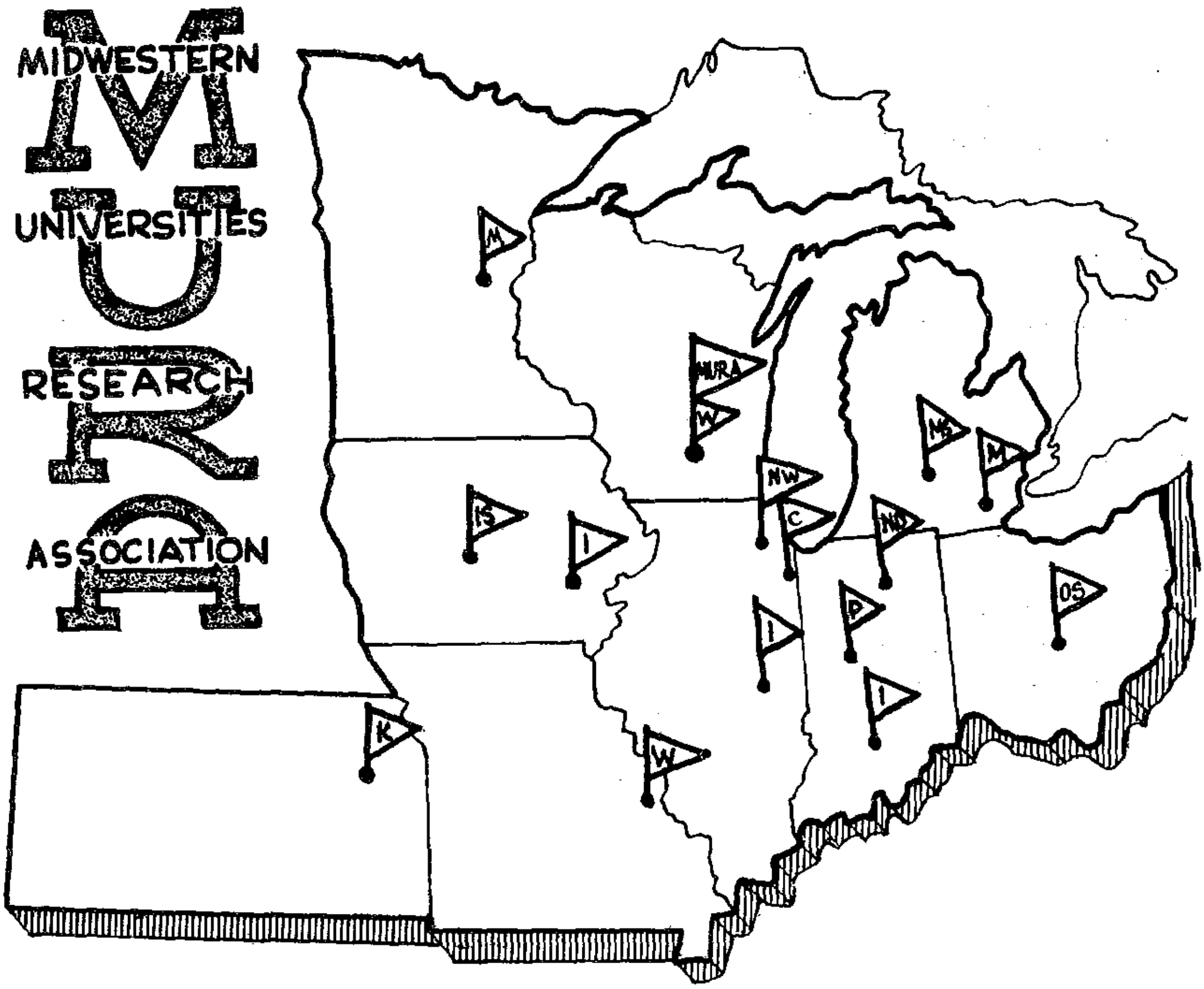

BUBBLE CHAMBER RESEARCH WITH THE MURA MODEL HEAVY LIQUID CHAMBER

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I. INTRODUCTION

This report attempts to describe the results of several experiments performed on the MURA model heavy liquid chamber. Some of the results give information especially applicable to the larger chamber that is being designed at MURA, while in some cases the results are applicable to heavy liquid chambers in general. Both will be discussed in this report.

The intriguing question, "Can a tank-car filled with propane be expanded and photographed through small ports?" lead to the basic concept of the 9 m^{-3} meter bubble chamber. After a few minutes of serious thought, it was clear that many questions needed to be answered before a working chamber could be designed.

Some of these questions were: (1) what are the problems of keeping a large volume of liquid free from impurities in order to photograph through a long optical path length; (2) are optical inhomogeneities arising from temperature gradients a serious problem; (3) what are the problems associated with the expansion of such a large volume of liquid will there be boiling around the diaphragm and does a large physical motion of the liquid near the diaphragm during expansion cause problems; (4) does wide angle photography offer serious problems; and, (5) can Scotchlite be successfully employed <u>inside</u> a liquid and used as a retrodirective device?

It was clear that optical inhomogeneities could be a serious problem in large heavy liquid chambers. The largest existing heavy liquid chamber at the time of the initiation of the program was the CERN heavy liquid chamber of Ramm. In this chamber, and even in smaller chambers such as the Berkeley and Paris chambers, optical inhomogeneities could easily be observed, suggesting that this could be a serious problem in a larger chamber.

Furthermore, experience with both the CERN and Paris chambers showed that boiling on the diaphragm occurred, suggesting that there could be serious problems associated with boiling on a diaphragm in expanding a still bigger chamber. Furthermore, it was not clear that the increased motion of the liquid near the walls, diaphragm, etc. might not cause specific problems.

With these questions in mind, it was decided to construct some sort of "model chamber" to study these problems before completing the ultimate design of the big chamber. Rather than build a scale model of the big chamber, it was decided to build a chamber which would permit a specific study of some of these problems. The shape of the model chamber was dictated by three factors: (1) the longest dimension should be at least as great as the path length to be photographed in the big chamber, (2) the column of liquid to be expanded should correspond to the same length as in the big chamber, and (3) the ratio of diaphragm area to liquid volume should be comparable to that of the big chamber.

The model should be expanded with large valves of about the same size as in the full scale chamber, in order to study the time constants of the system; scaling being accomplished by their number rather than their size.

Many other minor considerations enter into the detailed design of the model, but the above criteria set the configuration of this model chamber. A detailed description of the physical properties of the model chamber are given in subsequent chapters. A photograph of the chamber model is shown in Fig. I-1.

II. GENERAL DESCRIPTION OF THE MECHANICAL AND ELECTRICAL COMPONENTS

Chamber Body

The body of the chamber is a horizontal cylinder with flat ends. It is constructed of 24-in. schedule 40 carbon steel pipe with flanges welded on the ends. The inner diameter is 22.625 in., over-all length 72 in., and the cylinder wall thickness is 0.687 in. The ends are machined from 4-in. blind flanges and are attached to the body by 24 1.50-in. bolts. The expansion system occupies one entire end of the chamber.

Altogether there are seven windows in the chamber. One is in the center of the end flange, making it possible to look through six feet of liquid. The other six are equally spaced in the cylindrical portion, three on a side, separated by 90° to permit stereo photography. Reinforcements for the windows consist of studding outlets welded into the body of the chamber.

The maximum design stress for the chamber body was 11,000 psi at a pressure of 600 psig. Special consideration was given regions which had large section transitions. Full penetration weldments were specified; these were die penetrant and radiographically tested for cracks.

Figure II-1 shows the double diaphragm and holey plate assembly. The inner diaphragm A had Freon on one side and Freon solvent with nearly the same density on the holey plate side. This meant that the inner diaphragm assumed a shape determined by the stretching of the diaphragm only, unaffected by gravity. The outer diaphragm B separated Freon solvent and the air manifold. In the compressed position this diaphragm pressed against the holey plate at the top and bulged out at the bottom depending upon the volume of Freon solvent enclosed between the two diaphragms.

The holey plate C was machined from a 4-in. blind flange contoured on both sides. It was designed to be self-supporting and capable of sustaining 600 psig in the chamber. The front diaphragm is attached to the front of the holey plate by a contoured clamp ring. The diaphragm material is squeezed about 20% between the holey plate and the end flange. The cover plate D is another 4-in. blind flange which seals off the expansion end of the chamber. The whole assembly is then bolted to the end flange of the chamber by 24 1-1/2-in. bolts E. These bolts also provide the force needed to squeeze the diaphragms 20% which automatically takes place when all surfaces touch metal to metal. O-ring seals G are provided at the various interfaces, with double O-ring seals at the critical locations.

To fully exploit an experimental chamber such as this one, it was necessary to install numerous temperature and pressure sensors in it. There are four Kistler (Model 601A) quartz dynamic pressure transducers equally spaced along the bottom of the chamber. Temperature wells are installed on the bottom, one-third up, two-thirds up, and at the top of the chamber. There are more temperature probes along the length of the chamber to measure longitudinal gradients. TRI-R Type TP-7P thermister probes are used to measure the temperature. Three openings are provided on the bottom of the chamber for propeller shafts. One of these is presently used for an inlet valve. A vent valve is located in the end plate at the top where a relief valve and a gauge line are connected as well.

At the time when the body of the chamber was fabricated no attempt was made to polish up the interior surface. It was decided instead to paint the interior with a paint compatible with Freon 13-B1 which would smooth out the surface well enough to reduce boiling. Rough spots and weldments were ground flush and sanded down. The whole interior was then painted with two coats of O'Brian's white polyurethane paint. The choice of paint was made after an intensive investigation of many brands tested in liquid Freon 13B-1 for weeks at a time. It was discovered that although most of the polyurethane paint gave the desired smooth finish, some had poor adhesion properties and were more easily penetrated.

Precautions were taken to reduce boiling from various objects in the chamber. Openings were rounded off, sharp edges smoothed down and the "O" ring grooves in the end plate undercut to provide free access of the liquid to the seal. This prevented a squirt of high velocity liquid and consequently reduced boiling.

The temperature of the chamber is controlled by means of coils attached to the outside of the body. These coils consist of 1/4-in. copper tubes cemented to the wall with Devcon-F aluminum-loaded epoxy. Although the thermal conductivity of the epoxy is low, it was decided that with adequate insulation on the outside, a sufficiently stable condition of thermal equilibrium could be reached. Altogether there are 20 individual coils. Two temperature-controlled water baths are used to supply water to any of the coils. In this way desirable temperature gradients can be established in the chamber. Temperature sensors (TRI-R thermistor probes) monitor the incoming and outgoing water temperatures at the manifolds. Flow checks can be performed by diverting the water into a calibrated container. This system has allowed us to do reasonably accurate heat load studies.

In order to be able to photograph tracks through the end window, it was necessary to provide a retrodirective surface in front of the diaphragm. To make this possible a Ramm plate was installed. The first Ramm plate was made of 1/8-in. aluminum plate, had a clearance of 1-3/4 in. all around, and was located 6 in. in front of the diaphragm. It was suspended by springs attached to its front which allowed it to move backwards freely but restricted its forward motion. Although it provided the needed retrodirective surface, it did not perform as a true Ramm plate because of the large clearance. It has subsequently been replaced by another 1/8-in. aluminum plate which has only 3/8-in. clearance, and is suspended in the same way (see Fig. I-1 R). There has been a noticeable improvement in the operation of the chamber since the new plate was installed.

Soon after the chamber was pulsed for the first time, it became obvious that some means of agitation will be needed to eliminate thermal turbulence. The first attempt was to install a small propeller on the end flange. Since this propeller was coaxial with the cylindrical portion of the chamber, it tended to produce a rotation in the liquid. Intermittent operation of the propeller between pulses was tried with a certain amount of success.

The second attempt was to install three propellers equally spaced along the bottom of the chamber. They were driven by electric motors with individual controls capable of rotating in either direction at any speed. Conventional carbon seals were used at the shafts and performed quite well. Outboard motor propellers were tried and a study was made to determine the best shaped propeller. One of the propellers had a skirt on the bottom to capture the bubbles from the seal. We felt that enough is known now to minimize and contain the boiling from propeller seals.

Although propellers give adequate mixing and do eliminate temperature gradients, they also produce excessive liquid motion which is detrimental to the operation of a bubble chamber. In order to minimize liquid movement, it was decided that a rake consisting of round rods be tried out. After conducting some experiments in a water tank, we finally settled on a rake made up of 1/4-in. stainless steel tubing, 14-in. long spaced on 3/4-in. centers covering the entire length of the chamber (see Fig. II-1 H) These tines were heli-arc welded into holes drilled in a 3/4-in. stainless steel tube; their tips were crimped shut, welded and polished after which the whole assembly was leak checked.

The rake is driven by a shaft (Fig. II-2 A) which goes through a seal in the end flange and is attached to the rake inside the chamber. A pneumatic cylinder which is bolted to the outside of the end flange is used to power the rake, driving it through 85° of circular motion. In its rest position the rake (Fig. II-3 A) is against the side of the chamber covering the windows through which pictures are not being taken. With the present setup the total travel time for a round trip is three seconds. The rake actually traverses the chamber in one second and takes one second to decelerate and start in the opposite direction. It has been clearly demonstrated that a rake does eliminate thermal turbulence and produces very little liquid motion. This will be discussed in more detail elsewhere in the report

Windows

There are seven windows altogether in the chamber, six in the cylindrical portion and one in the end flange. Two of these are shown in Figs. II-2, 3 W. At first we used flat rounds of tempered glass (Herculite) 6 in. in diameter and 1-1/4 in. thick. Later on we obtained two hemispherical annealed glass windows. By positioning the camera lens at the center of curvature distortions due to the light passing through various glass thicknesses are eliminated and also reflections from the ring light don't get into the lens.

Conventional "O" rings are used to seal the windows. A teflon spacer confines the "O" ring on the outside periphery. No stop was provided for the "O" ring on the inside periphery. Experience has shown that a teflon spacer there, no matter how well designed, will always boil and obscure photography. Precautions are taken to evacuate behind the "O" rings when the chamber is evacuated to prevent the seals from being sucked in. This pumpout is built into a metal spacer which also acts as a stop for the clamp ring giving a predetermined squeeze on the seal. Pumping is continued during chamber operation providing an excellent means for immediately identifying a leak in the window seal.

The windows were designed for a maximum stress concentration of 700 psi giving a safety factor of about 10. The stresses in the hemispherical windows are considerably smaller.

The window assembly is attached to the body by a clamp ring with six 1/4-in. bolts. Metal-to-metal contact between the clamp ring, the spacer and the chamber give the predetermined amount of squeeze on the "O" ring seal.

During operation of the chamber all the windows which are not being used are covered with a 1-in. round steel plate with an "O" ring seal. When the chamber is left full overnight, all the windows are thus sealed. For visual observation a 1/4-in. plastic shield is used to cover the window for protection.

Photography and Illumination

A modified Beattie model CS-48 film transport was used to advance the film and the camera was made at MURA except for the lens which was changed depending on the nature of the experiment.

About three-quarters of the cylindrical portion of the chamber is covered by 3 M (SPR-704) Scotchlite retrodirective sheeting. This Scotchlite has a very narrow angle of retrodirection and the beads are quite uniform in size and very well distributed. In order to protect the Scotchlite from the Freon it was necessary to encapsulate it in mylar film. An intensive program was initiated to determine the best method of encapsulation. The method which was finally used and which proved to be very successful was to glue the Scotchlite on a mylar sheet (0.003 in.) using its own adhesive (care must be taken to prevent capturing air bubbles), then covering the Scotchlite with epoxy (General Mills Versamid Genepoxy combination) and finally placing another sheet of mylar (0.005 in.) on top of that. It is necessary to roll the top sheet on in order to squeeze out the excess epoxy and also the captured air bubbles. The sandwich resulting from this process is about 0.012-in. thick. It is then necessary to flame seal the edges, by placing the sandwich between two flat metal bars with the sheet protruding about 1/32 in. and passing over it with a cool torch. This fuses the mylar together permanently.

The Scotchlite mylar sandwich was then epoxied to the wall of the chamber with Armstrong C-1 epoxy. While the epoxy was curing, the Scotchlite was held in place by means of an inflated polyethylene bag. The chamber was held stationary while the epoxy was curing and this caused some of it to run down to the middle leaving some voids on the sides. These small airpockets were a continuous nuisance to us since they expanded when the chamber was evacuated and tended to pull the Scotchlite off the wall. It would have been desirable to rotate the chamber slowly while the epoxy was curing. This would prevent the epoxy from running out.

Scotchlite was also applied to the front side of the Ramm plate.

Expansion Recompression

The expansion recompression system is connected to the bubble chamber by means of a slip-on flange such that the straight-through section is coaxial with the chamber. The 10-in. expansion Grove valve is attached to one end of the straight section and the 8-in. recompression valve to the trunk section. Since all of this plumbing provided a large dead space, we inserted volume occupiers in this plenum providing only slightly more space for the flow of air than there is in the Grove valve orifice itself. The Grove valves are then connected to the expansion and recompression tanks by means of an 8-in. steel pipe.

Four 3/4-in. Barksdale (N.O. 2-110-23) solenoid valves are externally manifolded on the expansion Grove valve. These Barksdales are connected by ball valves such that any one or more could be completely isolated from the system. This allowed us to expand the chamber with different numbers of solenoid valves. The recompression Grove valve has two Barksdale valves externally manifolded on it, also through ball valves. We have found that only one of them was needed for adequate recompression. Faster recompressions, using both Barksdale valves excited the natural frequency of the chamber and lead to undesirably high surges in pressure.

