Columbia University
in the City of New York

LAMONT GEOLOGICAL OBSERVATORY
PALISADES, NEW YORK

Technical Report No. 1

CU-56-1-N6 ONR 266-37-Geol.

A Water Displacement Meter for Measuring the Maximum Size of an Underwater Explosion Gas Bubble

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A WATER DISPLACEMENT METER FOR MEASURING THE MAXIMUM SIZE OF AN UNDERWATER EXPLOSION GAS BUBBLE

by

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G. R. Hamilton

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December 1956

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I. 0 INTRODUCTION

It has long been desirable to study directly the so-called oscillating gas bubble of full scale underwater explosions. Compared with the rapid outgoing shock wave the gas bubble is a slow and localized phenomenon. The problem of studying the gas bubble really has been to develop a method utilizing equipment capable of surviving the shock wave.

Of particular interest is the maximum diameter of the first bubble expansion. This is directly related to the total energy associated with the gas bubble which when added to the easily measured shock wave energy gives the total energy release of the explosion. The division of the explosive energy between shock wave and bubble is of particular interest with respect to new types of explosives.

This report describes an instrument that makes direct measurement of the first underwater explosion bubble expansion for large depth charges. To do this the instrument records the flow of water away from the explosion during the bubble expansion by photographing oil droplets in the water relative to a reference sphere.

2.0 APPROXIMATE THEORY

A complete discussion of underwater explosion phenomena may be found in Cole, 1948. A more detailed exposition of underwater explosion bubble phenomena will be found in The Gas Globe, 1950, by various authors.

The energy of an underwater explosion divides between the rapidly expanding shock wave and energy transferred to the surrounding water by the impact of the shock wave as it passes. The latter effect causes a radial outward flow of water that, because of the momentum received, continues long after the shock wave passage. An approximately spherical bubble is formed containing water vapor and gaseous explosion products. At maximum size the internal gas pressure of the bubble is far below the hydrostatic pressure of the surrounding water. The explosion energy associated with the internal gas at that moment is negligible compared with that stored as potential energy in the displaced water. The bubble energy may therefore be expressed (Cole, 1948, p. 275):

$$\text{Total bubble energy} = Y = 4/3\, A^3_{max}\, Po$$

where Po = total hydrostatic pressure (water + atmospheric)

A_{max} = maximum bubble radius

For TNT the energy associated with the first bubble expansion is 41% (Cole, 1948, p. 283) of the total chemical energy available, the shock wave receiving the remaining 59%.

During the final phase of the bubble collapse that follows, the internal gases are highly compressed, resulting in the emission of a second shock wave or bubble pulse followed by a second bubble expansion. Simultaneously during the collapse the bubble will migrate toward the surface or toward a nearby object.

In this report we are interested primarily in measuring the maximum size of the explosion bubble and thereby the total energy associated with the bubble. Assuming free field radial flow the total displacement Δ of the water at a range R from the explosion is given by:

$$\Delta = \frac{A^3 max}{3R^2}$$

and therefore Y is given by

$$Y = 4\pi R^2 \Delta Po$$

Typical values of Δ under various conditions are:

Charge wt., W cast TNT lbs.	Charge Depth D ft.	1st bubble period seconds	Amax feet	R feet	Δ feet	Shock wave peak pressure PSI
3	40	0.18	4.6	8	0.50	3600
	150	0.08	3.4	8	0.20	3600
300	40	0.81	21.3	60	0.89	1800
	150	0.38	15.7	60	0.36	1800
	600	0.13	10.4	60	0.10	1800

Δ was calculated assuming TNT has 41% of 1080 calories/gram available for bubble phenomena (Cole, 1948, p. 284). For convenient calculations this may be expressed as

$$Amax = \left(\frac{2340}{D+33}\right)^{1/3}$$

The first bubble period is calculated for cast TNT from (Cole, 1948, p. 282):

$$T = \frac{4.36\, W^{1/3}}{(D+33)^{5/6}}$$

The shock wave peak pressure is based on the data in Cole, 1948, p. 240, and is indicative of the compressive strength required in the pressure vessels.

It should be noted that ocean water is seldom found without some velocity gradient in the surface water. For the conditions at Bermuda a velocity differential of 1/4 knot is not unusual. Any measurement of Δ in such a case would therefore be superimposed on a steady current flow of .42 ft/sec. In deep water the shock wave displacement of the water particles for large depth charges also has to be considered.

3.0 METHOD

Δ is measured by suspending in the horizontal plane of the explosion a photographic water displacement meter housed in a spherical casting. Six feet below, oil pump nozzles eject oil droplets which are photographed relative to a 4-inch-diameter high density sphere. The oil droplets being small and of neutral buoyancy move with the sea water. The reference sphere and flow meter housing being very heavy would not move appreciably. Their spherical shape, however, permits calculation of this motion. The flow meter is started a few seconds before the explosion to measure the current flow and to provide exposed film for film test development purposes.

4.0 INSTRUMENTATION

The water displacement meter consists of a cluster of individual pressure cases housed in a two-foot-diameter cast spherical fairing, Fig. 1. All pressure cases and electrical lead-ins have been tested to 10,000 psi in the Lamont Geological Observatory pressure vessel. The cluster of pressure cases shown in Fig. 2 and Fig. 12 consists of a camera case surrounded by 4 cases containing lights, a control case, a rotary pump, a rotary pump battery case and a piston pump. The instrument cluster and its spherical fairing do not have any preferred or required orientation relative to the initial point of explosion.

Tubes run from the oil pumps down to ejection nozzles in a plane six feet below the camera lens. One foot below this oil droplet ejection plane the photographic reference sphere is suspended by a 1/16-in. OD wire rope from the instrument cluster.

The water displacement meter was designed as a self-contained battery-operated unit. Electrical connections to the surface are primarily to start the unit. These electrical connections are also used to stop the equipment and permit a precise method of recording the camera speed at the surface. In the event of failure in these electrical leads after the equipment is started, film and batteries have a life of about 2 minutes.

Every effort was made in design of the equipment to improve the one-shot reliability. All operating functions are compartmentalized in separate pressure cases as much as possible. Four self-contained mutually independent lights are used. Two independent, different type oil pumps are used. All electrical circuits are run ungrounded so that a ground on one side does no harm. A ground on one light circuit does not affect the other three. An electrical cable to the surface is required only to start the equipment. The control case with 16 electrical lead-ins is most susceptible to sea-water leakage. It may be filled with transformer oil for critical work.

4.1 BATTERIES

In a rugged, compact, self-contained unit such as this water displacement meter the batteries are the heart of the entire unit. To make the battery problem even more difficult, we wanted to be able to use the unit in cold water, i.e. 40°F. Two types are principally used.

Standard Photoflash Drycells. These are available in a variety of sizes and have good low temperature characteristics at current drains up to 1 ampere for a few minutes. These are nominally 1.5 volts per cell. Mercury cells are definitely not suitable at such current drains for low temperature work. The photoflash dry cells were used for relay operation and to drive the camera and timing motors. Typically 28 size C cells in series provided 30 volts at one ampere at 40°F. These cells were soft-soldered together, then bound into appropriately-shaped battery bundles with Scotch #33 electrical tape. Spare units made up beforehand permitted easy replacement in the field.

Willard NT6 Lead Acid Battery: This is a small 6-volt storage battery rated at 10 amps for 9 minutes at 40°F. They cost about $5 each. Two are used in series to provide power for each lamp case and for the rotary pump. Typically for the lamps such a battery bank would supply at 40° a current of 16 amps at 10 volts dropping to 6 volts in two minutes. They may be recharged at .4 amps and used in any position. They are in non-spill cases 3.11/32" x 1.13/16" x 2.3/8", with two pigtail leads.

4.2 ELECTRICAL COMPONENTS

Pressure Case Electrical Lead-Ins: We employed the standard spark plug shown in Fig. 13, used at Lamont Geological Observatory for the past ten years on deep sea cameras. A miniature version was used on the control pressure case where many were needed and space was limited. After ten explosion tests with this equipment the lucite insulators began to fail by cracking. In the future we expect to use something of this type:

> Stupakoff Ceramic & Manuf. Co., Latrobe, Pa.
> single standard terminals #95.0016
>
> Fusite Corp., Cincinnati, Ohio single-feed-thru
> t erminals, #104TB series.

These are glass-insulated lead-thru terminals such as are used on transformer cans. We have tested the Stupakoff units to 10,000 psi; they require a 1/4" accurately reamed hole. Scripps Institution of Oceanography has successfully used the Fusite terminals for deep sea work. These have a simpler pipe thread installation.

External Wiring: Standard 5000-volt flexible, rubber-insulated, test prod wire such as Belden #8899 is used for the electrical wiring exposed to sea water between pressure cases. Spark plug connections are taped with Simplex ANHYDREX-X X splicing compound. Sea water grounds on such wiring are practically unknown.

Quick Disconnect Lugs: For convenience in quickly changing relay units, batteries and light bulbs AMP solderless terminals are used inside the pressure cases. These terminals, manufactured by Aircraft-Marine Products Co., hook together permitting rapid electrical connections to be made without the use of terminal strips or solder connections. A piece of electronic spaghetti or rubber tape serves to insulate them from accidental grounds.

Control Relays: Potter and Brumfield MH 17 D miniature telephone relays are used for most relay purposes. These are 4 PDT relays with 5 ampere contacts.

