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ABSTRACT

A unique optical system consisting of a source, reflector and camera has been constructed for the LRL 72-inch hydrogen bubble chamber. This paper describes the equipment, the reasons for its development, and some of the methods used in solving the design problem.

INTRODUCTION

The value of the hydrogen bubble chamber as a physics research tool is greatly enhanced with increase in size up to a limit determined by the maximum energy of the associated particle accelerator. The LRL 72-inch hydrogen bubble chamber is the first operating chamber of adequate size for a major accelerator, and represents a volumetric design extrapolation of more than ten. Such a large increase justifies a complete review of the prior art, coupled with vigorous operations and economic analyses.

A machine quite different from its ancestors has resulted. One manifestation of this research is the use of a single chamber window which transmits light in both directions; that is, into and out of the chamber.

Heretofore these functions have universally been reserved for separate, oppositely disposed windows.

WHY A ONE-WINDOW DESIGN?

A number of reasons exist for the choice of a large one-window bubble chamber. Such a design permits a configuration which maximizes safety and operating convenience at minimum construction and operating cost.

To understand the foregoing assertions, a general knowledge of hydrogen bubble chambers and their associated systems will help.

Briefly, a hydrogen bubble chamber is a flash-illuminated dynamic cryogenic pressure vessel mounted in a strong and uniform magnetic field, the volume of which must be photographed at a particular instant with respect to the passage through it, of charged nuclear particles.

Fig. 1

Cutaway Model of 72-inch
LRL Hydrogen Bubble Chamber

Figure 1 illustrates the complexity of a modern hydrogen bubble chamber. Any design concept which results in a more rigid and compact chamber (tub-shaped casting) will result in a correspondingly smaller vacuum tank, magnet coil, and overall dimensions. A one-window chamber not only eliminates half the glass and seals, but also results in a much more rigid shape for the chamber tub which results in economy of both material and space. More important, however, is the fact that the magnet core can be made much more efficient because the lower pole-piece is retained. The lowered magnet reluctance permits a significant decrease in ampere-turns resulting in a smaller, lighter magnet and much lower power demand.

Safety-wise, the advantage of a single window configuration as shown is apparent. Even if the window were to fail in service, no appreciable amount of hydrogen liquid would be lost. Consequently, vacuum-tank pressure rise would be comparatively moderate.

Operational convenience is assured by placing energized equipment (such as flashlamps) above the vacuum tank. Inspection, service, and/or replacement of lamps can be accomplished in a very few minutes - approximately one thousand times faster than if they were "buried" beneath the chamber.

One additional merit may be assigned the subject chamber design. One additional degree of freedom in chamber orientation with respect to the nuclear particle beam is available when the magnetic field is vertical with respect to gravity. This freedom of azimuthal orientation may be useful in certain projected physics experiments, as when it is desired to have the beam enter the side, rather than the end, of the chamber. Such a beam would tend to damage vertically oriented windows.

Please note that to place a two-window chamber in an equivalent orientation (i.e., with horizontal windows) would be extremely awkward because the optics would be likely to interfere with the floor.

OPTICS OF EARLY HYDROGEN BUBBLE CHAMBERS

The first chambers of this type employed no magnetic field and were therefore nearly unrestricted in the mode of lighting. Invariably, a straight-through lighting system was used. Elements of such systems are simple in concept and design, and are highly effective in application.

A diffused-light system can be made by use of opal glass placed betwixt the source and the rear window, yielding light-field track photographs of minimum contrast. This method was used on the UCRL 2 1/2-inch chamber.

Track scanners preferred a dark-field picture, however, and all subsequent chambers have used dark field lighting in one form or another.

The simplest and most efficient of the dark field systems involves placement of a condenser lens of sufficiently large aperture between the far (from the camera) window and the light source in such a way that the rays are focused near but alongside the camera lens. This system works very well but prohibits the use of a rear magnet pole piece. It is thus the preferred method for smaller chambers where magnet power requirements are of little economic significance.

The UCRL 10-inch hydrogen bubble chamber, which was fitted into an existing large electromagnet, was probably the first chamber to use a magnet with rear pole-piece. Since little space was available for illumination, a venetian-blind type light baffle was used to obtain a "dark field" effect, light being provided by a combination of a circular diffuser disk surrounded by ring flashlamps. This system provided good pictures, but the fact that the flashtubes were operating in a strong magnetic field and were inaccessible during an operating run constituted a serious disadvantage.

PHOTO CRITERIA

Camera output - filmstrip photos - must have physical characteristics and image quality acceptable to the scanners and automatic track measuring devices, all of which constitute elements of a large and complex information-gathering system.

The basic requirement is to provide information sufficient to permit mathematical reconstruction of all bubble tracks in (three-dimensional) space with enough accuracy to yield essentially precise calculation of their momentum and energy, and also to provide sufficient resolution to permit bubble-counting at any depth in the chamber.

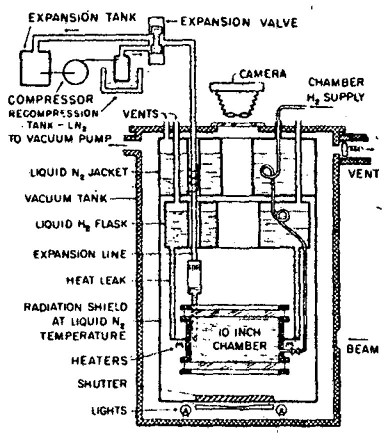

Fig. 2

Cutaway Schematic of 10" Bubble Chamber (The large 'vacuum' tank is lowered into the magnet, which is not shown.)

Additional requirements - related to readout equipment - involve items such as track-to-background contrast, uniformity of exposure, data information, margin marking, etc.

Evaluation of film from the 10-inch bubble chamber cameras during test measurements on the early "Franckenstein" film readers indicated that such machines could satisfactorily follow, automatically, tracks which were about ten times as dense as the background.

Since pictures made in good two-window chambers have track contrasts many times greater than ten, it was apparent that some of these systems might be considered "too good." In other words, if gains could be made in areas not specifically related to photography - such as economics and safety - at the expense of picture quality, this need not necessarily be detrimental to the <u>information</u> gathering ability of the system so long as picture quality (contrast?) did not fall below the necessary standards.

