DYNAMICS OF GAS BUBBLES IN AN OSCILLATING PRESSURE FIELD

Quarterly Report: July-September 1965

NAS 8-20152

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REPORT EM 65-10-1

DEPARTMENT OF ENGINEERING MECHANICS
THE UNIVERSITY OF TENNESSEE
KNOXVILLE, TENNESSEE 37916

OCTOBER 1965

GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA
CONTRACT NAS8-20152

N66-13604

FACILITY FORM 602

N66-13604 (ACCESSION NUMBER)	(THRU)
24 (PAGES)	1 (CODE)
CR-68301 (NASA CR OR TMX OR AD NUMBER)	23 (CATEGORY)

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I. INTRODUCTION

Contract No. NAS8-20152 between National Aeronautics & Space Administration (George C. Marshall Space Flight Center), and the Department of Engineering Mechanics at The University of Tennessee, became effective July 1, 1965. The objective of the research under this contract is exploration of the mechanism of bubble formation and the dynamics of bubble behavior in vibrating liquids. Of particular interest are the relationships of these phenomena to fluid properties.

Principal investigators are Dr. F. N. Peebles and Dr. C. J. Remenyik. Mr. Spivey Douglass is engaged as Research Assistant. The experiments are performed in the laboratory of the Department of Engineering Mechanics, with support, when necessary, from the Department's personnel. This report summarizes the first quarter's work under this contract.

As an introduction to experimental and theoretical investigations, the literature was surveyed and pertinent contributions critically examined. It became apparent that most of the theoretical work (1, 2, 4, 5, 6) has been based on the same method. The exceptions were usually short exploratory calculations done by investigators for whom bubble motion and formation was not the main problem. The various methods are dealt with in the discussions below.

Dr. Peebles, Dr. Remenyik, and Mr. Douglass visited the George Marshall Space Flight Center on July 29, 1965 to meet with personnel associated with this contract at the Applied Mechanics Laboratory, Propulsion and Vehicle Engineering Division. Discussed were background, main objectives, guiding principles, and some details of the research program. Time permitted also discussion of results obtained in the course of current research on bubble behavior at the Applied Mechanics Laboratory. During a tour of the facilities the visitors had an opportunity to view bubble phenomena. Finally, arrangements were completed for transfer of vibration equipment to The University of Tennessee.

For further familiarization with previous observations on the physics of this problem a sound film was borrowed from Southwest Research Institute who produced the film under contract with NASA.

During the latter half of August preparations were made for the installation of the vibration equipment. The equipment was operated August 31, 1965 for the first time.

The initial phase of experimentations had the purpose of reproducing observations reported on earlier by other researchers. On the theoretical side, an effort is being made to derive appropriate equations of motion for the description of bubble behavior in vibrating liquids. This approach is different from the one taken in the main part of the literature which was eventually abandoned because it is not considered sufficiently accurate. Also, its results do not seem to be consistent with observations. The method referred to employs Lagrange's equation. Since this equation describes the dynamic system in terms of the energies in it, expressions for the kinetic and potential energies in terms of the position coordinates have to be substituted before the equation can be solved for the motion of the system. But when the various modes of motion in the system are not known, as is the case here, they have to be assumed and, in such complex problems, estimation of the accuracy becomes uncertain.

For the purposes of the present research, it will be necessary to have quantitative information on local characteristics of the motions. Keeping this in mind, the contrast between the complexity of the observed motion and the simplicity of the assumed theoretical model raises serious questions as to the validity of the results for the present purposes.

II. EXPERIMENTAL ANL THEORETICAL PROGRAM FOR JULY-SEPTEMBER 1965.

In the following paragraphs experiments performed during the first quarter will be described and tentatively interpreted partly in the light of preliminary theoretical considerations. Although at this early stage no mathematical solutions are available and the experimental evidence is insufficient to draw final conclusions, it should be helpful for the planning of the research program, to tentatively relate observed events to each other and to develop preliminary hypotheses. Below most of the observations are described, then an attempt is made to correlate them and to combine them into hypotheses for the purpose of suggesting analytical methods and new experiments.

1. In a vertically vibrated column of liquid open at the top to the atmosphere small bubbles are observed forming when the amplitude of the oscillating acceleration is sufficiently large. During such oscillations the pressure drops momentarily to levels at which dissolved gases are released from the liquid or, the pressure may even drop below the vapor pressure of the liquid. If the process of releasing gas or vapor is nonlinear in the time derivative of the pressure, these oscillations may account for the formation of microscopic bubbles.

