THE CHARACTERISTICS OF

A BUBBLE CHAMBER USING

LIQUID NITROGEN AND ARGON

by

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For the Department

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I would like to express my thanks to Dr. Robert Stump for his aid and encouragement during the course of this project. I would also like to express my appreciation to the United States Air Force for their financial support of the project.

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INTRODUCTION

The last ten years have seen the development of a useful new tool for the study of high energy nuclear reactions and fundamental particles. This device, the bubble chamber, makes use of a superheated liquid to display the path of a charged particle as a trail of small bubbles.

The bubble chamber has several features which make it more useful in many experiments than either the cloud chamber or the nuclear track plate. Since the liquid in a bubble chamber is considerably more dense than the vapor in a cloud chamber, there is a much better possibility of seeing a nuclear interaction when the chamber is placed in a beam of high energy particles. Moreover, if an interaction does take place, the resulting particles are more likely to be stopped inside the chamber. Thus, more events occur in the bubble chamber, and these events are easier to interpret than in the cloud chamber. In addition to these benefits, most bubble chambers can be cycled faster than expansion-type cloud chambers, and they may be built with a larger sensitive volume than is practical with diffusion cloud chambers.

Particle tracks are easier to find in bubble chamber photographs than in nuclear emulsions since one need not look for them with a microscope. Due to the rapid growth of the bubbles, one can get some idea of the age of a track in the chamber by the size of its constituent bubbles. Thus, events like the formation of a neutral particle from a charged particle and the subsequent decay of the neutral particle elsewhere in the chamber into other charged particles may often be identified. This is virtually impossible with emulsions. Another advantage over emulsions is that the bubble chamber may be used effectively in a magnetic field, thus making it easier to determine the energy of particles traversing the chamber.

In spite of these virtues, the bubble chamber is not entirely the fulfillment of every high energy physicist's dreams. It is more difficult to construct and operate than a cloud chamber, and certainly more so than a nuclear track plate. The bubble chamber's most serious drawback, however, is its lack of "latent image." The disturbance caused by particles in the chamber is so short-lived that no one has yet been able to obtain a track by expanding the chamber after an interesting event has taken place.

The particular characteristics of a bubble chamber depend, of course, on the liquid used in the chamber. Liquid hydrogen has the advantage that interactions are easy to interpret, since incoming particles can only collide with protons. Liquid hydrogen has a density of only o.06[1] gm/cm^3, however, and its stopping power for high energy radiation leaves something to be desired. At the other extreme is liquid xenon. This liquid is about 38 times more dense than liquid hydrogen, so that the number of interactions to be expected per cubic centimeter of chamber volume is correspondingly greater. Various organic compounds have also been used as bubble chamber liquids, in particular propane and several of the "Freons." Propane has the advantage that it is somewhat (28 per cent by volume) richer in hydrogen atoms than liquid hydrogen itself. It also operates at a more convenient temperature. CF_3Br, one of the "Freons," is a more effective detector of gamma rays and charged particles than propane since it is 3.5 times more dense. Moreover, CF_3Br bubble chambers represent nearly the ultimate in convenience of operation, since they run at a temperature of 30° C under a pressure of 18 atmospheres.[2]

It was our desire to build a small bubble chamber to test the operating characteristics of liquid nitrogen and liquid argon. No detailed information about either of these liquids has yet appeared in the literature, although both appear to be well-suited to bubble chamber use. They are both transparent, isotopic liquids of moderate density and preliminary calculations indicated that the pressures and temperatures necessary to make these liquids sensitive to ionizing radiation would be achievable with no great difficulty. In building the small chamber, we hoped to gain experience in techniques of constructing and operating bubble chambers using these liquids before building a larger chamber suitable for use as a tool in high energy physics research.

SECTION II

THEORY

In order to better understand the experiment, it may be instructive to look at some of the broader aspects of the theory of bubble chamber operation. Charged particles are capable of producing visible tracks in the superheated liquid of the bubble chamber because this liquid is in a metastable state. If a liquid is gradually heated above its boiling point at a given pressure, the liquid does not immediately begin to boil, but rather remains quiescent until some irregularity in the vessel or disturbance in the liquid initiates the formation of bubbles. Thus, if the walls of its container are smooth, an undisturbed liquid will remain in a state of moderate superheat for long periods of time. If the degree of superheat is great enough, however, ionizing radiation will disturb the liquid sufficiently to initiate the boiling process. For instance, Glaser[3] found that cosmic rays could trigger eruptive boiling in diethel ether if the liquid was heated to 135° C, a temperature roughly 100C$^{\circ}$ above its normal boiling point. High speed motion pictures revealed that a track of bubbles formed along the path of the ionizing particle, and as these bubbles grew, they disturbed the neighboring liquid, initiating general boiling.

Seitz[4] has investigated the theoretical aspects of bubble nucleation by ionizing radiation. According to his theory, nucleation is a two-step process. As it passes through the liquid of the bubble chamber, the high energy particle occasionally knocks electrons out of the electron shells of atoms in the liquid. These fast electrons, sometimes called knock-on electrons or delta rays, soon lose their energy to nearby atoms of the liquid through coulomb interactions, and thus raise the temperature of the liquid through which they pass. If the "hot spot" caused by the delta ray in the liquid is of the proper size, and if sufficient energy has been transferred, the liquid within the "hot spot" evaporates, and a small bubble is formed. If the bubble is large enough, it will grow to visible size by evaporation from its surface. Thus, the ionizing radiation first forms delta rays in the liquid. These delta rays then produce "hot spots" which nucleate the bubbles of the visible track.

Two questions now present themselves. How large must a bubble in the superheated liquid be before it will grow by evaporation from its own surface? Also, how much energy must the delta ray transmit to the liquid to form such a bubble? The first question is easily answered by considering a small bubble of radius r in a superheated liquid with an equilibrium vapor pressure of P_e and surface tension σ. Let the external pressure on the liquid be P_o.

The pressure inside the bubble is P_e since the vapor in the bubble is in equilibrium with the liquid surrounding it. The pressure immediately outside the bubble is essentially the same as the pressure on the surface of the liquid, P_o, which is assumed to be considerably less than P_e. The force which keeps the bubble from expanding without limit is supplied by the surface tension of the liquid in the surface of the bubble. Let us assume that the bubble is of spherical shape. If we pass an imaginary plane through the center of the sphere, dividing the bubble into two hemispheres, we find that a force σ is exerted per unit length of circumference of the hemisphere due to the surface tension in the liquid. Since the surface of the hemisphere is normal to the plane of intersection along its circumference, this force is normal to the plane. Thus, the total force between the two hemispheres forming the bubble is simply the product of σ and the circumference of the hemisphere:

$$F = 2\pi r\sigma \qquad (1)$$

An opposing force is produced by the net pressure inside the bubble acting on the surface. This force, which tends to push the two hemispheres apart, is equal to the product of the net pressure inside the bubble and the projected area of the hemisphere in the intersecting plane:

$$F' = (P_e - P_o)\pi r^2 = \Delta P \pi r^2 \simeq P_e \pi r^2 \qquad (2)$$

The radius of a bubble in equilibrium with the liquid is found by equating the two forces above and solving for r:

$$r_e = 2\sigma/\Delta P \simeq 2\sigma/P_e \tag{3}$$

If the radius of the bubble formed by the delta ray is less than this value, the force due to surface tension will predominate, and the bubble will collapse. Conversely, if the bubble formed has a radius greater than r_e, the force due to pressure will predominate, and the bubble will eventually grow to visible size.

