3.5 PHOTOGRAPHY, EXPANSION DYNAMICS, OPTICAL INHOMOGENEITIES OF THE MURA MODEL HEAVY LIQUID CHAMBER

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(Presented by W.M. Powell)

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 came 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.

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 safet 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 and cross sectional area A acting as the mouth of a tank of volume V is $w^2 = C^2A/\ V$ 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

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

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, $V = 3/2 \quad = 22$ 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.

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 inhomogenietics 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) stuck 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 will be 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

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

$$n_H = 1.1908$$

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 $\mu = 0.0022$ poises. The torque on the rotating cylinder is $T = 2\ \ r^2\ \frac{dv}{dr}$ 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

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

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,

$$K = \frac{8 \times 0.0022}{1.5\, R^2} = \frac{11.7 \times 10^{-3}}{R^2}$$

This means that a cylinder of 1 cm radius will slow down to one e'th of its initial angular velocity in 85 seconds. For a 1 mm radius cylinder, it would take 0.85 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 slowly 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.

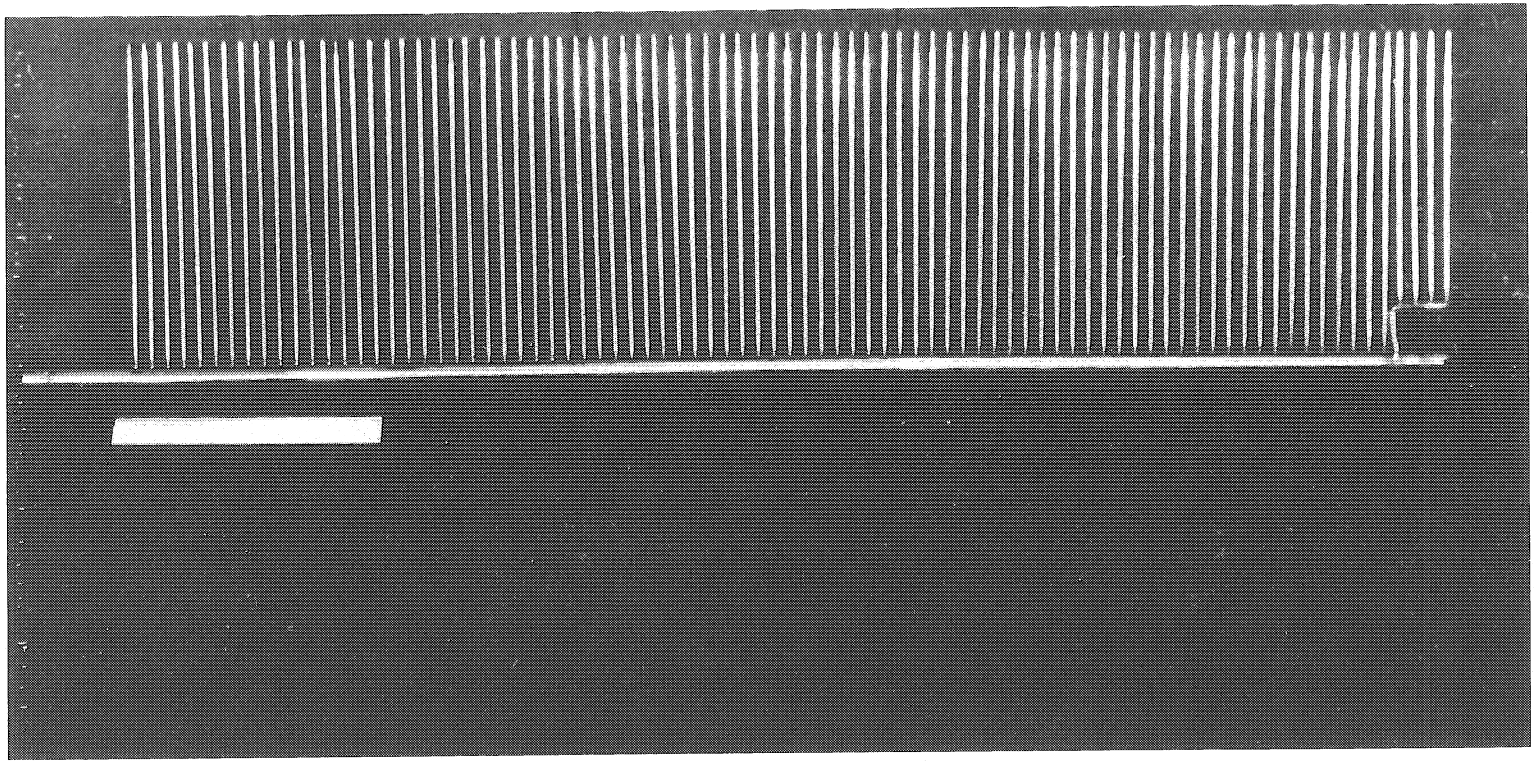


Fig. V-1. Rake Used in Model Chamber.