Figure II-4 shows a schematic of the air system. A 50-horsepower 10 x 4-1/2 x 9 Worthington compressor located in a shack outside the laboratory building pumped air into a main reservoir. The top pressure in this reservoir was 570 psig. Grove diaphragm regulator valves then supplied air to the recompression tank at 300 psig and the Grove valve recompression tank at 320. A back pressure regulator maintained the expansion tank at a predetermined pressure.

Another pressure regulator connected the expansion tank to the compressor intake. This was set at the design intake pressure.

There is a separate tank for the expansion pressure of the Grove valve. This tank is connected to the suction unloader on the compressor and as a result is maintained at atmospheric pressure.

Pilot pressure for the Barksdale valves was supplied from a dry N_2 bottle and was usually set at about 350 psig.

Temperature Controls

The temperature of the bubble chamber was controlled by two independent water systems. One system controlled the top one-third of the chamber and the other system controlled the bottom two-thirds. Each system consisted of a water tank in which a controller maintained the temperature at a preselected level. Two types of controller were used, a YSI Model 71 thermistemp temperature controller and a YSI Model 72 thermistemp temperature control. The former is a full load on and off controller while the latter is a proportional controller. Both of them operated heaters in the tanks when heat was needed and solenoid valves which dumped cold water into the tank when the water got too hot.

Separate pumps then pumped the water through the bubble chamber coils, through a bypass, and returned it to the tank. A single overflow maintained the level in the tanks. The bypass flow was adjusted so as to produce a lot of turbulence in the tanks and thus keep the temperature uniform throughout. Both systems worked extremely well, maintaining stable water temperatures to within $\pm$ 0.05°C and were very versatile and troublefree.

BUBBLE CHAMBER ELECTRONICS

This report describes in general the functions of the electronic equipment used in the operation of the model bubble chamber. It is a report to familiarize the operator or other interested parties with the equipment used. Figure II-5 is a typical block diagram of the chamber control equipment and will aid the reader in the following description. Control and monitoring are the two main functions of the electronic gear and are discussed in the following paragraphs.

Synchronized Control

All events that occur during the chamber cycle are triggered by a master trigger generator and its associated time delays. It is a MURA-built transistorized unit designed for general laboratory use and modified for chamber operation. The trigger generator, synchronized with the line frequency or self-exciting, supplies a 10-microsecond positive 12 volt pulse which triggers the time delays or other circuits. Presently the generator is set up to pulse the chamber at a repetition rate of three times per minute; however, this rate is variable and can be set to meet the requirements of the experiment.

Alternate Method of Triggering

When a radioactive source is used to produce tracks in Freon, the chamber cycle must be synchronized with the source. A solid steel rotating cylinder with a slot perpendicular to its axis placed between the chamber and the source acts as a shield except for a short period of time. This period of time is dependent on the speed of the drum (100 rpm), and the number of particles is dependent on the size of the slot and the strength of the source. Particles were allowed to enter the chamber every 50 ms in a pulse 2 ms wide.

A photo-voltaic diode is used to pick up a light source corresponding to the radiation pulse every 50 ms. The diode pulse fed to a signal conditioner and then to a pulse counter enables the operator to pick off a trigger pulse every 20 seconds. This method merely replaces the master trigger generator so that the chamber cycle can be synchronized with the radiation pulse.

Rake Control

The rake and its function are described in another section; therefore, only the control of the rake will be described here. The rake is operated by a pneumatic valve which is controlled by a solenoid. A variable monostable multivibrator, triggered by the master trigger generator, controls a relay that applies 110 VAC to the solenoid. The rake cycle time, determined by air pressure, takes approximately three seconds. Because this cycle must finish just before the chamber is expanded, a second pulse three seconds later must start the expansion cycle. This three-second delay is supplied by the master time delay.

Barksdale Valve Control

The Barksdale valves, of which four are expansion and two recompression, control the Grove valves. The Barksdale control circuits consist of:

1. Valve timing circuit.
2. Valve driver circuit and associated power supplies.

The valve timing circuit consists of six identical channels which are independent of each other. This is a versatile unit and can be operated in several modes which are:

1. Automatic

   An external trigger starts six variable gate circuits with a range of 10 to 200 milliseconds. These energized the valves.

This mode was used most of the time.

2. External Turn-Off

   An external start and stop trigger determined the open time of the valves.

3. Single Pulse

   A push button excites the trigger initiating the gates.

4. Continuous

   A valve can be opened and closed by means of a push button. This push button bypasses the variable gate.

These pulses go to the Barksdale driver units of which there are eight. A pulse from any of the six variable gates can energize any of the eight driver units.

The Barksdale driver units are fed from two power supplies, the booster power supply, and the sustainer power supply. A short pulse of a few milli-seconds is given by the booster supply followed by one from the sustainer which stays on for the full length of the gate. The booster supplies - 70 volts from a 400 μf condenser. The sustainer delivers 2 amperes per coil at - 15 volts.

A Barksdale disabler circuit opens the lines to these two supplies, turns them off, and discharges all capacitors.

Barksdale Valve Monitoring

It is important to know if the Barksdale valves are operating, therefore a monitoring system was devised to detect valve-stem movement. A steel slug attached to the stem moves inside a stainless steel tube when the valve is operated A transformer with 5-kc fed primary is wound on the stainless tube. The slug movement through the transformer changes the inductance and therefore changes the induced signal at the secondary. This signal is rectified, filtered, and sent to the alarm circuit and scope for monitoring. This signal is not a linear function of the distance the valve stem travels but it will tell the operator it is moving and how fast.

Xenon Flash Lamp Control

When photographing cosmic rays in the chamber, it was required that a picture be taken only when a cosmic ray went through the chamber during its sensitive time. In addition, the Xenon flash lamps must flash at a known time after the passage of the cosmic ray. The chamber was pulsed at 20-second intervals and no pictures were taken if no cosmic ray appeared in the right interval.

The 20-50 ms T. D. time delay in Fig. II-5 opened the gate timing circuit. The gate timing circuit removes the inhibit signal which prevents a cosmic ray pulse from initiating a flash. If a cosmic ray appears during this gate, it generates a pulse in the AND GATE.

The pulse from the AND GATE initiates the flashes through the Flash T. D. time delay and the double pulse flash delay.

A 2-kV power supply and a capacitor bank, variable from 4 μf to 24 μf, supply the energy to the flash lamp. There is a safety interlock incorporated in the flash lamp unit to protect the operator against dangerous electrical shock. It is merely a microswitch that will open up the AC feed line to the power supply if the flash unit is removed from the chamber body. It will also deenergize a shorting solenoid and allow a shorting bar to discharge the capacitor bank and power supply. This is the basic setup for single flash operation.

The double flash system requirements are a little more sophisticated because in addition to the basic single flash system of a power supply and capacitor bank the following functions must be performed by these double flash circuits:

1. Two charged capacitor banks must be isolated by an electronic switch.
2. The Xenon flash lamps must be triggered twice within a 10 to 25 ms period of time.
3. Xenon flash lamp must be capable of operating in single flash or double flash mode.

Two thyratrons isolate the capacitor banks and act as a series switch, at different times, in the flash lamp discharge path. A flash separation control determines the delay between the first and second flash by delaying the trigger to the second thyratron. This control also delays the second trigger to the flash trigger generator and ultimately the trigger to the flash lamp. Single flash is easily achieved by using a switch to disable the delayed trigger.

The flash monitoring system is just a capacitor discharge waveform taken from a bleeder resistor string in the capacitor bank unit. This signal is fed to an alarm operation detector and an oscilloscope. There are also neon bulbs that light during the charge time of the capacitor bank and are therefore a visual check to the operator.

Film Transport

The film transport is a modified Beattie model CS-48 that attaches to the flash lamp unit with four mounting bolts. The lens, also mounted in the flash lamp unit, will not be described in this section.

The film transports 110 VAC motor drives a gear train which advances the film. The AC power is applied through an isolation transformer because of the noise generated from the collapsing field when the motor is turned off. Control of the motor is obtained by using a relay in the secondary of the isolation transformer. This relay is a low voltage type operated by a monostable multivibrator circuit. The pulse that triggers this circuit also triggers a binary counter which records the frame number on the film and at a readout panel. The bulbs used for film readout are miniature penlite bulbs with focusing lenses.

Alarm System

The alarm system consists of two units, an operation detector and an alarm anunciator. The operation detector circuit will, upon proper adjustment, accept either a positive or negative voltage pulse from a sensing device. This pulse is conditioned and compared with the trigger pulse that initiates the operation of a piece of equipment of which the sensing device is part of. In event the pulse from the sensing device is absent or too small, a signal from the operation detector tells the alarm anunciator to turn on a warning light and actuate an audio alarm. It will not make any corrections or disable any equipment, therefore any precautionary or corrective measures must be performed by the operator. Its sole purpose is to make the operator aware of a malfunction and in what area it is.

Pressure Monitoring

Static pressure in the chamber body and associated pressurized vessels are monitored and displayed directly by pressure gauges.

Dynamic pressures are monitored by seven Kistler quartz pressure transducers, of which four are mounted in the chamber body, one in the tee, and one in each of two Grove valves. The signals from the seven pressure transducers are carried to a patch panel via shielded cable and here the operator can program any three of these signals to the three charge amplifiers. These Kistler charge amplifiers produce a signal of 1 mV per picocoulomb of input energy and this dynamic pressure curve can be displayed on an oscilloscope or recorder.

Oscilloscope and Camera

A Tektronix-type RM564 storage oscilloscope with a four-trace plug-in plays a very vital role in the operation of the chamber. It allows the operator to set up the timing sequence of the different components very accurately which is very important in chamber operation. Its storage mode allows the operator to study or compare waveforms for one or more cycles of the chamber plus the fact that a photograph can be taken of the stored image at any time. A Tektronix-type C-27 camera is used for this purpose.

There are as many as 19 signals available for display on the oscilloscope if the operator so desires, however, only four can be displayed at any one time; therefore a scope patch panel or programming panel is needed. With this type of unit the operator can dial in any one of the 19 signals on any channel of the scope desired. The block diagram shows where some of these signals originate; however, they are not directly connected to scope but to the scope patch panel where they are programmed to the scope.

III. GENERAL OVER-ALL OPERATION

The purpose of a model is fulfilled when mistakes in design are discovered rapidly and the resulting corrected designs are tested and found satisfactory.

A partial list of the many things discovered will give an idea of the usefulness of the model.

1. Mounting of windows.
2. Reduction in bubbling around window gaskets, probes and rotating seals.
3. Tests of paints used to cover rough walls.
4. Mounting of gaskets and diaphragms.
5. Tests of rotating gas-tight seals.
6. Experience in assembly.
7. Proper methods for transferring large amounts of Freon or propane.
8. Proper throttling and time controls on expansion and recompression valves.
9. Study of unexpectedly large pressure rises at the end of the chamber as the result of rapid recompression.
10. Advantages of expanding a chamber at the top of the liquid.
11. Study of stains in the walls of the chamber.
12. Dynamic effects of the gas in expansion and recompression.
13. Optical properties of Freon at nonuniform temperature.
14. Heat loads and requirements for proper thermal controls.
15. Experience in protecting Scotchlite from Freon and propane.
16. Bubble growth study with cosmic rays.
17. Dynamics study of Barksdale and Grove valves.
18. Study of methods for reducing thermal turbulence.

Not all of these subjects will be considered in detail. The model has been most successful from all points of view both in its original conception and in the details of its operation.

Initially the diaphragms of the chamber were made of a rubber belt material which had unfortunate characteristics and was easy to rupture. The oscilloscope traces did not repeat and showed erratic behavior. After installation of quarter-inch thick diaphragms made of 83 D durometer polyurethane, there was no further trouble with the diaphragms. The new clamping scheme shown in Fig. II-1 F was very successful.

Various mountings for Scotchlite were tested with little success until encapsulation of the Scotchlite in a mylar sandwich (see Section II). The cylindrical wall was then coated with the encapsulated Scotchlite over most of its surface except for the area around the side windows. This coating showed very little bubbling and withstood many evacuations of the chamber. Eventually breaks appeared over areas where air pockets were trapped behind the Scotchlite sandwich (see Section II).

A Ramm plate was installed at a distance of 8 in. from the inner diaphragm (Figs. II-1, 3). Mounted on springs and covered with Scotchlite it moved with the liquid during expansion with a clearance of 3/8 in. between it and the cylindrical wall of the chamber. Fiducial lines alternately 1 mm and 1/2 mm in width formed a grid of inch squares on the Scotchlite on the Ramm plate.

The double diaphragm described in Section II was restricted in motion by the space available for the motion of the outer diaphragm. This allowed a maximum expansion of about 2.5%.

The chamber was evacuated before filling to about 50 microns of pressure. A liquid Freon pump was used in filling the chamber, and the final topping off was done with a hydraulically controlled piston in a cylinder. The chamber was filled until the rate of rise of pressure increased sharply indicating that all gas bubbles had collapsed. Then a measured amount of Freon was removed with the piston.

Initially the dirt left in the system sank to the bottom of the chamber and caused excess bubbling. Pieces of dirt floating in the liquid were observed to bubble. Introduction of a one-half micron filter reduced this markedly. The liquid Freon pump was used to recirculate Freon through the filter for several hours.

Early analysis of the dynamics of the expansion of the chamber indicated the necessity for a sinusoidal expansion wave with a period three times that of the fundamental period of the pressure wave in the chamber. It was found possible to control this by varying the pressures and timing of the Barksdale valves used in controlling the expansion and recompression Grove valves.

The capacity of the compressor was just sufficient to permit an expansion to be made every 20 seconds. Leaks in the air system necessitated stopping expansions so as to build up the supply. The chamber would run for 40 minutes or 120 expansions before this was required. Figure II-4 shows a schematic of the air system. More detailed discussion of speeds and modifications to Grove valves and Barksdales are given in Section IV.

It was possible to expand the chamber five times in succession at two-second intervals. The expanded pressure rose each time, so that all expansions were not to the same depth. However, it was possible to see tracks in all five expansions.

The temperature of the chamber was controlled by two water supplies. The temperature of the inlet water was maintained constant. The temperature of the Freon was measured by thermisters at the top and bottom of the chamber, and the temperature of the two water circuits was changed by hand so as to maintain an appropriate Freon temperature.

A very marked improvement in operation resulted from the use of propellers to stir the Freon. When a large bubble at the top of the chamber was recompressed,the heat of condensation increased the temperature of the Freon. The bubble collapsed very slowly, and the liquid at the top remained hot. When the propellers were turned on, this problem was removed, the bubble collapsed quickly, and uniform temperature was reached quickly.

The upper third of the chamber wall was controlled in temperature by one water system. The lower two-thirds were controlled by the other water system. The upper system usually ran with input water about a degree colder than the lower one during running of the chamber.

A 10-in. Grove valve controlled by two Barksdale valves was used for expansion into an expansion tank usually maintained at 110 psig before expansion and rising to 120 psig after expansion. The recompression system used an 8-in. Grove controlled by one Barksdale valve. The recompression was too rapid and caused a large overshoot in pressure if both Barksdale valves were used. The recompression tank was maintained at about 310 psig and dropped to 295 psig on recompression.

A great convenience in operating the chamber was the persistent pattern oscilloscope Type RM 546 Tektronix storage oscilloscope. The pattern remains indefinitely and can be photographed subsequently. A second trace on top of the previous one makes it very easy to see small changes from pulse to pulse.

Presented on the four-channel scope were:

1. Pressures at five different points in the chamber and in the TEE.
2. Boot pressures in the Grove valves.
3. Opening times of the Barksdales.
4. Arrival time of cosmic rays.
5. Two light timing pips for double flash photographs.
6. Opening and closing of gate for acceptance of a cosmic ray.

Four traces could be made simultaneously. A typical setup would be: (1) pressure wave in chamber, (2) arrival time of cosmic ray, (3) double light flash pips, (4) opening and closing of gate for acceptance of a cosmic ray.

Two cameras were used, one at the far end of the chamber and one at the side. Both cameras looked through fisheye windows of glass with inner and outer radii of 5 and 6 inches. The camera lenses were located at the center of curvature of the windows.

High speed movies were made at 1600 frames per second, and movies at 50 and 70 frames per second from the end window. These exposures will be described below.

Gaseous Freon was recovered from the chamber when emptying after a run. This was done by attaching a helix of 3/4-in. copper pipe to the chamber and to the Freon storage tank. The helix was submerged in a dry ice alcohol mixture while open to the chamber. It was then submerged in hot water and connected to the storage tank. This was repeated until the pressure inside the chamber was reduced to 1 or 2 atmospheres.

Three internal propellers connected to variable speed motors were spaced along the bottom of the chamber. A long rake shown in Fig. V-1 going the full length of the chamber was used to study thermal turbulence.

Operating Conditions

Cosmic ray tracks could be obtained over a wide range of conditions. Typical temperatures of Freon 13B1 went from 27.5°C to 31.7°C. The recompression pressure was set 25 psi above the vapor pressure which varied from 248 psia to 310 psia. The expanded pressure ran at about 150 psig and down as low as 110 psig on some occasions.

The amount of liquid removed to permit expansion never exceeded 2.4% of the volume. This was an unwelcome limitation of the geometry of the double diaphragm. Because of this restriction it was not possible to lower the expanded pressure to increase the rate of growth of the bubbles.

