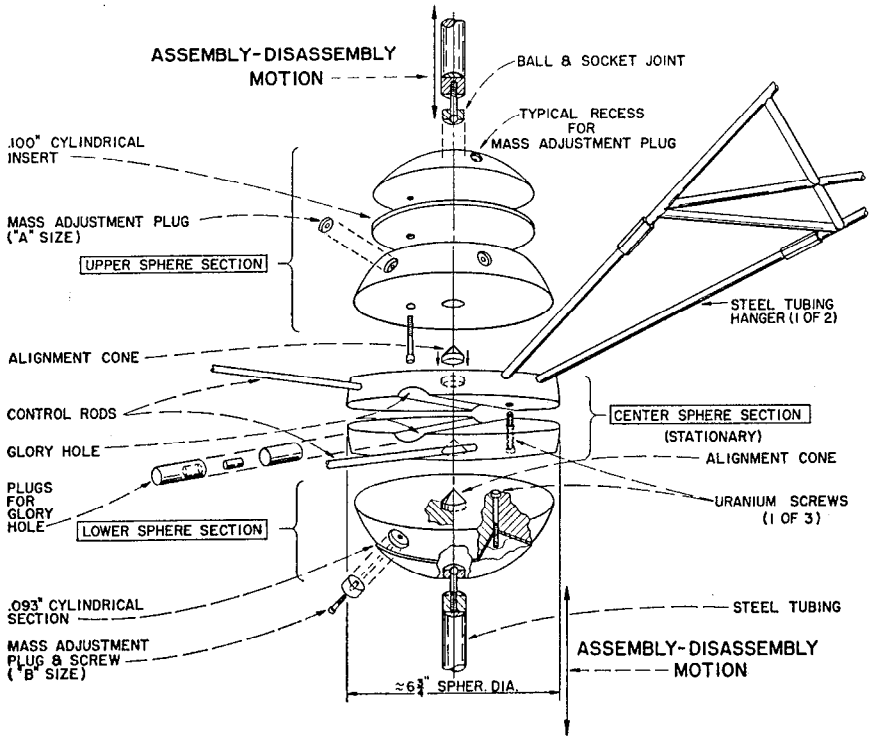


FIG. 1. View of Godiva components. With the exception of the steel support structure and the ball portions of the flexible mounts, all parts are uranium. The upper and center sphere sections are shown separated into basic pieces.

alignments in the assembly mechanism. The $\frac{15}{16}$-in. cylindrical channel or "glory hole" along a diameter of the sphere provides the required access to the interior of the assembly; space not occupied by experimental apparatus is filled with the uranium plugs illustrated in Fig. 1.

Continuously variable reactivity control is obtained with the two $\frac{7}{16}$ in. diameter uranium rods (Fig. 1) which may be inserted into the channels parallel to the glory hole. For making successive, equal changes in criticality, there are fourteen 0.25 in. deep, 0.875 in. diameter recesses distributed on the sphere surface. These accommodate uranium "mass adjustment plugs" 0.250 in. ("A" plugs) or 0.544 in. ("B" plugs) thick, which are held in place with uranium screws.

Figure 2 shows an over-all view of Godiva, including the steel tubing framework of the assembly mechanism, the air cylinder supporting the upper sphere section, and the hangers holding the center section. The control rod actuating motors, gear boxes, indicator selsyns, etc., constitute the mechanical unit shown to the right of the center sphere section. A small air cylinder included in this unit

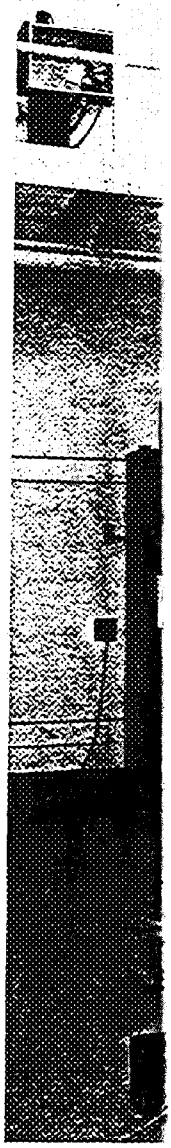
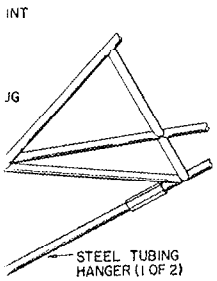


FIG. 2. Godiva. The u

is used to position
proach to a critical
draulic lift cylinder
the machine, has n



R SPHERE SECTION
(STATIONARY)
ALIGNMENT CONE
URANIUM SCREWS
(1 OF 3)
STEEL TUBING
LY-DISASSEMBLY
MOTION

steel support structure
. The upper and center

al channel or "glory
access to the interior
paratus is filled with

the two $\frac{7}{16}$ in. diame-
channels parallel to
criticality, there are
buted on the sphere
lugs" 0.250 in. ("A"
place with uranium

e steel tubing frame-
ing the upper sphere
ontrol rod actuating
echanical unit shown
included in this unit

