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A STUDY OF THE REACTION OF METALS AND WATER

Interim Report

By
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Azusa, California

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15 April 1955

A STUDY OF THE REACTION OF METAIS AND WATER

Contract AT(04-3)-44

Prepared by H. M. Higgins

Approved by C. A. Gongwer

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AEROJET-GENERAL CORPORATION

Azusa, California

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ABSTRACT

The molten metals zirconium, Zircaloy-2, uranium, uranium-molybdenum alloy, aluminum, aluminum-lithium alloy, and magnesium were introduced into water in order to determine whether or not violent reactions would result. As long as the molten metals remained as comparatively large globules, the reaction ceased after some surface scale formed. When a means of dispersing the molten metals in water was provided, all those tested except aluminum underwent a violent reaction (uranium and the alloy of uranium and molybdenum were not tested using the dispersal method). Pressure-time records and other data were obtained which indicate the degree of damage that might be expected from violent reactions of these metals and water.

Corrosion-rate tests were made on zirconium, uranium-molybdenum alloy, and stainless steel in water at atmospheric pressure. Corrosion-rate tests were made on zirconium and uranium in water vapor at 600 psi.

I. INTRODUCTION

A. OBJECTIVE

Most of the metals used in the construction of reactor cores would release considerable energy if they were reduced to their oxides. If these metals should react violently with the water or steam present (as in pressurized water reactors), extensive damage to the reactor could result. This study was undertaken in order to determine the effect of the sudden mixing with water of the molten metals zirconium, Zircaloy-2, Zircaloy-B, uranium, uranium-molybdenum, and other alloys designated by the Atomic Energy Commission. If violent reactions could be obtained, a second task would be to determine suitable means of inhibiting the reactions.

B. LITERATURE SURVEY

1. A search of the unclassified literature from 1936 to 1953 revealed little information on experimental research in which molten metals were brought into contact with water. The classified literature yielded somewhat more information. A thermodynamic study of the reaction of molten metals and steam and several investigations of the reactions of bulk metals with water vapor have been reported by Zapffe (Ref. 1). Fricke reports that the reactivity of iron with water varied with the method of preparation of the iron (Ref. 2). An X-ray examination showed that the active iron was characterized by smaller particle size and displacement of the atoms from the normal position in the lattice (Refs. 2 and 3). Guldner found that ductile zirconium reacted with H_2O vapor at 200-350°C, at rates comparable with those of oxidation by oxygen (Ref. 4). Hydrogen was released at elevated temperatures and ZrO_2 was formed. Russell reports that small quantities of beryllium added to magnesium-manganese alloys decreased the reactivity of the alloy in air (sparking) (Ref. 5). Shidlovskiy was able to induce explosions in slurries of aluminum powder and water, and in magnesium powder and water by providing confinement and using a sufficiently large initiating charge (Ref. 6). Work done at North American Aviation by Ruebsamen, Shon, and Chrisney showed that uranium, zirconium, aluminum, aluminum-lithium alloy and aluminum-uranium alloy can be caused to react explosively with water if sufficient energy is put into the metals to cause vaporization of the sample (Ref. 7). Kindsvater's experiments at Aerojet-General on the reaction of the light metals with water showed that a critical temperature ratio exists (temperature of molten metal, °K to melting point, °K) below which a slow reaction occurs and above which violent reaction takes place (Ref. 8). The results of these experiments are tabulated below.

Test Metal	Melting Temperature (T_m)	Critical Temperature (T_c)	T_c/T_m
Lithium	459 °K	473 °K	1.026
Sodium	370.5	383	1.034
Potassium	335	342	1.019
		Average	1.03

2. Other work at Aerojet-General, by Cox et al., showed that molten magnesium at 816°C reacted partially when sprayed into water and that molten aluminum under the same conditions did not react at all (Ref. 9). However, if small amounts of sodium or lithium were alloyed with magnesium or aluminum, explosive reactions resulted when the alloys were sprayed into water. Bostrom, of Westinghouse Atomic Products Division, reported that the reaction rate of Zircaloy-2 in water was rapid at temperatures near the melting point, but not explosive, even at temperatures greater than the melting point (Ref. 10).