Heat loads during expansion with and without the Ramm plate were measured (see Section IV).

IV. EXPANSION STUDIES

(1) A program was initiated to try to speed up Barksdale solenoid valves operating under bubble chamber conditions. A new coil was wound which could take a larger current than the one supplied. A stiffer upper spring was wound and the pilot stem modified. All of those steps were taken in a trial and error method until optimum conditions were obtained. It was possible to reduce valve opening time by 25%, valve closing time by 15%, and stem dwell time by 50%, reducing the total pulse from 50 msec to 32 msec. The duration of the electric pulse for the experiment was about 10 msec.

The Grove valves were modified such that they had more than one Barksdale valve externally manifolded. The poorly designed gas exhaust port in the original Grove valve was improved by the addition of flow channels and a holey plate over the exhaust port to prevent damage to the boot.

(2) The polyurethane diaphragm has shown no deterioration except for a small amount of stretching. There was no marked effect of heating from hysteresis in the diaphragm.

(3) Parasitic bubbling was greater at higher temperatures. Limitation in expansion ratio to 2.5 percent prevented study of bubble growth at low temperatures and expansion to lower pressures.

(4) Attempts to expand and recompress the chamber more rapidly resulted in marked stimulation of the fundamental period of the chamber with consequent large overshoots in pressure.

(5) Heat load studies before and after installation of the Ramm plate showed that the heat load was reduced from 14.9 x joules/liter to 11.2 y joules/ liter by its use.

(6) The Ramm plate tilted in the direction of expansion at the top so that the top moved 3/8 inch more than the bottom. The Ramm plate was 8 inches from the inner diaphragm. The diaphragm moved more at the top than at the bottom and was the cause of this tilt in the Ramm plate. This motion came from the fact that there were two diaphragms. The outer diaphragm, bowed out at the bottom during compression due to the greater hydrostatic pressure there from the freon solvent between the two diaphragms. The inner diaphragm was under tension and assumed a symmetric form. On expansion the bulge at the bottom of the outer diaphragm first moved out until it was restrained by the boundary of the air space behind it. Then the top moved out further because there was more room for it to move.

There was an oscillation which persisted until the chamber was recompressed. This had a period of 57 milliseconds and probably corresponded to an oscillation in the solvent-filled space between the two diaphragms.

Heat Load

The heat load caused by pulsing the chamber was determined by measuring the flow and temperature change of the heating water. To maintain the chamber without pulsing at 30°C against room temperature required about 37 BTU/min. Pulsing at a rate of 3 pulses per minute required 19 BTU/min. This means that each pulse developed 6 BTU of heat. This corresponds to the formation of bubbles amounting to 1.33 percent of the volume if all the irreversible work went into formation and collapse of bubbles. This amounts to 11.2 joules/liter.

Cosmic rays entering at one per sq. cm. per minute produce bubbles. If we assume a sensitive time of 33.3 milliseconds, ten bubbles per cm on each track, and that the bubbles grow to a diameter of 3 mm each at maximum size, this corresponds to 0.000760 percent of the chamber volume and results in irreversible work of 3.4 joules for the whole chamber or 0.0064 joules per liter. An equivalent amount of work would be produced by 1.5 tracks going the full length of the chamber.

The change in pressure on expansion was 170 psi. This expansion could be as great as 2.5 percent which leaves a difference of 1.35 percent for bubbles at their maximum size. This agrees with the heat load as measured. It should be pointed out that our measurements did not determine that the inner diaphragm moved the full 2.5 percent. However, a slightly longer delay between expansion and recompression gave audible evidence that the diaphragm was hitting the holey plate. The freon removed corresponded to 2.5 percent. It was removed at the vapor pressure of 260.8 psia. The liquid was recompressed to 311.4 psia which reduced its volume further so that it occupied a volume about 0.36 percent smaller. The maximum possible motion of the diaphragm was therefore 2.86 percent.

The reasonable conclusion appears to be that the heat load came from formation of bubbles which reached maximum size of about 1.4 percent of the chamber volume.

V. OPTICAL INHOMOGENIETY STUDIES

If no bubbles were formed in a chamber then the amount of irreversible work during a cycle of expansion and recompression is negligible. Optical inhomogenieties can appear from temperature differences on the walls of the chamber. These are very apparent as the chamber heats up, but disappear after two hours or more as equilibrium is reached.

The copper tubing (see Fig. II-2C) struck to the walls of the chamber was divided into an upper and lower group which were maintained at slightly different temperatures during pulsing of the chamber. Typical values are inlet 30.05°C, outlet 30.25°C at 2.8 liters/min for the upper group and inlet 31.75°C, outlet 30.90°C for the lower group at 6.3 liters/min.

It was at once apparent that the liquid must be stirred to achieve temperature equilibrium quickly. Initially one propellor was mounted on the end plate of the chamber. Later three propellors along the bottom of the chamber were used. These had a pitch of 8 inches per revolution and were run at speeds varying from 20 rps to 2 rps. The propellors permitted warm up and equilibrium to be accomplished in 20 minutes. There was no optical inhomogeniety or optical turbulence left.

After the chamber was heated, the chamber was filled completely full in the expanded condition. Then 2 percent of the liquid was removed. This left a bubble of freon gas at the top of the chamber.

A set of calculations will now be given for typical running conditions.

The operating freon temperature willbe chosen to be 85°F.

The expanded pressure 136.5 psia.

The recompressed pressure 311.7 psia.

We will assume that the 2 percent bubble is at the equilibrium pressure for 85°F which is 260.8 psia. We will apply the recompression pressure of 311.4 psia adiabatically and allow it to remain at that pressure during recompression of the bubble.

We will calculate the work done on the chamber by the diaphragm during this procedure.

For simplicity in calculation we will first calculate the work done on a bubble one cubic foot in volume at 260.8 psia. A reasonably close answer can be obtained by assuming that the work done in the initial rise in pressure is the average pressure = $\frac{260.8 + 311.4}{2}$ times the change in volume. The final volume will be assumed to be the equilibrium volume at 99°F where 99°F is the equilibrium temperature for gas at 311.4 psia.

A table of equilibrium conditions shows that:

Temperature °F	Pressure psia	Gas Volume cu ft/lb
39	136.5	0.2166
85	260.8	0.1072
99	311.4	0.0866

The work done on 1 cu ft of gas will be

$$144 \times \frac{260.8 + 311.4}{2} \times \left(1 - \frac{0.0866}{0.1072}\right) = 7917 \text{ ft lbs.}$$

The additional work to collapse the bubble will be the volume of the bubble 0.8078 cu ft minus the volume of the condensed liquid 0.051435 cu ft times the pressure in lbs per sq. ft.

$$144 \times 311.4 \times 0.7564 = 33918 \text{ ft lbs.}$$

This assumes that the liquid surface warms up immediately to 99°F due to the poor heat conduction of the liquid.

The total work done is 41835 ft lbs or 52.23 BTU or 56721 joules.

If the total volume of the chamber were 50 cu ft this would add 0.0114 BTU/lb to the liquid freon raising the temperature of the 49 cu ft of freon 0.054°F. In other words, the collapse of a 2 percent bubble just once will raise the temperature of the liquid throughout the chamber by 0.054°F. Since all this heat is released at the liquid surface, mixing is necessary to speed the collapse of the bubble and to equalize the temperature in a reasonable length of time.

A calculation can be made of the irreversible work done on bubbles formed in the chamber. The calculation presented makes the following assumptions:

(a) The bubble forms at the expanded pressure of 136.5 psia with the walls of the bubble at 39°F.

(b) The recompression is adiabatic.

(c) The bubble collapses at the recompression pressure of 311.4 psia with the walls at 99°F.

Initially the bubble does work in forming. Assume that the volume of the bubble at maximum size is 1 cu ft. Then the work done by the bubble is recompressed adiabatically. Its volume changes to 4.617/9.71 = 0.4755 cu ft. This takes place at an average pressure of $\frac{136.5 + 311.7}{2} = 224.1$ lbs.

The work done is 144 x .5245 x 224.1 = 16926 ft lbs. The bubble then collapses at 311.7 lbs with an amount of work of 144 x .4755 x 311.7 = 20316 ft lbs. The total irreversible work done on the bubble is 20316 + 16926 - 19656 = 17586 ft lbs or 23843 joules/cu ft of bubble.

The volume of the model is 18.86 cu ft. If 0.1 percent of the volume is occupied by bubble then the irreversible work will be 0.001 x 18.86 x 23843 = 450 joules. The heat load will be 225 watts if the chamber is expanded every two seconds. This amount of heat would raise the temperature of the freon one degree F for every half hour of running at this rate.

The joules/liter figure is $\frac{450}{18.86 \times 28.3} = 0.84$ joules/liter.

Since the thermal time constant of a chamber of this size is measured in hours, it is obvious that convection must be forced for a suitable temperature distribution to be maintained against this heat load.

Relationship to Optical Properties

We will define a thermal turbulence factor B in the following way. A bubble collapses with its walls at a temperature in equilibrium with the pressure. In our example this temperature is 99°F. A one cubic foot bubble causes an expenditure of work of 23843 joules or 22.6 BTU. It takes 3.08 BTU's per pound to raise the liquid from 85°F to 99°F. Therefore, it will raise 7.34 lbs of freon to the higher temperature. The volume of this amount of liquid will be 0.0818 cu ft. The ratio of liquid size to bubble size is therefore 0.0818.

The density of the liquid changes from 93.86 lbs/cu ft to 89.74 lbs/cu ft. This will change the index of refraction according to the Lorentz-Lorenz Law.

$$\frac{n^2 - 1}{n^2 + 2} \times \frac{1}{\rho} = \text{const.}$$

Assume that the initial index is 1.20 and the index when hot is n_H.

Then

$$\frac{n_H^2 - 1}{n_H^2 + 2} = \frac{89.74}{93.86} \quad \frac{0.44}{3.44} = .1222925$$

$$n_H = 1.1908$$

The ratio $\frac{n}{n_H} = \frac{1.20}{1.1908} = 1.00772$

The optical turbulence factor B will be defined as the product of the ratio of liquid to bubble volume times the index ratio minus one. This becomes B = .00772 x .0818 = .000631.

The calculation of the thermal turbulence factor B above is done on the basis of the total irreversible work. There is another way of looking at the problem which may give a better number. When a bubble evaporates it takes the heat of vaporization from the surrounding liquid. The bubble rises and leaves the cold liquid behind during evaporation. After recompression the bubble condenses giving the surrounding liquid its heat of vaporization. It rises during recompression and leaves a stream of hot liquid behind. After recompression is complete these hot and cold liquids continue to rise and fall away from each other by convection.

We will calculate the thermal turbulence factor for the hot and cold liquids assuming that they remain at 99°F and 39°F.

One cubic foot of vapor at 39°F contains 4.6172 lbs of freon. The latent heat is 40.05 BTU/lb. This takes 184.92 BTU from the surrounding liquid.

It takes 9.20 BTU/lb to cool the liquid from the initial 85°F down to 39°F so that the number of pounds of liquid cooled down is 184.92/9.2 = 20.1 lbs which has a volume of 20.1/104.86 = 0.1917 cu ft.

The density of the liquid changes from 93.86 lbs/cu ft to 104.86 lbs/cu ft. The index of refraction initially is 1.2 and after cooling is 1.2234, giving a ratio of 1.0195.

The thermal turbulence factor for the cold liquid is B_C = 0.1917 x 0.0195 = .00374.

A similar calculation for the recompression of the bubble at 99°F gives a volume of 0.4923 cu ft and an index ratio minus 1 of 0.0085 given B_H = .4923 x .0085 = 0.00418.

Adding B_C and B_H gives a total of 0.00792 which is 12.6 times bigger than B as calculated from the irreversible work.

The thermal turbulence constant B does not state anything about the size or location of the bubbles which cause thermal turbulence. The size plus the location with respect to the lens and object are important factors.

Visual observation of the chamber from the end window looking through 5 feet of freon at a 1-inch grid showed very marked thermal turbulence which persisted for the 20 seconds between pulses. However, if the propellors were run slowly this cleared up in about 10 seconds time. This condition, however, would require a waiting period of 10 seconds between pulses, and the desirable interval is only two seconds. It was obvious that more drastic measures must be taken to reduce thermal turbulence. Propellors alone would not accomplish this.

It is important that the liquid be nearly stationary when bubbles are formed. The light delay for satisfactory photographs should run between 2 and 4 milliseconds. It is desirable to keep the distortion due to irregular motion of the liquid down to about 0.3 mm. Velocities transverse to the magnetic field must not exceed 10 cm per second at points in the chamber where $H\rho$ measurements must be made with maximum accuracy.

An important quantity here is the time constant of an eddy or swirl in the liquid.

Slowing Down of a Rotating Cylinder in Freon

Suppose we have a cylinder of unit length of freon rotating as a solid body. Let R be its radius. Its moment of inertia is $I = \frac{\pi\rho}{2} R^4$ where ρ is the density.

Now let this cylinder lie inside another cylinder of radius C which is stationary. The space between is filled with freon with viscosity $\mu = 0.0015$ poises. The torque on the rotating cylinder is $T = 2 \quad r^2 \frac{dv}{dr}$ at all radii between R and C.

$$\text{Now} \int_R^C dv = v_C - v_R = -v_R = \frac{T}{2\pi\mu} \int_R^C \frac{dr}{r^2} = \frac{T}{2\pi\mu} \left(\frac{1}{R} - \frac{1}{C}\right)$$

$$\text{This gives a torque } T = \frac{-2\pi\mu\, v_R}{\frac{1}{R} - \frac{1}{C}} = \frac{-2\pi\mu\, Rw}{\frac{1}{R} - \frac{1}{C}}$$

where w is the angular velocity of the cylinder.

The equation of motion of the cylinder is

$$I\dot{w} = \frac{-2\pi\mu\, Rw}{\frac{1}{R} - \frac{1}{C}} = \frac{}{2} R^4\dot{w}$$

The time constant

$$K = \frac{\pi\mu}{\pi\rho/2\; R^4 \left(\frac{1}{R} - \frac{1}{C}\right)}$$

Let $C = 2R$.

Then $\frac{1}{R} - \frac{1}{C} = \frac{1}{2R}$

and K becomes $\frac{8\mu}{\rho R^2}$.

The density of freon is approximately 1.5 gm/cm^3. Therefore,

$$K = \frac{8 \times 0.0015}{1.5 R^2} = \frac{8 \times 10^{-3}}{R^2}$$

This means that a cylinder of 1 cm radius will slow down to one e'th of its initial angular velocity in 125 seconds. For a 1 mm radius cylinder, it would take 1.25 seconds.

Actually, a vortex in a liquid would probably slow down more rapidly at first because its angular momentum spreads out to larger radii almost immediately, thereby slowing down the center more rapidly. The outer parts of the eddy as it spreads have a longer time constant but start from a lower velocity. A good guess is that one can reduce the time by about one time constant below that calculated for the solid cylinder. A calculation of the angular momentum of the liquid between the cylinders of radii R and C reveals that it amounts to $\frac{\pi \rho R^4}{3} w_o$ where the angular momentum of the cylinder of radius R is $\frac{\pi \rho R^4}{2} w_o$ and conservation of momentum would slow down the whole thing. No attempt has been made to calculate the dynamic transients.

The calculation does indicate that if peripheral initial velocities are of the order of 200 cm/sec on eddys then an eddy about 1 mm in radius might be tolerable. Such a condition would result from a rake or comb being pulled through the liquid at 2 meters per second. The teeth on the comb would be about

4 mm wide on 8 mm centers. The comb then produces a Karman trail of vortices with radii of less than 2 mm which tend to cancel each other as they migrate in the liquid. These eddies should disappear in 1 second or less. However, rapid motion of large volumes of liquid have very long time constants and as a consequence no motions of large volumes of liquid can be tolerated.

These properties of liquid motion and their time constants suggest the two steps which must be taken to get rid of thermal turbulence by mixing.

The proposal involves the use of large units built like centrifugal blowers which are located along the bottom of the chamber. These draw liquid in over large horizontal areas with uniform velocity of 10 cm per second along the magnetic field. The liquid is forced out of the narrow periphery at a much higher velocity through heat exchanger combs. The liquid is then directed to the cylindrical walls of the chamber in an upward direction so that there is flow upward along the walls and to the top. Then the liquid flows down slowly across the center of the chamber and re-enters the centrifugal blowers or pumps.

Bubbles formed at the bottom of the chamber and near the bottom are drawn into the pumps and mixed and thrown out the sides. None of these bubbles can flow upward into the optical path. Bubbles formed in the liquid from tracks or dirt in the liquid will leave hot spots in the liquid which can be thoroughly mixed by the use of a comb raking through the liquid between pulses of the chamber.

Observations of Thermal Turbulence

The most illuminating experiment concerning thermal turbulence was performed in the following manner.

Motion pictures were made at f11 with a 4.5 cm focal length lens on 16 mm film from the end of the chamber. The Ramm plate was photographed at a distance of about six feet. The window was a "fish-eye" window, and the illumination was accomplished by sending a beam of light from a projection lantern placed along side the camera lens and pointing at the Ramm plate. This gave continuous and even illumination.

The chamber was pulsed at 2-second intervals for a maximum number of five consecutive expansions. A rake consisting of quarter-inch diameter rods on one-inch centers went the length of the chamber and was swept through the liquid by means of a rotating shaft going through the end plate of the chamber. The rake is shown in Figs. V-1, II-3.

