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LADY GODIVA: AN UNREFLECTED URANIUM-235 CRITICAL ASSEMBLY

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CRITICALITY HAZARDS

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CRITICALITY HAZARDS

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ABSTRACT

A spherical, unreflected U-235 critical assembly (52.6 kg) has been in operation 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 positioned in the sphere. The maximum power level during sustained operation is about 1 kilowatt. In addition to investigations of the neutron spectrum of the assembly, observation of the changes of reactivity produced by inserting foreign materials into the assembly, and the determination of parameters such as the temperature coefficient of reactivity, studies have been made of the behavior of the assembly at reactivities above prompt critical.

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CONTENTS

INTRODUCTION

Until 1951, studies of all-metal critical assemblies carried on at the Pajarito Site remotely-controlled laboratories, Los Alamos Scientific Laboratory, were concentrated on configurations of U-235 surrounded by reflectors of various metals and their alloys. With these critical assemblies, spatial dependence of fission rates, relations between critical mass and reflector thickness and material, the changes in reactivity produced by the introduction of nonfissionable materials into the assemblies the distribution-in-energy of neutrons in the fissionable material, and the time-dependent behavior of prompt neutrons from fission were investigated.

An extension of these studies with an assembly consisting entirely of fissionable material in a simple geometry seemed desirable, since the number of parameters affecting the interpretation of measurements should in this case be reduced. Accordingly an oralloy (uranium enriched to a nominal U-235 isotopic abundance of 93.5%) assembly, as nearly spherical as possible was constructed. The first delayed critical operation of this device, known as Lady Godiva, occurred in August 1951.

This report deals mainly with details of the design and with the operating characteristics of Lady Godiva, and is

descriptive rather than interpretative. Experimental programs based on this critical assembly will be mentioned only briefly, since the discussion is primarily intended to serve as a background for and supplement to other, more detailed accounts of experiments involving this untamped critical assembly.

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Section I. Design Objectives and Construction

In the design of the unreflected U-235 critical assembly, the objectives considered 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 materials introduced for structural purposes.

(b) Major, individually subcritical sphere sections should be brought together 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 oralloy components should, therefore, be effected through the design of these 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 oralloy casting processes.

(c) Access to the interior parts of the uranium sphere should be provided for the insertion of foils, counters, etc., in experiments.

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(d) Two systems of reactivity control should be included in the design. A continuously variable control should provide for reactivity adjustment with an accuracy of about 10^{-2} 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 control 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.

Neutron multiplication measurements made with various subcritical sizes of uranium spheres indicated that for a sphere of the density and U-235 concentration expected in the completed Godiva assembly, the critical diameter would be 6.848 inches. Other measurements carried out with a subcritical, approximately spherical uranium configuration yielded data regarding the reactivity change per unit mass increment as a function of the radial position of the mass increments; this information provided a quantitative basis for the design of the reactivity control systems.

The way in which the desired features were incorporated,

as far as possible, into the final Godiva design is indicated in Fig. 1, a view of the oralloy components of the critical assembly. It will be noted that the ideally desirable spherical geometry was not achieved, but that instead the assembled parts make up an elongated "sphere" -- the cylindrical insert in the lower sphere section (Fig. 1) was originally included as extra material considered adequate to counteract any possible underestimation of the critical diameter of 6.848 inches. This precaution, however, was overbalanced by a mass tabulation error in multiplication experiments, and after an initial unsuccessful attempt to bring the assembly up to critical, it was found necessary to add a second, 741 gm, 0.1 inch high cylindrical disc to the upper sphere section.

The uranium allotted for Godiva construction was selected so that the quoted U-235 isotopic abundance ranged from 93.6_9% to 93.7_4% with an average value of 93.7_1%; U-234 was present in about 1% abundance, and U-238 presumably constituted the remaining percentage. The average density of the assembled sphere was 18.7_1 gm/cm^3, or about 0.5% lower than the normal density of oralloy (18.81 gm/cm^3); a typical density achieved in fabrication of an individual component was 18.7_9 gm/cm^3.

As indicated in Fig. 1, proper positioning of the sphere sections is effected through the combined action of the

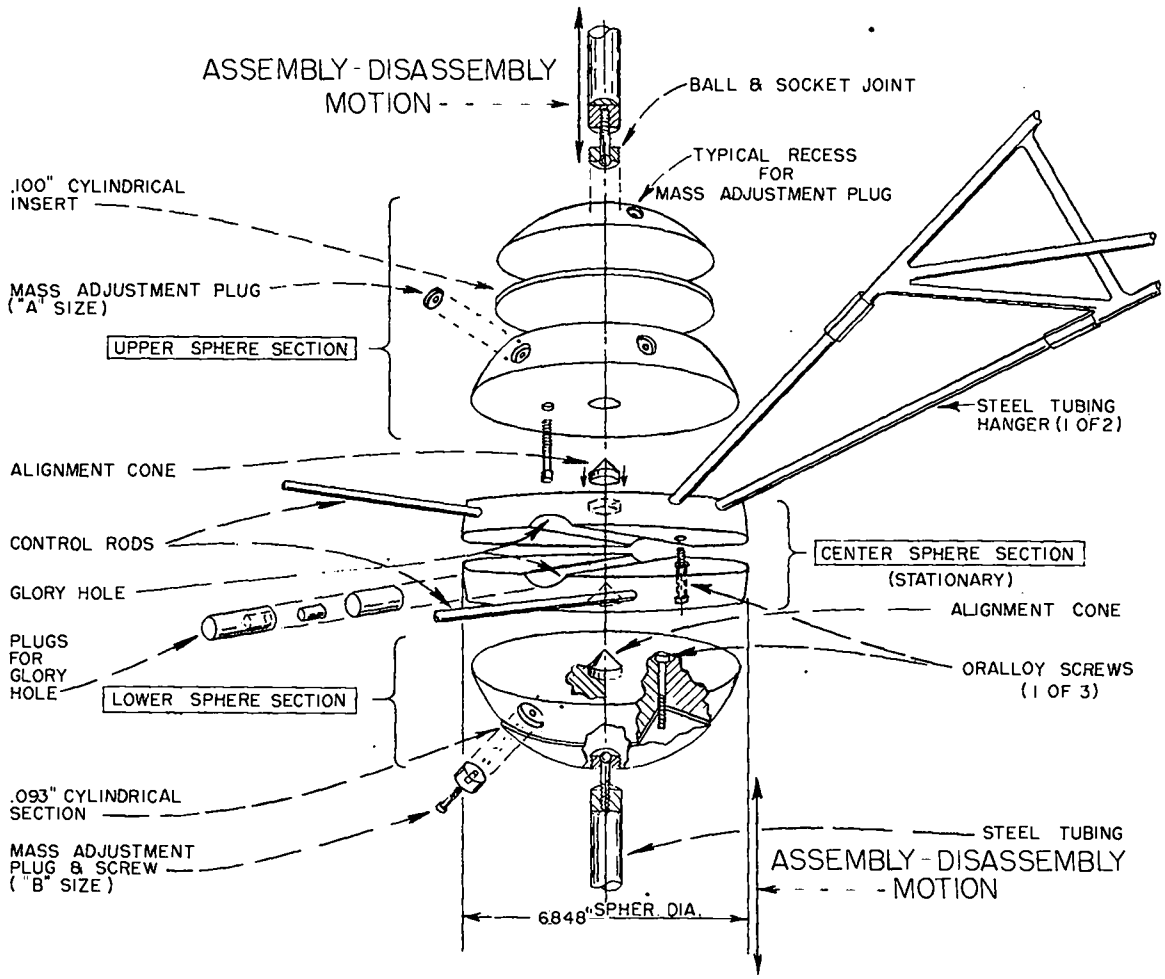

FIG. 1. View of Godiva components. With the exception of steel tubing support structure and ball portions of the flexible couplings, all parts shown are oralloy. Upper and center sphere sections are shown separated into their basic pieces, while the lower sphere section is shown with its parts bolted together.

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 misalignments in the assembly mechanism.

The 15/16 inch cylindrical channel or "glory hole" along a diameter of the sphere provides a means of inserting foils, counters, etc., into the assembly; space not occupied by experimental apparatus is filled with the oralloy plugs illustrated in Fig. 1.

Continuously variable reactivity control is obtained with the two 7/16 inch diameter oralloy rods (Fig. 1) which may be inserted into the channels paralleling the glory hole. For making successive, equal changes in criticality, fourteen 0.25 inch deep, 0.875 inch diameter recesses distributed on the sphere surface accommodate oralloy plugs (also known as "buttons") 0.250 inch ("A" plugs) or 0.544 inch ("B" plugs) thick, held in place with oralloy screws.