Analysis of the mathematical problem of tracks spatial reconstruction indicates that ability to measure to one-tenth the bubble-track width would yield all necessary physical information. Franckenstein-type film measuring equipment is able to measure to within a few microns. Thus a camera magnification of from one-tenth to one-fifteenth is implied. The latter number is actually used as a matter of economy of film and light.

Fig. 3

A LRL Automatic Film Reader
and Associated Electronic Racks

<u>THE LIGHTING SYSTEM</u>

Since bubbles in liquid hydrogen scatter incident light weakly, one must arrange to illuminate them in such a way that rays need be deflected only a few degrees to enter the camera lens (or lenses). If stray or background light is not present, one will thus obtain what is referred to as dark-field illumination, as described earlier in this report.

If an opaque (metal) wall replaces the rear (second) chamber window, one would naturally substitute a mirror (of some sort) for the second window, and place the source of illumination on the window side of the chamber. Any temptation to place the lamp in the cavity of the chamber itself is dispelled when the very practical difficulties such placement would cause, are appreciated.

If a uniform track density is to be achieved, the lighting must be arranged so that equal flux enters the camera (from same-size bubbles) anywhere in the chamber. An easy way of achieving this condition is to arrange things so that the light flux density is uniform throughout the chamber and so that the scatter angle or degree of bending of light is equal from all bubbles and to all lenses.

A 'spherical' or polar arrangement wherein the light source is central will perform as desired if the mirror (placed in the bottom of the chamber) is a portion of a sphere centered at the source, and if the camera lenses are all placed an equal distance from the source, in a plane containing the source and normal to a line from the center of the mirror to the source.

Now if the chamber window is canted in such a way that a reflection of the source is not seen by any of the camera lenses, only one basic difficulty can be found with the system just described: each track will be seen twice by the camera. The reflected images will tend to clutter the views, making scanning difficult unless the number of entering beam particles is reduced. Such a reduction would, in effect, double the cost of obtaining the required information.

Clearly, a "black mirror" is needed, one which will reflect light (as required) directly back to the source but one which, when viewed from the camera position, will appear dark.

If, in addition to the above properties, the mirror (or reflector) device were such that it could be made to fit compactly into the essentially flat, rectangular bottom of the chamber, we would indeed be fortunate.

One of the several optical schemes which were suggested for this application was the proprietary beaded reflector material, Scotchlite. Although tests of this interesting reflective material showed that it was not "good" enough for our application, a study of its properties and weaknesses may well have led us, eventually, to the system now being used.

The beaded materials have, for this application, three weaknesses, two of which can be partially remedied by making one change.

Before proceeding into a discussion relating to the improvement of beaded reflectors, it would seem prudent to describe briefly their optical characteristics.

Light centrally incident upon the bead (which should have a high index of refraction) is refracted toward the center, travels to the rear surface of the sphere, is reflected, and thence emerges at the front at a point diametrically opposite from its incident position, and is again refracted (bent) toward the "axis" of the bead so that the ray is now moving in a direction which is approximately opposite to its original direction.

Rays incident near the sphere's periphery are not refracted into the bead but are reflected from it and are thereby "wasted", creating an inefficient reflector. Rays incident just "inside" the critical angle are refracted too strongly, and the resulting return path deviates markedly from the desired direction.

Imagine for a moment a sphere from which the optically "poor" marginal edges are removed. If slabbed equally on six sides, a hexagonal optic with spherical ends will result. It will have superior optical performance compared to a whole sphere and furthermore, a closely fitting (honeycomb-like) matrix can be achieved.

If such an array is aluminized over the entire back surface, it will be a much more efficient reflector, and will have a sharper cut-off than the parent beaded screen. Several weaknesses yet remain, each of which can be eliminated by design change so that unless you're careful, you won't recognize the bead in the reflector!

Obviously, macroscopically-sized high-index glass beads cannot (yet) be economically cut - or molded - into these special shapes, so in our program polymethylmethacrylate was substituted. Because the lower-index plastic does not bend light as much as the original glass beads, it was necessary to lengthen the optic (producing a longer hexagon) with respect to the radius of the spherical ends, so that (most) of the rays were brought to a focus at the center of the rear (reflector) surface. (An elliptical refracting surface would result in perfect focus.) The retrodirective properties were good for incident rays parallel to the hex axis, but poor for others. An increase of radius of the reflecting surface, so that it was centered at the refracting surface, cured this situation and resulted in an optic which was, within limits, quite independent of the direction of incident light - nearly all would return to their source.

A matrix of these optic reflectors is in many ways similar to a plane mirror but with two big exceptions: You can "see" yourself in it even though the mirror is not at right angles to your line of sight, and if you tilt it beyond a "cut-off" angle it becomes dark. An interesting gadget.

How can this unit be put to work? If such an assembly were placed in the bottom of the bubble chamber and the central light source turned on, a "thousand" tiny reflections of the source would appear at all useable off-axis positions where the camera lenses might subsequently be placed. To make matters worse, images of bubbles could also be seen - about as bad as a plain mirror.

Something was done. Instead of aluminizing the ENTIRE bottom (rear) surface of each element, only a small central disk or spot was so treated, the rest being blackened with a light-absorbent optical lacquer. The spot was of such size that, from the intended position of a camera lens, no scattered light could be seen coming from inside the optics and they were superbly black! This change tended to increase the apparent brightness of the front-surface reflections.

Elimination of the front-surface reflection resulted when a radical departure from the hexagonal optic configuration was conceived.

Having failed to supress the source surface reflections sufficiently by use of optimum combinations of dielectric quarter-wave coatings, glass, and light filtering, it was realized that the only way to get rid of them would be to determine a surface configuration such that at no place on this (refracting) surface could a normal be erected which would lie in a plane containing the source, lens, and element of refracting surface. At the same time the cross-section of the previously-developed reflecting optic must be retained.

The result is what we at Lawrence Radiation Laboratory call a "coat hanger" because it somewhat resembles an (upside-down) plain wooden coat hanger. The cross-section is, of course, that evolved from the bead. And the large 'coat hanger' radius is equal to the lamp-reflector distance.

A few additional modifications have been made. First, it should be realized immediately that the aluminized spot has now become an elongated strip centered along the bottom of the element.

Finally, to perfect the retro direction of light, and thus "smooth out" illumination of the bubble tracks, the theoretically perfect elliptical cross-section was applied to the refracting surface.

