# DEVELOPMENT AND APPLICATION OF A VIBRATORY CAVITATION TESTER

by

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## I. INTRODUCTION

### A. The History of Cavitation

For many years ship propellers, hydraulic turbine runners, and pump impellers have been eroded away at a rate far more rapidly than is accounted for solely by corrosion. Until about 1930, the cause of such destruction was thought to be due to a chemical action which resulted from the release of dissolved oxygen in water. At this time it was suspected that a special type of erosion was taking place wherever steam or water impinged upon the surface of a material. Investigations had been made in England, however, which indicated that the cavity-forming action was mechanical rather than chemical and that it was caused by a rapid fluctuation of pressures due to the formation and collapse of minute bubbles on the surface of the turbine blades (4, p.26).

Recognizing the need for further progress, the Safe Harbor Water Power Corporation (Safe Harbor, Pa.) decided in 1934 to sponsor a research program to investigate the phenomenon. J. M. Mousson was in charge of the investigation which utilized an hydraulic cavitation apparatus. This apparatus consisted of a venturi tube which was fed by a water head pressure of 480 pounds per square inch. The cavitation specimens (4" x 1 1/4" x 1/4") were mounted in the throat of the venturi (6, p.399).

Although Mousson obtained significant results from his tests (6, pp.402-406), it must be realized that his apparatus was prohibitively bulky and costly. Also, a test period of 16 hours was used in order to obtain measurable weight losses. It was with these shortcomings in mind that Dr. Newton Gaines developed the first vibratory cavitation tester by utilizing a magnetostriction oscillator (2, pp.209-213). A description of the use of this device for cavitation testing is given by Dr. J. C. Hunsaker in his paper "Progress Report on Cavitation Research at Massachusetts Institute of Technology" (3, pp.423-424). This paper tells of measurable weight losses being obtained in less than one hour, although a three-hour test period was used. Gaines' apparatus consisted of a one-kilowatt magnetostriction oscillator which pounded the specimen into the test liquid, the latter being at rest in a container. More recent investigations in vibratory cavitation testing have been made by Kerr (5, pp.373-397), and Schumb, Peters, and Milligan (9, pp.1-9). The equipment used by these men differed only slightly from Gaines' original magnetostriction cavitation tester. In these extensive investigations a wide range of metals and several different solutions were tested.

## B. Objective of the Investigation

The prime objective of the investigation is to develop and perfect an electronic vibratory cavitation tester suitable for future cavitation studies. The unit is similar in some respects to that of Gaines' apparatus, although many modifications have been incorporated.

A somewhat abbreviated testing program was conducted after the completion of the construction work on the unit. Although conclusive results were obtained from most of the tests, the purpose of the tests was to assure the proper operation of the unit rather than to make an extensive study of cavitation.

## C. Cause and Results of Cavitation

Cavitation, or cavitation erosion as it is sometimes called, always includes the physical wearing away of a metal by erosion as a major factor in its action. The roughening of the metal by cavitation has somewhat the appearance of a pitting type of corrosion, but typical corrosion products may be substantially absent (4, p.26).

When the relative motion between the liquid and a metallic part in contact with the liquid is sufficiently rapid, pressure head may be locally reduced to the boiling point of the liquid at that reduced pressure. That is, local "vacuum distillation" occurs and the void formed in the liquid is filled with vapor. An instant later this vapor condenses and the liquid void collapses. Upon the collapsing of this void, a very high local pressure is created upon the surface of the metallic part (9, p.3). Considering that these small voids are forming and collapsing at a very rapid rate, it is conceivable that the exposed metallic surface will eventually become fatigued. As the metal suffers localized fatigue failures, microscopic pieces of the metal are cast from its surface. Cavitation is favored by high velocity liquid flow and, within some limits, the degree of damage increases with a rise in temperature.

Cavitation not only produces a direct loss of energy, but its erosive effect roughens the metal surfaces involved and increases the friction, thus producing a further energy loss as well as the eventual destruction of the equipment.

Although it is strongly desirable to incorporate designs which minimize cavitation, some conditions may arise where the complete elimination of surfaces subject to cavitation is impossible. Under such conditions only those metals which are highly resistant to cavitation should be used. Care must always be taken in choosing a metal so that it will not be chemically attacked by the impinging liquid (4, p.26).

## D. Corrosion Factor in Short-Time Cavitation Tests

The corrosion of a freshly exposed surface during the first instant of exposure is believed to be very rapid for many metals. However, this initially rapid attack usually decreases quickly through the formation of protective corrosion-product films. By continually removing such films, cavitation may permit the initially high rates of attack to persist and thus cause considerable local damage by corrosion in the regions of severe cavitation. Therefore, in a corrosive environment cavitation accelerates corrosion while corrosion intensifies cavitation. This mechanism accounts for the importance of corrosion in cavitation and for the desirability of using corrosion-resisting materials wherever necessary and economically permissible.

Whereas corrosion may definitely be a factor in cavitation failures under service conditions, it is not an appreciable factor in short-time cavitation tests such as the venturi and the vibratory tests. Although cavitation may occur at an alarming rate in industry, the short-time tests require only a very small fraction of the time required in service to produce an equal degree of cavitation. This is the greatest shortcoming of short-time cavitation tests. However, if the degree of corrosion which exists under service conditions can be estimated, a fairly logical interpretation of correlated short-time cavitation tests can be made (4, p.26).

# II. APPARATUS CONSTRUCTION

## A. Requirements and Limitations Imposed

The cavitation tester designed was to be capable of producing reliable test results, and was to be finished with such a degree of workmanship that it could justly assume a position in the metallography laboratory at Oregon State College. Although it was realized at the start that an oscillator having an input of one kilowatt or more was desirable, an oscillator having an input of only 250 watts was designed due to the prohibitive cost of the larger unit. The unit was to be semi-portable, and was to operate from the regular 60-cycle, 110-volt line service. The oscillator tubes used (VT-3 and 4) are not ideal tubes for this application. Their use was justified only by the fact that the tubes were available from war surplus, thus eliminating the high cost of a somewhat more desirable tube. The power-handling capacity of these tubes required that two of them be connected in parallel in order to obtain the desired power output. The chief disadvantage of using these tubes is the high ac drive required at the grid to produce the rated output. However, by designing the oscillator for the tubes this is no real shortcoming.

## B. General Construction Information

The cavitation tester designed actually consists of three major pieces. These are, the power supply deck, the oscillator deck, and the driving coil-specimen holder assembly. The power supply and oscillator have been built on separate heavy-duty chassis (13" x 17" x 4") which are equipped with bottom plates. One-eighth inch thick steel relay rack panels (17 inches wide) are attached to these chassis by means of screws and special chassis mounting brackets. The power supply panel is 19 1/4 inches high and the oscillator panel is 17 1/2 inches high. These two panels just fill the panel space of the "Bud" CR-1774 cabinet which was selected to house the two decks. The panels and cabinet have a grey wrinkle finish, trimmed with chrome-plated stripping. Heavy duty casters have been installed on the cabinet to facilitate moving the unit. Figure 1 shows a front view of the cabinet with the power supply (lower) and the oscillator (upper) decks in place. The meters on the oscillator deck are a 0-500 dc milliameter (M-1) and a 0-4000 dc voltmeter (M-2). These instruments measure the input current and voltage to the plates of the oscillator tubes, thereby enabling the calculation of the oscillator power input. The other panel controls will be discussed in detail later in this paper.

C. <u>The Power Supply Deck</u>

The power supply is of typical high voltage power supply design. This power supply is adequately protected as it includes an overload relay and a time delay relay

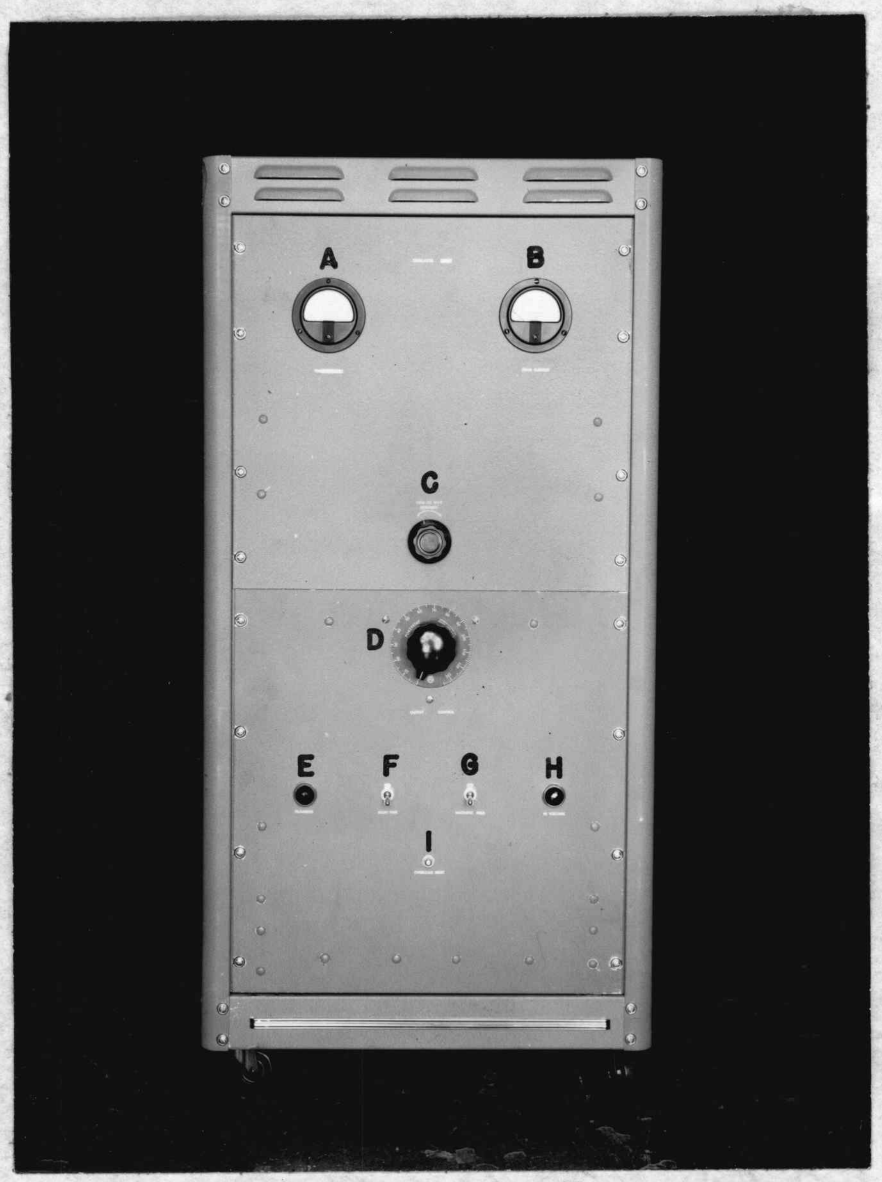



Figure 1. FRONT VIEW OF TESTER CABINET

A. Oscillator Plate Voltage (M-2)
B. Oscillator Plate Current (M-1)
C. Polarizing Current Control (R-3)
D. Power Input Control (T-2)
E. Filament Indicator (Green)(PL-2)
F. Main Power Switch (SW-2)
G. Polarizing Current Power Supply Switch (SW-3)
H. High Voltage Indicator (Red)(PL-1)
I. Overload Relay Reset Switch (SW-1)

which allows the cathodes or filaments of all of the tubes in the unit to become hot enough to emit electrons before they are subjected to high voltages. Figure 2 is a back view of the power supply deck showing the placement of the above chassis components. The panel mounting arrangement of variable transformer T-2 is clearly visible. The two pilot lights (PL-1 and 2) indicate when the high voltage is on (as controlled by the time delay relay), and when the filaments are on.

Two of the three filter chokes (CH-1, 2, and 3) are visible in Figure 2. The third choke is hidden by the high voltage plate transformer (T-1). The two toggle switches visible (SW-2 and 3) are the main power switch and the magnetic field or polarizer switch. The subject of oscillator polarization will be discussed in detail later in the context. The rectifier tubes used are 836's, a high vacuum type, half-wave rectifier. These tubes are interchangeable with the common 866 mercury vapor rectifiers, but create less "hash" than the 866's. Ratings for these tubes, as well as the others used in the tester, appear in the appendix of this paper (8, p.331).

The outlets at the rear of the power supply chassis are also visible in Figure 2. These are (from left to right): interlock switch socket, ac line input, Line 2 to the oscillator deck, and the high voltage output to the oscillator deck. Between the ac input socket and Line 2 is

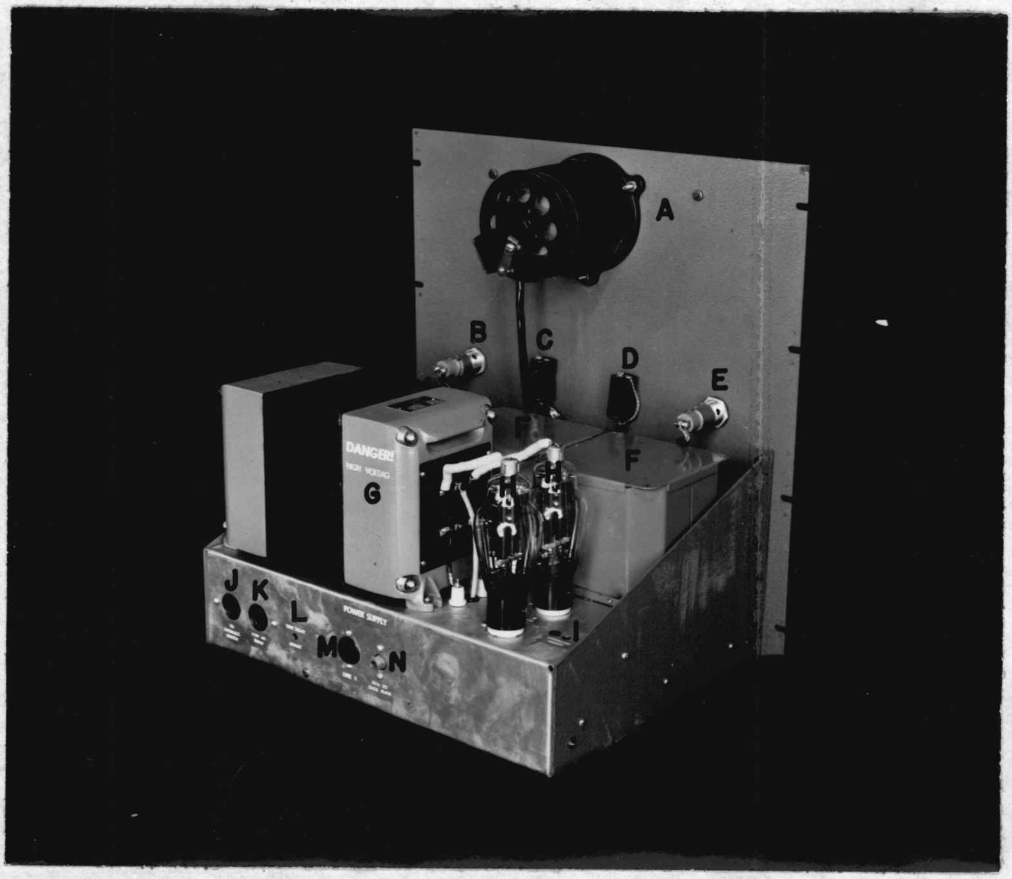



Figure 2. TOP VIEW OF POWER SUPPLY DECK

A. Variable Transformer (T-2)
B. High Voltage Indicator (Red)(PL-1)
C. Polarizing Current Power Supply Switch (SW-3)
D. Main Power Switch (SW-2)
E. Filament Indicator (Green)(PL-2)
F. High Voltage Filter Chokes (CH-1, 2, and 3)
G. High Voltage Plate Transformer (T-1)
H. High Voltage Rectifier Tubes (VT-1 and 2)
I. Overload Relay Adjustment
J. Receptacle for Interlock Switch Plug
K. 110 Volt ac Line Input Receptacle
L. Time Delay Relay Adjustment
M. Socket for Line 2 to Upper Deck
N. High Voltage Outlet for Line to Upper Deck

the screw-driver time delay relay adjustment. This relay (RL-1) is adjustable for a time delay of from 10 seconds to one minute. The overload relay (RL-2) also has a screw-driver adjustment. This adjustment is located near the bases of the 836 rectifier tubes, and its range is from 250 to 500 milliamperes. This relay should not be set to trip at a higher plate current than 300 milliamperes in the interest of extending the life of the oscillator tubes. Also the rating of the filter chokes used is 300 milliamperes and if this current is exceeded for any length of time the chokes will undoubtedly heat.

The overload relay has an electric reset which is actuated by the "overload reset" button (SW-1) at the bottom of the power supply panel. Care should be taken to place the variable transformer indicator to zero before attempting to reset the overload relay. This eliminates the arcing of the relay points upon closure. Likewise, this precaution should be exercised when first turning the unit on, as otherwise a momentary overload is created and the overload relay will open the circuit. Plate voltage increases, as controlled by the variable transformer, should always begin at zero and be made slowly. The momentary overload which otherwise exists is a result of the current required to initially charge the filter condensers (C-1, 2, and 3).

The maximum output voltage of the power supply is approximately 2600 volts at a plate load of 100 milliamperes.

This will vary somewhat with the line voltage fluctuations, but it was found that an input of 250 watts to the oscillator was possible at all times.

Figure 3 shows a bottom view of the power supply chassis with the bottom cover plate removed. The rectifier tube filament transformer (T-3) and the filter condensers are clearly visible. A 100,000-ohm, 100-watt bleeder resistor (R-1) is connected across the high voltage output. This resistor draws about 25 milliamperes and serves as a means of condenser discharge after the unit is turned off. This resistor also serves as a minimum load and therefore keeps the dc voltage from rising to values above the ratings of the filter condensers (8, p.326).

The two protective relays are also visible in Figure 3. AWG No. 10 tinned bus bars were used to wire all of the high voltage circuit. The schematic diagrams for this deck appear in Figure 4. The time delay relay (RL-1) is not shown in detail in this diagram. This relay operates on a thermal principle using a bi-metallic strip. The interlock switch mentioned previously is another safety feature which automatically turns off the entire unit when the rear cabinet door is opened. A push-button switch is mounted on a bracket in such a position that it is actuated by the rear panel door.