Now, let us determine how much energy is required to form a bubble of radius r_e in the superheated liquid. The energy of formation, E_f, is composed of the energy required to vaporize the liquid within the bubble, E_v, and of the energy of the bubble's surface, E_s. For a bubble in equilibrium,

$$E_v = n_v V H_v = 4\pi r_e^3 n_v H_v/3 \tag{4}$$

where V is the volume of the bubble, n_v is the number of moles per unit volume of the liquid, and H_v is the latent heat of vaporization per mole of liquid. The surface energy of the bubble is given by the relation:

$$E_s = \int_A \sigma\, dA = \sigma A = 4\pi\sigma r_e^2 \tag{5}$$

where A is the surface area of the bubble. If we substitute the value for r_e from equation (3) into this expression, we obtain:

$$E_s = 16\pi\sigma^3/P_e^2. \tag{6}$$

The total energy of formation is then given by the sum of E_v and E_s.

$$E_f = 16\pi\sigma^3/P_e^2 + 32\pi\sigma^3 n_v H_v/3P_e^3$$
$$= (16\pi\sigma^3/P_e^2)(1 + 2n_v H_v/3P_e). \qquad (7)$$

We have again made use of equation (3) to express r_e in terms of the pressure and surface tension. The energy E_f represents the minimum amount of energy which must be transferred to the liquid by the delta ray in order to form a bubble. Typical values for E_f are 4 ev for a bubble in liquid hydrogen and 131 ev in liquid propane.[5]

Empirical results indicate that the actual energy necessary to form a bubble, E_2, is of the order of 513 ev in liquid hydrogen and 1890 ev in liquid propane.[6] The derivation of the expression for E_f has not taken into account the loss of energy in the heated region by thermal conduction nor the energy expended in setting the liquid in motion. By taking these factors into account, Seitz has been able to arrive at values for E_f which are closer to those actually observed.

We have seen that if an electron is to be effective in forming a bubble in the liquid, it must concentrate most of its energy in a spherical region of the liquid whose radius is of the order of r_e. The range of an electron in the liquid is given approximately by the expression,

$$R = 0.58 \times 10^{-6} E_e^2/(Z/A)\rho , \qquad (8)$$

where R is the range in cm, E_e is the energy of the electron in kev, Z is the number of electrons per molecule of liquid, A is the molecule weight of the liquid in amu, and ρ is the liquid's density.[7] This relation holds quite well for electrons with energy less than or equal to 10 kev. Since the energy of the delta rays with which we are concerned is fairly low (of the order of several kev), the paths of these electrons through the liquid are quite crooked. The paths are bent so much by coulomb interactions that the net distance which the average electron travels (i.e., the actual distance from the point where the delta ray is formed to the point where it finally comes to rest) is only about one-half the length given by R. Thus, the energy of an electron with a good probability of forming a "hot spot" of the proper size to nucleate a bubble may be found by equating R/2 and the diameter of such a "hot spot," $2r_e$. This yields the result

$$E_e^{2} = 1.74 \times 10^{6} \rho (Z/A)(4\sigma/P_e) \qquad (8a)$$

E_e has a value of 257 ev in liquid hydrogen and 769 ev in liquid propane. This energy is roughly half of E_a, the observed amount required to form a stable bubble. Seitz concludes that bubbles are nucleated by exceptional delta rays of energy approximately equal to E_a, whose paths through the liquid have been so perturbed by coulomb interactions that the delta ray remains within a sphere of radius r_e.

The expressions for E_f and for E_e ~~are proportional to~~ vary as the surface tension of the liquid and inversely as

~~proportional to~~ the vapor pressure. Now, for most liquids, the van der Waals expression for surface tension,

$$\sigma = \alpha (1 - T/T_c)^n \tag{9}$$

holds, where T is the temperature of the liquid in ^oK, T_c is the critical temperature, and α and n are epirically determined constants.[8] For most liquids, n is of the order of 1.2. This expression obviously goes to zero as T approaches T_c. According to the Clausius-Clapeyron equation for the vapor pressure,

$$\log P_e = A - B/T , \tag{10}$$

P_e increases with increasing temperature. If the pressure, P_o, on the surface of the liquid remains constant, the energy required to nucleate a bubble decreases with increasing T, and goes to zero at the critical temperature. Thus if the temperature is raised sufficiently above the boiling point, or equivalently, of the pressure B lowered sufficiently below the vapor pressure, most liquids become sensitive to ionizing radiation. Because of the statistical nature of delta ray formation in a liquid, there is a large variation in energy of the delta rays produced by any one ionizing particle. Thus, the transition from insensitivity to sensitivity of a liquid in a bubble chamber is not abrupt, but rather quite gradual. As the temperature is increased, nucleation of bubbles becomes more and more probable as lower energy delta rays begin to nucleate bubbles. The result is that the number of bubbles per unit length along the track of the ionizing particle increases with increasing temperature.

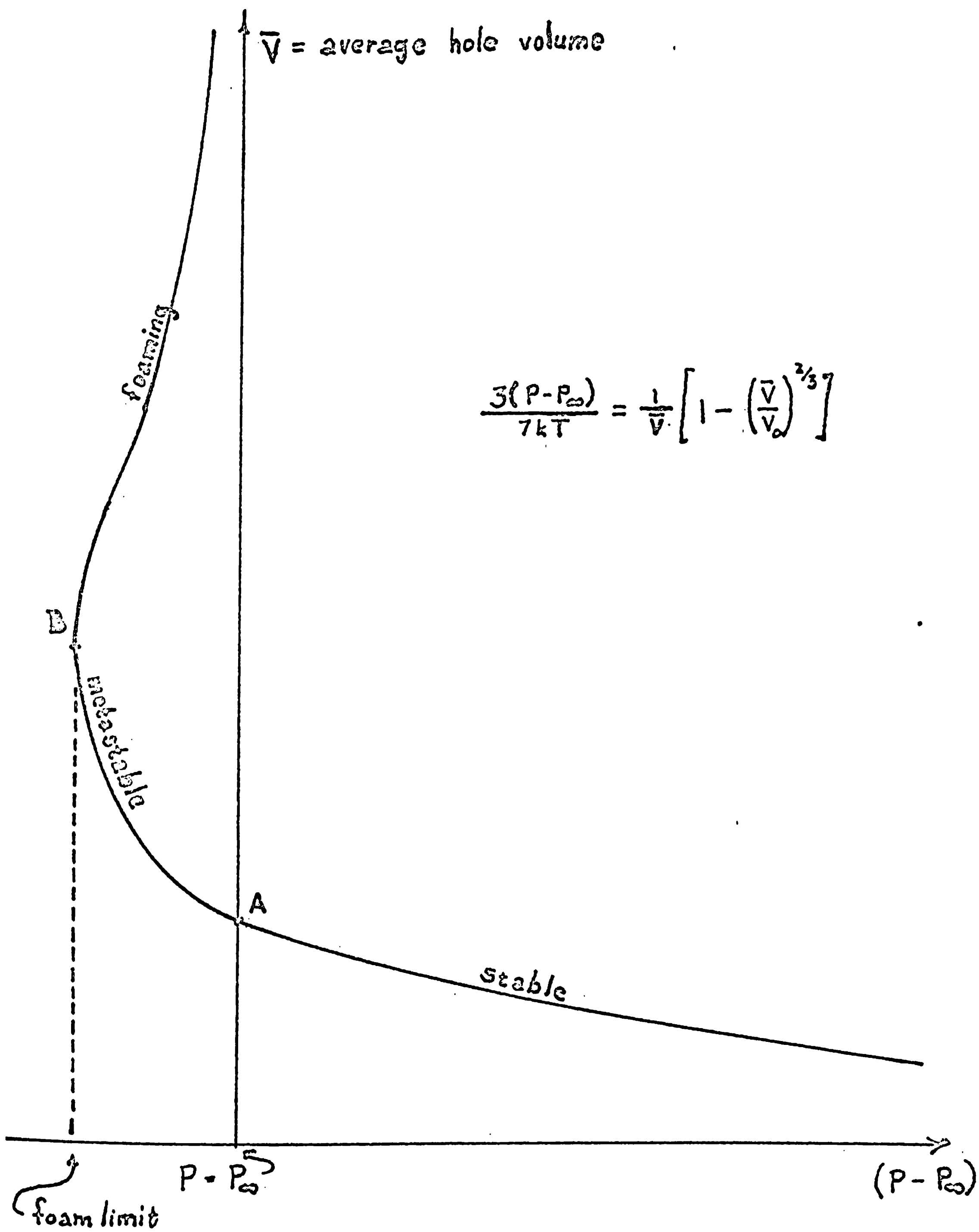

Figure 1: Graph of average hole volume vs. applied pressure for a liquid as predicted by Fürth.[1n]