Figure 2 shows an over-all view of the nuclear and the remotely-controlled mechanical components of Lady Godiva, including the steel-tubing framework of the assembly mechanism, the air cylinder supporting the upper sphere section, the hangers holding the center section, and the hydraulic cylinder

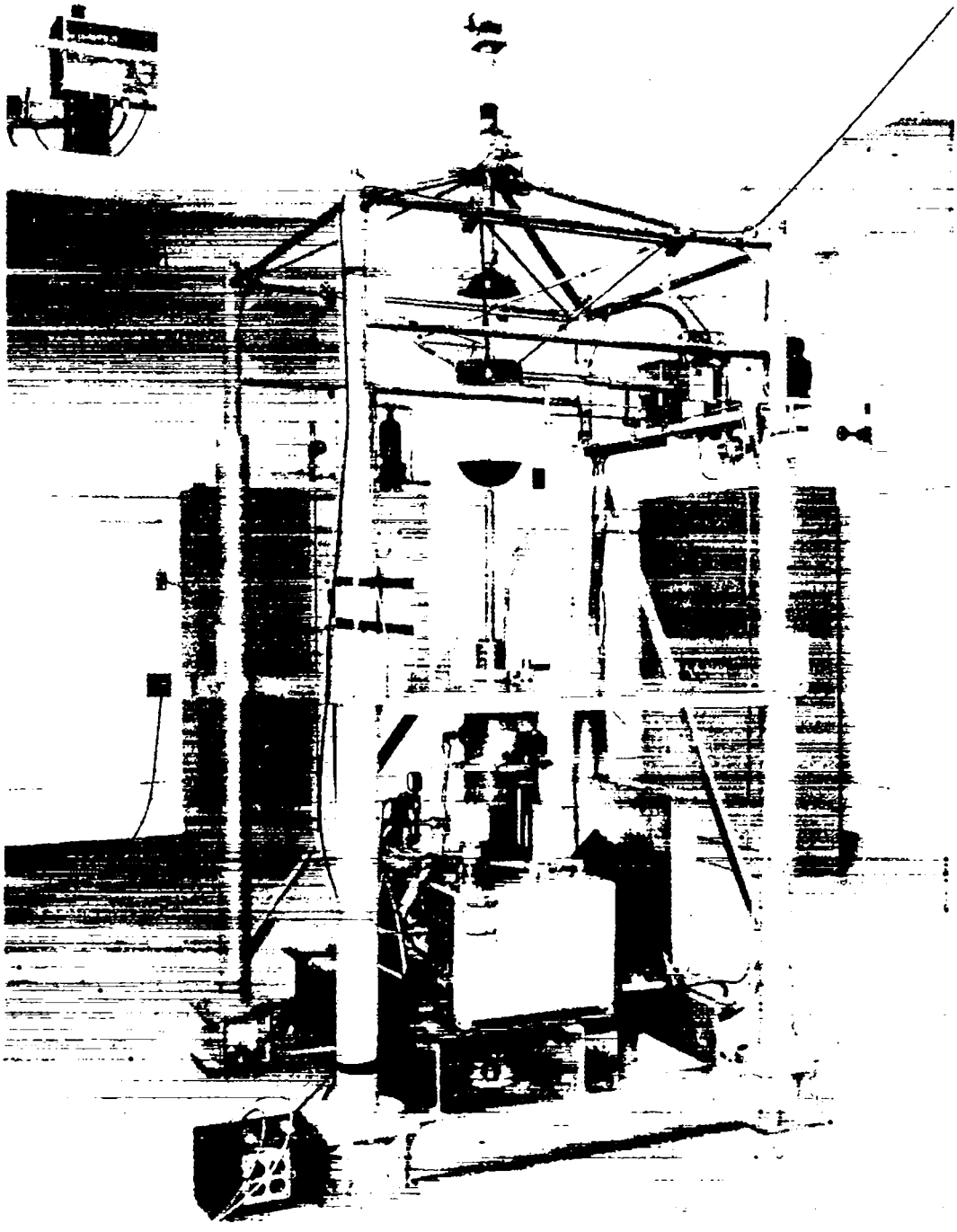

FIG. 2. View of Godiva, showing the oralloy components, and the remotely-controlled mechanical device for bringing the oralloy sphere sections together to form the critical assembly.

[redacted]

which controls the lower sphere 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 is used to position a neutron source near the surface of the sphere while an approach to a critical configuration is being made; in Fig. 2, this source holder is shown fully advanced toward the sphere. The pump and valves for operating the lower sphere section hydraulic lift cylinder are located in the base of the machine. In setting up the Godiva assembly mechanism, an existing machine was utilized, with the result that the lower parts are generally more massive than necessary.

The mechanical operations involved in making a routine assembly of the fissionable material and achieving a critical configuration are initiated by personnel in the control room about one-fourth mile distant from the "Kiva," as the fenced-off building which houses Godiva is called. 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 this sequence:

(a) The upper sphere section is lowered as air

[redacted]

pressure is gradually released from the lift cylinder; the alignment cones guide it into position on the center section of the sphere.

(b) Providing 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 inch overtravel beyond the point of contact with the center section before the lower lift piston comes to bear on a mechanical stop.

(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 components 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 located in the Kiva furnish a scram signal if the fission rate exceeds a specified value. Scramming also occurs if pressure in the compressed-air supply line drops below normal. Retraction of either the upper or the lower sphere section alone makes the assembly very subcritical, and only the unlikely simultaneous mechanical malfunction

of two independent actuating devices could prevent effective disassembly of the fissionable material.

A close-up view of the control rod drive is shown in Fig. 3. Each 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 (Fig. 3); the position of the rods at any given time is shown in the control room on selsyn-driven indicators calibrated to 0.001 inch.

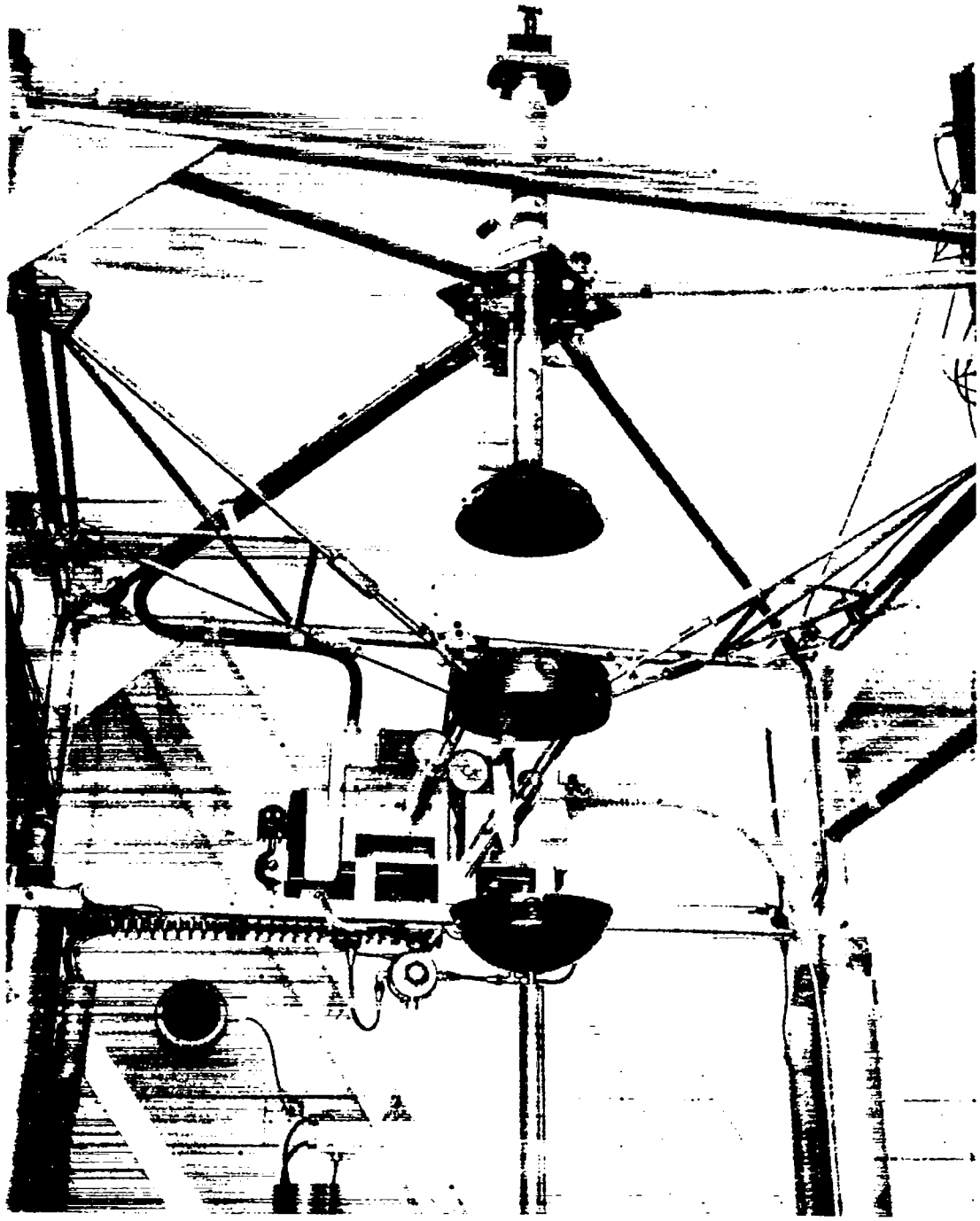

FIG. 3. Godiva control rod drive, hanger system, and oralloy sphere components.

