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EXPERIMENTAL STUDY OF THE Mk-IA PLASMA NEUTRON SOURCE

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FOREWORD

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This report documents research carried out from January 1966 through February 1968, and it was submitted for review and approval on 1 October 1968 to Lt. Steven D. Mohan, SMTTA.

Approved

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Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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ABSTRACT

An experimental investigation was carried out to determine the relationships between the significant parameters of an unusual pulsed neutron generator. The device employs a novel paraboloidal electrode geometry and belongs to the general class of plasma "focus" devices in which neutrons are generated by the compression of a dense deuterium plasma. Maximum neutron yields of the order of 10^9 neutrons/shot were obtained using a bank of six 14-μF capacitors at 23 kV for a bank energy of 22 kJ. The parametric variables studied included deuterium gas pressure, bank voltage, anode geometry, and electrode material in the vicinity of the focus. The neutron and x-ray spectra were measured.

CONTENTS

TABLES

FIGURES

I. INTRODUCTION

The plasma focus device is an unusual type of plasma accelerator that is receiving attention in many laboratories because of the intense burst of neutrons and x rays that it produces. Although geometries vary, in all of these devices energy stored in a high-voltage capacitor bank is suddenly switched to a pair of coaxial electrodes, one of which is mounted inside the other, the space between being filled by deuterium or a deuterium-tritium mixture at low pressure. Breakdown occurs in the gas, and magnetic forces drive the current sheet along the electrode structure. When the current sheet reaches the end of the inner electrode a very rapid and violent contraction occurs, and some of the plasma created in the discharge is compressed into a very hot dense plasma "focus." During the period of maximum compression (~50 nsec) large amounts of x radiation are emitted and also large numbers of energetic neutrons (as a result of the nuclear reactions $D + D \rightarrow He^3 + n$ or $D + T \rightarrow He^4 + n$).

Interest in the potential application of such sources of neutrons and x rays for military testing led to the initiation of a small-scale experimental program in the Plasma Research Laboratory in 1965. Virtually all of the experimental work carried on at other laboratories had utilized electrodes having a "coaxial accelerator" configuration. The Aerospace experiment employed an electrode geometry in which the spacing between the inner and outer electrodes monotonically decreased from the breech end to the focus region. The original hope was that this arrangement would provide greater plasma density than is produced in the strictly two-dimensional compression that occurs in the conventional geometry. The experiment was called a tridimensional (or 3-D) pinch experiment.

Early results with the original apparatus (Mk-I) were very encouraging (Ref. 1) in that neutron yields comparable to those achieved elsewhere with the conventional geometry were obtained in the Mk-I even though the stored capacitor-bank energy was appreciably smaller. The experimental effort was therefore enlarged, and the Mk-I apparatus was modified in several ways to increase its efficiency. The principal modification was the replacement of ignitrons by spark gaps as the main switching elements.

This report provides a detailed description of the modified apparatus (designated Mk-IA) and the results achieved in the experimental program in which it was employed. Section II contains a description of the apparatus, while an account of the measurements of plasma parameters and of the emitted x rays and neutrons is given in Section III. Section IV contains a summary of the conclusions derived from these measurements.

II. MARK-IA PLASMA PINCH

The plasma neutron source under study consisted of an annular insulator, a paraboloidal outer conductor, with an inner conductor roughly shaped like an inverted cone capped by a hemisphere (Fig. 1). Most plasma focus devices are fabricated with cylindrical inner and outer conductors.

A. POWER SUPPLY

The Mk-IA plasma pinch is driven by six Sangamo capacitors rated at 14 μF and 20 kV. The capacitors, monitored with a digital voltmeter that provides a high degree of resettability, are connected in pairs to three air-gap switches. These switches are connected to the pinch apparatus with Brand Rex type V-1433 coaxial cable. Twelve of these 4.2-ft 16-Ω cables are used in parallel. The capacitors were tested to 40 kV dc and successfully operated at 23 kV. The air-gap switches are triggered by three 0.01-μF, 14-kV capacitors; the capacitors are triggered by a single air-gap switch which in turn is triggered by a thyratron cascade system. This system permitted the use of starting trigger signals of low level, like those obtained from an oscilloscope gate. The time lag from trigger start to main-gap firing is typically 1.5 μsec with a shot-to-shot jitter of less than 100 nsec.

A 980-turn Rogowski current transformer was used to monitor the discharge current on all shots; five-turn pickup loops were used to measure fast transients above the upper frequency limit of the Rogowski. These loops were calibrated against the Rogowski transformer using an integrating circuit.

A frequently discussed criterion in plasma neutron generator work is the stored energy of the capacitor bank. Capacitor voltage vs stored energy is:

Capacitor Voltage, kV	Stored Energy, kJ
15	9.5
17	12.1
19	15.2
21	18.5
23	22.4
25	26.4

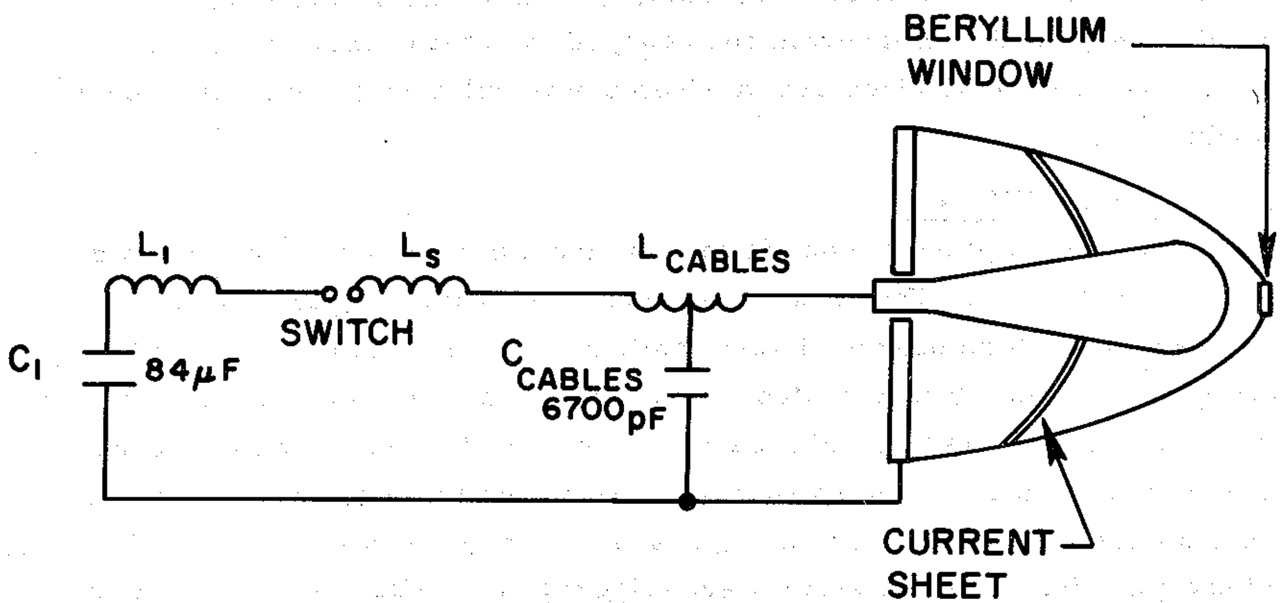

Fig. 1. Elements of Mk-IA Plasma Neutron Generator System

B. INDUCTANCE AND VOLUME CONSIDERATIONS

The tridimensional plasma compression concept involves a linear acceleration followed by a radial compression. In the usual coaxial accelerator, the "swept-up" volume and inductance increases linearly with distance along the axis of the plasma tube. Figures 2 and 3 are comparison plots of "swept-up" volume and inductance vs axial distance for a coaxial plasma accelerator and the Mk-IA.

C. CIRCUIT PARAMETERS

A series of ringing-frequency tests on various portions of the Mk-IA has provided values for the circuit shown in Fig. 1. Characteristics are:

C_1	=	84 μF
L_1	=	19 nH, capacitor and connection inductance
L_s	=	7 nH, switch inductance
L_{cables}	=	10 nH (12 cables, 4.2 ft long at 23 nH/ft)
C_{cables}	=	5000 pF (50 ft at 100 pF/ft)
C_{cables}	=	6700 pF, measured
$L_{plasma\ tube}$	=	67 nH
Total inductance	=	107 nH
Ringing frequency: cables shorted at plasma tube end	=	91 kHz
Ringing frequency: 1/4-in.-diam copper rod at focus end of plasma tube	=	47 kHz

D. PARASITIC RESONANCE

The capacity in the cables initially has no charge and becomes charged as soon as the switches operate (Fig. 1). This charging is through the inductance ($L_1 + L_s$), and the resulting transient is clearly observable at the time the current is turned on. The resonant circuit can also be localized by shorting across the switches and using a grid-dip meter for excitation.