3. In tests at Du Pont, crucibles containing molten metals were smashed under water (with considerable force and confinement). Under these conditions, pure molten aluminum (900°C) did not react but aluminum containing 1.0 to 7.4% of lithium reacted slightly to violently. Molten aluminum containing 5% uranium at 900°C reacted violently in 3 tests and slightly in 11 tests, out of a total of 20 tests. Higher temperatures did not increase the activity. At Argonne, West and Weills injected fine streams of molten aluminum at 1000°C into water (Ref. 12). No appreciable chemical reaction was observed.

4. Russell, of the Aluminum Company of America, reports that the pouring of molten aluminum into water has occasionally led to violent explosions (Ref. 13). This phenomenon was thoroughly investigated by Alcoa and the following facts, among others, were obtained:

a. Explosions could not be obtained in water depths of less than 1 in. or of more than 30 in.

b. Aluminum poured from a 1-in.-dia opening will not explode, under given conditions, whereas that poured through a 3-in.-dia opening will explode violently. A grid which breaks up the falling stream is effective in preventing explosions.

I Introduction (cont.)

C. SUMMARY

1. Molten-Metal Explosion Tests

a. In order to determine the reactivity of aluminum, nickel, zirconium, stainless steel, and aluminum-lithium alloy, these metals were poured, in a 1-in.-dia stream, into water. None reacted violently though a thin oxide coating was formed on the globules in each case.

b. In an attempt to obtain dispersion of the molten metal, the metal pouring setup was modified by the addition of a blasting cap beneath the surface of the water. A timing circuit was provided to fire the blasting cap at the instant the molten metal reached the desired position. With this setup, violent reactions were obtained with zirconium, Zircaloy-2, aluminum-lithium alloy, and magnesium. However, when aluminum and nickel were tested, no violent chemical reaction resulted; only the formation of a film of oxide occurred. Time did not permit the testing of uranium or uranium-containing alloys in this setup.

2. Metal-Water Slurry Tests

a. Detonation tests were performed on metal powders which had been moistened with water and with alcohol. Initiation was accomplished by a blasting cap and a tetryl booster charge.

b. Those mixtures which reacted violently were Mg-H_2O and Mg-CH_3OH. Those which did not react were Al-H_2O, Al-CH_3OH, Zr-H_2O, and Al-Mg-CH_3OH.

3. Low-Pressure Corrosion-Rate Tests

a. Small metal samples were heated by induction while immersed in water.

b. Corrosion tests of Zr, U-Mo, and stainless steel at temperatures near the melting point showed that the rate of reaction (corrosion) is comparatively slow and uniform. Even when the temperature of one U-Mo sample was raised above the melting point, the reaction though vigorous was not explosive.

4. High-Pressure Corrosion-Rate Tests

a. Metal wires were heated by resistance inside a vessel containing high-pressure, high-temperature water vapor.

b. Zirconium and uranium were tested, and from the small number of tests completed, it appears that the corrosion rates at high pressure are similar to the rates at lower pressures.

II. MOLTEN-METAL REACTION TESTS

A. EXPERIMENTAL EQUIPMENT AND PROCEDURE

1. Equipment

a. The test apparatus was installed in a standard, reinforced-concrete test bay, with one side open. The furnace support structure was mounted on the ceiling, thus permitting ready access to and complete freedom of movement of the water tank below. The water tank was placed on the floor (and later on a pedestal to reduce the height of drop). It was thought that, by keeping the supports for the furnace and the water container separate, maximum protection would be afforded to the furnace assembly. A photograph of the complete test apparatus is shown in Figure 1.

b. In early tests, the height of drop (distance from the bottom of the crucible to the water level) was 44.5 in. This distance was varied to as little as 11 in., but 20 in. was soon adopted as standard.

c. The water container used in most of the tests was constructed from a 10-in. length of 12-in. standard pipe (12.00-in. x 0.375-in. wall, with a rated burst pressure of 2941 psi). A 3/8-in.-thick plate was welded in place to form the bottom. The depth of the water was approximately 9 in., making the volume of water 1020 cu in., or 16.53 liters. Tap water was used in all tests.