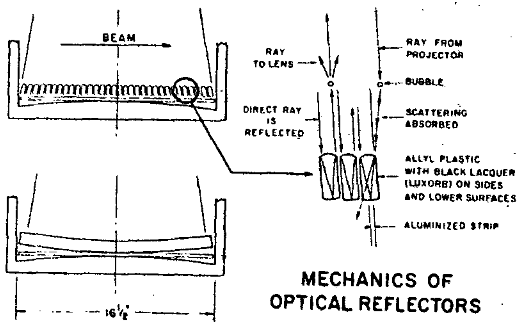

Fig. 4

Schematic of Coat Hanger Reflectors showing Light Ray Paths and Assembly in 15-inch Bubble Chamber.

DETERMINATION OF PHYSICAL CONSTANTS

Refraction constants for the dielectric materials employed were unknown at the temperature and pressures extant at instant of exposure. Scientific and engineering personnel combined to define these indices. Inasmuch as the density and consequently the index of refraction[1] of the liquid hydrogen at time of exposure is transient and somewhat variable, appropriate maximum and minimum values were derived from particle range measurements made on earlier photos from the 10-inch chamber. An experimental method was used to determine the index of the coat-hanger plastic material. Direct optical observations were made during cool-down from room to liquid nitrogen temperature, and a small extrapolation to liquid hydrogen temperature was made. Satisfactory results experienced with the large chamber optics have justified these methods.

15-INCH HYDROGEN BUBBLE CHAMBER

The 15-inch chamber, built to replace the 10-inch chamber, and to fit into the same magnet, was to serve as a prototype chamber in which the coat hanger illumination system would be tested. Of interest is the fact that although both units were fitted into the same magnet hole, the later machine, utilizing reflector illumination optics, has a useful volume over three times that of the earlier type! This increase is due largely to space economies permitted by the coat hanger system. The reflectors, which have a cross-section approximately one inch deep by three-eighths inch wide, are machined from cast allyl plastic sheet material[2] which is several times more scratch-resistant than popular polymethylmethacrylate (Lucite, Plexiglas, etc.).

The light source for this chamber consists of a Xenon-filled short (4 mm) arc flashtube[3] firing into a one-inch diameter light port through a double condenser projector. A spherical mirror behind the lamp increases light collection by approximately 40 percent. Power for this lamp is stored in a 7000 micro-Farad capacitor bank charged to about 300 volts. Two stereo cameras (yielding four stereo frames per chamber pulse) look into the chamber through a periscope mirror arrangement to yield a 16° stereo angle, giving excellent depth perception.

This illumination system gave better-than-expected results and the decision was made to adapt this design to the large chamber.

Fig. 5

Track Photograph Made With One-Window Illumination System Described Herein

OPTICAL ELEMENTS OF THE 72-INCH HYDROGEN BUBBLE CHAMBER

A 5-inch thick window measuring 75" x 24" in plan form serves as a closure at the top of the chamber body. This window is sealed to the chamber by means of a helium-filled inflatable stainless-steel and indium gasket. This gasket is fully pressurized only after the window has been sufficiently cooled and contraction has taken place. Cast of borosilicate crown glass by Jena (Schott) Glasswerke of Germany, the window is notable for its freedom from bubbles, inclusions and striae and is believed to be the largest high quality window billet ever cast. It is tilted 7 1/2° from the horizontal to remove source reflections and to remove bubbles which form against its underside.

One hundred eleven coat hanger reflectors - twenty-two inches long - span the chamber. The cross-section has been increased from prototype size to 1.8" x 0.6" to increase beam strength, permitting end-mounting by means of shallow coned holes and spring-loaded supporting pins.

Fifteen-thousandths of an inch clearance is provided between reflectors to permit hydraulic circulation and eliminate collection of dirt between them. The chamber is filled by condensing hydrogen therein, thus minimizing extrainment of foreign materials. A contaminant maximum of one part per million is permissible which, were a complete precipitation to take place, would result in a deposit thickness - on the reflectors - of less than one wavelength of light.

The reflectors are aligned by means of a mechanical tuning-fork device to "point" to the light entry port. Alignment is maintained by a spring clip at one end of the reflector. Lateral hydraulic forces applied when pulsing are balanced by geometric symmetry. Vertical forces are adequately resisted by the coat hanger's deep vertical section.

Machining the optical surfaces required a great deal of care, the operation having been carried out on a standard toolroom vertical mill with aid of a proper fixture.

Drawings call for a mis-alignment of the cooperating optical surfaces not to exceed two-thousandths of an inch, and calculations indicate that surface curvature should be maintained to better than three ten-thousandths! Polishing was done by hand using laps, muslin buffing wheels, and chamois skins. Between one and two hours' total polishing is required per reflector depending upon the quality of machine finish. Polish quality was compared to a standard by measuring light scattered from the polished surface. A photo multiplier tube circuit gave quantitative indications.

As in the 15-inch chamber, a projector is used to supply light to the reflectors. This permits trimming the illuminated field to the proper size, avoiding the problem of scattered light, spurious reflections and flare which would otherwise exist. The long chamber proportions pose an unusual lighting problem which is met by joining - Siamese fashion - three identical optical systems in a manner calculated to not only efficiently illuminate the 20" x 72" window, but also to permit "modelling" of intensity so that ends of the photographs would not be severely under-exposed. (See Figure 6.)

Three flashlamps[4] created especially for this application are arranged in line formation to fire into a single light port (1" x 4"). Each lamp is focussed by means of a set of fast (f/0.4) plastic condenser lenses into this port.

The lamps, of heavy-wall quartz tubing, are filled with Xenon gas and are capable of absorbing energy at the rate of 2,500 KW for 1/2 millisecond.

The projector assembly is housed in a nitrogen-pressurized aluminum box. A cadmium sulfide photo conductive cell is mounted above each lamp in such a manner that a portion of the 4 percent reflection from the first optical condenser surface is monitored. Lamp output is thus remotely indicated and electrical condenser bank voltages are adjusted accordingly at the control room. Nitrogen purging is necessary since in the presence of air (oxygen) the UV emission of the flashlamp will produce ozone.

The danger of highly-oxidizing ozone reacting with hydrogen (leakage) is such that the inert-gas purge was deemed necessary.

Other safety features in the lamp house include a key-lock access door which interlocks with the condenser bank power supply, and a purge gas pressure interlock.