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Section II. Critical Mass and Related Topics

Critical Mass

After the initial, unsuccessful attempt to bring Lady Godiva to delayed critical, the insertion of a 741 gm oralloy cylindrical section or "shim" into the upper sphere section (Fig. 1) made it possible to achieve a critical configuration with a total mass of 52.65 ± 0.02 kg. This mass included the 0.1 inch shim, one control rod completely inserted, the second rod approximately one-half inserted, and 11 of the "A" plugs. In anticipation of situations where the excess reactivity available through replacement of the "A" buttons and the filling of the remaining three surface recesses with the thicker "B" plugs would be inadequate for certain experiments, a 0.2 inch, 1480 gm shim was fabricated. When this shim was substituted for the 0.1 inch one, the observed critical mass, with one control rod completely in, the second about one-half inserted, and 2 "A" buttons in place on the sphere surface, was 52.88 ± 0.02 kg. The nominal 200 gm difference in critical mass is attributed to the additional deviation from spherical symmetry produced by the thicker 0.2 inch shim.

It is estimated that if the Godiva components had constituted a true sphere, the critical mass would have been about 400 gm less than the 52.65 kg value observed with the

[redacted]

0.1 inch shim (in this configuration, the sphere was elongated by 0.193 inch because of the presence of the shim and the 0.093 inch integral cylindrical piece in the lower sphere section). The value of the critical mass of an untamped uranium sphere, isotopic composition 93.7_1% U-235, about 1.0_5% U-234, and 5.2_5% U-238, with an average density of 18.7_1 gm/cm^3 is, therefore, about $52.2_5 \pm 0.1$ kg. The critical mass previously reported[1] on the basis of multiplication measurements with subcritical oralloy spheres was, for a sphere of normal density (18.8_1 gm/cm^3) and 93.8_6% U-235 concentration, 51.6 ± 0.2 kg. If this value is adjusted to correspond to the density and U-235 content of Godiva, the value is about 52.3 ± 0.2 kg. Results of the multiplication experiments are, therefore, in agreement with the observed critical mass of Godiva.

The equivalent mass contribution from neutron reflection to the Godiva sphere by hangers, etc., is probably less than 100 gm; this number is based on effects observed in multiplication measurements on subcritical "unreflected" spheres[2] and on the measured change in reactivity produced by placing additional dummy hangers near the sphere. A comparison of the critical mass of Godiva in the Kiva with the critical mass observed with Godiva located out-of-doors on a tower, 16 feet above ground level (see Fig. 4), indicates

that for the latter, presumably more nearly unreflected arrangement, the critical mass is about 40 gm more.

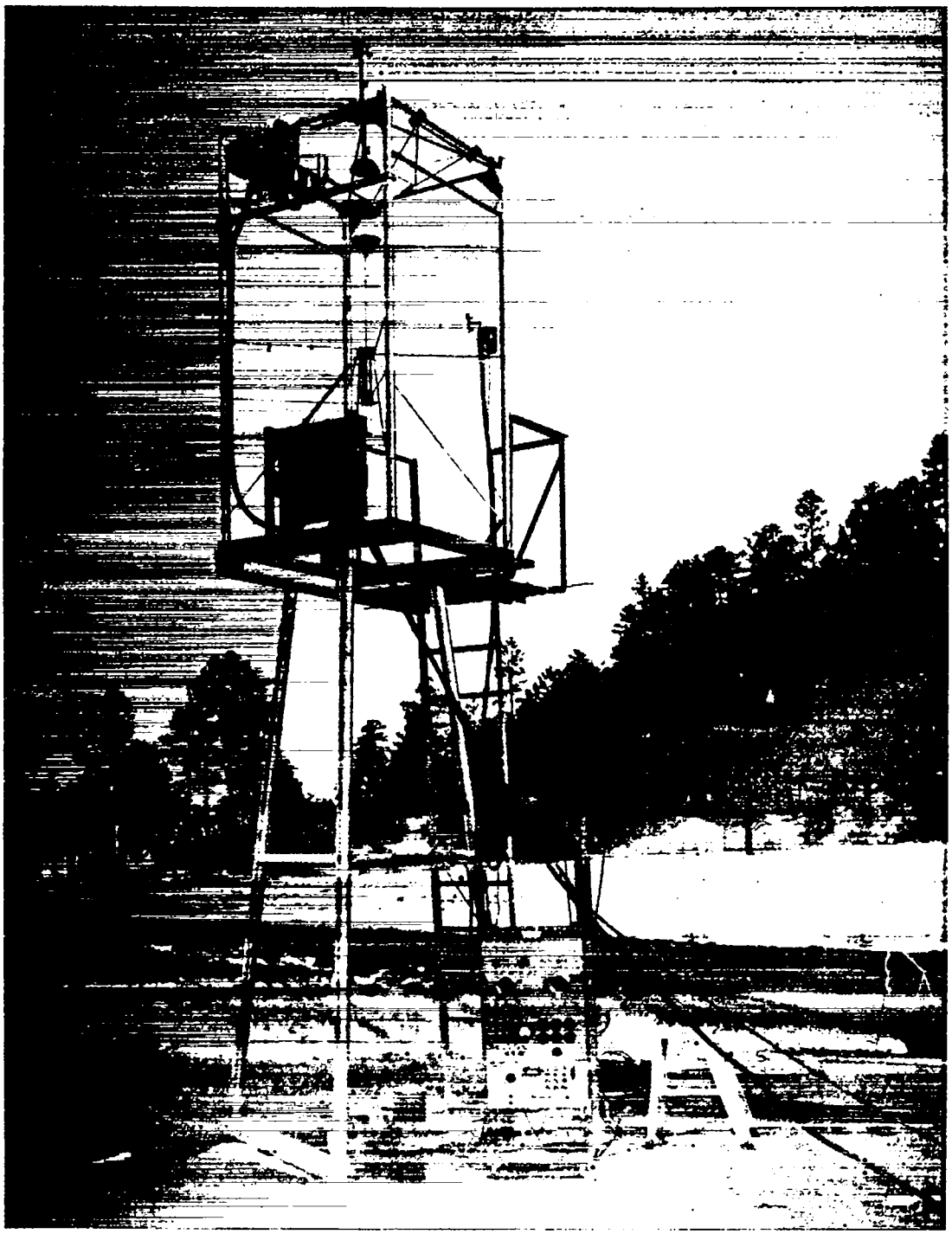

FIG. 4. View of Lady Godiva on tower out-doors. The critical assembly is 16 feet above ground level.

Control System

In the investigation and calibration of the control system, it was necessary to establish the reactivity change (Δk) produced by the insertion of the control rods and the addition of mass adjustment plugs and also to measure Δk as a function of control rod position. The basic procedure in reactivity calibration was to establish a delayed critical configuration as a reference point, increase the reactivity by inserting known amounts of control rod or 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 obtained using the delayed-neutron data[3] of Hughes, et. al. 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 inch control rods was observed to be about 44 cents per rod; however, nonlinearity of Δk vs. control rod insertion prevented, in practice, full use of the available control. With some sacrifice in total available Δk, improved linearity in one rod was achieved by the modification shown in Fig. 5; as the second rod was normally run at full insertion, its nonlinearity did not matter, nor was a precise calibration of its Δk vs. position necessary.