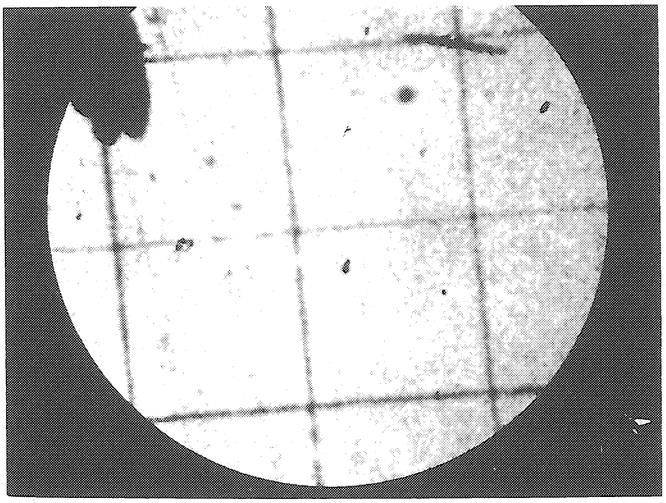


Fig. V-2. Full Scale Grid Before Expansions.

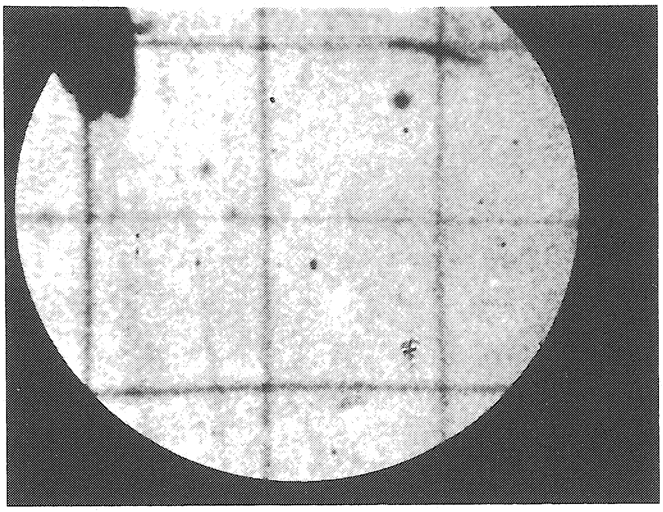


Fig. V-3. After Three Expansions at 2-sec Intervals with Raking.

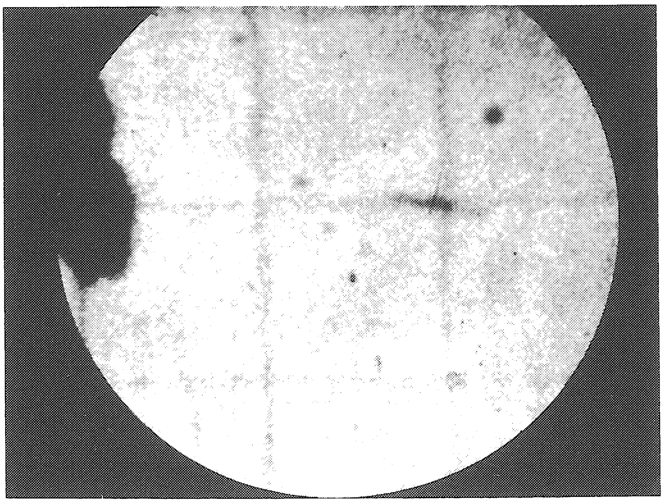


Fig. V-4. After Three Expansions at 2-sec Intervals without Raking.