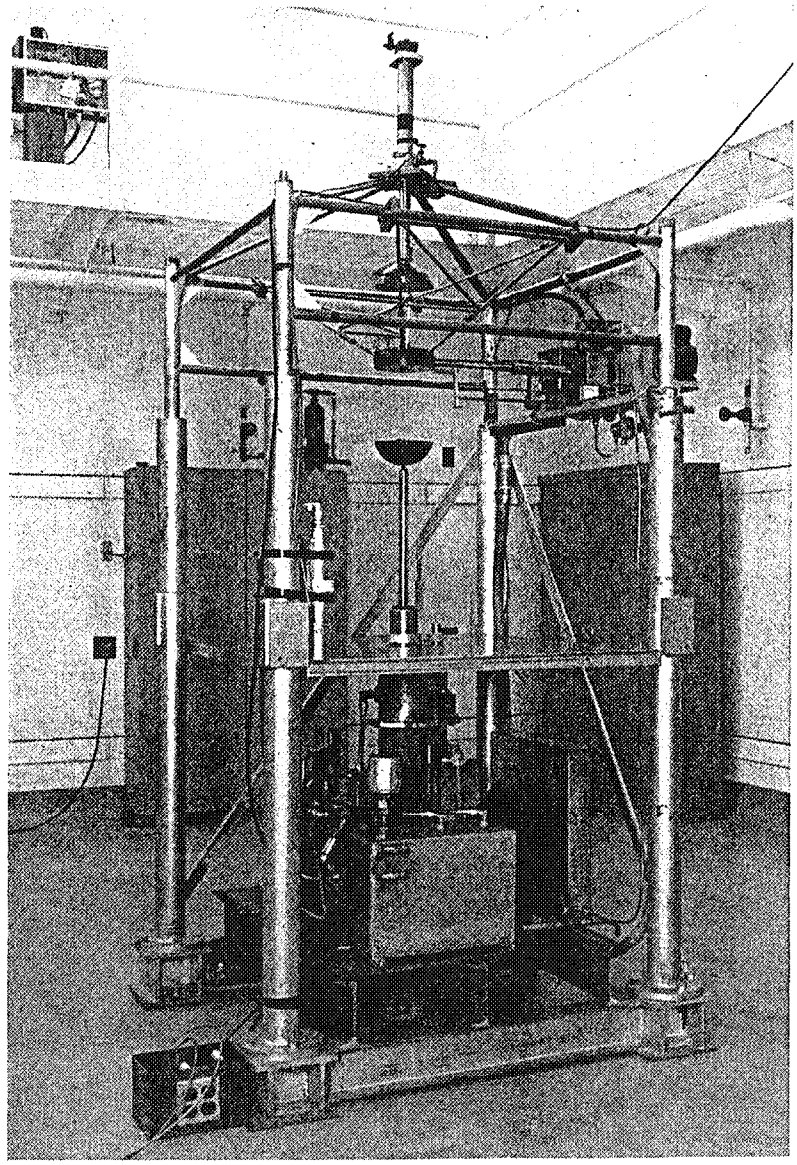


FIG. 2. Godiva. The uranium components are shown in place on the remotely controlled assembly machine.

is used to position a neutron source near the surface of the sphere while an approach to a critical configuration is being made. The lower sphere section hydraulic lift cylinder, shown with its associated valves and pumps in the base of the machine, has now been replaced with a lighter, air-powered mechanism.

The mechanical operations involved in making a routine assembly of the fissionable material and achieving a critical configuration are initiated by personnel in a control room about one-fourth mile distant from the building which houses Godiva. The progress of the assembly operation is shown by signal lights and selsyn-driven indicators coupled to moving parts of the assembly machine. Since, for reasons of safety, it is undesirable to vary more than one parameter affecting criticality at a given time, suitable interlocks permit the operator to move the fissionable components together only in the following sequence:

(a) The upper sphere section descends as air pressure is gradually released from the lift cylinder; the alignment cones guide it into position on the center section of the sphere.

(b) Provided the control rods have been withdrawn and the source holder advanced to the surface of the sphere, the lower section may be raised. To insure positive closure at the sphere section interfaces, the lower section is allowed about 0.01 in. overtravel beyond the point of contact with the center section before the lower lift piston comes to bear on a mechanical stop. This overtravel is accommodated by elastic deflection of the upper and central sphere section supports.

(c) The control rods may next be inserted as required to bring the assembled sphere to a delayed critical configuration. The source holder may be retracted if desired.

Disassembly of the sphere may be made in any sequence. Air and hydraulic valving is arranged so that an electrical power failure results in automatic separation, or "scramming," of the sphere sections. Suitable neutron detectors furnish a scram signal if the fission rate exceeds a specified value. Retraction of either the upper or the lower sphere section alone makes the assembly highly subcritical, and only simultaneous mechanical malfunction of two independent actuating devices could prevent effective disassembly of the fissionable material.