Since the pressure fluctuations are very different from the above when the container is closed on top and filled entirely with liquid the formation of bubbles should also be different, especially if the tank is also made more rigid. This experiment would give additional information on the pressure dependence of the bubble formation.

The difference of the pressure fields in these two cases is due to different boundary conditions. In the open container the pressure is constant at the liquid surface, but it can take on very low instantaneous values at the bottom. When the acceleration reaches a certain limit, the column of liquid must separate from the bottom. At sea level and for a column 50 cm high this limit is not reached until the acceleration is over 20.

When the container is closed, the pressure fluctuations at the two ends of the column are the same and only the d.c. pressure differs by the difference of hydrostatic pressures. The minimum pressure occurring anywhere in the liquid is only slightly different from the pressure at the top when the tank is at rest as long as compressibility effects and deformations of the tank do not become important.

Between these two cases as extremes, conditions can be continuously varied in a closed tank by filling the tank with liquid to different levels.

2. According to calculations by Bjerknes (3), bubbles pulsating in phase attract each other. This is very clearly observed in the vibrating aolumn of liquid. Due to the oscillating pressure field the bubbles pulsate and accelerate towards each other. This then would also explain why bubbles cling to the walls and the bottom of the tank. A solid plane boundary has the same effect as a second bubble in an unbounded body of liquid when placed symmetrically with respect to the plane of the solid

boundary. In a similar manner curved surfaces can also be replaced.

Solid spheres, since they do not pulsate, should not move towards each other as long as they move with the oscillations of the liquid. If their densities are different from that of the liquid some attraction should be ovservable because the difference in inertia results in relative motion between spheres and liquid. Indeed, hard plastic spheres(about one cm diameter) placed or suspended near each other in the vibrating liquid did not attract each other unless their separation was reduced to less than a millimeter, as expected. They were, however, strongly attracted to bubbles as predicted. It was also observed that the two plastic spheres suddenly approached each other when somewhere in the tank a larger bubble formed. This happened also according to expectations, since the body of liquid with the bubble in it is a compressible medium in comparison with the plastic spheres.

Finally, it was observed that the solid spheres collected small bubbles on their surfaces (even more so than the wall of the tank). It is not clear as yet whether the solid surface acts as a seed for bubble formation or it just attracts by the above mentioned mirror effect invisibly small bubbles which coalesce on the surface to visible size.

It should be mentioned here that bubble formation and migration is also observed in acoustic pressure fields. The motions of such fields are, however, different from the motions inside vibrated tanks. The major difference lies in the fact that the dominant fluid property involved in acoustic phenomena is its compressibility while compressibility of the liquid does not control the process under study here, at least not in the frequency range considered.

3. As a consequence of gravity the small bubbles rise. At the same time they coalesce by their attraction and may eventually stop rising provided the vibrational accelerations are large enough.

The theories of Bleich (2) and others, based on Lagrange's equation predict that the bubbles would stop rising or even move downward under certain conditions, but the criteria are the same for all bubbles and do not explain why small bubbles still rise when larger ones do not. Also, these theories cannot account for the horizontal motion of bubbles.

A theory based on equations of momentum should give more exact solutions, and the development of such a theory is now in progress. Because of the complexity of the equations, no solution has been obtained until now, but even a very simplified version of the analysis leads to highly non-linear differential equations for the pressure. This suggests that the pressure distribution does not fluctuate symmetrically around the mean distribution and may result in a net mean force counteracting buoyancy. It can move the bubble also in any direction other than vertical.

The above conclusions were derived from a simplified one dimensional analysis in which the three dimensional spherical bubble was replaced by a gas filled space in the liquid bounded by two parallel planes (one dimensional bubble).

4. Dependence of the bubble motion on size leads to assumption that the surface tension has a decisive role. The following reasoning supports this assumption.

When a bubble pulsates in a liquid the gas pressure inside the bubble drops with increasing radius faster than the effect of the surface tension. Inversely, it increases faster when the bubble contracts. This creates a restoring force tending to keep the bubble in the equilibrium state. Since the resultant of the surface tension points towards the inside of the bubble and varies inversely with the radius of curvature, it is negligible for larger bubbles, but smaller bubbles become more and more stiff under its effect. Consequently, very small bubbles behave almost like solid spheres which do not experience a net mean force due to the oscillations. So small bubbles rise with a velocity only determined by their buoyancy and the viscosity of the liquid.

Experiments with liquids having different surface tensions and viscosities are needed for understanding this behavior.