All of the component designations made throughout this paper refer to those shown in Figures 4 and 8. A complete

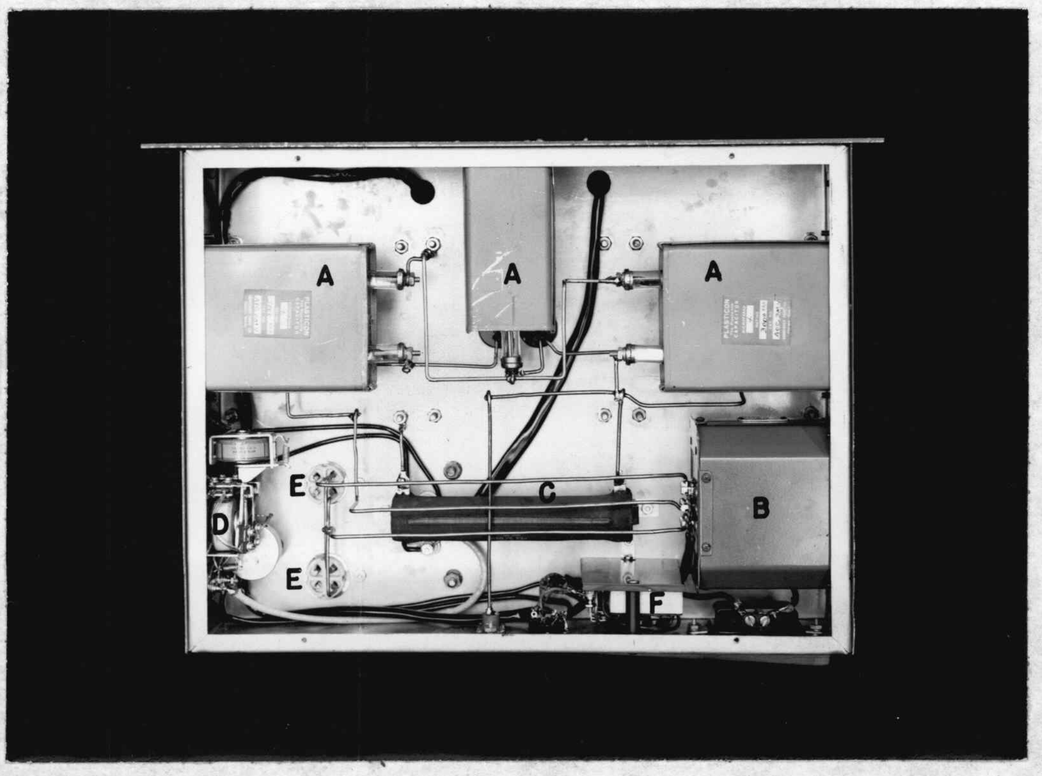



Figure 3. BOTTOM VIEW OF POWER SUPPLY DECK

A. High Voltage Filter Condensers (C-1, 2, and 3)
B. Rectifier Tube Filament Transformer (T-3)
C. Bleeder Resistor (R-1)
D. Overload Relay (RL-2)
E. Rectifier Tube Sockets
F. Time Delay Relay (RL-1)

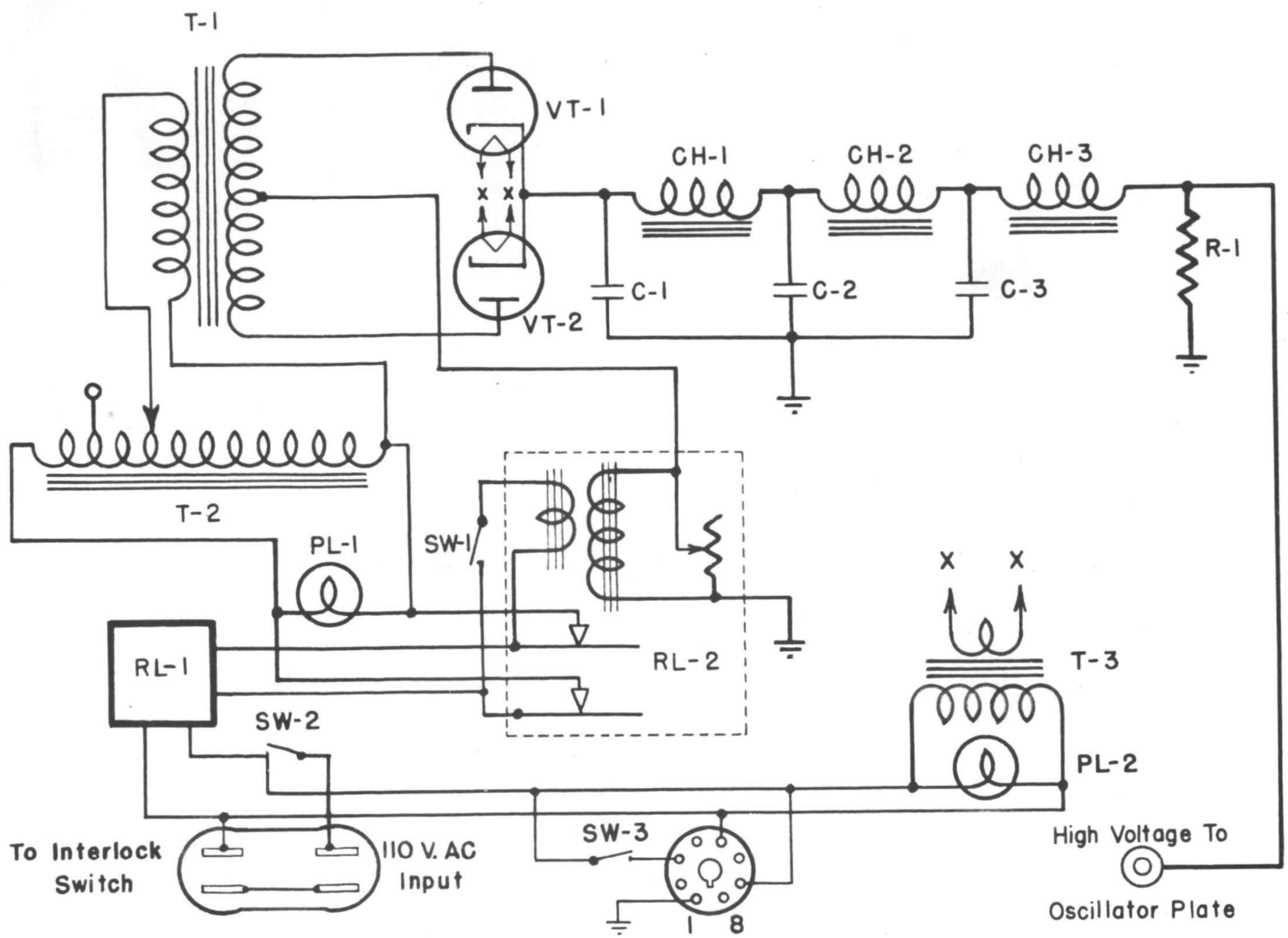



FIGURE 4. SCHEMATIC DIAGRAM OF POWER SUPPLY (LOWER DECK)

parts list, showing brands and values used in the construction of this unit, appears in the appendix of this paper.

D. The Oscillator Deck

Actually the oscillator deck consists of not only the oscillator, but a low voltage dc power supply as well. This low voltage direct current is used as a polarizing voltage in the driving unit of the tester. This unit will continuously supply approximately 35 volts at one ampere. The transformer for this supply (T-5) was specially wound for this application and the rectifier is a 6 ampere selenium bridge rectifier. A conventional $\pi$ filter network and a resistor network complete the supply.

The oscillator is a conventional tuned-plate, self-excited, parallel-fed, oscillator. The oscillator tubes are VT-127A's, power triode tubes having characteristics similar to the more common 100-TL. Both the tank coil (L-1) and the grid feed-back coil (L-2) are mounted externally on the specimen driver unit. This driver unit is connected to the oscillator deck by means of a 5 foot cable. As may be seen in Figure 8, this cable houses the driver coil feed lines, the shielded grid coil line, and the 110 volt line for the operation of pilot light, PL-3.

Figure 5 shows a back view of the oscillator deck. Behind the two oscillator tubes is mounted the isolating choke, CH-5. This choke, along with a blocking condenser

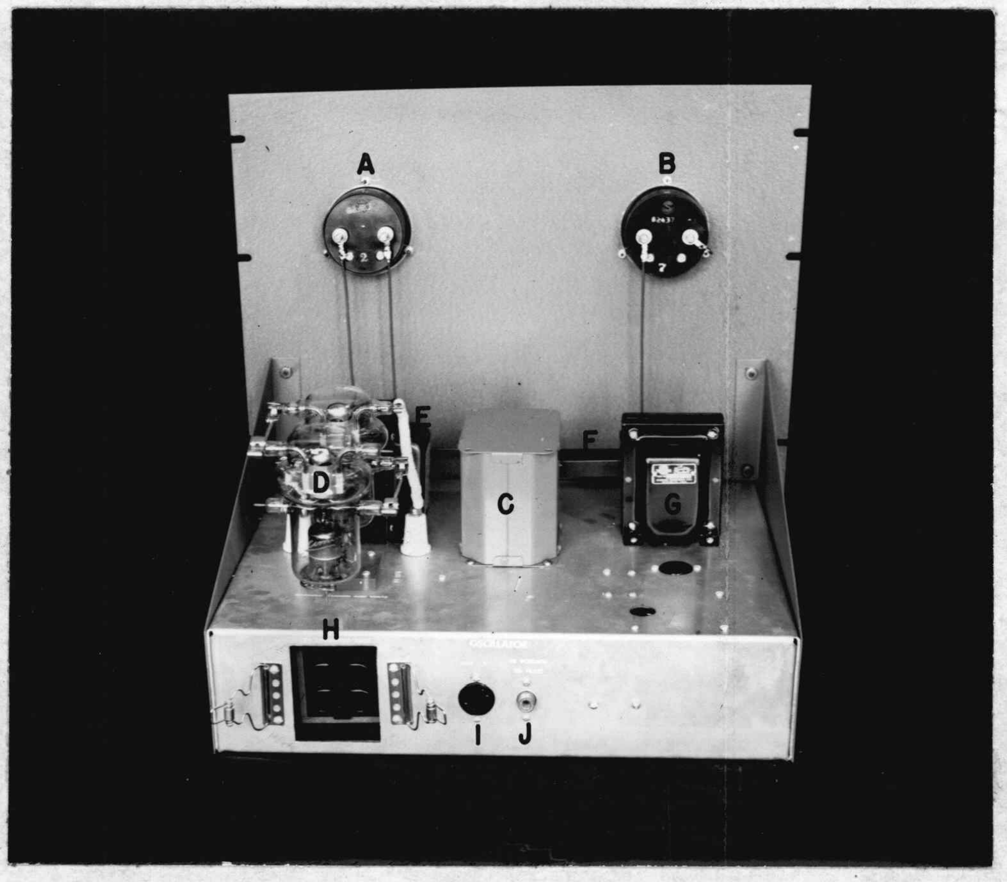



Figure 5. TOP VIEW OF OSCILLATOR DECK

A. Oscillator Plate Milliammeter (M-1)
B. Oscillator Plate Voltmeter (M-2)
C. Filament Transformer for Oscillator Tubes (T-4)
D. Oscillator Tubes (VT-3 and 4)
E. Isolation Choke for High Voltage Supply (CH-5)
F. Multiplier Resistor for Plate Voltmeter (R-5)
G. Polarizing Current Power Transformer (T-5)
H. Socket for Driving Unit Cable Plug
I. Socket for Line 2 Plug from Lower Deck
J. Jack for High Voltage Input from Lower Deck

(C-7), prevents any of the audio oscillations from being grounded through the power supply. The oscillator tubes' filament transformer (T-4) is mounted in the center and near the front of the top of the chassis. A range multiplier resistor (R-5) is mounted just in front of the top of this transformer. This resistor must be used in conjunction with the voltmeter, M-2, for accurate calibration of the meter. All high voltage leads passing through the chassis are made using ceramic feed-through insulators. The power transformer for the dc polarizing voltage supply may be seen on the right side of the chassis in Figure 5.

The connections on the back of the chassis are (from left to right): the driver unit outlet socket, line 2 from the lower deck, and the high voltage lead from the power supply. Line 2 contains a ground wire and the necessary 110 volt ac lines.

The remainder of the polarizing voltage supply is plainly visible in Figure 6. The larger choke at the left rear of the chassis is the isolation choke (CH-4) for the polarizing voltage supply. This choke performs the same duty for this supply as choke CH-5 does for the main power supply. That is, it prevents any of the audio oscillations from being grounded out through the supply.

The large black resistor on the underside of the chassis is the cathode resistor. This resistor creates the necessary bias at the grids of the oscillator tubes by

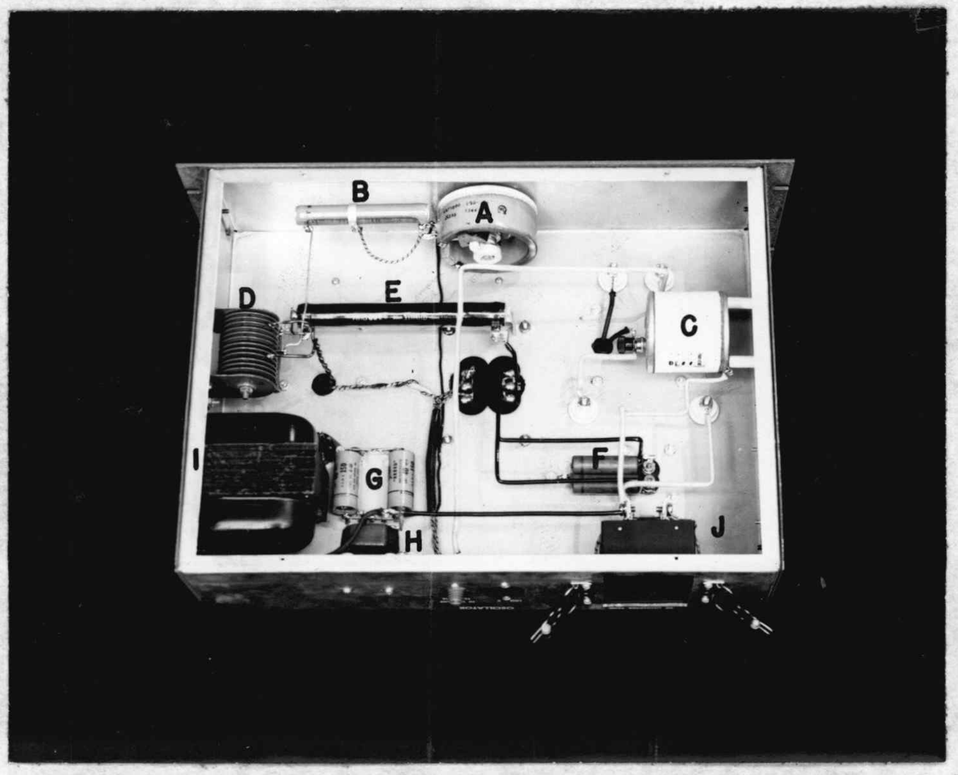



Figure 6. BOTTOM VIEW OF OSCILLATOR DECK

A. Polarizing Current Control Rheostat (R-3)
B. Polarizing Current Range Adjustment Resistor (R-3)
C. High Voltage Blocking Condenser (C-7)
D. Selenium Bridge Rectifier (SBR)
E. Oscillator Cathode Resistor (R-4)
F. Oscillator Cathode By-pass Condensers (C-8 and 9)
G. Polarizing Current Filter Condensers (C-5 and 6)
H. High Voltage By-pass Condenser (C-10)
I. Polarizing Current Supply Isolation Choke (CH-4)
J. Socket for Plug on Cable to Driver Unit

allowing them to become charged more negatively with respect to the plate (7, p.74). The cathode by-pass condensers (C-8 and 9) furnish an easy path for the audio oscillations to flow to ground (7, p.55). If these condensers were omitted, it would be necessary for the audio oscillations to flow through the filament transformer (T-4) and through the cathode resistor (R-4) before being grounded. This alternate path would offer a much greater resistance to the flow, and therefore cause the oscillator to be much less efficient. The audio current loop is then completed through the tank circuit (L-1, C-4) to ground. The circuit employed is almost self-explanatory in the schematic diagram in Figure 8.

A small portion of the energy in the tank circuit (L-1, C-4) is magnetically induced in the grid coil, L-2. The grid coil contains many turns of fine wire. Since the voltage produced by such a coil is proportional to the number of magnetic lines of force cut in a given period of time, it is also proportional to the number of turns of wire on the coil. The oscillator tubes used require an ac grid voltage of approximately 550 volts to drive them to full output (7, p.594).

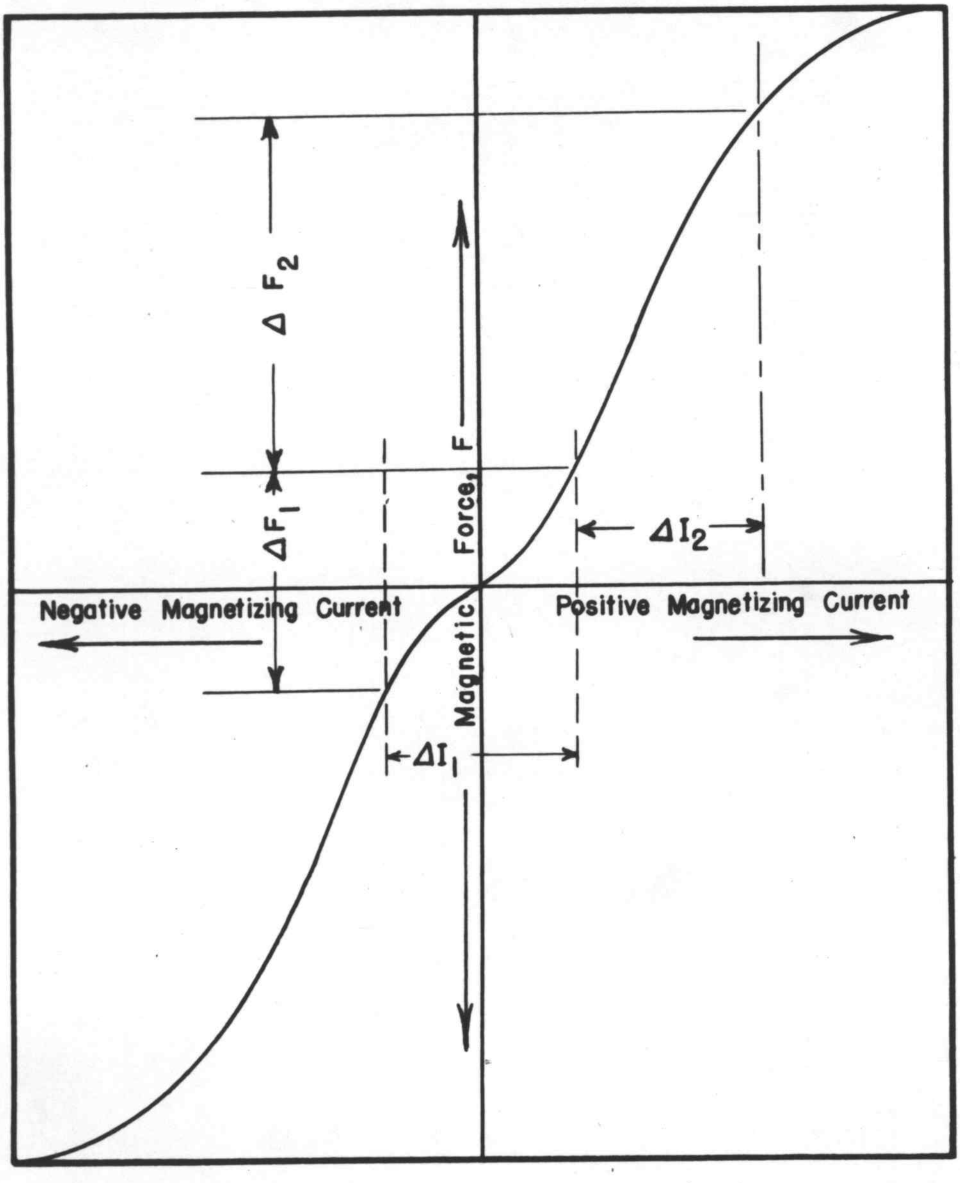
Figure 9 is a back view of the tester cabinet. The various connectors and cables are clearly visible. It may be noticed in this photograph that the 110 volt ac input is wired from the socket in the back of the power supply deck to another socket in the bottom back panel of the cabinet. This was done to enable the closure of the rear cabinet door without the removal of the power cord. This cord is equipped with a socket and plug combination at the cabinet to facilitate in moving the apparatus. The large plug near the lower left margin of the figure connects into the driving coil-specimen holder assembly which may be placed on a nearby table.

## E. The Driving Coil-Specimen Holder Assembly

The driving coil-specimen holder assembly is composed of the driver (tank) coil (C-1), the tank condenser (C-4), pilot light (PL-3), grid coil (L-2), a socket which receives the plug on the connecting cable coming from the oscillator, and a nickel tube which is 12 inches in length and has an outside diameter of 5/8 inch. This tube has a wall thickness of approximately 3/32 inch, and has been internally threaded on one end to receive the test specimen. Detail drawings of the specimens suitable for use with this tester are shown in Figure 11. A nickel tube is used because it possesses marked magnetostriction properties. Magnetostriction is the change in length of a ferromagnetic material when it is magnetized. Although the name implies that the change in length is always negative, both elongation and contraction are observed. When subjected to an alternating field, a cylindrical rod or tube of ferromagnetic material will pass through a complete cycle of magnetostrictive force during each half cycle of the exciting alternations. Therefore, the current tends to excite resonant vibrations of the rod at twice its fundamental frequency.