Support Cables: For tests with charges deep in the water a U. S. Steel cable is used that provides a combined support wire and electrical conductors in one cable. Type 3HI has an .182" OD and a breaking strength of 2700 pounds. It consists of two layers of steel armor oppositely wound over three small electrical conductors. Similar cable is used by Navy blimps for dunking sonars. It requires a special end connector manufactured by Telephonics Corp., Park Ave., Huntington, Long Island, N. Y., costing about $120. In shallow water work a wire rope and separate electrical cables are used.

4.3 CAMERA UNIT

4.3.1 CAMERA

The camera is a modified AN-N6 aircraft 16 mm movie gun camera with a 28-volt DC electric motor drive (Fig. 3). The camera uses a standard 50-ft. daylight loading magazine available in SUPER XX. We hand-load TRI X film. Three film speeds (16, 32 and 64 frames per second) are available. The shutter is the revolving type and is open for approximately 170° of the revolution. A lens opening F/4 is used with the lights described below at 64 fps. During bright Bermuda sunlight at depths to 60 feet the lights were not needed with F/8-11 at 64 fps.

The camera was modified by removing the timer that limits the running time of the camera for aircraft gun use. The timer's drive shaft, which operates directly from the camera drive motor, was used to drive a miniature microswitch to indicate camera speed for timing purposes. The cam used to drive the microswitch was made from a small 12-tooth brass gear by removing 8 of the teeth. The four remaining teeth are evenly spaced to produce 4 pulses per revolution of the drive shaft or one pulse per 6 film frames at 64 frames per second. These are recorded topside.

The original 35 mm focal lengths lens was replaced with a 16-mm-wide angle lens to increase the field of view from 12" x 16" to 24" x 30" at an object distance of 6 ft. Since the lens mount for the AN-N6 gun camera is not standard, a 16-mm focus, f/1.9, coated, Schneider Xenon lens in a focusing mount was made for the camera by Burke and James, Inc. of Chicago; the cost was $100 each. The resolution of this lens is more than adequate to resolve the 1/8" diameter drops at an underwater object distance of 6 ft. The camera focus settings used in water of course are decreased by 1/4 from those marked on the lens for use in air due to the increased refractive index of the water.

As a means of putting time directly on the films, two small NE-2 neon bulbs were mounted over number 80 wire drill holes drilled through the bottom of the camera and the edge of the film magazine. The flashes from the two produce either a spot or a streak on the edge of the film, depending on whether the film is stationary or in motion. It is possible for the film to be both stationary and moving during the time the light is flashed, in which case both a spot and a streak are produced.

4.3.2 CHRONOMETRIC TIMING MOTOR

As a means of providing good self-contained time in the camera case a Haydon 5800 series, 60 rpm, precision D. C. timing motor with a chronometer governor was included in the camera case. The chronometric timing motor has an accuracy of one part in a thousand and is used to close a miniature microswitch which flashed one of the neon bulbs on the bottom of the camera at the rate of 10 times per second. Power requirements are 250 MA at 20-30 volts. They cost about $100 each.

4.3.3 BATTERY PACKS

The camera and timing motor are powered from the same battery pack which is made by connecting 28 size "C" photo-flash cells in series. This battery pack has a normal no-load voltage of 42 volts which drops to approximately 30 volts under starting and full load conditions of 1 ampere. This battery is made of two stacks of 14 cells taped together, as shown in Fig. 3.

The battery to supply the high voltage for the neon lights is made by connecting 7-30 volt Eveready Mini-max No. 507E batteries in series. This battery pack is taped to the camera (Fig. 3) to use the void space between the rectangular camera and the cylindrical pressure case.

The battery pack to supply power for the control relays in the camera pressure case is made by connecting 7 size "C" photo-flash batteries in series. A similar battery is used to supply power to actuate the explosive motor for the piston pump from a relay closure in the camera pressure case. These two batteries are packaged as a single 14-cell unit.

4.3.4 CAMERA UNIT CIRCUIT

The camera unit circuit (Fig. 4) functioned in the following manner: a 10.5-volt pulse is received from the control case between the two spark plugs labelled control case with the polarity shown. The pulse starts to close the top 6-volt relay and at the same time charges the 200-MFD, 12 VDC electrolytic condenser whose charge completes the relay closure. The closure of this relay switches the control relay battery across its winding, holding it closed; closes the second 6-volt relay, and fires the piston pump. The second 6-volt relay turns on the camera, timing motor, neon lights, and connects the camera drive motor speed signal lead to the control case where it is connected to a surface wire.

The circuit provides three independent ways of timing the speed of the camera. The microswitch that is driven by the camera motor sends pulses to the control case between the spark plug marked signal and ground. These signals are sent from the control case to the recording unit at the surface. Timing signals from the surface are sent down the same cable with reversed polarity which actuates the sensitive 78 S sigma relay, which in turn flashes one of the neon lamps. The other neon lamp is flashed at the rate of 10 times per second by the microswitch driven by the chronometric D.C. timing motor and serves as the primary means of timing the camera speed.

The operation of the camera is stopped by applying minus 24 volts between the positive starting lead from the control case and ground. This closes the 24-volt relay which opens the power circuit to the 6-volt control relays.

4.4 LIGHTS

One of the difficult problems to solve in designing the water displacement meter was to provide lights for the movie camera. They had to be self-contained, bright, shock-proof, fit into a limited space and be pressure-proof. Of the many suggestions received and explored, an over-voltaged automobile lamp proved best capable of meeting the requirements. Over-voltaging a tungsten lamp increases the efficiency of the bulb but at the same time the life is shortened considerably. For this application the life could be as short as two minutes (the length of time required for a 50-ft. film magazine to run through the camera at a speed of 16 frames per second).

Each light consists of 7 Eveready #209 automobile lamps . connected in parallel (Fig. 5) . The lamps are rated at 15 cp each at 6-8 volts and are over-voltaged from 25 to 40 percent to give a total light output for each light, approximately 800 cp. The power required for each light is 165 watts, which is furnished by 2 type NT6 Willard storage batteries in series. Experience is required on the degree of battery charge to be used with this combination of over-voltaged light bulbs and storage battery to keep from burning out the lights when voltage is first applied. With a "hot" battery the lights will burn out at 60^{o}F but not at 40^{o}F. A small trickle charger (Fig. 6) is used to charge the NT6 batteries in series.

4.4.1 LIGHT CIRCUIT

The circuit of the light units, Fig. 7, operates as follows: a switch closure in the control case closes the 6-volt relay with power from the two NT6 storage cells through the two contacts on the 24-volt D. C. relay. One set of contacts of this relay is used to hold the relay closed and the other three contacts are used to apply power to the lamps. The light is turned off by applying 24 volts negative pulse between the positive spark plug and ground which closes the 24-volt relay and opens the power circuit to the 6-volt relay.

4.5 CONTROL UNIT

The function of the control unit, Fig. 8, is to turn on and off the other units of the instrument cluster when electrical pulses are received from the surface.

The circuit of the control unit (Fig. 9) functions as follows. A positive 30-volt pulse is applied between the surface start spark plug and ground which closes the sensitive 200 S sigma relay, starting the sequence of operations. In the event the signal cable is partially shorted to ground, a negative 270-volt pulse can be applied between the surface-start spark plug and ground to start the sequence of operations by closing the sensitive 10,000 S sigma relay. In normal use both pulses are applied in sequence. The IN34 rectifier is in series with the coil of the 200 S sigma relay to prevent it from shorting the 10,000 S relay. The closure of either of these relays closes the power circuit to the 6 volt relay. In turn the top 6 volt relay closes the power circuit to the middle 6 volt relay, which closes the power circuit to the bottom 6 volt relay. The 6 volt relays are operated in this sequence to reduce the current drain on the batteries. The three 6 volt relays turn on all the equipment; 10.5 volt pulses are sent to the camera and rotary pump battery units, making a switch closure for each of the 4 light units, and transferring the surface start cable to the signal lead from the camera unit.

To stop the operation of the instrument cluster units, 24 volts D. C. is applied between the "surface stop" spark plug and ground with the ground being positive. This closes the 24 volt relays, which opens the power circuits of the 6 volt holding relays.

4. 5. 1 CONTROL UNIT BATTERY PACKS

The control unit has two battery packs of 10. 5 volts each that are made by soldering 7 size "C" photoflash batteries in series (Fig. 8). The pack is formed by standing 6 cells in a circle with one in the center. The battery pack is insulated with a covering of black Scotch electric tape. Standard size "C" cells cannot be used as the diameter of the pack when finished is about 1/16" larger than the 3" inside diameter of the pressure case.

4. 6 ROTARY PUMP

A gear-type fuel pump driven by a 12 volt D. C. motor is the nucleus of the rotary pump (Fig. 12). This is a surplus pump originally manufactured by Thompson Products, Cleveland, Ohio. The D. C. motor is immersed in a General Electric No. 10C transformer oil. A diaphragm provides hydrostatic compensation and eliminates the necessity of high pressure seals in the output shaft. The pump delivers 3 gallons per hour at 100 psi. The drop liquid reservoir is also provided with hydrostatic compensation.

The pump effectively operates from hydrostatic pressure to 100 psi above hydrostatic pressure at the pump outlet.

4.6.1 ROTARY PUMP BATTERY UNIT

The D. C. motor is powered by two Willard NT6 batteries in a separate pressure case (Fig. 10). The circuit of the rotary pump (Fig. 11) operates as follows: a 10.5 volt pulse is received from the control unit between the two spark plugs labelled control case with the polarity shown. This pulse starts to close the 6 volt relay and at the same time charges the 200 MFD, 12 volt condenser whose charge completes the relay closure applying power to the D. C. motor through the two spark plugs labelled pump. The pump is stopped by applying a 24 volt pulse to the spark plug marked plus and ground closing the 24 volt relay, which opens the power circuit of the 6 volt relay.