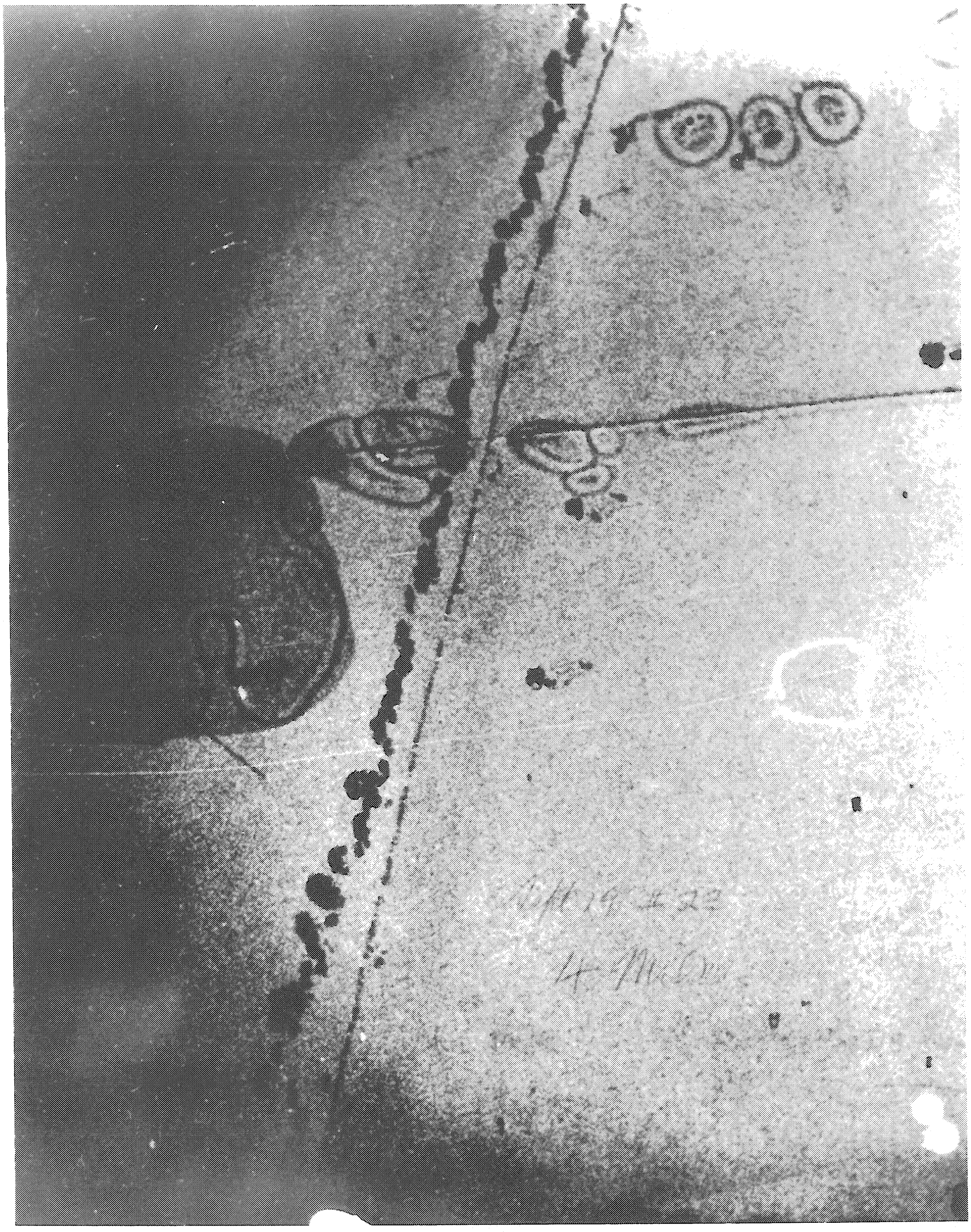


Fig. V-5. Double Flash Picture Showing the Initial Track and Final Position of the Bubbles After Recompression.

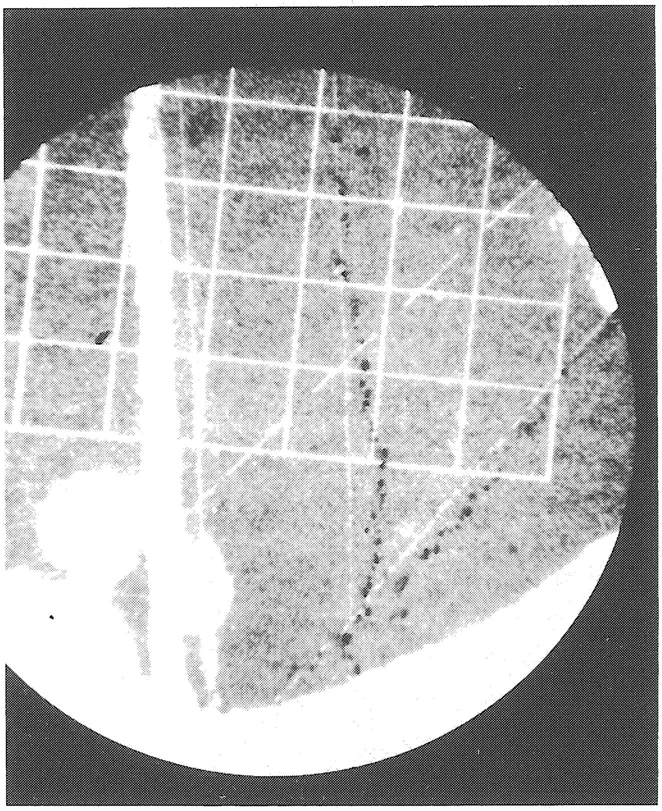
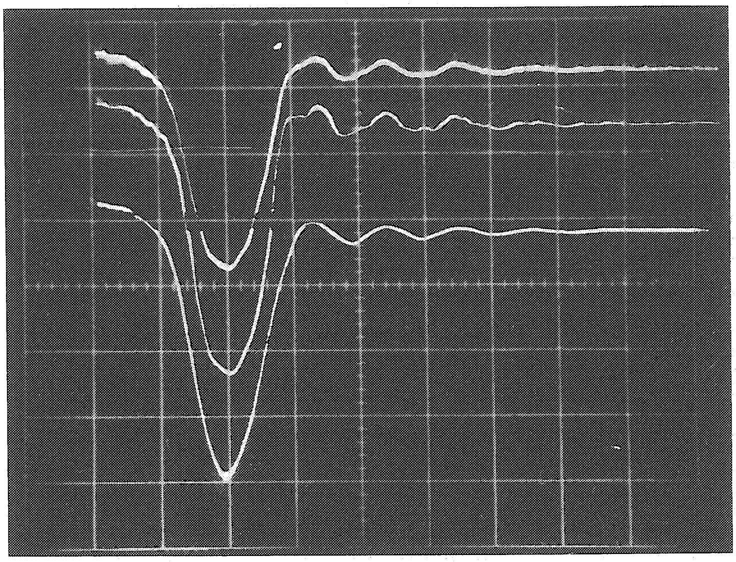