The use of a polarizing voltage with an instrument of this type is mandatory if optimum results are to be obtained (1, p.272). Figure 7 is a typical magnetization curve for a ferromagnetic material, and it demonstrates the need for a polarizing system. This curve shows how the magnetic force varies with the exciting current in an electromagnetic system such as is included in the driver unit of this tester. Without a direct current polarizing voltage an exciting alternating current $I_1$ will produce a change in magnetic force equal to $F_1$. However, if some optimum value of polarizing direct current is passed through the driving coil in addition to the alternating current, the magnetic system operates farther to the right (or left) of the center line on the magnetization curve. This results in a much larger change in the magnetic force created ( $F_2$). By using the correct polarizing voltage approximately twice as great a change in magnetic force is created with the same value of alternating excitation current. The importance of this is evident when it is realized that the magnitude of the length variations in the nickel tube is proportional to this change in magnetic force. The

FIGURE 7. TYPICAL MAGNETIZATION CURVE SHOWING THE PURPOSE OF A D.C. POLARIZING POTENTIAL




NOTE: $\Delta I_1$ is <u>without</u> a DC polarizing potential

$\Delta I_2$ is <u>with</u> a DC polarizing potential

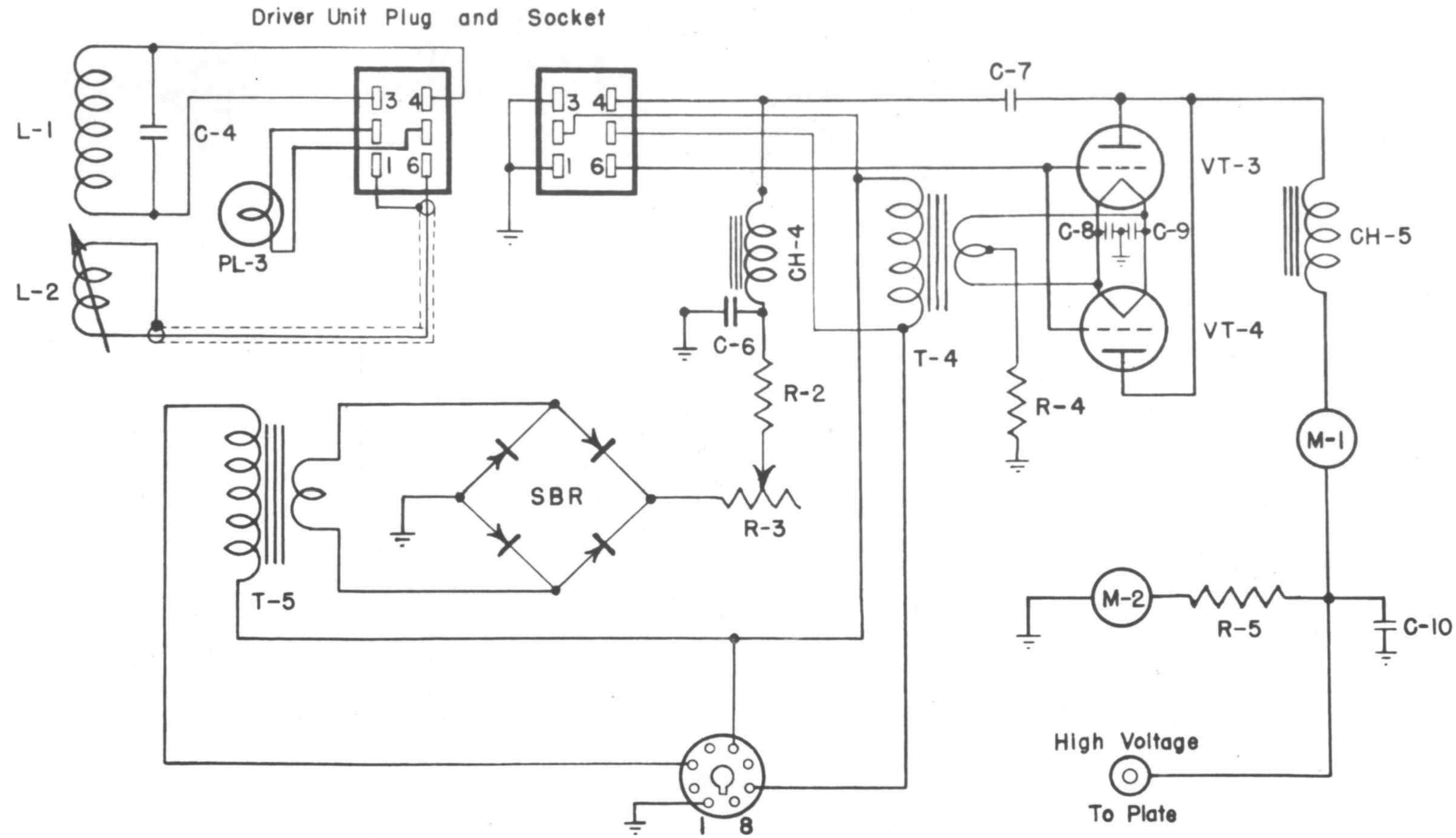



FIGURE 8. SCHEMATIC DIAGRAM OF OSCILLATOR DECK


Figure 9. REAR VIEW OF TESTER CABINET

A. Oscillator Deck
B. Plug on Driver Unit Cable
C. Line 2 (Connecting the Decks Together)
D. High Voltage Line
E. Power Supply Deck
F. Interlock Switch
G. 110 Volt ac Input Receptacle
H. Line Cord and Plug
I. Input Plug to Driver Unit

polarizing voltage may be adjusted to the optimum value by means of rheostat R-3, which is labeled "Tune to Maximum Intensity," and is located on the oscillator panel. The optimum position is determined by observing the magnitude of vibrations of the specimen into the test liquid.

Figure 10 is a photograph of the driving coil-specimen holder assembly as it is set up for cavitation testing. The grid coil actually is not mounted on the standard with the other components. Through experimentation it was found that by supporting the grid coil separately by means of a clamp and laboratory standard, optimum conditions of coupling between this coil and the plate coil could be obtained. To be most efficient, an oscillator of this type should have no more magnetic flux removed from the driver coil than is necessary to furnish adequate grid driving power to the oscillator tubes. Another advantage of the variable coupling between these two coils is the resultant slight change in the frequency of oscillations. This is due to the slight change in capacity created between the grid and ground. As the grid coil is moved closer to the plate coil, the effective grid to ground capacity is raised by a very slight amount. This in turn tunes the oscillator to a correspondingly lower frequency. This operational characteristic was found to be advantageous since the narrow frequency range thus produced was just wide enough to enable resonance to be reached with slightly different specimen

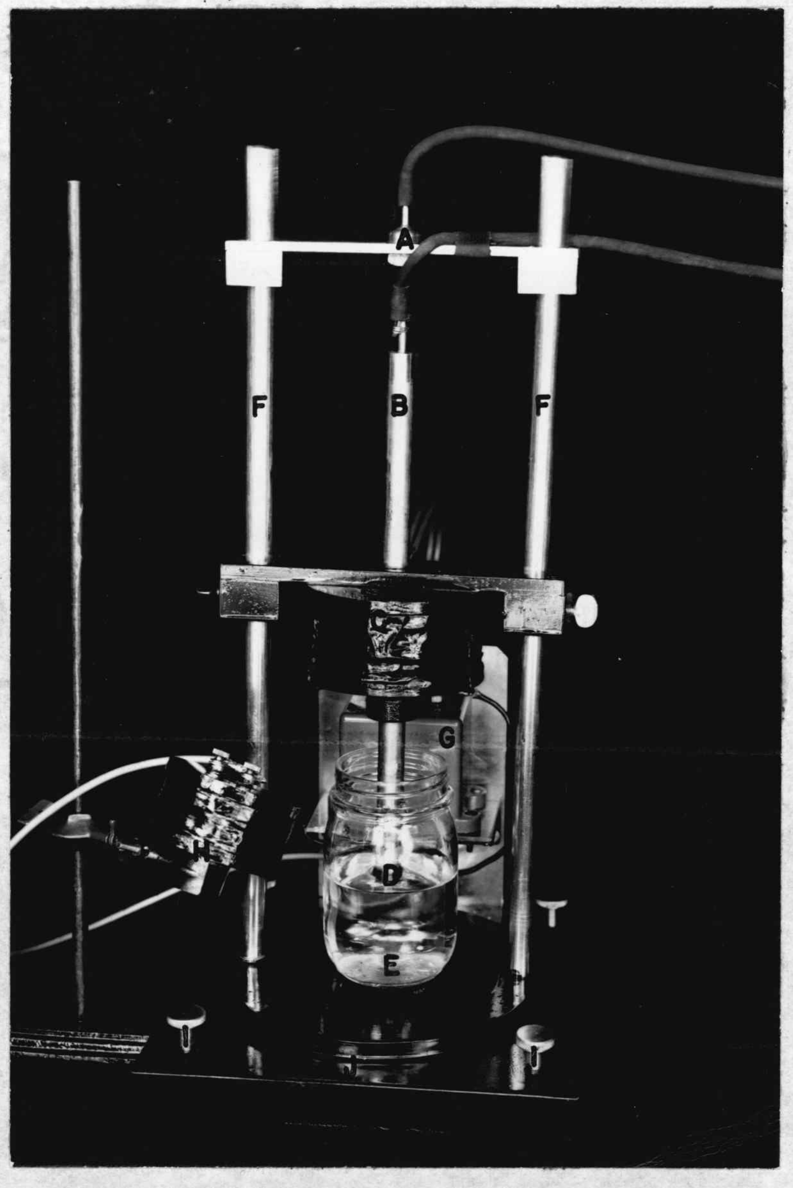



Figure 10. DRIVING COIL-SPECIMEN HOLDER ASSEMBLY

A. Water Extractor Tube Mount
B. Nickel Tube (5/8 inch ID, 12 inches Long)
C. Driving (Oscillator Plate) Coil (L-1)
D. Specimen (Threaded into Nickel Tube)
E. Test Liquid and Container
F. Vertical Brass Rods (5/8 inch Diameter)
G. Oscillator Tank Circuit Condenser (C-4)
H. Variably-Coupled Grid Coil (L-2)
I. Brass Leveling Screws
J. Cast Iron Base

# CAVITATION TEST SPECIMENS

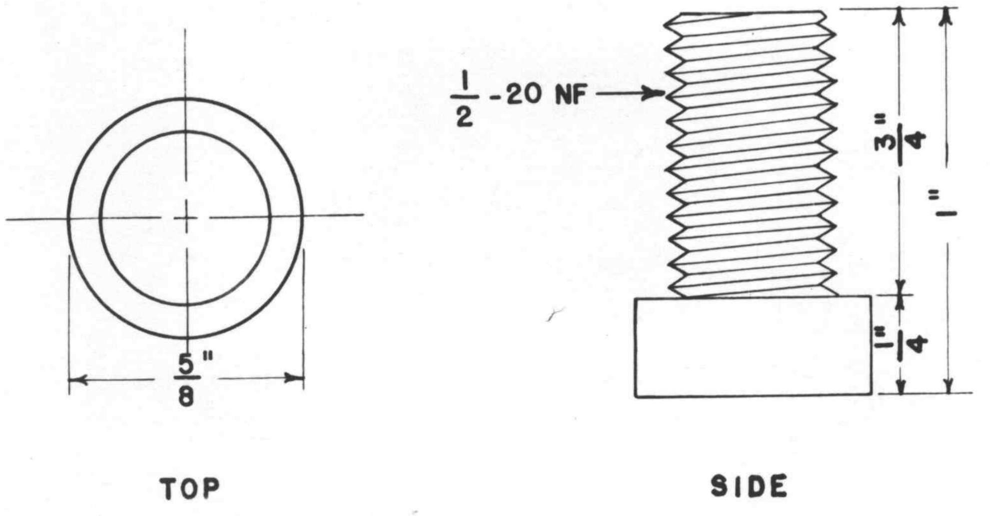



FIGURE II A. LIGHT METAL SPECIMEN DESIGN

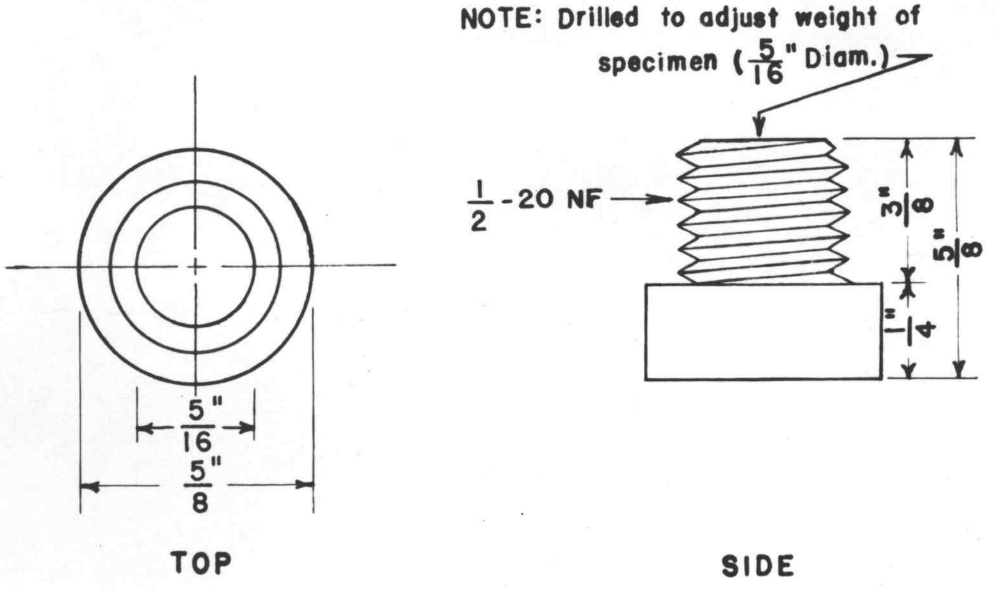



FIGURE II B. HEAVY METAL SPECIMEN DESIGN weights. Therefore, specimen weight tolerances were not too important as far as reaching the resonant frequency of the tube and specimen is concerned.

The container of liquid in Figure 9 is the stationary test liquid. The correct level for this liquid is just up to the end of the nickel tube. This results in the face of the specimen being submerged to a depth of 1/4 inch. The depth of liquid below the face of the specimen is not too important, although a minimum depth of from one to two inches is recommended.

Figure 12 is a sectional view of the driving coil showing the method employed of securing the nickel tube. Since the tube is oscillating at twice its natural frequency the node is located approximately at the center of the tube. The true node will vary with different specimen weights and must be determined experimentally. This necessitated the designing of a mount for the tube which would secure the tube during test periods, but which would be adjustable also. The sponge rubber packing gland was decided upon and has since proved to be very satisfactory. Sponge rubber sheet approximately 1/16 inch thick is recommended for re-packing this gland.

Since the nickel rod displays ferromagnetic properties and is in the center of a strong magnetic field, it is evident that induction heating will occur. Considerable heat is generated in the vibrating tube, and unless this is

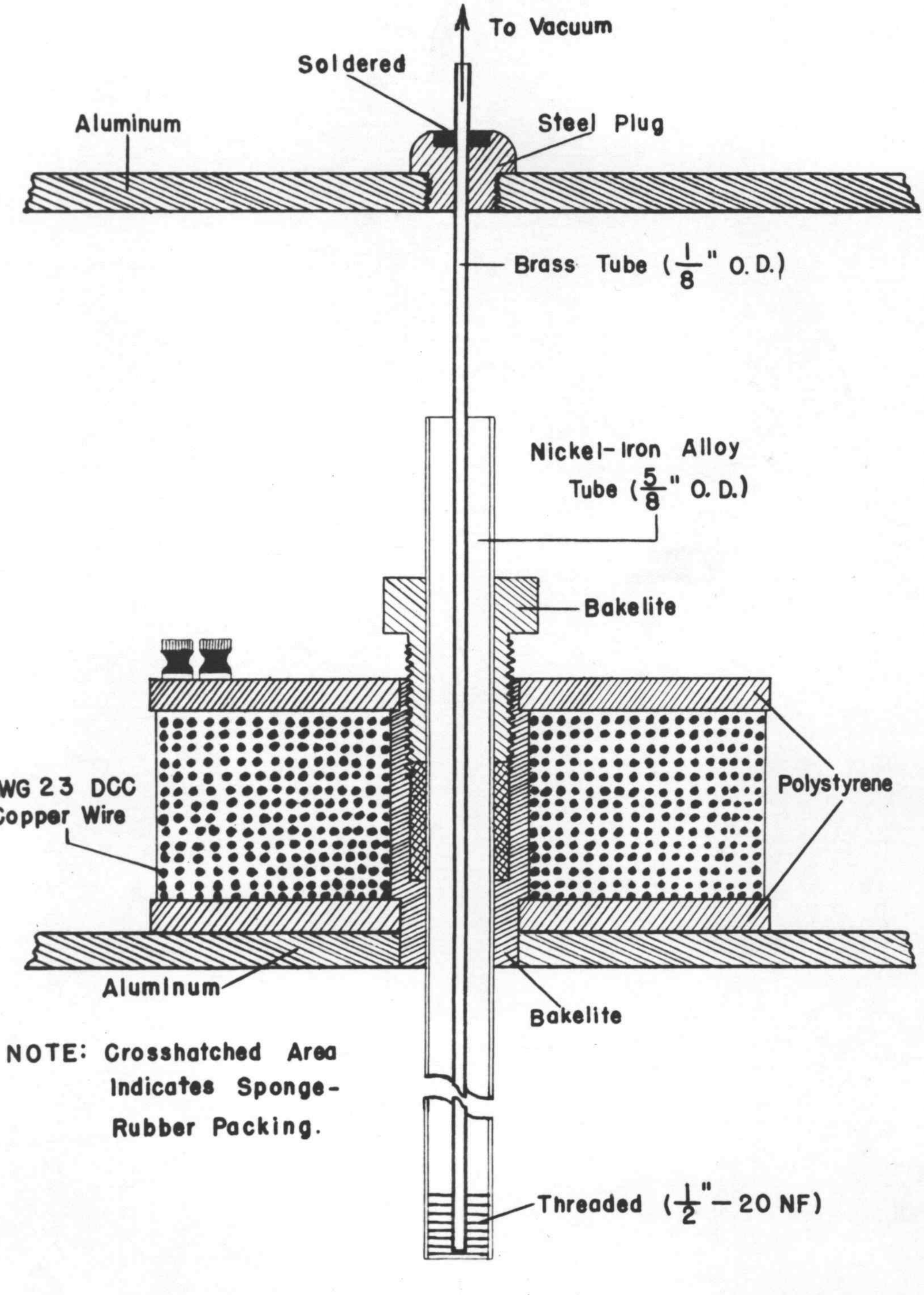



FIGURE 12. SECTIONAL VIEW OF DRIVING COIL ASSEMBLY, SHOWING COOLING WATER EXTRACTOR TUBE

dissipated the oscillation frequency will drift and the vibration will cease. If long testing programs are being conducted, it is advisable to air cool the driving coil with an electric fan (9, p.4).

Cooling water at a constant pressure head is delivered through a glass nozzle at the top of the nickel tube. This nozzle is mounted in such a position that it is not in physical contact with the vibrating end of the tube, but merely directs a small stream of water to the inner surface of the tube. Uniform and substantially complete removal of the water from the tube must be effected in order not to damp the vibration or alter the frequency of the tube. Figure 12 shows the 1/8 inch diameter brass cooling water extractor tube which extends down into the nickel tube to a level just above the specimen. The threaded portion of the specimen serves not only to retain the specimen in the tube, but also as a cooling-water seal. The cooling water is extracted from the nickel tube by connecting the extractor tube to a water aspirator. All cooling water connections are made from the driver unit by means of 1/8 inch id rubber tubing.