4.7 PISTON PUMP

A double-acting surplus hydraulic cylinder is the nucleus of the piston pump. This cylinder has a 2" bore and a 6" stroke of which 1/4 of the stroke is used. Power is provided by three gasoline engine valve springs placed inside the cylinder around the piston rod. The unit is cocked by pumping the oil drops liquid into the cylinder with a hydraulic hand pump, compressing the springs until an external latch mechanism on the piston shaft is set. The latch is released by a small two volt explosive motor. Once cocked, the latching mechanism holds the springs under tension, permitting the oil droplet fluid to compensate hydrostatically through the oil line. Our latch mechanism is not yet sufficiently reliable on this pump. It has a tendency to jar loose, spraying the surroundings, while the instrument cluster is being loaded or the displacement meter is being hoisted over the side.

The explosive motors used to trip the latch are manufactured by Hercules Powder Co. They provide 1/16" motion at a precise time for applications such as electrically operating a standard stop watch. Our tests in a pressure vessel indicate they operate satisfactorily at 2000 psi.

4.8 PUMP LINES

Several methods of piping the oil down to the plane where the drops are photographed were tried. The method that works best is to pipe oil down with 1/4" flexible high pressure hydraulic tubing to a triple outlet nozzle. Rigid tubing and less durable flexible tubing are often damaged when putting the gear into the water.

4.9 DROP LIQUID

The liquid for making the drops is a non-drying neutrally buoyant white paint, titanium oxide and mineral oil with a copper resinate added to keep the solution in suspension. The liquid was specially developed for the purpose by Dr. Peter King's group at the Naval Research Laboratory, Washington, D. C.

4.10 REFERENCE SPHERE

A small reference sphere of 4-in. diameter is suspended 7 ft. below the instrument cluster with 1/16-in. stainless steel wire rope. The reference sphere was cast from Hevimet (a tungsten copper alloy of density 18). To preserve the spherical shape, a fiege fitting is countersunk into the sphere to attach the sphere to the wire. The sphere is painted with white refrigerator enamel to increase the contrast between the sphere and the dark background. Two bands of black Scotch electric tape are placed across the top of the sphere perpendicular to each other to serve as a reference axis.

4.11 PRESSURE CASES

The pressure cases, Fig. 12, were bored from Alcoa 2024-T4 solid round aluminum bar stock. This alloy has a minimal compressive yield strength of 46,000 psi (Alcoa, 1955, p. 47). 2014-T6 with a minimal compressive yield strength of 60,000 psi would have been more suitable. The sea water seal on the end cover for these pressure cases is made with a single circular "O" ring. If the manufacturer's specifications are followed with these "O" rings they have never in our experience leaked at pressures to 10,000 psi. The electrical lead-ins are the spark plug type, Fig. 13, described earlier.

The camera pressure case was bored from 6'' OD 2024-T4 stock to have 3/4'' walls. The cover and blank end were 1 1/4'' thick. The formula for the collapse of such thick wall cylinder due to external pressure (Roark, 1954, p. 276) is

$$P = \frac{b^2 - a^2}{2a^2} S$$

where
P = collapse pressure = 10,000 psi

S = compressive yield strength = 46,000 psi

a = inner radius

b = outer radius

The camera window was HERCILITE plate glass 1 inch thick of 2-inch diameter manufactured by Pittsburgh Plate Glass Co. A glass-to-metal seal for the window was made by grinding the window into a recess in the end of the pressure case with a No. 500 grit carborundum. Stop-cock grease was used between the two surfaces to improve the seal. An "O" ring gasket seal would also have been satisfactory.

The pressure case for the lights and rotary pump battery unit were bored from 4-in. bar stock with a wall thickness of 1/2 in., and with ends and covers of 3/4-in. thickness. Such a cylinder has a minimal collapse pressure of 10,000 psi. The windows for the lights are 3 1/2-in. diameter Hercilite plate glass 1 in. thick recessed into the end of the pressure case, with an "O" ring gasket seal.

The case for the rotary pump and rotary pump reservoir is made from a short piece of standard Alcoa 6063-T5 aluminum pipe with a bulkhead between the rotary pump and the drop liquid reservoir. Flexible diaphragms on each end of the pipe provided hydrostatic compensation for the reservoir and rotary pump.

We discussed with Dr. Paul Fye at NOL how strong the pressure cases should be to withstand the momentary peak shock wave pressure. He expressed the idea, on a rule of thumb basis from his WHOI experience, that failure would occur at a static pressure equal to peak shock wave pressure plus hydrostatic pressure due to the operating depth.

4.12 INSTRUMENT CLUSTER FAIRING

Two of the spherical fairings for the instrument cluster were cast from aluminum and one from cast-iron. A cover with openings for the lights and camera lens was designed to fit over the instrument cavity. It was made by hammering to shape a sheet of 1/8" thick soft aluminum using the casting itself as a die.

The aluminum fairings are the ones used most frequently because of the difficulty in handling the additional weight of the cast-iron sphere. The spheres are very hard to handle because of their shape. An angle-iron frame was designed to hold the fairing when on deck (Figs. 1 & 2), and as the basis of a shipping crate. Two 1-in. bolts served as a hinge for rotating the fairing in this frame.

The instrument cluster is set into the fairing and bolted in place, while the spherical fairing is in an upside-down position. The cover shown in Fig. 1 is then placed over the instrument cluster and screwed down; the complete unit can then be rotated in the frame, a lifting strain taken, the 1-in. hinge bolts removed and the entire unit then lifted over the side. The vertical slot in the angle iron frame that may be seen in Figs. 1 and 2 permits the fairing to be rotated easily while the 3HI cable is connected into the top of the fairing. This is a fairly stiff cable. Reference sphere, oil lines and nozzles are attached and the hinge bolt holes plugged while the unit is held over the side prior to lowering.

5.0 EXPERIMENTAL RESULTS

The water displacement meter has been used to date with a series of small charges at shallow depth. For these tests the water displacement meter was suspended from an oil drum with shock cord. The charge was suspended from an independent float and was horizontally spaced from the meter with a stick. The charge and drop outlet were at the same depth. The results of these tests gave measurements of the maximum bubble size about 10 percent less than the value calculated. An approximate correction for the movement of the water displacement meter with the bubble water flow gave results within a few percent.

Results to date have indicated several difficulties where the equipment must be modified and improved. These troubles and possible improvements are:

5.1 PHOTOGRAPHIC REFERENCE SPHERE

The shock wave deflects the support wire and causes cavitation around it. The deflection causes the hevimet sphere to list and then to bounce as it drops. The cavitation blocks or blurs the field of view. The only feasible solution seems to be to do away with the reference sphere although a shock cord support will be tried before it is abandoned.

5.2 OIL DROPLETS

The forming of the droplets is primarily determined by the size of the nozzle and the velocity of the sea current past the nozzle since the pump output is constant. If the current is slower than expected the drops are large and are shattered by the shock wave into unusable clouds. The radial current flow from the bubble expansion and contraction was sufficient to prevent drop formation during that time. The liquid pumped at that time broke immediately into a fine spray. Small neutral buoyant spheres such as nylon are being investigated as a possible replacement for the oil droplets. These would be stored in similar tubing and ejected by a back pressure generated by the oil pump. Another possibility is the use of high drag vanes of light metal.

5.3 MOTION OF METER DUE TO COUPLING TO SURFACE FLOATS

Surface waves or the shock wave move the surface float and unless the displacement meter is well decoupled it will move as well. In the most successful of our tests the equipment was suspended from a boom alongside a dock.

6. FUTURE PLANS

During the summer of 1957 at Bermuda we expect to carry out additional experimental work with improvements along the lines discussed above. At the same time the theoretical questions involved in the equipment will be investigated more completely.