5. The growing bubble reaches another critical size when its surface becomes unstable under the oscillating pressure

and the fluctuating radial velocity.

At first the simple pulsation with smooth spherical surface observed in the light of a strobotac changes to restless vibration with irregular surface. After the bubble has grown a little further by absorbing a few more smaller bubbles the irregular surface motion becomes so intense that the bubble breaks up into a cluster of a few adhering bubbles.

As far as it could be ascertained, the onset of this decomposition depends on frequency f, volume of the bubble v, pressure fluctuation p' and possibly kinematic viscosity ν and surface tension s. It is conjectured that the determining dimensionless number is

$$\frac{fvp'}{s\nu} .$$

6. The cluster grows further by absorbing smaller bubbles. Associated with increasing size are increasing pressure gradient and volume fluctuations. As a consequence, small bubbles stream now with great acceleration towards the cluster. The pressure peaks tend to a maximum, i.e. to a state of resonance. During this development and at resonance the behavior of the bubble cluster undergoes a variety of changes, some of which agree with theoretical predictions.

First, it was observed that the bubble cluster reaches a limiting dimension at which point it stops growing (except temporarily under one observed circumstance to be mentioned later).

It is noteworthy that the bubble cluster has then approximately the resonant radius as calculated with the expression for the resonant frequency f by Smith (7)

$$f = \frac{\left[3\gamma\left(P_o + \frac{2\sigma}{r}\right)\right]^{\frac{1}{2}}}{2\pi r\sqrt{\rho}} \quad ,$$

where r = radius, γ ratio of specific heats inside the bubble, P_o hydrostatic pressure in the liquid, σ surface tension, ρ density of liquid.

The fact observed here that the bubbles stop growing right when they reach resonant dimensions needs explanation because some reports suggest that larger than resonant size bubbles have also been observed. Based on a reasoning presented later. under 8), it is conjectured that if the bubbles become turbulent before they attain resonant size they cannot develop further. On the other hand, if the bubbles do not break up when they resonate they can continue growing. Having reached limiting size, a bubble or rather bubble cluster seeks a specific location along the tank wall. It seems that this location is different from the area where most of the small bubbles can be seen. This might be confirmation of Bjerknes' (3) prediction that smaller than resonant size bubbles converge to pressure anti-nodes, larger than resonant size bubbles converge to pressure nodes. Before this can be determined, however, it has to be clarified what point can be properly considered a node or an anti-node in the complex field of a non-homogeneous liquid-bubble mixture.

Approaching the limit, the bubble changes also its appearance. Individual bubbles of the cluster cannot be distinguished any longer because of their fast random motion. The amplitude of the pulsation of the bubble diameter is so large and the bubble surface is so turbulent that the irregularities grow to spikes. Because of the rough surface, the bubble assumes a white color and its appearance becomes similar to a dandelion head.

Small bubbles approaching the "limit cluster" move on a path arching upward. This can be the resultant effect of buoyancy and the net force pushing the small bubbles towards the large one. When the limit cluster settles at a point away from the bottom of the tank, the distribution of small bubbles arriving to it can be very asymmetric. Occasionally no bubbles can be seen at all to come from below to the lower part of the cluster. It is possible that this happens only when there is but one limit cluster present in the tank and this one has remained at the same place for some time. This observation strengthened the supposition that the stable position of the limit bubble is different from the most preferred site of formation of small bubbles.

Both, theoretical reasoning and the slowed-down moving pictures, (6) indicate that the pulsating of the limit cluster is non-linear, meaning that the radial motion of the bubble is not symmetric around the mean radius. It can be observed on a large resonating cluster that it contracts much more impulsively than it expands. This non-linearity is probably present in both small and large bubbles, but the effect of small bubbles on the main pressure field in the tank is so small that it is undetectable. When, however, the bubble becomes big and it ocillates with large amplitudes this effect appears in various ways on a large scale.

When a large bubble approaches the resonant state, the contraction phase of its pulsation becomes implosion like and one begins to hear the sound of a water hammer. The approaching of the resonant state is indicated also by the oscilloscope trace of a transducer signal monitoring the pressure in a hole inside the tank bottom. At this time, the pressure field of the bubble has such an intensity that it alters the basic sinusoidal pattern of the pressure field in the entire tank. This secondary pressure field reaches a maximum at resonance. The development towards this state is first marked by a distortion of the sinusoidal pressure variations namely, the trace on the oscilloscope becomes pointed during the phase of contraction (build up to implosion). During the other phase, the maximum becomes flat, then indented two more and more pronounced maxima develop.