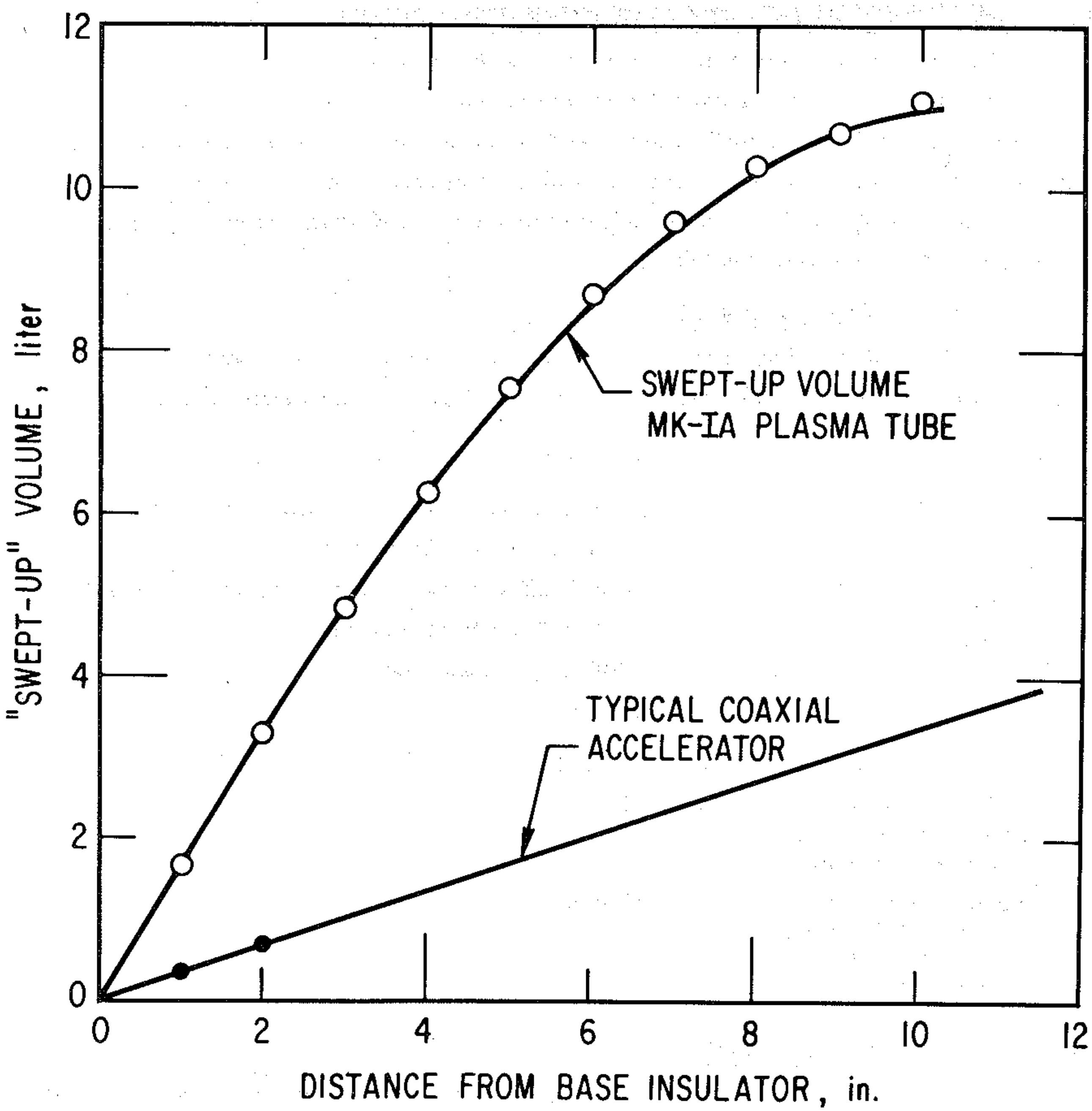

Fig. 2. Comparison of "Swept-Up" Volume (Assumes Current Sheet Perpendicular to Axis)

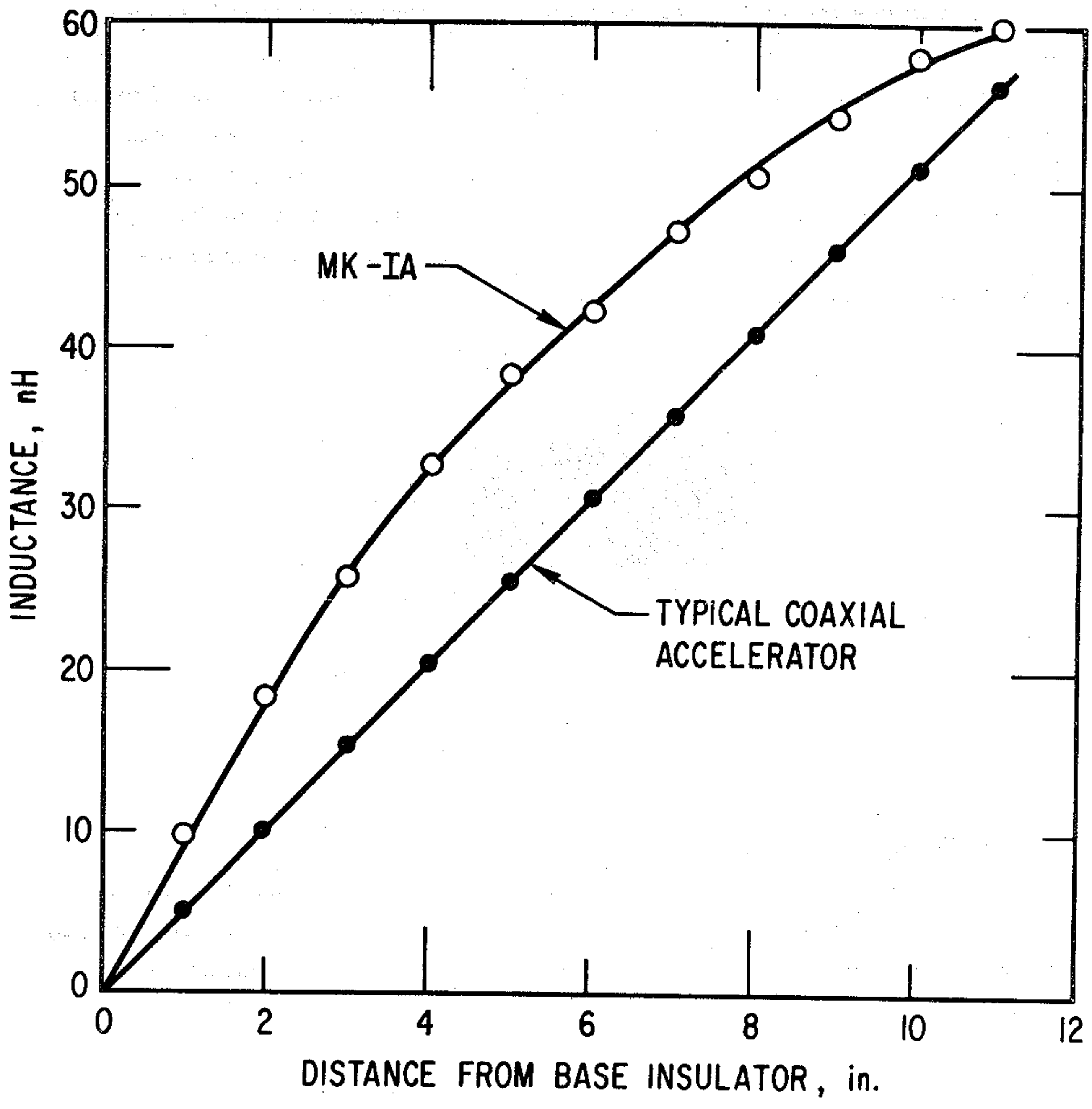

Fig. 3. Comparison of Inductance vs Axial Distance Down Plasma Tube (Assumes Current Sheet Perpendicular to Axis)

An interesting feature of the parasitic resonance is that it is excited not only at the time of current turn-on but also occurs at the time of neutron generation. On the "shots" that produce a small number of or no observable neutrons, the second parasitic resonance is not observed. A typical parasitic oscillation, at the time of neutron generation, is shown in Fig. 4. The characteristics are a frequency of 17 MHz, $C_{measured} = 6700$ pF, and $L = \frac{1}{(2\pi f)^2 C} = 13$ nH. The low inductance is indicative of current flowing near the base insulator.

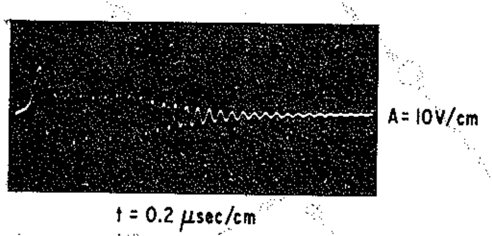

Fig. 4. Parasitic Oscillation Observed with Current Loop at Time of Neutron Generation

E. CURRENT CALIBRATIONS

There are various ways to calibrate the current monitor in a capacitance discharge circuit. If it were possible to have a capacitor discharging into a small inductance with no losses of any kind, the current at its maximum would be given by

$$I_{max} = V\omega C$$

where

C = total capacity of the capacitor bank

ω = $2\pi \times$ the ringing frequency

V = voltage on the capacitor bank prior to the discharge

Since all real circuits have losses, it is necessary to plot the waveforms on semilog paper and extrapolate back to zero time. Figure 5 is a semilog plot of the relative height of the current peaks. The first current peak falls below the estimated straight line. If one takes the value of the oscilloscope readings, one can estimate the maximum value of the current peak; e. g.,

Voltage = 80 V, extrapolated to zero

Voltage = 38 V, measured at peak current

I_{max} = $V\omega C \times 38/80$

ω = 4.2×10^5 rad/sec (measured from oscilloscope traces)

V = capacitor voltage set to 18 kV

C = capacity of bank 84×10^{-6} F

then

$$I_{max} = 3.0 \times 10^4 \text{ or } 300 \text{ kA}$$

A second method is to use a Rogowsky transformer that transforms current as 1/N, provided the total inductance/resistance (L/R) time constant is long compared to the transient being measured. The transformed current can be determined by measuring the voltage developed across a low-resistance shunt (in the present case, 0.1 Ω). The Rogowsky transformer had 980 turns and gave a current of

$$i = \frac{V_{scope}}{r_{shunt}} \times N = \frac{38 \times 980}{0.1} = 370 \times 10^4 \text{ or } 370 \text{ kA}$$