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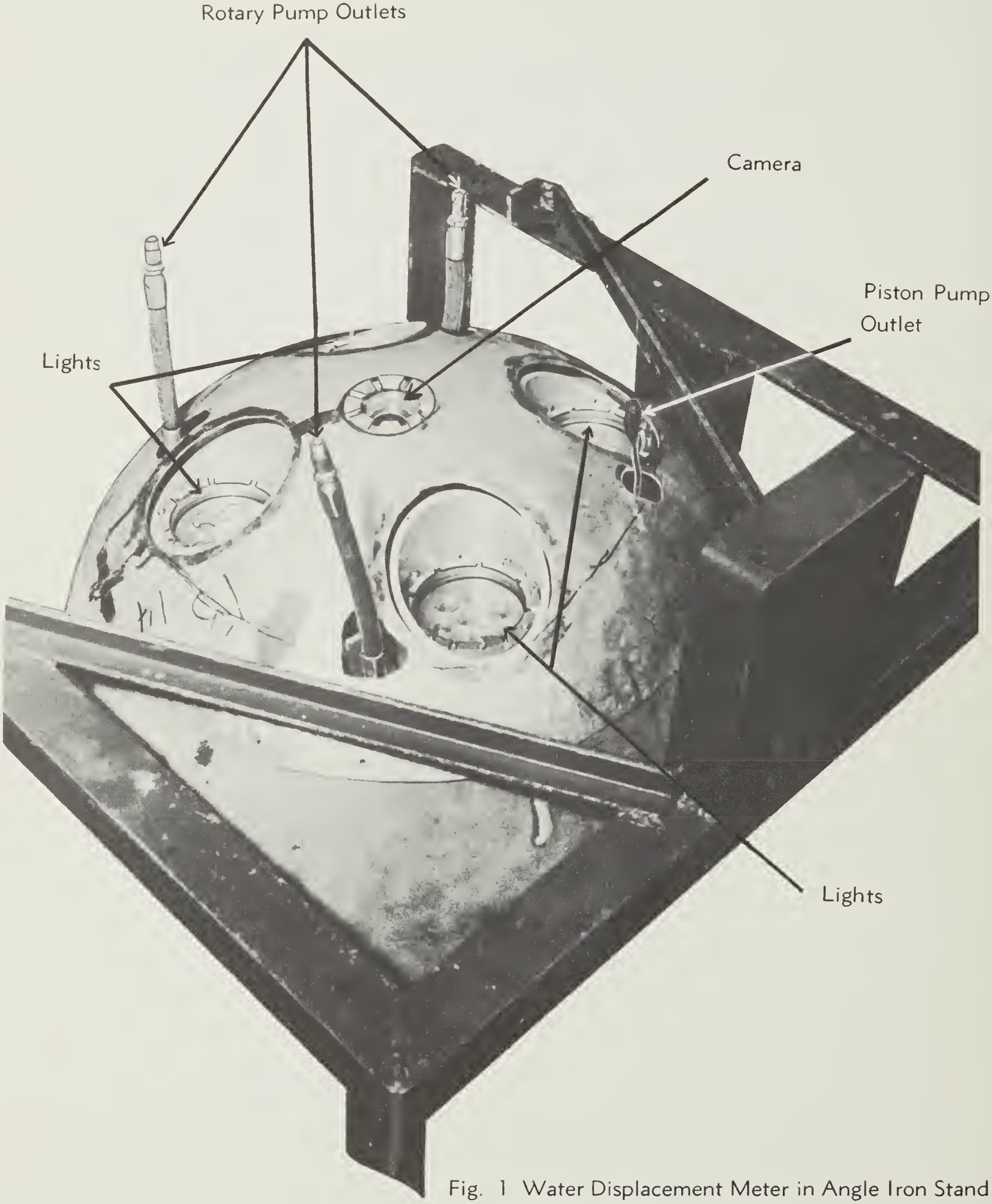

