THE NUCLEAR TEST GAUGE

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ABSTRACT

The "Nuclear Test Gauge", a slightly sub-
critical assembly for quality control of
reactor components, was designed, con-
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test pile.

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INTRODUCTION

It is desirable to test pile components before they are charged into a reactor that operates at high specific power. One of these tests is the measurement of the "specific reactivity" of the component. This test is usually performed by measuring the effect that the component has on the kinetic behavior of a chain-reacting "test pile". This danger coefficient measurement, however, is time consuming and requires a large initial investment in equipment.

The testing time can be reduced by operating the pile at a reactivity sufficiently below criticality to minimize the effects of the delayed neutrons. In a subcritical condition the testing for reactivity consists of the observation of changes in the neutron population or in the "multiplication".

In view of the advantages of speed, safety, and simplicity that might be derived from this method, experiments were made to determine whether the method provided enough sensitivity to compete with an existing test pile.[1] These experiments[2] demonstrated that a subcritical assembly of enriched uranium not only is superior to a test pile of natural uranium by a factor of ten in speed of testing, but also is equivalent to the test pile in sensitivity. In view of the success of those exploratory experiments, the decision was made to design and construct a production model of a subcritical test pile. The device is called the "Nuclear Test Gauge", or NTG.

The present report describes the mechanical features, the instrumentation, and the safety features of the NTG. The results of loading and calibration experiments are also discussed.

SUMMARY

A "Nuclear Test Gauge" was designed, constructed, and placed in operation. It is a slightly subcritical assembly that is used for quality control of reactor components. It consists of a strong neutron source and sufficient fissionable material and moderator to yield a multiplication of approximately 100. Calibration experiments demonstrated that the sensitivity of the NTG is adequate, and that approximately one minute is required to make a measurement compared with the ten minutes required for a danger coefficient measurement in a chain-reacting test pile. Other advantages of the NTG over a chain-reacting pile are lower capital investment and lower operating costs, the ability to resolve inhomogeneities in long pile components, the ease with which the NTG can be adapted to test different types of samples, and the greater inherent safety of a subcritical assembly.

The NTG is equipped with a system of safety sheets that are inserted within 0.3 second after the initiation of a scram signal.

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The safety sheets control sufficient reactivity to shut the NTG down promptly in case of any conceivable supercritical excursion caused by an error in loading.

DISCUSSION

DESCRIPTION OF THE ASSEMBLY

General Arrangement

The Nuclear Test Gauge was designed to accommodate a variety of reactor components. As shown in Figures 1 and 2, the NTG tank has horizontal fuel tubes, and a central sample tube which is part of a removable plug. The safety devices include two safety sheets which are mounted above the tank and can be dropped into the fuel lattice, and a dump valve which drains the moderator into a dump tank located below the NTG tank. Concrete shielding surrounds the tank on four sides. Access through the shielding to either face of the fuel lattice is provided through openings that are covered by loading doors and removable shielding tanks which are filled with water. Both safety sheets are inserted automatically into the lattice and the moderator is dumped automatically by the scram circuit if any attempt is made to open the loading doors during operation. The light-water moderator is circulated continuously during operation from the dump tank through an ion exchange resin and filter into the NTG tank. The level of the moderator in the tank is controlled by an overflow tube which carries water to the dump tank. The neutron detectors consist of six ion chambers, lined with B-10, which are located inside the NTG tank.

The NTG Tank

Details of the NTG tank are illustrated in Figures 3 and 4. The tank is formed from 2S aluminum plate that is one-quarter inch thick. The tank is 38-7/8 inches long, 38-1/4 inches wide, and 44-1/4 inches high.

The Lattice

The lattice is composed of 120 thin-walled tubes of 2S aluminum, each 38-7/8 inches long. Each tube has an O.D. of 1.090 inches and an I.D. of 1.020 inches. The tubes are arranged in a hexagonal array with a center-to-center spacing of 1.687 inches, as shown in Figure 5.

In critical experiments made at Oak Ridge National Laboratory[3], the spacing of 1.687 inches was found to be the optimum spacing for minimum critical mass. With this spacing, any accidental deformation of the core produces a decrease in the reactivity of the assembly. A change of 0.1 inch in the lattice spacing reduces k by one per cent. It will be noted in Figure 5 that the lattice spacing was modified along two vertical planes to accommodate the two safety sheets.

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The fuel occupies the central two feet of each fuel tube. Rods of polyethylene are inserted at each end of the fuel tubes. This arrangement provides an effectively infinite reflector of water around the core because the moderating properties of the plastic are very similar to those of light water. The fuel is enriched uranium-aluminum alloy in the form of cylinders, one inch in diameter and 12 inches long. The extrapolated critical mass of the NTG is 4.09 kilograms of U-235; the mass of fuel in the NTG at a multiplication of 100 is 4.00 kilograms of U-235. The loading varies, depending on what material is being tested. This small mass gives the critical NTG such a large advantage in sensitivity over a conventional critical test pile[1] that the subcritical NTG becomes sensitive enough for nuclear testing, whereas a subcritical pile of natural uranium would not be sensitive enough.

The seven central tubes are situated in a hexagonal polyethylene plug that extends the length of the tank (Figure 3). This plug can be removed and, by means of suitable adapters, specimens of different shapes and sizes up to an O.D. of 3.5 inches can be accommodated.

The Source

A polonium-beryllium source was used to supply neutrons to the assembly. During the experiments described in this report the source strength varied from 6.6×10^7 to 1.9×10^7 neutrons per second. The location of the source in the lattice is shown in Figure 13.

The Moderator System

The moderator of the NTG is deionized light water. The water is stored in the dump tank whenever the NTG is shut down. It is pumped from the dump tank through a column that contains a mixture of cation and anion exchange resins. The deionized light water then passes through a ten-micron filter, which is in the line to prevent dispersion of resin throughout the system. The water then enters the NTG tank. The water level in the tank is controlled by the height of an overflow tube. This tube returns the overflow to the dump tank, and the cycle is repeated. The system is designed to circulate the moderator at the rate of three gpm. The arrangement of the equipment and of the piping is shown in Figure 6. A moderator level indicator is located on the front face of the NTG.

The dump valve shown in Figure 4 is of sufficient size to drain the water to the midplane of the lattice in five seconds.

The size of the dump tank is sufficient to store all of the light water in the system. Light water can be added to the system through the line shown in Figure 6 to make up for losses.

Shielding

The shielding design can be seen in Figure 1. A concrete wall two feet thick and nine feet high surrounds the entire assembly except for openings on the sides and on the top. Additional shielding for thermal neutrons is provided by a cadmium liner, 1/32 inch thick, which is placed on the inner face of the concrete. Both the NTG tank and the dump tank can be removed through the top of the shielding structure should this become necessary.

Openings through two opposite faces of the concrete shield provide access to the fuel tube lattice. During operation of the NTG each of these openings is shielded as shown in Figure 1 by a water-filled tank which is 24 inches thick, and by a lead-filled loading door which is 2-3/4 inches thick. A seven-inch hole through the loading door is shielded by a lead cover shown in Figure 7. This cover aligns the source and fixes its position in the fuel lattice by means of a locking clamp. A second opening in the cover accommodates the sample carrier tube which extends through the shielding tank and engages the center tube of the hexagonal plug. A similar cover on the rear face of the NTG has only one opening which permits discharge of the test samples.

Loading and unloading of the fuel in the NTG requires the removal of both the loading doors and the water-filled shield tanks. Test samples, however, can be loaded and unloaded without removing the shielding.

Instrumentation

The neutron detectors are six ion chambers lined with B-10. These chambers are suspended inside the fuel tank. The ion currents from two of these chambers are amplified on two Beckman micromicro-ammeters, which in turn actuate the scram system. These Beckman micromicroammeters can be seen in Figure 2. The remaining four ion chambers are connected in parallel and feed the differential electro-meter. Except for the ion chambers and the differential electro-meter[4], commercially available instruments were used. This differ-ential electrometer incorporates a source of bucking current together with a scale expansion feature which permits changes in the ion current of the order of 0.1 per cent to be measured. The output from the differential electrometer is registered on a Brown recorder, which is also shown in Figure 2. A typical section of recorder chart is shown in Figure 8. It illustrates the response time, the sensi-tivity, and the noise level. The lower part of the trace shows the flux at equilibrium for an acceptable sample. Then a sample of lower concentration was inserted and the flux fell off sharply, coming close to equilibrium in one minute. The new sample contains about 1.5 gm of U-235 less than the standard.

The details of construction and circuit diagrams for the ion chambers and the differential electrometer are discussed in the Appendix.

During loading, a LiI (Sn) scintillation counter is pro-
vided to monitor the neutron flux several feet away from the core.

The Safety System

Although the NTG is not meant to go critical, many safety
features are included that are common to chain-reacting assemblies.
Two large safety sheets are suspended above the fuel tank. The safety
sheets are of 1/8-inch thick boral. The boral is clad with aluminum
and welded into aluminum frames. The reactivity worth of the safety
sheets, $\Delta k/k$, was measured to be approximately minus 30 per cent.
When the sheets are inserted into the fuel lattice, they divide the
lattice into three sections. The sheets are suspended by electro-
magnets which are attached to cables carrying manually operated
counterweights outside the shielding. Interruption of the electrical
current to the electromagnets will release the safety sheets at any
time, regardless of their position. Approximately 0.3 second is re-
quired for the sheets to fall freely into the lattice from the full-
out position. Moistened cellulose sponges on the tank top snub the
fall of the sheets. This system is shown in Figure 9. The safety
sheet support frame, which is shown in Figure 10, has "Micarta"
guides that extend into the lattice and act as runways for the safety
sheets.

The light-water moderator can be removed very quickly from
the tank by means of an air-operated dump valve, which will drain the
water to the midplane of the core in five seconds. The quick opening
valve is shown in Figure 4. It consists of an air cylinder and
gasketed closure disc. The closure disc is forced by air pressure
against an eight-inch opening in the bottom of the NTG tank. When a
scram signal occurs, a solenoid-actuated valve reverses the direction
of air pressure on the piston, quickly forcing the closure disc down-
ward. Air for operation of the dump valve is supplied from a receiver
tank which is located on top of the NTG tank. A small compressor out-
side the shielding maintains the pressure in the receiver tank.

The scram system of the NTG, which is composed of two inde-
pendent circuits, will cause the safety sheets to fall and the dump
valve to open simultaneously if an unexpected increase occurs in
neutron level, or if the loading doors in the NTG tank are raised
during operation. A block diagram of the scram circuits is shown in
Figure 11. The scram system consists of two linear Beckman micro-
microammeters, the control panel, and the associated power supplies.
A scram can be initiated in either of the two channels which are inde-
pendent up to the control relays. The micromicroammeters derive
their input signals from two of the neutron-sensitive ion chambers.
These chambers are located on opposite sides of the lattice in the
moderator to afford protection even if the flux distribution is
asymmetric. A Weston "Sensitrol" meter-relay is connected in series
with the meter in the micromicroammeter, and is adjusted such that
the contacts on the meter-relay pull in at about 95 per cent of full
scale. When these contacts pull in they cause a Western Electric
relay, No. 275B, to drop out. If the power fails this relay also
drops out, which gives a "fail safe" feature to this part of the

circuit. The contacts on each of the Western Electric relays are connected in series with the scram line in the control circuit proper. Each of these relays can be bypassed by means of switches on the control panel. The scram circuit is so arranged, however, that if both of the independent scram lines are bypassed simultaneously a scram will occur. Bypassing is necessary to preclude spurious scrams when the range of the Beckman micromicroammeters is changed. The by-pass switches, as well as the main power switches, are key operated to prevent unauthorized use. Red lights on the control panel, which is shown in Figure 2, indicate when a scram circuit is bypassed. A green light on the control panel indicates when the safety sheets are "cocked".

Another safety feature is a system of interlock switches. Two of these microswitches trigger the scram circuit if either of the loading doors is raised. Another microswitch performs the same function if the tank is lifted from its support. A fourth micro-switch controls the power to the dump valve solenoid switch and pre-vents closing the dump valve unless the safety sheets are raised.

Detailed explanations of the action of the circuit following a scram and of the circuit diagram are given in the Appendix.

Further protection against nuclear accidents is afforded by the design of the sample carrier. If the lattice of the NTG is ar-ranged to test neutron-absorbing specimens such as target pieces, it is important that no fissionable specimen be inserted in the sample tube. The sample carrier is slotted to accept only one size of sample. If an attempt is made to insert a different size sample, the error is immediately obvious.

Another safety precaution is the slow rate at which the water is raised in the tank. The time required to fill the tank is approximately 20 minutes. This is slow enough to allow effective operation of the scram devices if raising the water brings the NTG to criticality.

Operational procedures incorporate other safety features. These include:

1. All changes in the fuel configuration are made with the water drained from the tank, with the neutron source inserted in the lattice, with the safety sheets cocked, and with two independent scram circuits in operation.

2. Suitable lattice configurations are used for testing each material that is available. The highest k at-tainable during operation is 0.990.

3. The water is drained from the tank at the end of each day.

4. Proper operation of the two scram circuits is confirmed each day before the water is pumped in.

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5. The safety sheets are cocked before the water is pumped in.

6. The neutron source is always inserted in the lattice before the water is pumped in.

7. Only the type of material being tested is allowed in the vicinity of the NTG.

CALIBRATION EXPERIMENTS

Operational Characteristics

Equations that describe the kinetics and the sensitivity of a subcritical pile have been discussed in DP-48[2]. The time-dependent behavior of N, the number of neutrons produced per second, when small changes in the fuel loading are made, can be represented by:

$$N(t,k) = SM \pm \Delta N e^{-t/\ell M} \tag{1}$$

S is the number of neutrons per second emitted by the source; M is the multiplication, $\frac{1}{1-k}$; k is the effective multiplication constant; ΔN is the change in neutron production resulting from a small change in k; t is the time; and ℓ is the effective neutron lifetime.