(Later check of the pressure transducer put the reliability of its output in question). (See also under 9). This is certainly a non-linear effect and it might even be possible that the actual pressure fields of bubbles pulsate with double the driving frequency. In order to verify that more refined instrumentation is needed.

For practical applications, the distortion of the pressure field seems to be a convenient means to detect formation of limit clusters.

There is also a sharp change in the root mean square value of the accelerometer signal upon formation of a bubble cluster. This instrument measures the vibration table accelerations and when a limit cluster develops, its rms signal shoots up to a multiple of its value. Such a change is evidence that the forces due to the liquid motion in the tank are strong enough to affect the table. But then the actual physical process is obscured because the forced motion of the tank varies in an unknown manner. To remedy the situation, first the meter circuit will be changed for the observation and measurement of the instantaneous value of the output. (In order to see in detail what happens.)

7. As the bubble (cluster) activity hits its highest intensity the bubble also reaches its final magnitude. This magnitude is quite uniform over the whole height of the column except close to the surface where it increases considerably.

Such a limit bubble cluster can be maintained indefinitely unless the amplitude of the table vibration is made too large. It may remain the only such bubble (cluster), or other, usually smaller, similar ones may form. These in turn may eventually merge into the principal bubble (cluster) or may stabilize at other locations. In either case, there is clear evidence that these bubbles (clusters) strongly interact with each other. When the limiting cluster does absorb a similar second one, temporarily its size becomes larger, but eventually it reduces to its original magnitude. The slowness of this return to stabl size indicates that it is not a primary mechanical boundary condition that determines the cluster size (the limit) but rather an equilibrium between absorbtion and diffusion of small bubbles.

8. The process of limit bubble formation then rises the question: How does the limit cluster maintain its size while small bubbles are being seen to stream continually into it?

At close look, one can distinguish a misty layer enveloping the violently turbulent cluster. This layer is thicker when the forced vibration amplitude is larger and it seems a reasonable conjecture that it consists of microscopic bubbles broken off the large one by the intensly turbulent motion at the latter's surface. Being in the pressure field of a large bubble, these tiny bubbles should return to it. However, we remember that very small bubbles are supposed to be made very rigid by the surface tension and thus relatively insensitive to pressure fluctuations. At the same time it would be surprising if the steady stream of bubbles (somewhat larger than the microscopic ones) toward the big limit cluster did not set up a secondary flow. Such secondary streams could then easily sweep away the microscopic bubbles which disappear from sight as they become more thinly dispersed but reappear at the anti-nodes after they have coalesced to larger size.

It is also possible that the assistance of a secondary flow is not even necessary. Buoyancy alone may dominate and carry away those small bubbles or the force resulting from interaction with the cluster may be repulsion due to phase difference. The cluster stops growing when the volume lost in this manner equals the volume gained.

9. If the amplitude of the vibration is made too large the turbulent activity grows to an intensity where size and number of the bubbles cast off become so much that the whole liquid column is transformed into a foamy mixture. At this point the properties of the fluid are so changed that the process breaks down, dissolving the limit cluster.

Several other qualitative observations have also been made, most of which were based on pressure measurements.

They will not be evaluated because the applied method of measuring is now considered unreliable, as mentioned once above, (under 6).

When the liquid in the tank is brought into rotation, the liquid surface and the constant pressure levels are paraboloids. In such a configuration the gradient of the energy potential is no more parallel to the forced motion and to the inertia forces associated with the motion and a finite radial component of the force acting on the bubbles results. This force moves the bubbles to a stable position along the center line of the tank. Experiment shows that a very slow rotation suffices to stabilize the bubbles in this fashion.

In order to identify the actual mechanism of this response the tank would have to be vibrated at an angle to the vertical. The tank probably would have to be spherical, because otherwise the boundaries cannot be made symmetrical around the surface. Such a tank would permit also studies on effects of geometry.

Further, it was observed that limit clusters moved towards and entered the open end of a Plexiglas pipe of one-half inch diameter held into the liquid. Immediately after the disappearance of one limit cluster a new one started forming near the pipe entrance and followed the previous one. Presence of the tube near a limit bubble caused the intensity of the audible noise to increase markedly.

All experiments were performed in a six inch diameter plastic tank with one-half inch thick wall (see photographs). The liquid was dyed methyl alcohol.