d. An Ajax Type P5 induction furnace was bolted to the 1-in.-thick bottom plate of the furnace support structure. A through hole was provided in the furnace and in the 1-in. plate to permit the use of a bottom-tapped crucible. After considerable investigation, graphite was chosen as the most suitable crucible material for zirconium. Carbon black was used for insulation. A graphite valve head and rod assembly projected out through the crucible lid and was attached to an air cylinder to permit remote operation. A sight tube with a Vycor window (heat-resistant glass), combined with a system of mirrors, made it possible to view the molten metal from a safe location. A sleeve (steel, and later aluminum foil) was installed between the furnace and the water line in order to contain the inert atmosphere. An argon atmosphere, purified by passing it through beds of desiccant and lithium wire (heated to 250°F) was maintained in all spaces. Figure 2 is a closeup view of the furnace assembly, showing the valve rod, the air cylinder, an argon-flow-indicator bottle, and the supporting structure.

e. An Ajax-Northrup 20-kw high-frequency converter, located in the control room, supplied power to the furnace coil.

f. In some tests a blasting cap was used to disperse the molten metal in the water. When this system was used, the No. 6 blasting cap was mounted 5 in. below the surface of the water and aligned directly beneath the outlet of the crucible. In order to energize the 1.5-v blasting-cap circuit at precisely the right moment, an auxiliary 24-v circuit was

installed which operated a relay switch which, in turn, fired the blasting cap. This relay switch was closed upon the breaking of a lead wire (1/4-amp fuse wire) which was stretched across the path of the molten blob and approximately 1 in. above the blasting cap. A circuit diagram for this system is shown as Figure 3. Two automatically operating safety features were incorporated into the circuit design. One was a relay switch which short-circuits the blasting cap until just prior to firing time, and the other, a delayed-operating relay switch which de-energized the blasting-cap circuit 1 sec after the firing.

g. The information obtained consisted of measurements of the molten-metal temperature, measurements of the pressure produced by the reaction, visual observation, and photographic recording of the damage. For the metals with low melting points (Al, Al-Li, Mg), the temperature was taken by means of an iron-constantan thermocouple and recorded on a Brown Electronik strip-chart recorder. When high-melting-point alloys were tested, temperature measurements were made at regular intervals, using a Leeds and Northrup No. 8622 optical pyrometer. Calibrations were made in order that an allowance could be made for intensity losses in the two mirrors and the Vycor window.

h. The pressure pickup was mounted in the water container approximately 6 in. to one side of the blasting cap. A barium titanate crystal pickup (Atlantic Research Corporation No. BC-30) was used because of its high pressure range and fast response. The signal from the pickup was fed into a cathode-ray oscilloscope. The circuit was set up so that the input signal would trigger the sweep. The pressure-time trace was photographed, using a Dumont Polaroid-Land camera mounted opposite the face of the cathode-ray tube. Several records were made of the pressure-time trace produced by the No. 6 blasting cap alone in order to obtain a standard for comparison.

i. The noise (or lack of it) produced by the reaction of the metal with the water was also important for comparisons. Visual observation of the damage done to the test setup, supported by photographs, is considered to be good evidence for comparisons.

2. Procedure

a. The test sample (consisting of small pieces) was pickled to remove surface impurities, dried, and loaded into the crucible. Purified argon then was used to purge all cavities for approximately 20 min.

b. The furnace power was turned on and held at a level of 10 kw for 10 min, or until the temperature reached 1500°F. Then the power was raised to 20 kw for rapid heating and melting. The zirconium was dropped as soon as possible after the melting temperature had been reached in order to minimize the carbon pickup.

c. Information recorded on the data sheet included the analysis of the sample, weight, temperature when dropped, height of drop, size of orifice, weight of metal recovered, water temperature before and after the drop, and the quantity of water before and after the drop.

B. RESULTS

1. Testing of Aluminum-Lithium Alloy

a. The addition of a small percentage of lithium to aluminum is known to result in an alloy that reacts vigorously with water (Ref. 9, 11). It was therefore decided to test an alloy of 95% Al and 5% Li first in order to establish the validity of the test. Nine runs were made using this alloy with a drop height of 11 in. and a water depth of 9 1/2 in. Some popping was heard and some smoke and flame were seen during each test. Examination of the products indicated that from 10 to 50% of the alloy had reacted, but the reaction was not self-sustaining or violent.

b. In order to test the effect of dispersion on the reactivity of this alloy, a blasting cap was added to the drop-test apparatus (as described in paragraph II,A,1,f). Four tests were made and violent, nearly complete reactions resulted in each case. In one test, damage to equipment was extensive, as shown in Figure 4. A close examination of the residue indicated the presence of only fine granules of aluminum oxide and a flocculent white precipitate, lithium hydroxide. Assuming a complete chemical reaction to have occurred, it was computed that 150 grams of this alloy liberated 212 liters of hydrogen gas at (STP) and produced 557 kilocalories of heat.

c. The results of these tests are presented in Table I.