One propellor was rotating so as to sweep the liquid toward the wall of the chamber. It rotated at a speed of about two revolutions per second.

Two sets of movies were made, one without raking and one with raking. The propellor was rotating throughout both sets.

These movies showed that with raking the one-inch grid and tracks at the end of the chamber were clear and undistorted, while those taken without raking were blurred by the thermal turbulence.

The O-ring seals around the window bubbled during expansion. Other bubbles swept across the line of sight near the lens. These came from the end plate seals. The bubbles close by made the one-inch grid disappear in some places. However, this hot liquid soon dissipated. The propellor swept some of the heated liquid up from the bubbles at the bottom of the chamber and from rough places on the rakes and walls so that it caused blurring of the grid.

Almost all of this blurring disappeared after passing the rake back and forth once in the two seconds between expansions. When the rake was not used there was much more residual blurring of the one-inch grid on the Ramm plate. Fig. V-2 shows the grid before any expansions. Fig. V-3 shows the grid after three expansions with raking. Fig. V-4 shows the grid after three expansions without raking. Fig. V-3 shows a little blurring and Fig. V-4 shows very bad blurring. The lines are 1 mm and 0.5 mm wide with one inch spacing.

Distortions Due to Liquid Motion

The side camera took pictures with two flashes 30 milliseconds apart. The first image shows a fine track, and the second shows the same set of bubbles again. After 30 milliseconds the bubbles have grown and they have also moved with the liquid. In the picture shown (Fig. V-5) the liquid has recompressed so far that it has moved to the left about a quarter of an inch. The corresponding picture (Fig. V-6) shows the same track taken by the end camera. The picture shows how the original negative appeared. This shows a narrow track which is light against the gray Scotchlite background. As it passes close to the lower right-hand corner of the picture the light from the side camera flashes again. It is possible to see the bubbles in the end camera pictures as black dots on the gray Scotchlite background. These bubbles are large enough to scatter appreciable light from the side camera light.

The bubbles have moved sideways about 0.4 inches at the point of greatest motion. A careful measurement of the thin track shows that it is distorted by about one-eighth of this distance. The thin track was photographed with a delay of 4 milliseconds.

The liquid motion is greatest near the bottom end. The rakes are going more dlowly at this point. It is concluded that this motion was not produced by the rakes but rather by the propellor along the side of the chamber. The velocity of the liquid is about 33 cm/sec as derived from the photograph.

VI. BUBBLE GROWTH RATE AND MOTION

The double flash pictures show that bubbles grow to a size of about 2 to 3 millimeters in diameter in 30 milliseconds. At that long delay the pressure in the chamber has risen more than a third of the way back to the recompression pressure as shown in Fig. VIII-1 and the bubbles are no longer growing. The vertical distance moved by bubbles from tracks during the expansion cycle never exceeds 3 cm. Larger bubbles go further, but those coming from cracks and rough surfaces appear to seldom exceed 5 cm.

Very good track images can be obtained with a light delay of 3 milliseconds. The bubbles appear to be about 0.4 mm in diameter. Our experiments were restricted to cosmic rays, and these occurred sufficiently rarely that it was impossible to pick the best arrival time for maximum rate of growth. The operating conditions with an accurately timed beam of particles could easily be chosen to give better results than we were able to obtain. It is quite possible that tracks with a 2-millisecond light delay would be entirely satisfactory. We have shown that a 3-millisecond delay under our unfavorable conditions is entirely adequate.

Measurements of the rate of rise of bubbles made from motion pictures indicate a maximum of 60 cm per second. However, conditions were not ideal because of lack of knowledge of the motion of the liquid.

Due to limitations of the expansion system it was not possible to go to lower temperatures and lower expanded pressures to explore a region where bubble growth would be expected to be more rapid.

VII. EXPANSION DYNAMICS

The velocity of sound in Freon at operating temperature is approximately 890 ft/sec. In a six-foot long chamber with expansion at one end the Freon can oscillate like a sound wave in a pipe with one closed end. The lowest frequency is at a wavelength of 24 feet with a period of 27 milliseconds. Higher modes are 3, 5, 7, etc. times shorter.

When the fundamental is excited, the pressure is constant at the open end and at the closed end the pressure would oscillate over a range equal to twice the change in pressure upon expansion. This is an undesirable mode because the pressure is uniform only at one instant during the expansion cycle and at that instant the rate of change of pressure at the closed end is at its maximum. Bubble growth would not be uniform over the length of the chamber.

It is most desirable to expand the chamber in such a way as not to excite this mode of oscillation. An air pressure wave which is sinusoidal and with a period three or six times the fundamental period will not excite this mode. A wave with a period shorter than three times the fundamental will always excite this mode. Therefore, the entire cycle cannot be shorter than 81 milliseconds and it might be safer to increase this. The chamber was usually expanded and recompressed in about 140 milliseconds and there is evidence from the traces that the fundamental mode was excited (see Fig. VII-1). The end of the trace shows an oscillation with a period of 26 milliseconds.

Movies taken at 1600 frames per second of a track formed near the expansion end of the chamber showed oscillations in the size of the bubbles with a period of 23 milliseconds. The period of this oscillation corresponds to the fundamental period of the liquid in the chamber. There is every indication that the sizes of bubbles at any instant are a strong function of the shape of the pressure wave in the liquid around them.

The air system also can oscillate, but in a different fashion. The air moving in the pipes connecting the chamber and the expansion acts like a weight and the expansion tank acts like a spring.

In the model the air system starts at the chamber with a dead volume of about 2 cubic feet. An 8-in. diameter pipe 8-feet long connects to an expansion tank with a volume of 29.5 cu ft. The simple formula for the oscillation of air in a tube of length ℓ and cross sectional area A acting as the mouth of a tank of volume V is $w^2 = C^2 A/\ell V$ where C is the velocity of sound and w is the angular frequency. If there are two volumes, V_1 and V_2, at either end of the tube, then

$$w^2 = C^2 A/\ell \quad (V_2\, V_1/V_2 + V_1) \; .$$

In the model C = 1000 ft/sec and A = 0.2864 sq ft.

$$V_2 = 29.5 \text{ cu ft} \quad \text{and} \quad V_1 = 2 \text{ cu ft.}$$

$$w^2 = 1.911 \times 10^4 \qquad w = 138.2$$

The frequency is $V = 3/2\pi = 22$ cycles/sec. The period is 45.4 milliseconds.

A similar calculation can be made for recompression. The pressures which can result from the air motion are very large and can cause overshoots of 150 psi if the initial pressure change is 150 psi if there is no damping.

In actual operation of the chamber the Grove valves are opened and closed in such a way as to avoid overshoots. However, if the control of a Grove is not maintained properly, as in the case of electronic failure, such pressure overshoots can be observed. These are never observed to exceed 70 psi owing to viscosity losses and the smaller apertures of the Grove valves in the lines.

Care must be taken in the design of a large chamber not to have the air periods correspond to the fundamental period of the liquid. The complete dynamics of liquid and gas must be calculated for a satisfactory design.

In operating the model particular care was necessary in recompressing the chamber to avoid large pressure rises at the closed end. The chamber operated with a recompression pressure of 300 psig. A safety valve at the closed end of the chamber was set to relieve at 400 psig. A small adjustment in the timing of the recompression Grove valve would cause this relief valve to open momentarily. The cause of this overshoot came mainly from a wave with a period of 26 milliseconds corresponding to the fundamental period of the Freon in the chamber.

VIII. PHOTOGRAPHY

The development of a reflective coating of sufficiently fine grain and uniformity by the Minnesota Mining Company has made its use possible in bubble chambers.

The advantages of Scotchlite are many:

1. The power required for illumination is at least an order of magnitude less than that for other methods.
2. The bubble size required for a given size image is smaller because the entire bubble throws a shadow. Other methods produce spots of light smaller than the bubbles. The image of a bubble does not change in brightness with depth in the chamber as is the case with side illumination.
3. The uniformity of appearance of the images makes it possible to over-expose uniformly so that the images on the film are smaller than the resolving power of the lens would indicate by about a factor of two.
4. The background-to-noise ratio in automatic track following equipment is much lower because the image on the film is clear against a blackened background.
5. The lights can be located outside the chamber where they are readily accessible when there are light failures.

An objection to Scotchlite arises from the fact that the front element of a wide angle lens must be made small so that the ring light around the lens may have a sufficiently small radius to satisfy the angularity requirements of the Scotchlite. This restriction on the front element of the lens makes the problems of distortion in the image more difficult.

An objection raised by others has been heard which goes as follows. Suppose that due to thermal turbulence the image of a bubble is badly out of focus. Then the contrast of the image is sufficiently low as to fail to leave perceptible lightening on the black background of the negative. However, if sufficient illumination is available for dark field illumination, a blur will appear as a darkening of the negative. The difficulty with the argument arises from the fact that clear tracks will then be greatly overexposed, will spread by halation on the film, thereby losing much detail. This is a characteristic of the variation of exposure with depth in the chamber when side lighting is used.

This objection to bright field illumination can be stated in another way. Suppose the bubbles are very much smaller than the circle of confusion of the lens. Then with bright field illumination the bubbles will not show. However, with dark field illumination sufficient light can be powered in to make them visible. The same difficulty with this argument appears again. Bubbles close to the lens will be badly overexposed, thereby losing detail as before.

6. Another argument in favor of bright field illumination concerns the ability to scan visually very fine tracks. A very fine white line on a black background is easy to see. A similarly fine black line on a white background takes much greater visual acuity. Since the widths of tracks in these large chambers vary by at least a factor of five depending upon the distance from the lens, this greater ability to see very narrow images on the film becomes very important.

Photographs of Tracks

Figures VIII-1, 2 show a cosmic ray photographed three milliseconds after arrival. Figure 1 is the end view taken 73 in. away through Freon. The demagnification on the film is 48 times. The grid consists of one-inch squares. The heavier lines are 1-mm wide, and the lighter lines 1/2-mm wide. They are drawn on the Scotchlite.

Figure VIII-3 shows a life-size blow-up of the delta ray on the 3 millisecond delay track. The picture was taken from the end and the demagnification on the film is 48 times.

Figure VIII-2 shows a photograph taken by the side camera. The cosmic ray enters through the Scotchlite on the walls of the chamber and at that point is 31 in. from the side camera objective. Figure VIII-4 shows a life-size reproduction of the delta ray. The film demagnification is 24 so that the grain size should be nearly half as big as in Fig. 3. Bubble count can almost be made in Fig. 4 but not in Fig. 3. The delta ray in Fig. 4 is 27 inches from the side camera objective.

The focal length of the side camera lens was 32 mm and pictures were taken at f 11. The radius of the diffraction disk is 0.2 mm, diameter 0.4 mm at the track. The bubbles appear to be about 0.4 mm in diameter. The pictures taken by the end camera have a diffraction disk at the track about twice as big. The bubbles, or rather the track, appears to be twice as wide.

As earlier experience has shown, Scotchlite pictures give images of bubbles of the same size or smaller than the diameter of the Airy disk.

Figure 2 was made with the lights flashed twice 30 milliseconds apart. In this interval the Freon recompressed and the bubbles moved to the left with the liquid. This motion is irregular due to currents in the Freon produced by the propellers and raking. At the far wall the motion is about 8 mm. The bubbles have grown to a diameter of about 3 millimeters in this time. A track which arrived earlier left bubbles about twice this diameter.

It is interesting to note that the track shown in Fig. 2 was made with a double flash. The bubbles in the delta track are of the same order of magnitude (probably smaller) as the size of the Airy disk. The film is also exposed a second time, which reduces the contrast. In spite of this, the contrast appears to be very good.

At a delay of 2 milliseconds the bubbles are too small to give satisfactory pictures. One of these events is shown in Figs. VIII-5, 6. The arrows show a straight track coming out of the Scotchlite plate at the end of the chamber and a pair of tracks coming out of the side wall of the chamber. Figure VIII-7 shows the pair viewed from the side camera 1.1 times life-size. Figure VIII-8 shows the straight track viewed by the side camera life-size. This track was 18 in. from the side lens, whereas the pair was 31 in. from the side lens. Figure VIII-9 shows the straight track at 3.3 times life-size, and finally, Fig. VIII-10 shows the straight track viewed from the end camera. This is life-size.

Figure 8, as mentioned before, is life-size. The bubbles appear to be not greater than 0.1 mm in diameter. This track can be seen by the end camera where the radius of the Airy circle is 0.4 mm in radius. On the basis of these photographs we can say that Scotchlite illumination permits observation of bubbles which are four times smaller than the radius of the Airy circle.

FIGURE CAPTIONS

FIGURE CAPTIONS (continued)

Fig. VIII-2. Side View of a Cosmic Ray With a Delta Ray Near the Center of the Picture. The Tines of the Rake Show at the Top of the Picture. The Expansion End of the Chamber is Out of the Picture to the Right.

Fig. VIII-3. Life-Size Blow-Up of the Delta Ray Taken with the End Camera. Magnification From Film 48x.

Fig. VIII-4. Life-Size Blow-Up of the Delta Ray Taken with the Side Camera. Magnification From Film 24 x.

Fig. VIII-5. End View of a Cosmic Ray With a 2 msec Light Delay.

Fig. VIII-6. Side View of the Same Cosmic Ray Track as Shown in Fig. VIII-5.

Fig. VIII-7. A Pair with a 2-msec Light Delay Photographed with the Side Camera. 1.2 Times Life-Size.

Fig. VIII-8. The Straight Track Viewed From the Side Camera Life-Size. The Point of the Pair Shows at the Bottom of the Picture.

Fig. VIII-9. The Straight Track Viewed From the Side Camera 3.3 x Life-Size.

Fig. VIII-10. The Straight Track Viewed From the End Camera Life-Size.