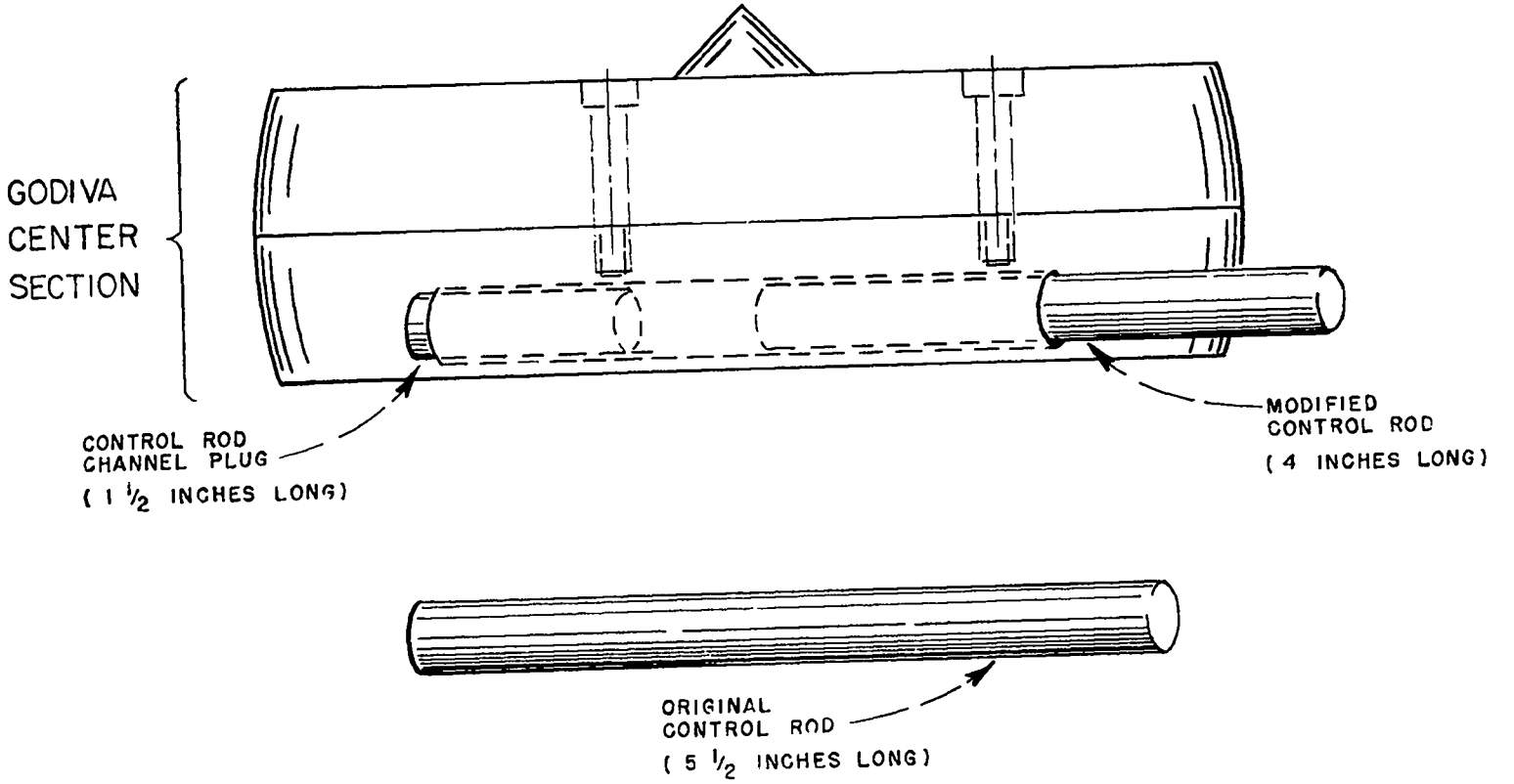

FIG. 5. Modified control rod for Godiva.

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Δk as a function of position of the modified rod is shown in Fig. 6; data were obtained by balancing reactivity changes produced by mass plug additions with changes in rod position so as to maintain a delayed critical configuration. On the linear portion of the curve, Δk per inch of control rod is about 11.7 cents; the total control available with the modified rod is approximately 33 cents.

Because of the elongation of the Godiva sphere, Δk for a mass adjustment plug depends upon its position on the sphere; this is illustrated by the plug Δk values listed in Table I. "A" size buttons are designated as A' buttons if placed in either of the two recesses on the polar cap of the upper sphere section (see Fig. 1) and are called A_U (A-upper) if placed in any of the five recesses on the bottom component of the upper sphere section. "A" size plugs placed on the lower sphere section in positions corresponding to the A' and A_U recesses are labeled A" and A_L, respectively. "B" size buttons are identified in a similar manner. The average mass of an A button plus its screw is 49.0 ± 0.1 gm, and that of a B button and screw, 98.7 ± 0.15 gm.

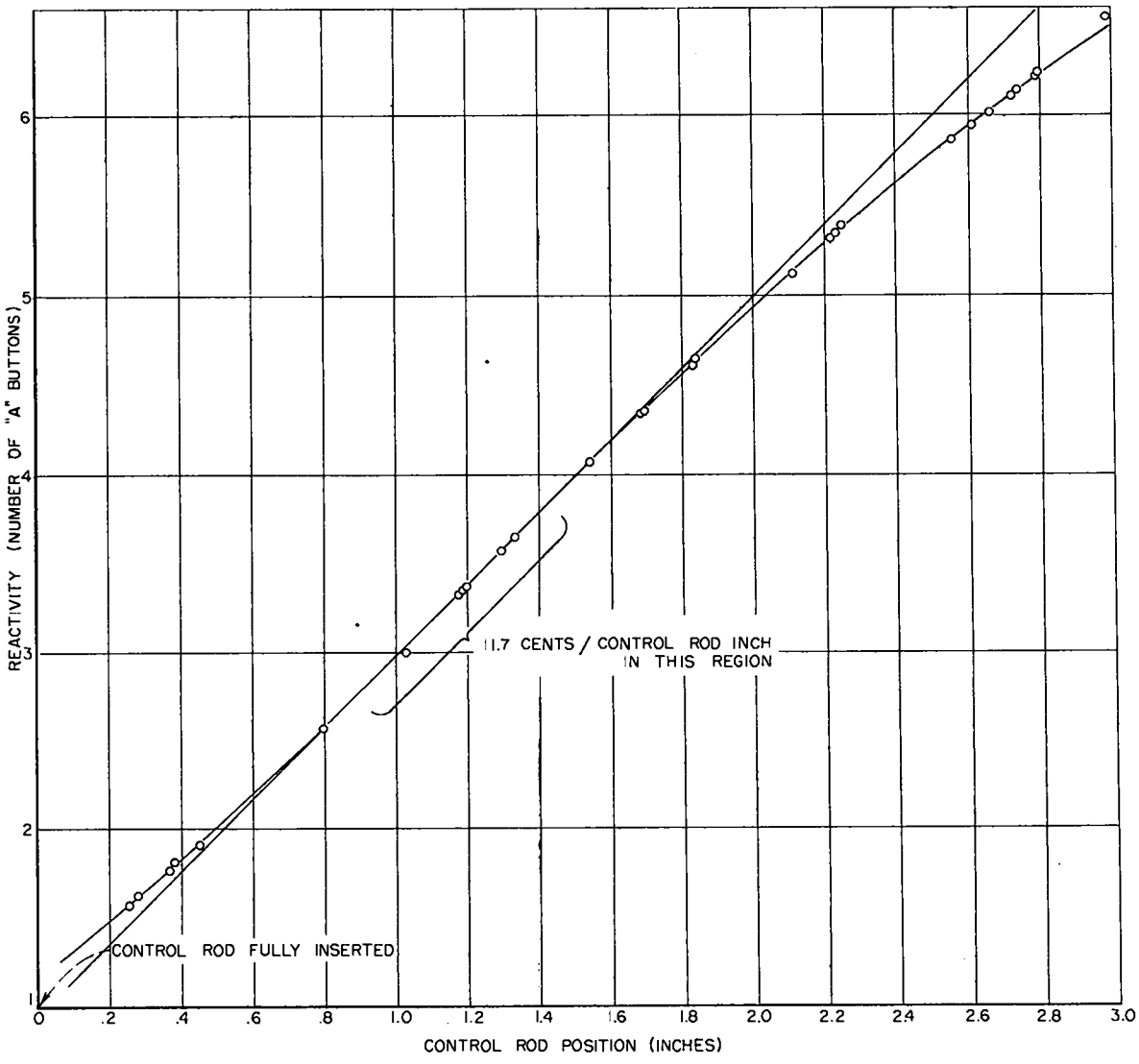

FIG. 6. Calibration curve for modified control rod, showing deviation from linearity.