If the temperature is raised far enough above the boiling point, however, another effect takes place. Bubbles form spontaneously throughout the liquid, and the bubble chamber immediately fills with foam. This effect is best explained from the standpoint of the "hole" theory of liquids, as proposed by Fürth and reported by Bugg.[9] Due to the random thermal motion of molecules in a liquid, there is always the possibility that the molecules in a given small region at a given instant may move toward each other, producing a small region of abnormally great density, or conversely, they may move mutually away from one another, producing a neighborhood of abnormally small density. Thus, at a given instant, the density of a liquid is not constant throughout its volume. Indeed, it appears that these fluctuations produce tiny short-lived holes filled with saturated vapor in the liquid. As the temperature of the liquid increases, the average volume of these holes becomes greater, as we can see from Fürth's expression for this quantity:

$$\frac{3(P-P_\infty)}{7kT} = \frac{1}{\bar{v}}\left[1-\left(\frac{\bar{v}}{v_0}\right)^{2/3}\right] \qquad (11)$$

Here, k is Boltzmann's constant, $\bar{v}$ is the average volume of the holes, v_0 is a constant, P is the pressure applied to the surface of the liquid, T is the temperature of the liquid and P_∞ is the equilibrium vapor pressure at that temperature. Figure 1 is a graph of $\bar{v}$ vs. $(P - P_\infty)$.[10] the region of this curve to the right of point A represents the condition in which the pressure on the surface of the liquid is greater than the vapor pressure. Here, the temperature of the liquid is below the boiling point. Between points A and B, the vapor pressure of the liquid is greater than the applied pressure, but the behavior of the hole volume is the same as in the stable region to the right of point A. This represents the metastable superheated state of the liquid. Above point B, the behavior of the hole is quite different. Here, as the pressure decreases in the hole, the volume of the hole continues to increase indefinitely, and each of the small holes can increase in size without bound. This part of the curve corresponds to the formation of foam in the liquid. In the metastable region, the degree of superheat is indicated by the difference between P and P_{∞}. Since any attempt to reduce P below the foam limit results in the formation of foam, this limit sets an upper bound on the degree of superheat attainable in a liquid. If a liquid is to be useful in a bubble chamber there must be a pressure between P_{∞} and the foam limit at which the energy of formation of a stable bubble is small enough that such bubbles may be produced with good probability by delta rays formed by ionizing radiation.

SECTION III

APPARATUS

The bubble chamber described in this section was designed expressly for the purpose of finding the temperature and pressure at which liquid nitrogen and liquid argon are sensitive to ionizing radiation. Experiments with a number of different substances have shown that most liquids are sensitive at one-half the critical pressure and at a temperature two-thirds of the way between the boiling point and the critical temperature.[11] Since the critical pressure of argon is 48 atmospheres, the chamber must withstand a pressure of at least half this value, or 350 psi.

Of the two fluids, N_2 would be expected to operate at the lower temperature, since its critical temperature is lower than that of argon. According to the approximate expression given above, N_2 should be sensitive to radiation at a temperature of about 110° K. Thus, the bubble chamber must be designed to operate at fairly low temperatures as well as at high pressures.

The chamberis designed to operate in a range of temperatures between room temperature and the normal boiling point of liquid nitrogen, and in a range of pressures between atmospheric pressure and 500 psi. All the components of the pressure system were designed to withstand a pressure of at least 1000 psi, although the pressure in the system is limited to 500 psi by a safety valve. The volume of the chamber, 22 in.^{3}, is fairly small so that only a modest quantity of liquid is necessary to fill the chamber.

Figure 2 is a drawing of the bubble chamber and its related cooling equipment. The bubble chamber itself is fashioned from a 3-inch stainless steel reducing cross joint. A stainless steel flange is silver soldered to each of the 3-inch ends of this fitting, and a stainless steel ring is bolted to each of the flanges to clamp the window cells (Figure 3) onto the bubble chamber. The bottom opening of the cross joint is sealed with a stainless steel plug; and the entire piece of apparatus is suspended from the top plate of the vacuum tank by a 14-inch section of 2-inch stainless steel pipe. Stainless steel is a relatively poor conductor of heat, so this pipe insulates the cold bubble chamber from the walls of the vacuum tank, which are at room temperature.

A double walled cooling jacket formed from stainless tubing fits inside the 2-inch supporting pipe, and is silver soldered to a brass flange which can be bolted securely to the top of the vacuum tank. The central passage of this jacket connects the bubble chamber to the pressure system, while the outer chamber serves as a reservoir for the liquid nitrogen used to cool the bubble chamber. Also enclosed in the vacuum tank is a thermal radiation shield made of sheet

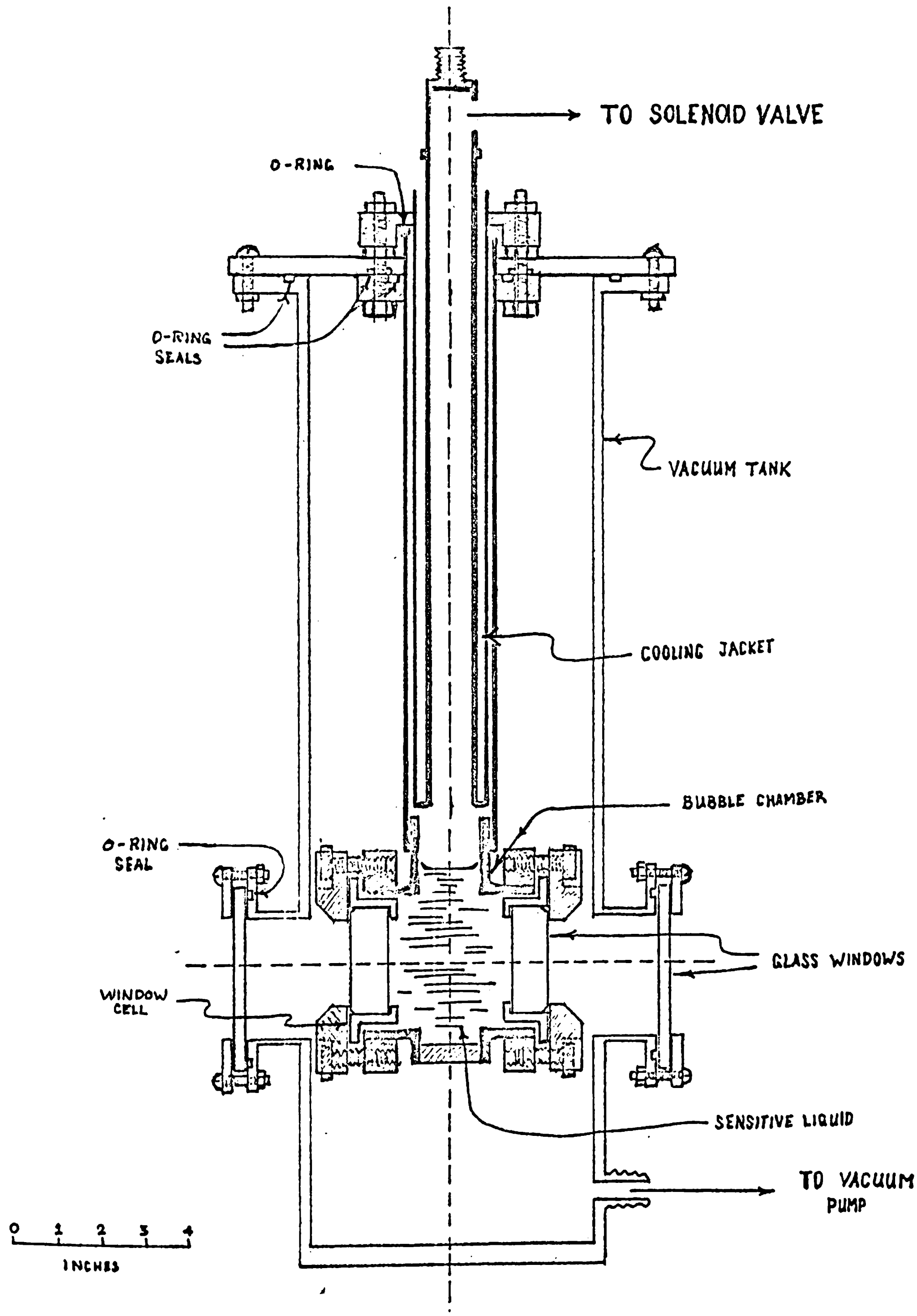

Figure 2: The bubble chamber in its vacuum tank. For the sake of clarity, the outer radiation shield is not shown in this drawing.