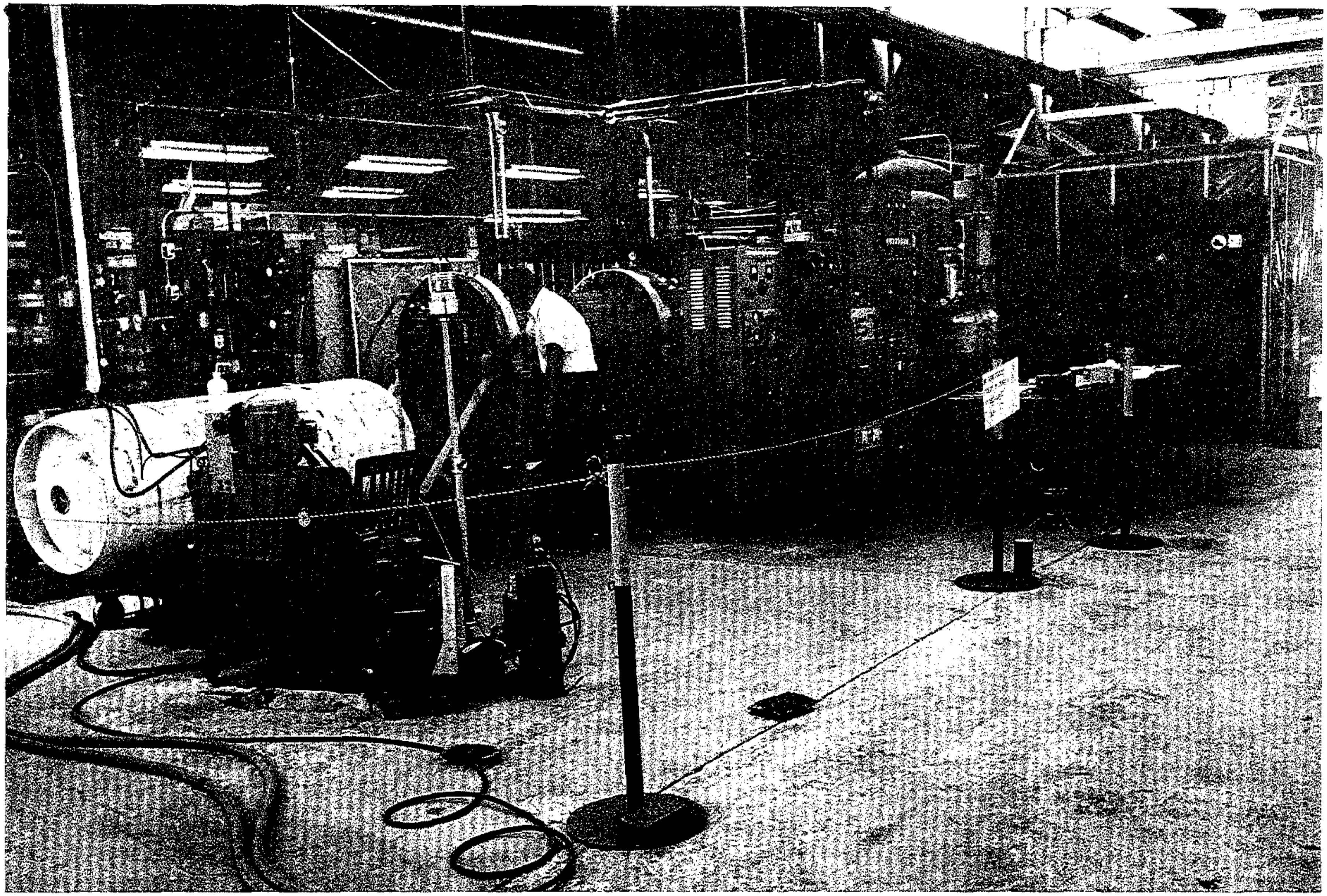


Fig. I-1. The Model Chamber

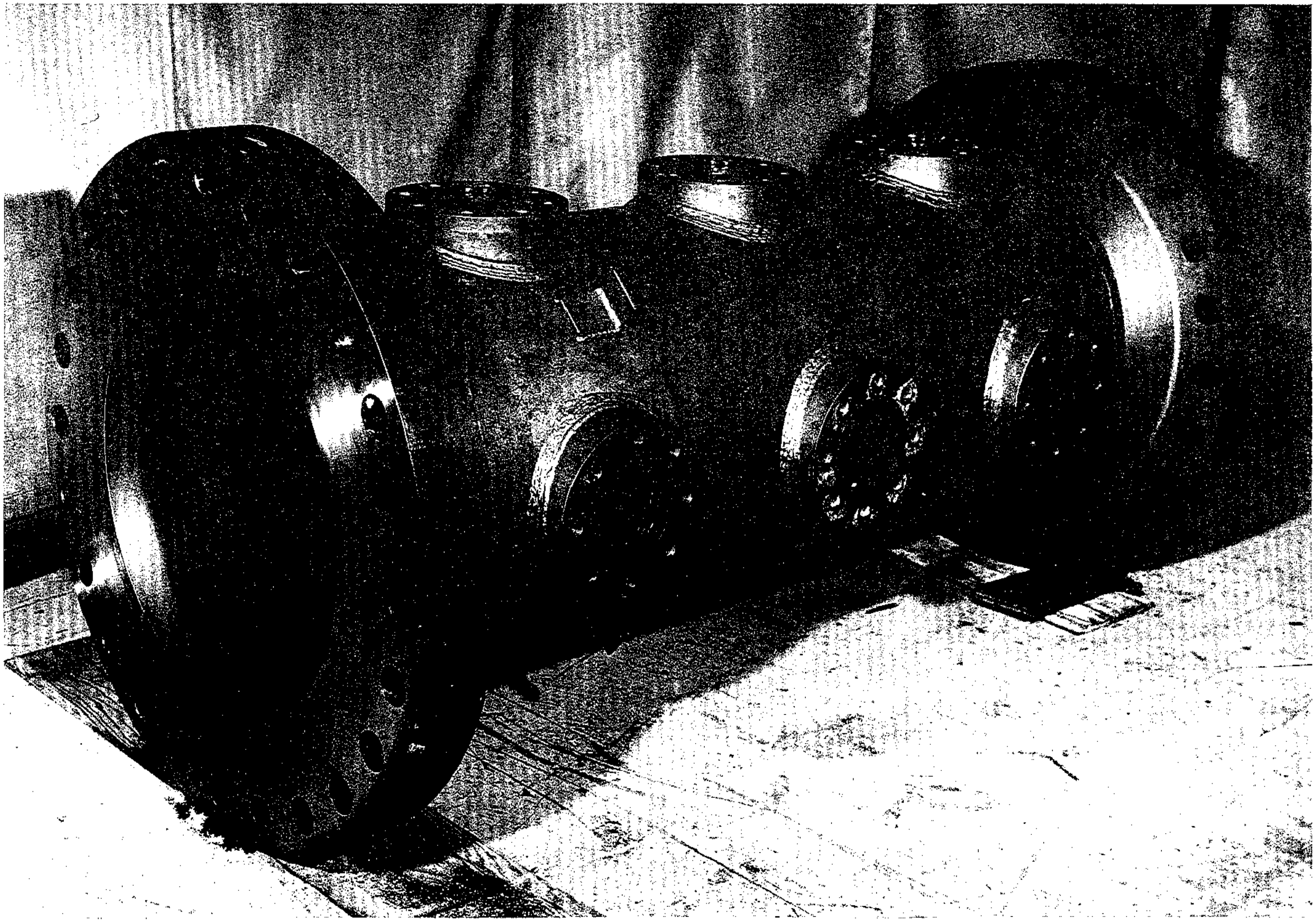


Fig. I-2. The Chamber Body After Welding.

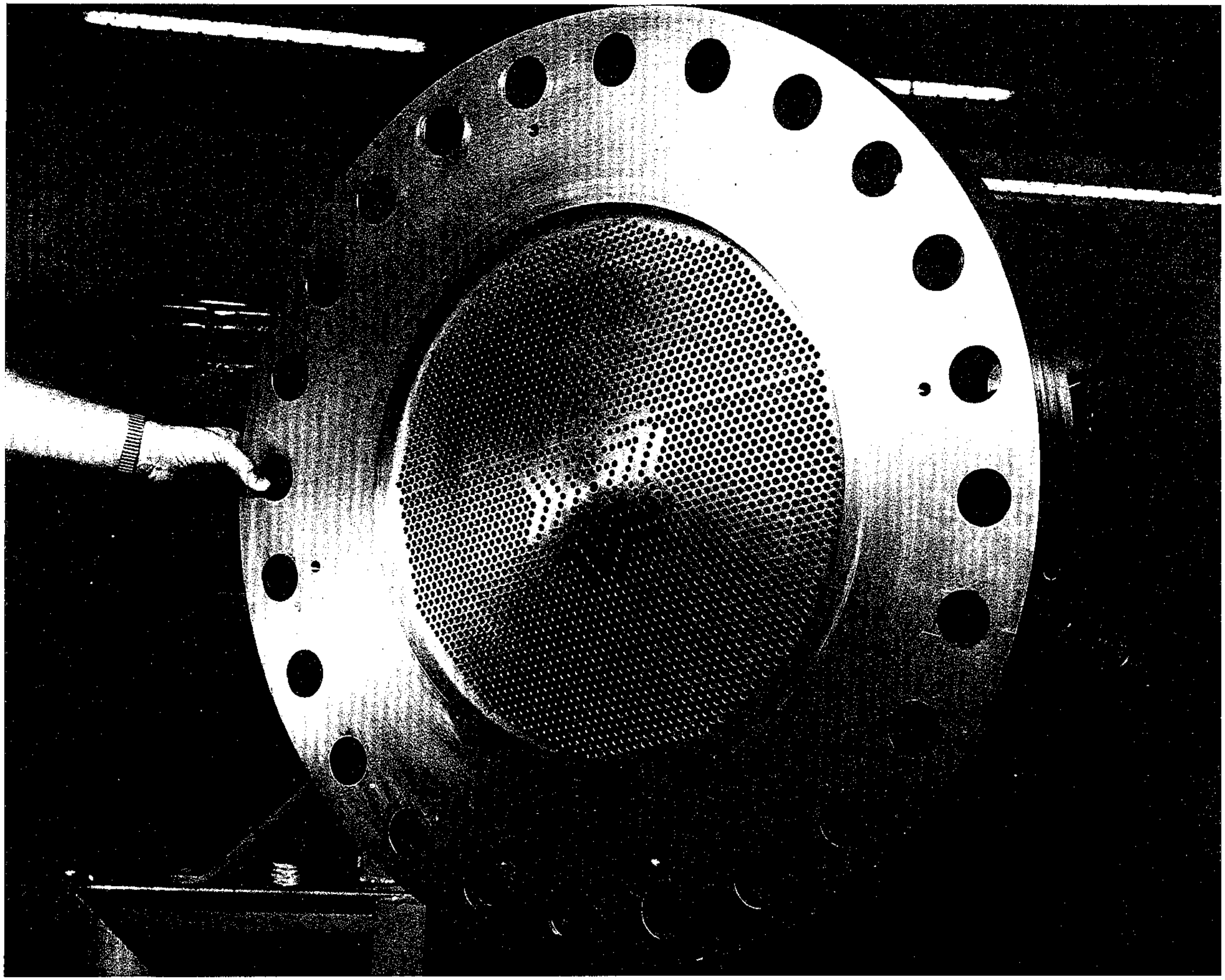


Fig. I-3. The Convex Side of the Holey Plate.

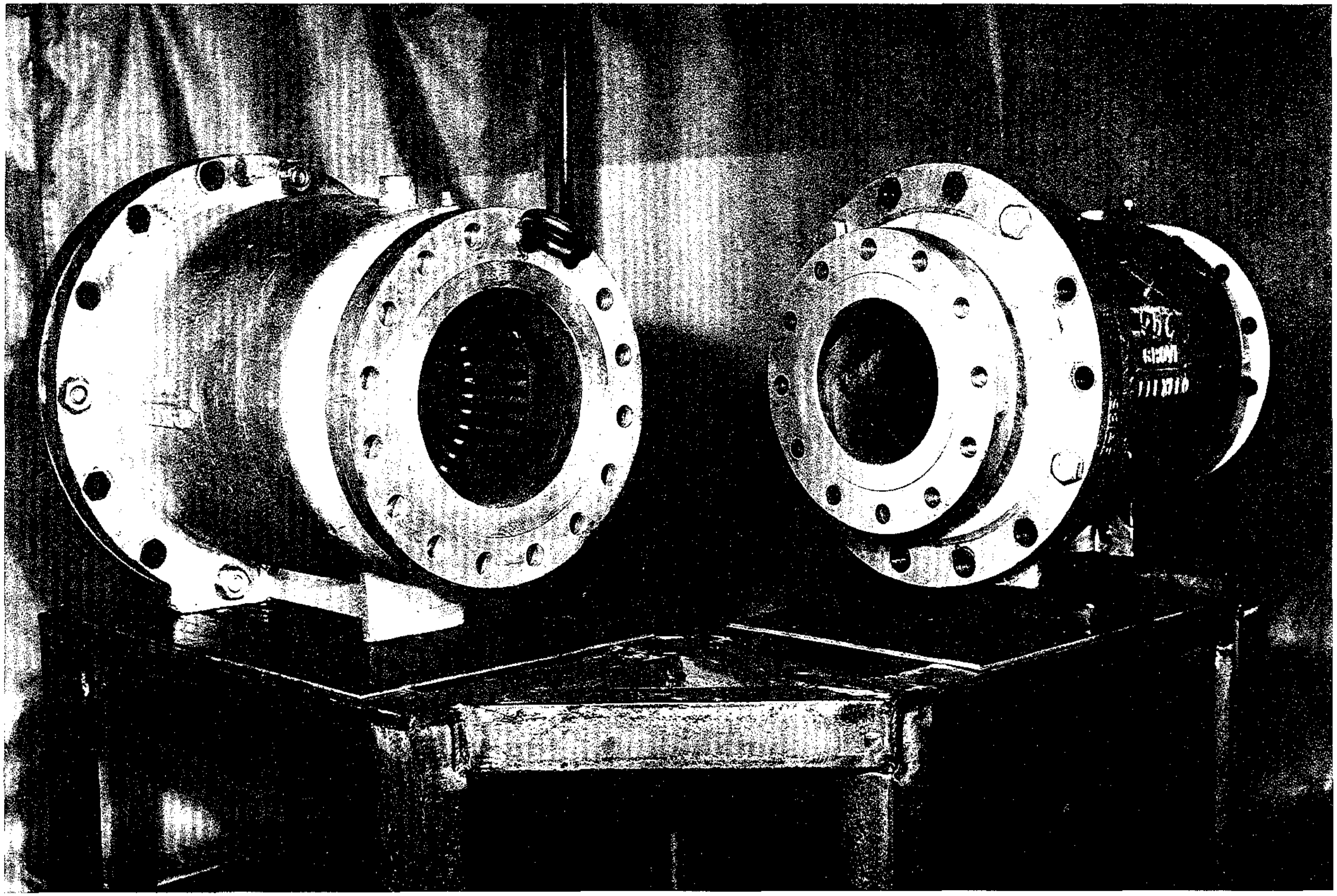


Fig. I-4. The 10-in. and 8-in. Grove Valves.

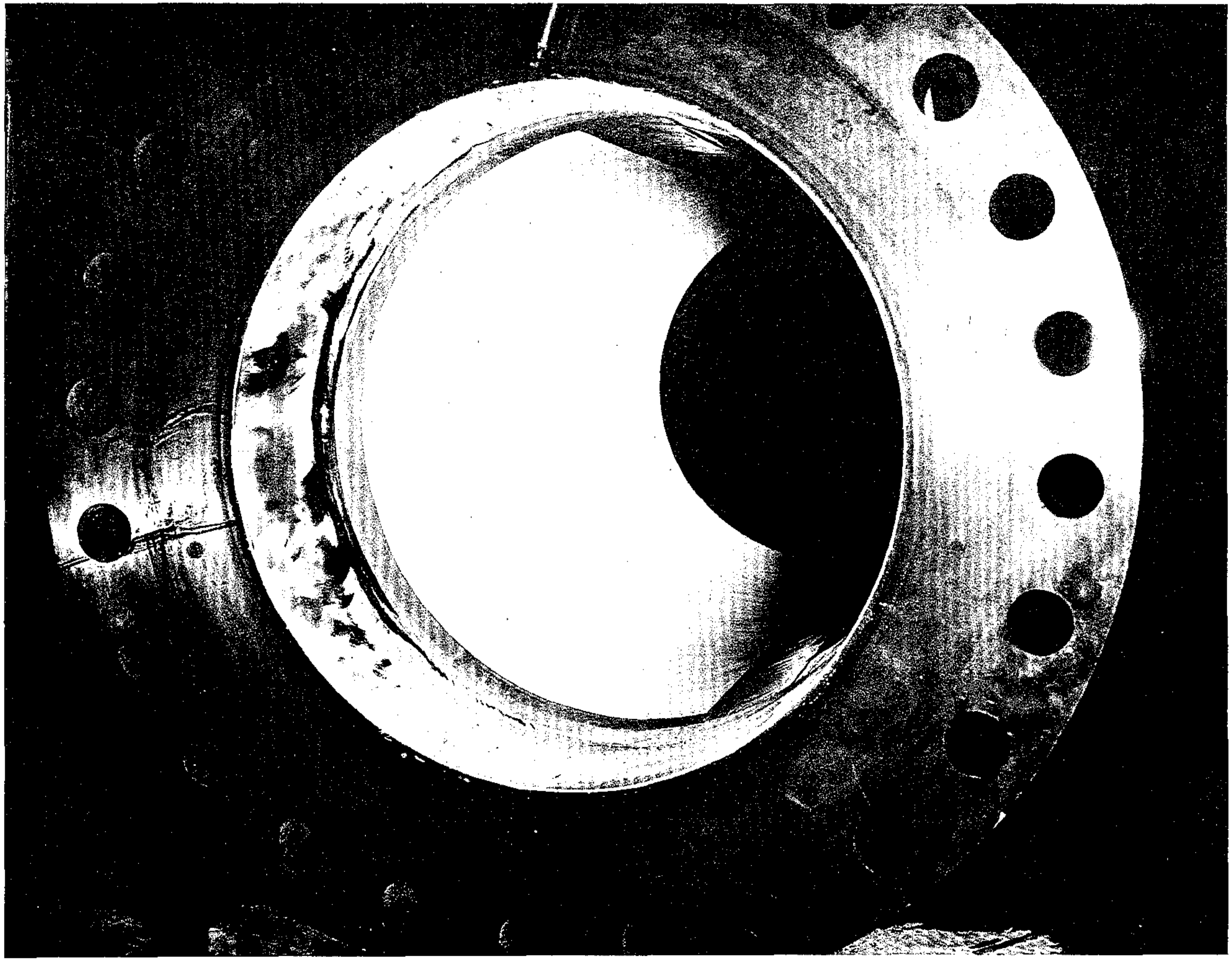


Fig. I-5. The Scotchlite on the Inner Wall of the Chamber.