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TABLE I.

Δk values for mass adjustment buttons. Δk is expressed in linear control rod inches. One linear control rod inch is equivalent to 11.7 cents.

Godiva configuration	Button	Δk
0.1 inch shim in upper sphere section	A'	0.449
	A"	0.451
	$A_U \cong A_L$	0.492
	$B_U \cong B_L$	0.758
	B'	0.693
	B"	0.696
0.2 inch shim in upper sphere section	A' + A"	0.878
	A_U	0.514
	A_L	0.487
	B'	0.659
	B"	0.676
	B_U	0.793
	B_L	0.746

[redacted]

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 oralloy at various points in the assembly. The desired data were obtained by determining the change in reactivity associated with insertion of a 30 gm, 1/2 inch diameter, 1/2 inch long oralloy 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 tuballoy and plutonium samples into the assembly, are shown in Fig. 7; the reactivity change produced by a sample at a given radial position is expressed in cents per mole of the replacement material.

In principle, the curve for oralloy, Fig. 7, 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 oralloy at the surface of the sphere and from this obtain the number of moles corresponding to a 100 cent reactivity change. However, the result obtained is very sensitive to the shape of the curve at the sphere surface, and also, because of the elongation of Godiva, the radius at

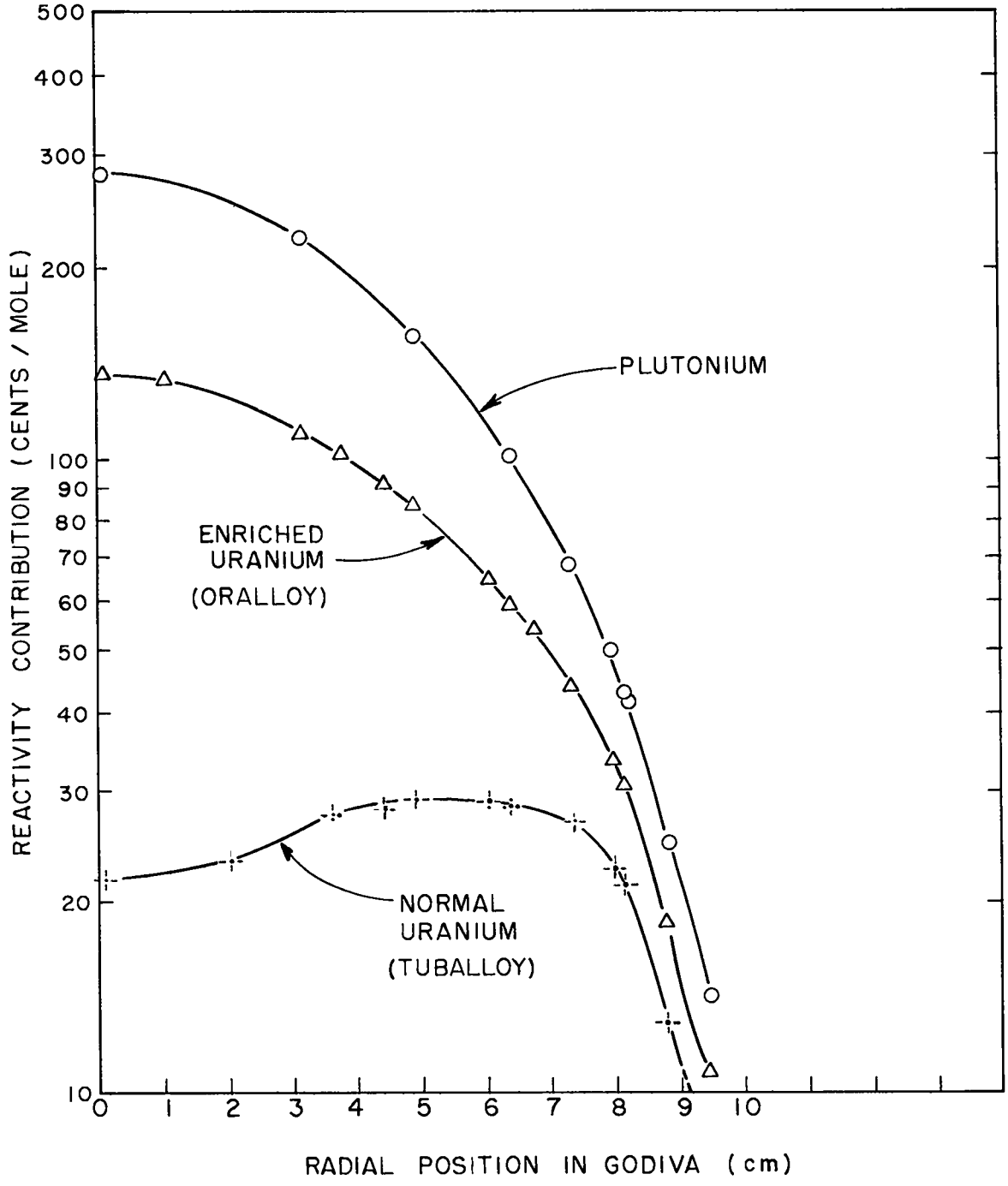

FIG. 7. Reactivity contributions of some fissionable materials at various radial positions in Godiva. The data were obtained with "replacement" specimens of 1/2 inch diameter, 1/2 inch length.

which the effective "surface" occurs is not precisely defined. A reasonable radius to use in this procedure is 8.73_0 cm (3.43_7 inches), the radius of a 52.2_5 kg oralloy sphere (52.25 kg is the estimated critical mass of Godiva if the assembly were truly spherical). On this basis, the mass difference between prompt and delayed critical is found to be 1225 gm.

A more reliable value of this mass increment is 1270 gm.[4] The method of evaluation in reference (4) is based on an integration of the reactivity contribution per mole of oralloy over the volume of the sphere; in this case, results are not extremely sensitive to the value chosen for the "effective" radius of Godiva. Data used in the integration were corrected for the effects of finite sample size on the observed reactivity contributions. (Experimentally, it had been observed that the apparent per mole reactivity contribution of oralloy was about 3% greater when 1/4 x 1/4 inch cylindrical samples, rather than 1/2 x 1/2 inch cylinders, were used in replacement measurements.)

Temperature Coefficient of Reactivity and Reactivity Reproducibility

A simple calculation involving the thermal expansion coefficient of uranium, the 1270 gm mass difference between prompt and delayed critical, and a proportionality between critical mass and the reciprocal of the second power of the oralloy density showed that the temperature coefficient of reactivity should be about - 0.34 cent/^{o}C for Godiva. The measured variation of reactivity with temperature is shown in the curve of Fig. 8, which indicates that the temperature coefficient is about 0.034 control rod inch/^{o}C, or - 0.40 cent/^{o}C. The variation of Godiva reactivity with room temperature, a factor of practical concern in the operation of the critical assembly, is illustrated in Fig. 9. (A preliminary value of the temperature coefficient, obtained from the data of Fig. 9, was - 0.5 cent/^{o}C.) This temperature-induced variation in reactivity can be very troublesome, since the relatively small thermal capacity of Godiva permits rather rapid fluctuations in the assembly's temperature; however, it has been possible to control the "local" temperature near Godiva by mounting the thermostat for the Kiva heating system on the assembly machine in a stream of air blown past the sphere by a fan. Variation of air temperature near Godiva could then be made small and regular