Fig. 1 Water Displacement Meter in Angle Iron Stand
Cover in Place

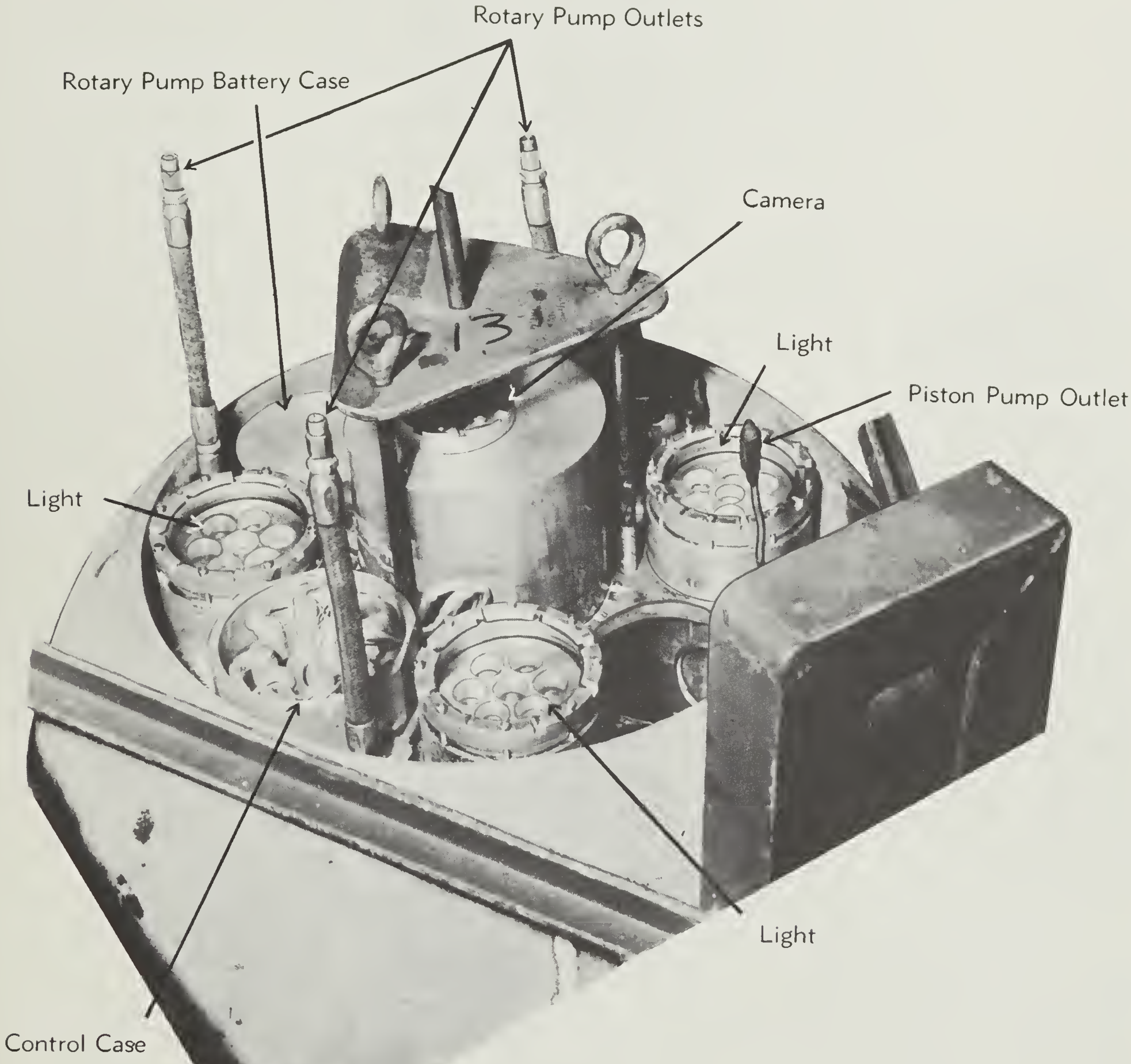

Fig. 2 Water Displacement Meter in Angle Iron Stand, Cover Removed

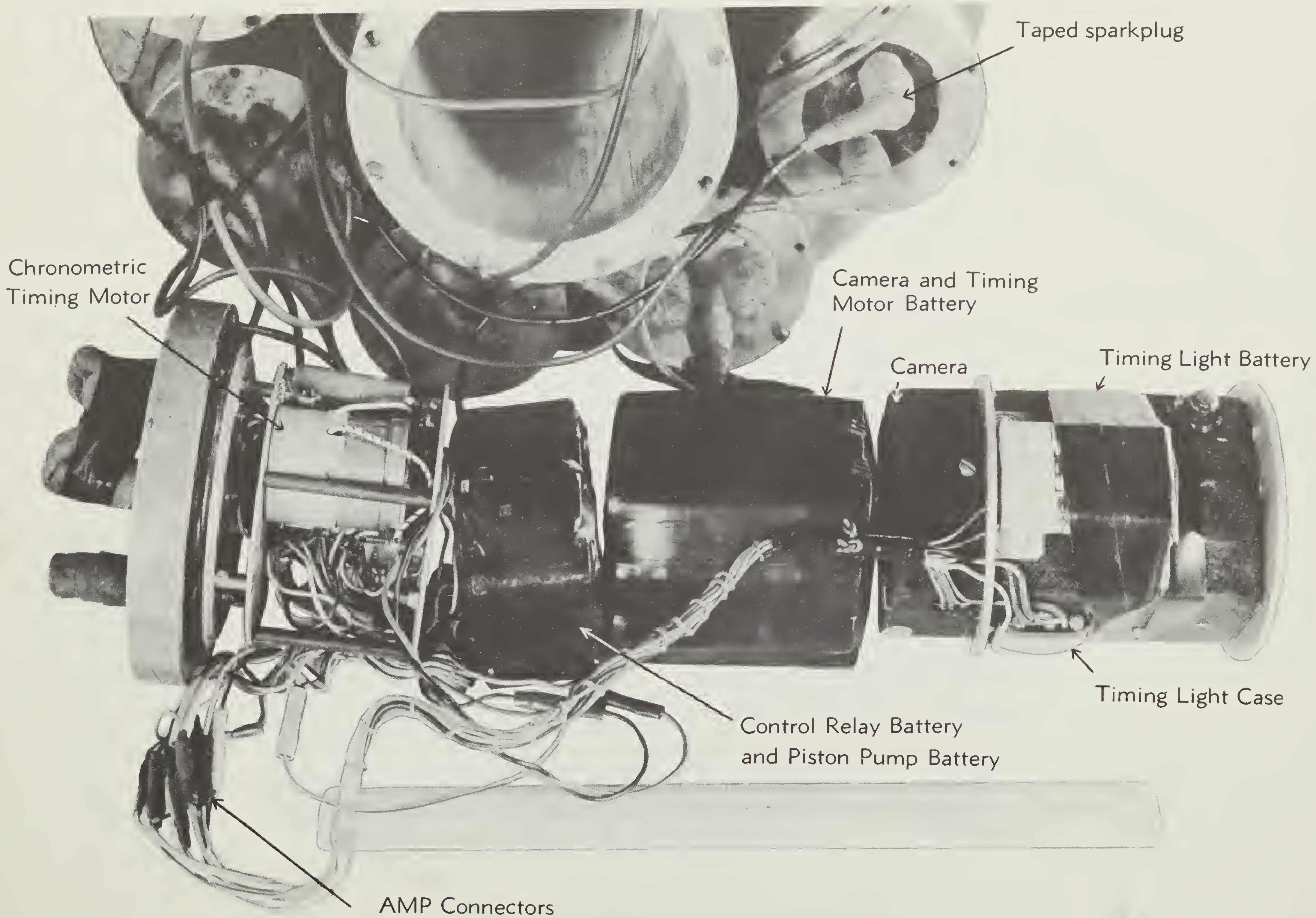

Fig. 3 Camera Unit