The change in the equilibrium value of N resulting from a change, Δm, in the amount of fuel is found by differentiating the time-independent part of N in Equation 1 with respect to m. To carry out this differentiation one must know the behavior of k as a function of m. Experiments with the NTG showed that, for values of k above 0.95, this relationship was linear:

$$\frac{\Delta k}{\Delta m} = \frac{\alpha}{m_o} \tag{2}$$

where α, the shape of the "loading curve", depended on the statistical weight of the loading position, and where m_o is the critical mass of the assembly. With this expression for $\frac{\Delta k}{\Delta m}$, the relation between changes in neutron production and loading becomes:

$$\Delta N = \frac{\alpha S M^2}{m_o} \Delta m \tag{3}$$

If the change, Δm, is small, N is a linear function of m. For significant changes in the loading, the change in multiplication M must be taken into account when the recorder chart is calibrated in terms of the fuel content of the test specimens.

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Initial Loading

The ion chamber currents and the count rates were measured for a multiplication of one (i.e., with the source inserted and the water raised) before the fuel was loaded into the lattice. These values served as a reference to compute the multiplications of subsequent loadings. Since these experiments extended over a period of several months, the reference values had to be corrected for the decay of the source.

Before fuel was added, the source was inserted, the water was drained, and the safety sheets were cocked. After each addition of fuel, the water was raised slowly and the multiplication was measured. The water was then dumped to get ready for the next loading step. Smaller increments of fuel were added in subsequent steps, as criticality was approached. The average of the inverse multiplication is plotted in Figure 12 as a function of the mass of U-235 in the core. The lattice configuration that produced a multiplication of 100 (k = 0.99) is shown in Figure 13. The tubes that did not accommodate fuel or the source were filled with polyethylene rods.

Statistical Weight in the Sample Hole

The sensitivity of the NTG depends on the statistical weight of the central channel as shown in Equations 2 and 3. The statistical weight could be increased by removing some of the fuel from the innermost ring of tubes and then adding to some of the peripheral positions to compensate for the resulting reduction in multiplication. The sensitivity, $\Delta N/\Delta m$, of the lattice shown in Figure 13 was determined by measuring the change in the differential electrometer reading when two samples of known but different concentrations were alternately positioned in the sample hole. The lattice was altered by removing the fuel from the innermost ring of tubes, and the sensitivity was measured again.

Noise Level in the Ion Chambers

For a given multiplication, source strength and critical mass, the limit in sensitivity of the NTG depends on the noise level in the neutron-detecting system. Accordingly, several precautions were taken to minimize noise: (1) the instruments derived their power from a "Stabiline" electronic voltage regulator; (2) ground connections were made in such a way as to avoid ground loops; and (3) leads from the ion chambers were carefully shielded. The calculations in the Appendix indicate that the remaining noise is of the order to be expected from the statistical fluctuations in the ion current.

To achieve a high signal-to-noise ratio, and hence, a high sensitivity, the largest possible fraction of neutrons leaking from the core must be detected. The primary detecting system for most of

the experiments consisted of four boron-lined ion chambers connected
in parallel. For the measurements reported for slugs of enriched
uranium-aluminum alloy and slugs of natural uranium, however, only
two chambers were available. Had all chambers been of equal ef-
ficiency for detecting neutrons and placed in regions of equal flux,
the sensitivity of the NTG should have doubled when the number of
chambers was doubled. The measured ratio of sensitivities was 1.7.

For operating convenience, a 0.1-μf condenser was placed
between the common signal lead from the ion chambers and ground. The
condenser served to smooth out ion chamber fluctuations without seri-
ously lengthening the response time.

Flux Distribution in the NTG

Radial and axial flux traverses were made with indium foils
which had a thickness of 100 mg/cm^2, for the lattice shown in
Figure 14. Each foil was counted on two end-window beta counters.
The saturated activities corrected for decay, counter dead time, and
foil weight, are shown in Figures 15 and 16 as functions of position
in the NTG lattice.

The axial traverse was made in lattice position (07,35).
For the radial traverse, one group of foils was
placed between fuel pieces, while another group of foils was placed
in the moderator. For a given radius, the latter foils were more
active than the former.

The axial flux extended over a distance of about 38 inches.
Any portion of a sample outside this interval had no effect on the
neutron population. The reactivity worths of samples of different
lengths were estimated as proportional to the square of the flux
integrated over the extent of the sample.

NUCLEAR HAZARDS

The possible consequences of inserting the wrong type of
sample into the various lattices that were chosen are summarized in
the following table. The highest possible value of the effective
multiplication constant is quoted for each particular mistake.

The consequences of an uncontrolled excursion with k = 1.
are discussed in detail in the Appendix. It is assumed that the
safety sheets and the moderator dump valve fail. The power excursion
would proceed for approximately five minutes at which time the fuel
would begin to melt. The resultant change in lattice spacing would
shut down the reactor.

The radiation levels adjacent to the NTG shield are moni-
tored during operation. In areas where personnel are required for
operation, the dose rates are below six mrem per hour. When tubes
enriched uranium-aluminum alloy are tested, a fast neutron dose rate
of about 20 mrem per hour is encountered immediately adjacent to
shielding doors.

Since sample slugs are inserted in the neutron flux for
only a minute, they are not strongly activated and can be handled
with gloves immediately following their discharge from the NTG. When
longer elements, such as plates or tubes are scanned, they are ir-
radiated for longer periods and the resulting activity must be al-
lowed to decay before the elements are handled. However, by dis-
charging the exposed element into a rack, another sample can be
tested while the preceding one is cooling. In this way, delays in
testing are avoided.

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APPENDIX

DESIGN AND CHARACTERISTICS OF THE ION CHAMBERS

Neutron-sensitive ion chambers of suitable size and sensitivity were not commercially available. A chamber shown in Figure 33 was designed at the Laboratory. The sensitive volume consists of the two annular spaces formed by the three inner, coaxial, aluminum tubes. A fourth aluminum tube forms the outer case of the chamber and provides rigid mechanical support for the "Teflon" insulators. The neutron-sensitive coating material was fully enriched B-10 suspended in mineral oil. The tubes were first degreased in "Triclene" and then the B-10 was painted on the surfaces shown in Figure 34 with a camel-hair brush. The tubes were then baked in a nitrogen atmosphere at 300°C and at atmospheric pressure for two hours. The tubes were rotated continuously at approximately 30 rpm while in the oven to obtain a uniform coating. The tubes were allowed to cool for two hours in the nitrogen atmosphere before they were removed. Two such coatings per surface were required to obtain a thickness of 0.54 mg/cm². Filling arrangements were made by drilling a 1/4-inch hole in the plug and soft-soldering a copper tube into the hole. Electrical connections to the aluminum tubes were made by attaching clips, which were taken from female Jones plugs, over the edges of the tubes. These clips protruded through 3/16-inch holes drilled in the insulators. Two "Kovar" seals were soft-soldered into holes in the chamber cap to provide gas-tight connections to the outside of the chamber. The chambers were evacuated and then filled with argon to atmospheric pressure, evacuated, and refilled. The chambers were then sealed by pinching the copper filling tube and soldering over the end.

The chambers were placed near a neutron source and their saturation voltages were obtained. All the chambers saturated between 200 and 300 volts. Since the differential electrometer provides a regulated B+ supply of 300 volts, the chambers in the NTG were operated from this supply.

The linearity of the chambers was obtained by comparison of their current outputs with that from a large wide-spectrum chamber manufactured by the General Electric Company. All the chambers were linear over a current range of three decades. The sensitivity of the chambers was estimated to be on the order of 10^{-13} ampere per nv.

THE DIFFERENTIAL ELECTROMETER

A schematic diagram of the differential electrometer is shown in Figure 35. The bucking circuit consists of a negative voltage supply that contains two voltage-reference tubes and a ten-turn "Helipot". The voltage that appears across this "Helipot" is used to buck out the voltage drop in the input resistors of the electrometer. The stability of the No. 5651 voltage reference tube is 0.1 volt. This amounts to a maximum instability, due to drift in the bucking voltage, of 0.15 per cent full scale. Drift tests on the electrometer with no input signal showed a stability of plus or minus 0.1 per cent full scale over a period of 24 hours.

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CONTROL CIRCUIT

The operation of the control system will be described by consideration of the events that follow the initiation of a scram. Figure 36 is a diagram of the control circuit. Assume that the control relay circuit has been broken, either by the "Beckman-Sensitrol" combination, the master scram switch, or the interlock switches on the loading doors:

1. Relay No. 3 opens, interrupting the flow of current to the electromagnets that hold the boron-aluminum safety sheets out of the lattice against the force of gravity.

2. Relay No. 2 opens, interrupting the flow of current to the transformer that supplies the solenoid actuator on the dump valve.

3. Relay No. 1 drops out as it is connected across the transformer mentioned in (2) above.

Relays 1, 2, and 3 are self-locking, i.e., one of the normally open contacts is connected in series with the coil. This means that if the current in the relay coil is broken the relay will fall open and stay open, regardless of the behavior of the control signal, until the normally open contact is bridged long enough by other means for the relay to pull in again. This feature insures that a scram will go to completion even if the control signal is returned to normal. The "reset" switch performs the function of bridging the normally open contacts on Relays No. 2 and No. 3. This switch is spring loaded to return to the open position when the toggle is released. The reset function for Relay No. 1 is performed by a microswitch that is mounted on the safety sheet support such that it is closed only when the safety sheet is in the "up" position. The second normally open contact on Relay No. 1 is connected in series with the coil on Relay No. 2. This method of connection prevents the dump valve from being closed unless the safety sheets are in the "up" position. One set of contacts on the microswitch are used to light a green light on the control panel to indicate when the safety sheets are "cocked". The master scram button is located in the center of the control panel. The contacts on this switch are also in series with the scram line so that manual operation of the scram circuit is possible.

NOISE LEVEL IN THE IONIZATION CURRENT

With a multiplication of 100 and a source strength of 3×10^7 n/sec, the current from two chambers in parallel was about 2×10^{-8} ampere. The statistical fluctuation to be expected is[s]

$$\frac{\Delta i}{i} = \sqrt{\frac{Me}{i\tau}} \tag{A-1}$$

where M is the average number of ion pairs produced by each neutron absorbed in B-10, e is the charge of the electron in coulombs, i is

the ion current in amperes and τ is the resolving time of the detection system. The resolving time depends on the input time constant, on the time required to collect the electrons in the chamber, and on the frequency response of the amplifier.

The energy released in the B-10(n, α)Li-7 reaction is approximately 2.5 Mev, and the energy required per ion pair in argon is approximately 25 ev. Thus $M \cong 10^5$ ion pairs.

The response time of the system is governed principally by the response time of the recorder. It was on the order of 0.1 second. When the values are substituted in Equation (A-1), a relative noise level, $\frac{\Delta I}{I}$, of 0.3 per cent is obtained, which is approximately the observed value.

HYPOTHETICAL EXCURSION IN THE NTG WITH k = 1.002

The following assumptions were made:

1. The effective multiplication constant increases from 0.99 to 1.002 instantaneously at time t_o.

2. Both safety sheets fail to fall and the dump valve does not open.

3. No heat is transferred from the fuel to the moderator.

4. No deformation of the fuel occurs until the melting temperature is reached.

The third assumption is made on the basis that the O.D. of the fuel slugs is 1.005 inches and the I.D. of the supporting tube is 1.020 inches. The resulting air gap tends to insulate the fuel. As the slug heats and expands, this gap decreases but does not completely close before the melting temperature is reached.

The constants used in this calculation are given below:

$\bar{\phi}$ (average flux in core at k = 0.99) 10^6 n/cm^2-sec

σ_f (fission cross section of U-235)   580 b

σ_a (absorption cross section of U-235) 687 b

V (volume of core) 8.3×10^4 cm^3

Σ_a^{eff} (effective macroscopic absorption) 0.0749 cm^{-1}

C_p(Al) (specific heat of Al)   0.214 cal/gm-$^\circ$C

E (energy absorbed in Al per fission) 175 mev = 6.69×10^{-12} gm-cal

$\Delta\theta$ (temperature rise in aluminum)   640°C

T (period of reactor with k = 1.002)   20.5 sec

f (thermal utilization)   0.764

The initial fission rate at k = 0.99 is given by $\Phi\Sigma_a^{eff}$ fV σ_f/σ_a, which is 4.0×10^9 fissions per second. The neutron flux, at any time t, is proportional to $e^{t/T}$. If the heat produced is equated to the heat absorbed in the aluminum, the equation is

$$C_p M\Delta\theta = E\bar{\Phi}\Sigma_a^{eff} \; fV \; \frac{\sigma_f}{\sigma_a} \int_{t_o}^{t_1} e^{t/T} dt \qquad (A-2)$$

where t_1 is the time at which the temperature rise, $\Delta\theta$, is obtained.

Then,

$$e^{t_1/T} = 1 + \frac{C_p M\Delta\theta}{E\Phi\Sigma_o^{eff} \; fV \; \frac{\sigma_f}{\sigma_a} \; T} = 1.80 \times 10^7 \qquad (A-3)$$

Therefore,

$$\frac{t_1}{T} = 16.7$$

and t_1 = 342 seconds

Under the assumptions made, it takes 342 seconds for the fuel slugs to reach the melting point of aluminum, which is 660°C.

During the heating phase and before melting of the fuel occurs, a positive contribution to the reactivity might result from the decrease in density and, hence, the decrease in the self-shielding of the fuel. This change was estimated to be $\Delta k = + 0.001$; the contribution was neglected in the calculation. If this additional reactivity were considered, the period would decrease in the course of the excursion from 20 seconds to nine seconds.