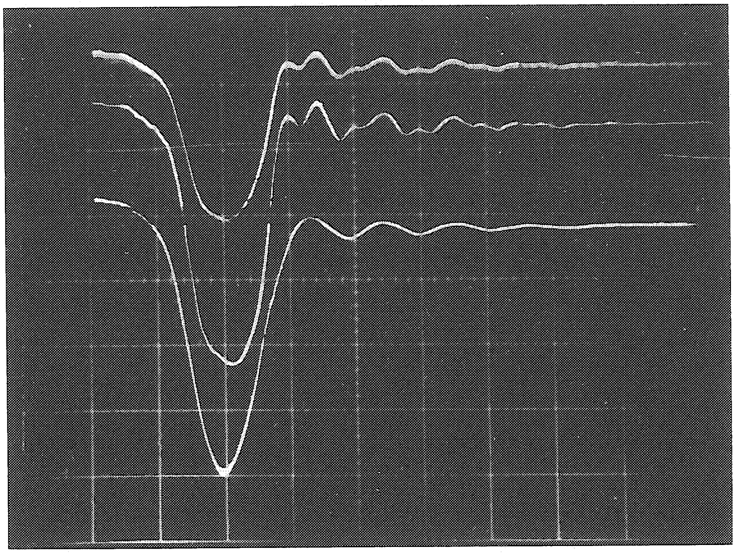
Fig. V-6. The Black Dots are Bubbles Illuminated by the Side Camera Lights on the Second Flash 30 msec After the First Flash.



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.

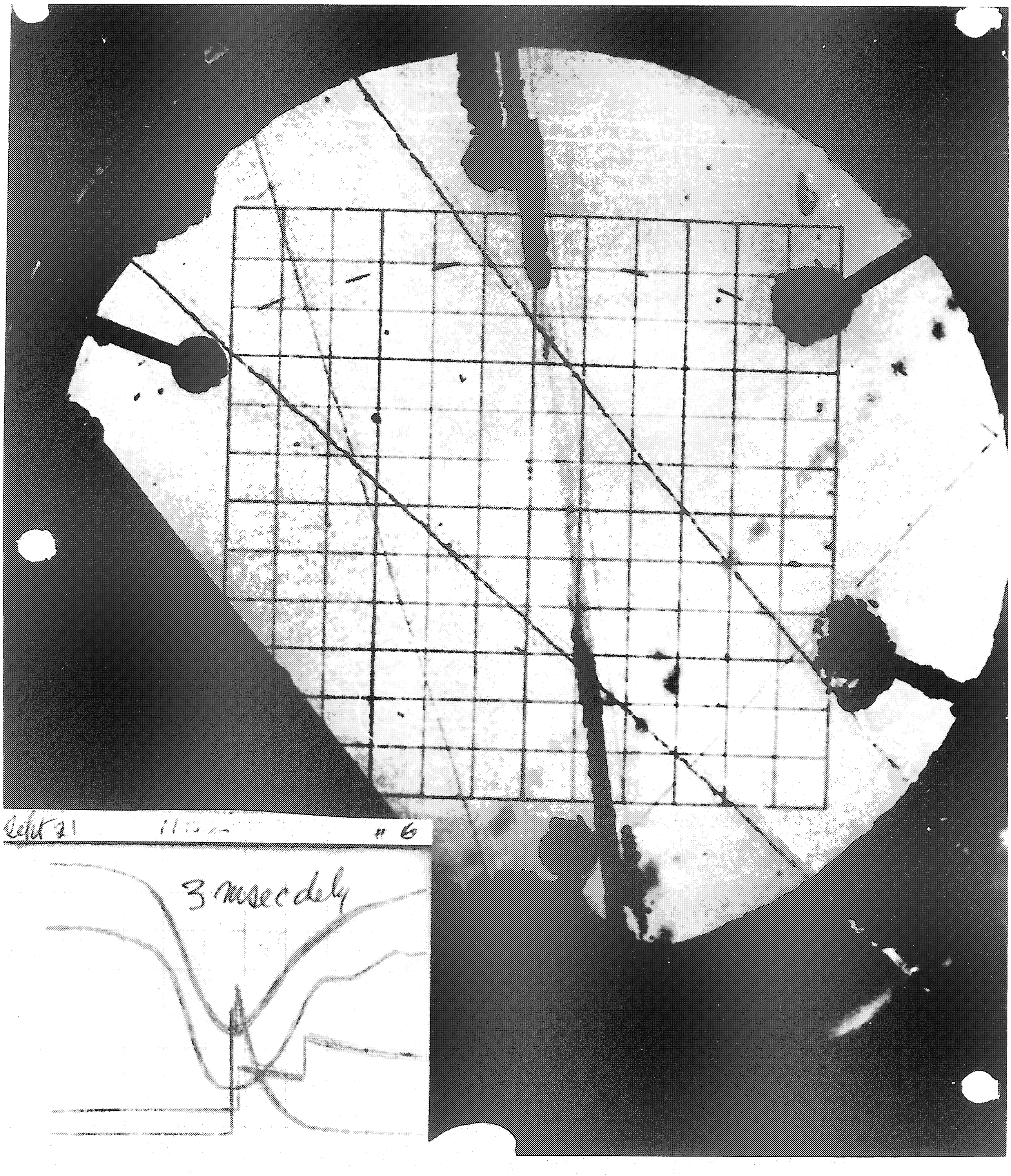


Fig. VIII-1. End View of a Cosmic Ray with a 3-msec Light Delay. The Narrow Track with the Delta Ray Near the Top is the Timed Track. Two Other Cosmic Rays Arrived Earlier.