Another method, which serves as a crosscheck on the coupling of the Rogowsky current transformer, is based on the conservation of the charge in an LRC discharge. If perfect integration were possible, the integral of the current over a long time period should equal the total initial charge on the capacitor, which is equal to the capacitor voltage times the capacity; i. e.,

$$\int I dt = Q = CV_{cap}$$

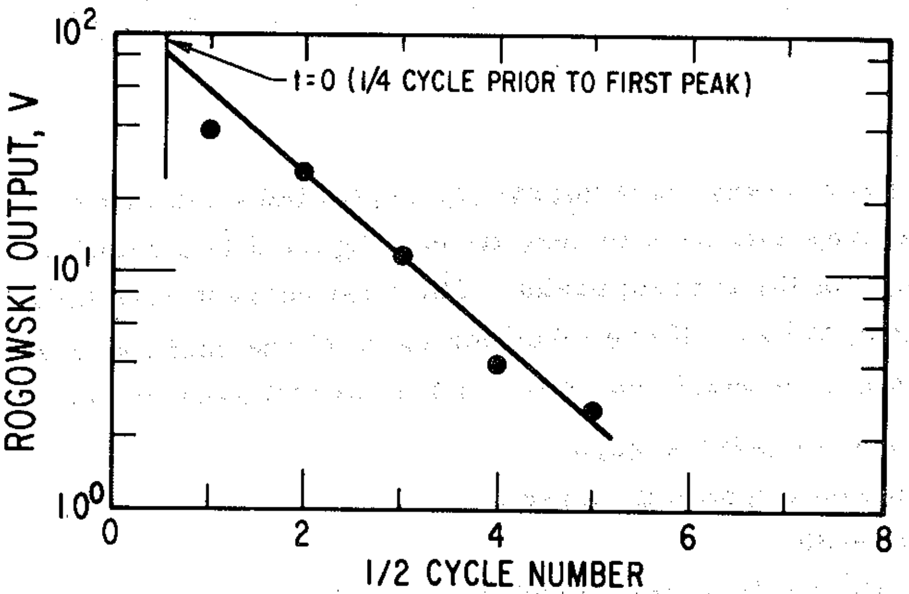

Fig. 5. Relative Heights of Current Peaks

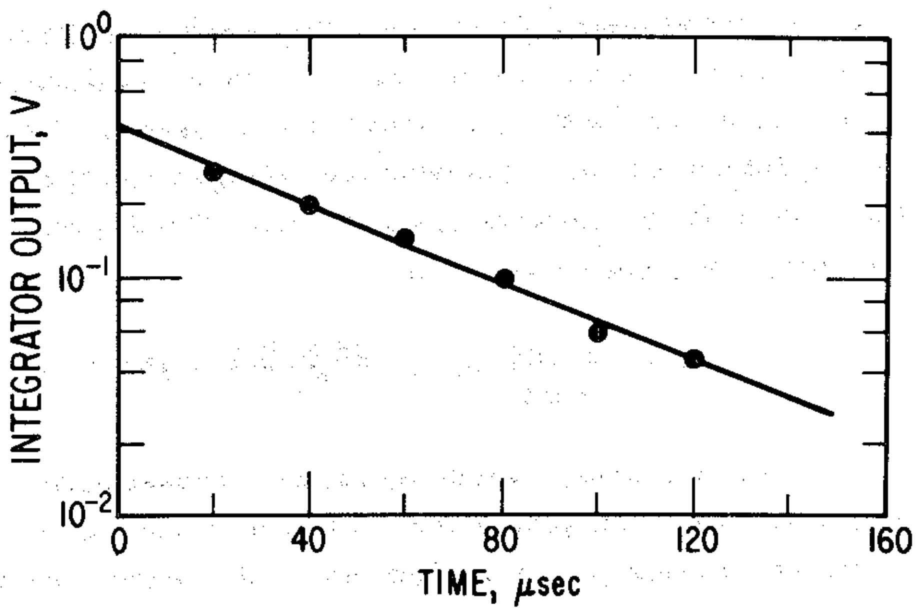

Fig. 6. Integrated Rogowski Voltage vs Time

An RC integrator has a transfer function

$$V_{out} = \int \frac{V_{in}dt}{(RC)}$$

If we let the voltage across the Rogowsky shunt be the voltage into the integrator, i.e.,

$$V_{in} = \frac{Ir}{N}$$

we may determine an effective turns ratio as

$$V_{out} = \frac{1}{(RC)} \int V_{in}dt = \frac{1}{(RC)} \int \frac{Irdt}{N} = \frac{r\int Idt}{(RC)N} = \frac{rCV_{cap}}{(RC)N}$$

The voltage out of the integrator can be measured on an oscilloscope. Since integrators are not perfect, the resultant voltage is extrapolated to zero time on semilog paper (Fig. 6) and an effective turns ratio N determined.

$$V_{out} = \frac{rCV_{cap}}{(RC)N}$$

or

$$N = \frac{CV_{cap}}{V_{out}(RC)r}$$

From Fig. 4, with an 18-kV discharge

C	=	84×10^{-6} F
V_{cap}	=	18×10^{3}V
(RC)	=	500×10^{-6}sec, integrator time constant
r	=	0.1Ω (Rogowski shunt)
V_{out}	=	0.42 V
N	=	720 turns

An effective turns ratio of 720 indicates that the maximum current is significantly less than determined by the other two methods. The discrepancy in the measurement has not been resolved since the refinement of theory does not require a closer knowledge of the current at the present time.

F. VOLTAGE MEASUREMENT

The voltage pulse was measured by means of the circuit shown in Fig. 7. The cable, terminated at both ends with 50 Ω, reduces reflections and acts as one element of a 100:1 divider. A 10:1 divider is used to reduce the signal to a level that can be read on an oscilloscope. Voltage pulses of 30 to 40 kV are observed at the time of the neutron generation.

G. OPERATING PROCEDURES

When not in operation, the Mk-IA plasma neutron generator is kept at high vacuum by means of a 4-in. diffusion pump. When continuous flow operation is desired, the main gate valve to the pump is closed and a small bypass line is used for pumping. Two methods of operation have been tried, namely, static fill and constant flow of the deuterium gas. The system may be pumped down to hard vacuum after each discharge, or a number of discharges may be made on one pump setting. At times, the neutron yield appears to respond to various filling techniques, but in general the performance is not directly related to the filling technique.

With high-voltage power supply, the capacitor bank charging takes about 40 sec, allowing neutron pulses to be generated at ~1/min. Since one does not wish to make adjustments during the high-voltage charging, the neutrons are generated ~1 min after the pump is valved off the system.

It was found that if a thermocouple pressure gauge on the plasma tube were left connected, it would be destroyed by circulating ground currents. Therefore, a pirani gauge near the gate valve is used to monitor the deuterium gas pressure. The pressure is set by observing the reading of a Matheson flow meter; the actual pressure variations, as indicated by the pirani gauge are recorded on a strip chart. The strip chart enables one to determine whether the desired pressure was maintained at the time of the discharge and also to determine the pressure increase that results from the discharge. The Mk-IA plasma neutron generator, upon occasion, demonstrates pressure bursts during the first few discharges after reassembly. When pressure bursts are observed, the neutron yield is usually reduced.

The voltage to which the capacitors are charged is monitored by means of a digital voltmeter. Although it was initially thought that the neutron yield would be sensitive to minor changes in capacitor voltage, this was not the case. However, the digital voltmeter monitor has been retained as a convenience.

The capacitors are discharged through three air switches. The triggering system consists of a conventional cascade of thyratrons, starting with a 2D21 that drives a buffer 3C45 which drives a 5C22. The 5C22 drives an air-gap switch that grounds three identical capacitors connected to the triggers in the three air switches. In spite of the cascade operation, current is switched on in 1.5 μsec with a jitter of <100 nsec.

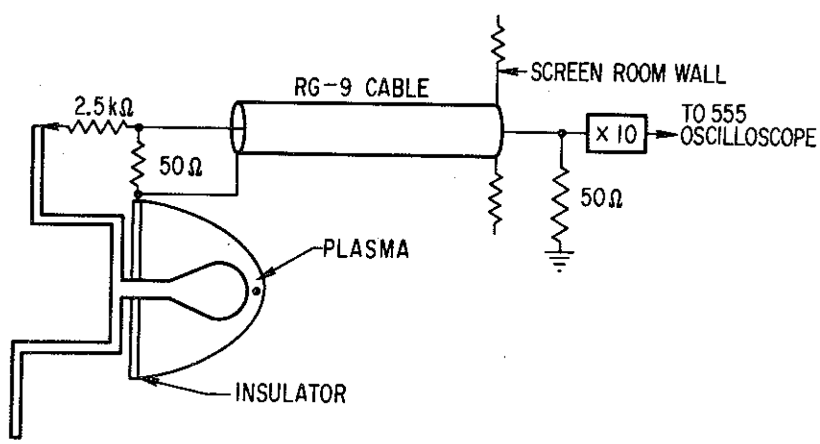

Fig. 7. Circuit for Measuring Voltage Pulse

III. MEASUREMENTS

A. DOSIMETRY

The total neutron yield was determined by means of an array of four geiger tubes wrapped in silver and placed in a paraffin moderator. The paraffin thermalizes the neutrons so that capture in the silver is possible. The activated silver then decays with a half life of 24.2 sec and 2.3 min, producing energetic beta particles and gamma rays that are then counted by the geiger tubes.