When the fuel reaches its melting point, it will deform. This deformation can only act to decrease the reactivity and halt the excursion, since the lattice spacing is chosen to give the minimum critical mass.

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SAFETY SHEET ASSEMBLY
AIR CONTROL VALVE
AIR RECEIVER TANK
LOADING DOOR

TOP COVER
ION CHAMBER HOLDER
TANK INTERLOCK SWITCH
TANK SUPPORT

CONCRETE SHIELDING
SHIELDING TANK
SAMPLE CARRIER

RECIRCULATING PUMP
RESIN COLUMN
FILTER

SAFETY SHEET COUNTERWEIGHT

DUMP TANK

LOADING DOOR
INTERLOCK SWITCH

DUMP VALVE

H. T. G. TANK
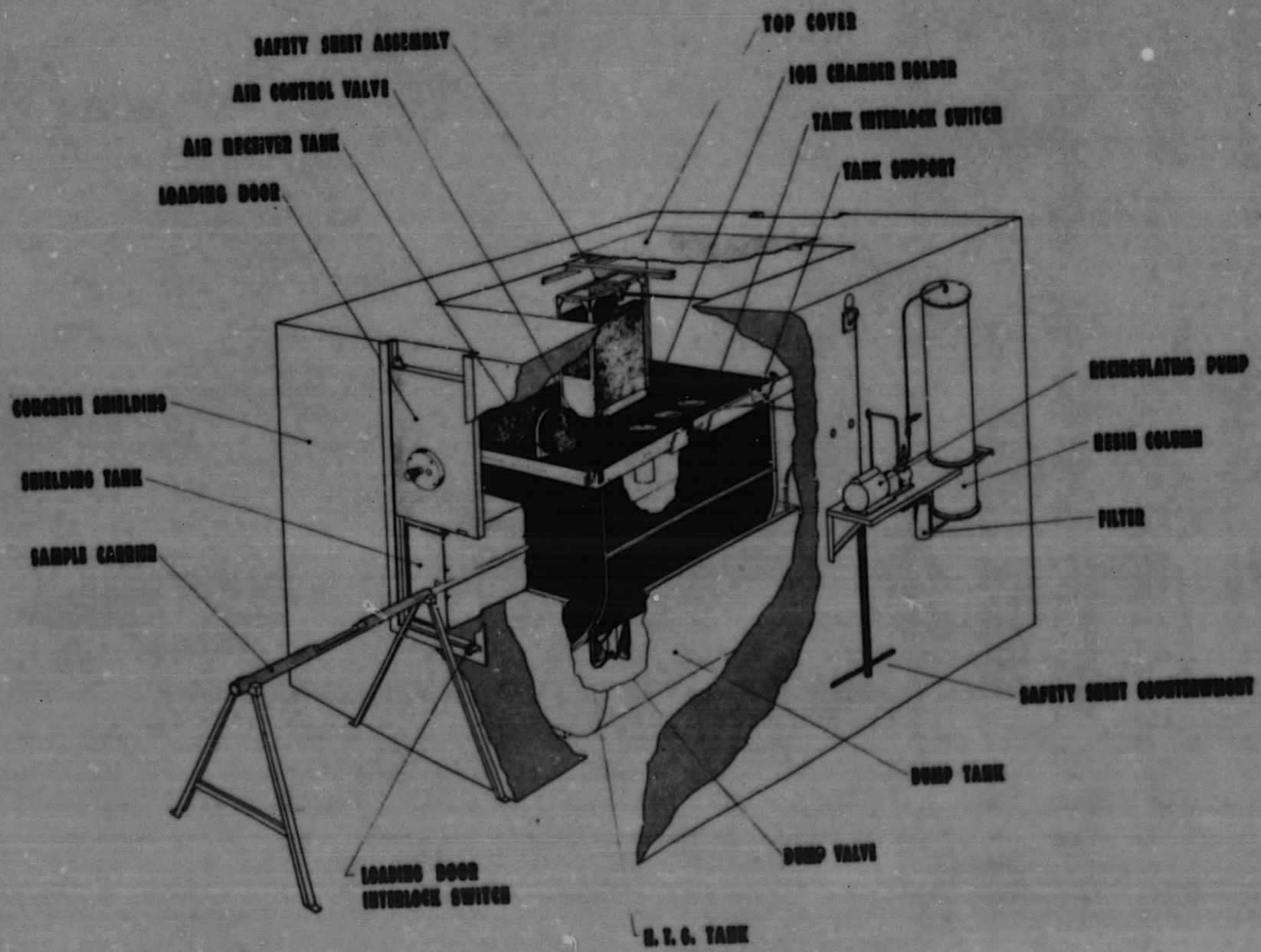
FIGURE 1

DRAWING OF THE ASSEMBLY
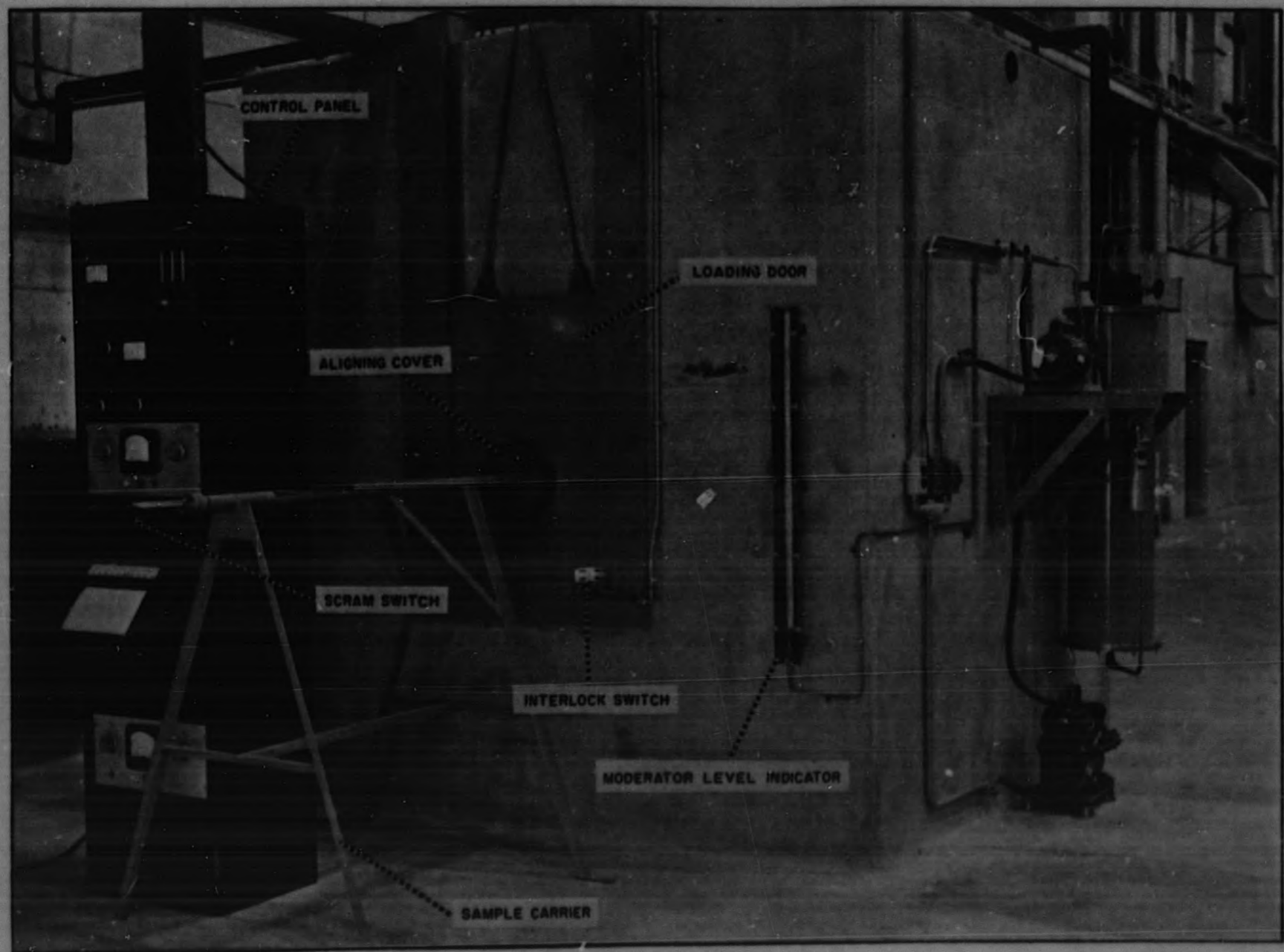
PHOTOGRAPH OF THE ASSEMBLY

FIGURE 2

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FIGURE 3

OVERFLOW TUBE

FUEL TUBES

HEXAGONAL PLUG

SAMPLE TUBE

TANK, TOP VIEW

FIGURE 4

Labels on figure:
HEXAGONAL PLUG
OVERFLOW TUBE
CLOSURE DISK
AIR CYLINDER
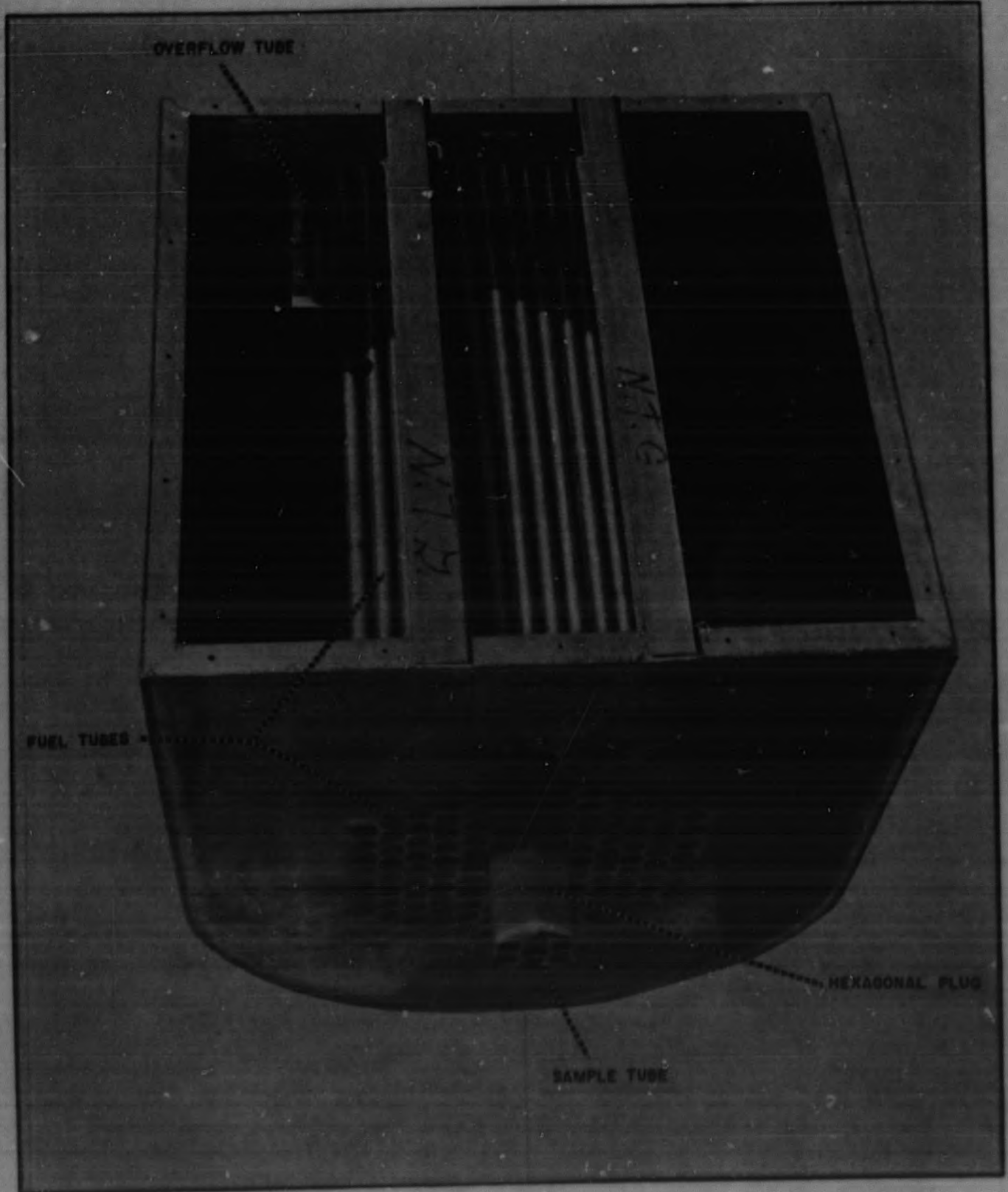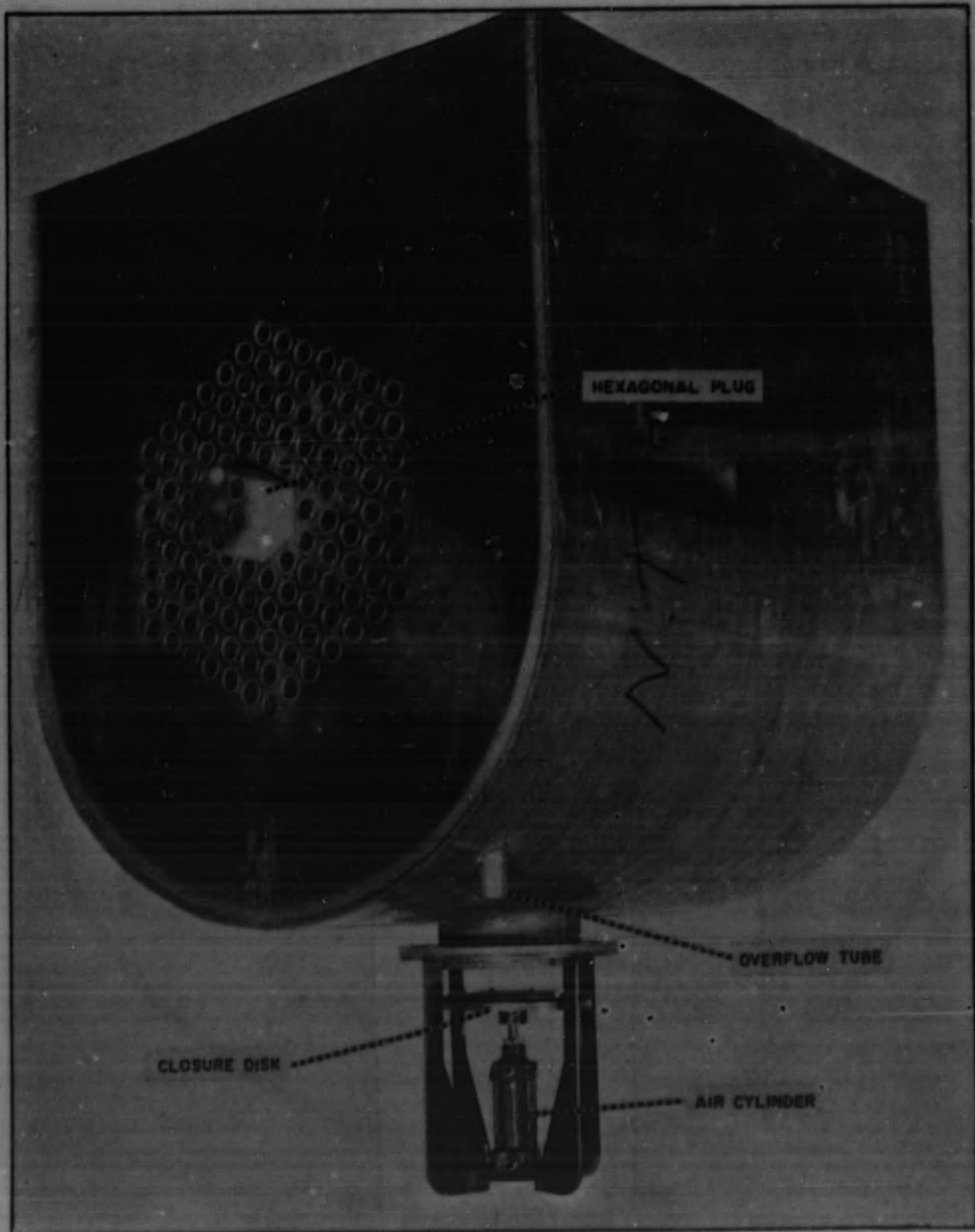
TANK AND DUMP VALVE ASSEMBLY