Figure 13 is a detail sketch of the driving coil-specimen holder assembly. This sketch includes notes explaining what materials were used for the various component parts of the assembly, as well as many of the more important dimensions. The movable-grid driving coil has been omitted

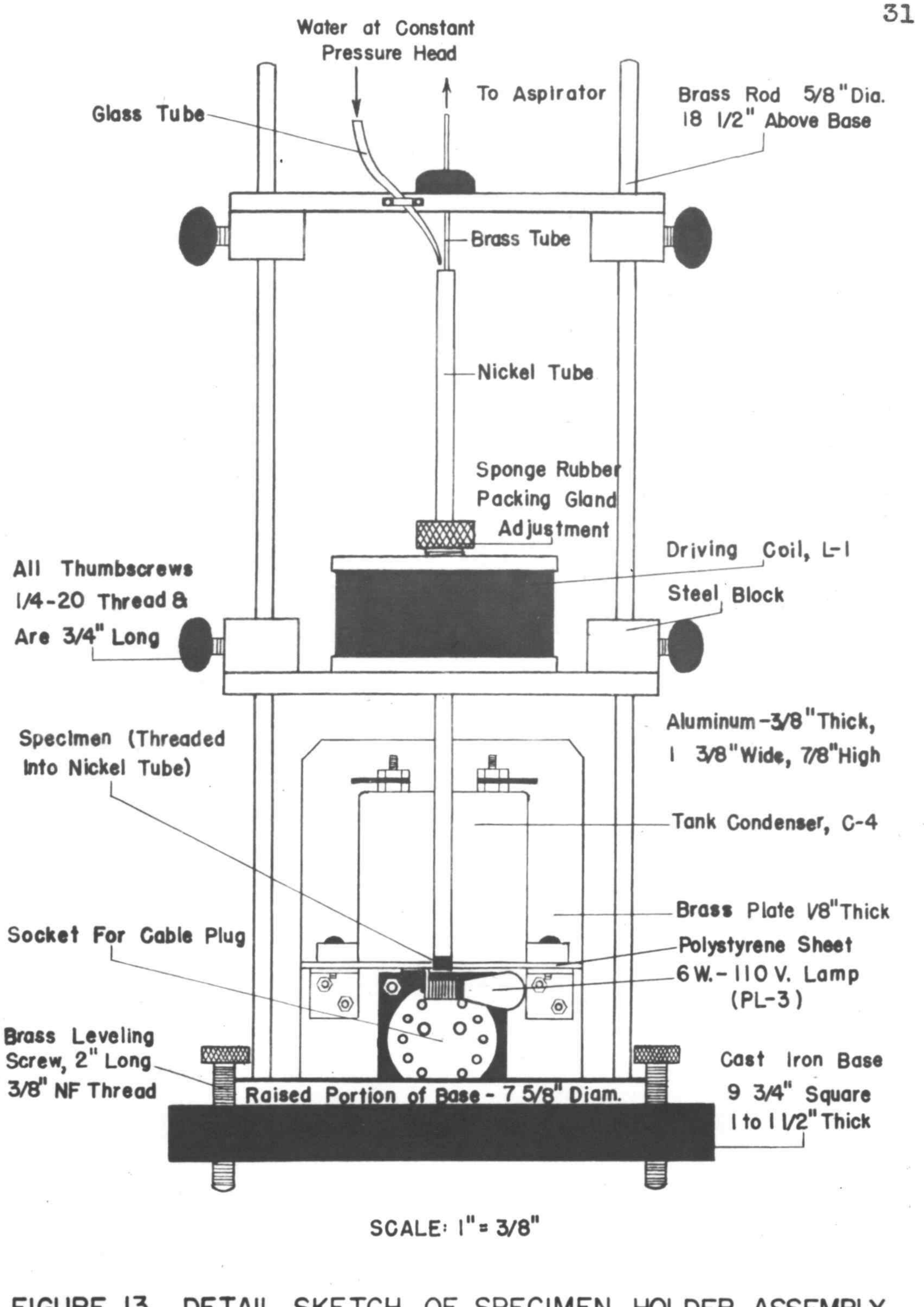



FIGURE 13. DETAIL SKETCH OF SPECIMEN HOLDER ASSEMBLY

from this sketch.

## III. VIBRATORY CAVITATION TESTING PROCEDURE

### A. Preparing the Test Specimen

The intended purpose of the vibratory cavitation tester constructed was to determine the relative resistance of metals to cavitation. However, there is no reason to assume that vibratory cavitation testing cannot be successfully applied to non-metallic specimens as well.

Far less machining is required if a 5/8 inch od bar stock of the desired specimen metals is obtained. With the exception of aluminum, magnesium, and possibly non-metallic specimens, the specimen stock should be machined to the dimensions specified in Figure 11-B. For the lighter material specimens the dimensions should follow those shown in Figure 11-A. The prime factor is to keep the weight differential among the specimens tested in any one group to a minimum. If both light and heavy metals are included in a group of metals to be tested, the light metal specimens should be machined first. The weight of the heavier metal specimens may then be adjusted (by drilling as shown in Figure 11-B) to be as near that of the lighter metal specimens as possible. In order to machine very hard steel specimens, stellite-tipped or carboloy lathe tools and high speed drills must be used. If it is desired to test stellite, it is recommended that a medium carbon steel specimen be made up and merely capped with stellite by arc welding with stellite welding rod. The face of the specimen may be cleaned up by grinding and the weight adjustment may be made by drilling into the much softer base metal.

The specimen weights must be aa nearly constant as possible in order to insure frequency and vibration magnitude stability throughout a group of tests. It was found experimentally that a specimen weight differential of approximately six grams was tolerable provided that the heaviest specimen weighed less than 15 grams. The magnitude of vibration was measured with the aid of a "Strobotac" and a Leitz measuring microscope. Since the vibration frequency of approximately 8900 cps greatly exceeds the upper limit of the "Strobotac," a sub-multiple of the natural frequency of the nickel tube must be chosen in the "Strobotac's" range which will partially stop the motion. This operation obviously must be carried out in a darkened room, and it is necessary to unscrew pilot light PL-3 from its socket.

The measured amplitude was approximately 0.05 millimeter when the specimen weight was below 15 grams. Specimens weighing more than this tend to damp out the vibratory motion, thereby effecting a less severe test. As mentioned before, the nickel tube is suspended near its center, therefore, placing the points of maximum vibratory amplitude at the two ends of the tube. If the nodal point of the vibrating tube is accurately found, the magnitudes of the vibrations at the two ends of the tube should be nearly equal.

After machining the specimens as accurately as possible, the specimen faces should be smoothed on a fine belt sander (No. 120 belt or finer). The specimens must then be manually polished on metallographic polishing paper down to and including 000 paper. Experiments were made initially to discover what benefits, if any, would result from polishing the specimens to a mirror finish by using metallographic polishing wheels and finer abrasives. It was found that this made no detectable difference in the test results, and therefore the testing program was carried out with the specimens polished only to and including a 000-grit paper. The specimens should always be stored in a desiccator until tested to prevent rusting or corrosion.

B. Specimen Installation and Oscillator Tune-up Procedure

Upon removal of the specimens from the desiccator for testing, they must be thoroughly brushed and cleaned. It is recommended that they be rinsed in carbon tetrachloride or other pure solvent to insure an oil-free surface. After the specimen is thoroughly cleaned and free from any minute metal chips, it should be weighed on an accurate laboratory balance. It is very important that the balance used be highly sensitive, since the weight losses due to cavitation will be small. A "Chain-o-matic" balance was found to give the most reliable results, and was used throughout most of the tests conducted.

After accurately weighing the specimen and recording this weight, it may be screwed into the lower end of the nickel tube on the driver assembly. This operation should initially be carried out using only the fingers. After the specimen is screwed in as tightly as possible with the fingers, a pair of pliers, the jaws of which have been thoroughly padded, may be used for the final tightening operation. Any looseness whatever of the specimen in the nickel tube will reduce the amplitude of vibration. It may be necessary to restrain the nickel tube from rotating in its packing gland with another pair of pliers. Whereas it is very important for the specimen to be screwed as tightly as possible into the tube, it is vitally important that the specimen not be marred by the jaws of the pliers. If any marring is noticed, the wisest procedure is to re-weigh the specimen and begin anew since otherwise the test results might be in doubt. It would be wise to construct a pair of special wrenches with which the nickel tube and the specimen could be gripped without any danger of marring their surfaces. Such tools could be constructed by attaching suitable handles to split brass blocks that have been drilled to the proper diameter, lined with leather, and equipped with locking thumbscrews.

After the specimen has been tightened, the upper aluminum cross-bar of the driver unit should be lowered until the end of the cooling water extractor tube touches the specimen. The cross bar is then raised approximately 1/64 inch in order to give adequate clearance between the extractor tube and the specimen when vibration begins. It is important that the extractor tube be concentrically mounted with respect to the inner walls of the nickel tube, so that the nickel tube is free of contact with any other part and, therefore, free to vibrate. Water should now be passed through the aspirator which supplies the vacuum for the cooling water extractor tube, and the cooling water allowed to pass through the glass nozzle and down the inside wall of the nickel tube. The flow of cooling water should be such that the aspirator draws about equal amounts of air and water from the tube. This is necessary to assure a constant minimum level of water at the bottom of the nickel tube. A length of glass tubing inserted in the vacuum line allows the air in the water to be seen and thereby aids in making this adjustment.

The test liquid should now be placed in a transparent container and placed on the driver unit base platform in such a position that the liquid level comes just to the end of the nickel tube. This submerges the face of the specimen to a depth of 1/4 inch. In all of the tests performed, Pacific Ocean sea water was used for the test solution.

Although any standard test solution could be used, sea water was chosen because it is more conducive to cavitation than fresh water. Pure distilled water theoretically will not cavitate a metal due to the absence of any small nuclei. Before cavitation can occur these microscopic nuclei must be present in the liquid before the minute bubbles can be formed. If no bubbles are formed there is no water-hammer action and therefore no cavitation. It would be possible, therefore, to prepare a standard test solution using measured volumes of distilled water and some form of suspension such as powdered chalk, dust, or talcum.

At this point the oscillator may be turned on. To do this, first set the power switch to the "On" position. When this is done the green filament indicator should light. In approximately 20 seconds the time delay relay will automatically turn on the high voltage supply, as will be indicated by the red high voltage pilot light. The polarizing current control should now be turned to near its maximum clockwise position and the "Magnetic Field" switch turned to the "On" position. The "Power Output" control setting should then be slowly increased until it is approximately in the center position. If the grid coil is in the proximity of the plate driving coil, the oscillations should begin.

When the oscillations begin the optimum grid coil position should be found experimentally by moving it closer to and farther away from the plate coil. The optimum condition will be evidenced by a small downward stream of bubbles emanating from the center of the specimen face. The grid coil should be placed at the farthest point from the plate coil where the greatest magnitude of vibration is obtained. After the optimum grid coil position has been determined, the "Power Output" control may be slowly increased to the desired output (or input) level. All of the tests to be described in this paper were made at a constant oscillator power input of 250 watts. Upon increasing the power output to near the maximum, it will be found that the magnitude of the oscillations decreases. This is due to the unstable operational characteristics of this type of oscillator. To regain resonance, however, it is necessary only to vary the setting of the polarizing current control. When resonance is obtained, a sizable stream of fine bubbles will flow downward from the face of the specimen, and the test liquid will appear to be in a state of constant agitation. A photograph showing the appearance of this action is shown in Figure 14. Many larger bubbles such as the out-of-focus bubble shown in this figure will be found in the bottom and around the sides of the liquid container.

Whereas most of the specimens tested projected a stream of bubbles such as shown in Figure 14, there were a few exceptions. In some cases the stream of bubbles appeared at first and disappeared after a few minutes of exposure. In

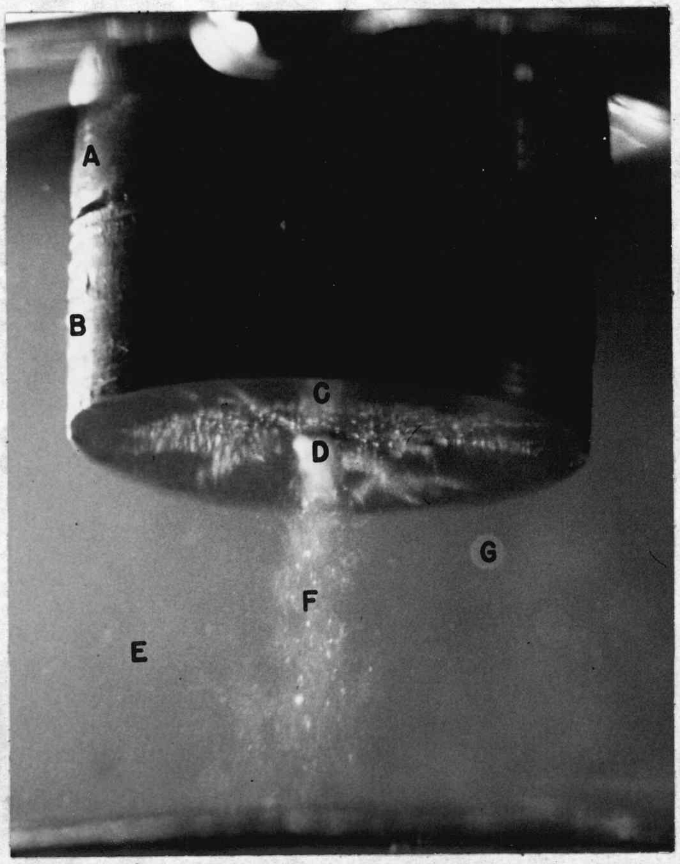



Figure 14. SPECIMEN UNDERGOING VIBRATORY CAVITATION TEST

A. End of Nickel Tube
B. Side of Metallic Specimen
C. Polished Face of Specimen
D. Area of Most Severe Cavitation
E. Test Liquid (Sea Water)
F. Stream of Bubbles
G. Out-of-focus Bubble

other cases the bubbles first appeared after several minutes of exposure. If it is impossible to obtain the stream of fine bubbles at first, it is suggested that the tightness of the specimen in the nickel tube be checked. If the specimen is tight and no stream of bubbles is formed, resonance will be indicated by the water-hammer pattern on the face of the specimen (also visible in Figure 14) and by the fact that the test solution is thrown into a state of violent agitation. The resonant peak will be found to be quite sharp.

## C. Description and Procedure of Testing Program

A group of eleven specimens was tested. These specimens were given the letter designations shown on the following page. Each specimen was subjected to vibratory cavitation for three one-hour periods. The specimens were initially weighed and then re-weighed and photographed after each of the one-hour test periods. All of the specimen photographs were taken at a magnification of five diameters on a "Leitz Micrometallograph."

An electric time clock was employed throughout the testing program to turn off the unit after a period of one hour. This eliminates the need of being present at a certain specified time to shut down the unit. It should be mentioned that the vibrations produced are quite intense and at a frequency which is very penetrating to the human ear.

## CAVITATION SPECIMEN DESIGNATIONS

| Designation | Name of Metal | Composition | BHN |
|---|---|---|---|
| A | Machinable Brass | Not Known | 66 |
| B | Free-Cutting, Hard Drawn Brass | Not Known | 85 |
| C | Hard-Drawn Naval Brass | 60% Cu, 39.25% Zn, 0.75% Sn | 71 |
| D | Hard-Drawn Tobin Bronze | 58.79% Cu, 40.43% Zn, 0.88% Sn | 87 |
| E | Hard-Drawn Copper | Commercially Pure | 63 |
| F | Aluminum, 2S-H18 (Alcoa) | Commercially Pure | 38 |
| G | Aluminum, 24S-T4 (Alcoa) | 93.4% Al, 4.5% Cu, 1.5% Mg, 0.6% Mn | 89 |
| H | US Steel #G-1 (Low Carbon) | Not Known | 56 |
| I | US Steel #G-6 (Medium Carbon) | 98.978% Fe, 0.38 C, 0.03% S, 0.012% P, 0.60% Mn | 81 |
| J | US Steel #G-9 (High Carbon) | 98.509% Fe, 0.97% C, 0.039% S, 0.032% P, 0.45% Mn | 135 |
| K | Cold-Drawn, Annealed, Free-Machining, Stainless Steel (18-8 Class) Type 303 | 17-19% Cr, 0.15% C (max), 8-10% Ni; 0.07% min P, S, and Se; 0.6% max of Zr and Mo | 94 |

Although it is not recommended that the unit be left running unattended throughout an entire one-hour test period, it is recommended that the operator leave the room for 15 minutes at a time. Human exposure to these intense vibrations will cause temporary partial deafness--especially to high frequency sounds. This "deafness" will usually last from one to four hours. Throughout the test it is advisable for the operator to periodically check the specimen and retune the polarizing current control to assume peak resonance. If it is found that the vibration has ceased completely, it is very likely that the specimen has worked loose from the nickel tube.

At the end of a one-hour test period, the proper procedure is as follows: turn off the oscillator (unless already turned off by a time clock), turn off the cooling water, remove the specimen (being extremely careful to avoid marring), and clean the specimen thoroughly. Any rust should be removed by scrubbing with a brush having bristles softer than the metal specimen. On hard steel specimens the moderate use of steel wool aids in removing any rust deposit from the inner surface of the weight adjustment hole. After the specimen has been thoroughly cleaned, it should be dried as well as possible by an absorbent lint-free cloth and then placed under a warm air specimen drier to complete the drying operation. When the specimen is thoroughly dry and cooled, the weight should be checked and

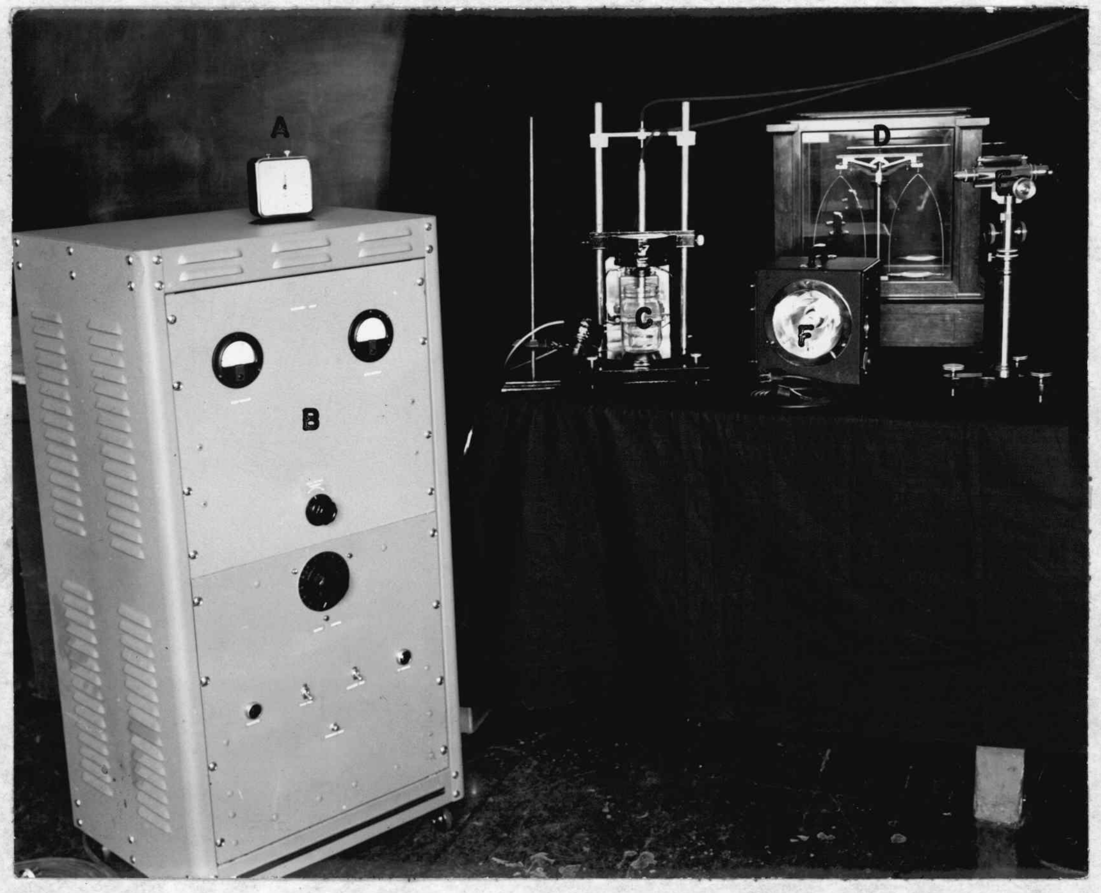



Figure 15. VIBRATORY CAVITATION TESTING SET-UP

A. Timer Clock
B. Magnetostriction Oscillator Unit
C. Specimen Holder-Driving Coil Unit
D. Accurate Laboratory Balance
E. Measuring Microscope (Leitz)
F. "Strobotac" Electrical Tachometer

recorded. After photographing, the specimen should be placed in a desiccator until it is to be subjected to the next one-hour test period.