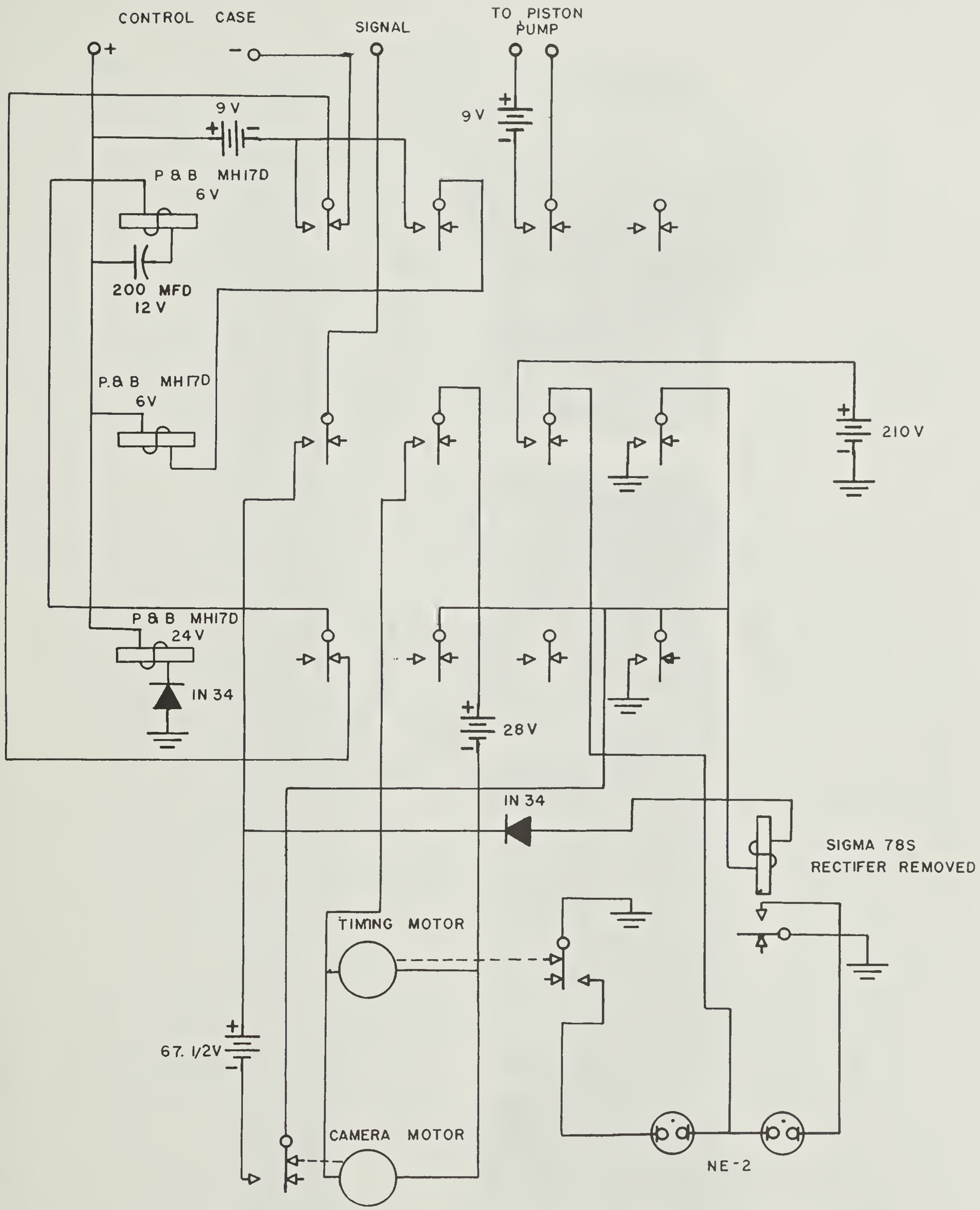

FIG. 4. CAMERA CASE CIRCUIT

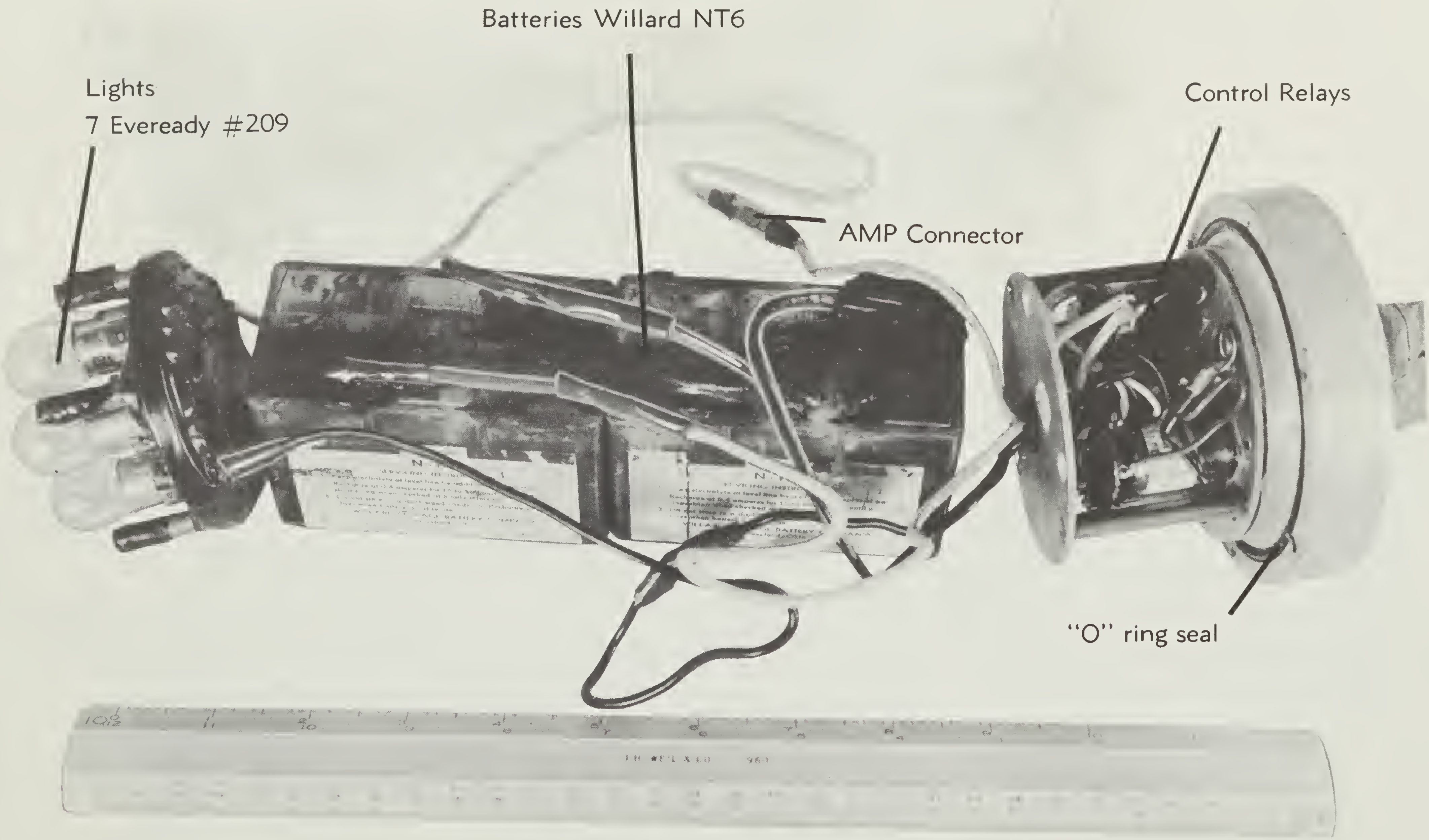

Fig. 5 Light Unit

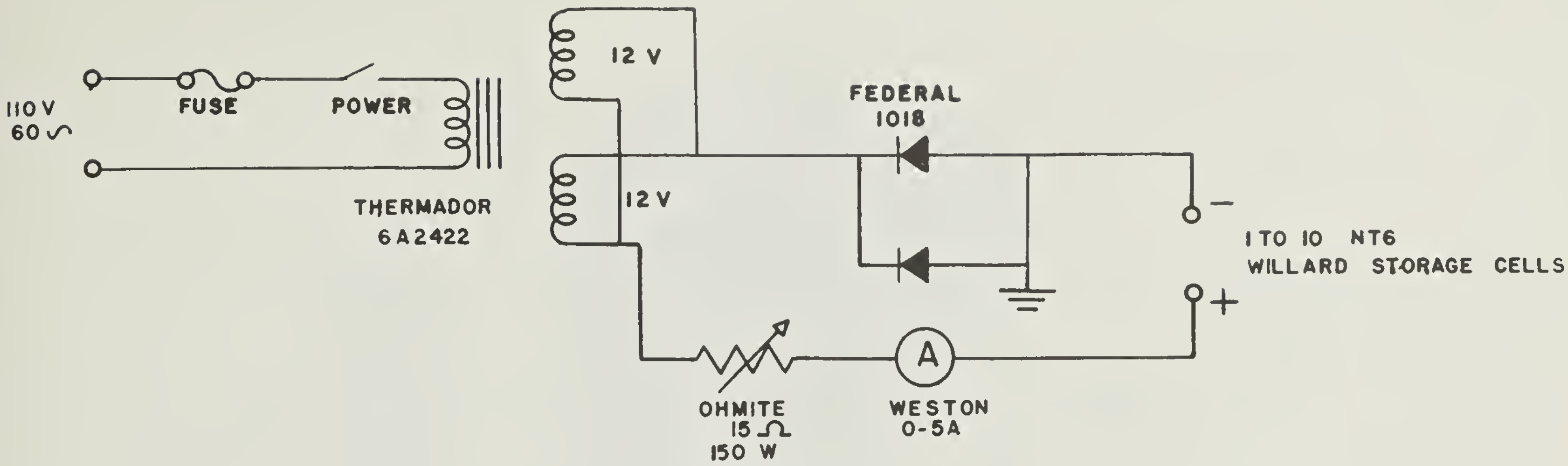

FIG. 6 BATTERY CHARGER CIRCUIT FOR NT6 WILLARD STORAGE CELLS

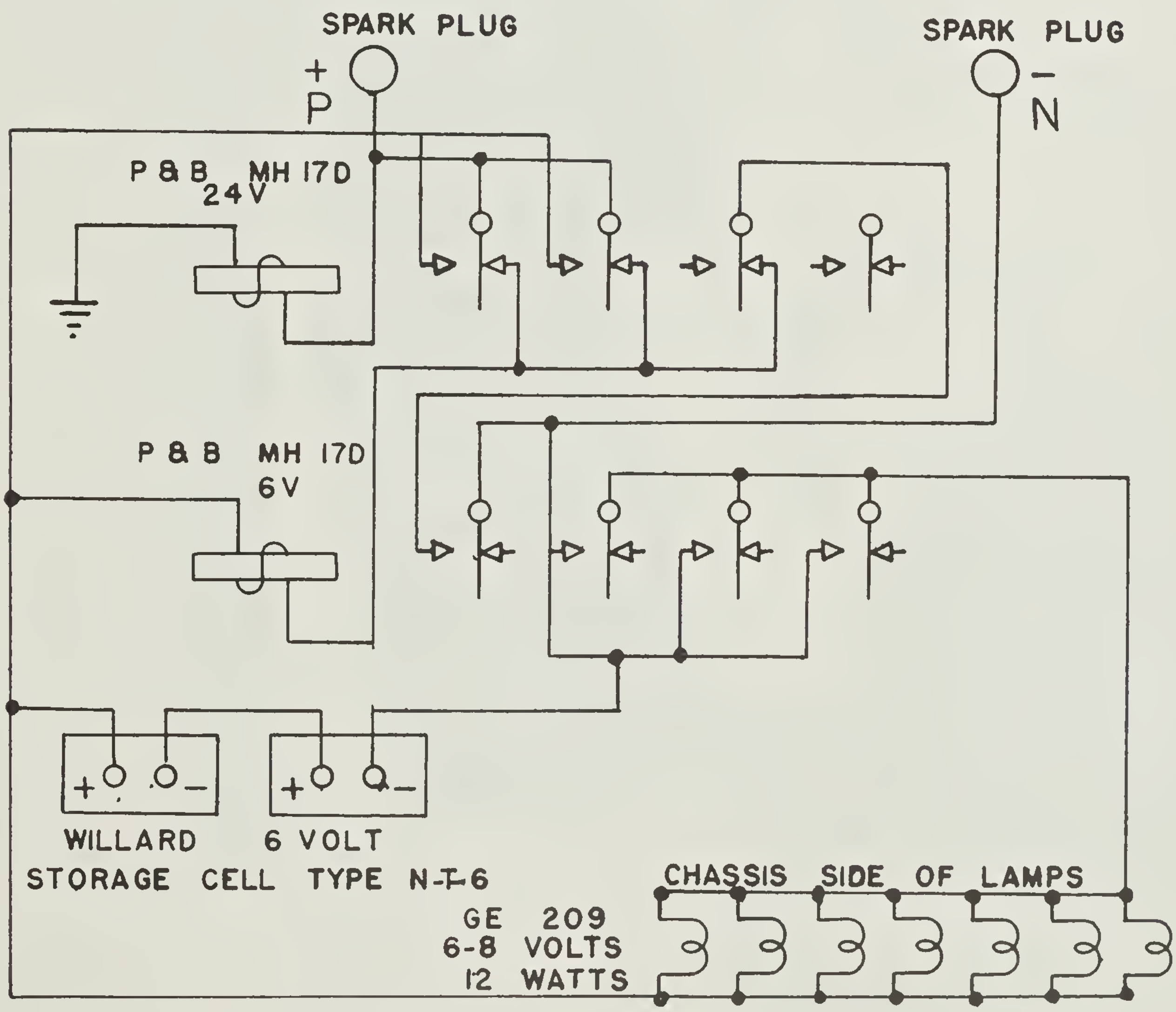