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FIGURE 5

TANK DETAILS

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FIGURE 6

RECIRCULATING PUMP

BUILDING WATER SUPPLY

RESIN COLUMN

FILTER

COMPRESSOR

MODERATOR SYSTEM

-29-

SHIELDING AND SOURCE LOCATION
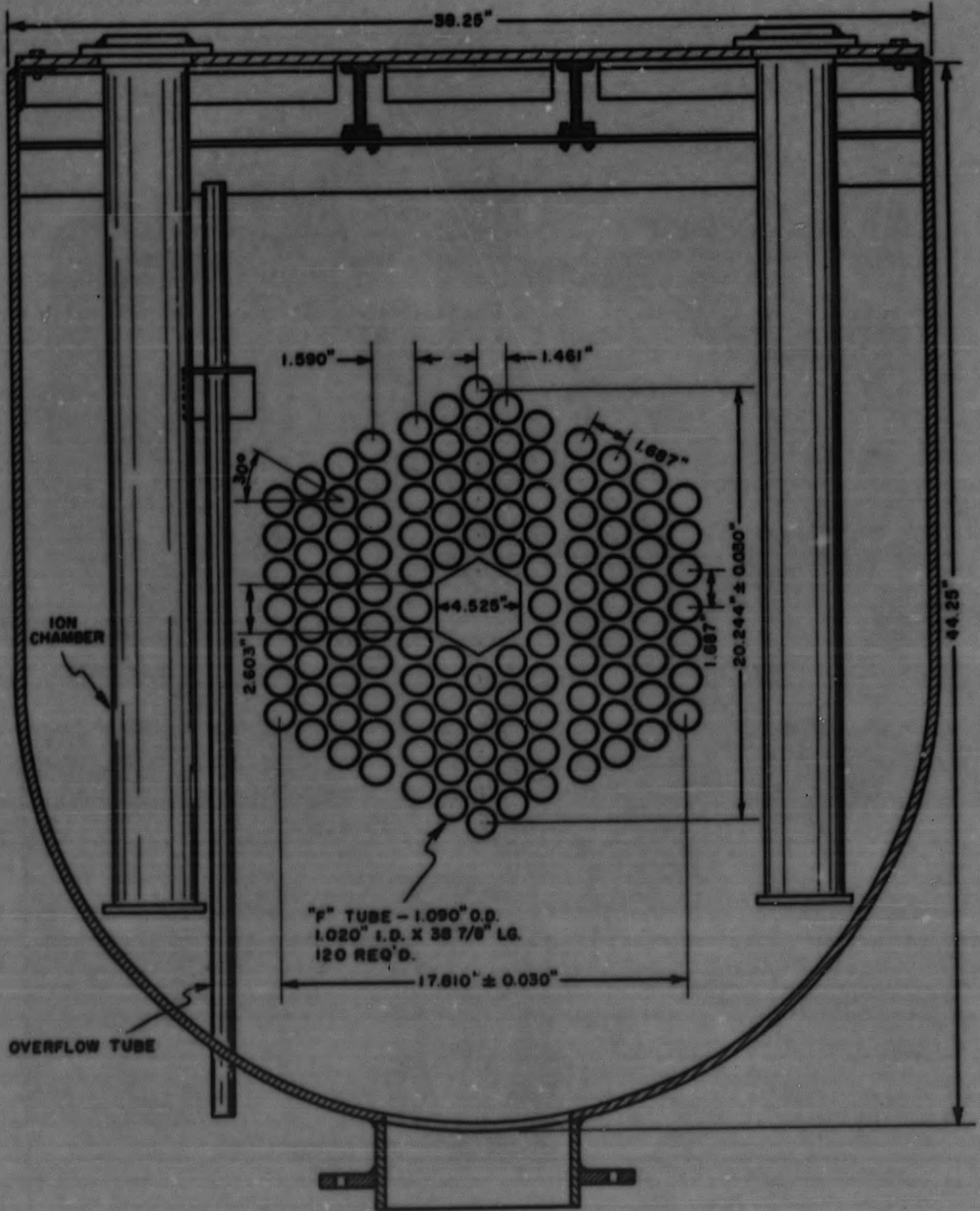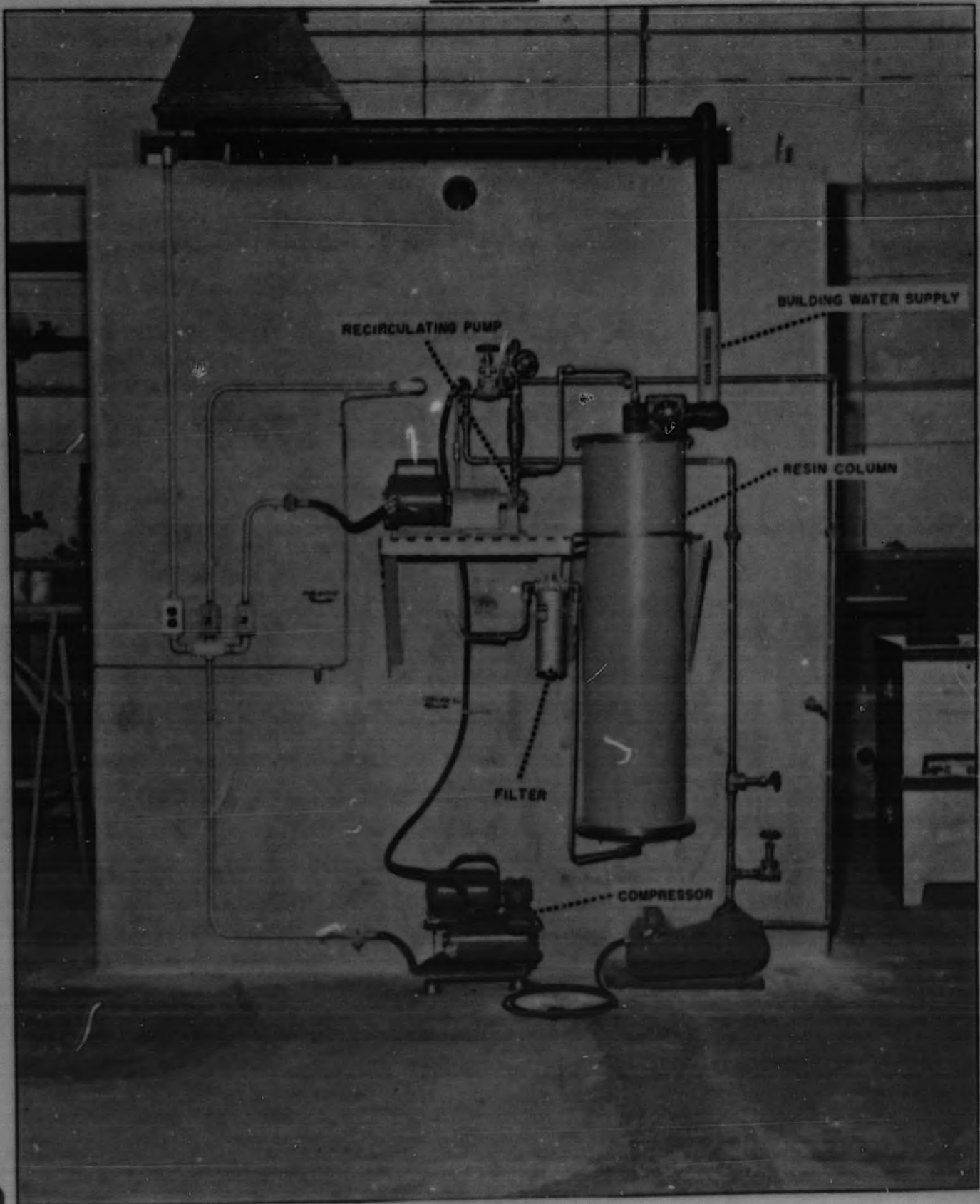
FIGURE 8