Figure 15 is a photograph showing most of the equipment used in the testing program. The electric time clock, the specimen desiccator, and the tools used are not shown. The laboratory scales shown in this figure are of the standard balance type, which early in the test program was replaced by the more sensitive "Chain-O-Matic" balance. The rubber tubes leading from the top of the driver unit are connected to the vacuum and cooling water supply.

Rockwell hardness tests were made on the stock metals from which each of the specimens was machined. These readings, as well as their Brinell hardness number equivalents, were recorded on the test data sheet. The actual specimens were not used for the hardness tests since there is a possibility that their face surfaces were cold-worked and therefore hardened by the cavitation tests.

## D. Test Results

The test data for the eleven specimens tested appear in the appendix. From these data the curves shown in Figures 16 through 20 were constructed. Photographs of each of the specimens were taken at the end of each of the one-hour test periods. These photographs were included in the

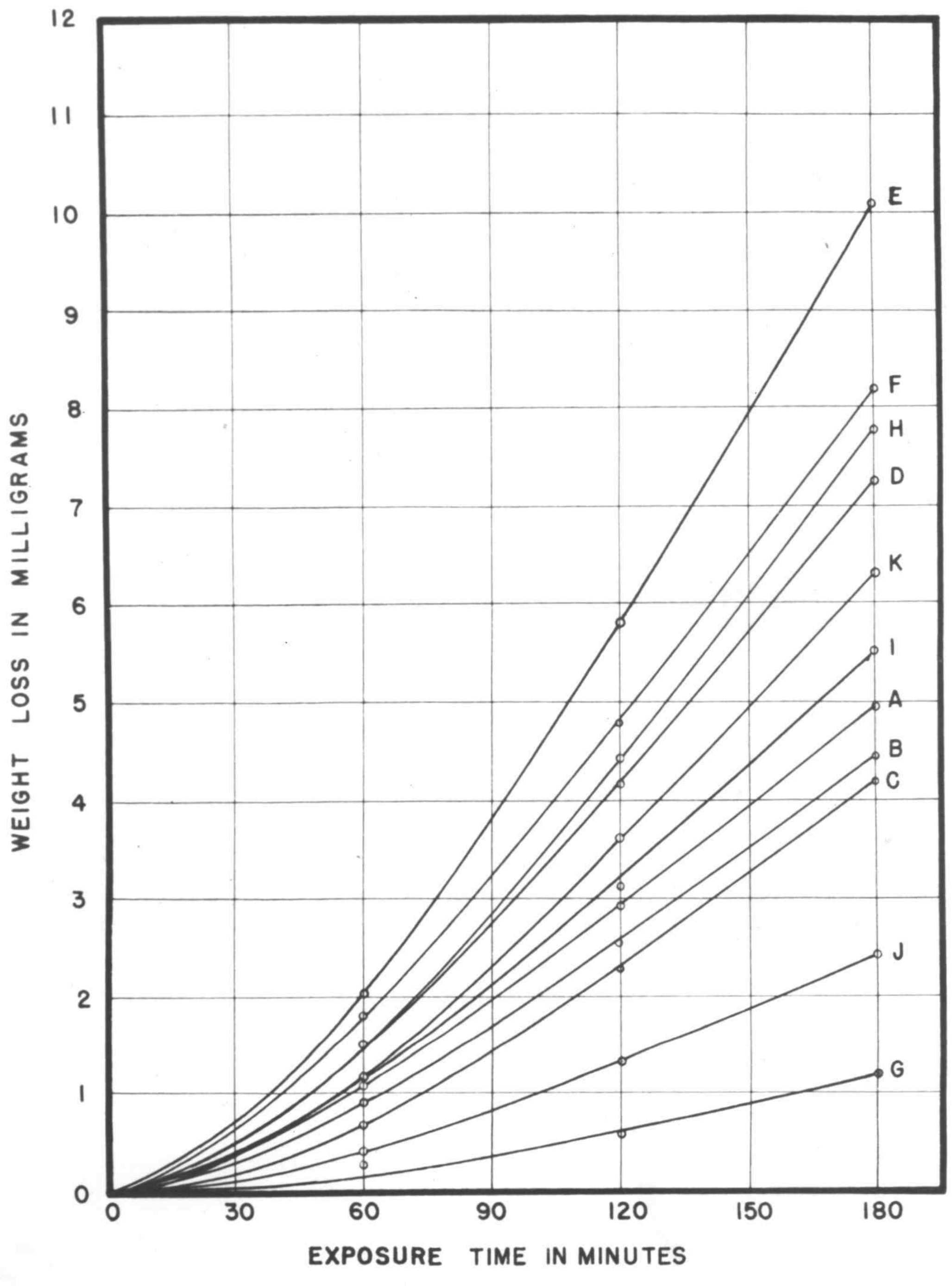



FIGURE 16. CAVITATION RATES ON WEIGHT-LOSS BASIS

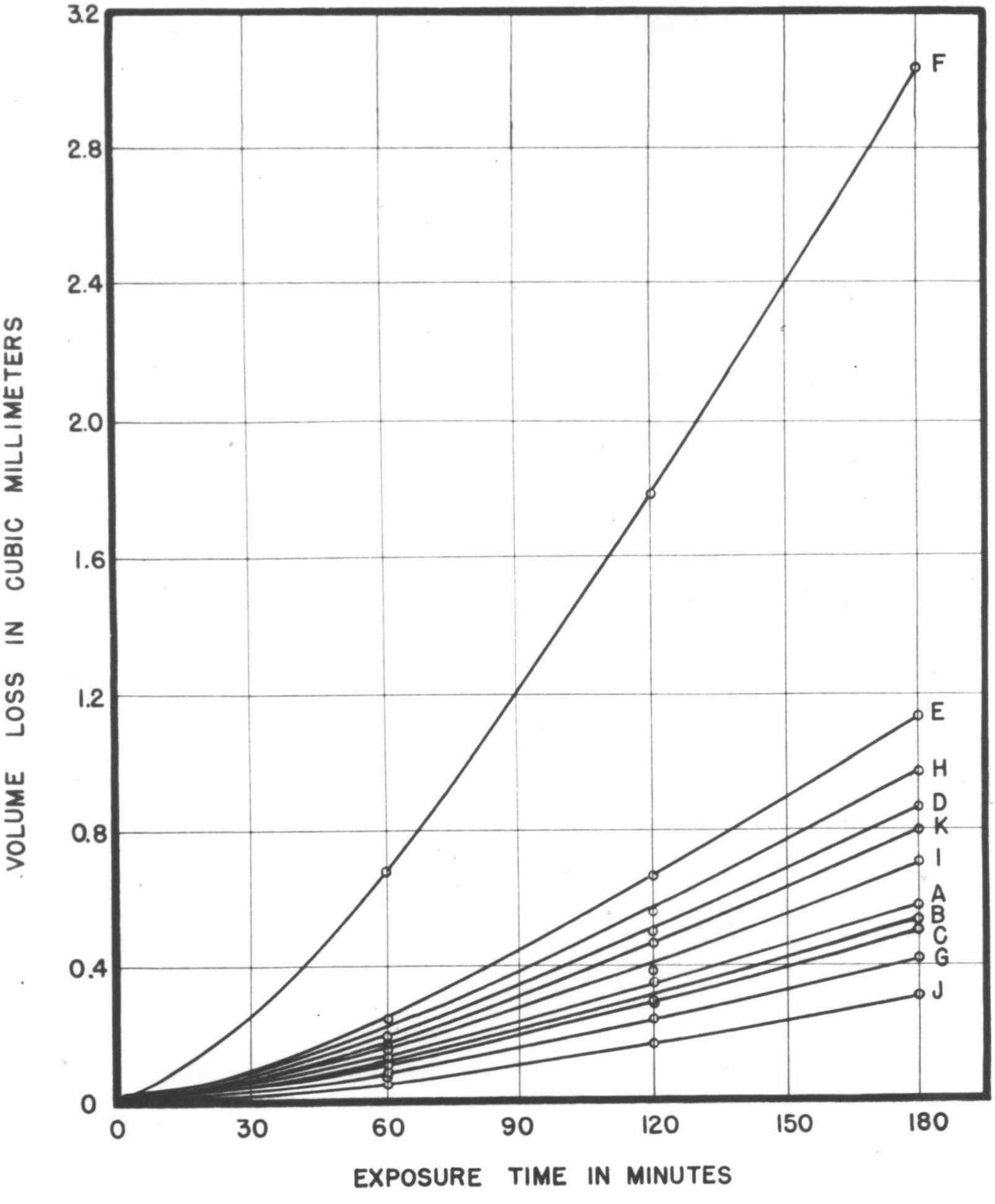



FIGURE 17. CAVITATION RATES ON VOLUME-LOSS BASIS

appendix rather than in the "Test Result" section due to the considerable number of pictures taken.

The initial test data, which involves the specimen weight losses, were plotted in Figure 16. With the exception of the curve shown in Figure 20, there are a zero point and three test points to define each curve. Since the densities of the specimens tested varied greatly, the "Weight Loss vs Exposure Time" curve (Figure 16) gives an erroneous presentation of the test results. Figure 17 shows the cavitation rates on the more logical volume loss basis. Since the volume loss is the prime factor in cavitation testing, the weight loss measurements were merely a means to an end.

It will be noted that Specimen F, pure aluminum, very greatly exceeded all of the other specimens tested for volume loss. This high degree of cavitation is also evident in Figure 26, the corresponding photograph for this specimen. The pure aluminum specimen nearly exceeded the much heavier copper specimen in weight loss. The other ten specimens tested all showed relatively low volume losses as compared to the pure aluminum. In order to spread out the result curves for these other specimens, the test results for the non-ferrous and the ferrous specimens have been plotted separately. These curves appear in Figures 18 and 19 respectively. It should be noticed that all of these curves show the same contours, which indicates that the

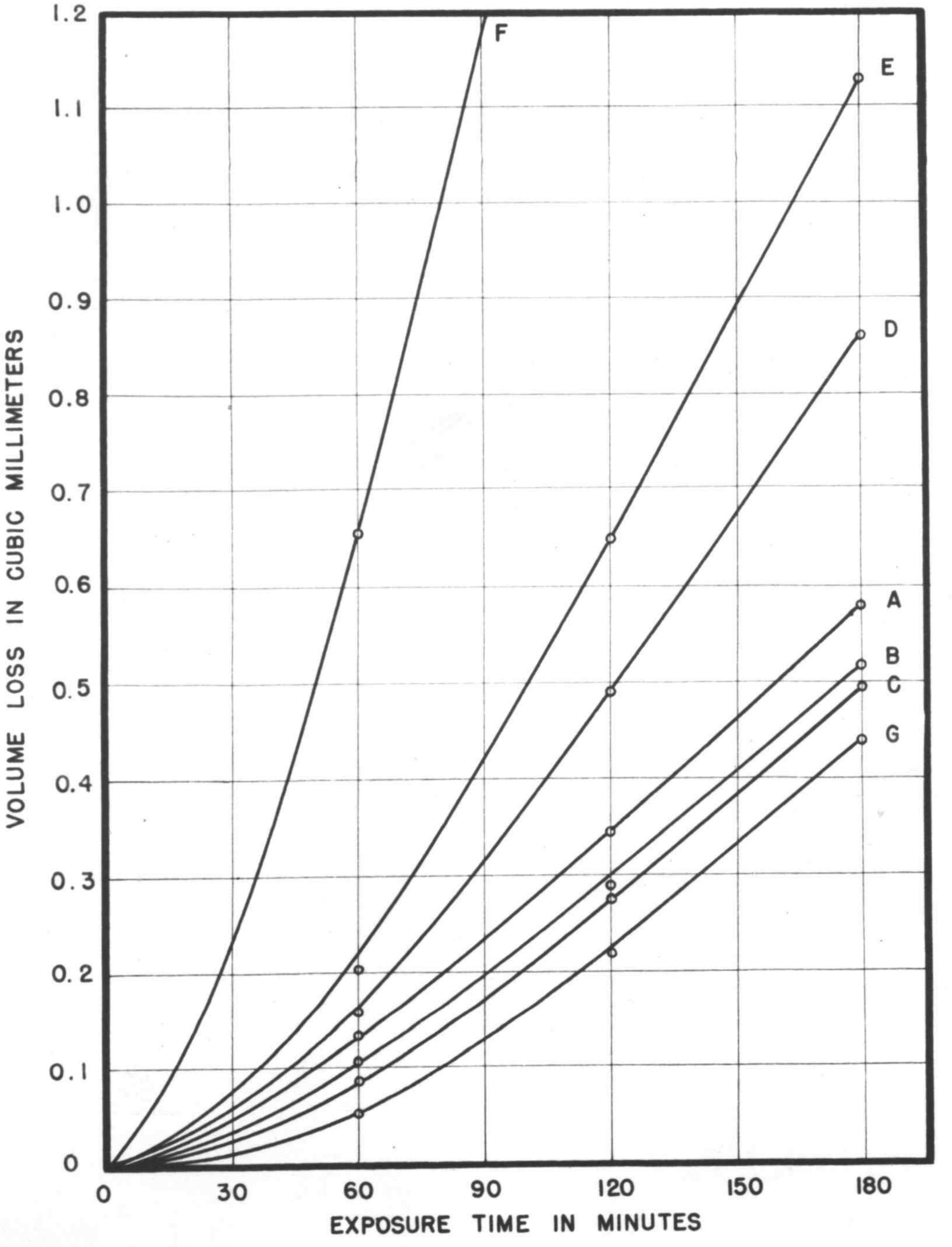



FIGURE 18. CAVITATION RATES OF NON-FERROUS METALS TESTED ON BASIS OF **VOLUME** LOSSES

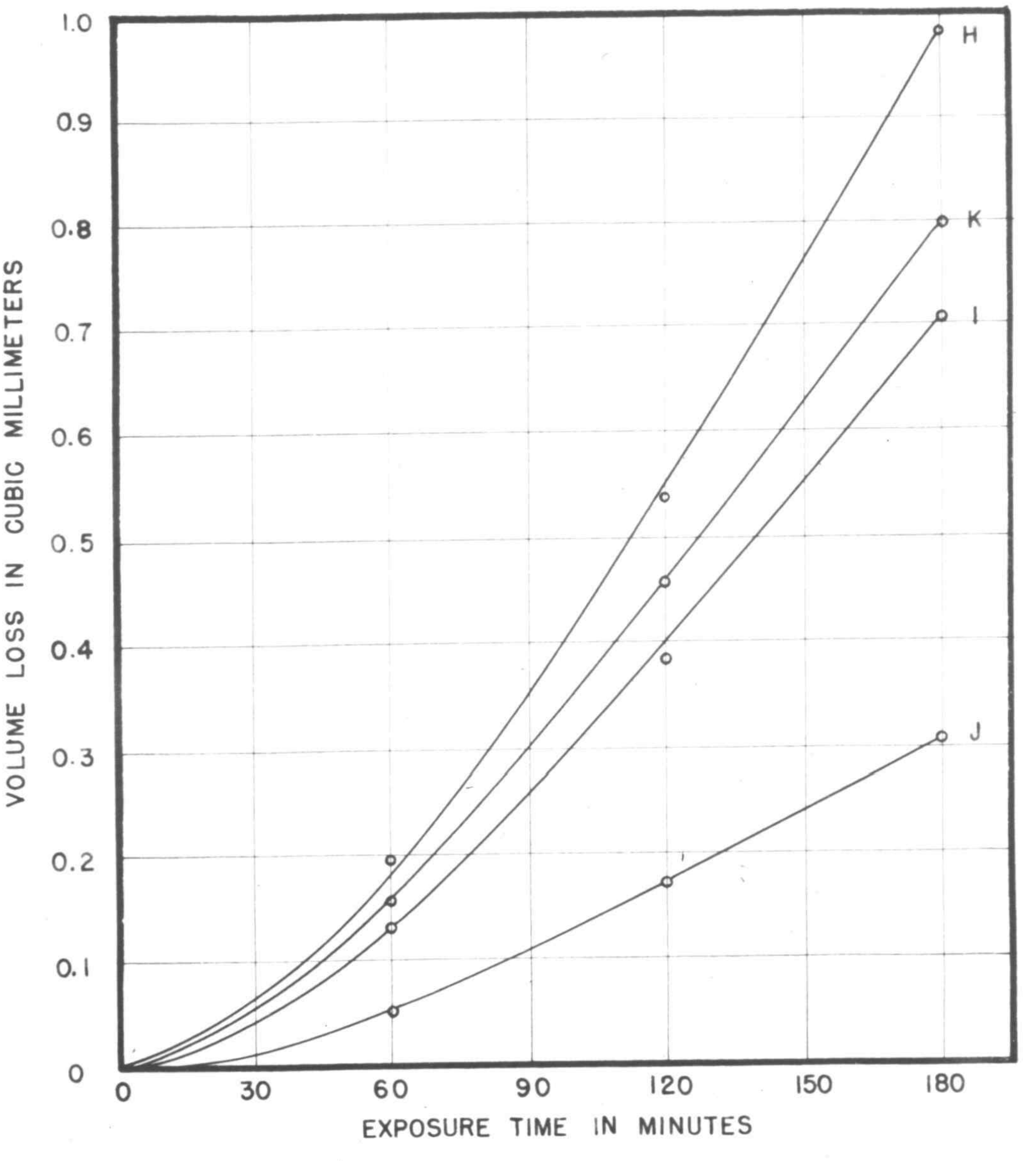



FIGURE 19. CAVITATION RATES OF FERROUS METALS TESTED ON BASIS OF VOLUME LOSSES

cavitation rate for the initial hour test period is not nearly as great as for the succeeding two one-hour periods.

The improvement of the cavitation resistance of aluminum, by alloying and heat treating, is shown by the curve for Specimen G (Alcoa 24-ST4) in Figure 17. While aluminum in its pure form had the highest volume loss of any of the metals tested, the alloyed aluminum had the next to the lowest volume loss. The lowest volume loss obtained was with high carbon steel, Specimen J. The stainless steel specimen (K) showed the next to the highest weight loss in the ferrous group. It was originally anticipated that this metal would be the most resistant to cavitation, although the tests conducted disproved this. The fact that the stainless steel tested was in the annealed condition could be responsible for its relatively low cavitation resistance.

Figure 18 shows that the three different types of brass tested (Specimens A, B, and C) all had approximately the same resistance to cavitation. The bronze specimen tested (Tobin bronze) showed a slightly lower resistance to cavitation than the brass specimens.