III. PROGRAM FOR OCTOBER-DECEMBER 1965

Experimental: In the preceding paragraphs several experiments have been suggested which will be performed whenever feasible. One of the most important program points concerns, however, the question: To what extent does the flow in the liquid column affect the vibration table? And more in detail: Is the appearance of a second, third, ... limit cluster just a different stable mode consistent with the same forced vibration or do they develop because the motion of the vibration table has changed with the formation of the previous limit cluster?

Other effects requiring investigation are those of tank rigidity, liquid compressibility, viscosity, visco-elasticity, surface tension, closed and completely filled tank, static pressure and tank geometry.

For the study of the flow field it is planned to do experiments with Milling Yellow. For this purpose a plane-walled, narrow tank will be built.

Theoretical: Development of equations of motion appropriate for the present boundary conditions will continue and solutions will be sought analytically and by computer.

IV. REFERENCES CITED

1. Baird, M.H.I., "Resonant Bubbles in a Vertically Vibrating Liquid Column," Canadian Journ. Chem. Engr. 41, 52-55 (1963).

2. Bleich, H. H., "Effect of Vibrations on the Motion of Small Gas Bubbles in a Liquid," Jet Propulsion, 26, 958-79 (1956).

3. Bjerknes, V., "Die Kraftfelder," Friedrich Vieweg & Sohn, Braunschweig, (1909).

4. Buchanan, R. H., G. Jameson, and D. Oedjoe, "Cylic Migration of Bubbles in Vertically Vibrating Liquid Columns," Ind. Eng. Chem. Fundamentals, 1, 82-86 (1962).

5. Kana, D. D. and F. T. Dodge, "Bubble Behavior in Liquids Contained in Vertically Vibrated Tanks," Southwest Research Institute. Report No. 4 Project No. 02-1391, August 1964.

6. Kana, D. D. and F. T. Dodge, "Bubble Motion in Vertically Vibrated Tanks," 16 mm Movie, Southwest Research Institute.

7. Smith, D. F., "On the Destructive Mechanical Effects of the Gas Bubbles Liberated by the Passage of Intense Sound Through a Liquid," Phil. Mag. 19, 1147-51 (1935).