TYPICAL SECTION OF RECORDER CHART

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ELECTROMAGNET

AIR RECEIVER TANK

SAFETY SHEET

CELLULOSE SPONGE

ACTUATOR CABLES
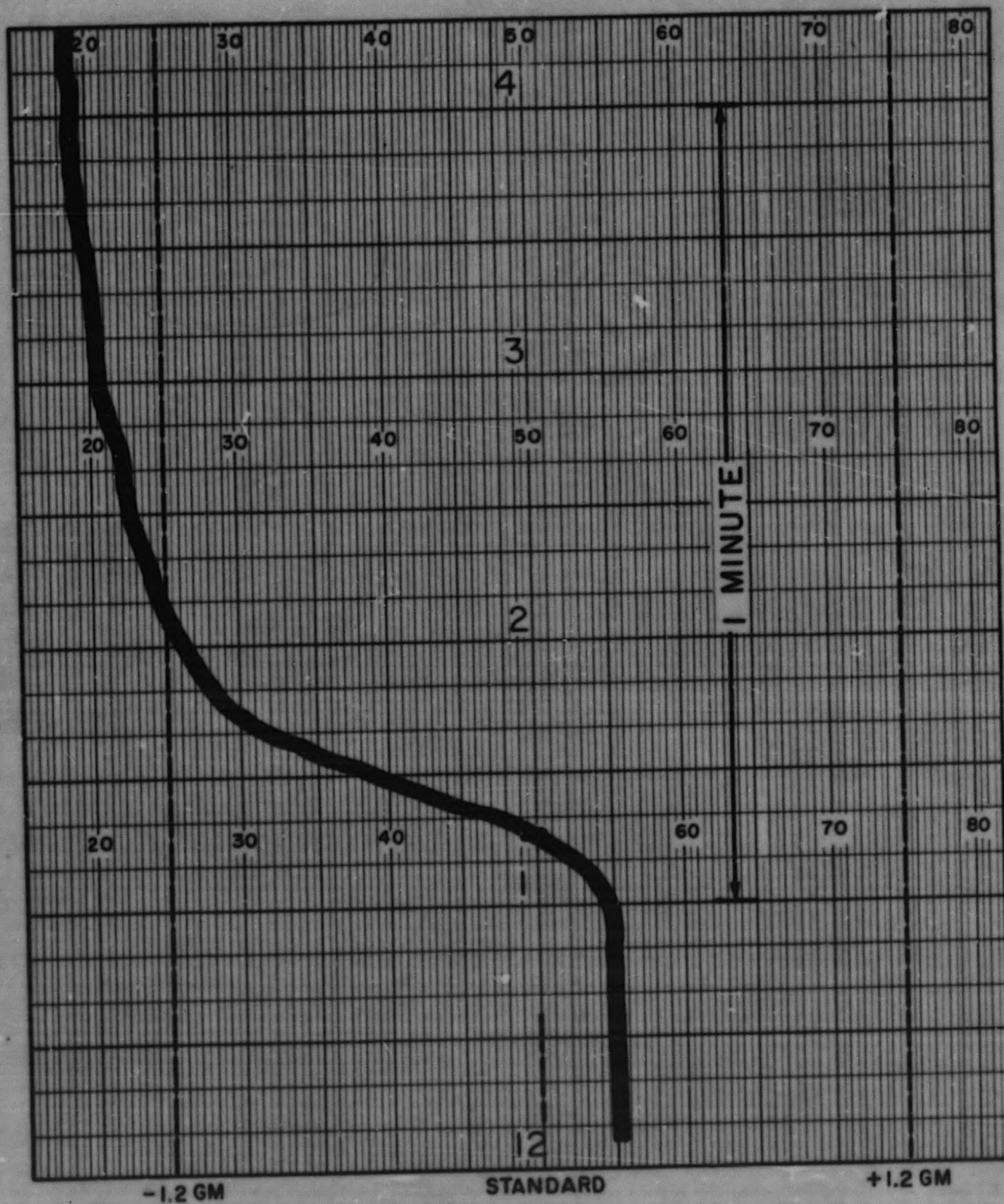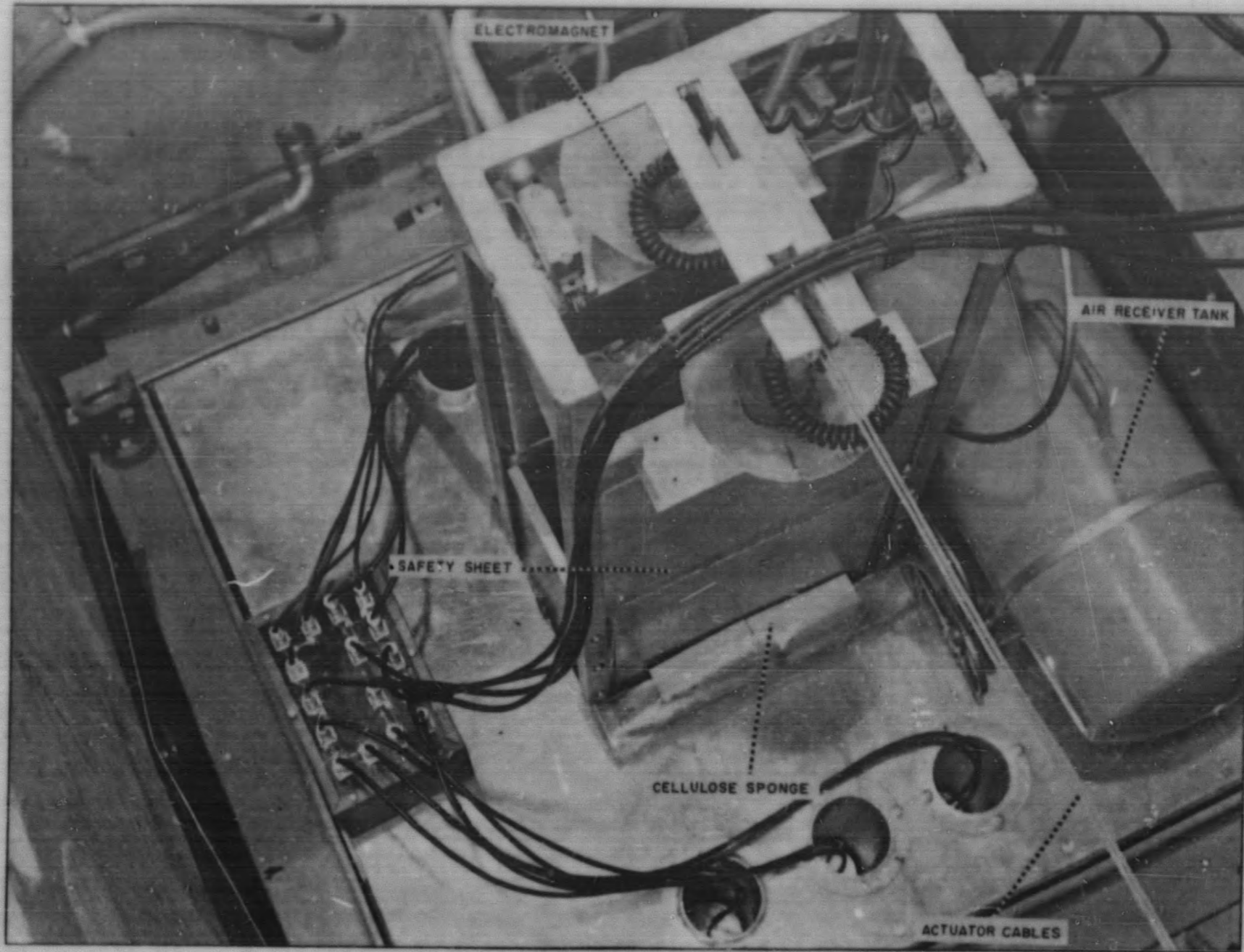
SAFETY SYSTEM

FIGURE 9

FIGURE 10
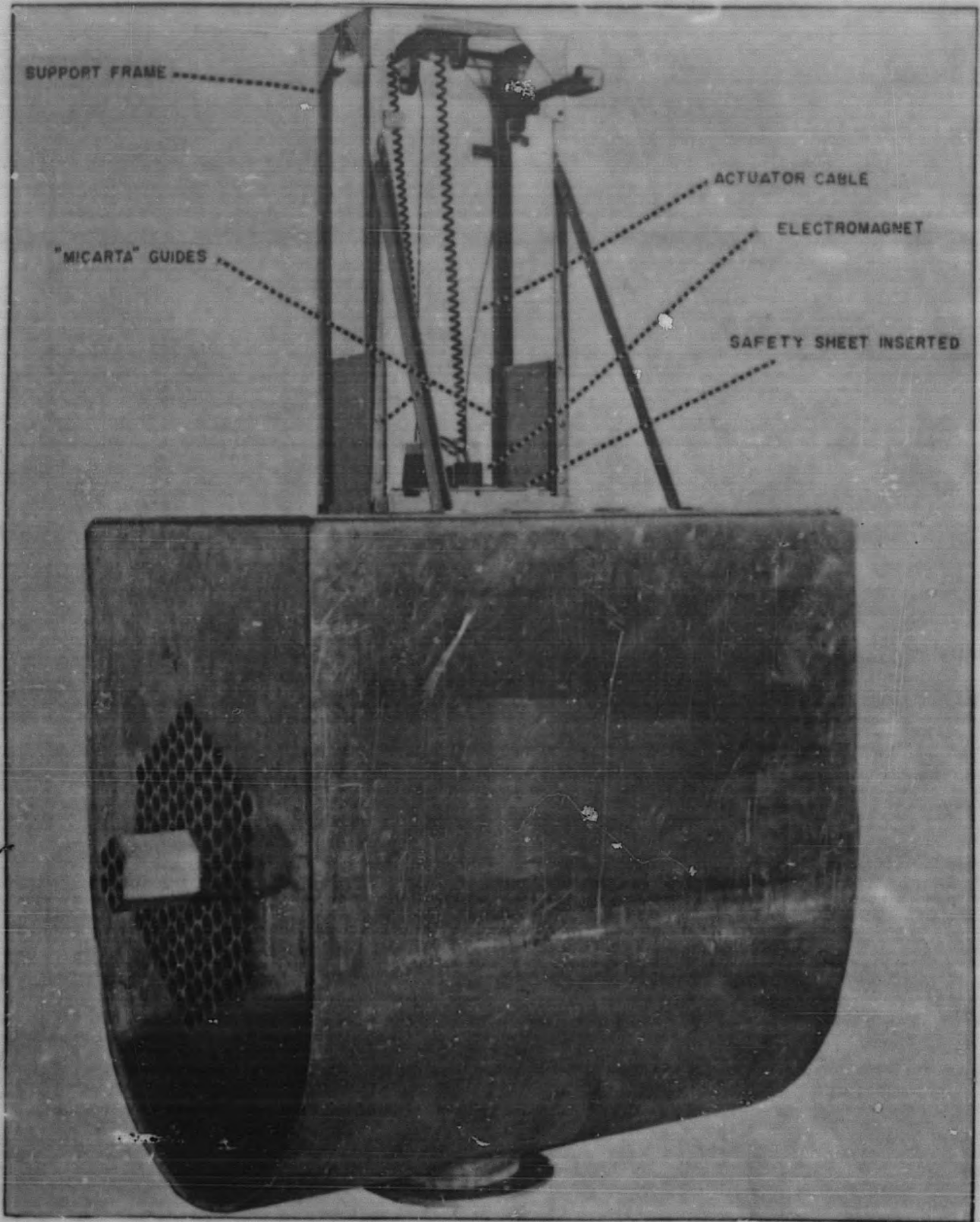
SUPPORT FRAME FOR SAFETY SHEETS

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DECLASSIFIED
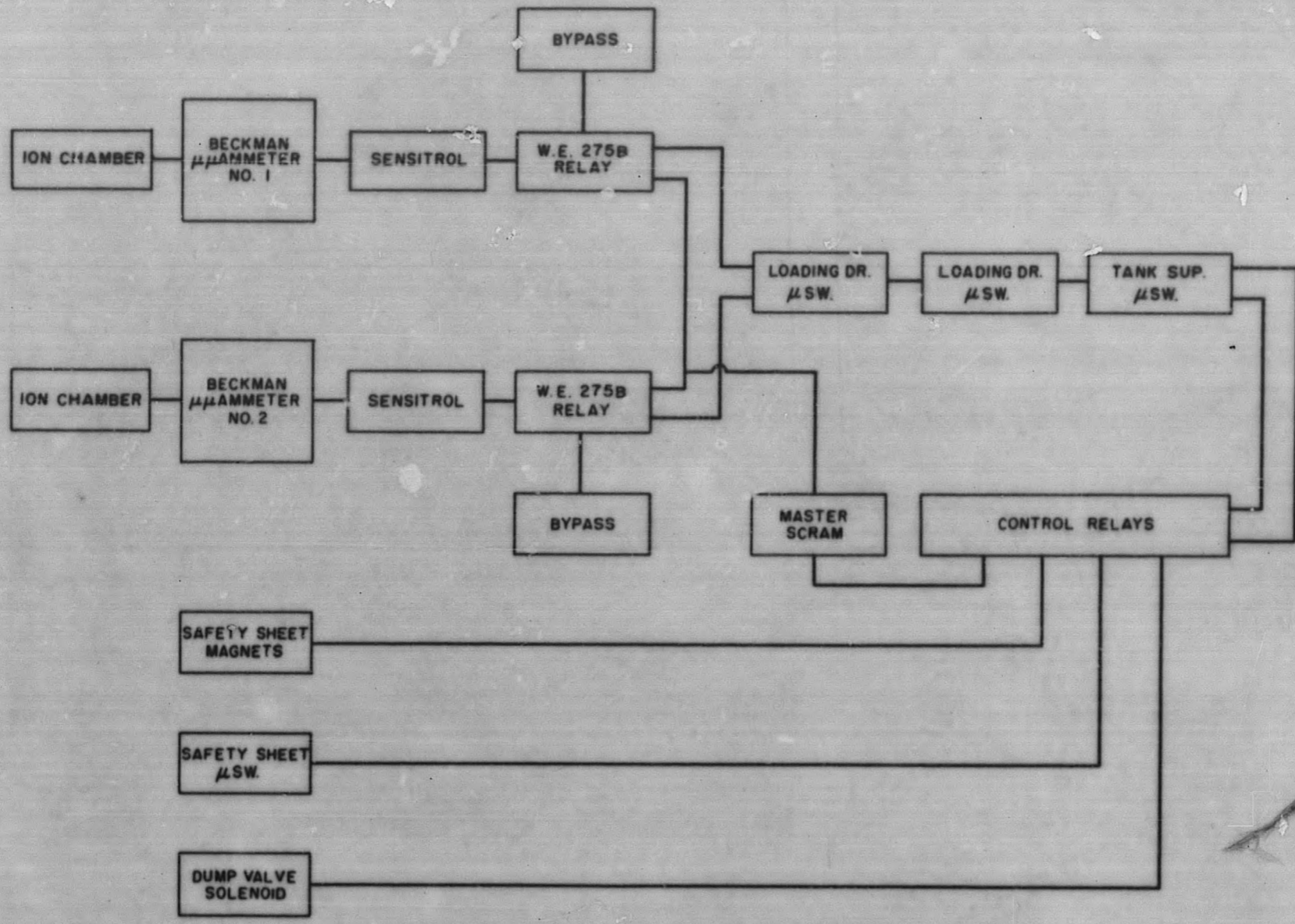
BLOCK DIAGRAM OF THE SCRAM SYSTEM