The paraffin was cast in a 6- × 12- × 12-in. block and is similar to arrays used at the Los Alamos Scientific Laboratory for measuring the yield of pulsed neutron devices (Ref. 2).

The measurement is made by counting the geiger tube pulses for 1 min after the neutron burst and by using the expression from Ref. 2

$$\text{Yield} = 30\,(5.3 + D^2) \times \text{counts/min}$$

where D is the distance in inches from the neutron source.

The neutron yields were measured at right angles to the axis of the plasma tube. A series of tests with an uncoated array indicated that the flux at right angles is about 70% of the flux on the axis. Test with a cadmium-coated, four-tube, silver counter indicated that the uncoated counter was about 30% low. If both these corrections are valid, the "on-axis" yield is a factor of 2 greater than stated in this report.

B. ARRIVAL TIMES

The linear acceleration phase of the plasma neutron generator may be compared with that of the plasma acceleration snow-plow model. The snow-plow model for plasma acceleration is based on a cylindrical plasma being compressed radially by a current that increases linearly with time. In the classic snow plow, the compression time is proportional to the fourth root of the initial pressure. Although the Mk-IA plasma neutron

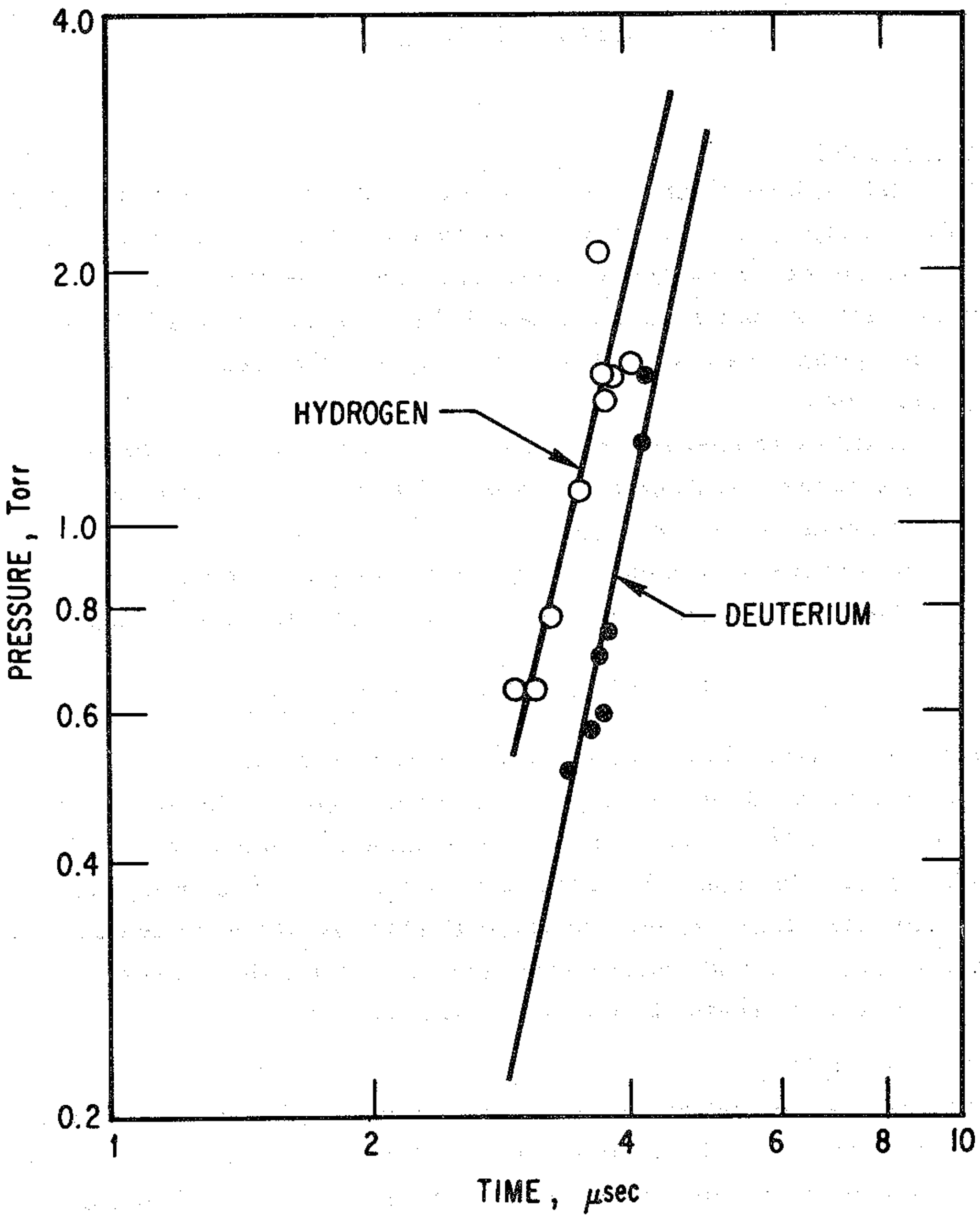

Fig. 8. Hydrogen and Deuterium Acceleration Times

generator bears little geometrical relationship to a collapsing cylinder, the compression time relationship appears to approximate that of the snow-plow model.

The existence of a current and voltage transient at the time of the plasma focus makes the compression time, or "arrival time" measurement very simple. It is made by measuring the time between the start of the current and the transient.

Measurements made with hydrogen gas and deuterium gas are shown in Fig. 8. The hydrogen and deuterium acceleration functions may be compared with that derived from a snow plow:

Snow-Plow Theory	Hydrogen Curve	Deuterium Curve
$T = KP^{0.25}$	$T = 3.45\ P^{0.26}$	$T = 4.0\ P^{0.22}$

where T is in microseconds and pressure is in Torr. For a given pressure, the ratio of arrival times for hydrogen and deuterium should go as the fourth root of the mass ratio. At 1 Torr, the proper ratio of arrival times are observed, with the hydrogen appearing to arrive at the focus slightly faster at lower pressures and slightly slower at higher pressures than would be indicated by the fourth-root relationship.

An interesting sidelight observed during the hydrogen tests was the production of a small quantity of neutrons in one of the nine "shots." The yield was about twice the normal background (or about 3×10^6), which is considerably higher than would be realized from statistical fluctuations of the background count of the Geiger-Mueller tubes. The effect was noticed only once and therefore could not be studied. It could be attributed to deuterium occluded in the electrodes and released by the hydrogen arc, or possibly to the 10^{-4} natural abundance of deuterium in hydrogen gas.

C. X-RAY STUDIES

A knowledge of the time history and spectrum of the x rays emitted from a deuterium plasma neutron generator may provide insight into the neutron generation mechanism and the associated plasma conditions. The first measurements of such x rays were reported in Ref. 3; these measurements were made with uncalibrated film and with carbon and aluminum absorbers. Two groups of x rays were detected. The first group, which was found to have no correlation with neutron yield, had the properties either of 15-keV line radiation or a distribution of x-ray energies peaking in the vicinity of 15 keV. The second group of radiation, which appeared to be proportional in intensity to the neutron yield, consisted of a distribution of x-ray energies ranging from 30 to at least 300 keV. At 30 cm from the pinch, this second group produced on the order of 1 mrad/shot.

The main effort to measure the x-ray spectrum was made in the energy interval from 5.46 to 29.2 keV. Seven pairs of Ross filters were used with calibrated x-ray films to measure the x-ray energy content in seven energy intervals for each shot made on the pinch apparatus. The x-ray spectrum outside the pinch apparatus showed little radiation below 5 keV, a peak just above 13 keV, and decreasing amounts of radiation up to 29 keV. These data are in good agreement with the data from the absorber studies. When this spectrum is corrected for the attenuation of the x rays between source and detector, a power-law spectrum is obtained:

$$I = 430\ E^{-1.7}$$

where I is in erg/cm^2/keV at 53 cm from the source and E is in keV (Ref. 3).

The power-law spectrum is a good approximation of the x-ray spectrum between 5.46 and 29.2 keV (Ref. 3). The line radiation of neutral copper is also noted by two of the Ross filter pairs measuring

7.11 to 8.33 keV and 8.33 to 8.98 keV. The amount of copper line radiation is variable, as is the intensity of the "power-law" radiation. It is quite clear that the radiation measured in the Ross filter studies has little or no correlation with the neutron yield.

The total x-ray energy measured in a typical shot is 55 erg/cm^2 at a point 53 cm from the source on the axis of the machine. After a correction for attenuation of the x rays between source and detector, the energy is ~100 erg/cm^2 for all x rays between 7.1 and 29.2 keV. If one assumes the x-ray flux to be isotropic, the total x-ray flux over 4π sr is 3.5×10^6 erg or 0.35 J. The very hard x rays detected in the absorber studies might easily double this amount. The x rays with energy < 5.46 keV are at the moment an unknown quantity.

The source of the x rays has been located in the Mk-IA plasma pinch using x-ray pin-hole camera techniques. The source of the x rays between 7.1 and 29.2 keV is located within 0.05 in. of the anode surface and possibly on the anode surface itself. This x-ray source is highly variable in shape, intensity distribution, and area. These sources varied from small "hot spots" with an area of 0.01 in.^{2} to diffuse regions with areas in excess of 1 in.^{2} The total x-ray output variation is generally much less, a standard deviation of 35% being typical for a series of shots. The x rays observed with the pin-hole camera are in the same energy range as those in the Ross filter measurements.