Figure 20 is a curve showing the trends which exist between the cavitation resistance and the hardness of a metal. Again, the ferrous and the non-ferrous specimen results have been plotted separately. The absolute accuracy of these curves perhaps is somewhat doubtful, although a definite trend is indicated by the test points. The trends indicated by Figure 20 show that the cavitation resistance of metals increases with increases in hardness. Since the cavitation phenomenon is a result of the fatigue failure of a metal, it is likely that cavitation resistance is a function of fatigue resistance. No tests were made to verify this however.

It should be noted that in some cases the three photographs taken of each specimen do not all appear to be of the same specimen. This is due to variations in the illumination of the specimens when the pictures were taken. Also, some of the specimens appear to be less severely cavitated than they actually were since some of the photographs do not bring out the very deepest cavities. With a single exception (Figure 24-A), oblique illumination was used for the photographing in order to create shadows which tend better to show the depressions in the specimen faces.

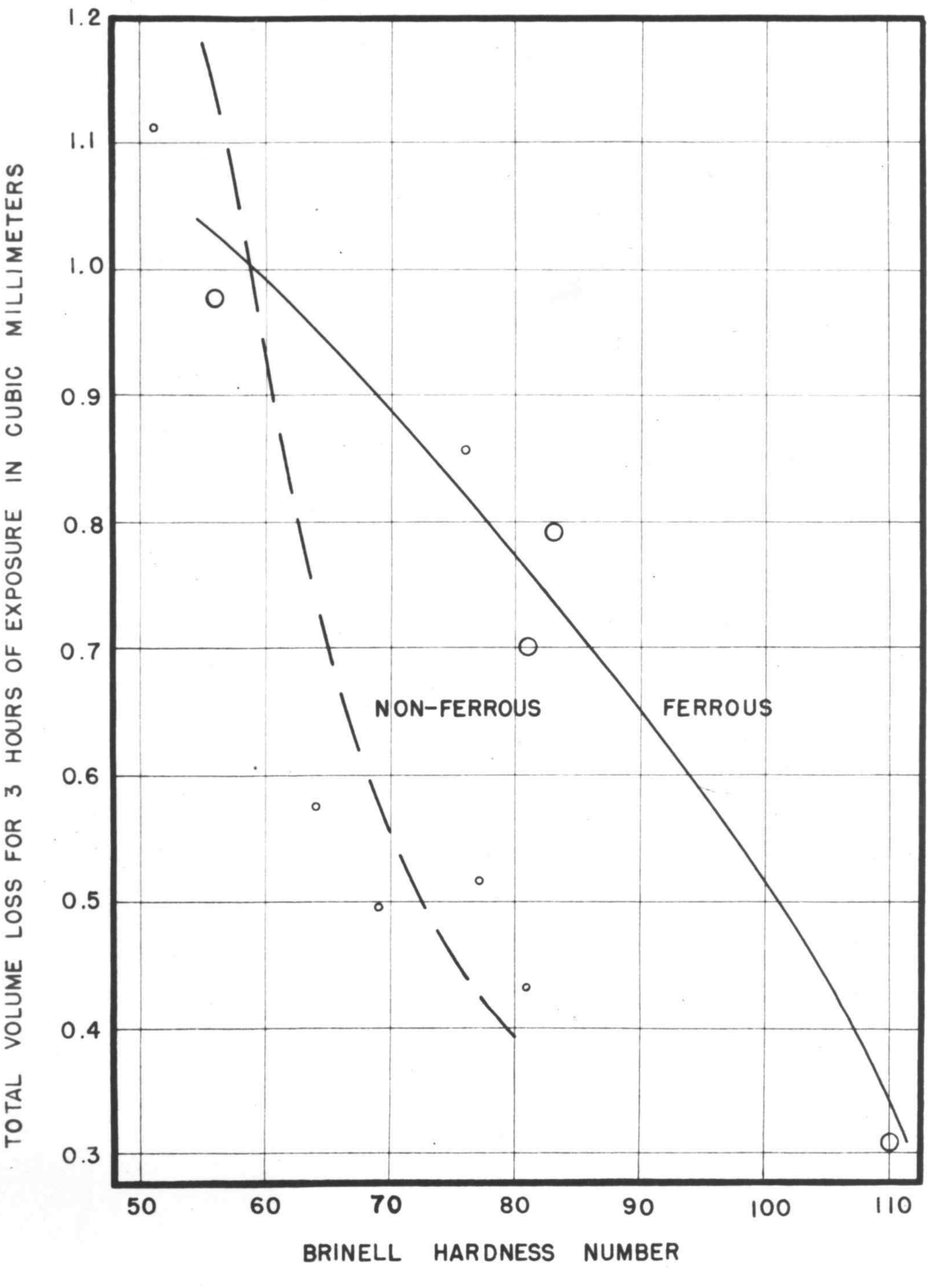



FIGURE 20. TRENDS OF CAVITATION RESISTANCE VS HARDNESS RELATIONSHIPS

## IV. CONCLUSIONS

The vibratory cavitation tester constructed gave reliable test results, although extreme caution must be exercised in cleaning and weighing the specimens. Since the weight losses are very small any accidental weight losses or gains, such as result from the marring or insufficient cleansing of the specimens, could cause completely erroneous test results. If it had been financially possible, it would have been preferable to construct an oscillator having an input of one or even two kilowatts. An oscillator this large would inflict weight losses great enough so that small weight variations due to handling would be of minor importance.

The results of the tests conducted indicate several trends. In all of the specimens tested the volume losses for the first hour of exposure were considerably less than the volume losses for the second and third hour tests.

This initial period of relatively high resistance to cavitation is due to the fact that the surface of the metal must be worked to a point of fatigue failure before any great losses in weight will result. Variations in finish or heat treatment may have a measurable effect upon this initial breaking down of the surface. However, after the surface has once been broken through, destruction progresses at a relatively uniform rate.

The reliability of vibratory cavitation test results is most likely to depend upon the following factors:

(1) Constant frequency and amplitude of vibration

(2) Accuracy of weight-loss determinations

(3) Uniformity of the test material

(4) Uniformity of test fluid composition and temperature

By matching the frequency of the magnetostriction oscillator with that of a calibrated variable frequency audio oscillator on an oscilloscope screen, the resonant frequency of the nickel tube and specimen was found to be very near 8900 cps. The oscillator input was maintained at 250 watts throughout the testing program; this resulted in a nearly constant vibration amplitude of 0.05 millimeter.

It was found that there was a definite trend existing in the correlation between cavitation resistance and material hardness. The cavitation resistance of a metal was found to be roughly proportional to its hardness.

The cavitation resistance curves which were drawn from the test data will not apply to cases where there is any form of corrosion working with the cavitation erosion. This is the prime shortcoming of accelerated cavitation tests. However, by correlating the corrosion data for a certain metal in a certain liquid with the vibratory cavitation test data for these two materials, the life of this metal in service may be fairly accurately predicted. In selecting a cavitation-resistant metal on the basis of cavitation test data alone, due attention must be paid to prevent any chemical incompatability which might result in galvanic corrosion.

If the true worth of the vibratory apparatus constructed is to be gained, it should be used in the future for a more extensive cavitation testing program. Such parameters as test liquid temperature, test liquid composition, and atmospheric pressure should be investigated. Also a wider range of metals should be tested. The heat treatments of the metals tested should be altered in order to discover the effect of this parameter on cavitation resistance.

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APPENDICES

A. <u>Ratings and Characteristics of Tubes Used</u>

<u>VT-127A</u> Power Triode Tubes (2 used in oscillator deck)

| | |
|---|---|
| Plate Dissipation (watts) . . . . . . . . . | 100 |
| Filament Voltage . . . . . . . . . . . . . . | 5 |
| Filament Current (amperes) . . . . . . . | 10.4 |
| Maximum Plate Voltage . . . . . . . . . . | 3000 |
| Maximum Plate Current (milliamperes) . . | 200 |
| Maximum dc Grid Current (milliamperes) . | 30 |
| Amplification Factor . . . . . . . . . . . | 15.5 |
| Interelectrode Capacitances (micro-microfarads) | |
| Grid to Filament . . . . . . . . . . . | 2.7 |
| Grid to Plate . . . . . . . . . . . . . | 2.3 |
| Plate to Filament . . . . . . . . . . . | 0.35 |

<u>836</u> High Vacuum, Half-Wave Rectifier Tube (2 used in power supply deck)

| | |
|---|---|
| Filament Voltage . . . . . . . . . . . . . . | 2.5 |
| Filament Current (amperes) . . . . . . . . | 5 |
| Maximum Inverse Plate Voltage . . . . . | 5000 |
| Maximum Plate Current (milliamperes) . . | 1000 |

B. Parts List for Cavitation Tester

| Part No. | Description |
|---|---|
| C-1 | 4 Microfarad, 3000 Volt transmitting filter condenser (Plasticon) |
| C-2 | ditto |
| C-3 | ditto |
| C-4 | 0.005 Microfarad, 8000 Volt mica condenser (Sangamo type B) |
| C-5 | 40 Microfarad, 150 Volt dry electrolytic condenser (Akrad) |
| C-6 | ditto |
| C-7 | 0.02 Microfarad, 3000 Volt mica condenser (Sangamo #G1-312) |
| C-8 | 0.1 Microfarad, 600 Volt paper by-pass condenser (Akrad) |
| C-9 | ditto |
| C-10 | 0.01 Microfarad, 3000 Volt mica condenser (Sangamo type A) |
| CH-1 | 20 Henry, 300 milliampere chokes, 4000 Volt insulation |
| CH-2 | Dc resistance = 90 ohms (UTC type S-33) |
| CH-3 | ditto |
| CH-4 | 1 Henry, 600 milliampere choke |
| CH-5 | 10 Henry, 250 milliampere smoothing choke, 3000 Volt insulation, dc resistance = 125 ohms (Merit C-3182) |
| L-1 | Plate coil wound with AWG #23 dcc wire, dc resistance = 17 ohms, inductance (with nickel tube inserted) = approximately 0.07 Henry |
| L-2 | Grid coil wound with AWG #29 enameled wire, dc resistance = 200 ohms |

| | |
|---|---|
| M-1 | 0-500 Milliampere dc milliameter (Simpson model 26) |
| M-2 | 0-4000 Volt dc voltmeter (Simpson model 26) |
| PL-1 | Faceted pilot light with 110 Volt S-6 bulb, red (Drake model 75-AP) |
| PL-2 | ditto (green) |
| PL-3 | S-6 bulb and plain socket |
| R-1 | 100,000 ohm, 100 watt resistor (IRC type HA) |
| R-2 | 25 ohm, 50 watt, adjustable tap resistor (Ohmite type 0562) |
| R-3 | 100 ohm, 100 watt rheostat (Ward-Leonard type 100R) |
| R-4 | 200 ohm, 200 watt resistor (Grove's) |
| R-5 | External range multiplier resistor for meter, M-2 |
| RL-1 | Time delay relay, 110 Volt ac coil (Advance type 300) (10 second to one minute delay) |
| RL-2 | Remote reset overload relay (250 to 500 ma range), (Advance type 750) |
| SBR | Selenium bridge-rectifier, 35 Volts output at 6 amperes (Seletron #G2B1S1B) |
| SW-1 | Push button switch, 125 Volt, 1 ampere (ICA-H&H) |
| SW-2 | Heavy-duty power switch, 125 Volt, 10 ampere (H&H) |
| SW-3 | ditto |
| T-1 | Plate transformer, primary: 115 volt, 60 VA (CCS). Secondary: 2335-1700-0-1700-2335 ac volts, dc output voltage: 1500-2000, 300 ma (Thordarson T-21P82) |
| T-2 | 1 KVA variable transformer, 115 Volt primary, 0-135 Volt output (Superior #116-U) |

| | |
|---|---|
| T-3 | Filament transformer, 2.5 VCT, 10 amperes, 10 KV insulation (UTC type S-57) |
| T-4 | Filament transformer, 5 VCT, 13 amperes (UTC type S-59) |
| T-5 | Power transformer, (special-wound), 115 Volt primary, 100 watts, 40 Volt ac secondary (originally Stancor type P-6146) |
| VT-1 | Type 836 half-wave, high vacuum, rectifier tubes |
| VT-2 | ditto |
| VT-3 | Type VT-127A high-frequency, power triode tubes |
| VT-4 | ditto |

Miscellaneous Parts List

| Quantity | Description |
|---|---|
| 2 | 4 Prong rectifier tube sockets (Millen #33004) |
| 2 | High voltage safety terminals (Millen #37501) |
| 1 | Driver unit plug and socket assembly ( on oscillator chassis) (Jones P-506 CE and S-506 DB) |
| 1 | Relay rack panel for oscillator deck, 17 1/2 inches high, grey wrinkle (Bud #PS-1259) |
| 1 | Relay rack panel for power supply deck, 19 1/4 inches high, grey wrinkle (Bud #1260) |
| 1 | Deluxe relay rack cabinet, 36 3/4 inch panel space, grey wrinkle (Bud #CR-1774) |
| 2 | Heavy duty chassis, zinc plated, 13" x 17" x 4" (Bud #CB-1770) |
| 2 | Bottom plates for above, 13" x 17" (Bud #BP-679) |
| 4 | Heavy duty truck casters (Bud #RC-7756) |
| 1 | Interlock switch (Bud #SW-743) |

2 pr Chassis mounting brackets, 8 1/2 inches high, 13 inches deep, grey wrinkle (Bud #MB-45)

Assorted builder's hardware, hook-up wire, etc

C. CAVITATION TEST RESULTS

| Spec | Time in Hr | Orig Wt in Gr | After Exposure Wt in Gr | Wt Loss in Mg | Density at 68 F in Gr/Cm$^3$ | Volume Loss Mm$^3$ | Rockwell & Brinell Hardness |
|---|---|---|---|---|---|---|---|
| A-1 | 1 | 12.9853 | 12.9841 | 1.2 | 8.50 | 0.141 | B-28 |
| A-2 | 2 | " | 12.9824 | 2.9 | or | 0.341 | (66) |
| A-3 | 3 | " | 12.9804 | 4.9 | 0.1176 mm$^3$/mg | 0.576 | |
| B-1 | 1 | 12.3733 | 12.3724 | 0.9 | 8.50 | 0.106 | B-52 |
| B-2 | 2 | " | 12.3708 | 2.5 | or | 0.294 | (85) |
| B-3 | 3 | " | 12.3689 | 4.4 | 0.1177 mm$^3$/mg | 0.517 | |
| C-1 | 1 | 12.3343 | 12.3336 | 0.7 | 8.41 | 0.083 | B-35 |
| C-2 | 2 | " | 12.3320 | 2.3 | or | 0.274 | (71) |
| C-3 | 3 | " | 12.3301 | 4.2 | 0.1189 mm$^3$/mg | 0.498 | |
| D-1 | 1 | 13.3007 | 13.2978 | 1.4 | 8.40 | 0.167 | B-54 |
| D-2 | 2 | " | 13.2965 | 4.2 | or | 0.500 | (87) |
| D-3 | 3 | " | 13.2935 | 7.2 | 0.119 mm$^3$/mg | 0.858 | |
| E-1 | 1 | 13.7884 | 13.7864 | 2.0 | 8.96 | 0.224 | B-23 |
| E-2 | 2 | " | 13.7826 | 5.8 | or | 0.648 | (63) |
| E-3 | 3 | " | 13.7783 | 10.1 | 0.1117 mm$^3$/mg | 1.129 | |
| F-1 | 1 | 7.3965 | 7.3947 | 1.8 | 2.71 | 0.664 | H-4 |
| F-2 | 2 | " | 7.3817 | 4.8 | or | 1.77 | (38) |
| F-3 | 3 | " | 7.3883 | 8.2 | 0.369 mm$^3$/mg | 3.021 | |

C. CAVITATION TEST RESULTS (CONTINUED)

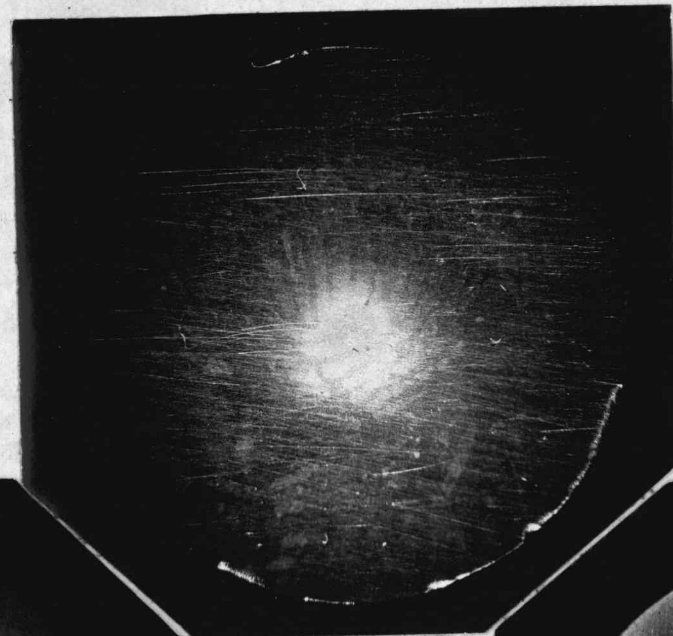
| Spec | Time in Hr | Orig Wt in Gr | After Exposure Wt in Gr | Wt Loss in Mg | Density at 68 F in Gr/Cm$^3$ | Volume Loss Mm$^3$ | Rockwell & Brinell Hardness |
|---|---|---|---|---|---|---|---|
| G-1 | 1 | 8.7683 | 8.7681 | 0.2 | 2.77 | 0.072 | B-54 |
| G-2 | 2 | " | 8.7677 | 0.6 | or | 0.220 | (89) |
| G-3 | 3 | " | 8.7671 | 1.2 | 0.361 mm$^3$/mg | 0.434 | |
| H-1 | 1 | 12.6642 | 12.6628 | 1.4 | 8.96 | 0.178 | E-61 |
| H-2 | 2 | " | 12.6598 | 4.4 | or | 0.559 | (56) |
| H-3 | 3 | " | 12.6565 | 7.7 | 0.127 mm$^3$/mg | 0.979 | |
| I-1 | 1 | 13.2853 | 13.2842 | 1.1 | 7.849 | 0.141 | B-48 |
| I-2 | 2 | " | 13.2821 | 3.2 | or | 0.408 | (81) |
| I-3 | 3 | " | 13.2798 | 5.5 | 0.1275 mm$^3$/mg | 0.702 | |
| J-1 | 1 | 13.1148 | 13.1144 | 0.4 | 7.835 | 0.051 | B-74 |
| J-2 | 2 | " | 13.1135 | 1.3 | or | 0.166 | (135) |
| J-3 | 3 | " | 13.1124 | 2.4 | 0.1276 mm$^3$/mg | 0.308 | |
| K-1 | 1 | 11.5912 | 11.5900 | 1.2 | 7.93 | 0.151 | B-59 |
| K-2 | 2 | " | 11.5868 | 3.6 | or | 0.454 | (94) |
| K-3 | 3 | " | 11.5849 | 6.3 | 0.126 mm$^3$/mg | 0.794 | |

SPECIMEN A

Machinable Brass

FIGURE 21

1. 1 hour
2. 2 hours
3. 3 hours



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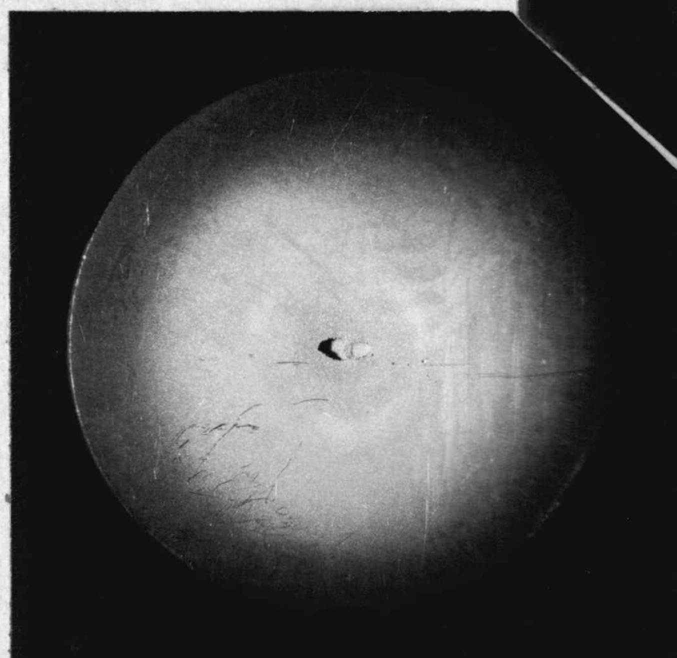