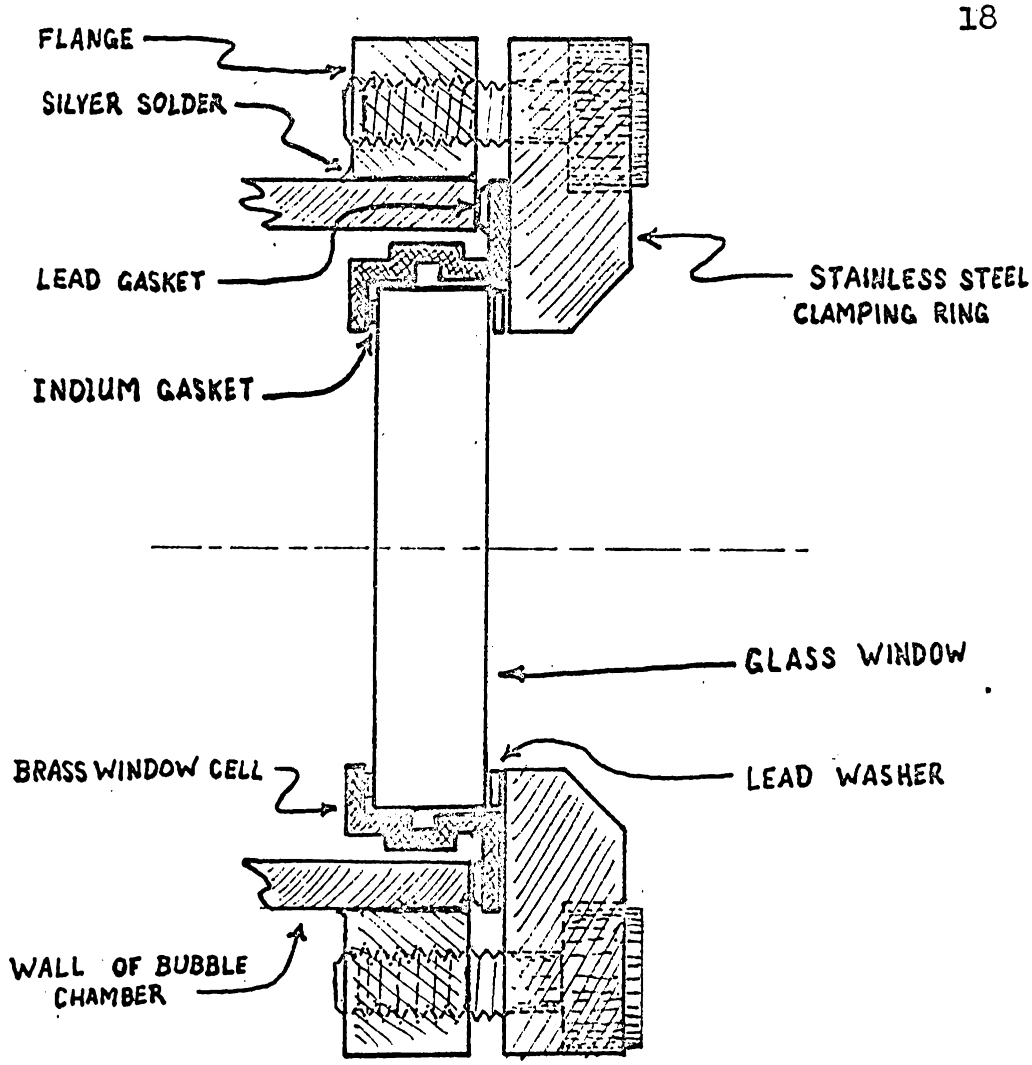

Figure 3: The bubble chamber window cell. Lead and indium gaskets were used because these materials remain pliable at the temperature of liquid nitrogen.

copper. This shield fits loosely around the bubble chamber and is connected to two brass cylinders which are suspended inside the vacuum tank by sections of 1/2-inch o.d. stainless steel tubing. These tubes extend through the top of the vacuum tank and allow the brass cylinders to be filled with liquid nitrogen. Thus, the shield is kept at the normal boiling point of liquid nitrogen, 77.3° K, and helps to cool the bubble chamber by radiation. The liquid nitrogen used to fill the radiation shield reservoirs and cooling jacket is obtained from commercially available pressurized dewars.

Four 220 ohm carbon resistors are used to indicate the level of liquid nitrogen in the heat shield reservoir and cooling jacket. These resistors exhibit a large change in resistance when cooled to liquid nitrogen temperature. Resistors are placed at the top and at the bottom of each of the tanks containing nitrogen; their resistance is measured by a bridge circuit. A current flows through the resistor when it is connected to the bridge, causing the resistor to dissipate a certain amount of heat at all times. Since the thermal conductivity of the liquid is considerably greater than that of the vapor, the resistor operates at a lower temperature in the liquid, and an abrupt change in resistance can be seen as the resistor passes from the vapor into the liquid or vice versa. The value of the resistor at the top of the tank is observed while the tank is being filled. A sudden decrease in its resistance indicates that the tank is full. The value of the bottom resistor is then observed, and when it increases, indicating that the level of the liquid has fallen below the resistor, the tank is refilled.

In operation, the temperature of the liquid in the bubble chamber is controlled by regulating the amount of liquid nitrogen in the cooling jacket and by adjusting the current which flows through a 20-watt wire-wound resistor fastened to the bottom of the bubble chamber. The temperature of various parts of the bubble chamber is indicated by a potentiometer which may be connected to any of three thermocouples fastened to the outside of the chamber wall. One thermocouple is soldered to the stainless steel plug which forms the bottom of the bubble chamber. A second is fastened half way up the side of the chamber, and a third is soldered to the top of the chamber, where it joins the supporting pipe. The thermocouples are made from Minneapolis-Honeywell iron-constantin thermocouple lead wire. The heater and thermocouple connections are brought out of the vacuum tank through a header soldered to its lid.

A Cenco "Hyvac" forepump is used to evacuate the vacuum tank.