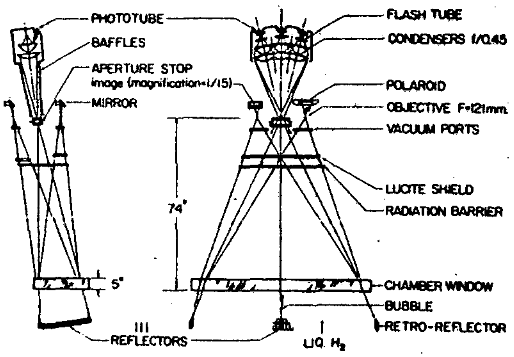

Fig. 6

Schematic of Optics in the 72-Inch Bubble Chamber

Electrical energy for the flashlamps is stored in three of the four interchangeable capacitor banks. Each bank has a 512 micro-Farad capacity, and may be charged to 2500 volts. Again, safety interlocks are provided.

The stereo camera consists of an L-shaped body of welded one-fourth inch aluminum plate; a mechanism plate containing four lenses, vacuum platens, film drive capstan and motor, vacuum storage tank, vacuum solenoids, associated alarms and electrical wiring; and two 1000-ft. film magazines.

Fig. 7

Bottom View of Stereo Camera Showing Stereo Lenses

The camera body, which measures approximately 40" x 30" x 12" deep is dowel-pinned onto the three associated camera view ports to insure precise relocation and parallelism with the chamber window. Thus, the camera is tilted 7 1/2° from the horizontal. (See figure 11.)

The three stereo-taking lenses are spaced 20 inches apart in a 90° ell, and thus produce a stereo angle of approximately 16 degrees measured in the chamber. The third stereo view insures that all tracks can be accurately measured regardless of direction, and also permits seeing certain parts of the chamber which would otherwise be unuseable. The placement of the lenses is such that the scatter angle of light at the bubbles is nearly the same from all positions. The six-element 120 mm wide-angle objectives[5] yield excellent definition and off-axis transmission (see Fig. 8). Barrel-mounted, they are being used at f/22.

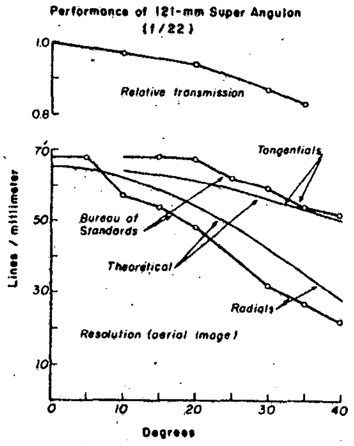

Fig. 8

Resolution and Transmission of Stereo Objective Lenses

The fourth lens, a 100 mm f/4.5 enlarging lens,[6] is equipped with a rotary solenoid-operated single-leaf shutter, and photographs a portion of the nearby refrigeration control panel through an 80° Roof prism. Instruments and counters in this region provide pertinent information necessary for chamber record and operations analysis.

Lens focussing is in all cases fixed, adjustment being made by shimming. Image platens are equipped with pulsed-vacuum backs which have built-in vacuum failure alarm circuits.

The placement of lenses has led to the use of 45° mirrors to fold the image rays in such a way as to simplify, as much as possible, the path of film through the camera.

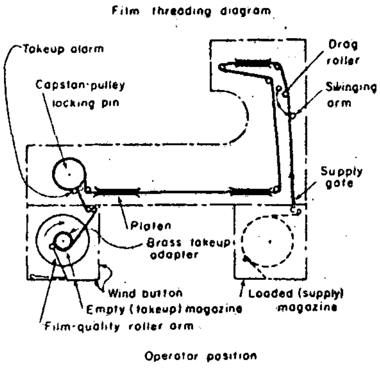

Fig. 9

Diagram Illustrating Path of Film

Roll film width is 1 13/16 inches which provides adequate margins outside the chamber image for optical application of margins marks. These are subsequently used by film readers for automatic stopping.

The film advancing mechanism, a one-turn crank, rack and pinion device, produces a harmonic-type motion. Advance is 16 1/2 inches per chamber pulse. The layout is such that exposures from the four lenses interleave efficiently so that no film wastage occurs. Film is advanced in three seconds. Maximum repetition rate is twelve pulses per minute.

Five magazines have been provided with the camera so that at the average rate of one hour per roll an extra loaded magazine is always available. The magazines are designed to facilitate loading. Film may be transferred directly - without rewinding - from the factory container to the magazine reel. A reel having but one flange permits such loading. The loaded, self-centering reel may be casually placed in the magazine; magazine lid latches cannot be closed unless the film quantity indicator arm is correctly positioned. Neither the reel nor magazine are fitted with bearings; thus the reel rests loosely inside. Instead, the hubs are designed to center on vertical supply and takeup spindles on the camera box. Takeup torque is provided by a filled-teflon cone clutch pinned to the constantly rotating 60 RPM takeup spindle. Braking torque is similarly provided by an identical cone on the static supply spindle. This unorthodox arrangement, by utilizing the variable weight of the film reels as they wind or unwind, tends to maintain a nearly uniform tension in the film.

Fig. 10

Photograph of Stereo Camera Showing Mechanism Plate (Camera Doors and Magazine Covers Removed)

Design emphasis has been placed upon convenience of loading and maintenance. For instance, all film gates and platens are one-side open so that by grasping the upper corner of the end of a fresh roll of film the operator can, without releasing his grip, thread the entire camera in what amounts to one continuous motion. Thus, a reloading may be completed in less than thirty seconds.

gnetically shielded. In view of the hazardous location, all switches and motors are non-sparking or explosion proof. The connector plugs at external and internal locations are modified to "kill" energy before contacts can be broken. In addition to the usual vacuum and electrical services, this camera is provided with both dry and moist air supply. The former is used to purge that portion of the camera (beneath the mechanism plate) which contains the lenses and cold vacuum ports. Jets of dry air impinge on those windows to prevent fogging. The zone above the mechanism plate contains the film. Use of moist air (60-70 percent relative humidity) eliminates static discharges and flattens the film which prior to the moist air treatment had a severe tendency to curl.

A humidity sensor located on the mechanism controls a commercial humidifier unit at a safe (remote) station, and provides indication and limit warnings in the control room.

Fig. 11

General View of Camera and Lighting Equipment From Operating Platform

Auxiliary equipment is provided for direct monitoring the chamber. This equipment utilizes a fourth (viewing) port which is symmetrically placed with respect to the corresponding ports occupied by the stereo camera. A sliding adaptor permits operators to view the chamber directly or to take Polaroid-Land photographs.