FIGURE 11

-34-
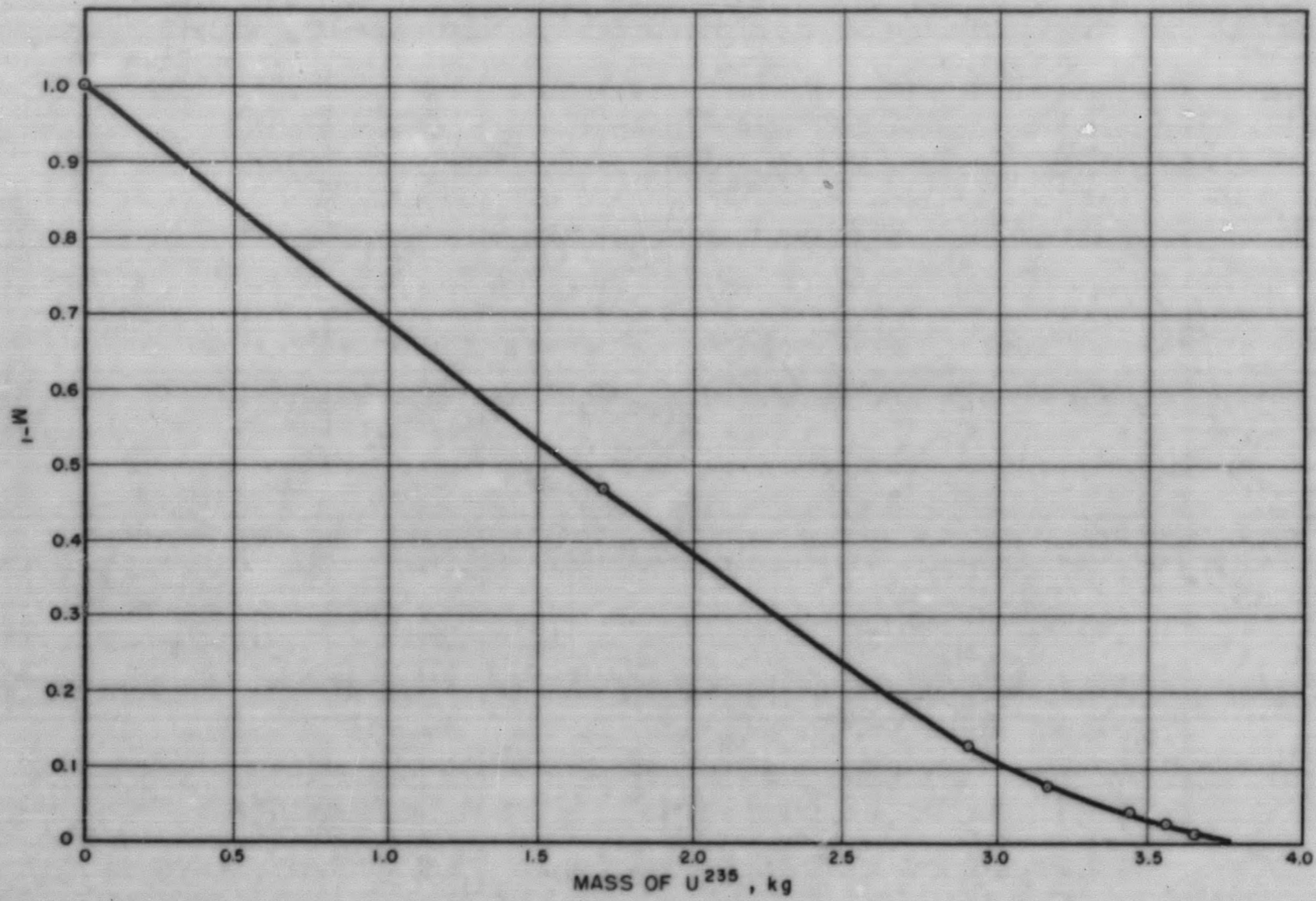
FIGURE 12

LOADING CURVE

FIGURE 13
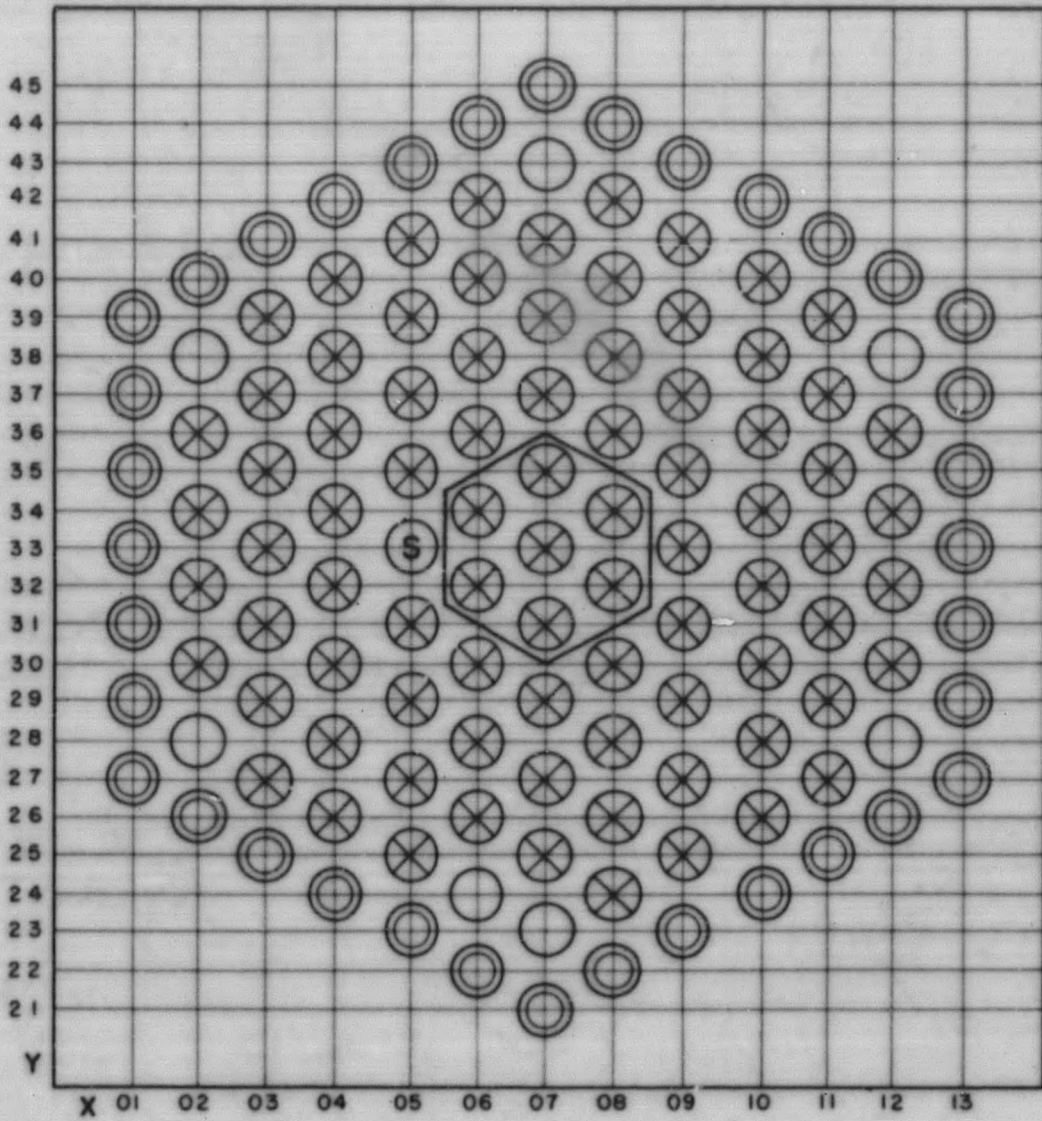
FIGURE 13

⊗ FUEL

◎ PLASTIC

Ⓢ SOURCE

LATTICE CONFIGURATION FOR k=0.990

-36-37-

FIGURE 15

RELATIVE FLUX
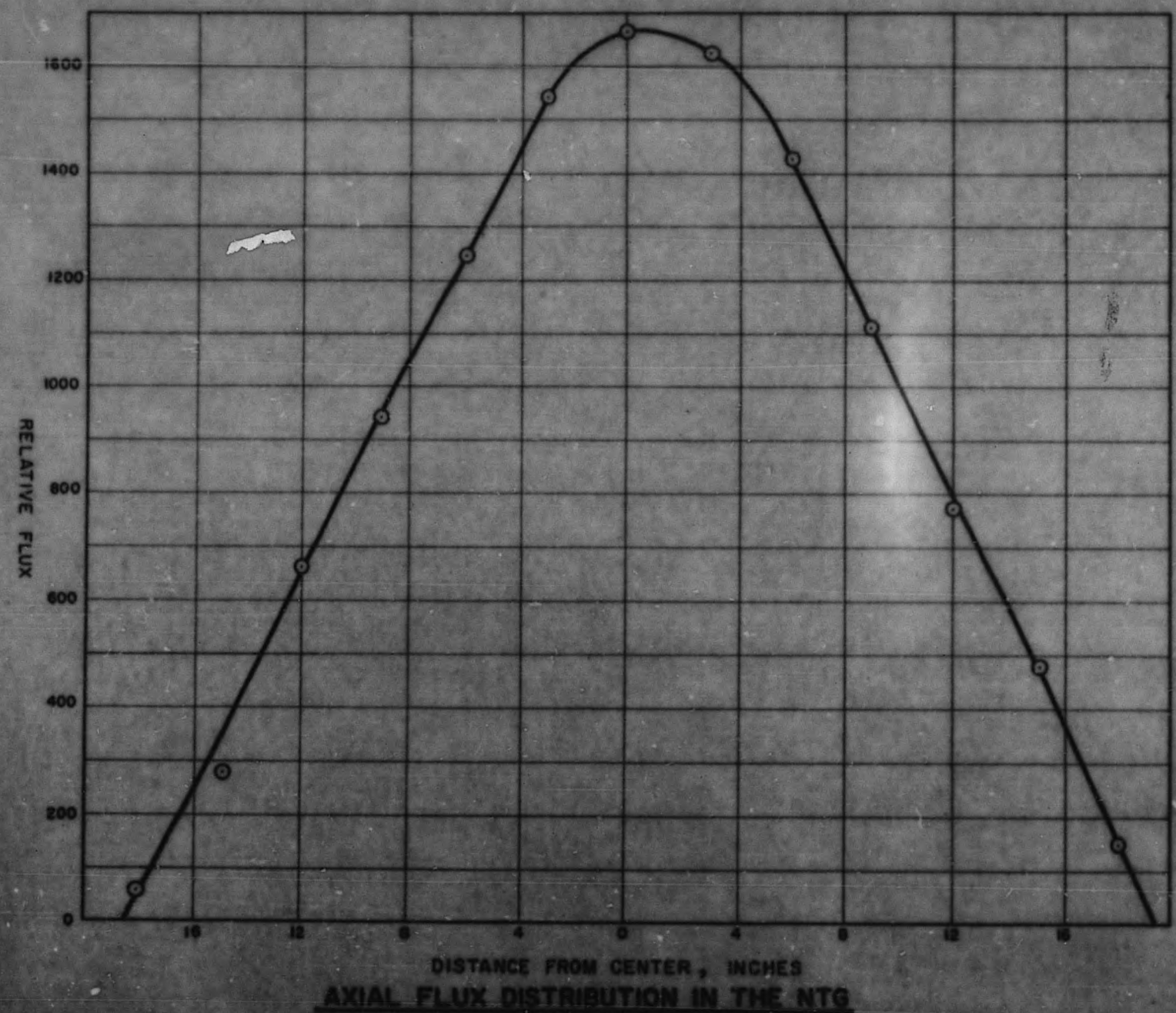