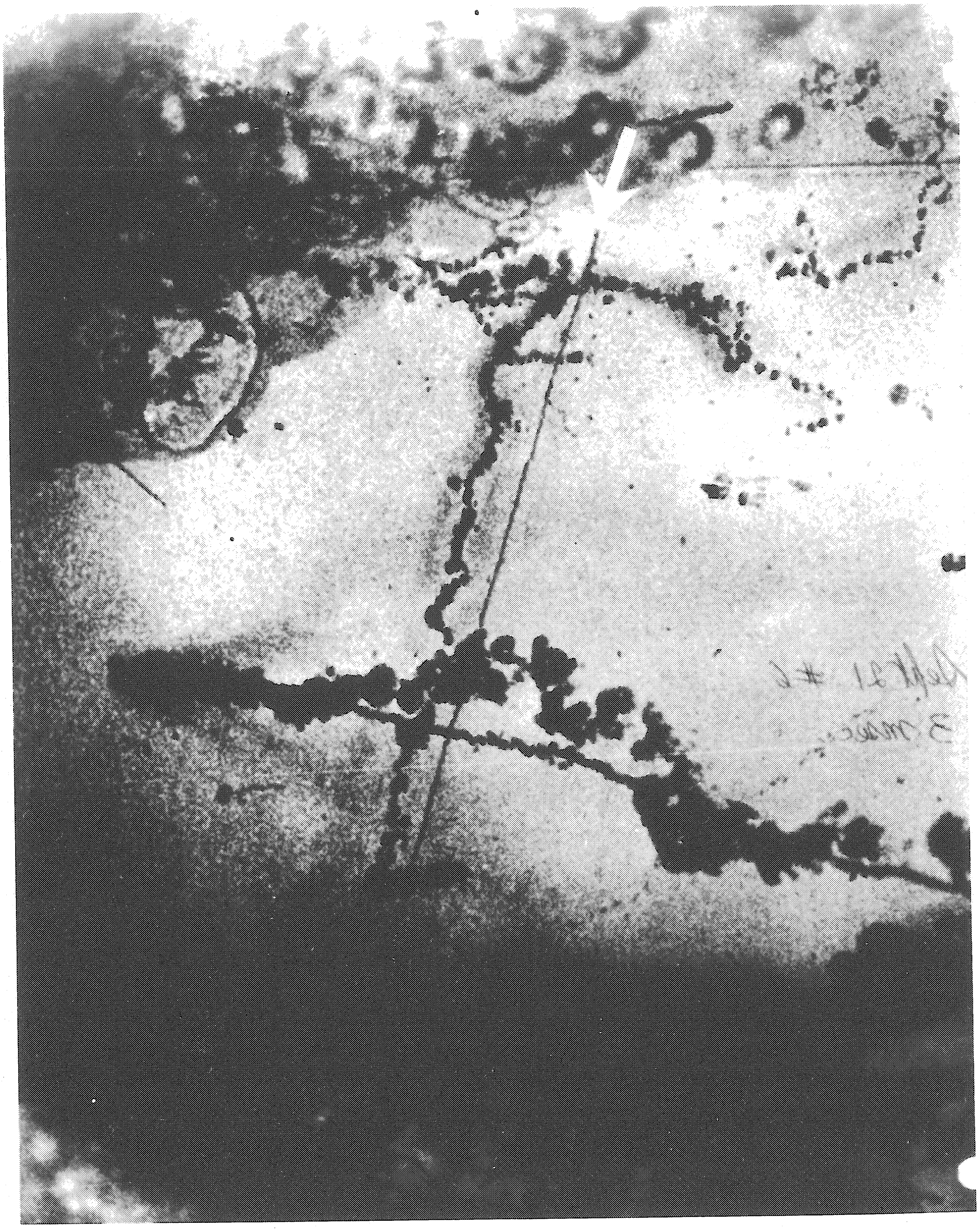


Fig. VIII-2. Side View of a Cosmic Ray With a Delta Ray Near the Center of the Picture. The Tines of the Rake Show at the Top of the Picture. The Expansion End of the Chamber is Out of the Picture to the Right.