Each control rod is moved by a 40-pitch lead screw driven by an electric motor through a magnetic clutch and a gear box. Rod speed is varied by changing the field current through the clutch. The entire control rod drive unit is held in a fixed position relative to the sphere by tie bars parallel to the rods; the position of the rods at any given time is shown in the control room on selsyn-driven indicators calibrated to 0.001 in.

DELAYED CRITICAL OPERATION

Critical Mass

After an initial, unsuccessful attempt to bring Godiva to delayed critical, the insertion of a 0.1 in. thick uranium cylindrical section or "shim" into the upper sphere section (Fig. 1) made it possible to achieve a critical configuration with a total mass of about 50 kg. This mass included the 0.1-in. shim, one control rod completely inserted, the second rod approximately one-half inserted, and 11 of the "A" plugs. In a
able by filling all s
quate, the 0.1-in. sh
then obtained with
only 2 "A" plugs in

The equivalent n
supporting hangers,
effects observed in
spheres and on the n
dummy hangers nea
and the critical mass
15 ft above ground l
and walls decreases

Control System E

The basic procedu
justment plugs was
point, increase the r
adding a given num
increased in the (s
change in configura
Hughes *et al.* (*2*) in
or "positive period,"

Δk for the origina
rod; however, nonlin
in practice, full use o
Δk, improved linear
plug in the end of it
a function of positio
tion of the curve, Δ
available with the n
normally used at fu

Because of the elo
depends upon its p
6.0 cents for "A" plu

Reactivity Contri

A quantity of int
theoretical considera
nium at various poi
termining the chang

the "A" plugs. In anticipation of experiments where the excess reactivity available by filling all surface recesses with the thicker "B" plugs would be inadequate, the 0.1-in. shim was replaced with one 0.2 in. thick. Delayed critical was then obtained with approximately the same control rod configuration, but with only 2 "A" plugs in place on the sphere.

The equivalent mass contribution from neutron reflection to the sphere by supporting hangers, etc., is probably less than 100 gm; this number is based on effects observed in multiplication measurements on subcritical, unreflected spheres and on the measured change in reactivity produced by placing additional dummy hangers near the sphere. A comparison between the critical mass indoors and the critical mass observed with Godiva located out of doors on a tower about 15 ft above ground level indicates that neutron reflection from the building floor and walls decreases the critical mass by less than 0.2%.

Control System Effectiveness

The basic procedure in the reactivity calibration of control rods and mass adjustment plugs was to establish a delayed critical configuration as a reference point, increase the reactivity by inserting known amounts of control rod or by adding a given number of plugs, and measure the rate at which the fission rate increased in the (supercritical) assembly. Δk associated with the particular change in configuration was then obtained using the delayed-neutron data of Hughes *et al.* (*2*) in the inhour equation relating the fission rate *e*-folding time, or "positive period," to the excess reactivity above delayed critical.

Δk for the original 5.5-in. control rods was observed to be about 44 cents per rod; however, nonlinearity of Δk as a function of control rod insertion prevented, in practice, full use of the available control. With some sacrifice in total available Δk, improved linearity was achieved in one rod by placing a $1\frac{1}{2}$ in. long uranium plug in the end of its channel and shortening the rod by an equal amount. Δk as a function of position of the modified rod is shown in Fig. 3. On the linear portion of the curve, Δk per in. of control rod is about 11.7 cents; the total control available with the modified rod is approximately 33 cents. As the second rod is normally used at full insertion, nonlinearity is of less importance in this case.

Because of the elongation of the Godiva sphere, Δk for a mass adjustment plug depends upon its position on the sphere. The effectiveness ranges from 5.2 to 6.0 cents for "A" plugs and from 8.1 to 9.3 cents for "B" plugs.

Reactivity Contribution of Interior and Surface Mass

A quantity of interest in routine use of the critical assembly, as well as in theoretical considerations, is the reactivity contribution per unit mass of uranium at various points in the assembly. The desired data were obtained by determining the change in reactivity associated with the insertion of a 30-gm,

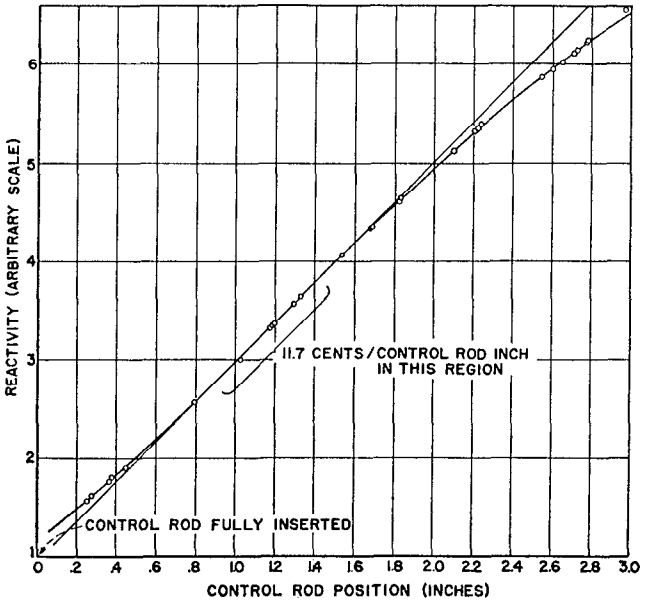


FIG. 3. Calibration curve for modified control rod.