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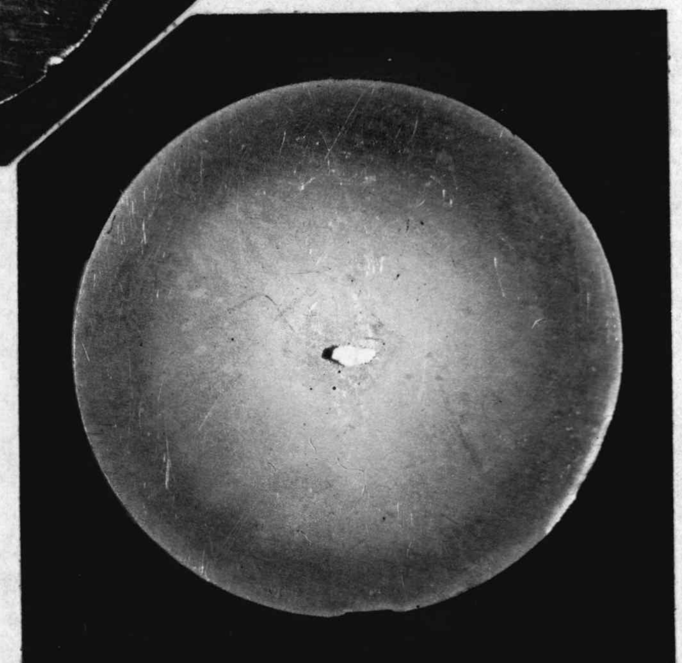
3

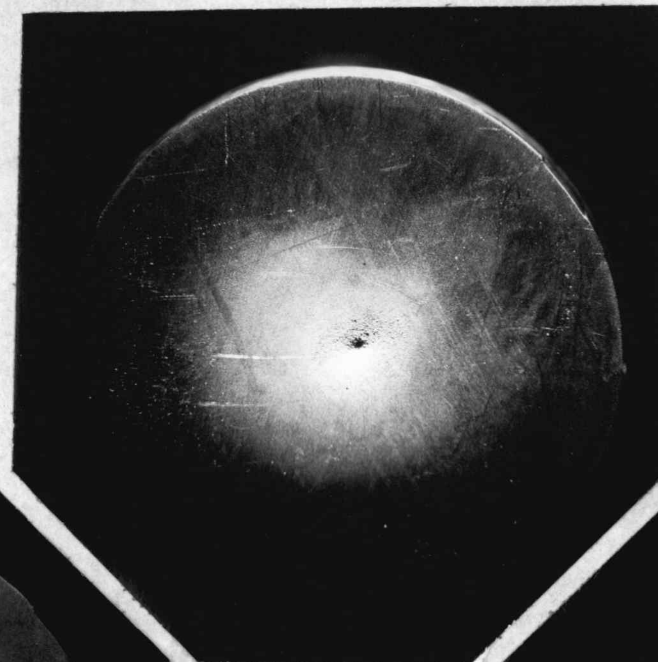


SPECIMEN B

Free-cutting, Hard-
Drawn Brass

FIGURE 22

1. 1 hour
2. 2 hours
3. 3 hours



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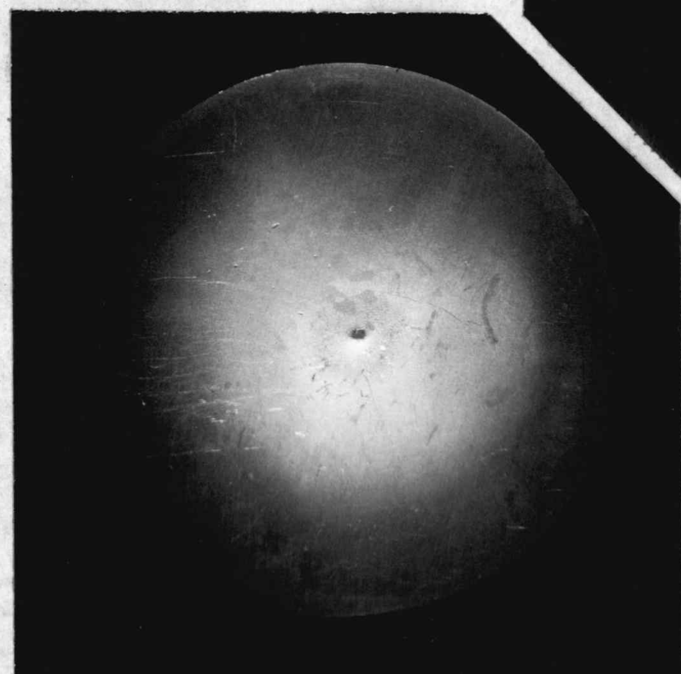

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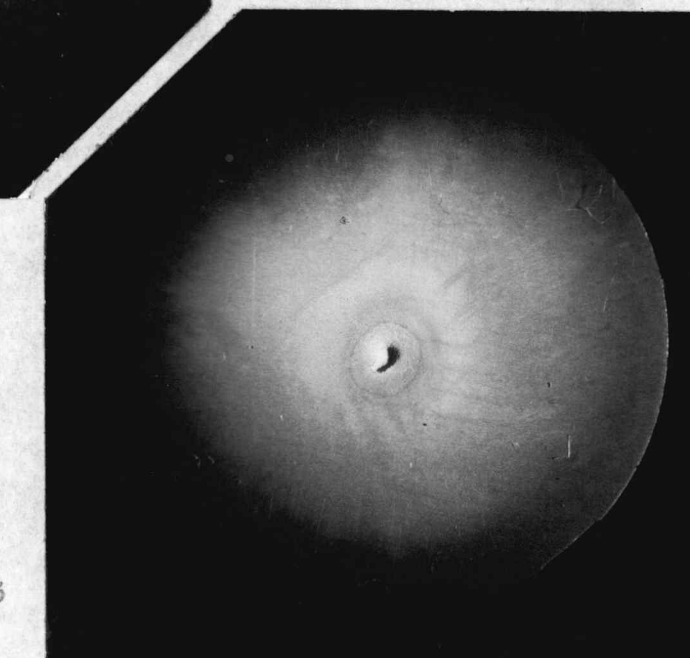


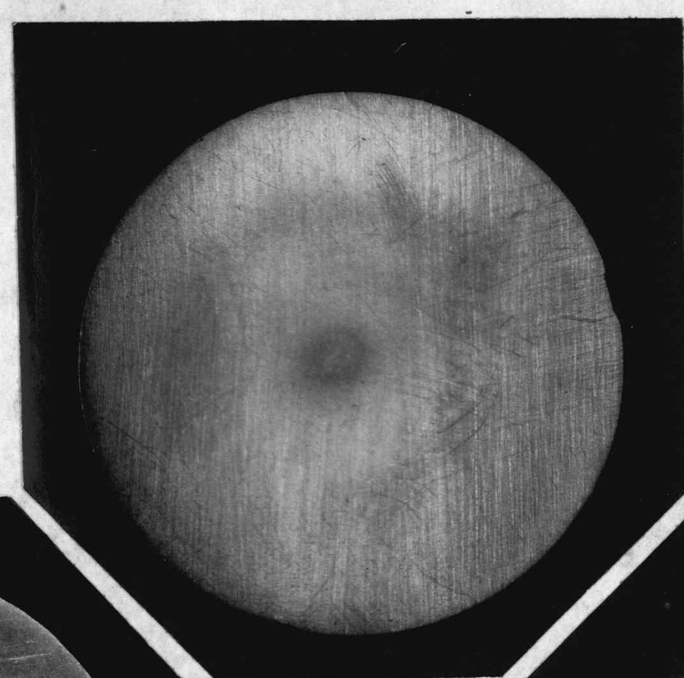
3

SPECIMEN C

Hard-drawn Naval Brass

FIGURE 23

1. 1 hour
2. 2 hours
3. 3 hours



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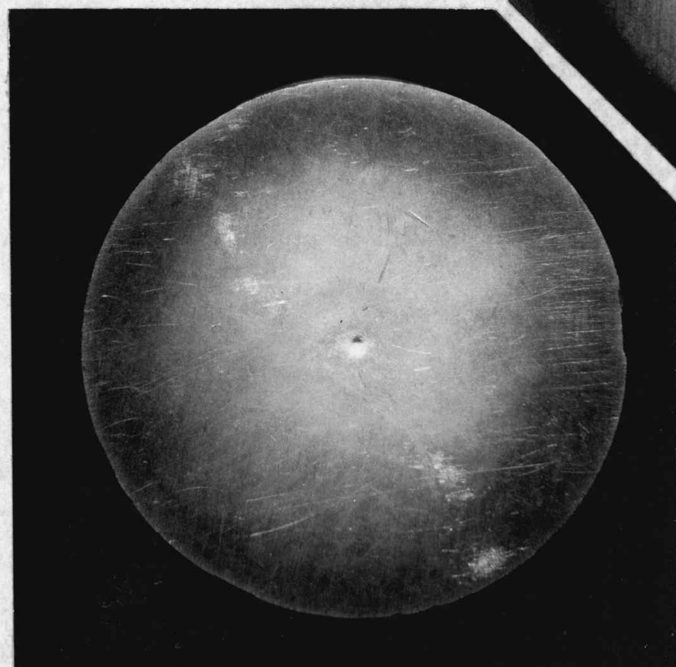

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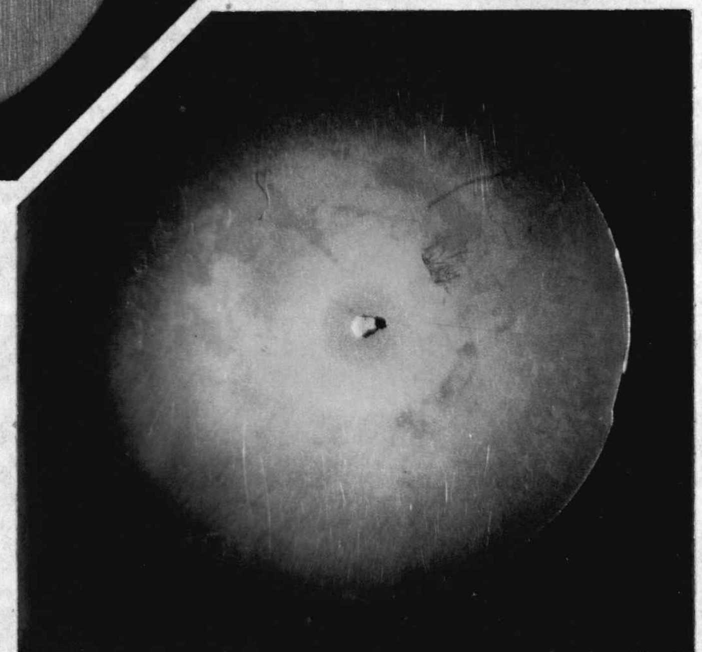


3

SPECIMEN D

Hard-drawn Tobin Bronze

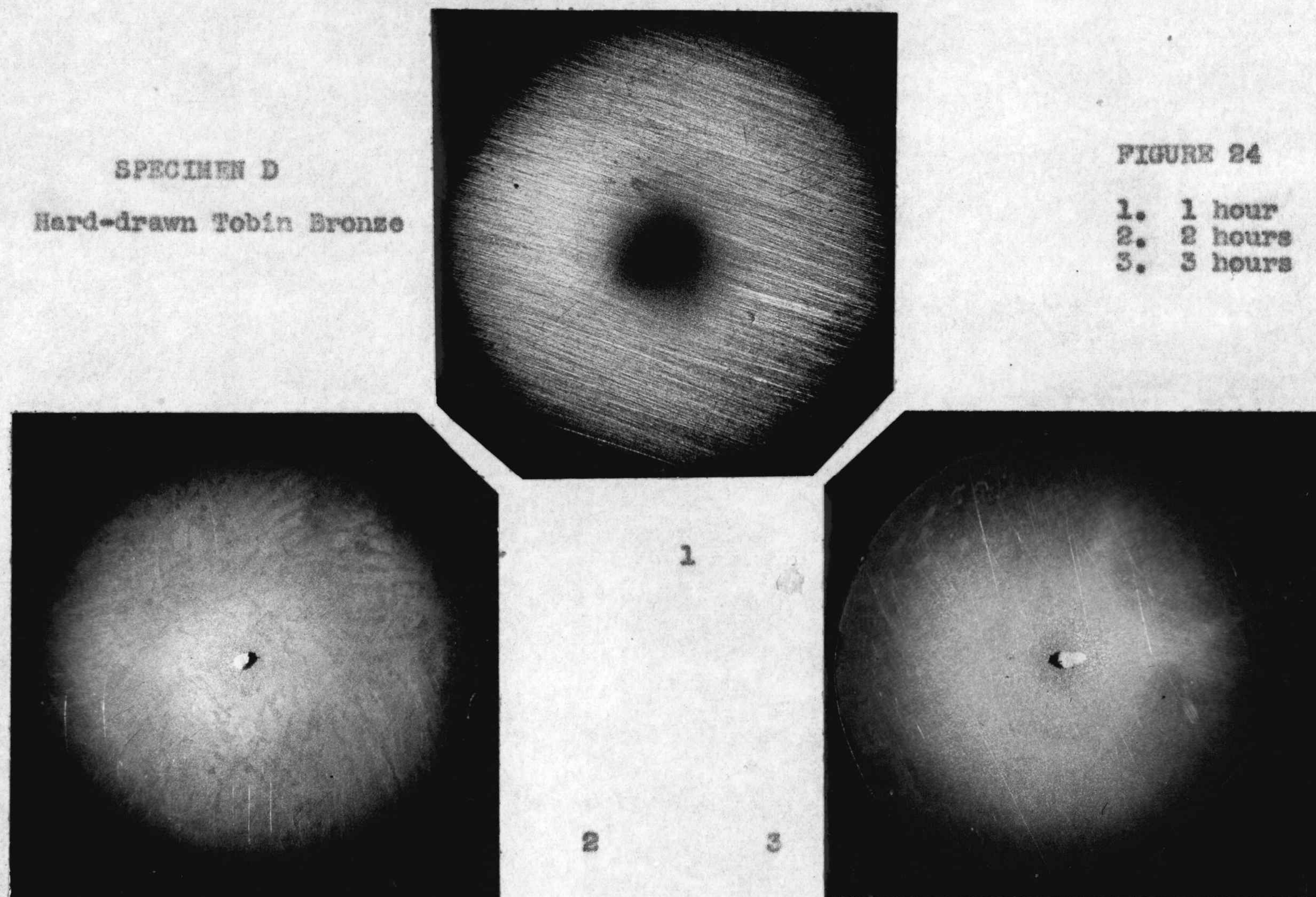
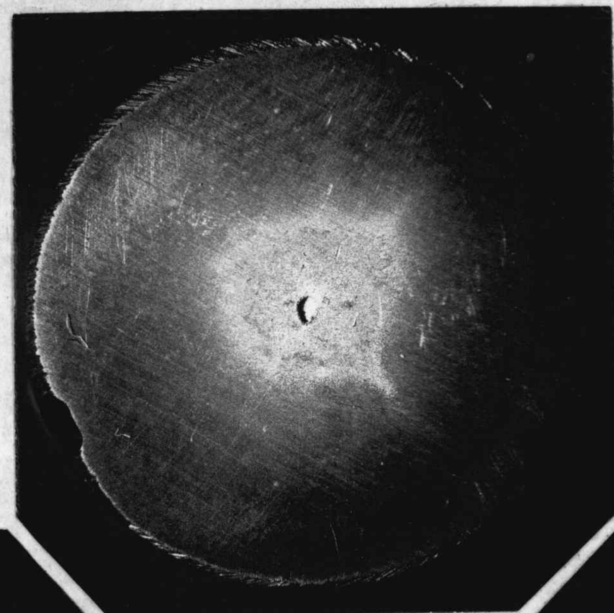


FIGURE 24

1. 1 hour
2. 2 hours
3. 3 hours

SPECIMEN E

Hard-drawn Copper



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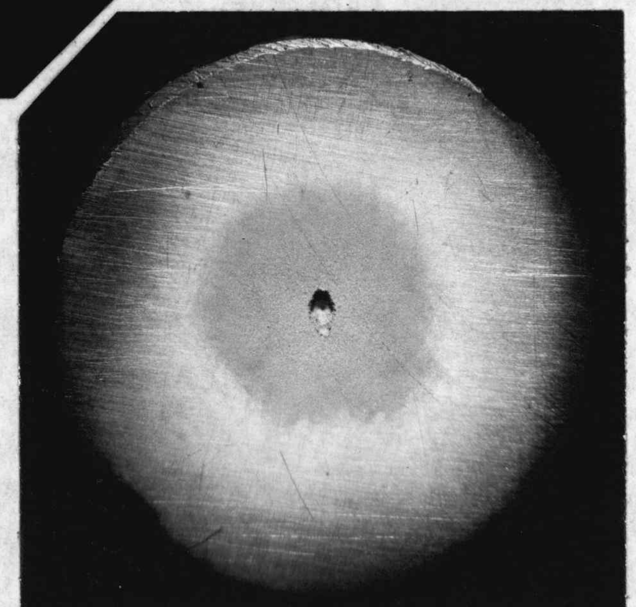
2



3

FIGURE 25

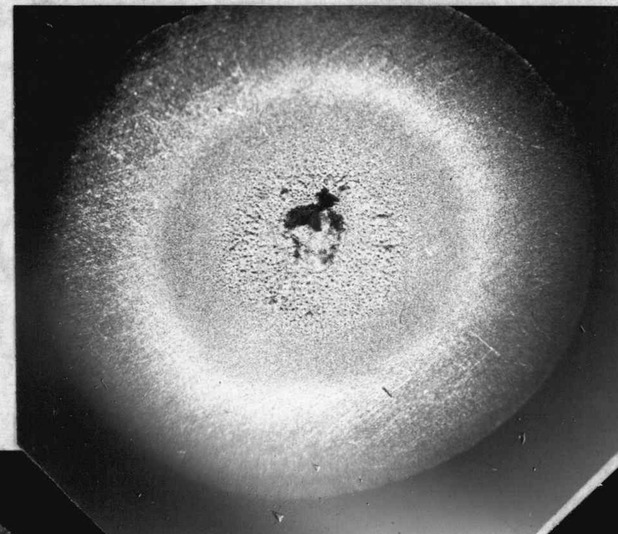
1. 1 hour
2. 2 hours
3. 3 hours

SPECIMEN F

Aluminum, 2S-H18

FIGURE 26

1. 1 hour
2. 2 hours
3. 3 hours



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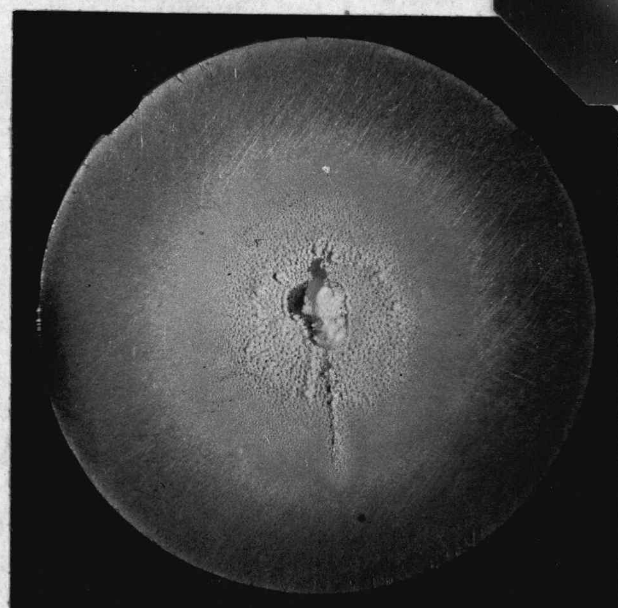