LIST OF FIGURES

Figure 1. Motor-Generator Unit for Frequency Control

Figure 2. Vibration Table and Control Unit

Figure 3. Stable Limit Cluster

Figure 4. Close-up View of Stable Limit Cluster

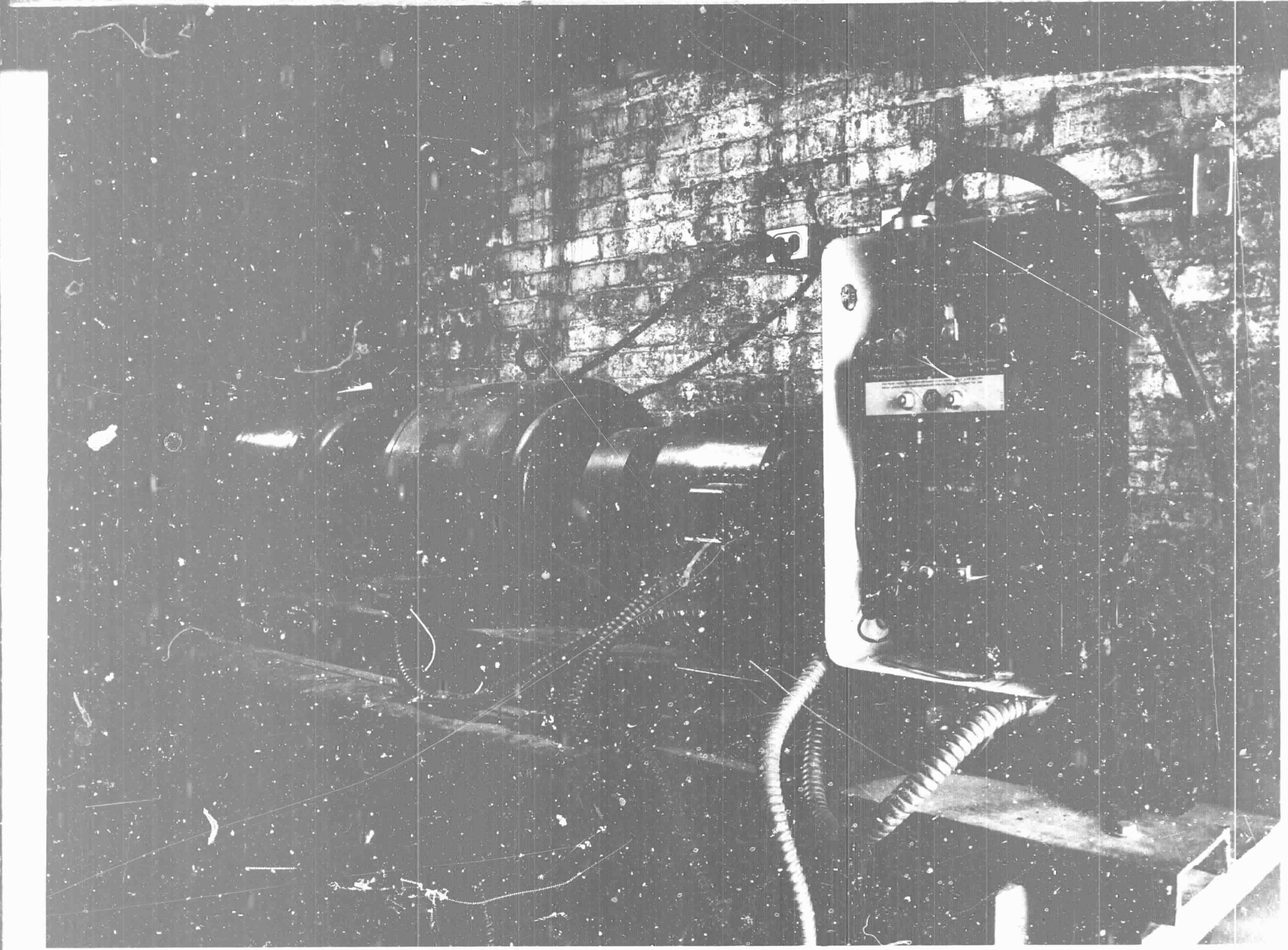

FIGURE 1

FIGURE 1