$\frac{1}{2}$ in. diameter, $\frac{1}{2}$ in. long uranium cylinder into a corresponding cavity in one of the glory hole plugs, whose radial position in Godiva could be varied. The results of these "replacement" measurements, which were extended to include introduction of normal uranium and plutonium samples into the assembly, are shown in Fig. 4; the reactivity change produced by a sample at a given radial position is expressed in cents per mole of replacement material.

The curve for uranium, Fig. 4, can be used to determine directly the mass increment between a delayed critical and a prompt critical Godiva configuration; one needs only to read off the reactivity contribution per mole of uranium at the surface of the sphere and from this obtain the number of moles corresponding to a 100-cent reactivity change. The mass difference between prompt and delayed critical is thus found to be between 1200 and 1300 gm.

Temperature Coefficient of Reactivity and Reactivity Reproducibility

A simple calculation involving the thermal expansion coefficient of uranium, the mass difference between prompt and delayed critical, and a proportionality between critical mass and the reciprocal of the square of the uranium density showed that the temperature coefficient of reactivity should be about -0.34 cent/C° for Godiva. The measured variation of reactivity with temperature is shown in the curve of Fig. 5, which indicates that the temperature coefficient is about 0.034 control rod in./C°, or -0.40 cent/C°.

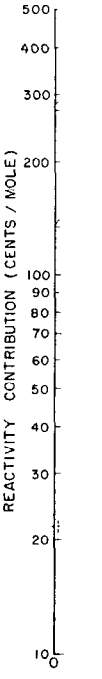


FIG. 4. Reactivity
able materials in Godi
sphere surface.

This temperature
temperature produc
mal capacity of the
perature changes is
which made the "loc
amplitude, 10 min
reactivity of a give
out under these con
no more than ±0.0
a three-day period.
tion rather than me
delayed critical vari

Power Level

Godiva is necessa
tem, nor shielding t

od.

nding cavity in one
uld be varied. The
extended to include
to the assembly, are
ple at a given radial
rial.
directly the mass in-
odiva configuration;
le of uranium at the
les corresponding to
prompt and delayed

TY REPRODUCIBILITY

efficient of uranium,
nd a proportionality
the uranium density
uld be about −0.34
with temperature is
nperature coefficient

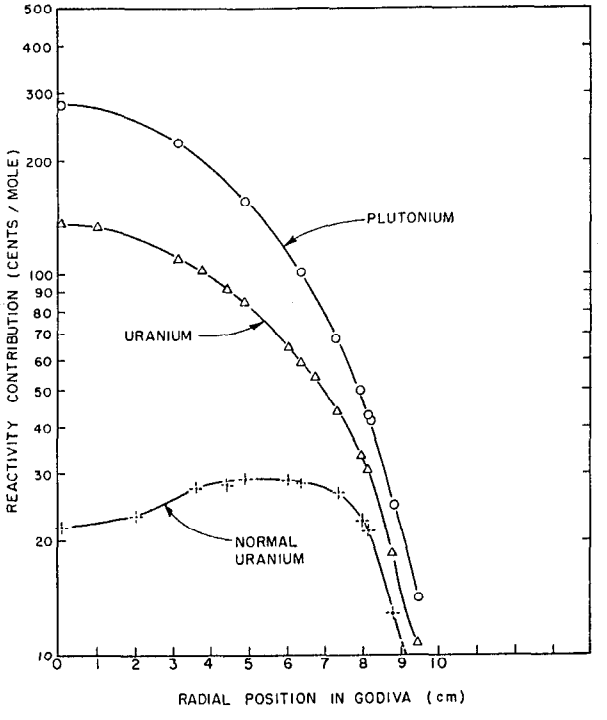


FIG. 4. Reactivity contribution values (per mole of replacement material) for fissionable materials in Godiva. The graph includes data from measurements made outside the sphere surface.

This temperature coefficient is sufficiently large so that fluctuations in room temperature produce troublesome shifts in reactivity, particularly since the thermal capacity of the assembly is small and the time of response to ambient temperature changes is correspondingly short. A system of thermostatic control which made the "local" ambient temperature variations small and regular (0.5C° amplitude, 10 min period) was found to give adequate reproducibility of the reactivity of a given configuration of the assembly. In one experiment carried out under these conditions, the control rod setting at delayed critical varied by no more than ±0.010 in. (±0.1 cent) in repeated assembling of Godiva during a three-day period. On the basis of accumulated experience, temperature variation rather than mechanical trouble is generally suspected if the rod setting for delayed critical varies by more than ±0.005 in. in successive assembly operations.