2

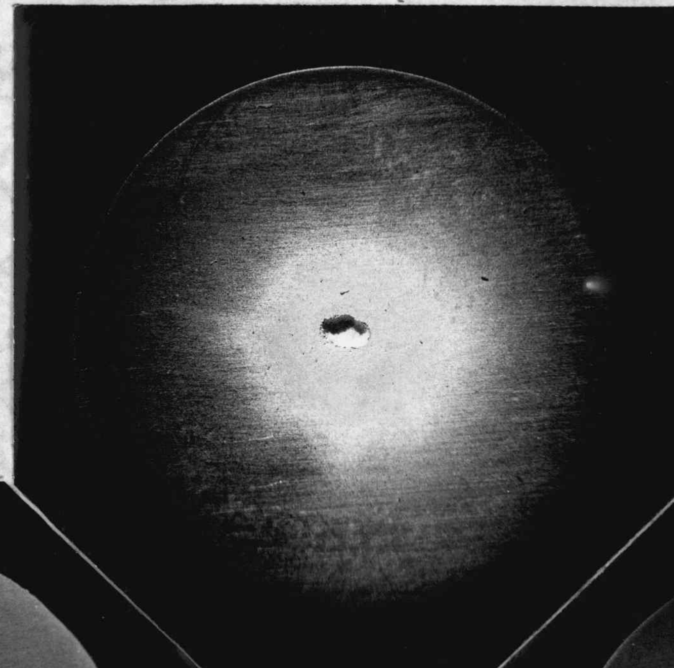
3

SPECIMEN G

Aluminum, 24S-T4

FIGURE 27

1. 1 hour
2. 2 hours
3. 3 hours



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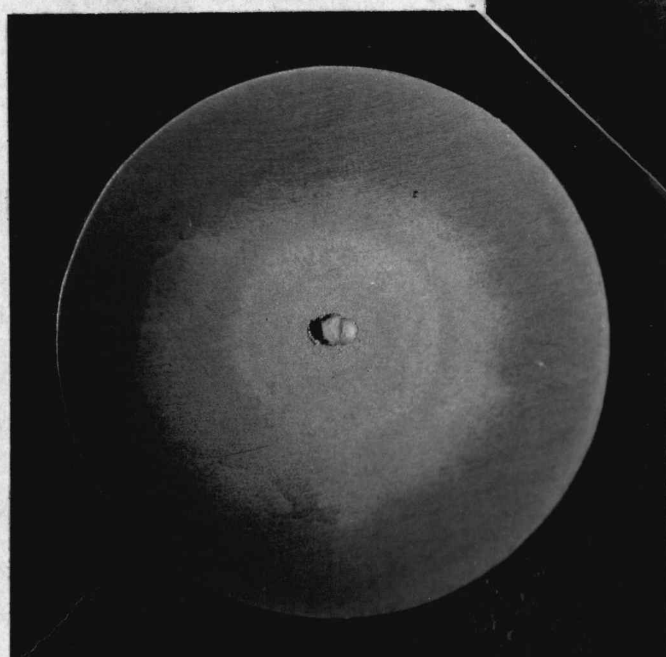

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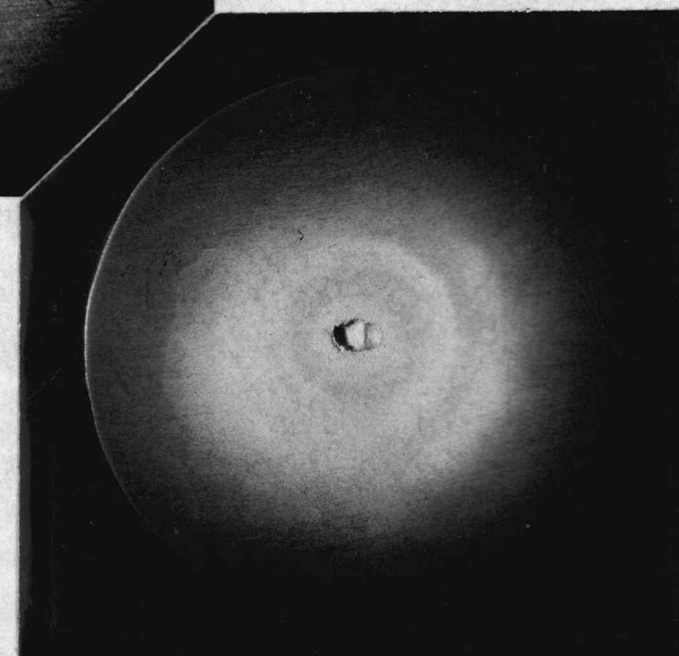


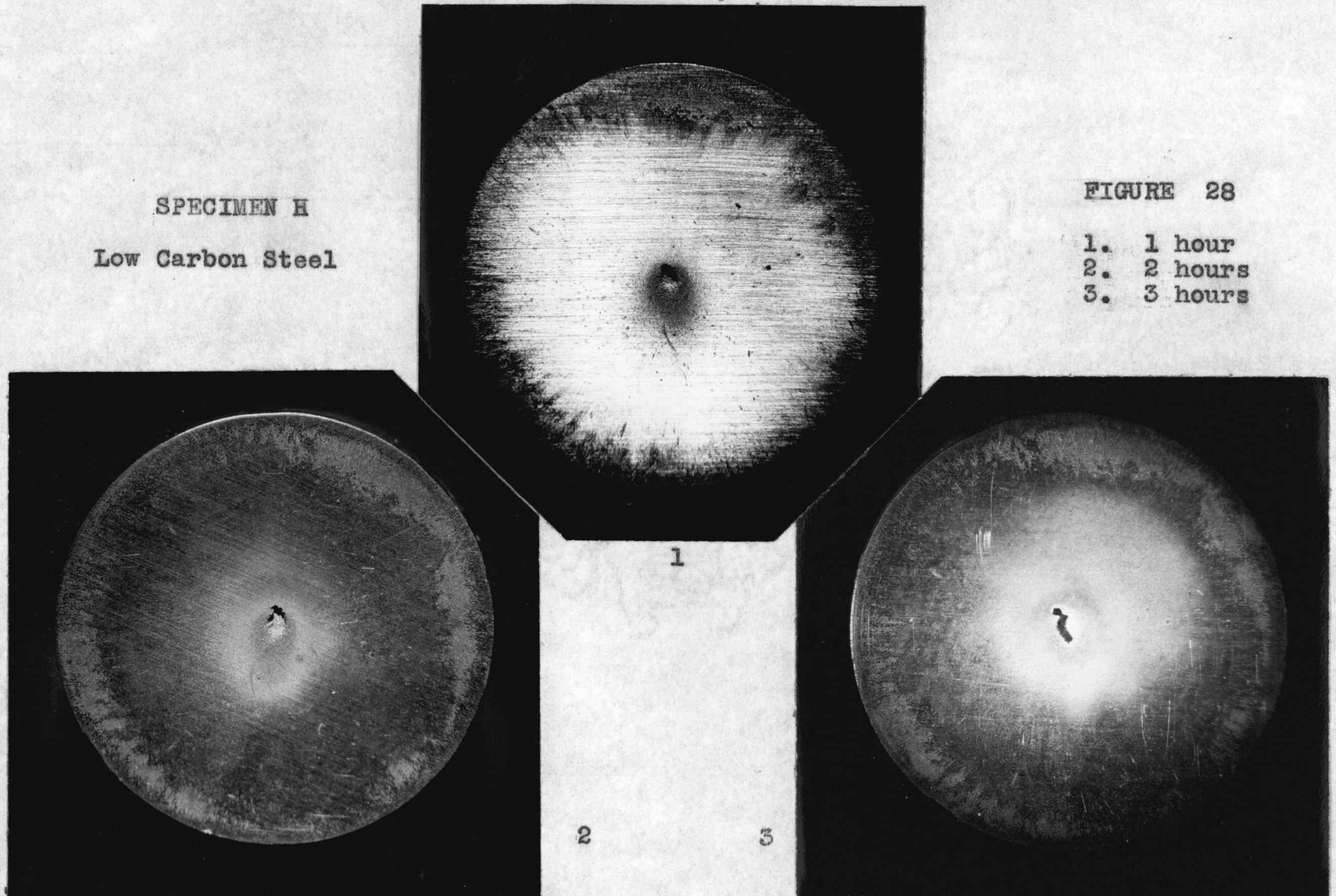
3

SPECIMEN H

Low Carbon Steel

FIGURE 28

1. 1 hour
2. 2 hours
3. 3 hours



1

2

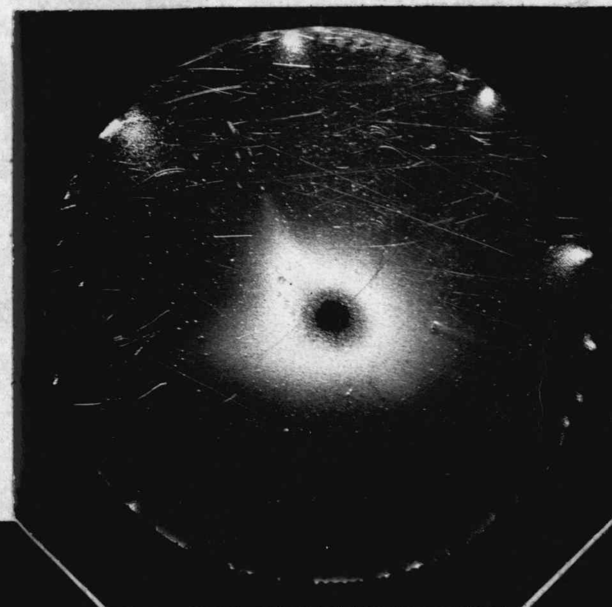
3

SPECIMEN I

Medium Carbon Steel

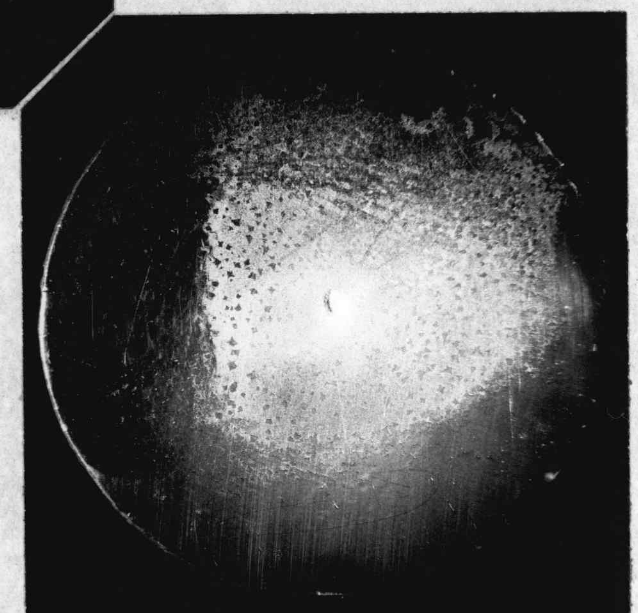
FIGURE 29

1. 1 hour
2. 2 hours
3. 3 hours



1

2



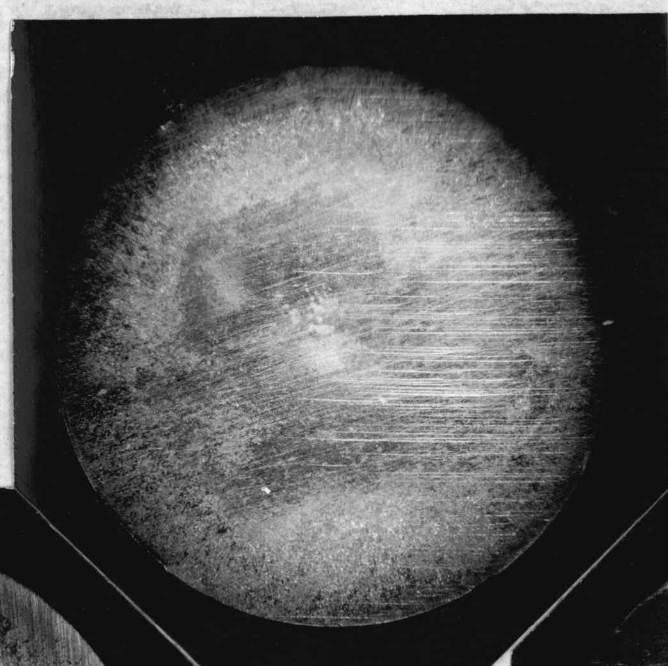
3

SPECIMEN J

High Carbon Steel

FIGURE 30

1. 1 hour
2. 2 hours
3. 3 hours



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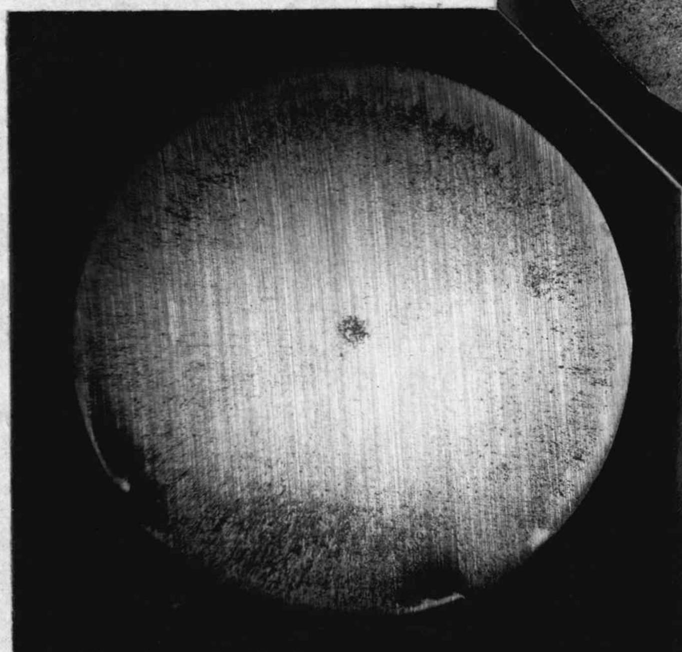

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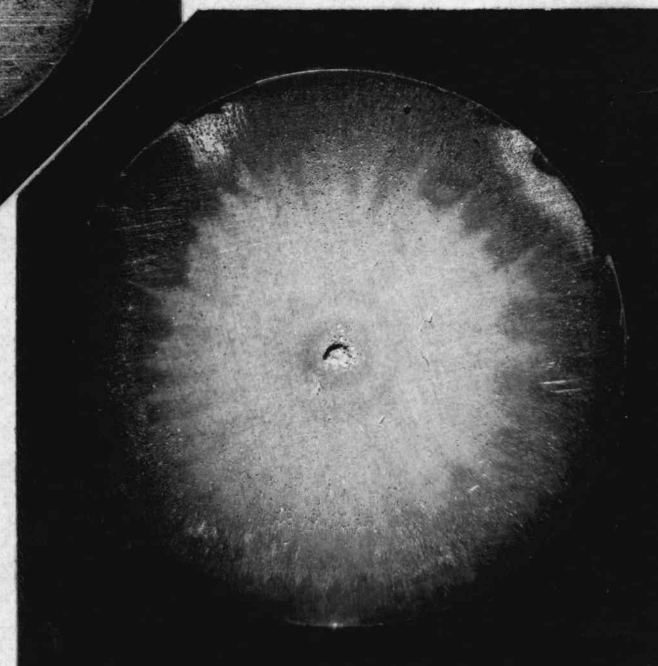
3



SPECIMEN K

Annealed 18-8
Stainless Steel

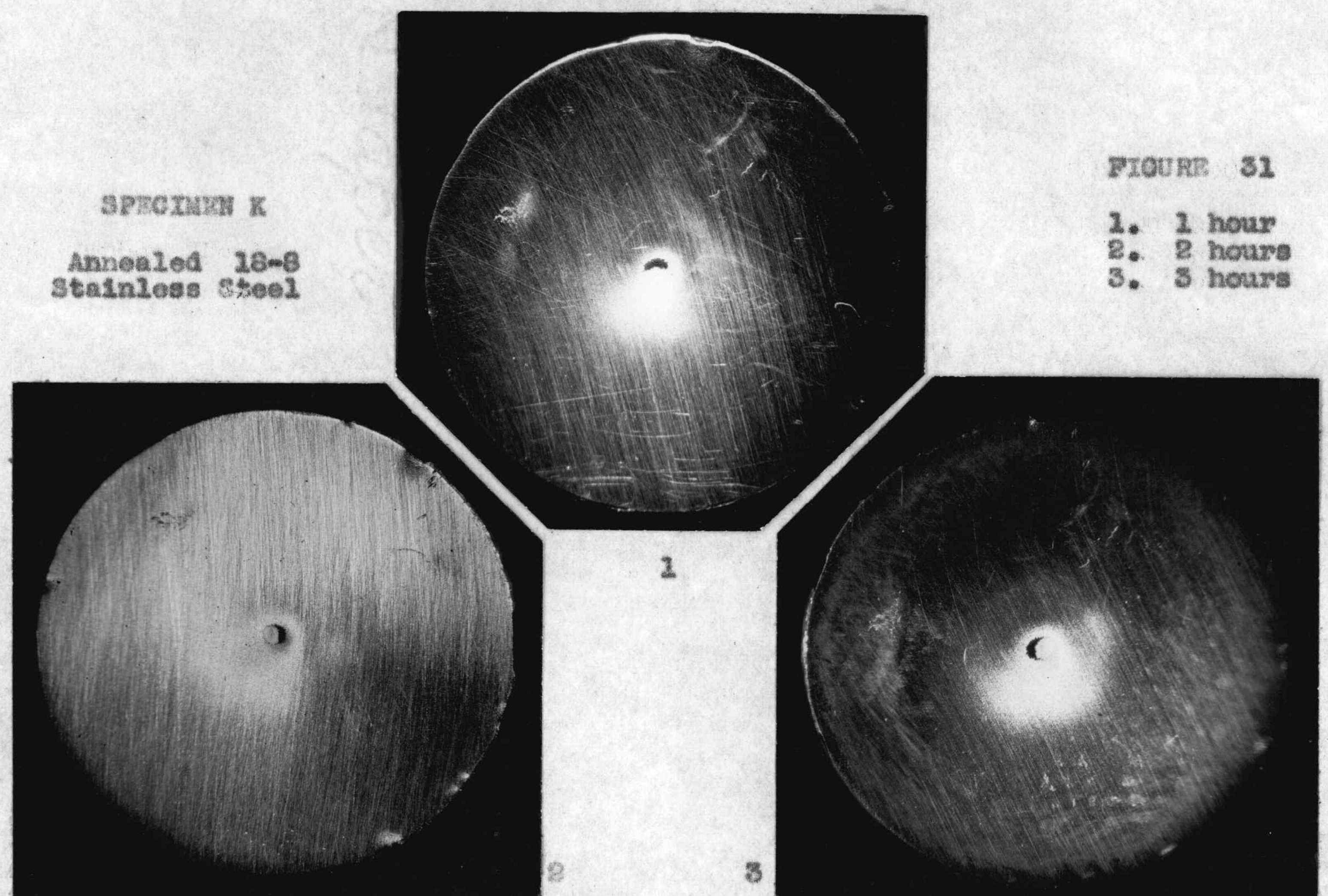



FIGURE 31

1. 1 hour
2. 2 hours
3. 3 hours