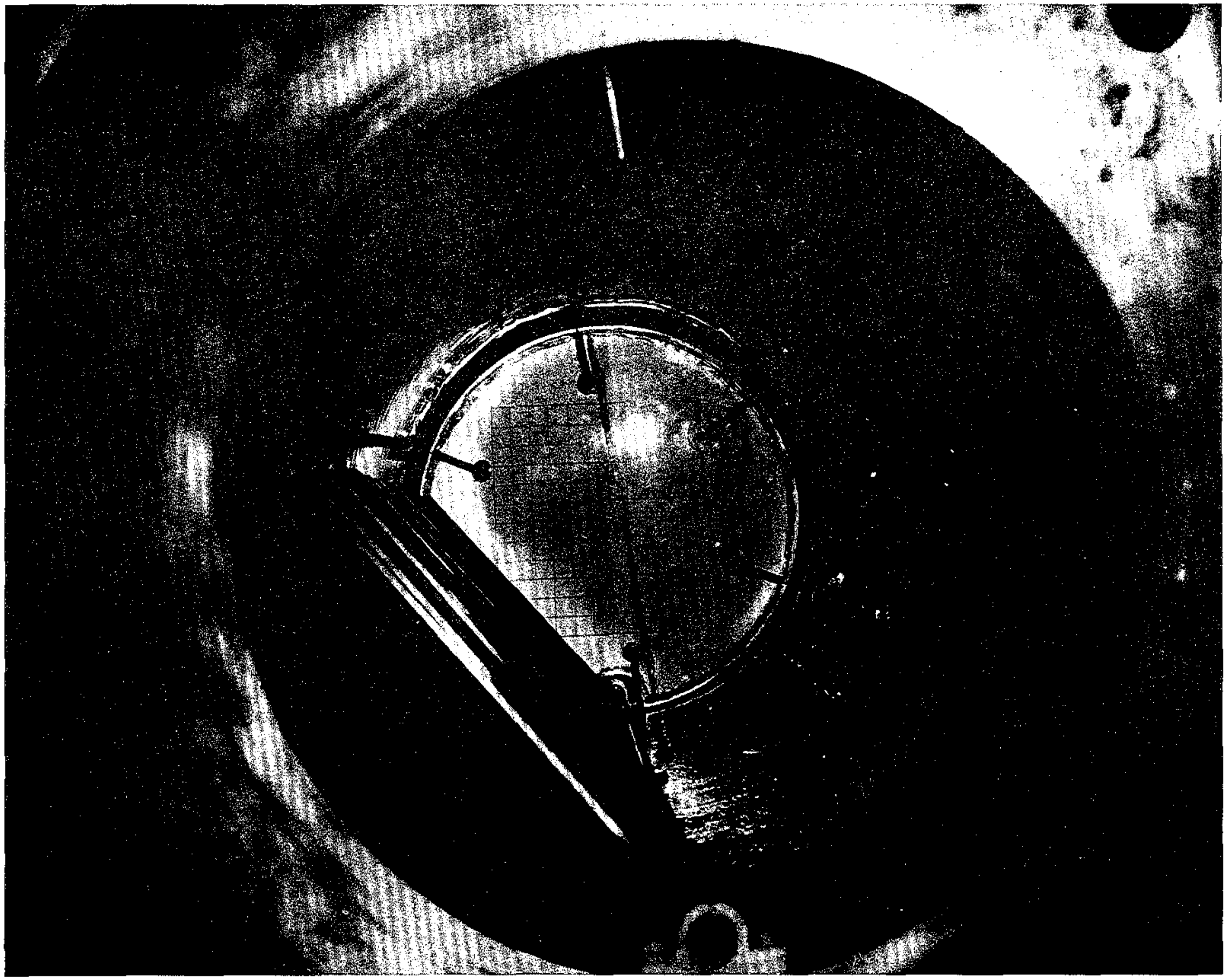


Fig. I-6. A View From the Closed End of the Chamber Showing the Rake and the Ramm Plate.