DISTANCE FROM CENTER, INCHES

AXIAL FLUX DISTRIBUTION IN THE NTG

-38-
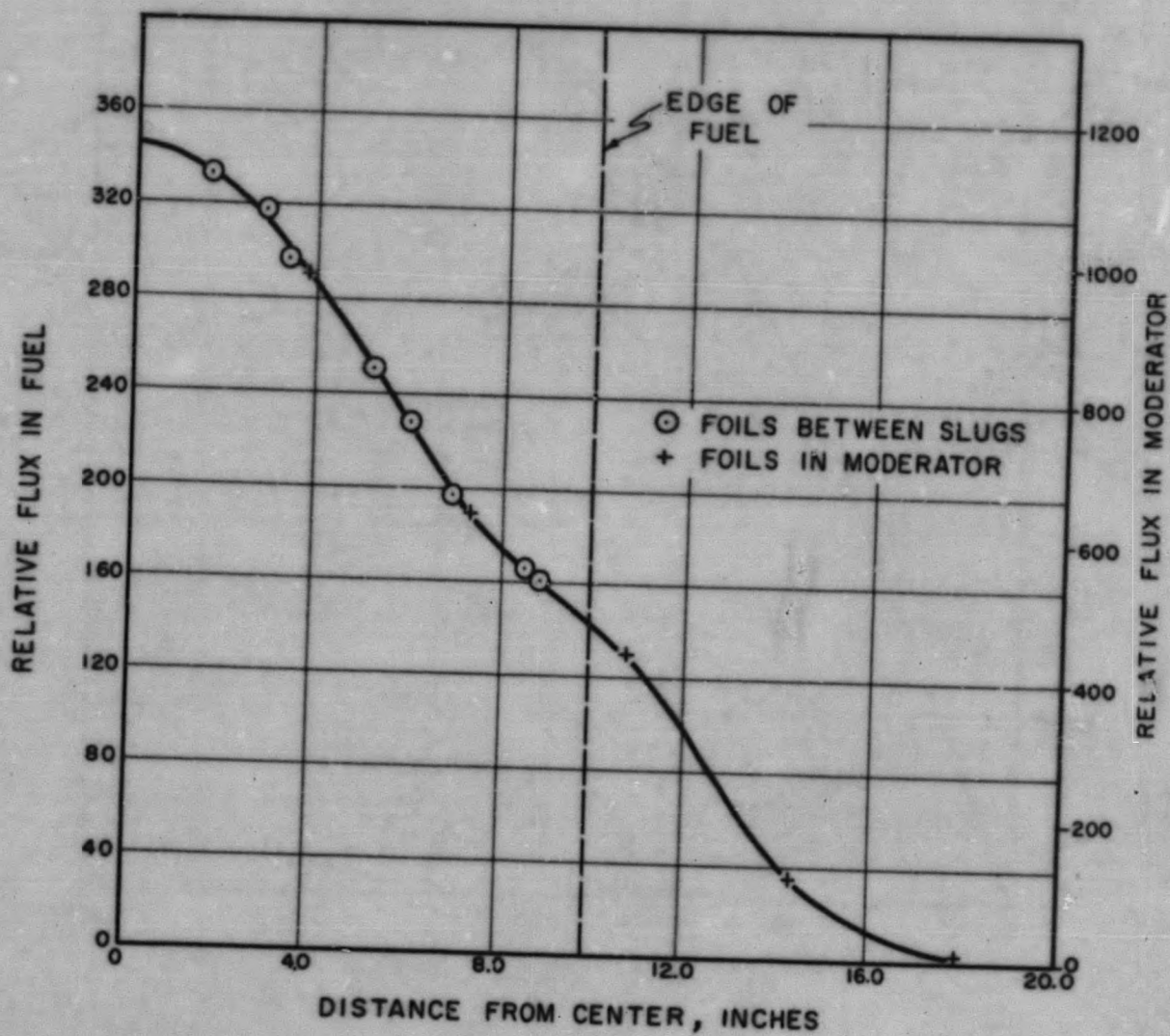
FIGURE 16

RADIAL FLUX DISTRIBUTION IN THE NTG

DECLASSIFIED

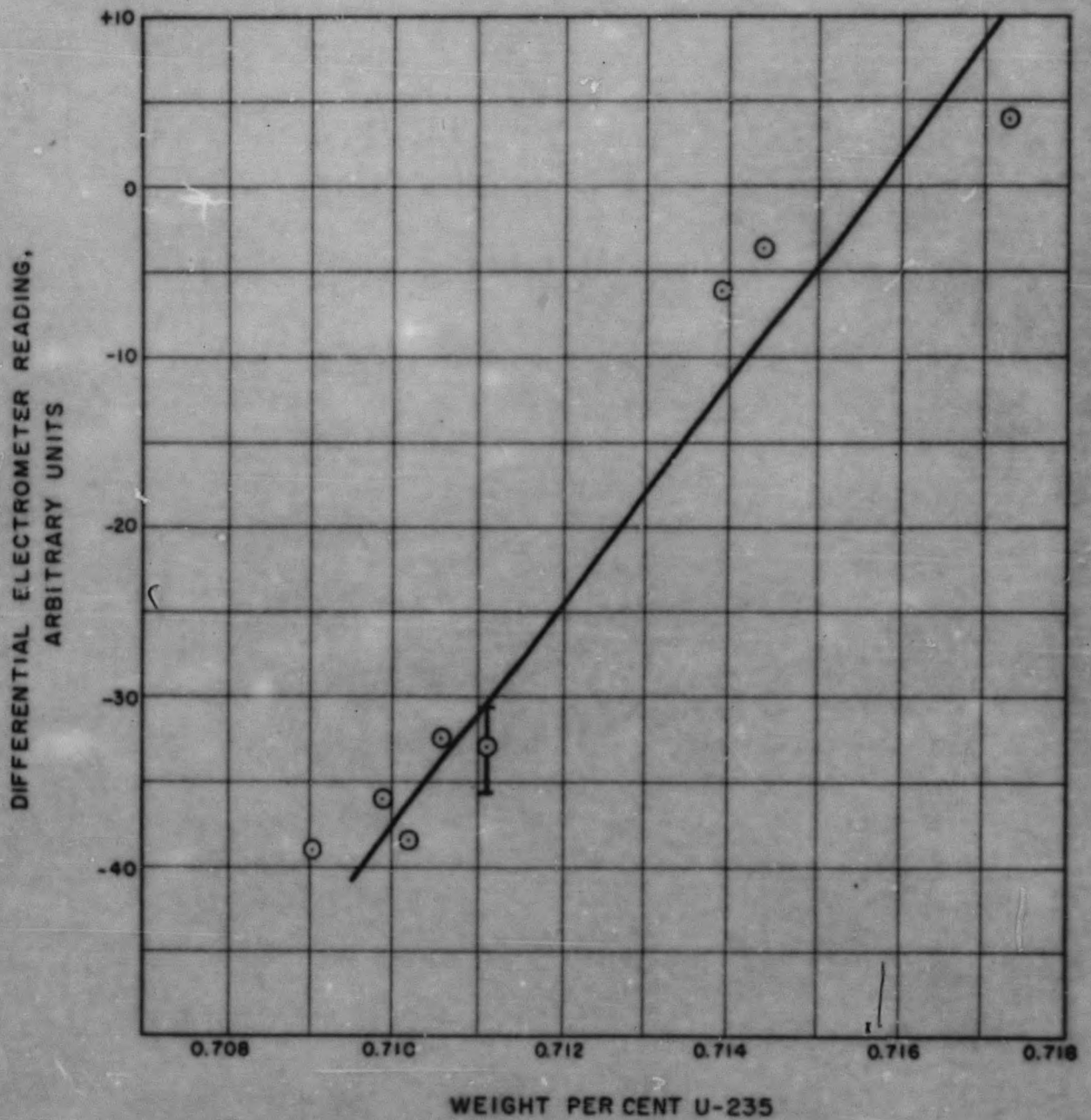FIGURE 17
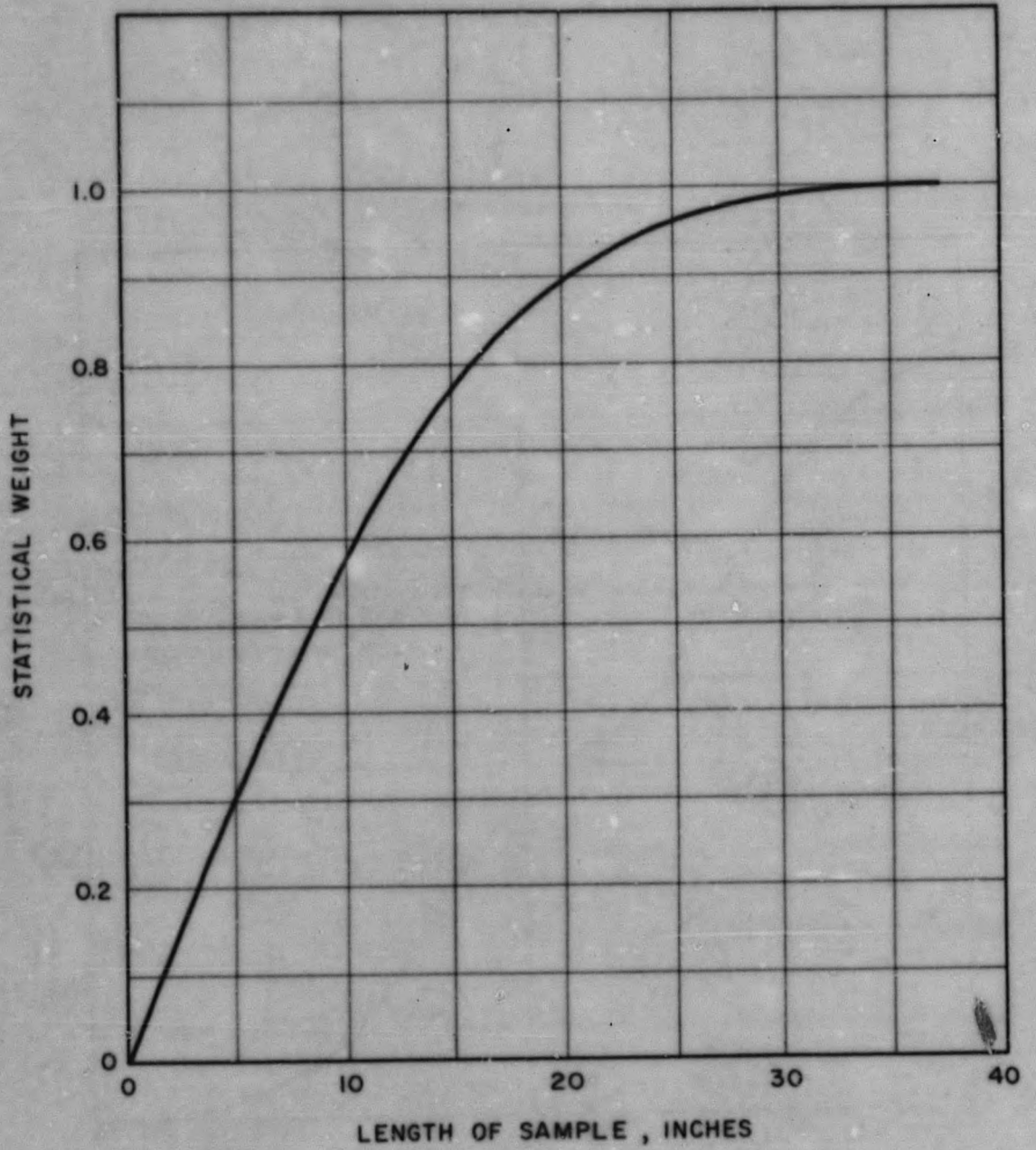
EFFECT OF SAMPLE LENGTH ON k