Figure 4 is a schematic diagram of the pressure system used in conjunction with the bubble chamber. The fluid (either nitrogen or argon) to be used in the chamber

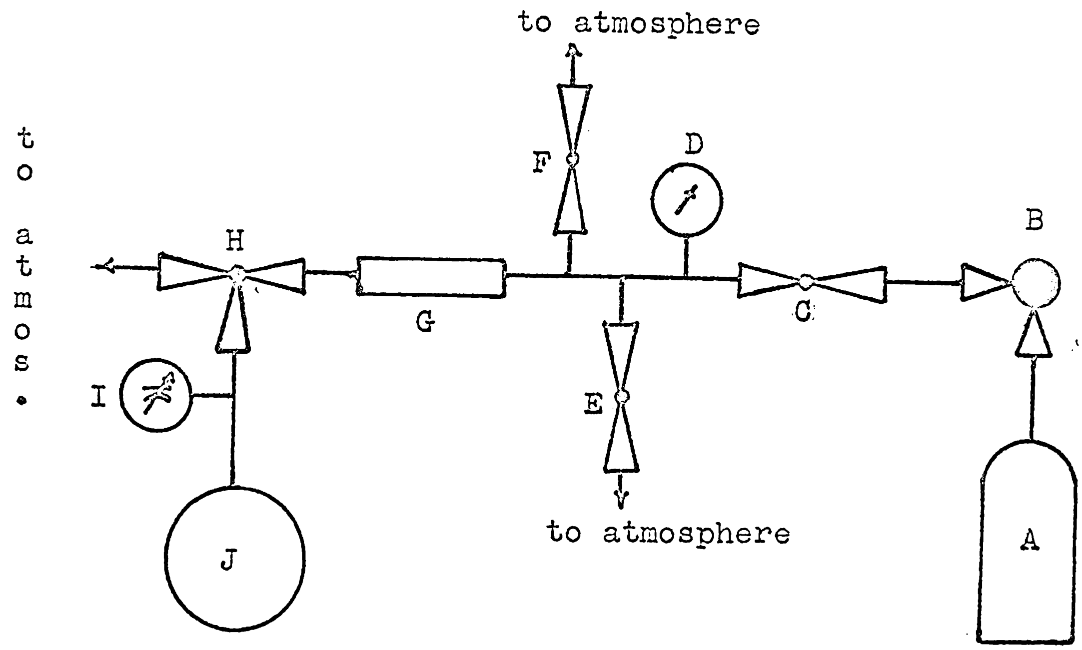

Figure 4: Diagram of the pressure system.

LEGEND

A. Cylinder of gas at high pressure

B. Regulator valve

C. Inlet valve

D. Bourdon pressure gauge

E. Exhaust valve

F. Safety valve

G. Repressurization tank

H. Solenoid valve

I. Transient pressure gauge

J. Bubble chamber

is supplied in gaseous form at high pressure from the commercial bottled gas cylinder (A). The pressure of the gas is lowered by the regulator valve (B) to the pressure desired in the bubble chamber. The gas is then admitted to the repressurization tank (G) through valve (C) and eventually finds its way into the bubble chamber through the solenoid valve (H).

The repressurization tank is an 18-inch section of wrought iron pipe threaded at each end and fitted at the top with a 3/4-inch bell reducer. The bottom end is closed with a cap. A special 3/4 inch i.d. brass elbow fitting connects the tank to the solenoid valve. The tank is connected to the valve cluster containing the needle valves (C) and (E), the safety valve (F), and the gauge (D) by a 3-foot length of 1/4-inch copper tubing. Valve H is a Crescent No. 103863 electrically operated solenoid valve, manufactured by the Barksdale Valve Company. The valve normally connects tank (G) to the bubble chamber, but when its coil is energized, the valve closes the connection to the repressurization tank and opens the bubble chamber to the atmosphere.

Gas from the pressure system is liquified to fill the bubble chamber. On its way into the bubble chamber, the gas passes through the cooling jacket filled with liquid nitrogen. There the gas is cooled and condenses into droplets of liquid. These droplets fall to the bottom of the bubble chamber where they evaporate, taking their latent heat of vaporization from the walls of the chamber. In this way, the gas helps to speed the process of cooling the bubble chamber. Eventually, the walls become sufficiently cold that the droplets no longer evaporate, but collect in the chamber, filling it with liquid.

When the chamber is in operation, the inlet valve is closed, and the cooling jacket is allowed to run dry. Under these conditions, the pressure in the system as measured by the Bourdon gauge is roughly equal to the vapor pressure of the liquid in the bubble chamber. This liquid is superheated by opening the solenoid valve. The pressure in the chamber then rapidly drops to atmospheric pressure. Since the inner surface of the chamber is slightly rough, boiling commences immediately along the walls. The liquid in the chamber must, therefore, be photographed before the bubbles formed on the walls have a chance to grow large enough to disturb the central area of the chamber and obliterate any tracks which may have been formed there. The valve closes approximately 25 ms. after being opened, and the chamber is repressurized in another 25 ms. by the gas in the repressurization tank. Since the pressure has been returned so rapidly, bubbles formed in the superheated liquid do not have time to rise an appreciable distance before they collapse once more under the increased pressure. When a bubble collapses, the heat of vaporization returns to the same location from which it was extracted when the bubble grew to visible size. If the bubbles were allowed to rise before the pressure was reapplied to the liquid, two undesirable effects would occur. First, heat would be extracted by rising bubbles from the liquid at the bottom of the chamber and replaced near the surface, causing a large temperature gradient in the liquid. Second, some bubbles would rise to the surface and break, thereby increasing the quantity of heat lost and the amount of liquid evaporated each time the chamber was operated.

During operation of the chamber, the pressure is indicated by the transient pressure gauge (I), which is connected to the pressure line between the valve and the chamber. The sensitive element of this gauge is a circular brass diaphragm one side of which is exposed to the pressure in the chamber, and which bends outward as the pressure in the chamber increases. This increases the capacitance between the diaphragm and a fixed plate placed near the diaphragm. The capacitance of the gauge, then, is proportional to the pressure in the chamber. The gauge acts as the tuning capacitor in an oscillator circuit whose chassis is fastened directly to the body of the gauge. The frequency of the signal from the oscillator is determined by the value of the gauge capacitance, and therefore, is also a function of the pressure. The signal passes through a cathode follower into a coaxial cable which carries it to the remotely located detector circuit. The detector produces a voltage proportional to the signal frequency. The signal from the detector is connected to the y-axis amplifier of an oscilloscope whose sweep is triggered by the pulse which opens the solenoid valve. Thus, each time the pressure in the chamber is released, the oscilloscope displays the behavior of the chamber pressure as a function of time.

The bubble chamber is illuminated through one of its two windows and photographed through the other. The illuminating apparatus consists of a General Electric type FT-230 electronic flashtube, a translucent diffuser screen and a condensing lens. This equipment is assembled in a light-tight box and arranged so that it beams its light into the chamber through one of the windows of the vacuum tank. The camera uses a Zeiss Tessar f/4.5 lens with a focal length of 10.5 cm. No provision is made for focusing this lens, since the camera is always placed 12 inches from the center of the bubble chamber. The film is carried in a Beattie-Coleman Model C-54 motor operated film magazine.

Since the entire photographic system is protected from stray light, no shutter is used in the camera. Exposures are made by firing the flashtube. The duration of the light flash from the FT-230 tube is only five microseconds, so the photographs are not blurred by motion, even though the bubbles grow very rapidly. Since the camera is in the direct beam of the light from the condensing lens, the bubbles appear as dark spots on a light background.

The valve, flashtube, and camera film advance are controlled by an electronic pulse circuit of conventional design. The operation of this equipment is initiated by closing a pushbutton switch. After a delay of adjustable duration, a capacitor is discharged through the solenoid valve magnet, opening the valve momentarily. After a second preset interval, the circuit fires the flashtube to photograph the chamber and advances the film to the next frame.

SECTION IV

EXPERIMENTAL RESULTS

Photographs were taken of liquid nitrogen and argon with the equipment described in the previous section. A gamma ray source was placed near the chamber to produce Compton electrons in the liquid. The pressure was released from various initial values to atmospheric pressure, and the number of bubble clusters or tracks in a standard volume of the chamber was counted for each trial. Since the number of Compton electrons formed in the chamber in each trial is fairly uniform, the number of bubble clusters observed is indicative of the sensitivity of the liquid. The results of this experiment are summarized in Figure 5 for liquid nitrogen and in Figure 6 for liquid argon. The Bourdon gauge used to measure the initial pressure actually indicated the difference between this pressure and that of the atmosphere. Since the chamber was always expanded to atmospheric pressure, the abcissas of the graphs correspond directly to the degree of superheat in the liquid.