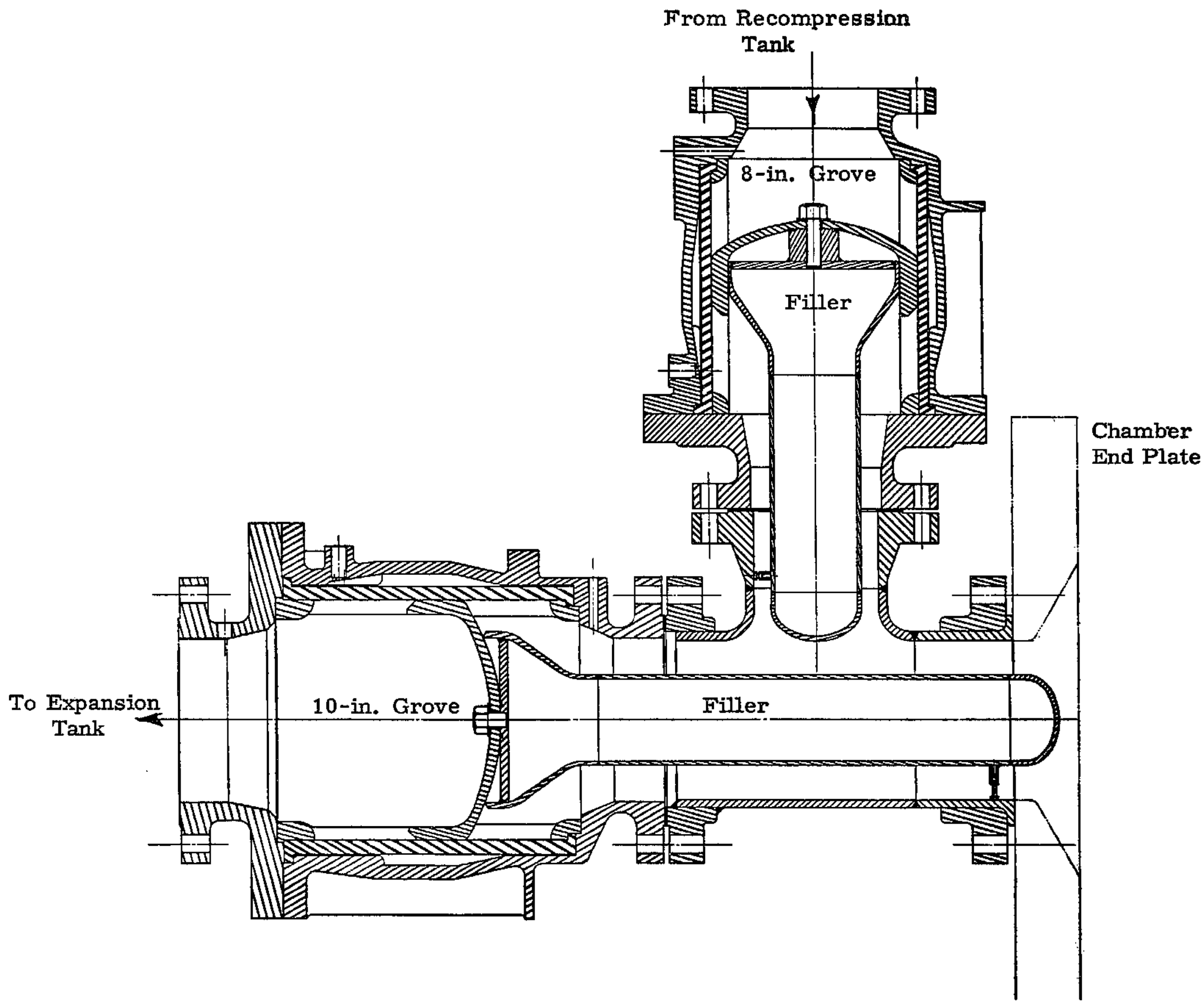


Fig. I-7. Grove Valve Assembly

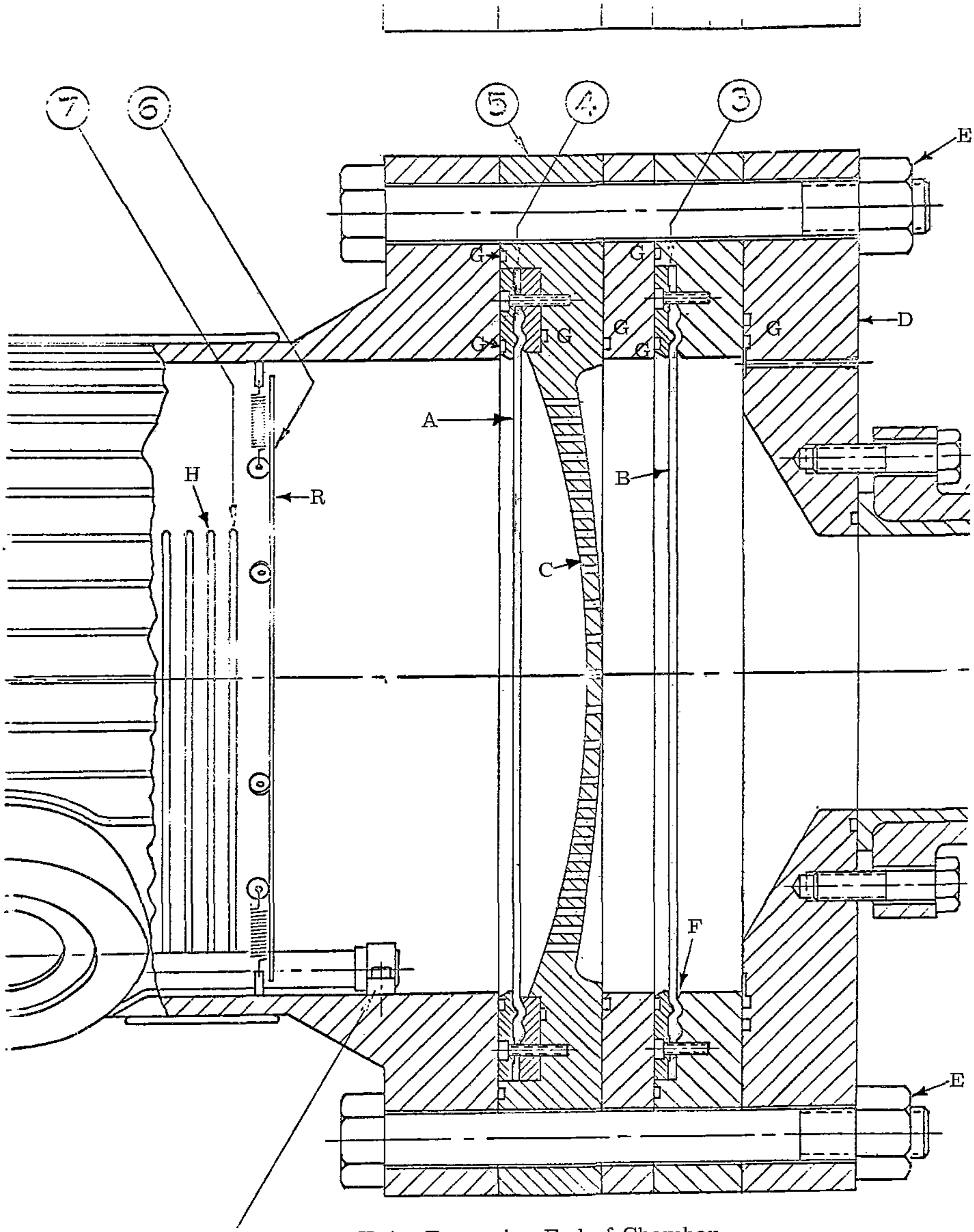


Fig. II-1 Expansion End of Chamber

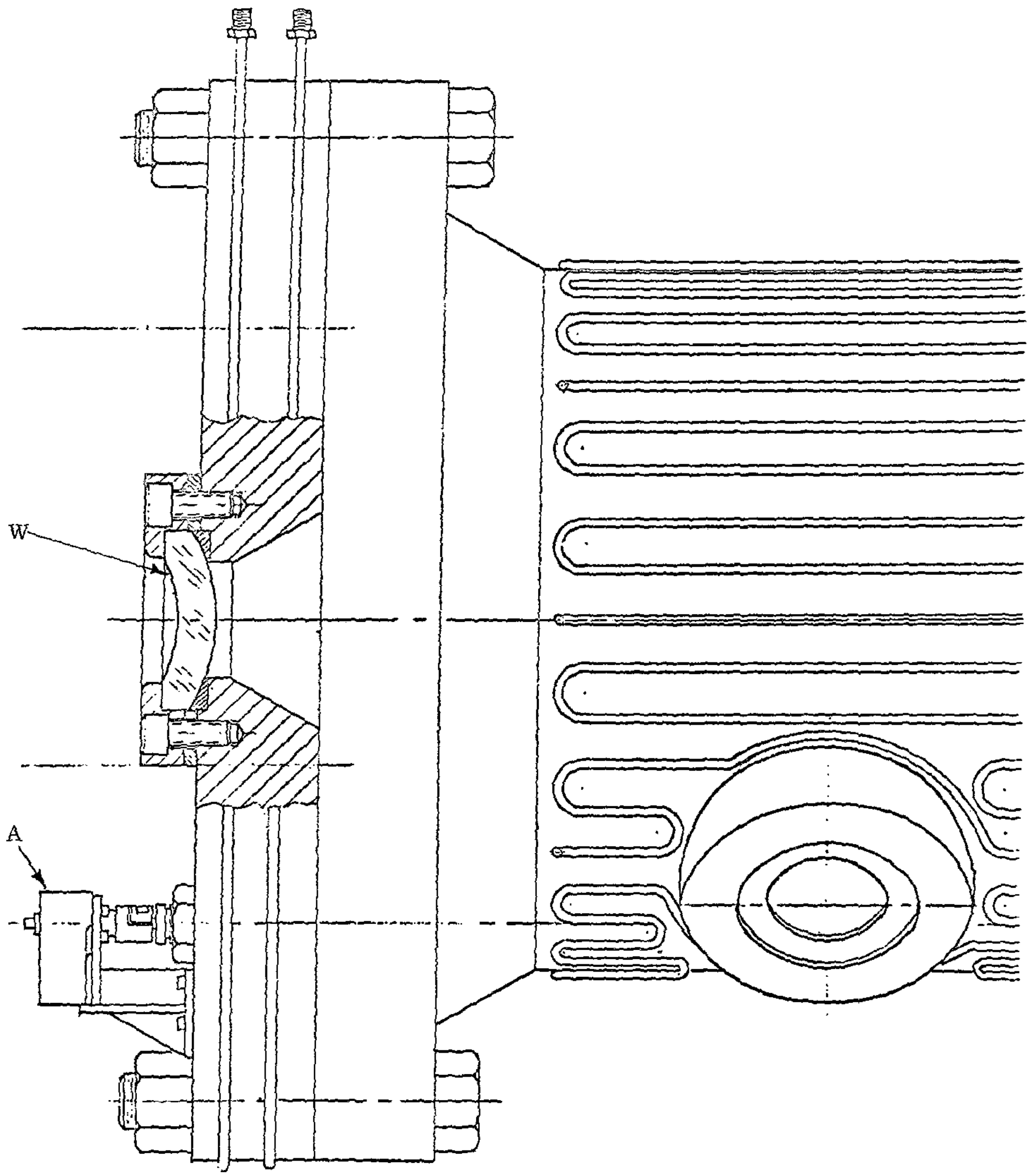


Fig. II-2 Closed End of Chamber

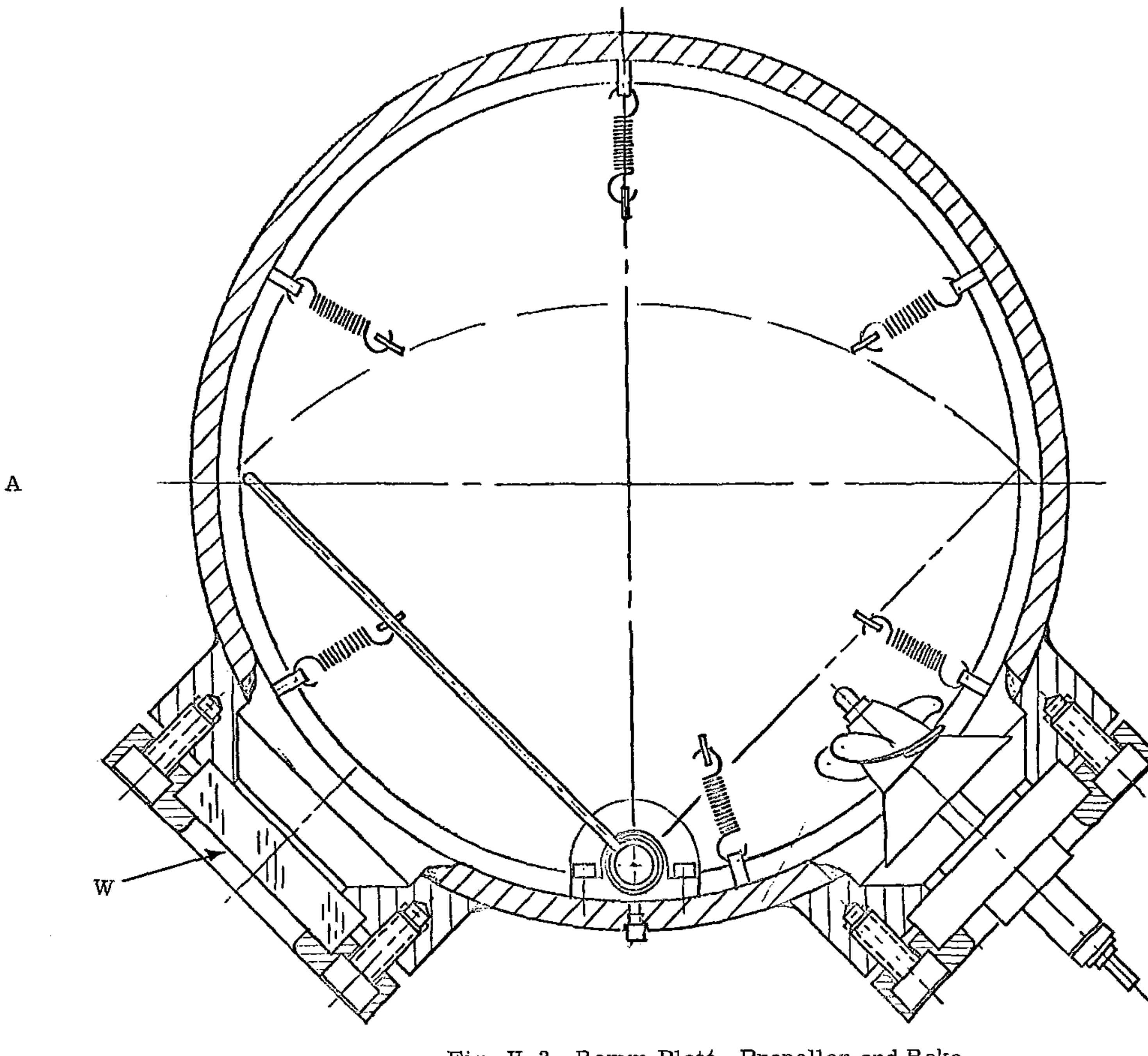


Fig. II-3 Ramm Platé, Propellor and Rake
Viewed from Closed End of Chamber

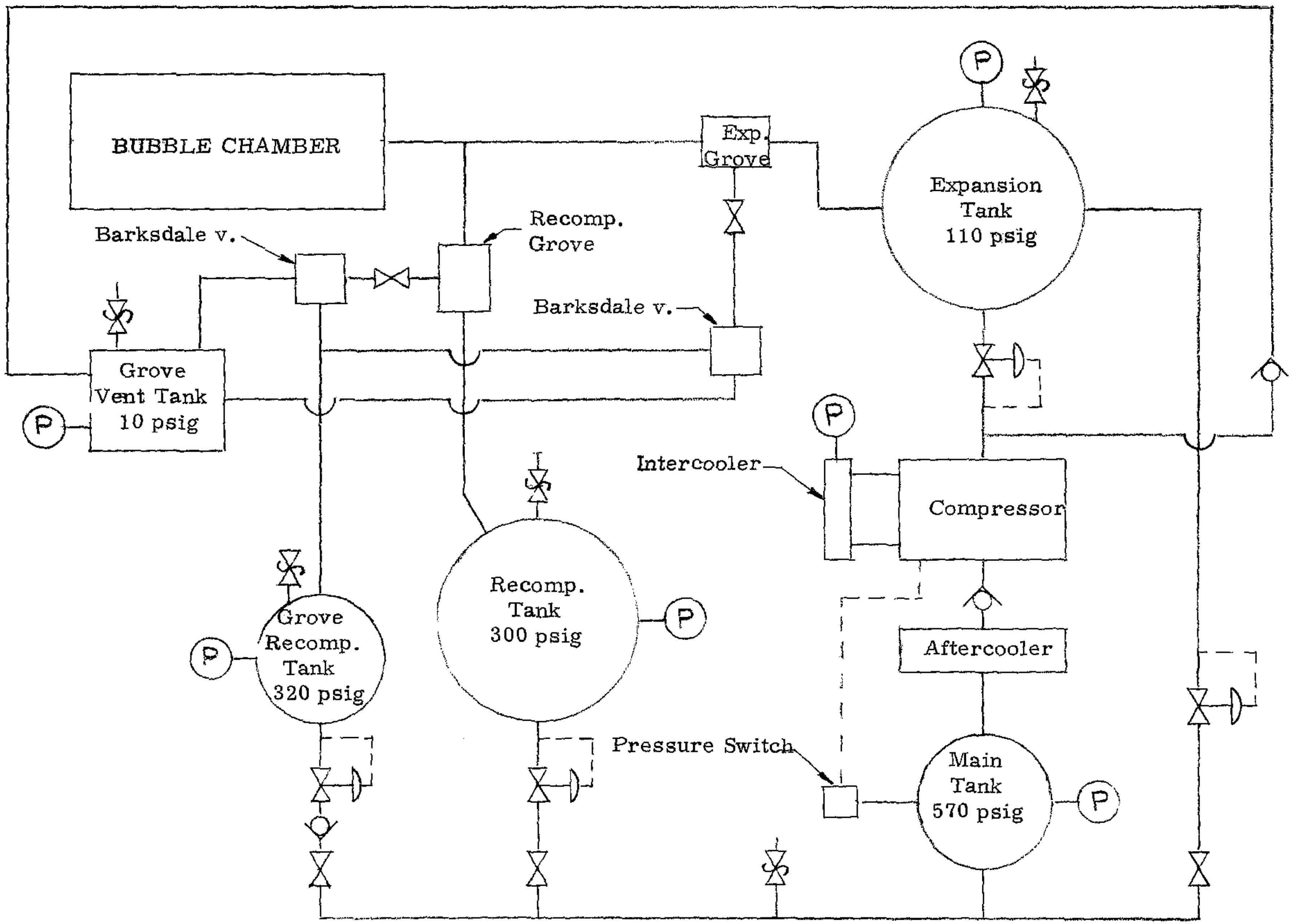


Fig. II-4. Schematic of the Air System

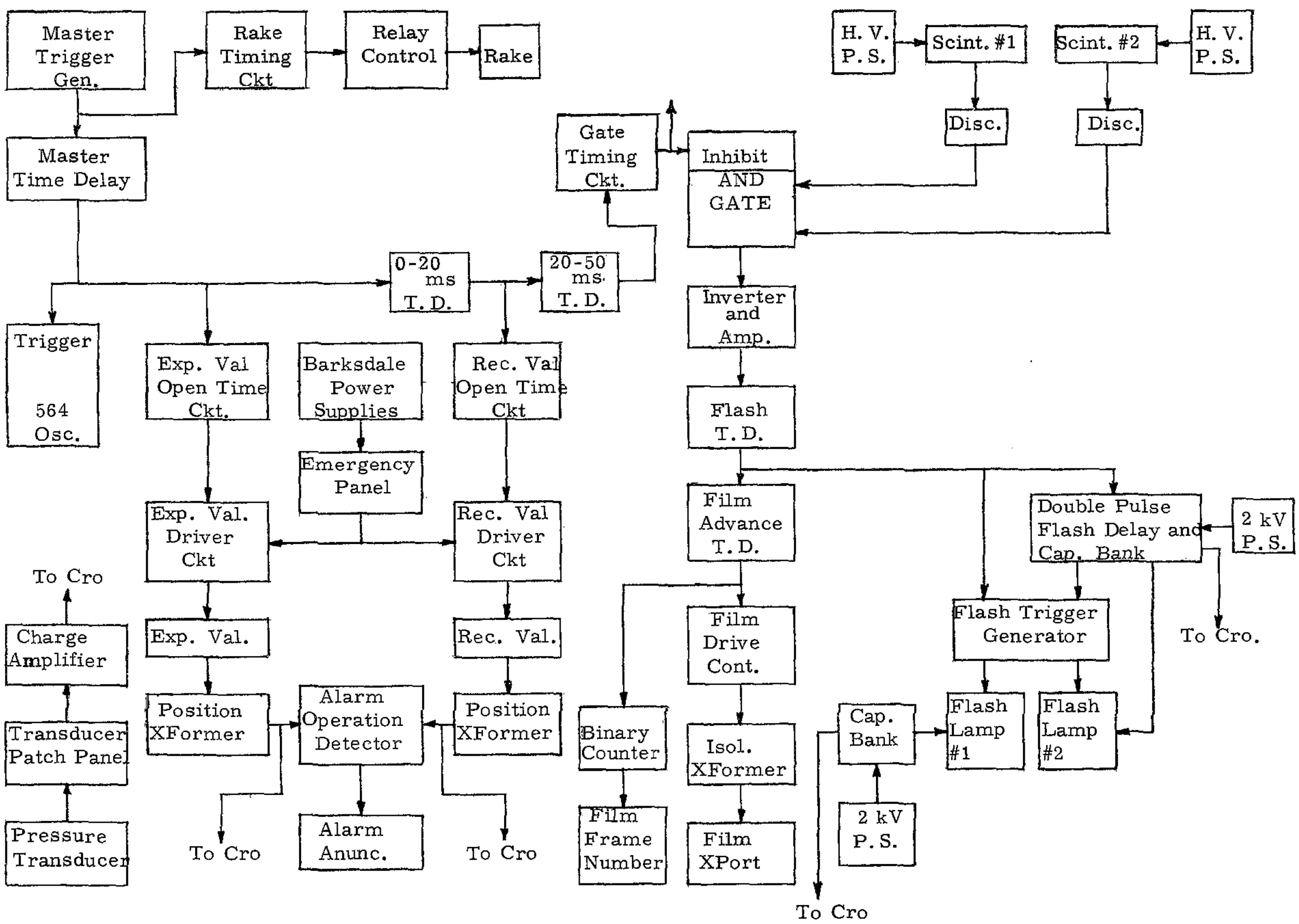


Fig. II-5. Block Diagram of Chamber Electronics

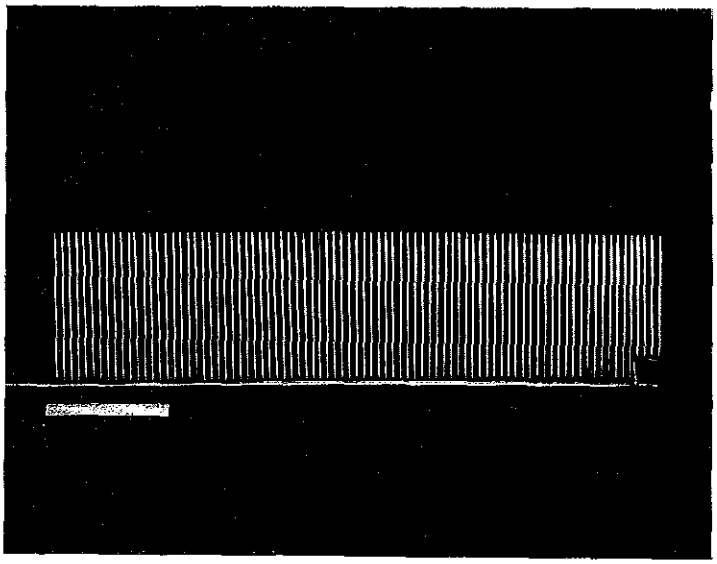


Fig. V-1. Rake Used in Model Chamber.

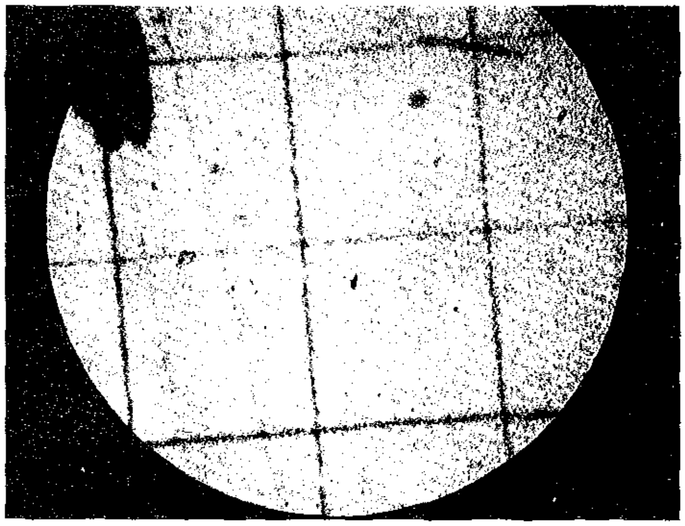


Fig. V-2. Full Scale Grid Before Expansions.

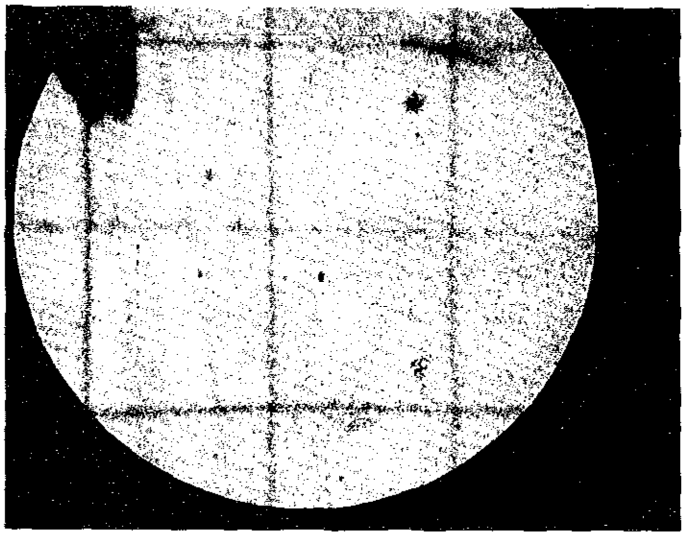


Fig. V-3. After Three Expansions at 2-sec Intervals with Raking.

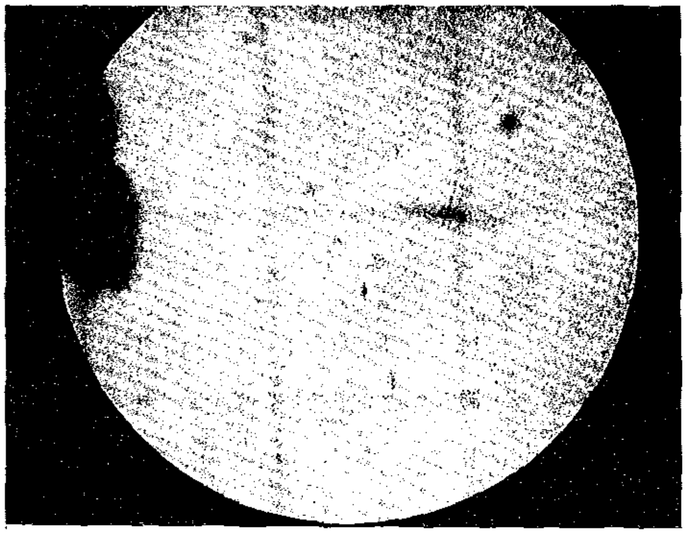


Fig. V-4. After Three Expansions at 2-sec Intervals without Raking.

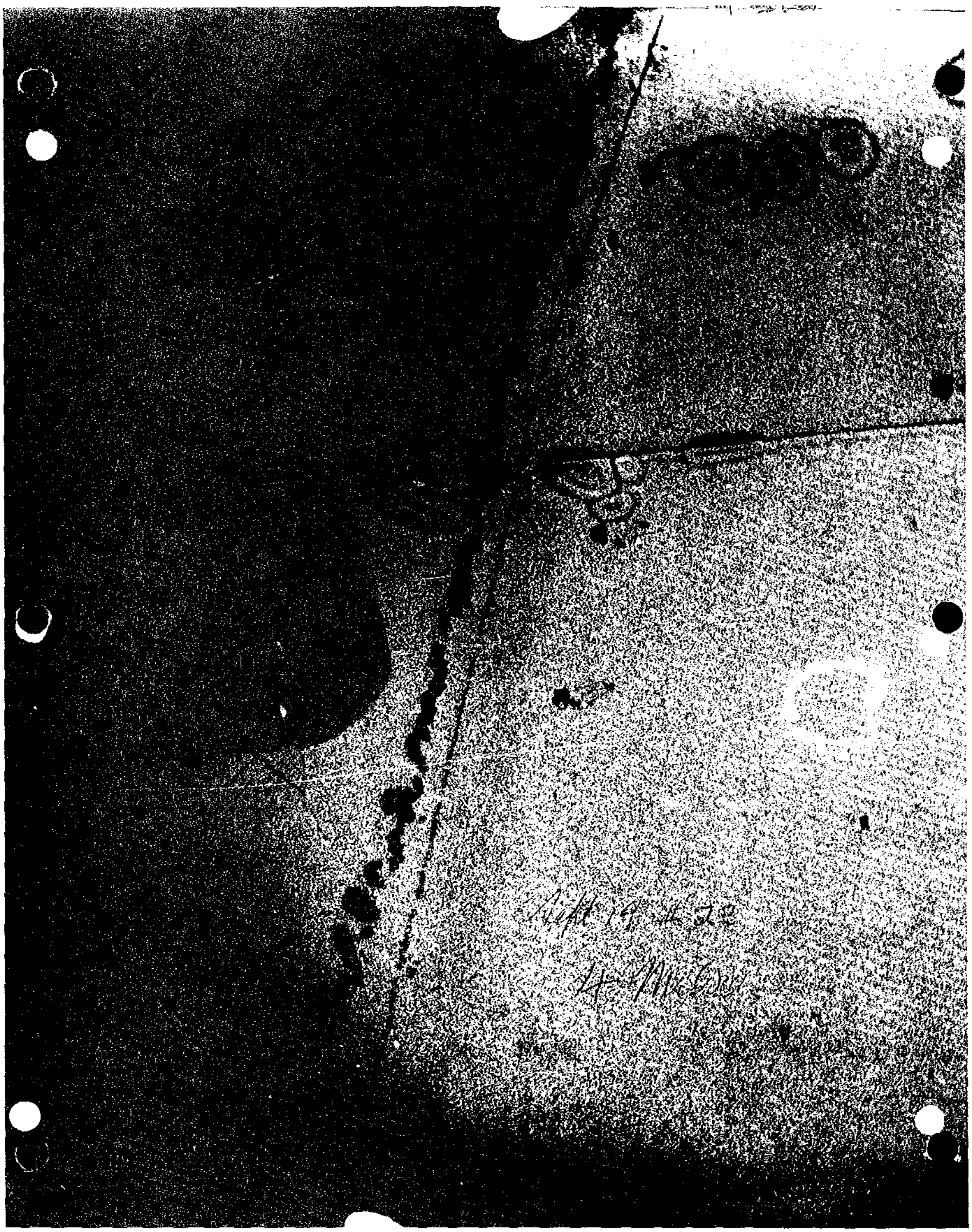


Fig. V-5. Double Flash Picture Showing the Initial Track and Final Position of the Bubbles After Recompression.