FIG. 7. LIGHT HOUSING CIRCUIT

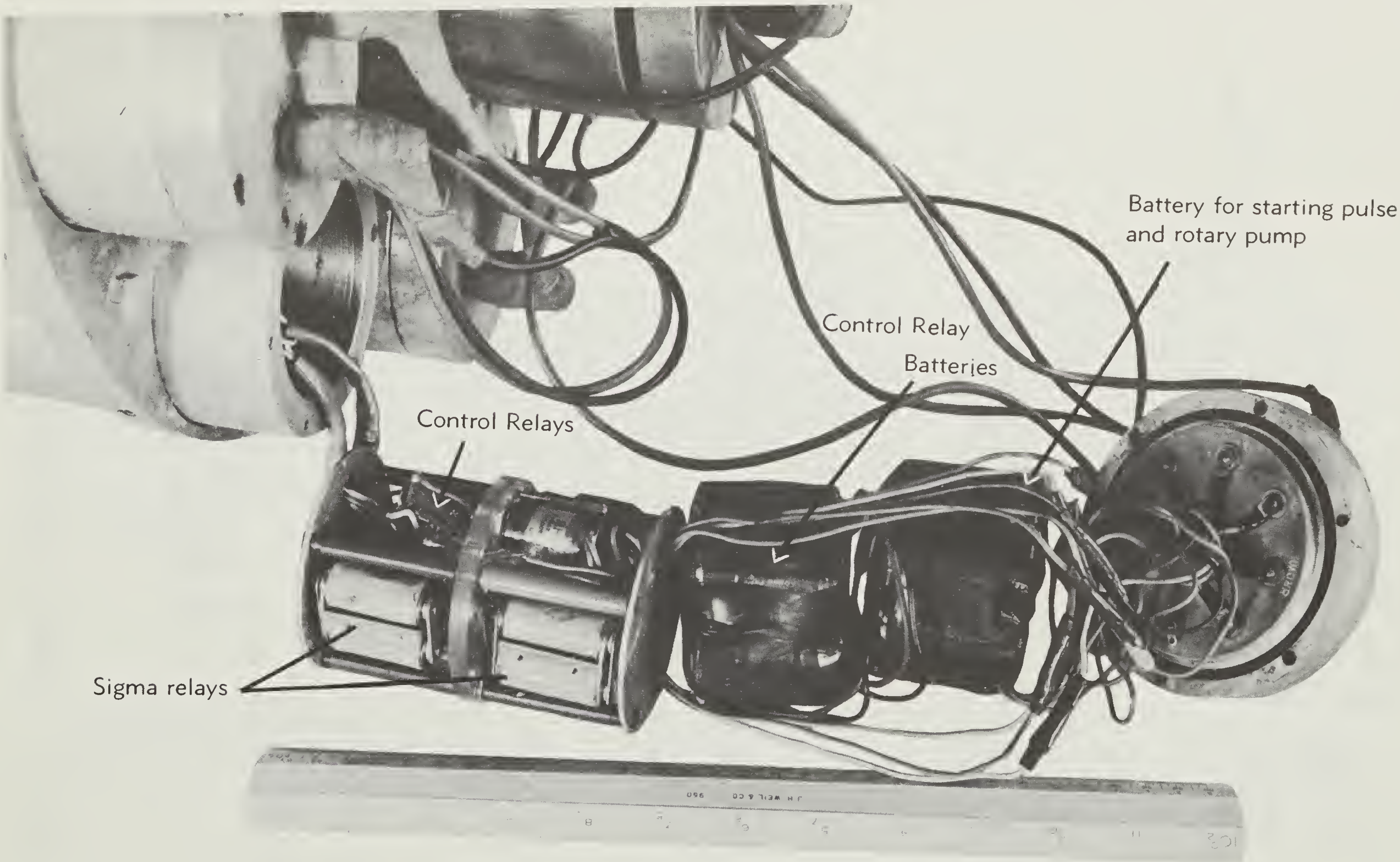

Fig. 8 Control Unit

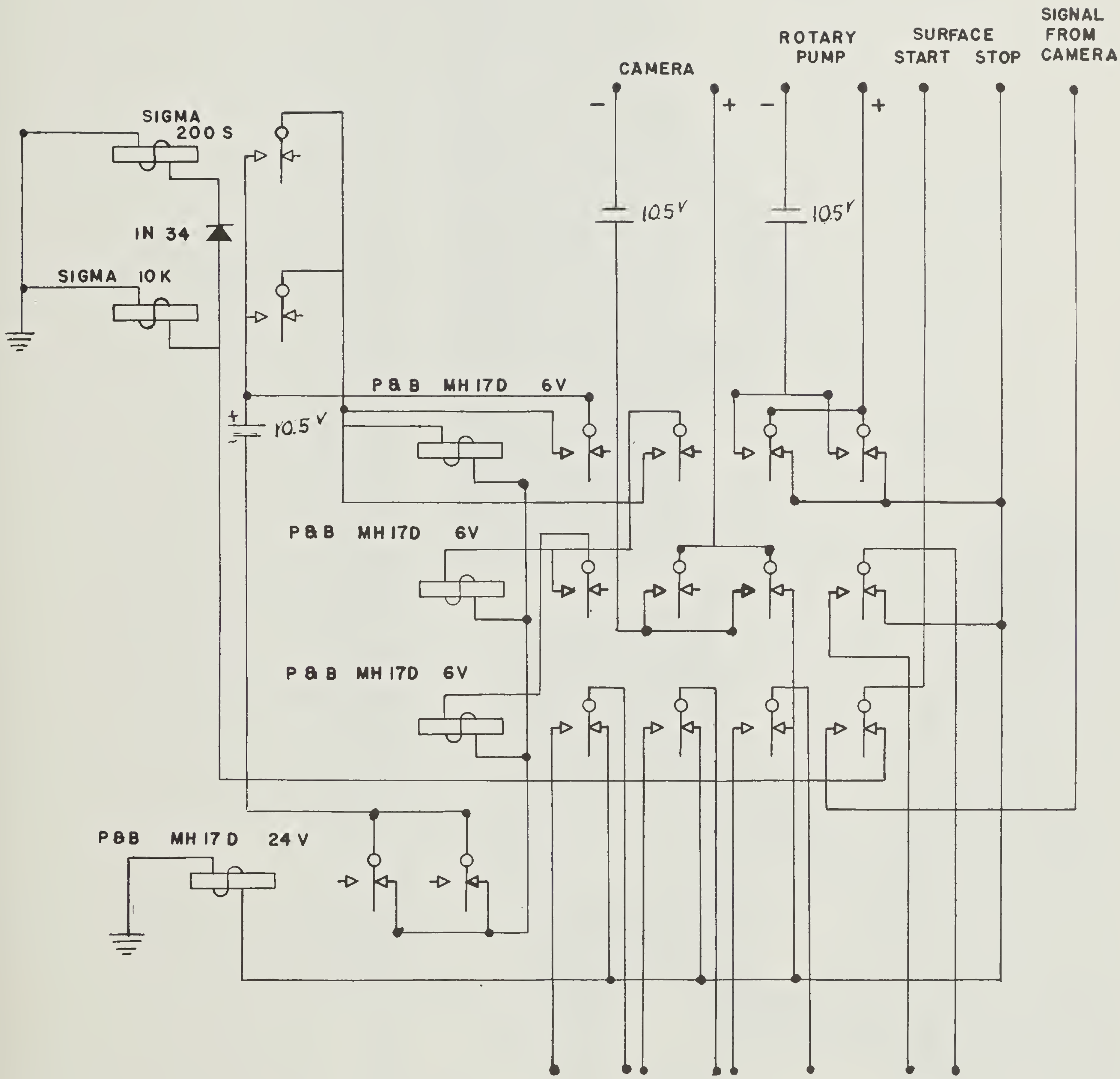

FIG. 9 CONTROL CASE CIRCUIT

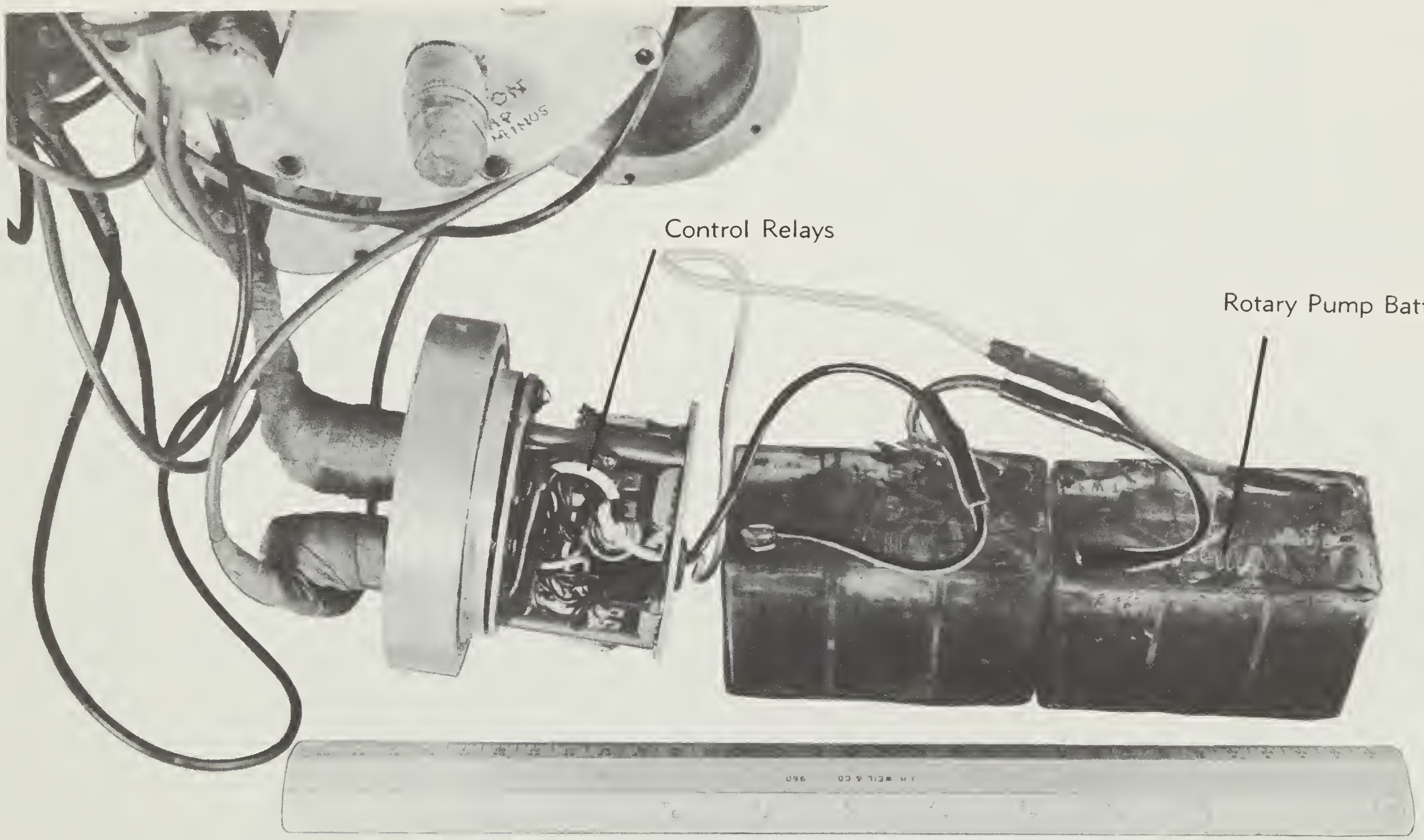

Fig. 10 Rotary Pump Battery Unit