-40- 43-
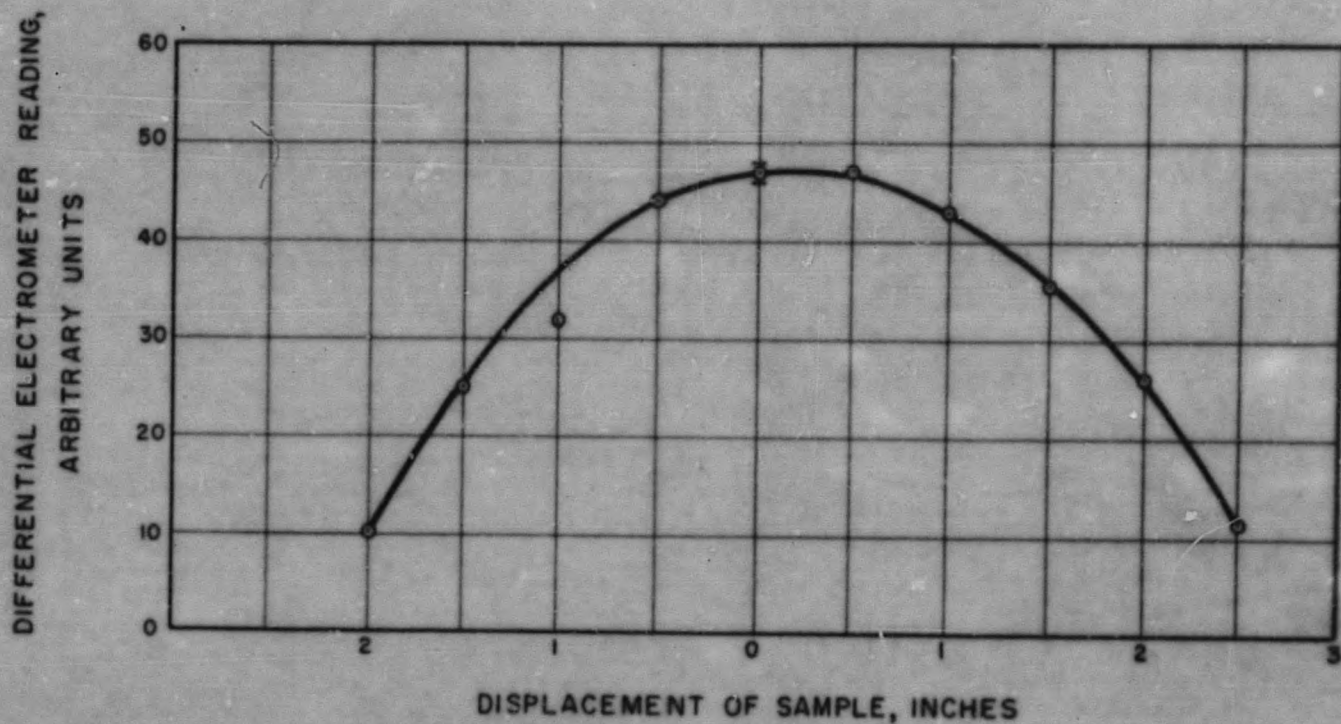
FIGURE 21

EFFECT OF DISPLACING SAMPLE FROM
THE CENTER OF THE CORE

-44- -45-

FIGURE 23

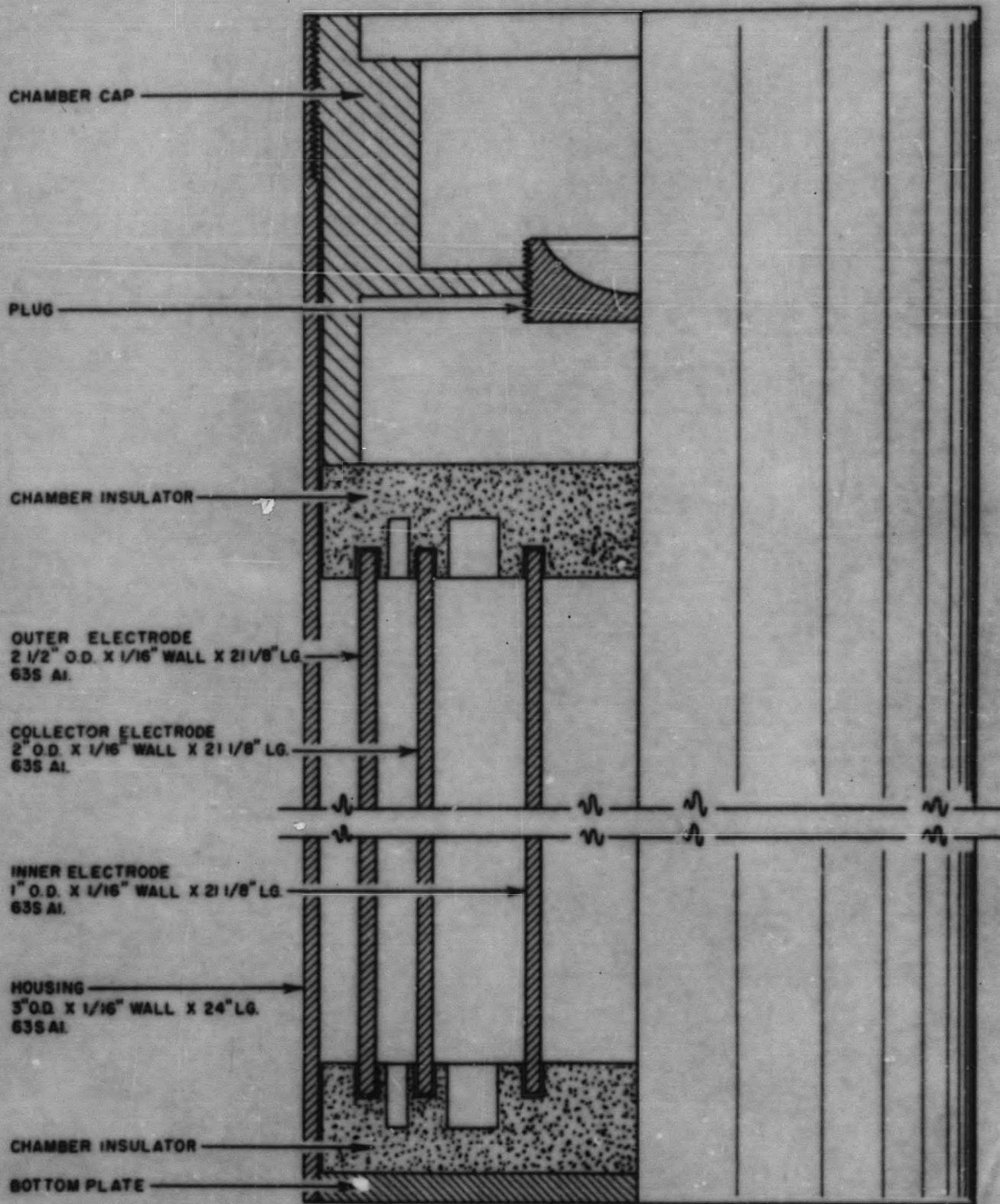CALIBRATION FOR NATURAL URANIUM SLUGS

FIGURE 33

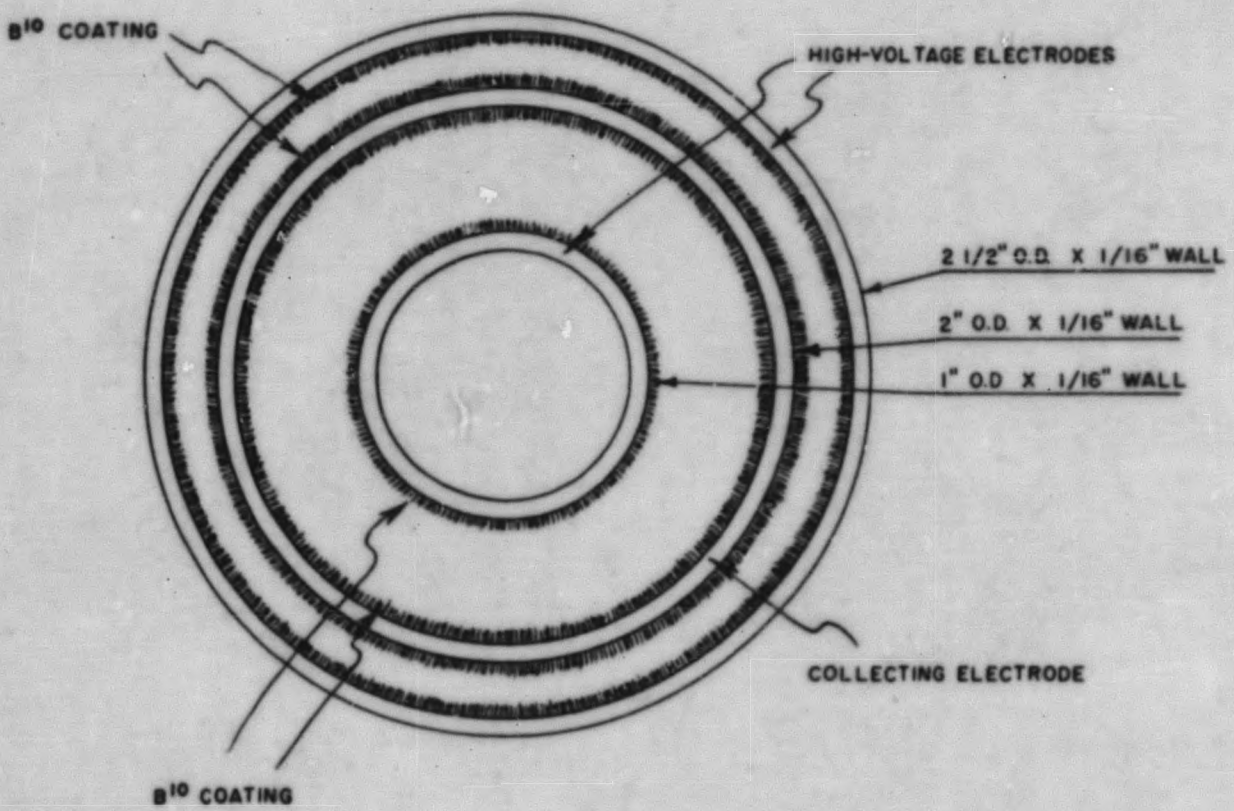CHAMBER CAP

PLUG

CHAMBER INSULATOR

OUTER ELECTRODE
2 1/2" O.D. X 1/16" WALL X 21 1/8" LG.
63S Al.

COLLECTOR ELECTRODE
2" O.D. X 1/16" WALL X 21 1/8" LG.
63S Al.

INNER ELECTRODE
1" O.D. X 1/16" WALL X 21 1/8" LG.
63S Al.

HOUSING
3" O.D. X 1/16" WALL X 24" LG.
63S Al.

CHAMBER INSULATOR

BOTTOM PLATE

NEUTRON—SENSITIVE ION CHAMBER

FIGURE 34

B^{10} COATING

HIGH-VOLTAGE ELECTRODES

2 1/2" O.D. X 1/16" WALL

2" O.D. X 1/16" WALL

1" O.D. X 1/16" WALL

B^{10} COATING
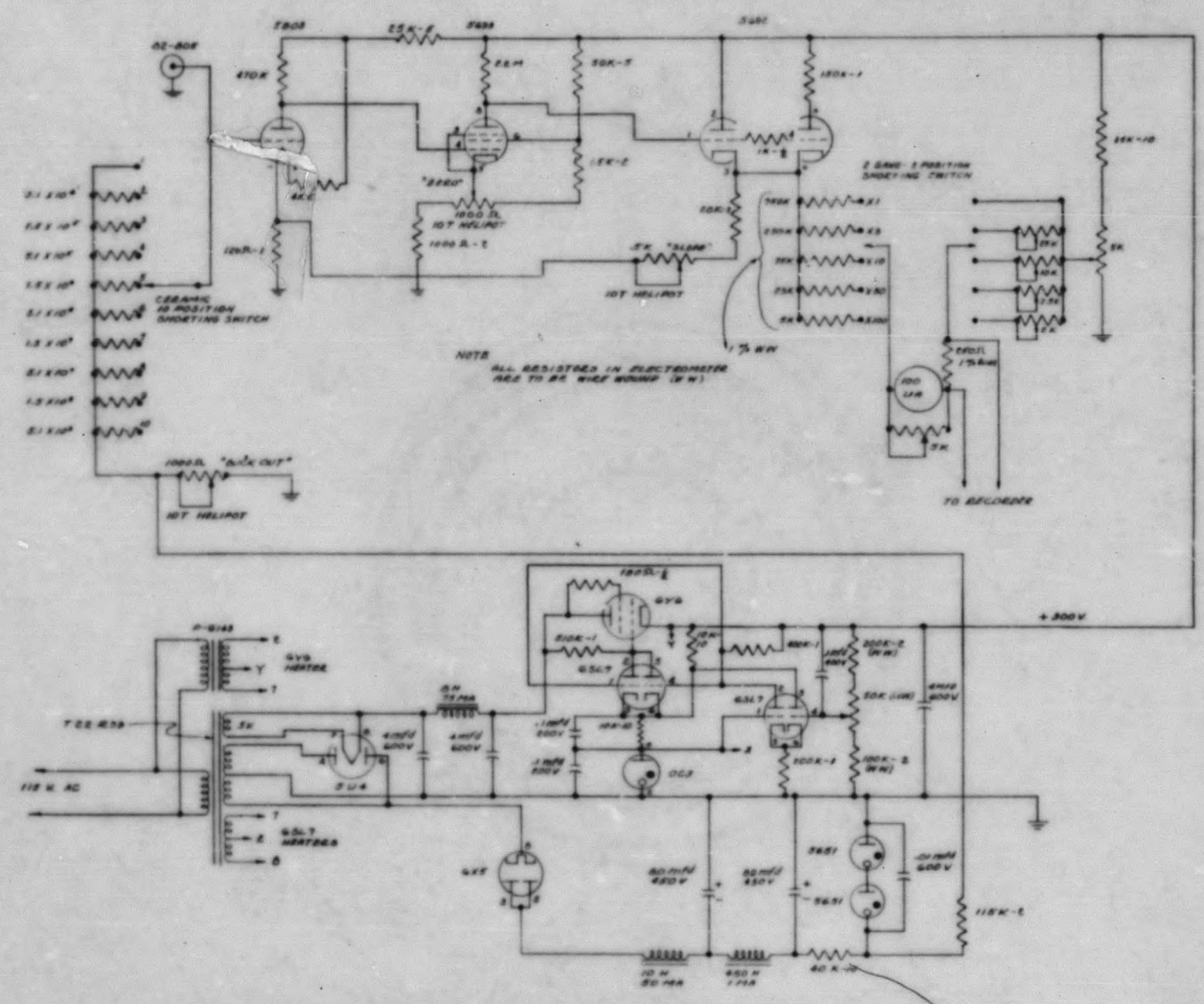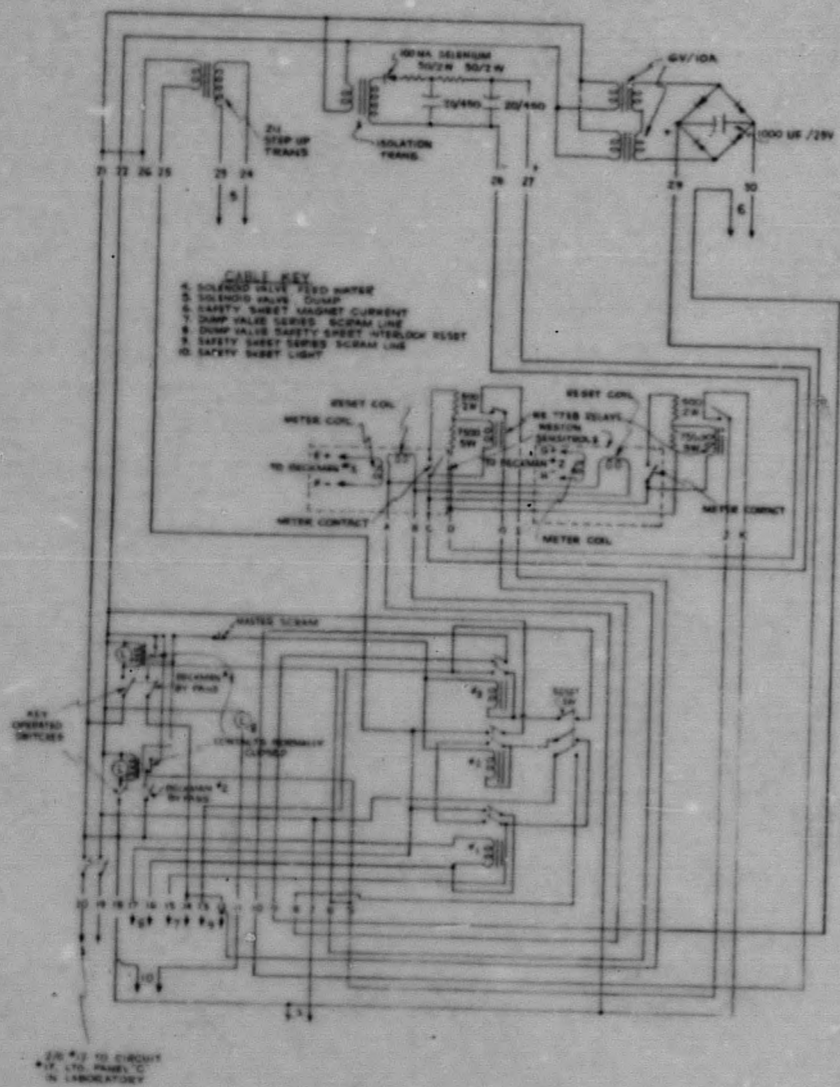
COLLECTING ELECTRODE

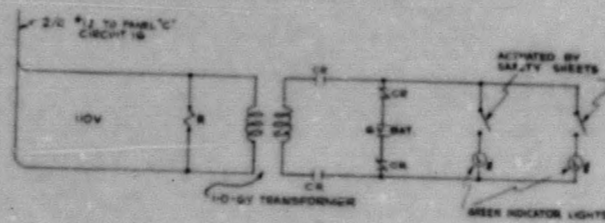## CROSS SECTION OF ION CHAMBER

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SCHEMATIC DIAGRAM OF THE DIFFERENTIAL ELECTROMETER

FIGURE 35

CONTROL CIRCUIT

FIGURE 36

NTO SAFETY SHEET "DOWN" INDICATOR LIGHT CIRCUIT

END