Chamber illumination during visual inspection is provided by three 150-watt reflector-type projection lamps[8] mounted above the Edgerton flash-tubes. This circuit is energized by a push button conveniently located near the viewing port. Polaroid pictures may be taken at this port by means of a slide-mounted camera which is equipped with a lens identical to the ones used in the stereo camera. Time of day and corresponding stereo reel and frame numbers are automatically recorded on the Land photo, thus providing a useful permanent record which is entered in the operator's log book.

CONCLUSION

At the present time well over two hundred rolls of film, representing something beyond 100,000 chamber pulses, have been exposed in the stereo camera. Members of the Dr. Luis W. Alvarez Physics Research Group, for which the system and equipment described herein was produced, are pleased with the results obtained.

Responsible persons are convinced that the bold departure from past practice in chamber illumination has been justified. In conjunction with its associated equipment, the large bubble chamber produced new basic information on its very first scheduled physics run.

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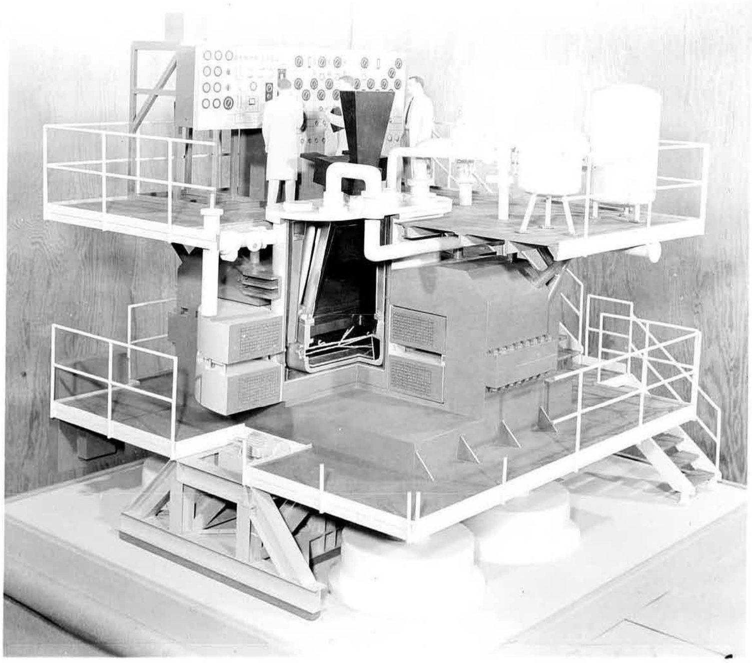
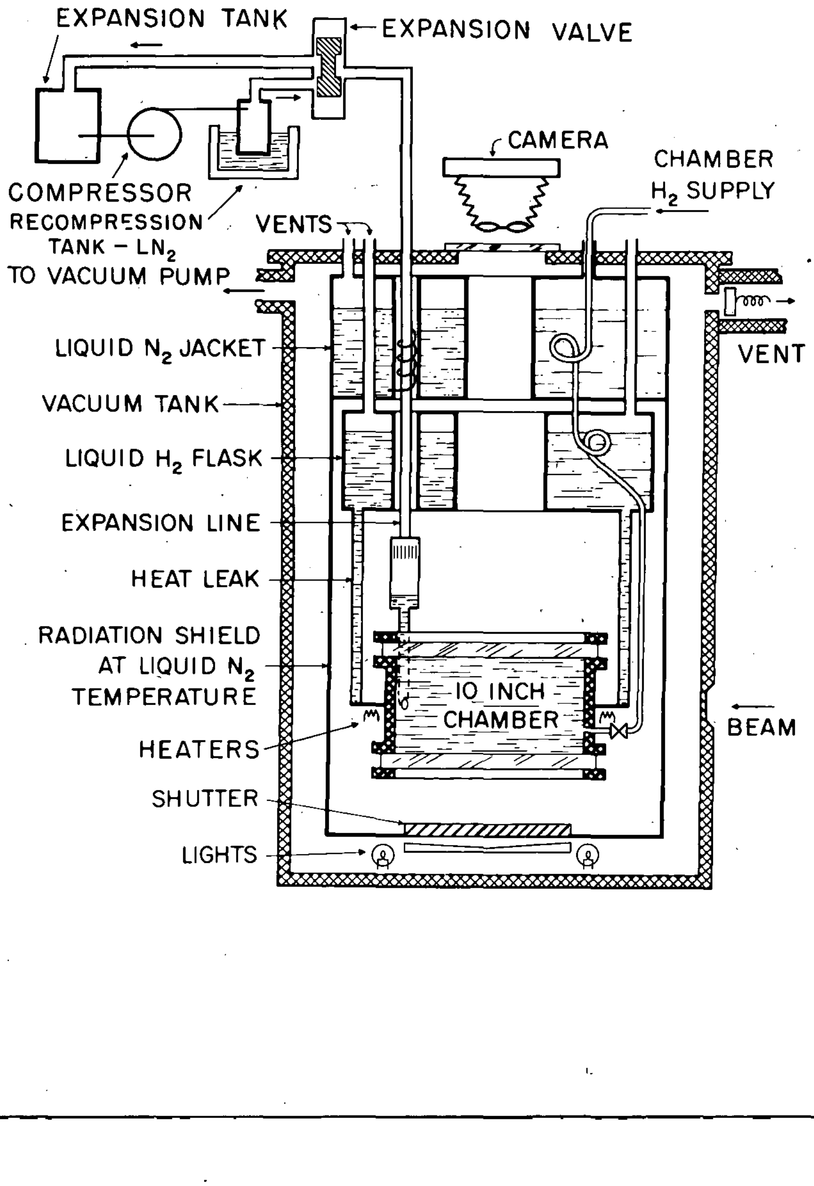