POWER LEVEL

Godiva is necessarily operated only at low power, since neither a cooling system, nor shielding to protect personnel entering the building after operation, is

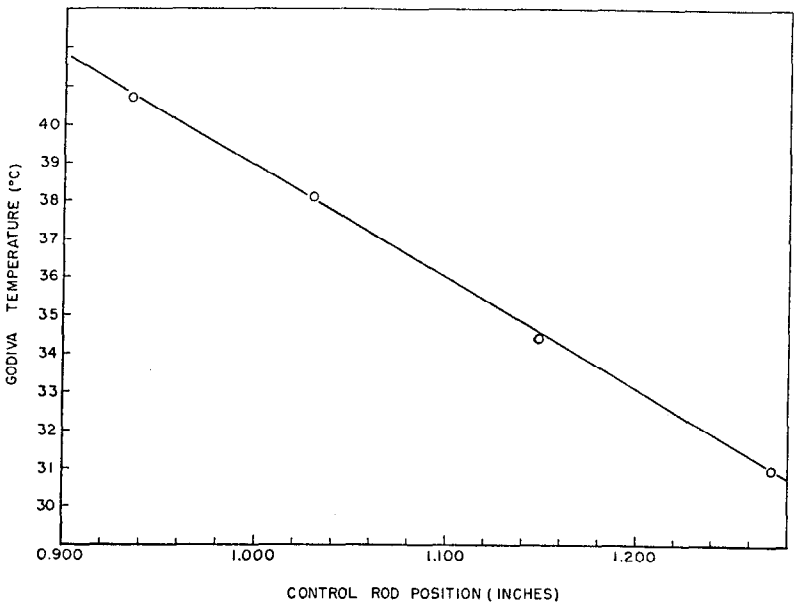


FIG. 5. Control rod position required to maintain a delayed critical configuration at various temperatures of the critical assembly. The slope of the curve is −0.034 in./C°, or −0.40 cent/C°.

provided. In practice, experiments involving precise reactivity measurements are generally carried out at power levels of from 0.1 to 1 watt, so that self-heating does not produce appreciable changes in reactivity. In other types of experiments, where a high neutron flux rather than accurate control of criticality is needed, a power level of about a kilowatt may be reached. At this power, excess reactivity available in the control rods is sufficient to offset the effects of temperature rise in the assembly for only about an hour's running time; since the radiation level at the surface of Godiva is of the order of 100 r/hr following such operation, it is not feasible to increase reactivity by adding mass adjustment plugs manually.

At 100 watts, the neutron leakage from Godiva is about 5×10^{12} n/sec.

MEASUREMENTS

Brief descriptions of neutron energy and cross section comparison measurements involving the Godiva assembly are presented in the following sections. A discussion of some aspects of the studies made at reactivities above prompt critical is included.

Energy Spectrum of Leakage Neutrons

Measurements of the energy spectrum of leakage neutrons from Godiva have been made with nuclear emulsions and with a hydrogen-filled cloud chamber.

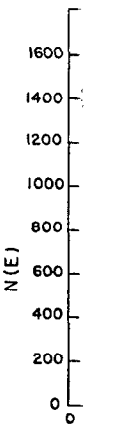


FIG. 6. Comparison of t
The cu

The data were obtai
the critical assembly
duced the backgrou
are shown in Fig. 6.
nuclear plate measu

Fission Cross Sec

Many attempts h
spectra of various cr
direct interior measu
in U^{234}, U^{235}, U^{238}, a
tabulation of relati
over the assembly's
of separately measu
give indications of d
The results of me

Spectral Measuremen

Ratio
$\sigma_f(U^{235})/\sigma_f($
$\sigma_f(U^{234})/\sigma_f($
$\sigma_f(Np^{237})/\sigma$

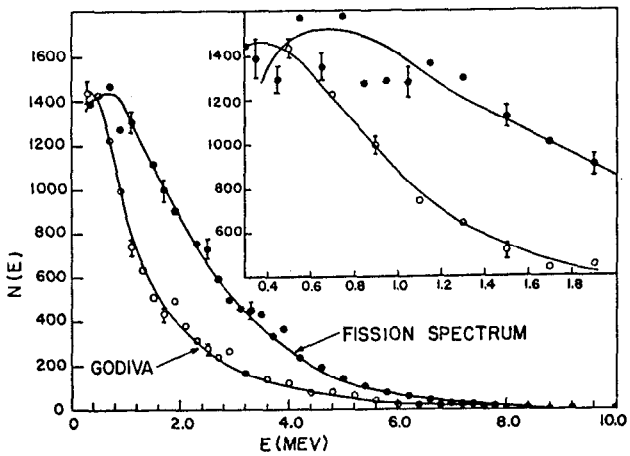


FIG. 6. Comparison of the Godiva leakage spectrum and uranium fission neutron spectrum. The curves are normalized on the basis of their integrals.