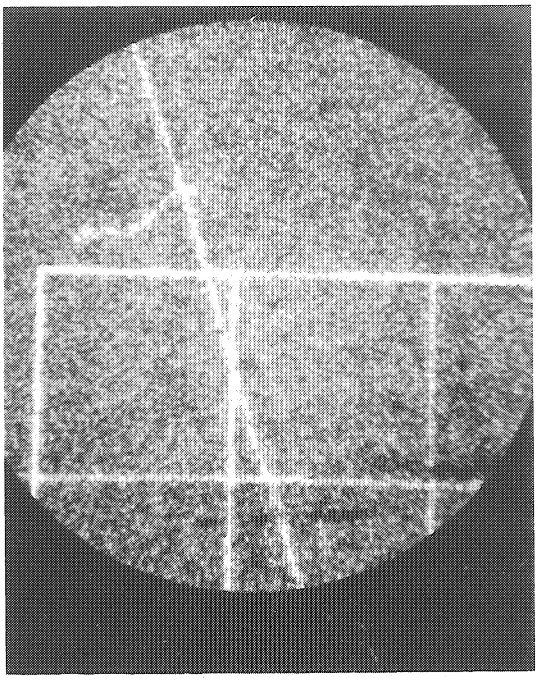


Fig. VIII-3. Life-Size Blow-Up of the Delta Ray Taken With the End Camera. Magnification From Film 48 x.

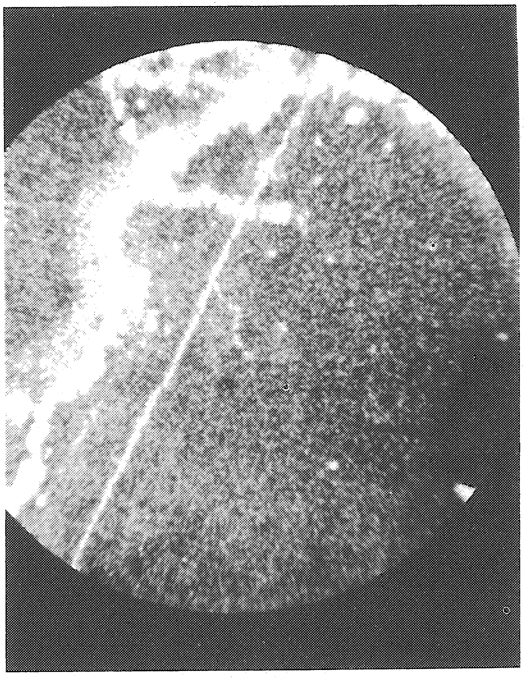


Fig. VIII-4. Life-Size Blow-Up of the Delta Ray Taken With the Side Camera. Magnification From Film 24 x.