Fig. 1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EXPANSION VALVE
CAMERA
CHAMBER H$_2$ SUPPLY
COMPRESSOR
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VENT
LIQUID N$_2$ JACKET
VACUUM TANK
LIQUID H$_2$ FLASK
EXPANSION LINE
HEAT LEAK
RADIATION SHIELD AT LIQUID N$_2$ TEMPERATURE
10 INCH CHAMBER
HEATERS
BEAM
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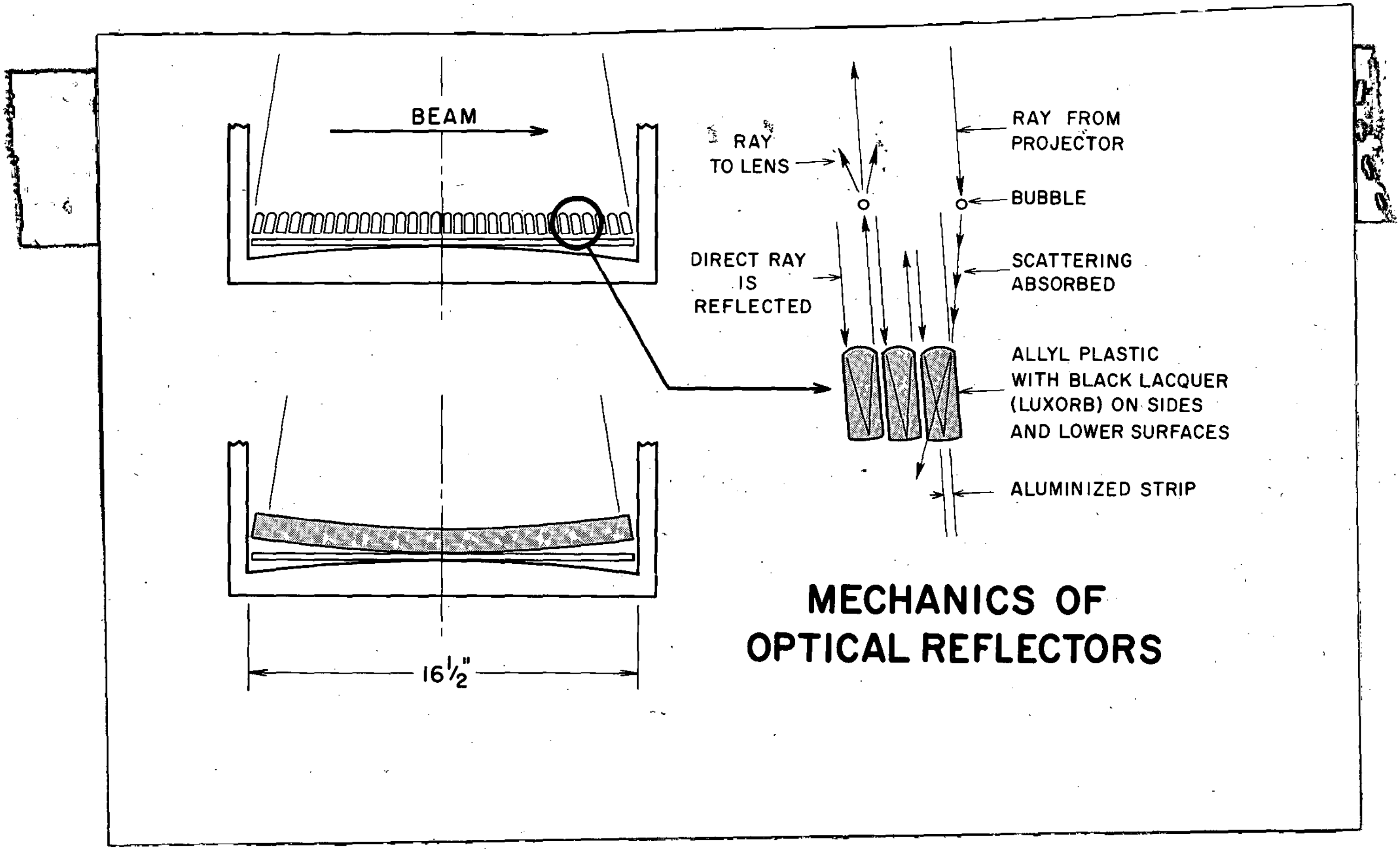
LIGHTS