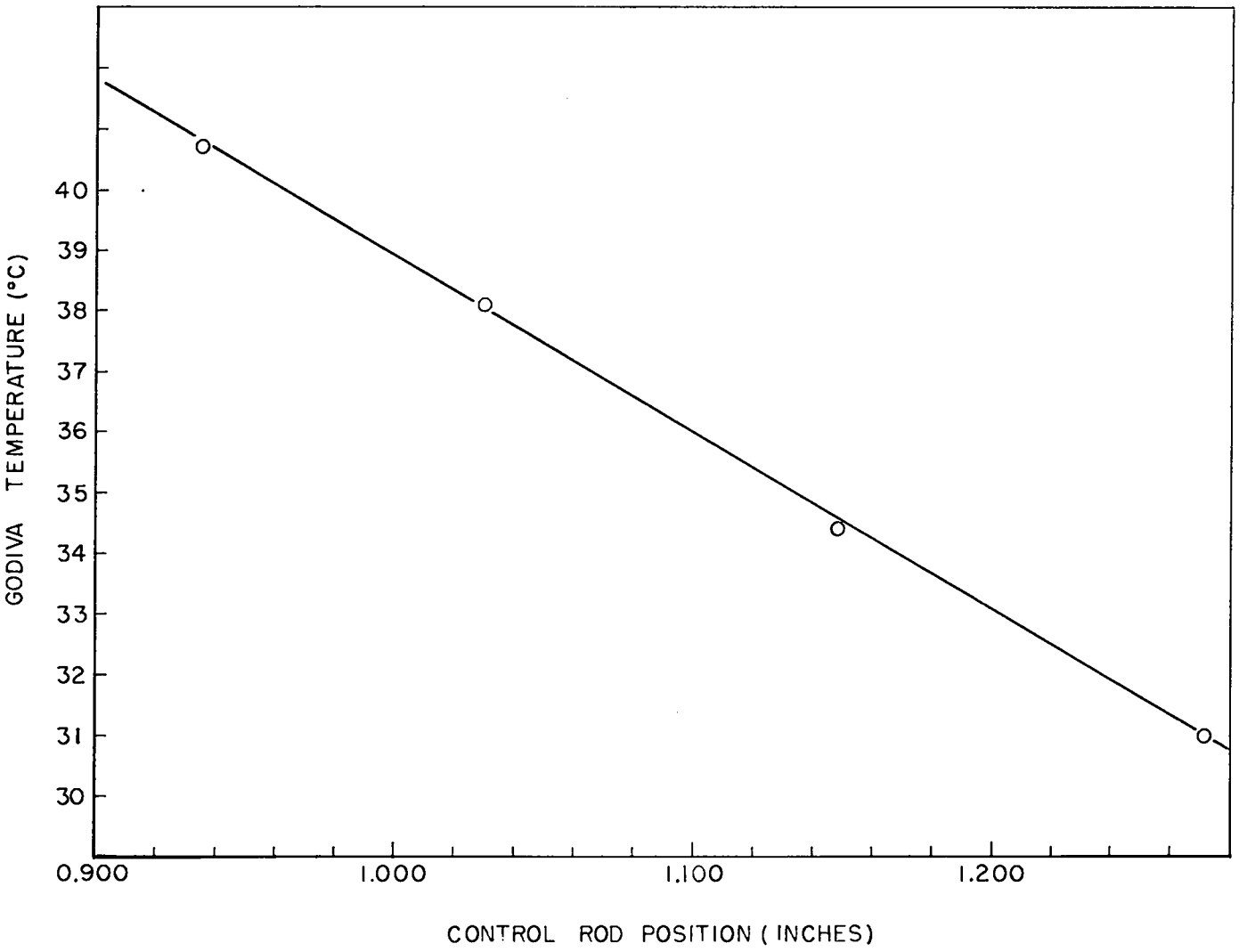

FIG. 8. Temperature coefficient of reactivity for Godiva. The control rod position required to maintain a delayed critical configuration is shown for various temperatures. The slope of the curve is - 0.034 control rod inch/°C, or, for a value of 11.7 cents/control rod inch, - 0.40 cent/°C.

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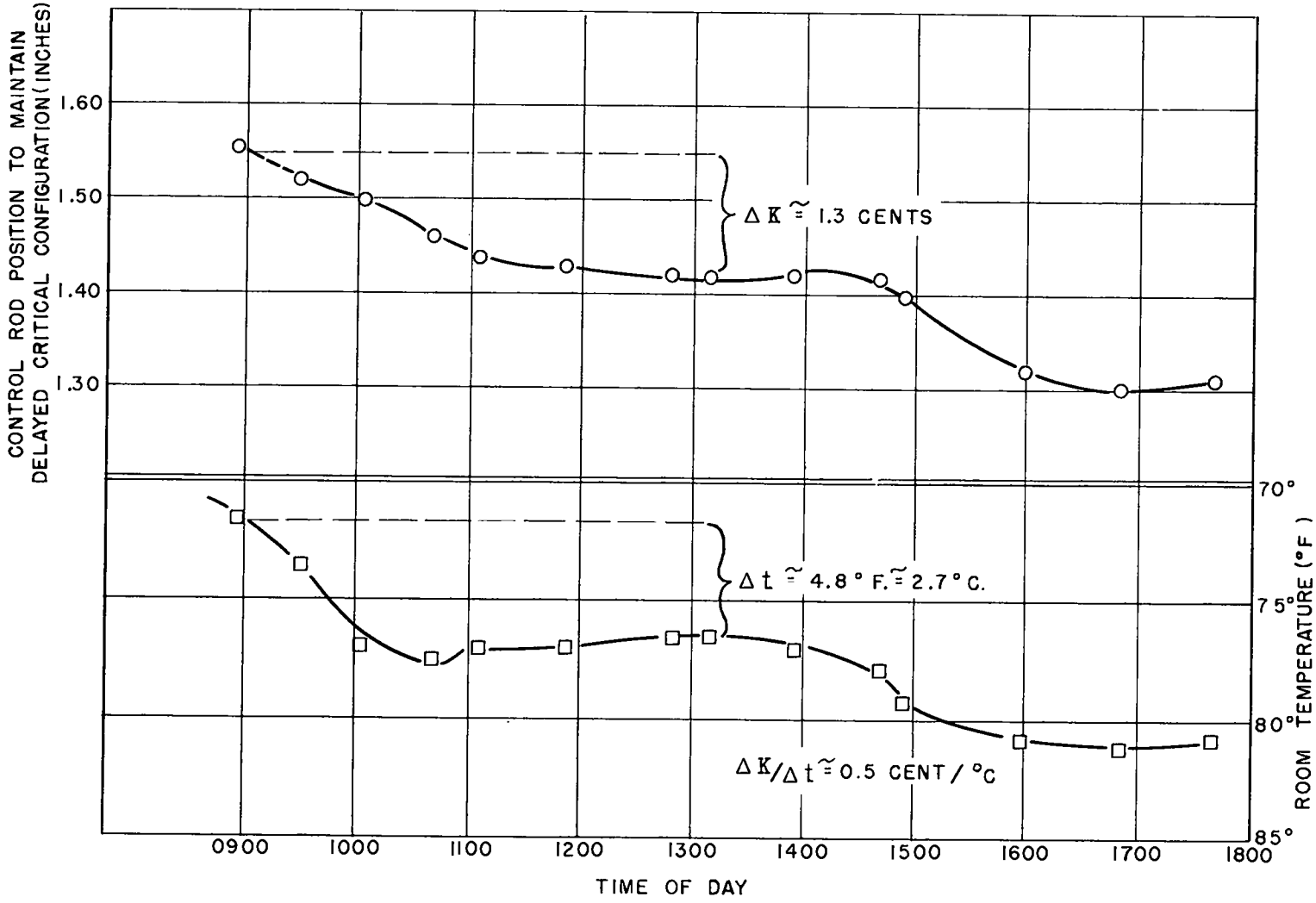

FIG. 9. Variation of Godiva reactivity with room temperature. The data illustrate the need for accurate temperature control when precise measurements of reactivity are to be made. A preliminary estimate of $\Delta k/\Delta t = -0.5$ cent/°C was obtained from these data.

[redacted]

($0.5^{o}C$ amplitude with a 10 min period). In one experiment carried out under these conditions, the control rod setting at delayed critical varied by no more than ± 0.010 inch (± 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 inch in successive assembly operations.

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Power Level, Neutron Flux, Etc.

Godiva is necessarily operated only at low power, since neither a cooling system, nor shielding to protect personnel entering the Kiva after operation, is provided. In practice, experiments involving precise reactivity measurements are generally carried out at powers of from one-tenth to 1 watt, in order that self-heating should not produce appreciable changes in reactivity. In other types of experiments, where a high flux rather than accurate knowledge of the reactivity is needed, power levels in the region from one-tenth to 1 kilowatt are attained; at the latter power, excess reactivity available in the control rods is generally overbalanced by the decreased reactivity accompanying the temperature rise after about an hour of operation, and 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 restore reactivity by adding mass adjustment buttons. At 100 watts, the neutron leakage from Godiva is about 5×10^{12} neutrons/second, and the gamma ray dose rate at a distance of 1 meter is about 0.13 r/sec.

[redacted]

Section III. Notes on Experimental Programs

The following brief descriptions of some measurements and experiments carried out with Godiva will be amplified in other Laboratory reports currently in preparation; in some cases, only preliminary results are available at this time.

Fission Cross Section Ratios; Spectral Indices

It has seemed desirable to attempt to obtain data concerning the differences in neutron spectra in various critical assemblies operated at Pajarito Site; in the absence of means for direct measurements of neutron energies, a comparison between the fission rates of U-235, U-238, Np-237, and U-234 foils inserted into the critical assemblies permits tabulation of the relative fission cross sections averaged over the spectra of the various assemblies. These "spectral indices," interpreted on the basis of obtainable data on fission cross sections as a function of neutron energy, give indications of the variations in neutron spectra between one critical assembly and another.