The data were obtained with Godiva located out of doors on a scaffold such that the critical assembly was about 15 ft above ground level; this arrangement reduced the background of scattered neutrons. The results of the emulsion work are shown in Fig. 6. The fission spectrum (as obtained by Rosen (*3*) in recent nuclear plate measurements) is also shown for comparison.

FISSION CROSS SECTION RATIOS: SPECTRAL INDICES

Many attempts have been made to obtain data on differences in the neutron spectra of various critical assemblies at Los Alamos. In the absence of means for direct interior measurements of neutron energies, a comparison of fission rates in U^{234}, U^{235}, U^{238}, and Np^{237} foils inserted into the critical assemblies permits tabulation of relative values of the respective fission cross sections averaged over the assembly's spectrum. These "spectral indices," interpreted on the basis of separately measured fission cross sections as a function of neutron energy, give indications of differences in the neutron spectra of the critical assemblies.

The results of measurements made at the center of Godiva and in a fission

TABLE I

SPECTRAL MEASUREMENTS: OBSERVED FISSION CROSS SECTION RATIOS OF FOUR NUCLEI IN TWO NEUTRON SPECTRA

Ratio	Fission spectrum	Godiva spectrum (central)
$\sigma_f(U^{235})/\sigma_f(U^{238})$	3.9	5.9
$\sigma_f(U^{234})/\sigma_f(U^{238})$	4.2	5.0
$\sigma_f(Np^{237})/\sigma_f(U^{238})$	3.8	4.5

TABLE II

ENERGY DISTRIBUTION OF FISSION SPECTRUM AND (CENTRAL) GODIVA SPECTRUM NEUTRONS

Neutron energy group	Fraction of neutrons per energy group	
	Fission spectrum	Godiva spectrum (central)
0-0.4 Mev	0.10	0.21
0.4–1.4 Mev	0.34	0.41
>1.4 Mev	0.56	0.38

spectrum (*3–7*) of neutrons are shown in Table I. Some of the data were obtained with a small "double" ionization chamber containing foils of each of the two isotopes used in a given measurement; in addition, radiochemical analysis and γ-counting of foils irradiated in the assembly were also employed in determining relative fission rates. It has been estimated that the relative values of a given cross section ratio in the two spectra are uncertain by $\pm 3\%$. The ratio of cross sections for a given pair of nuclei in a particular spectrum is less certain, since these values depend upon foil weight determinations. The data of Table I imply the approximate neutron energy distribution listed in Table II for the Godiva spectrum; neutron distribution in the fission spectrum is included for comparison.

Continuing improvement in counting techniques, plus further investigation of the background problem encountered in the fission spectrum measurements, should improve the precision of this method of spectrum comparison.

MATERIAL REPLACEMENT MEASUREMENTS

The reactivity contributions of small samples of various elements (nonfissionable as well as fissionable) introduced into corresponding cavities in Godiva have been determined as functions of position. Data on the reactivity contributions may be used in estimating the relative average transport cross sections of different elements. For certain elements, it may be possible to evaluate the relative importance of neutron capture and inelastic scattering of neutrons in producing the observed reactivity contribution of the replacement element.

The results of measurements of the reactivity contributions per mole of a number of elements are given in Table III; data on uranium, normal uranium, and plutonium are not included in Table III since these are shown graphically in Fig. 4. Additional data have been reported by Avery *et al.* (*8*).

PROMPT CRITICAL STUDIES WITH GODIVA

With one exception (*9*), previous studies of critical assemblies at Los Alamos have been limited to the reactivity range between delayed critical and some point well below prompt critical. Recently, a renewed interest in extending this range to include reactivities greater than 100 cents above delayed critical initiated what has been known as the "prompt-burst program," involving a general

REACTIVIT

Element or isotope	0.
Be	
B	-
B^{10}	
(~85%)	-
C	
Al	
Fe	-
Co	-
Ni	-
Cu	-
Zn	-
Ag	-
Au	-
Bi	-
Th	-

investigation of the
range from about 95
urements were these
of the rapid rise in f
with the calculated
parison between the
would determine, at
and abundances use
reactivity scale as pr
critical if, for instan
(c) The availability
burst, suggested a n
short-time irradiatio
period delayed neut
would otherwise be

Godiva was chose
reactivity could be a
operated routinely a
major modification
the provision of a t
uranium cylinder w
explosive charge to
mately 100 cents.