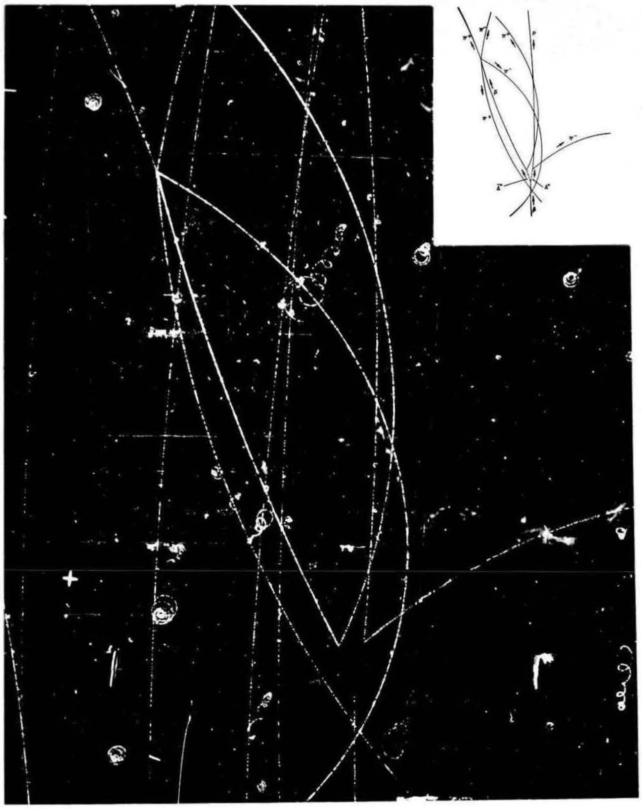
Fig. 2

Fig. 3



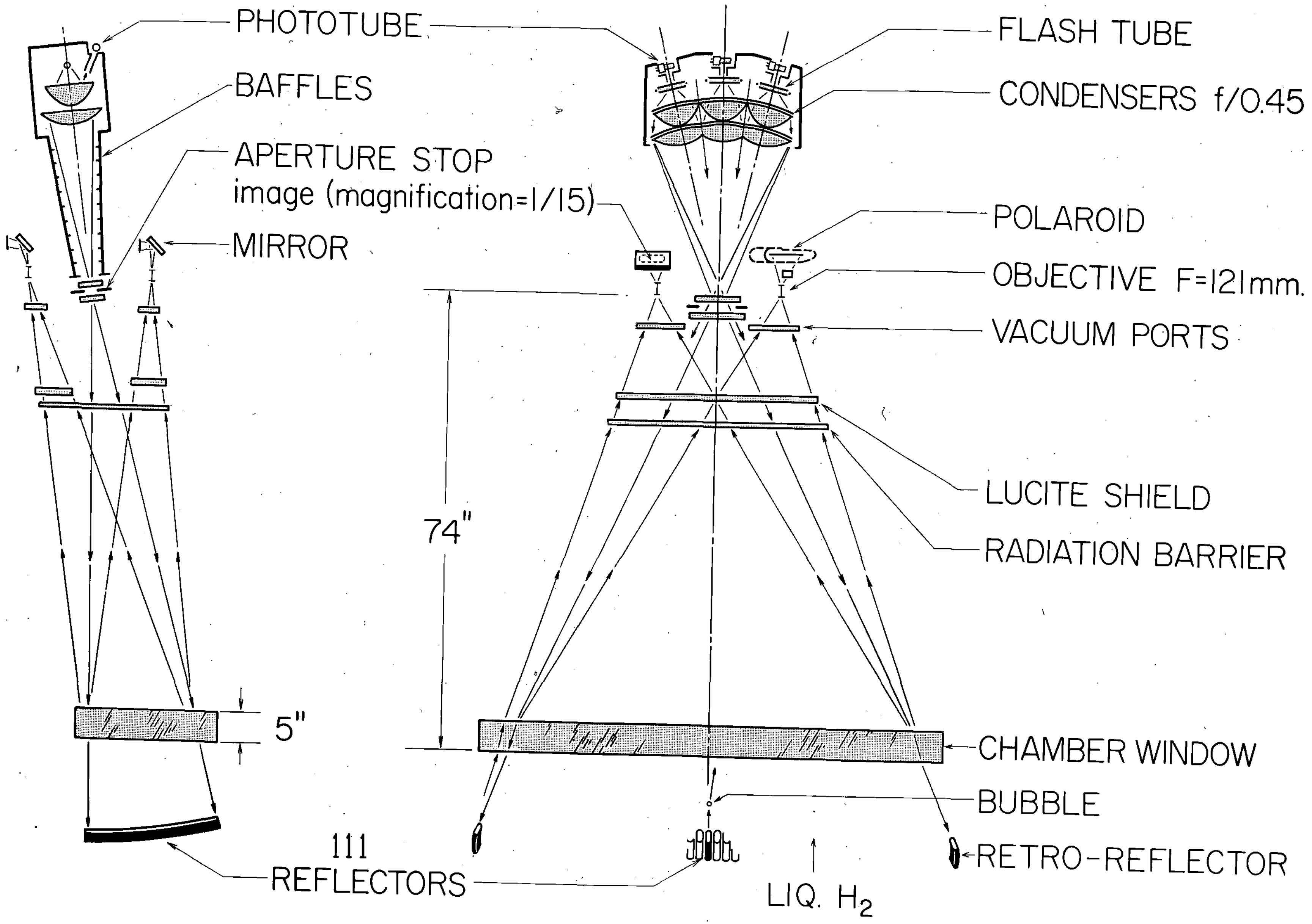
MECHANICS OF OPTICAL REFLECTORS

Fig. 4



Production and decay of neutral lambda and anti—lambda hyperons

Fig. 5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REFLECTORS
FLASH TUBE
CONDENSERS f/0.45
POLAROID
OBJECTIVE F=121mm.
VACUUM PORTS
74"
LUCITE SHIELD
RADIATION BARRIER
CHAMBER WINDOW
BUBBLE
RETRO-REFLECTOR
LIQ. H_2