The foam limit for nitrogen occurs at approximately 290 lb/in^2. The liquid is sensitive to radiation between 230 lb/in^2 and the foam limit. A nominal valuefor its operating point, then, is 260 lb/in^2. Argon exhibits a foam limit of 430 lb/in^2, a lower limit of sensitivity of 315 lb/in^2, and a nominal operating point of 375 lb/in^2.

Two factors contribute to the scatter in the experimental points. First, the number of Compton electrons formed in the chamber by the source during each expansion is subject to random variation. Second, the pressure in the chamber before each expansion may not correspond exactly to the equilibrium vapor pressure of the liquid.

Figure 7 and Figure 8 are photographs of electron tracks taken in liquid argon and liquid nitrogen, respectively. Figure 9 shows the track of a cosmic ray traversing the chamber. In this photograph, the liquid nitrogen is not at its maximum sensitivity, as is evidenced by the low bubble density along the track. The behavior of the liquid above the foam limit is shown in Figure 10.

Figure 11 shows a typical oscilloscope trace of the pressurein the chamber during expansion. The sweep rate of the oscilloscope shown in this photograph was 7.5 ms/division. The vertical line near the minimum of the curve indicates the instant when the flashtube was fired.

FIGURE 5:
SENSITIVITY CURVE
LIQUID NITROGEN

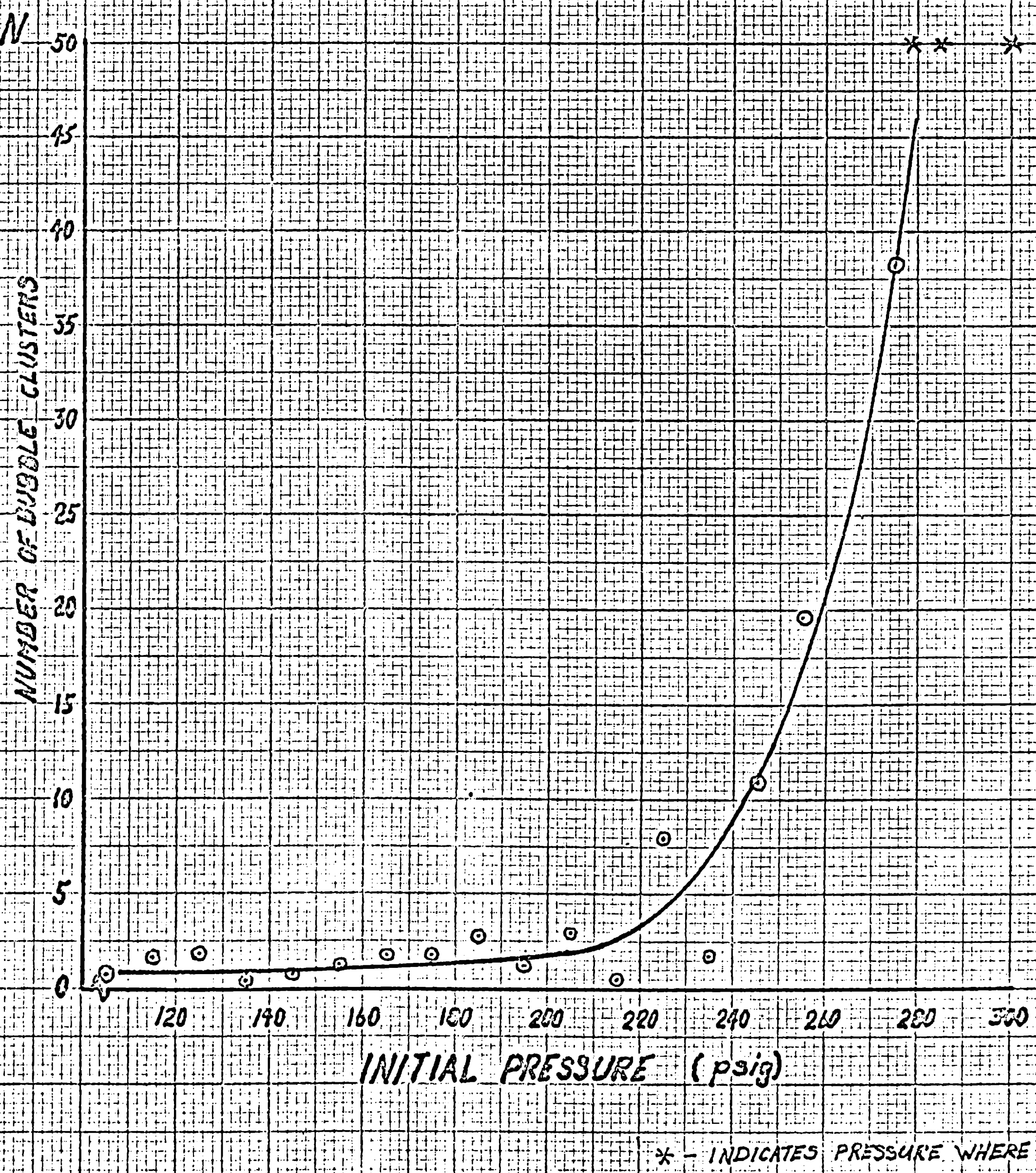

FIGURE 6:

SENSITIVITY CURVE

LIQUID ARGON

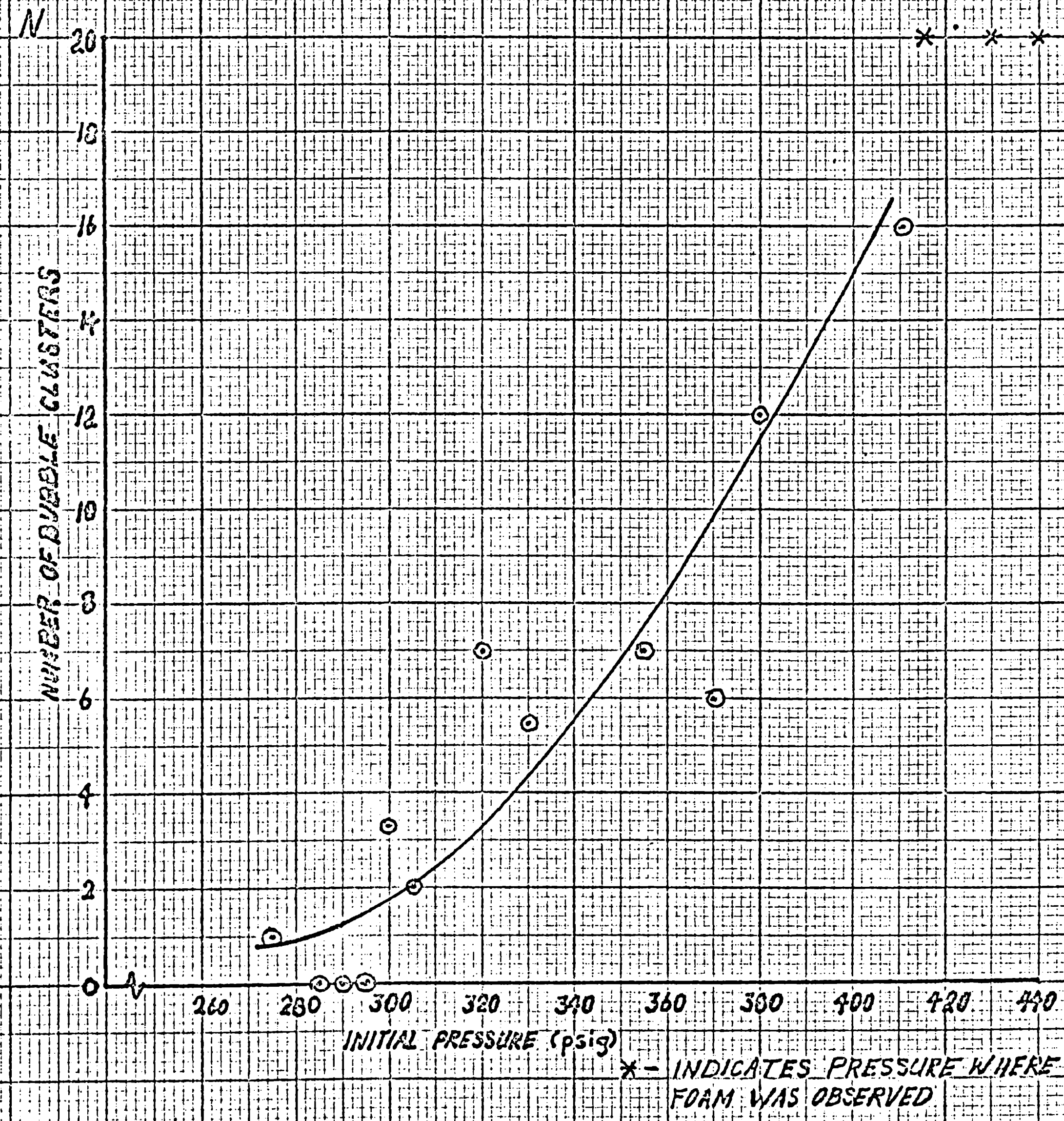

Figure 7: Electron tracks (circled) in liquid argon. The initial pressure was 335 lb/in.^{2}

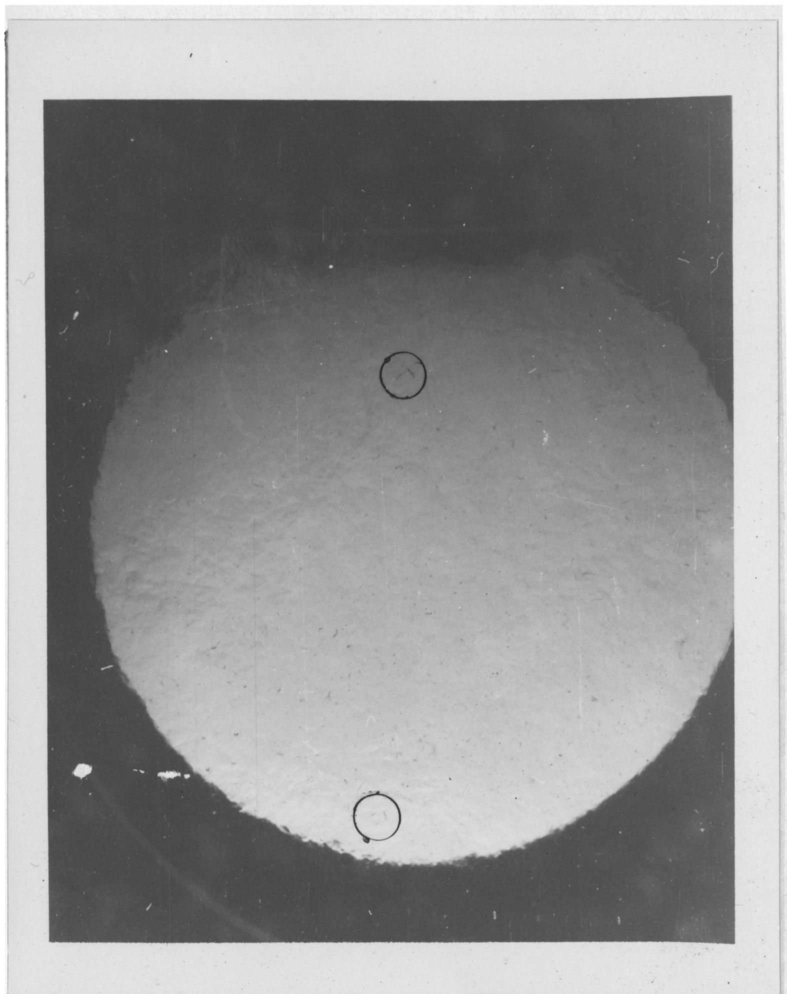

Figure 8: Electron tracks (circled) in liquid nitrogen. The initial pressure was not recorded, but was evidently over 300 lb/in^2. The photographs immediately preceding and succeeding this one show only foam.

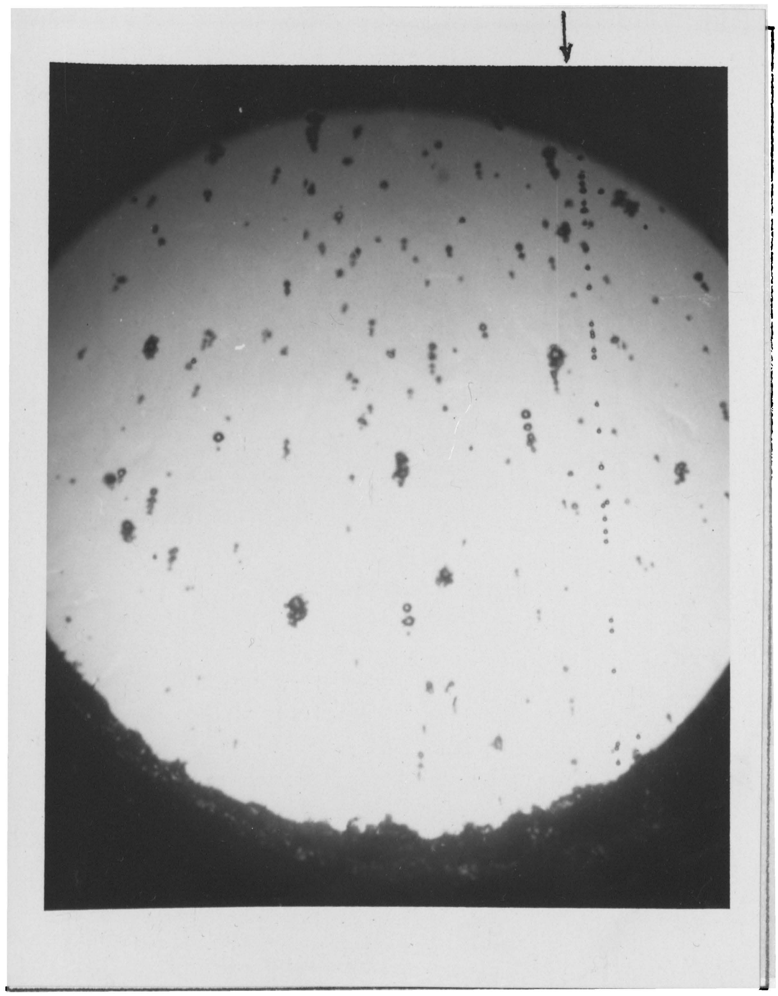

Figure 9: Cosmic ray track (indicated by the arrow) in liquid nitrogen. The initial pressure was 267 lb/in.^{2}