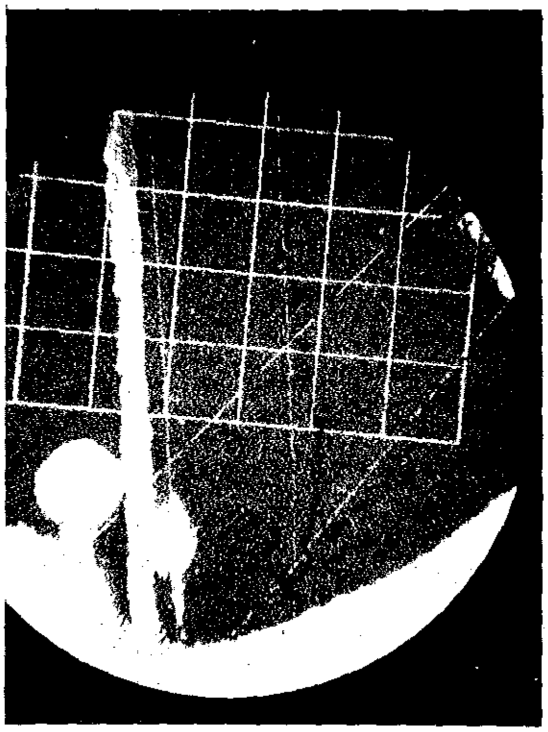
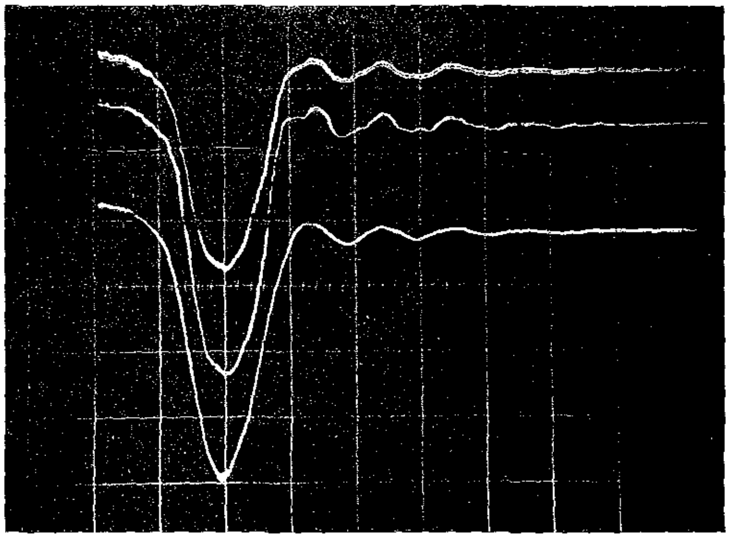


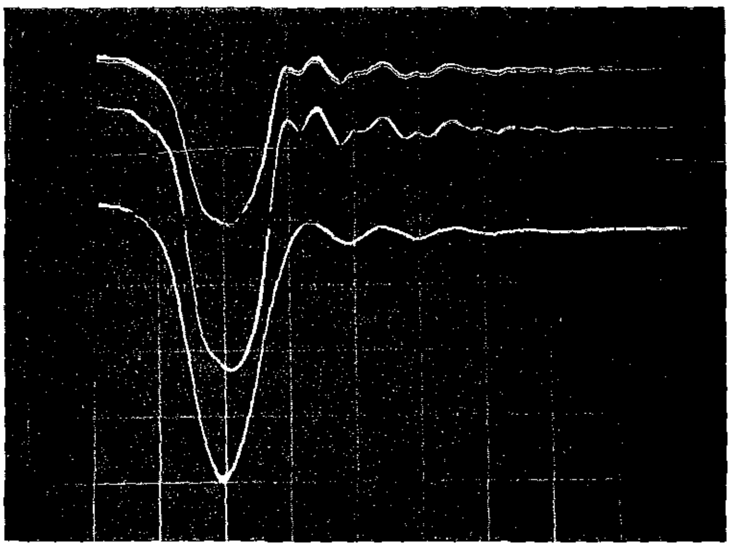
Fig. V-6. The Black Dots are Bubbles Illuminated by the Side Camera Lights on the Second Flash 30 msec After the First Flash.



14.4 inches from diaphragm

28.8 inches from diaphragm

Pressure in the TEE



43.2 inches from diaphragm

57.6 inches from diaphragm

Pressure in the TEE

Fig. VII-1. Pressure Waves in the Chamber, 50 msec per cm.

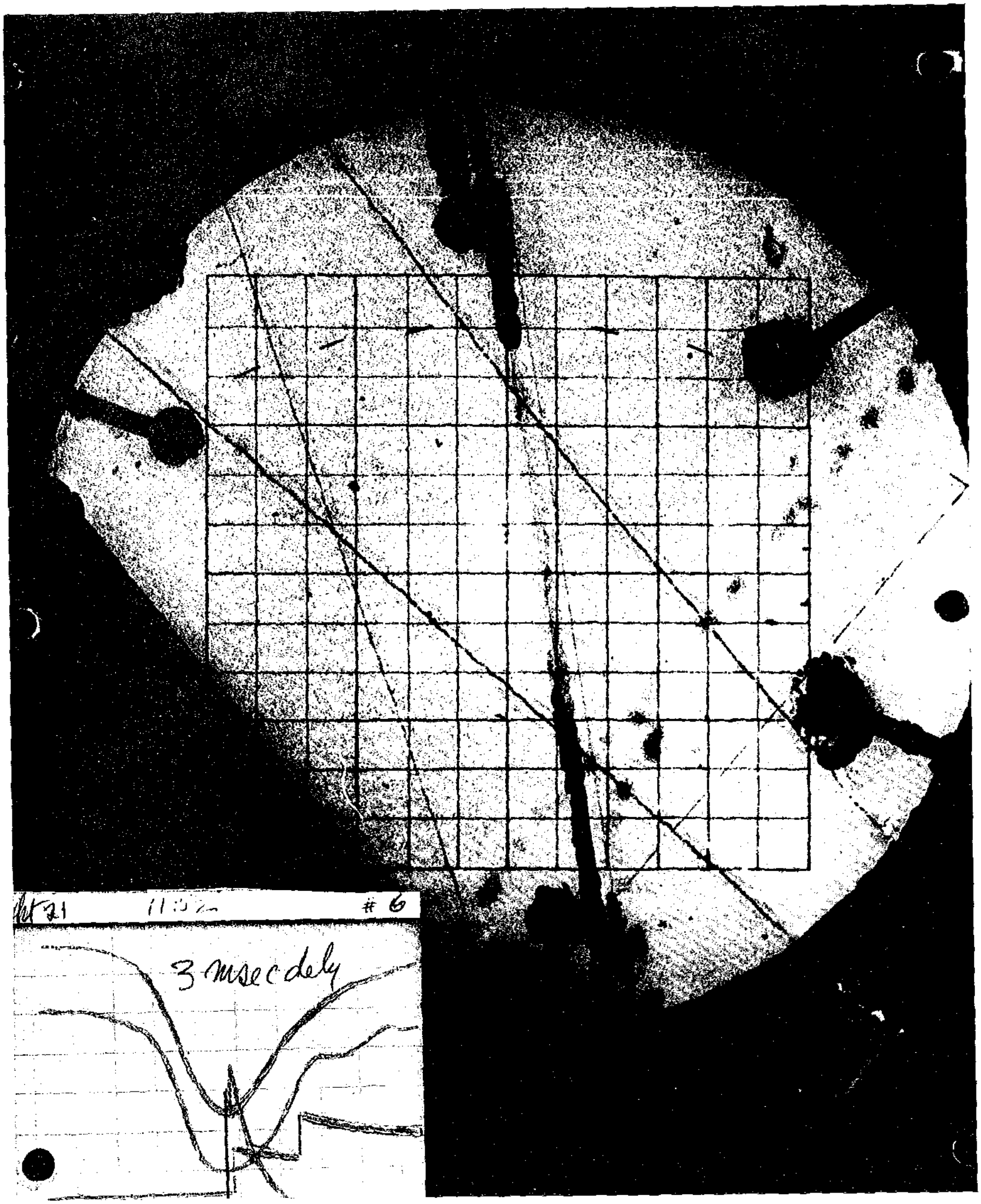


Fig. VIII-1. End View of a Cosmic Ray with a 3-msec Light Delay. The Narrow Track with the Delta Ray Near the Top is the Timed Track. Two Other Cosmic Rays Arrived Earlier.

Fig. VIII-2. Side View of a Cosmic Ray With a Delta Ray Near the Center of the Picture. The Tines of the Rake Show at the Top of the Picture. The Expansion End of the Chamber is Out of the Picture to the Right.

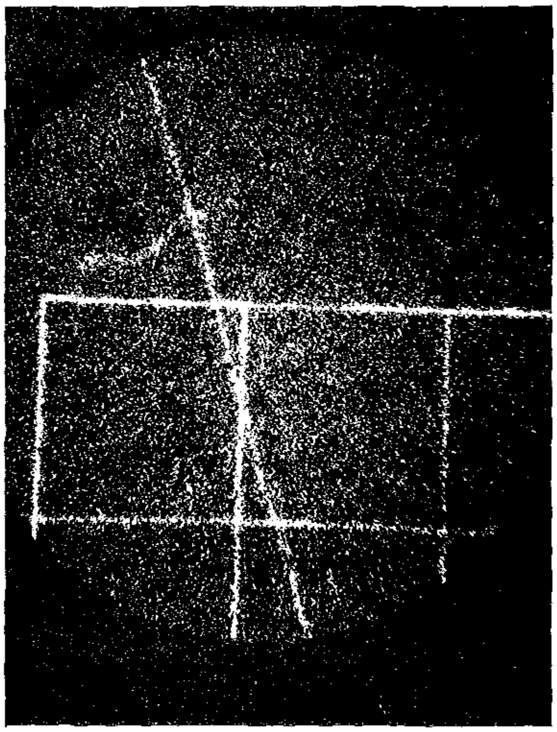


Fig. VIII-3. Life-Size Blow-Up of the Delta Ray Taken With the End Camera. Magnification From Film 48 x.

Fig. VIII-4. Life-Size Blow-Up of the Delta Ray Taken With the Side Camera. Magnification From Film 24 x.

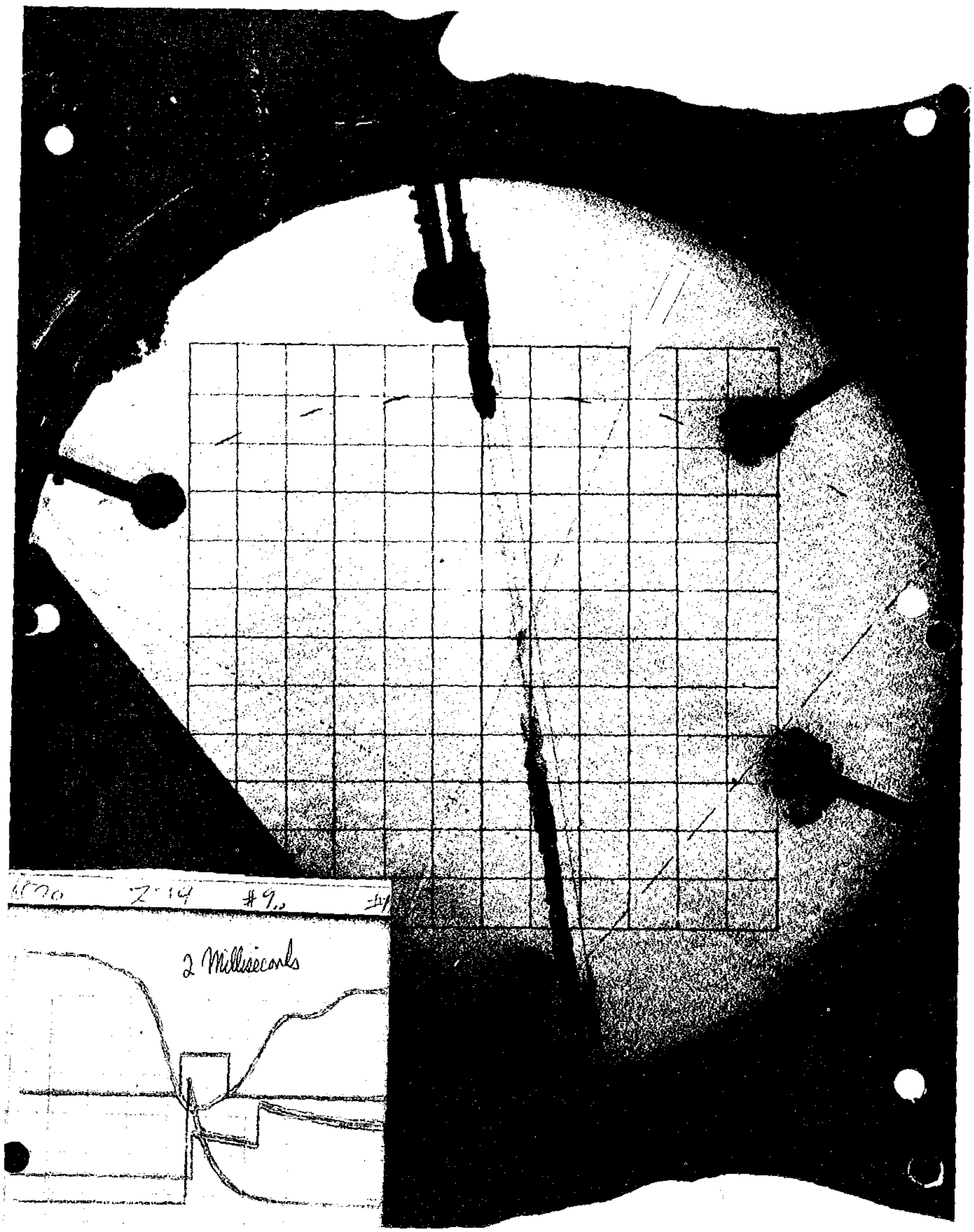


Fig. VIII-5. End View of a Cosmic Ray With a 2 msec Light Delay.

Fig. VIII-6. Side View of the Same Cosmic Ray Track as Shown in Fig. VIII-5.

Fig. VIII-7. A Pair with a 2-msec Light Delay Photographed with the Side Camera. 1.2 Times Life-Size.

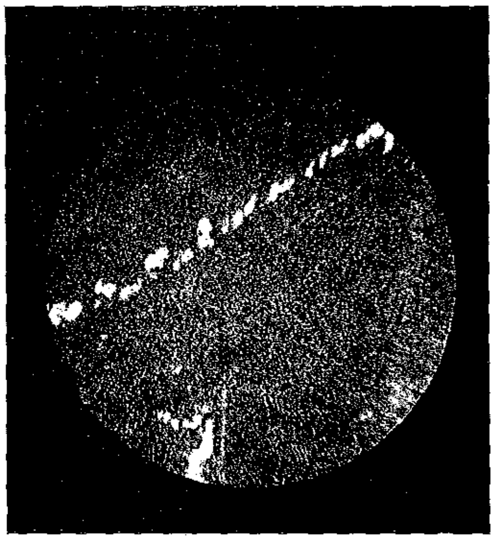


Fig. VIII-8. The Straight Track Viewed From the Side Camera Life-Size. The Point of the Pair Shows at the Bottom of the Picture.

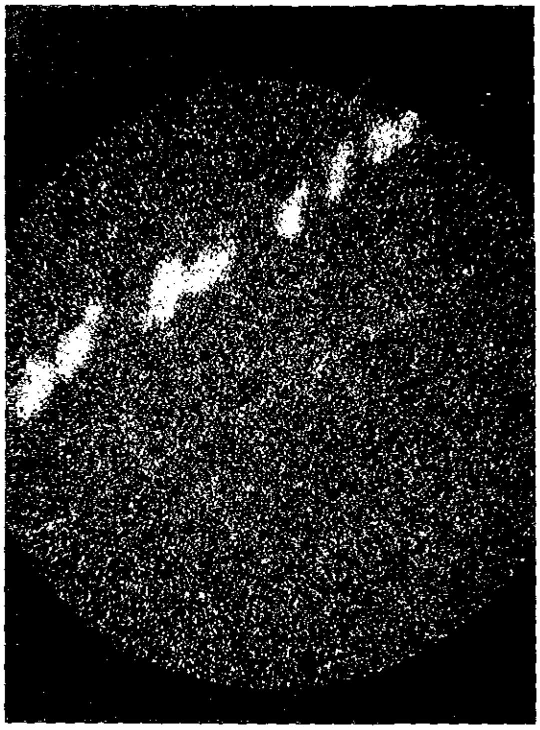


Fig. VIII-9. The Straight Track Viewed From the Side Camera 3.3 x Life-Size.

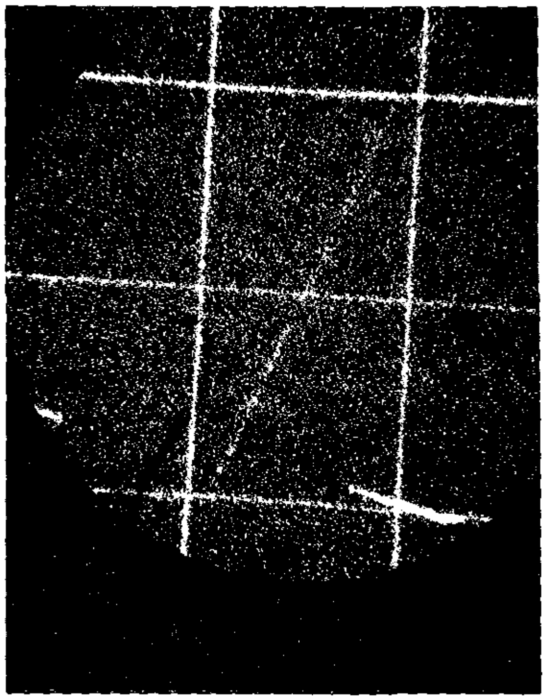


Fig. VIII-10. The Straight Track Viewed From the End Camera Life-Size.