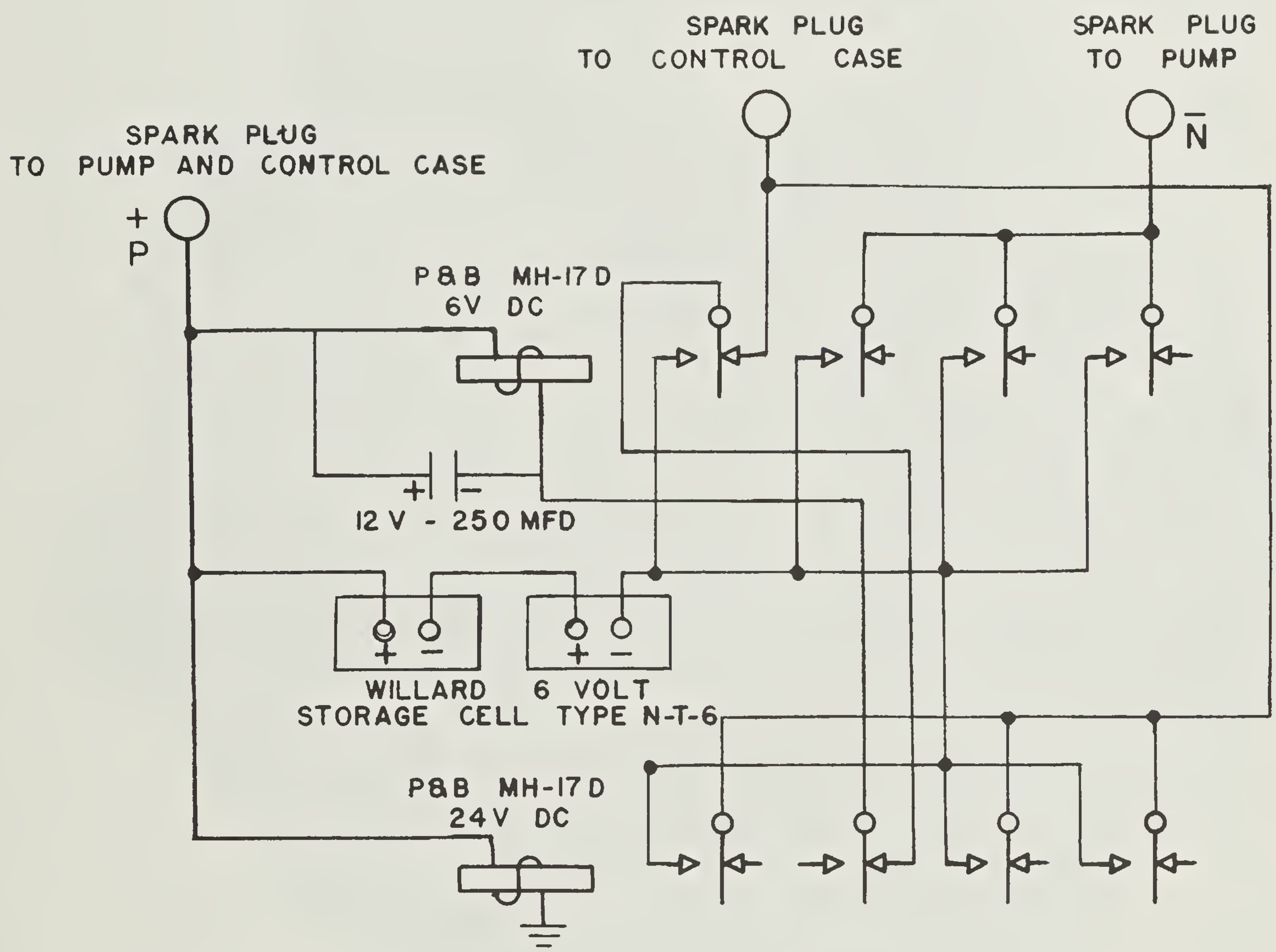

FIG. 11 ROTARY PUMP BATTERY CIRCUIT

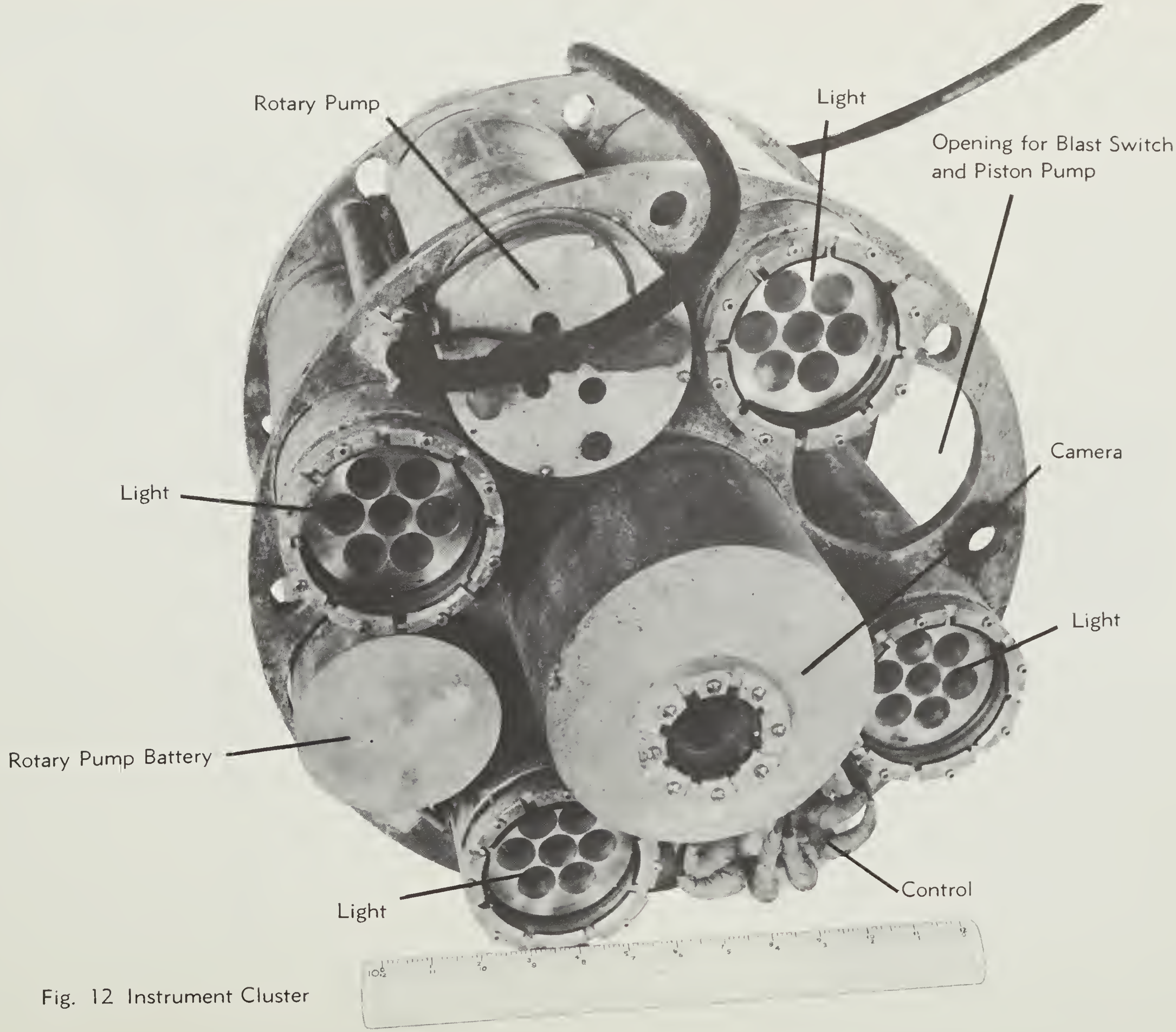

Fig. 12 Instrument Cluster

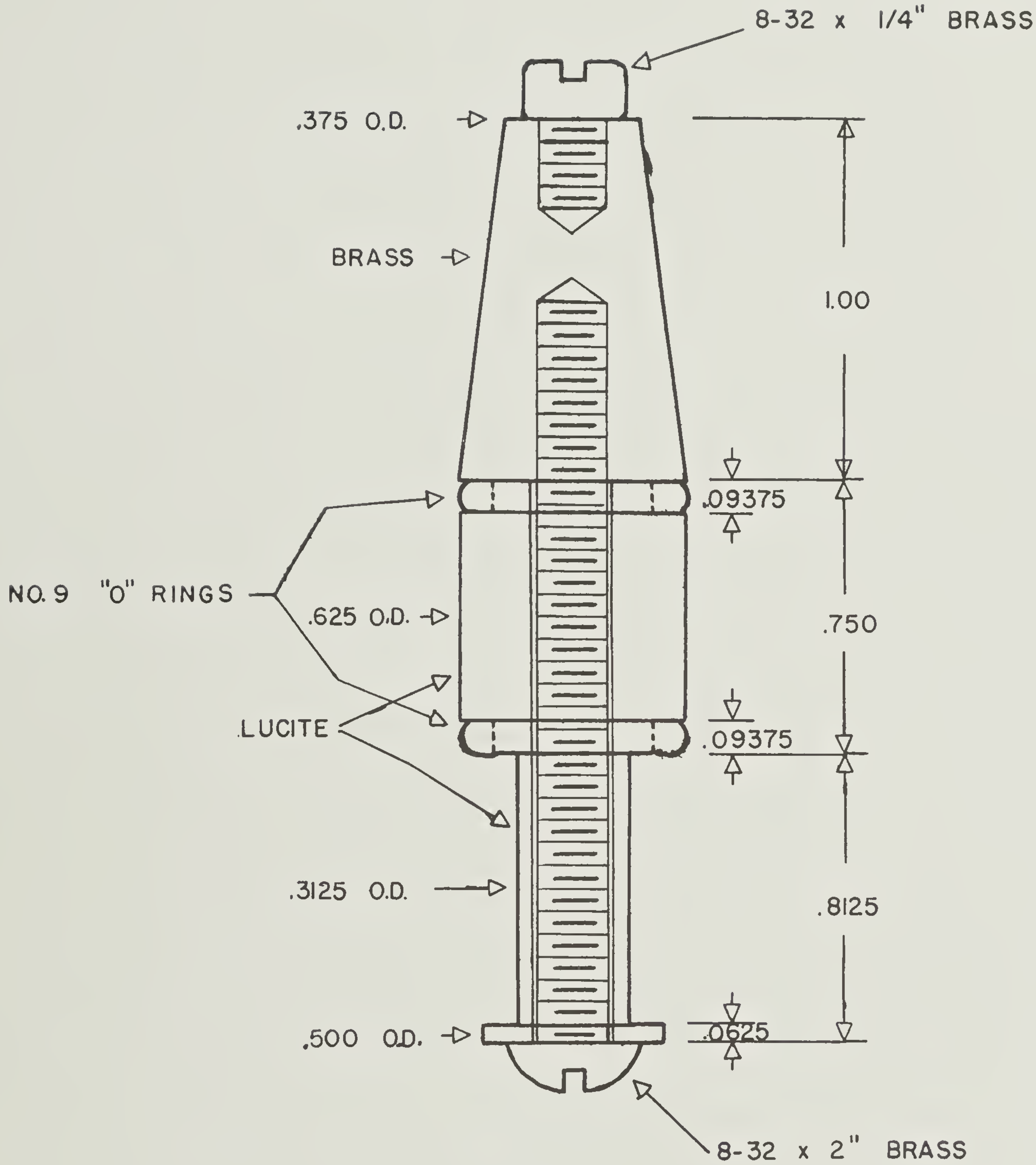

FIG. 13 SPARK PLUG
FOR
PRESSURE CASE
LEAD - IN'S