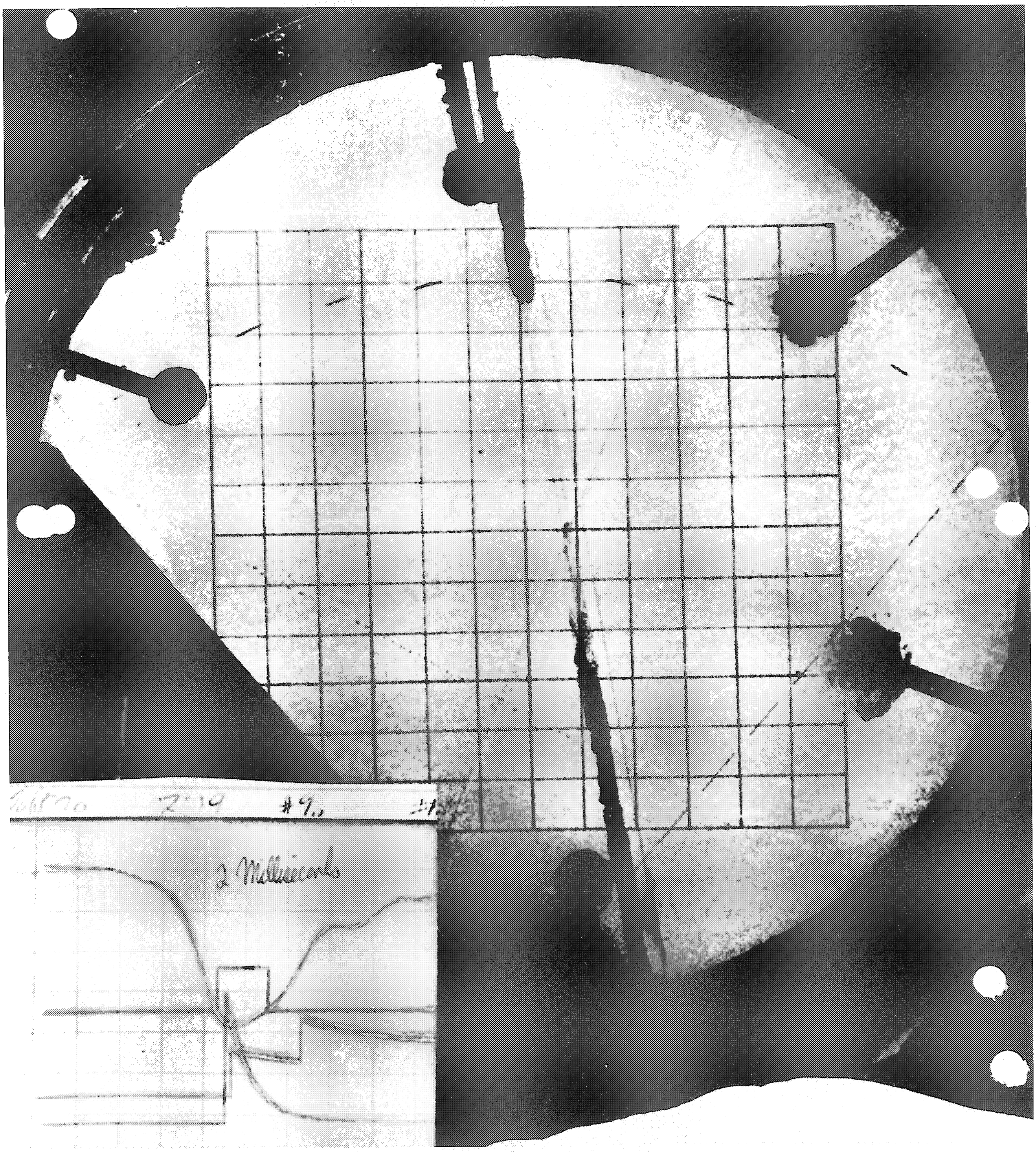


Fig. VIII-5. End View of a Cosmic Ray With a 2 msec Light Delay.

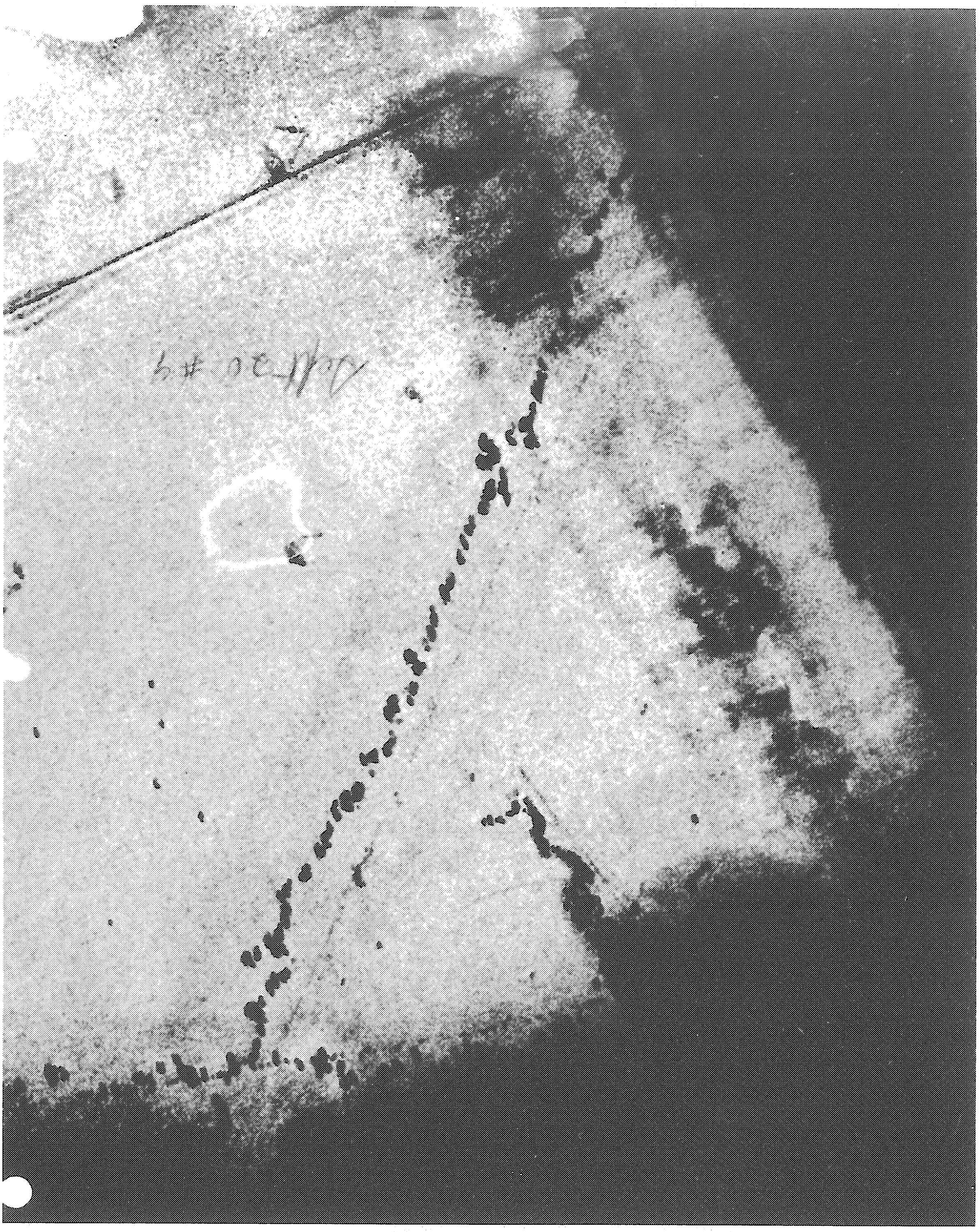


Fig. VIII-6. Side View of the Same Cosmic Ray Track as Shown in Fig. VIII-5.