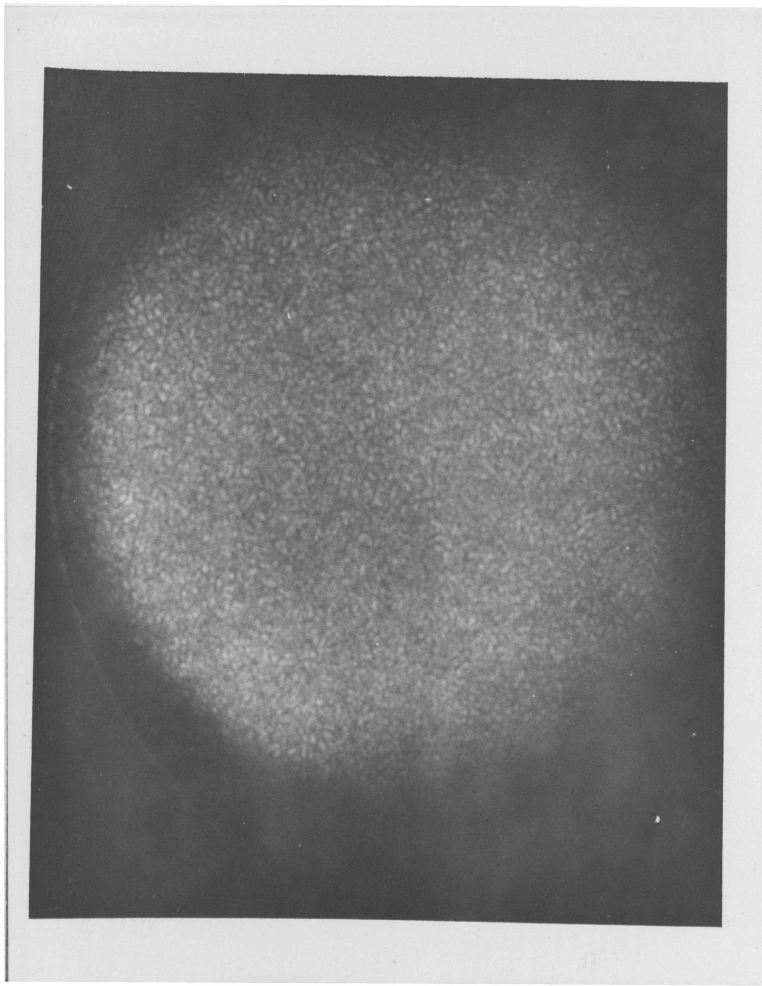

Figure 10: Foam.

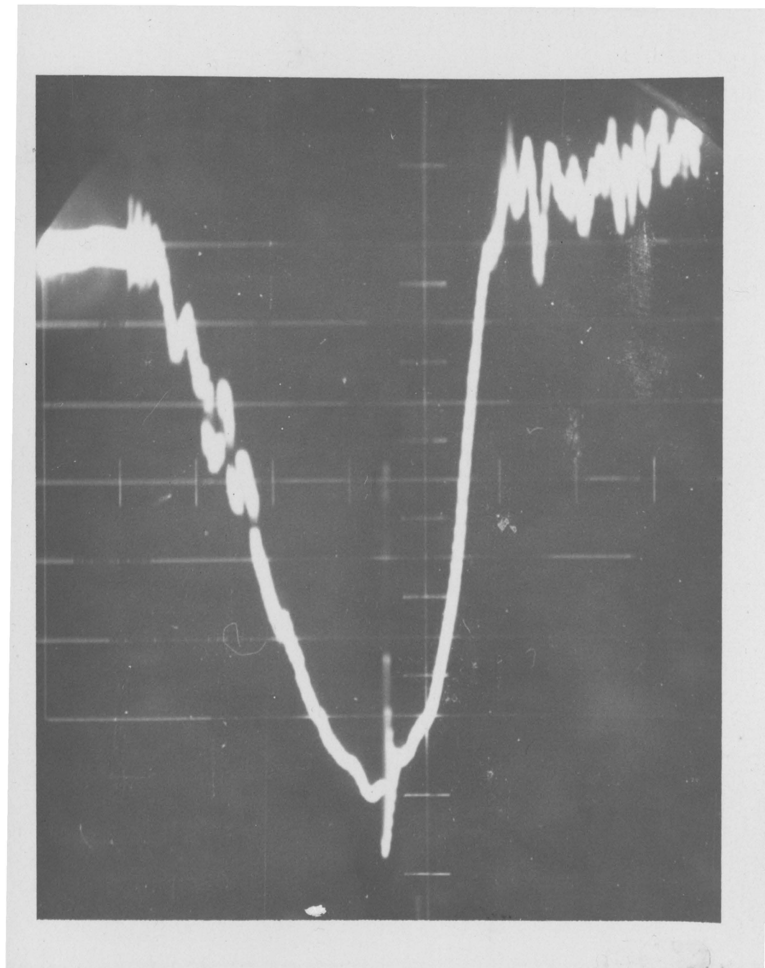

Figure 11: Oscillogram of the pressure in the bubble chamber during a typical expansion. The sweep rate was 7.5 ms/division.

SECTION V

CONCLUSION

The operating characteristics of nitrogen and argon are compared with those of similar liquids in Table 1. As would be expected, these characteristics are intermediate between those of xenon and hydrogen.

The operating pressures of both liquids tested appear to be slightly greater than half the critical pressure, whereas hydrogen and xenon are reported to operate at pressures slightly under half their respective critical pressures. This difference may be partially due to a difference in definition of the operating point. Most bubble chambers constructed elsewhere are used in conjunction with high-energy accelerators, and the chamber sensitivity is adjusted until some arbitrary optimum bubble density is obtained in tracks of minimum ionizing particles. This method of determining the operating point would not be expected to yield the same result as was obtained by the method described in this paper. Also, the pressures obtained in this experiment represent upper bounds to the actual vapor pressure of the liquid in the chamber, so the liquid vapor pressure during operation of the chamber may be somewhat smaller than the value quoted in Table 1.

Liquid	Pressure	Temperature	Density
Hydrogen	70 lb/in^2	27° K	0.06 gm/cm^3
Helium	0.58 "	3.4° K	--
Nitrogen	260 "	114 "	0.7 (est.)
Argon	375 "	135 "	1.2 (est.)
Xenon	380 "	254 "	2.3

Table 1

Operating characteristics of various isotopic liquids in bubble chambers.[12, 13]

Bugg [14] defines a parameter K associated with the foam limit of a liquid as

$$K = (P_\infty - P_f)(kT)^{1/2}\sigma^{-3/2} \qquad (12)$$

where T is the temperature and P_∞ is the equilibrium vapor pressure of the liquid at the foam limit, P_f is the pressure on the liquid after expansion, k is Boltzmann's constant, and σ is the surface tension of the liquid. Theoretically, this parameter should have the constant value of 1.3, and is therefore useful in predicting the foam limit of a liquid. Table 2 lists the foam limit of various liquids along with the experimentally determined values of K. The values of K obtained in this experiment are somewhat higher than might be expected from results published for other liquids, but again, this is probably due to the fact that the values obtained for P_∞ in this experiment represent upper bounds to the actual values.

The primary result of this experiment has been to make available the operating points of two more isotopic liquids in bubble chambers. These liquids, which are of intermediate density, are relatively inexpensive, easily obtained, and appear to be quite suitable for use as sensitive liquids in bubble chambers for high-energy physics research.

Liquid	P_{∞} (lb/in^2)	P_s(lb/in^2)	T ($^{\circ}$ K)	K
Hydrogen	101	20	29	0.63
Helium	14.7	11.8	4.2	0.16
Nitrogen	290	14.7	115	1.5
Argon	430	14.7	139	2.3

Table 2

Behavior of several isotopic liquids at the foam limit.[15]

FOOTNOTES

(1) D. V. Bugg	"The Bubble Chamber," Progress in Nuclear Physics, Vol. 7, New York, Pergamon Press, (1959), p. 35
(2) D. V. Bugg	loc. cit.
(3) D. Glaser	"The Bubble Chamber," Encyclopedia of Physics, XLV, Berlin, Springer Verlag, (1958), p. 314
(4) F. Seitz	Physics of Fluids 1, 2 (1958)
(5) F. Seitz	ibid., p. 3
(6) F. Seitz	ibid., p. 4
(7) F. Seitz	ibid., p. 6
(8)	International Critical Tables, Vol. 4 New York, McGraw-Hill (1928), p. 434
(9) D. V. Bugg	op. cit., p. 6
(10) D. V. Bugg	op. cit., p. 6
(11) D. V. Bugg	op. cit., p. 5
(12) D. V. Bugg	op. cit., p. 35
(13) M. M. Block, et.al.	"A Liquid Helium Bubble Chamber," International Conference on High-Energy Accelerators and Instrumentation, Proceedings, Geneva, CERN, (1959), p. 461
(14) D. V. Bugg	op. cit., p. 7
(15) D. V. Bugg	op. cit., p. 7

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