The results of measurements made in Godiva, in the normal-uranium-tamped oralloy assembly,[5] and in a fission spectrum of neutrons are listed in Table II. Data were obtained by placing the U-235, U-238, etc., foils in a "double"

TABLE II.

Ratios of the average fission cross sections of four fissionable nuclei for various neutron spectra. The radial positions at which measurements were made in the Godiva and Topsy critical assemblies are indicated as distances from the centers of the assemblies. The 8-1/4 inch position in Topsy falls in the normal uranium tamper.

Ratio	Fission spectrum	Godiva 3 inch position	Topsy 1/4 inch position	Topsy 8-1/4 inch position
$\frac{\sigma_f(\text{U-235})}{\sigma_f(\text{U-238})}$	3.94	5.52	6.83	74.7
$\frac{\sigma_f(\text{U-234})}{\sigma_f(\text{U-238})}$	4.25	5.01	5.15	13.9
$\frac{\sigma_f(\text{Np-237})}{\sigma_f(\text{U-238})}$ *	4.08	4.65	5.02	12.6

* Np-237 foil weight is in doubt; further measurements are desirable.

ionization chamber so that fissions in each of the two foils being compared could be counted simultaneously while the foils were exposed to the same neutron flux. Relative values of the cross section of a particular nucleus in the different spectra are estimated to be uncertain by about 3%. The ratio of cross sections for a given pair of nuclei in a specified spectrum are less certain because of possible errors in foil weight determinations. Values (Table II) are listed at only one radial position in Godiva, since in only one case (U-235 compared to U-238) was an appreciable radial dependence of the cross section ratios noted. Table III indicates the magnitude of this variation for the case of U-235 and U-238. Measurements on fission cross section ratios are being continued in an attempt to improve the accuracy; a more extensive discussion of the program will be given in a future Laboratory report.

[redacted]

TABLE III.

Variation of the ratio of fission cross sections of U-235 and U-238 with radial position of these detectors in Godiva. Data are based on radio-chemical analysis of foils irradiated in the critical assembly.

Detector Position: Inches from center of Godiva	Ratio: σ_f(U-235)/σ_f(U-238)
0.02	6.32
0.50	6.23
1.02	6.06
1.56	6.05
2.08	6.06
2.62	5.82 *
3.15	5.81 *

*The discrepancy noted between 3 inch position values of σ_f(U-235/σ_f(U-238) as listed in Table II and Table III, presumably results from uncertainty in the weight of foils used in obtaining the data of Table II.

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Measurements of Alpha

A parameter of interest in critical assemblies is "alpha," the time constant associated with fission chains sustained by prompt neutrons. A comparison of a calculated and a measured value of alpha for a particular assembly serves to indicate whether the cross sections and the neutron spectrum used in the calculation were correctly chosen. For the Godiva assembly, the calculated value of alpha at delayed critical was about 25% larger than that observed. This fact initiated a series of measurements of alpha at several reactivities between prompt and delayed critical; it was hoped that by observing the variation of alpha with reactivity, any error occurring in the originally-measured value of alpha at delayed critical might be brought to light. Data were obtained by two methods: by the "Rossi method,"[6] and through observation of the decay of prompt neutrons generated in fission chains initiated by pulsed irradiation of the critical assembly with gamma rays from a betatron.[7] Results of the measurements are given in Fig. 10; reactivities were determined by observing the "positive period" of the assembly and applying the inhour equation. The well-defined dependence of alpha on reactivity shown by both sets of measurements indicates that -1.03×10^6, the originally observed delayed critical value of alpha (which is difficult to

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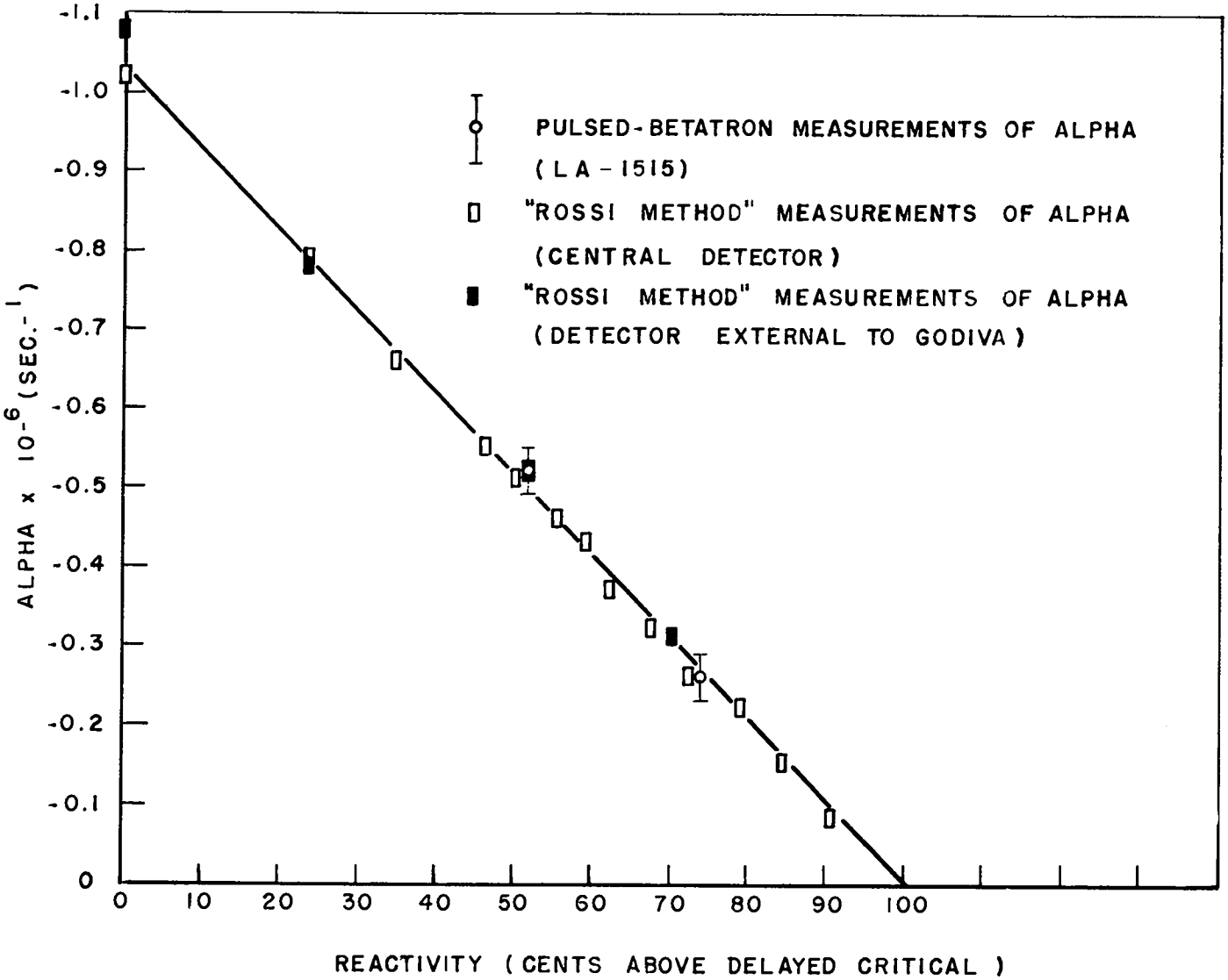

FIG. 10. Alpha as a function of reactivity. The discrepancy between measurements made with internal and external detectors at the delayed critical point is not understood.

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determine with precision because of the requirements on the time-resolution of the apparatus) is substantially correct. However, some recent check measurements indicate that alpha at delayed critical may be as large as $-1.09 \times 10^{6} sec^{-1}$. In these latter experiments, an attempt was made to discover any effect of scattered neutrons on the observed alpha by making measurements (a) in the Kiva, and (b) with Godiva located out-of-doors, 16 feet above ground level. No variation in alpha was observed for these two cases.

In addition to the more detailed information given on the betatron measurements in reference (7), further discussion of the "Rossi method" measurements and of calculations of alpha will be presented in a scheduled Laboratory report.