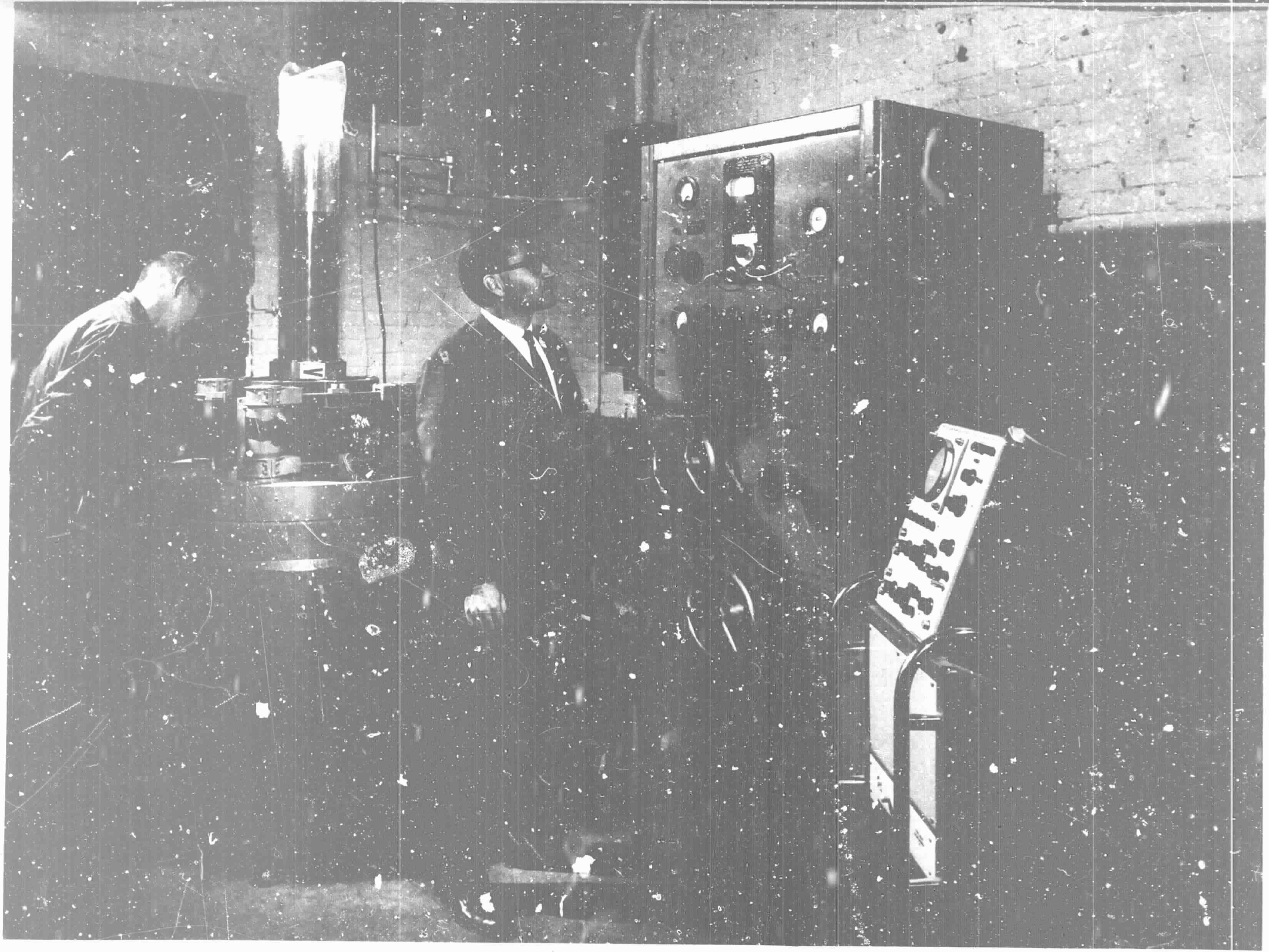

FIGURE 2

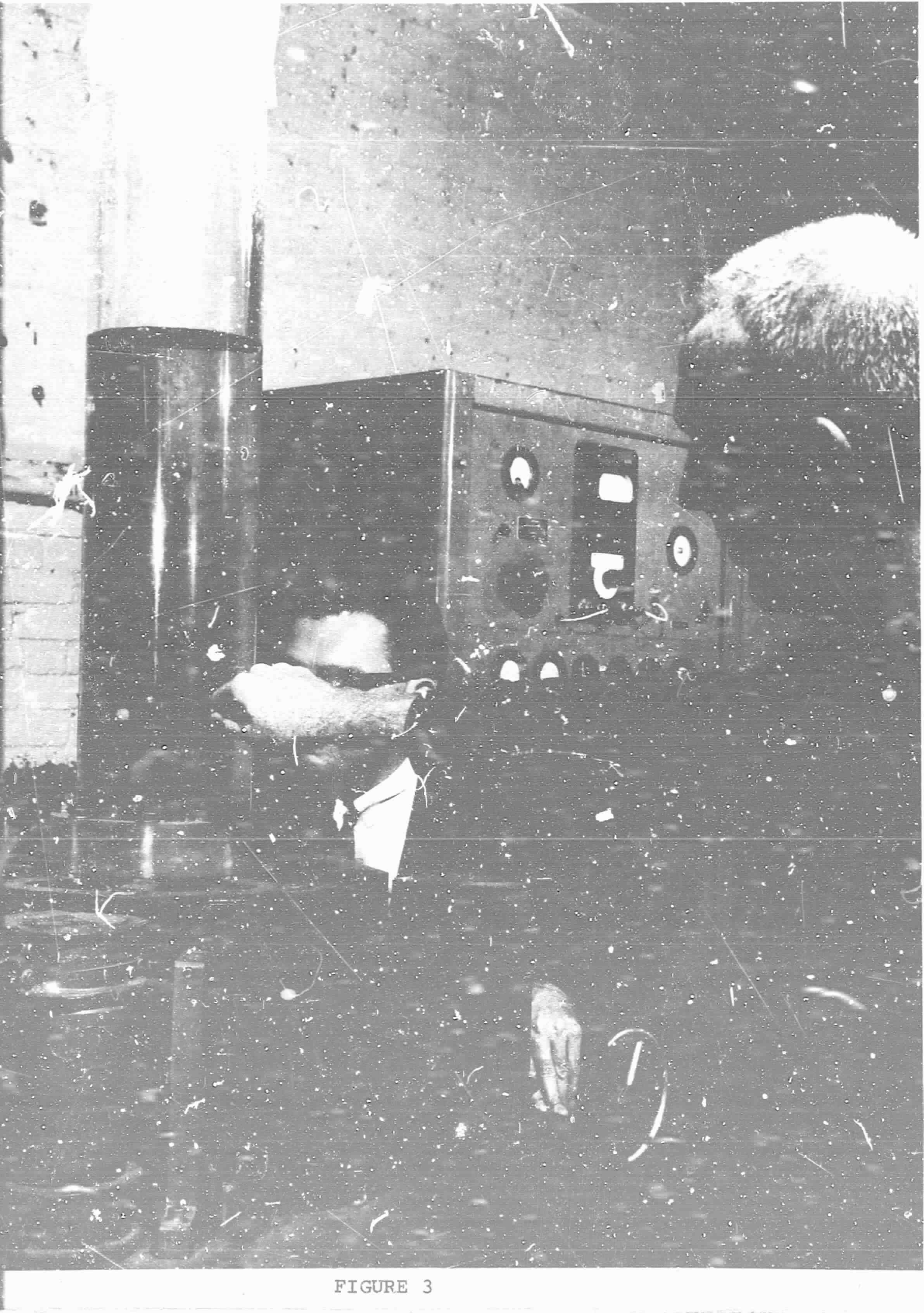

FIGURE 3

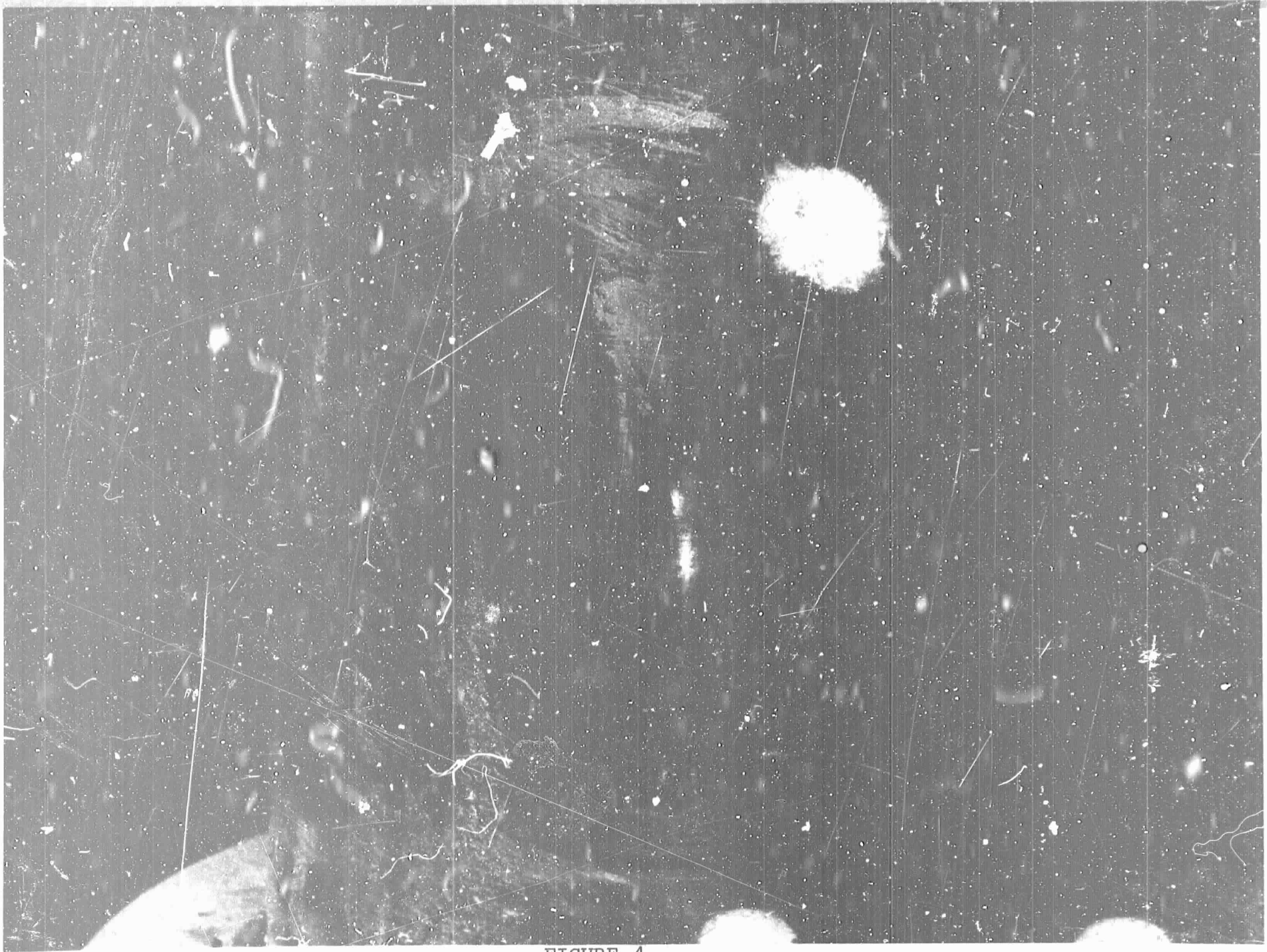

FIGURE 4