Time resolved x-ray measurements were also made using solid state x-ray detectors and Ross filters. The spectral response of these detectors is not known, but they are sensitive from at least 3 keV to several tens of keV. X-ray pulses of the same shape were detected by both counters on most shots using a pair of matched detectors and different combinations of filters. The implication is that within 10% the time history of the various spectral intervals between 5 and 29 keV is substantially the same in a given shot. Only one shot showed an additional burst of copper line

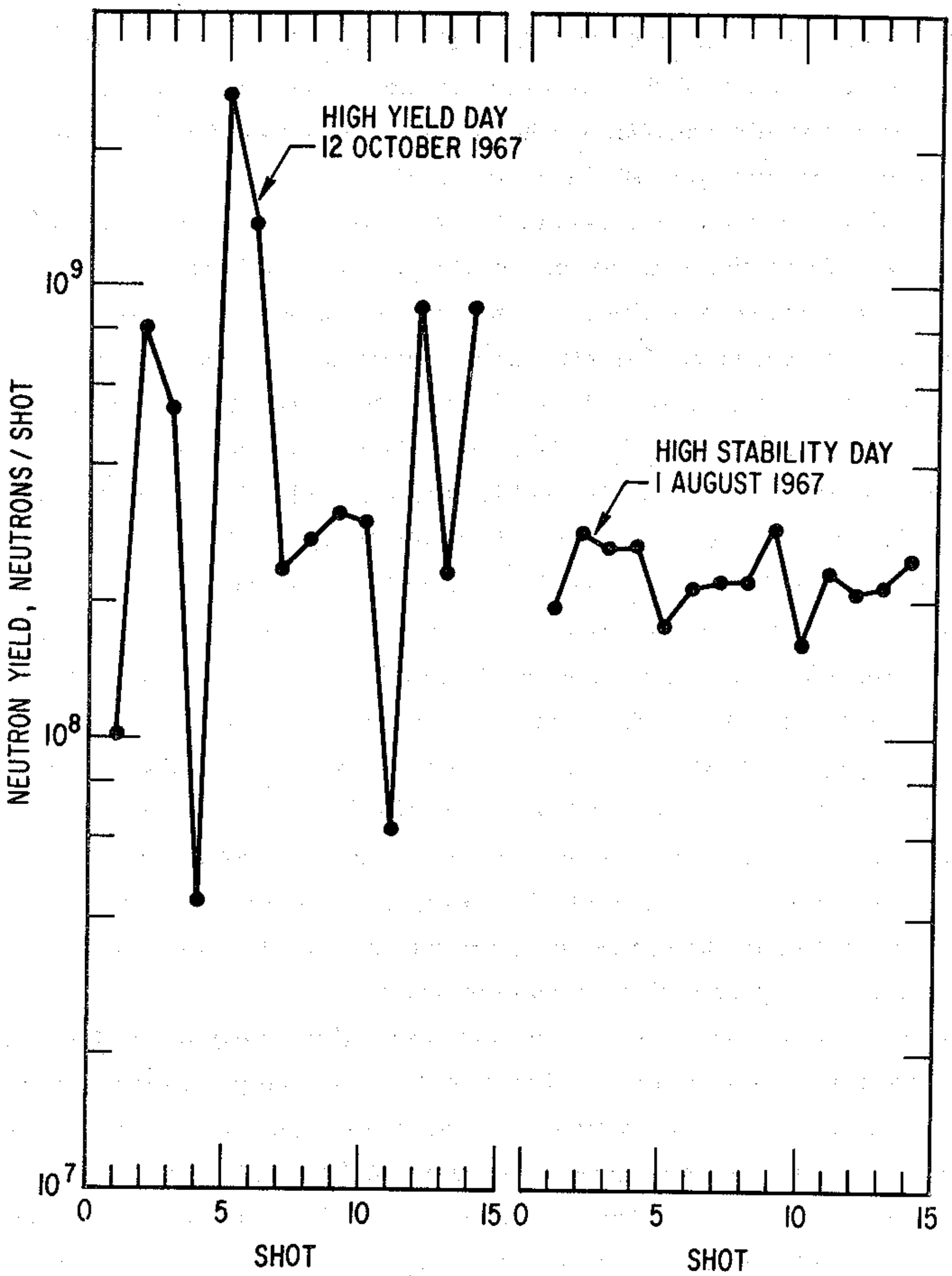

Fig. 9. Neutron Yield Obtained on Successive Shots on the Mk-IA on Two Different Days Under Approximately the Same Conditions

radiation during part of the x-ray pulse. For the vast majority of shots, the spectral distribution of x rays is not a function of time.

D. PARAMETRIC RELATIONSHIPS

The neutron yield of the Mk-IA plasma neutron generator is a function of its operating parameters and some variables not under control. With all controllable parameters held constant, the standard deviation of the neutron yield from shot-to-shot is frequently over 90%. Procedures have been developed to control the operating pressure to better than 1%, but even variations of 10% have little effect on the neutron yield. The charge on the capacitors is controlled to better than 0.1%, but this also is not the problem. The firing times of the three air-gap switches have been monitored and found to be in synchronism to within 10 nsec.

The one variable that may be a source of difficulty, and which is not practical to control, is the shape of the electrodes. With each shot the electrodes erode. The tip of the anode develops a 1/4-in.-wide and 1/2-in.-deep hole after ~100 shots. It is not practical to change the tip after each shot since a new metal anode must be fired for several shots before any significant yield can be obtained. The only qualitative observation is that a new spherically tipped anode is less effective in producing neutrons than a well-worn one.

The studies made of the position of the pinch by using an x-ray pinhole camera have shown that this too is variable. The position of the x-ray source wanders around randomly in a 1-in. circle at the tip of the anode. The intensity and shape of the x-ray source also is quite variable. The relationship of these observed x-ray phenomena to any other parameter is not clear. These observations suggest that in this apparatus the collapse of the pinch is highly variable.

Figure 9 illustrates the variation in neutron yield from shot-to-shot. The reason for this variation in yield is not apparent.

Most of the operation of the Mk-IA was carried out with the anode originally designed for it, the "copper bowling pin." Of the various anodes tried, this anode worked best. The average neutron yield obtained with various anodes under the same conditions of pressure and voltage are shown in Table I.

Table I. Typical Electrode Performance for Various Types of Electrodes

Electrode	Average Neutron Yield/Shot
Copper Bowling Pin	2.7×10^8
Bowling Pin with Beryllium Tip	1.4×10^8
4-in. -diam Cylinder with Flat End	0.68×10^8
4-in. -diam Cylinder with Spherical End	0.55×10^8
1.5-in. -diam Cylinder	0.26×10^8

In the development of an x-ray window, it was noted that when the material at the end of the cathode was changed, a change occurred in the neutron yield. The material originally used was copper. When aluminum was used, the yield was reduced. It was also noted that the surfaces of both anode and cathode became coated with aluminum as a result of using 0.8-in. -diam insert. A nickel insert was tried, and the results were essentially the same as those obtained with copper. A beryllium cathode window gave neutron yields that were markedly better than those obtained with the other materials used. The average yields obtained with four different materials at the cathode surface at the focus end of the tank are:

Material at Cathode	Neutron Yield
Copper	3.9×10^7
Aluminum	2.9×10^7
Nickel	3.9×10^7
Beryllium	10.0×10^7

A carefully controlled series of measurements was made to determine the effects of voltage and pressure on the neutron yield. Three voltages and seven pressures were used. Three shots were made in random order for each combination of voltage and pressure (Fig. 10). The neutron yield clearly increases with voltage; variation of neutron yield with pressure appears more complex.

Another relationship of neutron yield vs voltage is apparent when the highest yield shot from a group of shots at the same voltage is selected and then plotted for several voltages. Figure 11 shows results from runs made 1 year apart; Fig. 11 appears to indicate that the maximum neutron yield goes as the third power of the bank energy.

Several different gas filling systems were tried. One system maintained pressure by continuously pumping against a controlled leak. Another system consisted of filling the tank with deuterium gas after having been pumped to a hard vacuum, firing one shot, and repeating the procedure. A more convenient system made several shots on one such filling. A palladium leak was installed in the gas inlet in order to remove all non-hydrogen impurities from the filling gas. A puff system was also tried in which a controlled amount of gas is discharged into the chamber just before firing. None of these variations appear to have had a significant effect on the neutron yield or the reproducibility.

E. RESIDUAL GAS MEASUREMENTS

Tests with a Varian (Model No. 974-0036) partial-pressure gauge indicated no measurable change in any of the typical contaminants of vacuum systems, with the exception of the mass 3 component that increases about 25% after each discharge and decays back to normal with about a 3-min time constant. The mass 3 component is always observable when deuterium gas is analyzed because of formation of DH molecules. The abundance of DH is 10^8 greater than the maximum possible amount of tritium or helium 3 that could be generated in conjunction with the neutron generation.