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Material Replacement Measurements

The reactivity contributions of small samples of various elements (fissionable as well as nonfissionable) used as fillers for small cavities in Godiva have been determined in an extension of a series of similar measurements carried out with other critical assemblies at Pajarito Site. The theory and some applications of such measurements are discussed in reference (4). Data on the reactivity contributions of oralloy, for instance, may be used in evaluation of the quantity γf, and estimates of the relative average transport cross sections of different elements may be made; for certain elements, it is possible to estimate 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 (at various radial positions in Godiva) of the reactivity contributions for a few elements are given in Table IV; data on oralloy, normal uranium, and plutonium are not included in Table IV, since these are shown graphically in Fig. 6. Further results and a more detailed account of the replacement measurement program will be included in a report being prepared by H. C. Paxton.

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TABLE IV.

Reactivity contributions of some elements in Godiva. The tabulated values are derived from the changes in reactivity produced by filling a 1/2 x 1/2 inch cylindrical cavity in Godiva with correspondingly-sized cylinders of the various materials. Positions at which the cylinders were inserted are indicated as "effective" distances from the center of the critical assembly.

Element or Isotope	Reactivity contribution, cents/mole, at designated positions					
	0.030 inch	1.242 inch	1.930 inch	2.512 inch	3.142 inch	3.206 inch
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

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Measurements of the Spectrum of Leakage Neutrons

Preliminary measurements of the energy spectrum of leakage neutrons from Godiva, made with nuclear emulsions and with a hydrogen-filled cloud chamber, yielded unsatisfactory results because of the presence of a large background of scattered neutrons. Both measurements are being repeated with Godiva located outdoors, 16 feet above ground level; backgrounds will in this case presumably be small. No results are as yet available.

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Some Special Measurements

With one exception,[8] 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 up to somewhat more than 100 cents above delayed critical initiated what has been known as the "Godiva prompt-burst program," involving, during the past year, a general investigation of the behaviour 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: the observed self-termination (via thermal expansion) of the rapid rise in fission rate in a (approximately) prompt critical assembly may be compared with the calculated shape, size, and duration of the fission "burst"; a determination of the mass at which prompt critical is reached indicates whether or not the cents value of specified mass additions, previously calibrated at reactivities near delayed critical with the aid of the inhour equation, are correct, since deviations in the reactivity scale determined by the inhour equation would occur near prompt critical if there were undiscovered, short-period delayed neutron emitters. The availability of a high intensity neutron pulse, as produced by a fission burst, suggests a method

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of looking for short-period delayed neutrons, since short-time irradiation of U-235 (favoring saturation of any short-period delayed neutron activity) could be accomplished in higher fluxes than would otherwise be obtainable at Los Alamos.

The Godiva assembly was selected for the prompt burst program since it was very reproducible reactivitywise, in successive assemblings, and had, in the series of alpha measurements, 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 3/8 inch diameter, 7 inch long oralloy 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. The photographed 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 microseconds. In the largest fission bursts observed, approximately 2×10^{16} fissions occurred, the major portion of the energy being released in about 50 microsec. The average rate of energy release during the main portion of the fission burst was, therefore, about 10^4 megawatts. The resulting temperature rise of the assembly was $100^{\circ}C$.

A graph of the observed e-folding times as a function of reactivity is shown in Fig. 11. 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 measured periods short compared to delayed neutron periods. The period of the assembly at prompt critical is about 0.74 millisec.

A preliminary evaluation of the cents/control rod inch value consistent with the observed change in configuration required to bring the assembly from delayed to prompt critical yields 11.8_5 cents/inch. This value differs by slightly

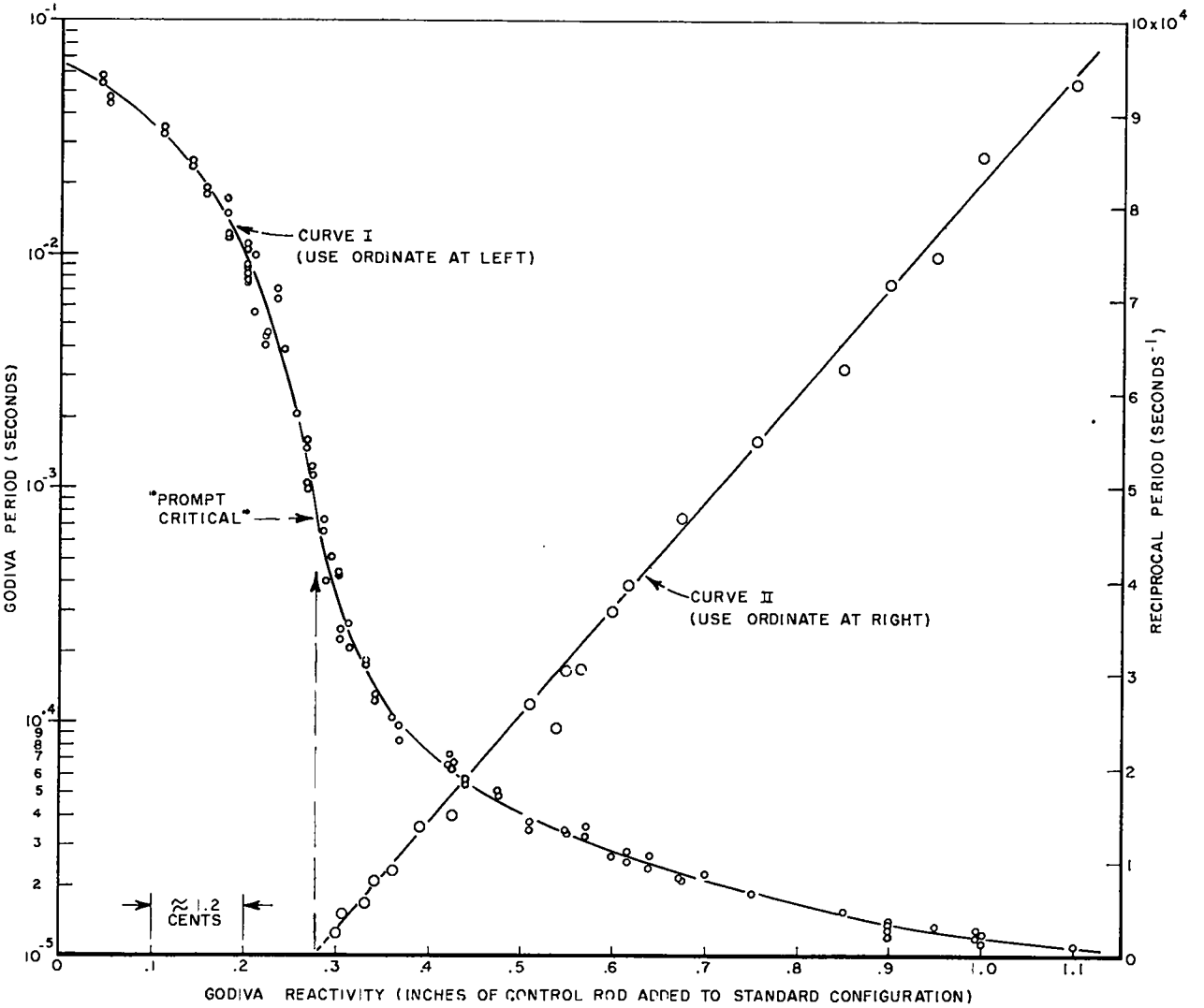

FIG. 11. Data from the Godiva "prompt burst" program. Curve I shows the measured periods of the critical assembly as a function of reactivity. The reciprocal of the period, 1/T, is plotted in Curve II. Extrapolation of Curve II to the point 1/T = 0 defines the point at which alpha becomes zero; i.e., the "prompt critical" point.

more than the estimated error in measurement from the 11.7 cents/inch previously obtained in the 0-60 cent reactivity range, but there is no clear evidence at this time that the inhour equation used with delayed neutron periods and abundances of Hughes et al does not adequately give the relation between the period of the assembly and its reactivity. Only preliminary work has been done on experiments in which the shortest-period delayed neutrons previously reported (or other short-period neutrons) would be observed directly in a sample of U-235 irradiated in a short-duration, high-intensity neutron burst.

REFERENCES

(1) Private Communication.

(2) LA-1209, "Measurements on Untamped Oralloy Assembly," J. D. Orndoff.

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(4) LA-1525, "Material Replacement Experiments: Theory and Measurements for the Lady Godiva Assembly," G. E. Hansen.

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(6) LA-744, "Time Scale Measurements by the Rossi Method," J. D. Orndoff.

(7) LA-1515, "Alpha Measurements on the Lady Godiva Critical Assembly Using a Betatron," P. J. Bendt.

(8) Phys. Rev. 74, 1330 (1948), "Delayed Neutrons from U-235 after Short Irradiation," de Hoffmann, Feld, and Stein.