Fig. 6

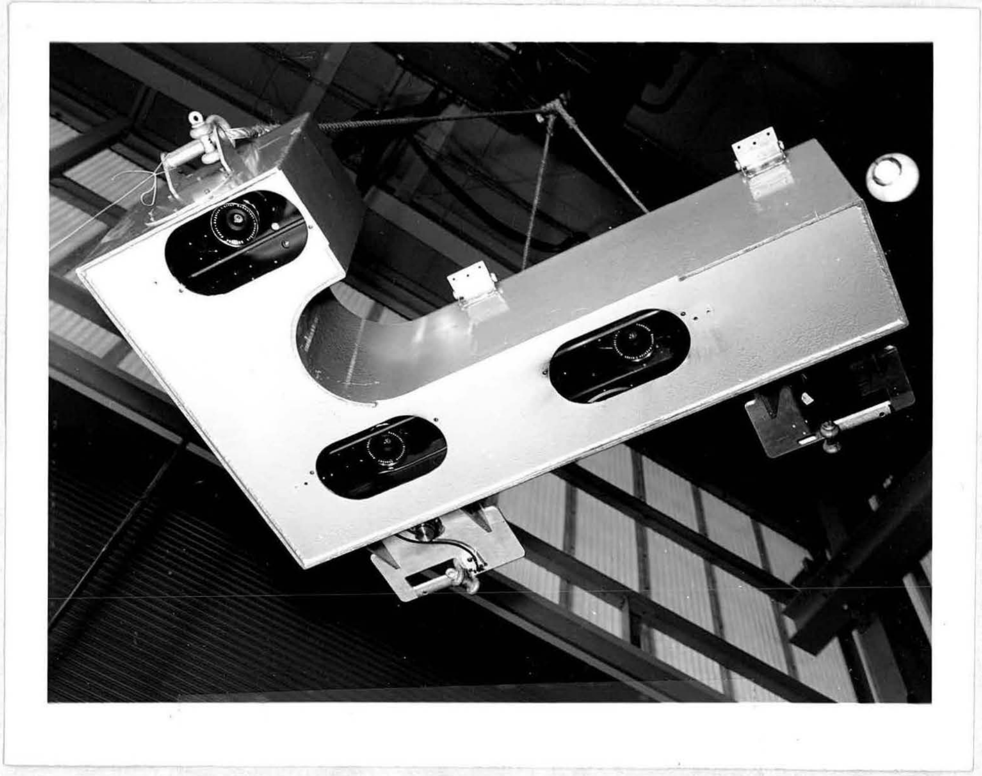

Fig. 7

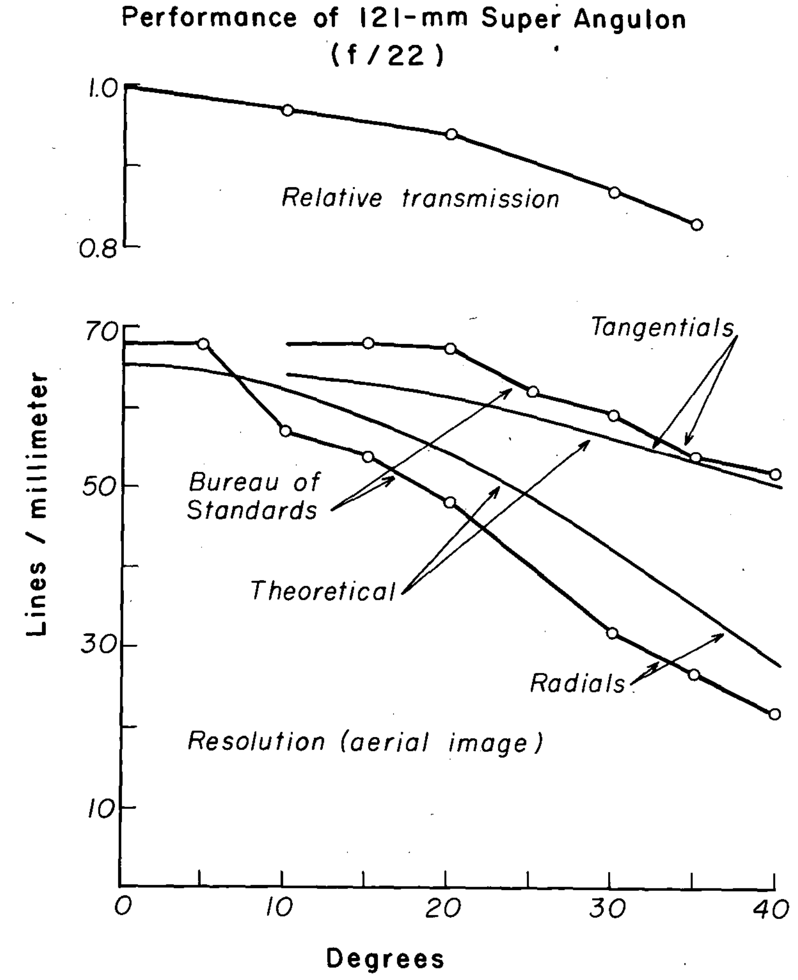
Performance of 121-mm Super Angulon
(f / 22)
1.0
0.8
Relative transmission
70
50
30
10
Lines / millimeter
Tangentials
Bureau of Standards
Theoretical
Radials
Resolution (aerial image)
0
10
20
30
40
Degrees

Fig. 8

Film threading diagram

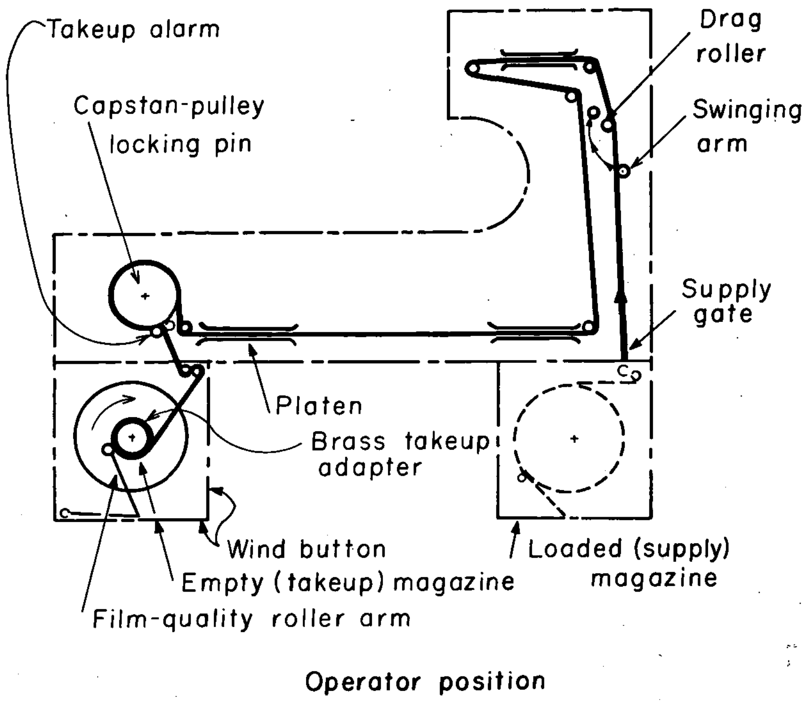

Fig. 9

Fig. 10

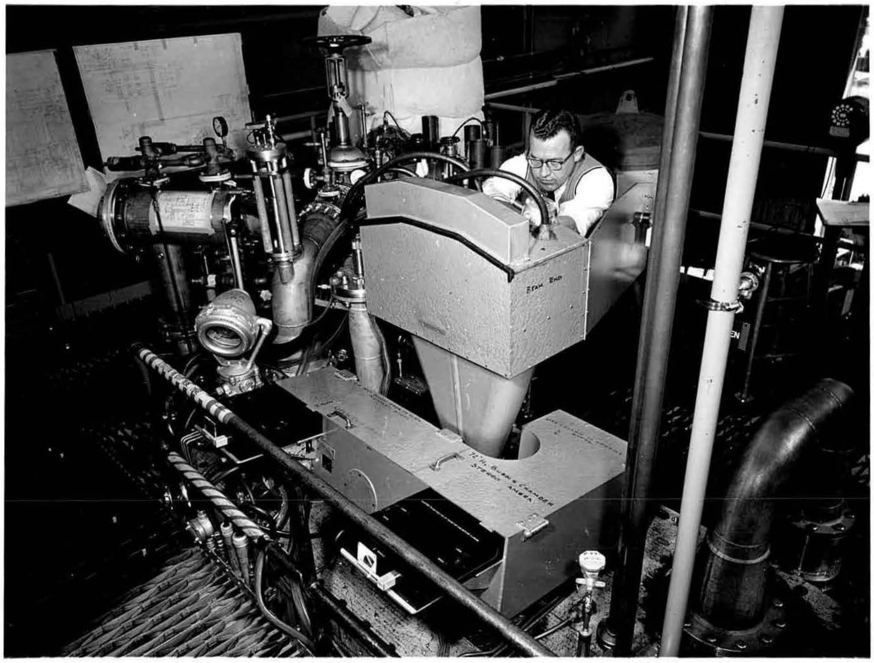

Fig. 11