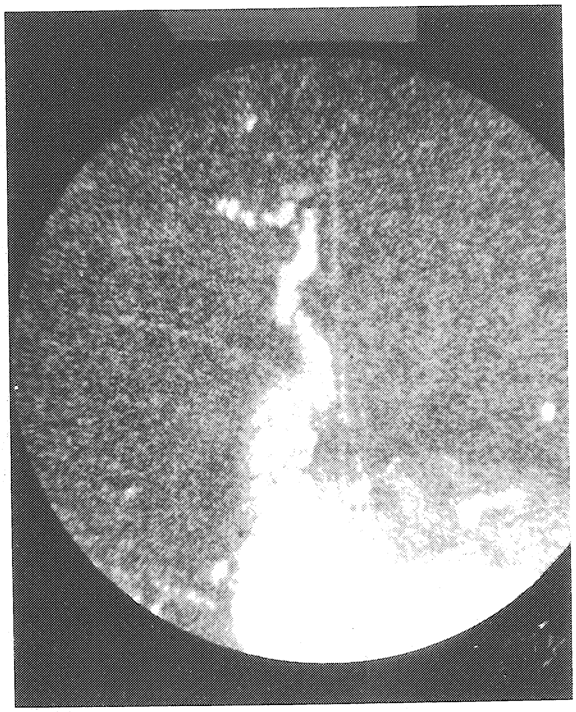


Fig. VIII-7. A Pair with a 2-msec Light Delay Photographed with the Side Camera. 1.2 Times Life-Size.

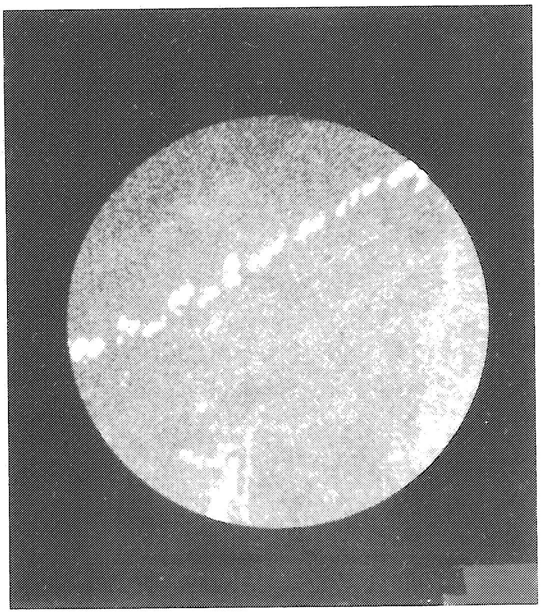


Fig. VIII-8. The Straight Track Viewed From the Side Camera Life-Size. The Point of the Pair Shows at the Bottom of the Picture.

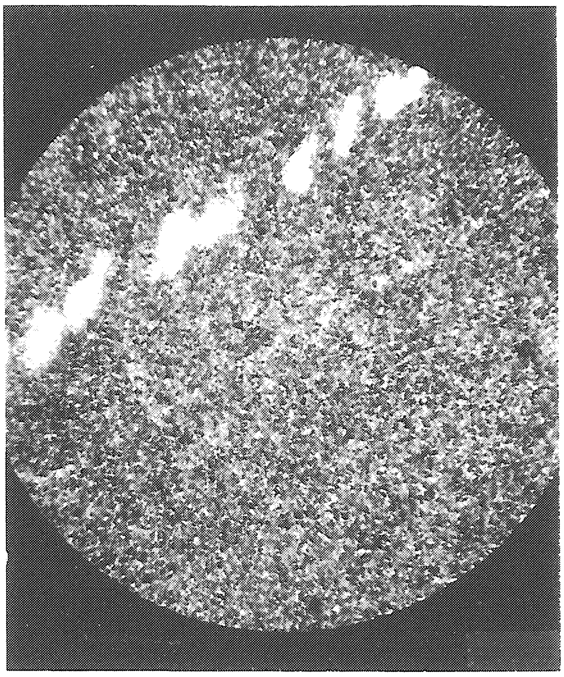


Fig. VIII-9. The Straight Track Viewed From the Side Camera 3.3 x Life-Size.

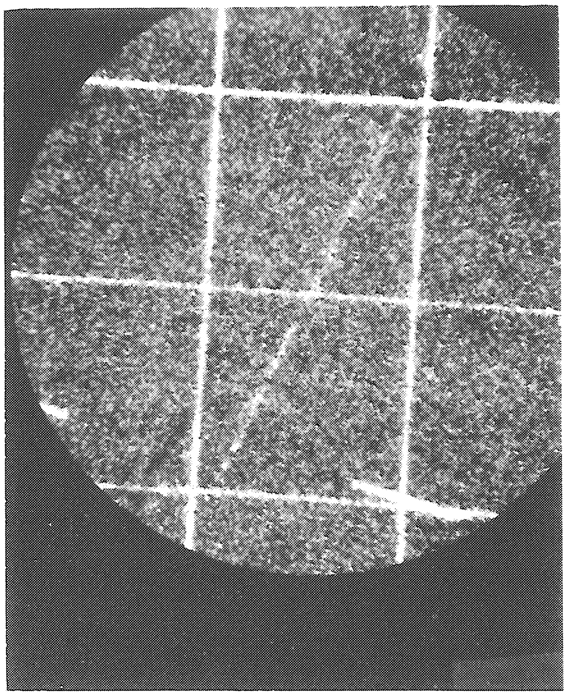


Fig. VIII-10. The Straight Track Viewed From the End Camera Life-Size.