TABLE III

REACTIVITY CONTRIBUTIONS OF SOME ELEMENTS IN GODIVA

Element or isotope	Reactivity contribution, cents/mole, at designated radial positions					
	0.030 in.	1.242 in.	1.930 in.	2.512 in.	3.142 in.	3.206 in.
Be	6.7	9.4	11.6	10.8	9.4	
B	−6.3	−0.7	4.9	8	7.9	
B^{10} (~85%)	−42.1			−0.1	6.6	
C	2.2	5.0	9.0	10.4	9.7	
Al	0.4	4.6	9.3	9.9		8.1
Fe	−0.1	3.9	8.2	10.6		9.0
Co	−0.5		9.7	12.2	11.1	
Ni	−4.0	2.0	8.0	10.7		9.6
Cu	−1.6	4.1	9.3	11.8		10.5
Zn	−2.3	4.5	9.0	11.7		11.6
Ag	−9.2		8.4	14.1	13.7	
Au	−7.6	2.2	11.6	17.8	17.8	
Bi	−1.5		16.6	21.8	19.8	
Th	−1.2	8.7	18.8	21.6		20.0

investigation of the behavior of a critical assembly at excess reactivities in the range from about 95 to 110 cents. Some points of interest in such a set of measurements were these: (a) The observed self-termination (via thermal expansion) of the rapid rise in fission rate in a prompt critical assembly could be compared with the calculated shape, size, and duration of the fission burst. (b) A comparison between the observed and the predicted prompt critical configuration would determine, at least in principle, whether or not the delayed neutron periods and abundances used in the inhour equation are correct; deviations from the reactivity scale as predicted by the equation should be most apparent near prompt critical if, for instance, the shorter period and abundance values were in error. (c) The availability of a high-intensity neutron pulse, as produced by a fission burst, suggested a method of looking for short-period delayed neutrons, since short-time irradiation of fissionable materials (favoring saturation of any short-period delayed neutron activity) could be accomplished in higher fluxes than would otherwise be obtainable at Los Alamos.

Godiva was chosen for use in the prompt-burst program because a selected reactivity could be accurately reproduced; also the assembly had previously been operated routinely at reactivities as high as 95 cents above delayed critical. The major modification to the assembly for studies of prompt critical behavior was the provision of a third "control rod," consisting of a $\frac{3}{8}$ in. diameter, 7 in. long uranium cylinder which could be propelled into the (modified) glory hole by an explosive charge to yield a rapid, reproducible change in reactivity of approximately 100 cents.

As a 10-channel, gated scaling system employed in recording routine positive period measurements was not practical to use for e-folding times shorter than about 0.1 sec, the time dependence of the fission rate at high reactivities was observed by applying the signal (proportional to fission rate) from a scintillator-photomultiplier detector to the x-axis deflection plates of a cathode ray tube while driving the y-axis deflection system with an (adjustable frequency) oscillator to furnish a time base. A photograph of the oscilloscope trace would then yield the data required to obtain the fission rate as a function of time during a burst.

Starting at about 95 cents above delayed critical, periods were measured at reactivities closely spaced in the interval between 95 and 110 cents, the latter point corresponding to a fission rate e-folding time of about 12 μsec. In the largest fission bursts observed, approximately 2×10^{16} fissions occurred, the major portion of the energy being released in about 50 μsec. The average rate of energy release during the main portion of the fission burst was, therefore, between 10^3 and 10^4 Mw. The resulting temperature rise of the assembly was 100°C. Details

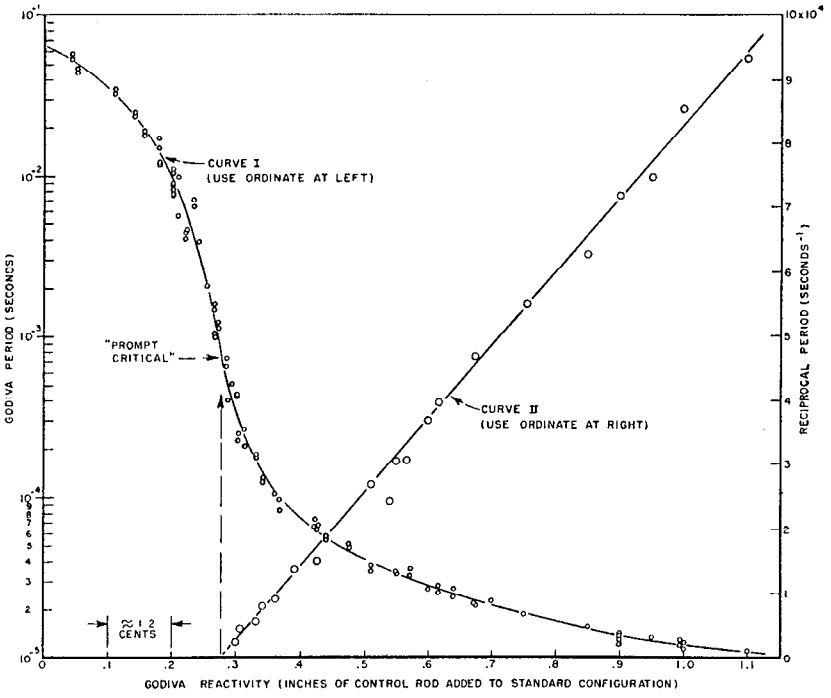


FIG. 7. Data from the Godiva "prompt burst" experiments. Curve I shows the measured periods of the critical assembly as a function of reactivity. The reciprocal of the period, $1/T$, is plotted on Curve II. Extrapolation of Curve II to the point $1/T = 0$ determines the prompt critical configuration.

of the burst shape w
able excess reactivit
prompt critical burs
problems. It appear
above prompt critic
the size of the fissio

A graph of the ob
of reactivity is show
established by extra
reactivity, a valid p
pared to delayed ne
is about 0.74 msec.