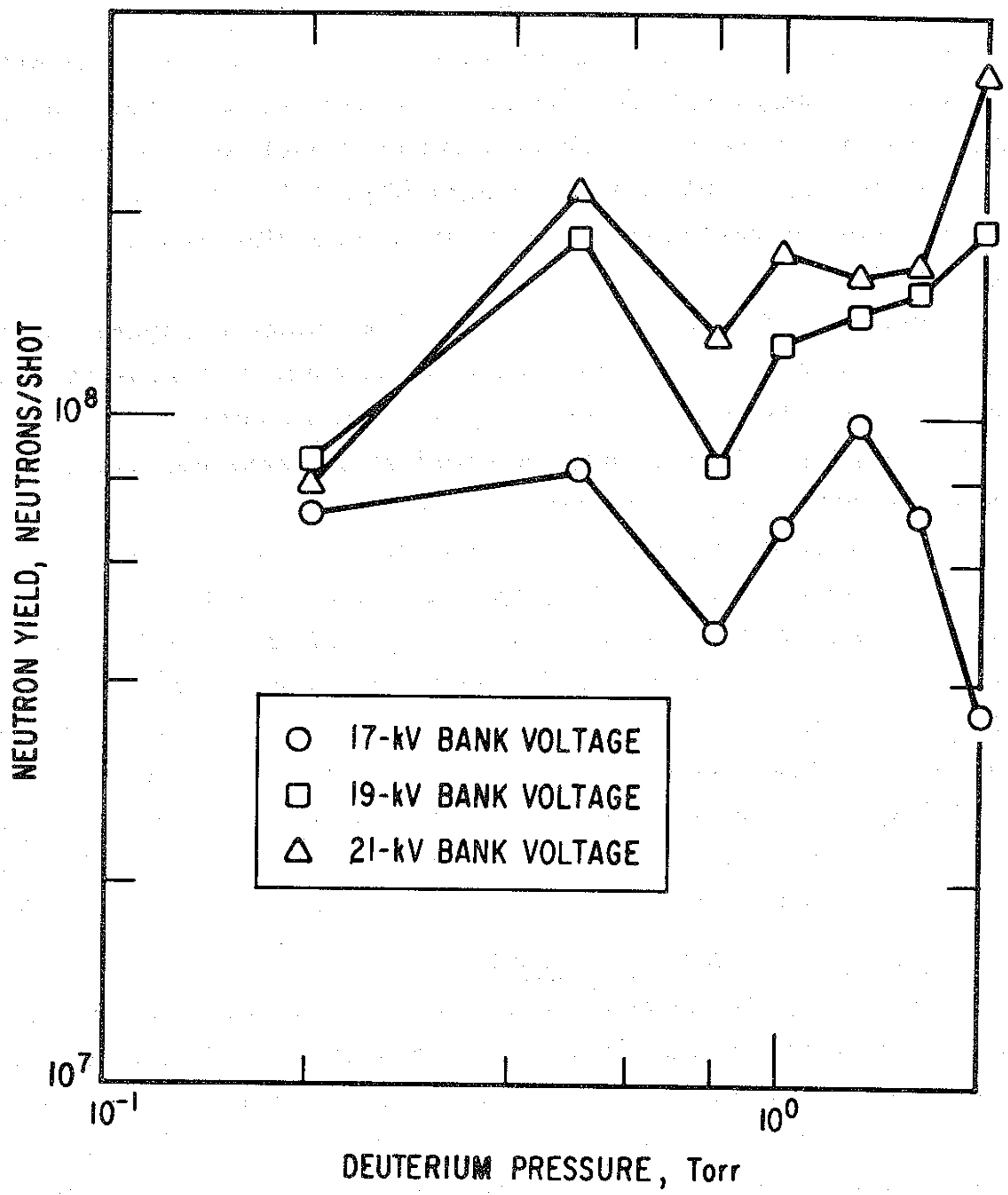

Fig. 10. Neutron Yield as a Function of Pressure and Voltage

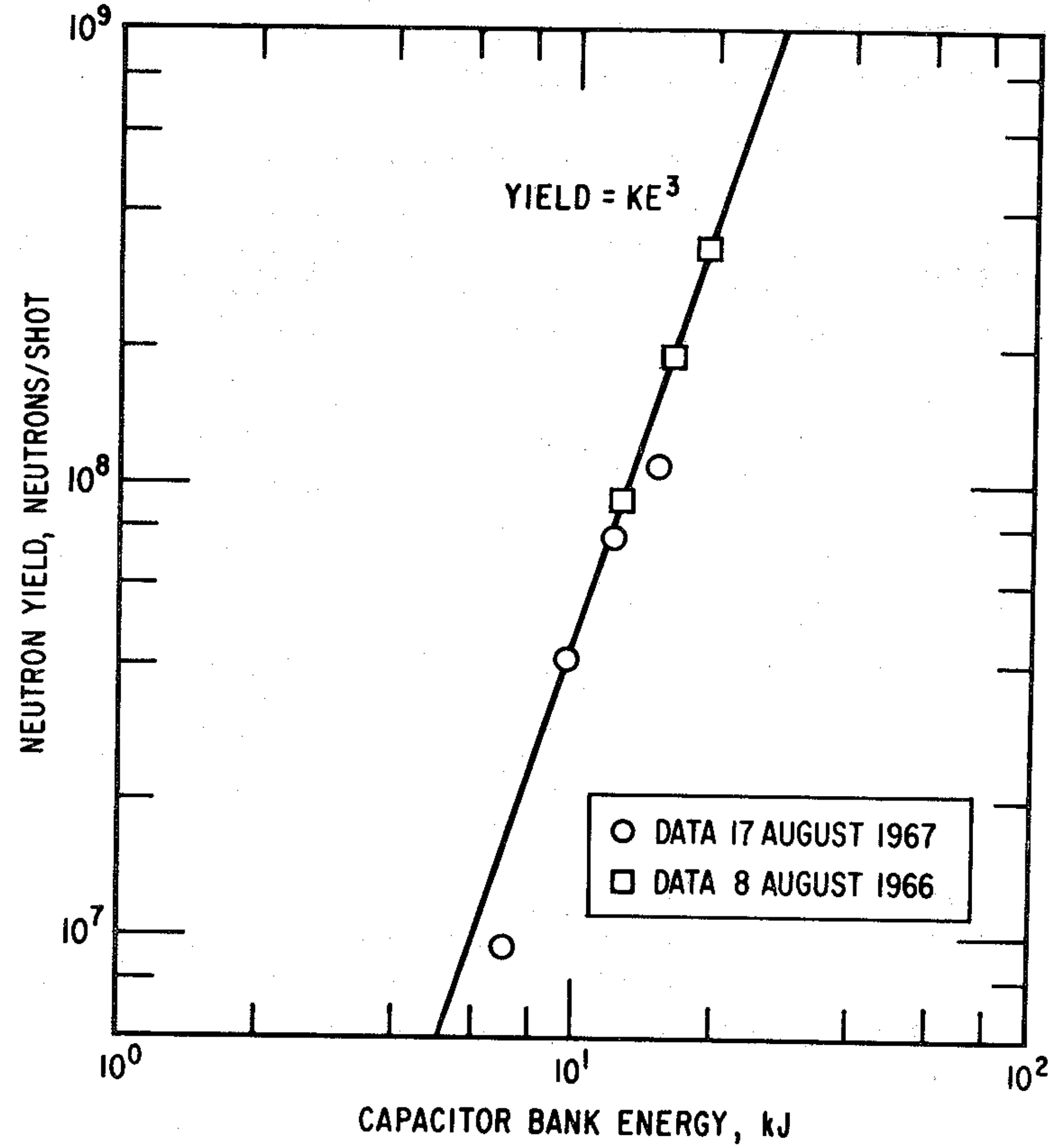

Fig. 11. Best Observed Neutron Yield as a Function of Capacitor Bank Energy

Components observable with the plasma tube at high vacuum and with 1 Torr of deuterium are given in Table II.

Table II. Analysis of Residual Gases

Mass Number	Ion	Partial Pressure at High Vacuum, Torr	Partial Pressure with Bleed Open and 1-Torr D_2 in Plasma Tube
2	H_2^+ D^+	1.5×10^{-9}	6×10^{-8}
3	DH^+	6×10^{-9}	2.5×10^{-8} (before shot) 3×10^{-8} (after shot)
4	D_2^+	3×10^{-10}	3×10^{-6}
18	H_2O^+	2×10^{-10}	1×10^{-9}
20	$CO^+ + N_2^+$	2×10^{-9}	8×10^{-10}
40	Ar^+	7×10^{-10}	2.8×10^{-9}
44	CO_2	2×10^{-10}	5×10^{-10}

F. NUCLEAR EMULSION STUDIES

The reaction products of the D-D reaction are ${}_1H^3$, ${}_2He^3$, ${}_2He^4$, and ${}_0n^1$. Of these products, only the neutrons with no electrical charge and 2.45-MeV energy can pass through several inches of metal without being seriously affected. The neutrons produced by the Mk-IA are detectable at all positions around the apparatus.

One of the techniques of detecting neutrons and measuring their energy makes use of nuclear emulsions, thick photographic films supported on glass plates. The neutron collides with a hydrogen atom in the photographic emulsion, transferring energy to the hydrogen atom. The resulting recoil proton leaves a track in the emulsion which can be measured with a microscope.

From a knowledge of the proton spectrum and of the direction of the incoming neutrons, it is possible to determine the neutron spectrum. Such measurements have been made of the neutron produced in the Mark-IA apparatus that emerge in either the forward or the backward direction along the axis of the device. A separate report (Ref. 4) has been prepared in which the neutron spectral measurements are described in detail. In Fig. 12 are shown the measured energy spectra of the recoil protons and of the neutrons produced in Mark-IA.

The observed forward-backward asymmetry in the Mark-IA neutron spectrum is not compatible with a neutron-production model in which the neutrons emerge from a stationary plasma at thermonuclear temperature. The asymmetry is consistent with a model (accelerator model) in which large locally induced electric fields (~100 kV) accelerate some of the deuterium ions along the axis or with a model (moving boiler model) in which a column of plasma at thermonuclear temperature is moving at high velocity (2×10^8 cm/sec) along the axis.

G. TIME-OF-FLIGHT STUDIES

The neutron energy can also be measured by making time-of-flight (TOF) measurements. A typical neutron pulse from the Mk-IA has a width of 50 nsec as measured from the 50% points. These neutrons also require some 125 nsec to travel 10 ft. It is possible, in this case, to make neutron velocity measurements with reasonable accuracy.

The neutrons were detected by a pair of 6810A photomultiplier tubes equipped with hydrogeneous scintillators, such as Pilot-B. These scintillators are also sensitive to x rays. A 1/4 in. of lead shielding had to be used to attenuate the x-ray signals to a level such that the neutron and x-ray signals were comparable. The signals from the photomultipliers were recorded on a pair of Tektronix 517 oscilloscopes. A square-wave gate pulse was recorded as a time reference marker. The sweep

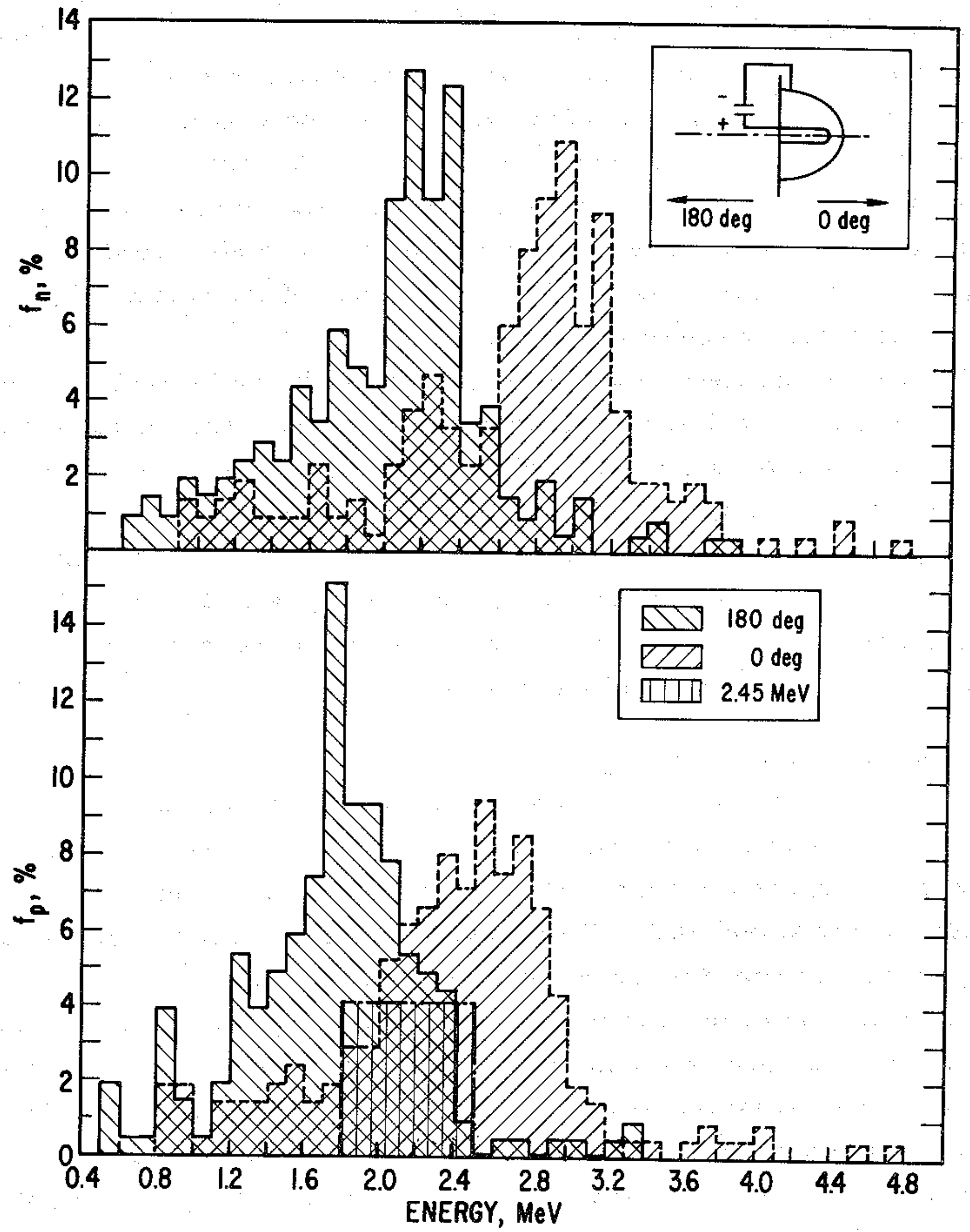

Fig. 12. Energy Spectra of Recoil Protons and Neutrons

characteristics of the two oscilloscopes were taken into consideration in the data reduction. Figure 13 shows traces made by photomultipliers at 8 and 16 ft from the neutron source.

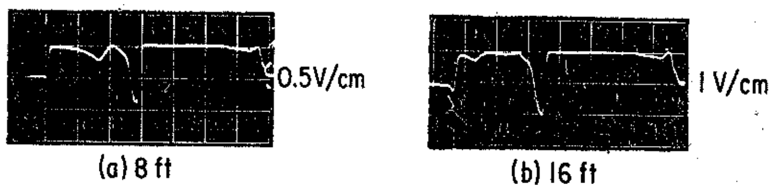

Fig. 13. Traces from Photomultipliers at 8 and 16 ft from the Neutron Source

In the data reduction, some variation was found in the apparent TOF depending on what time reference was used. Either the gate start, gate end, or x-ray pulse could be used for the time reference marker. The time error was typically 3 to 6 nsec. A second source of error, for which correction was made, was an apparent difference in the transit times of the two photomultiplier tubes.

The results of the TOF measurements are shown in Figs. 14 and 15. After making a correction for the x-ray transit time, it was found to be most convenient to use the x-ray peak as the time marker. The neutron velocity along the axis is 12.8 nsec/ft and at 90 deg to the axis 12.4 nsec/ft. These energies are consistent with the nuclear emulsion work.

H. YIELD ISOTROPY MEASUREMENTS

The neutron yield at various angles around the Mk-IA was measured with a pair of silver activation counters. These counters were 5-in.-diam × 6-3/8-in.-high cans filled with a paraffin moderator. Victoreen-type IB85 Geiger tubes surrounded with 0.010-in. silver foil were mounted at the center of each can. The technique is the same as discussed in the section on dosimetry.