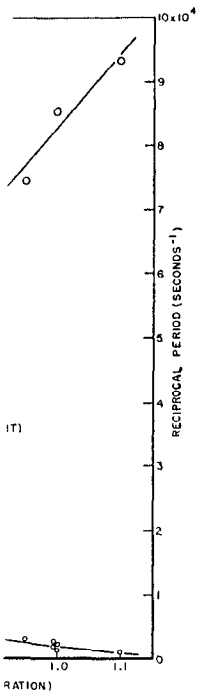
An evaluation of
change in configurat
critical indicates a c
slightly more than t
obtained in the 0–60
therefore, indicate d
(2) used in the inho
and period over the
direct measurements
yield a set of periods
(2). Putting these la
ment between calcul
reactivity near prom

The work of designi
joint effort by all memb
ance was given by the
Rosen of the Physics I

1. H. PAXTON, *Nucleo*
2. D. J. HUGHES, J. D
3. L. ROSEN, private c
4. N. NERESON, *Phys.*
5. T. BONNER, R. FE
6. D. HILL, *Phys. R*
7. B. WATT, *Phys. R*
8. R. AVERY, D. OKR
in Geneva, UN-6
9. F. DEHOFFMANN, B.
10. G. R. KEEPIN and
Geneva, UN-831

ling routine positive
5 times shorter than
high reactivities was
) from a scintillator-
a cathode ray tube
le frequency) oscilla-
pe trace would then
tion of time during a

ls were measured at
110 cents, the latter
2 μsec. In the largest
irred, the major por-
erage rate of energy
erefore, between 10^3
y was 100°C. Details



ve I shows the measured
eciprocal of the period,
$1/T = 0$ determines the

of the burst shape were in agreement with those predicted on the basis of available excess reactivity. This demonstration of the self-limiting characteristic of prompt critical bursts in Godiva is of interest in consideration of reactor safety problems. It appears that at least for moderate values of the excess reactivity above prompt critical, the negative temperature coefficient of reactivity limits the size of the fission burst in an effective and highly reproducible fashion.

A graph of the observed fission rate e-folding times, or periods, as a function of reactivity is shown in Fig. 7. The point designated as "prompt critical" was established by extrapolating linearly to zero a plot of reciprocal period against reactivity, a valid procedure if the extrapolation is based on periods short compared to delayed neutron periods. The period of the assembly at prompt critical is about 0.74 msec.

An evaluation of the control rod effectiveness consistent with the observed change in configuration required to bring the assembly from delayed to prompt critical indicates a control rod worth of 11.85 cents/in. This number differs by slightly more than the estimated error in measurement from the 11.7 cents/in. obtained in the 0–60 cent reactivity range. A comparison of these values does not, therefore, indicate definitely whether or not the delayed neutron data of Hughes (*2*) used in the inhour equation gives accurately the relation between reactivity and period over the entire range between delayed and prompt critical. Recent direct measurements of delayed neutron periods at Los Alamos (*10*), however, yield a set of periods (and abundances) somewhat different from those of Hughes (*2*). Putting these latter values into the inhour equation produces better agreement between calculated and measured fission rate e-folding times at a specified reactivity near prompt critical than does the use of the Hughes' values (*2*).

Acknowledgments

The work of designing, setting up, and operating the Godiva critical assembly was a joint effort by all members of the Pajarito Site group under Hugh Paxton; invaluable assistance was given by the Metallurgical and Electronics sections of the Laboratory. Louis Rosen of the Physics Division was in charge of the nuclear emulsion spectroscopy.

References

1. H. Paxton, *Nucleonics* **13**, No. 10, 49 (1955).
2. D. J. Hughes, J. Dabbs, A. Cahn, and D. Hall, *Phys. Rev.* **73**, 111 (1948).
3. L. Rosen, private communication.
4. N. Nereson, *Phys. Rev.* **85**, 600 (1952).
5. T. Bonner, R. Ferrell, and M. Rinehart, *Phys. Rev.* **87**, 1032 (1952).
6. D. Hill, *Phys. Rev.* **87**, 1034 (1952).
7. B. Watt, *Phys. Rev.* **87**, 1037 (1952).
8. R. Avery, D. Okrent, and H. Hummel, Proceedings of the International Conference in Geneva, UN-609 (1955). (To be published.)
9. F. deHoffmann, B. T. Feld, and P. Stein, *Phys. Rev.* **74**, 1330 (1948).
10. G. R. Keepin and T. F. Wimett, Proceedings of the International Conference in Geneva, UN-831 (1955). (To be published.)