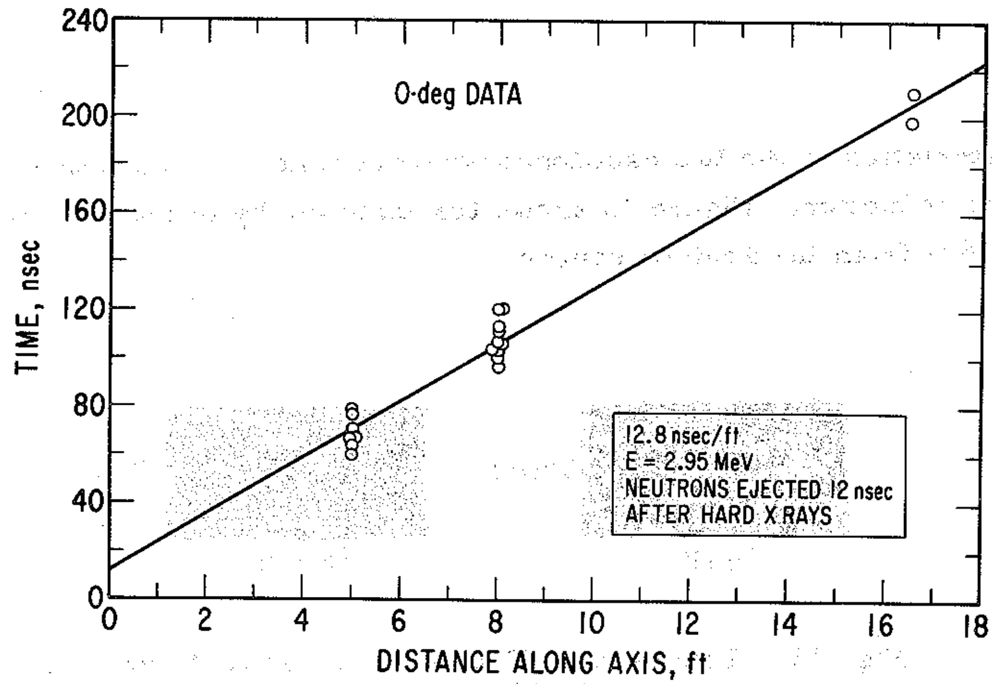

Fig. 14. Delay Between X-Ray Peak and Neutron Peak at 0 deg

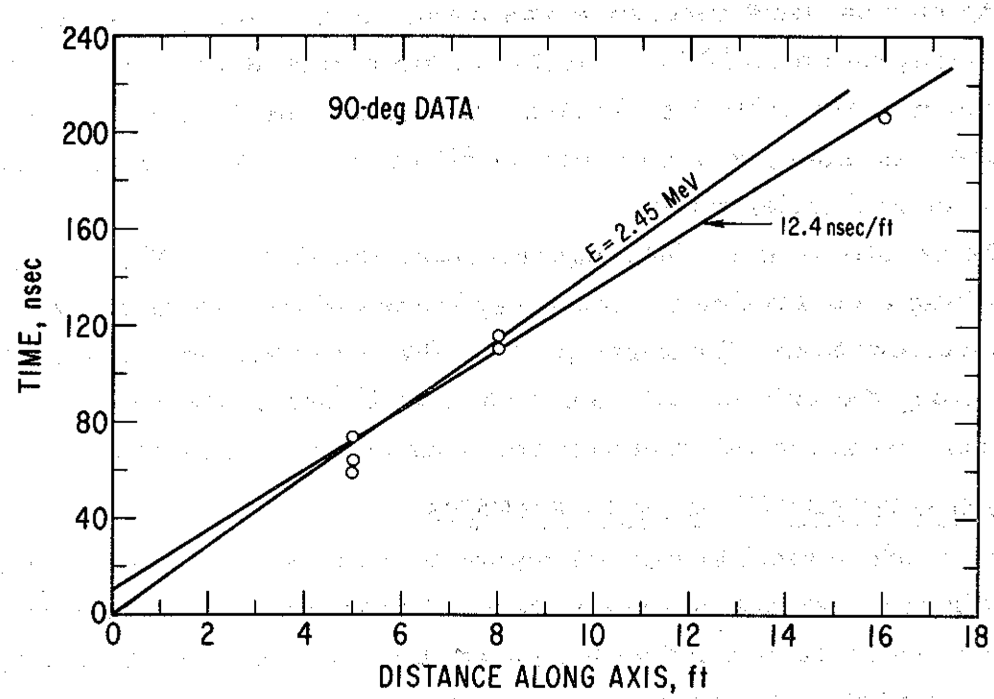

Fig. 15. Delay Between X-Ray Peak and Neutron Peak at 90 deg

One of the counters was kept at the 0-deg point on the pinch axis in the forward direction. The other counter was then moved to various positions in a horizontal plane that contained the pinch axis and the other counter. The count recorded for each counter was noted, the background count subtracted, and a ratio taken of the reading from the moveable counter to that of the fixed one (Fig. 16). With both counters at the 0-deg position (side by side), the two counters showed a 15% RMS deviation. The angular variation of neutron yield expected on the basis of the accelerator model (100 kV) is also given in Fig. 16 as is the neutron yield expected from the moving boiler model (mean ion energy 25 keV). These two curves are based on G. G. Comisar's unpublished data[1] on the expected yield isotropy for the two models.

The results are not conclusive because of the experimental problems experienced. It is possible that the massive copper-coated aluminum anode or possibly some of the surrounding environment scatters large numbers of neutrons.

I. RELATIONSHIP OF NUCLEAR PHENOMENA TO THE VOLTAGE PULSE

A series of measurements were made to determine the time relationship between the voltage pulse and the x-ray and neutron pulses. The same apparatus used in the TOF measurements was used to record the voltage across the base of the electrode. Timing markers from a pulse generator were placed on each oscilloscope trace, and the data were recorded on Polaroid film. The oscilloscopes were calibrated, and it estimated that the data are accurate to within 5 nsec.

In order to compare the signals received by the various oscilloscopes, certain corrections had to be made. The signal from the photomultiplier tube that records the neutron and hard x-ray pulses experiences a

[1] G. G. Comisar, "Degree of Yield Anisotropy in Low Energy D-D Reactions," Plasma Research Laboratory IOC No. 4020-GGC-89 (11 December 1967).

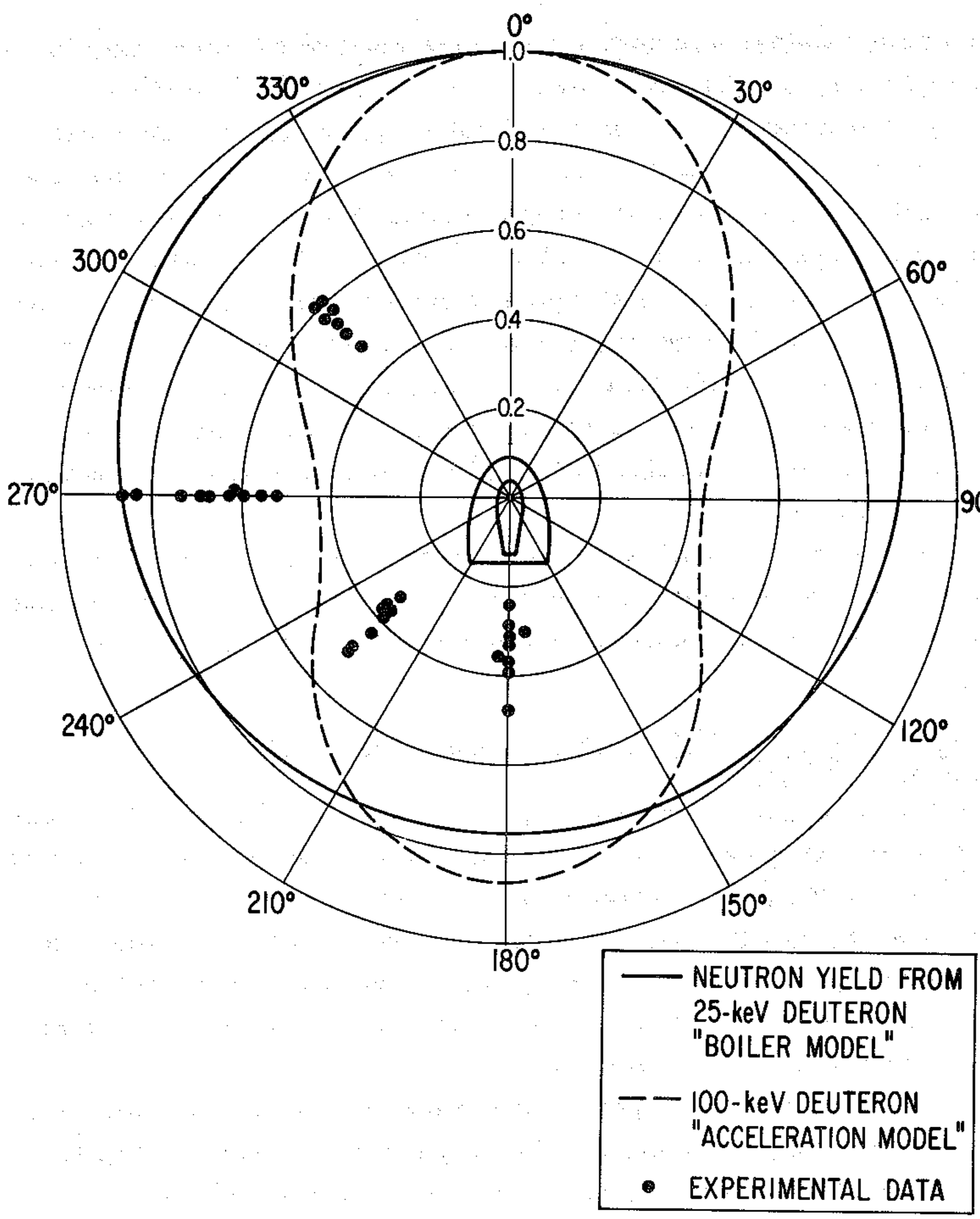

Fig. 16. Neutron Yield vs Angle

substantial transit-time delay.[2] At the tube voltage used in this experiment, a correction of 110 nsec must be made for the tube transit time.

The soft x rays were detected by a double diffused silicon diode detector (Solid State Radiations, Inc.) with a risetime of 10 nsec and a probable transit time of 1 or 2 nsec. These times are short compared to the scale of the events.

A set of typical waveforms is shown in Fig. 17. For ease in data reduction, only the peaks, departure points, and inflection points were measured and later replotted by joining these points with straight lines. The events shown occurred some 4000 nsec after the start of the discharge. The hard and soft x rays start within 2 nsec of each other at the time of the peak of the voltage pulse. The neutron pulse starts ~10 nsec later and lasts about twice as long as the x-ray pulses.

It appears that the extreme conditions associated with the 30-kV positive voltage pulse are necessary to produce the observed neutrons and x rays.

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[2] M. H. Dazey, "Neutron X-Ray Time Sequence in the Mark-IA Plasma Generator," Aerospace Corp. Internal Memo No. 4020-MHD-95 (15 January 1968).

The state of the theory is such that it is not possible to say whether the pressure and voltage effects are critical to the initial breakdown phase, the acceleration phase, or the focus phase. It will be necessary to determine experimentally, or analytically, how each phase is affected by the important parameters before one may make a systematic attempt to derive scaling laws.

It is felt that the tridimensional plasma neutron generator (Mk-IA) could be made to operate in the 10^9 neutrons/discharge region by suitable adjustments of pressure and voltage. There were indications that somewhat higher yields were possible with the same geometry and a higher voltage; however, the failure rate of the auxiliary equipment and insulators became excessive when the voltage was greater than 21 kV, although the 20-kV capacitors did not fail.

Neutron TOF data and emulsion studies indicate that an acceleration process is probably present. Voltage transients of the order of 30 kV are observed at the time of neutron generation and are a likely source of acceleration fields, although the short duration of transients and the small size of the plasma focus prevented determination of ion trajectories.

The Mk-IA was intended to be a parametric study device and was not amenable to optical and spectroscopic plasma diagnostic techniques. In future experiments, it would appear advisable to make a close study of the three phases of operation that lead to neutron production (i. e., initial breakdown, acceleration, and radial compression) and to correlate the conditions of the three phases with each other and with the neutron yield.

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3. H. L. L. van Paassen, X-ray Measurements on the Mark 1A Three-Dimensional Plasma Pinch, TR-1001(2550-10)-1, Aerospace Corporation (April 1967).

4. D. A. Meskan, H. L. L. van Paassen, and G. G. Comisar, Neutron and X-Ray Production in a Focused Z-pinch, TR-0158(3220-50)-1, Aerospace Corporation (December 1967).

5. F. Kirsten, "Multiplier Phototube Special Characteristics," Counting Note No. CC 8-A (Rev. 5, March 1964), Lawrence Radiation Laboratory, Berkeley, California.