2. Testing of Pure Nickel

a. The validity of this test setup was ascertained further by testing nickel, a metal known to be passive. Three tests were made not using a blasting cap. A large steam cavity was formed as the metal entered the water and a distinct thump was heard. The test material was collected from the water container and weighed. It was determined that less than 1% of the nickel had reacted. The collected material is shown in Figure 5. The molten metal apparently breaks into smaller blobs upon striking the water.

b. Three tests were made on nickel, using the blasting cap for dispersion. The metal was broken up into much finer particles and the extent of oxidation was much greater, approximating 15% in one test. The residue from one such test is shown in Figure 6. No blast was heard, however.

c. The results of the tests on nickel are also presented in Table I.

3. Testing of Pure Zirconium

a. Two tests were made on Grade 1 zirconium without the blasting cap. The weight of the sample charge for each test was 454 grams. A black, glass-like layer of oxide film 0.005 in. thick was formed on the metal. Calculations based on this film thickness and on average droplet size show that approximately 16% of the zirconium was oxidized before the metal chilled sufficiently to become passive. The reaction was not violent. Some water was ejected from the container by the steam and hydrogen bubbles. A photograph of the zirconium metal after one of these tests is shown as Figure 7.

b. Three tests were made with zirconium, using a No. 6 blasting cap. All or nearly all of the metal reacted in each case. Loud blasts accompanied by smoke and flame resulted. The blasts in the first two tests were not as loud or damaging as in the most damaging test with the Al-Li alloy. However, in the third test with zirconium, the reaction was violent, with sparks thrown 50 ft. Figure 8 shows the apparatus after the test. It is seen that the water container remained in place on the pedestal because it was bolted down with four 3/4-in. bolts. However, the bottom of the container (3/8-in.-thick, flat steel plate) was blown completely loose, severing the continuous weld (see Figure 9), and both this bottom and the pedestal top (1/2-in.-thick, flat steel plate) were dished approximately 2 in., as shown in Figure 10. The cylindrical section of the water container had yielded on one side. Stress calculations indicated that a pressure of at least 2200 psi would be necessary to produce the effects noted. A pressure-time record was obtained on this run, though the pickup was damaged beyond repair by the ensuing events. The rate of pressure increase was so rapid that the trace was invisible for part of its travel. It appears from the record that the peak pressure was approximately 280 psi, but since the full scale deflection was set at 300 psi and the stress calculations indicate a much higher value, it must be concluded that the pressure peak was not recorded. A replot of the pressure-time record is presented as Figure 11. Also shown is the pressure-time trace for the explosion of a No. 6 blasting cap. Figure 12 shows the furnace assembly and the damage caused by the pressure applied through the 4-in.-dia hole in the furnace mounting plate. Figure 13 shows the residue (mostly ZrO_2) from one of these tests. Some of the larger pieces shown were removed from the crucible. Assuming 100% reaction, the 454 grams of zirconium produced 235 liters of hydrogen and released 214 kilocalories of heat.

c. The results of these tests of zirconium are shown in Table I.

4. Testing of Zircaloy-2

a. Two tests were made using Zircaloy-2 (1.5% Sn, 0.1% Fe, 0.1% Cr, 0.05% Ni, 98.25% Zr). A blasting cap was used in each test. The weight of the test samples was 227 grams, one-half the weight of those used in the tests on pure zirconium. This reduction was effected in order

to minimize damage to the equipment. In the first test, faulty valve operation permitted the metal to drop as a series of small globules. Therefore, only a small portion of the metal was actually dispersed by the blasting cap. The blast which resulted was sharp but did no damage. In the second test, however, the resulting blast was sharp and loud. Inspection of the test bay revealed that the furnace support stand was blown away from its mounting in the ceiling and was lying upside down on the floor. The furnace assembly was damaged beyond repair. Figure 14 shows the support stand and furnace coil. The water container, which had been fitted with a 1/2-in.-thick bottom after Run No. 44, was undamaged except for a slight bow in the bottom. No metallic residue was found, and it was assumed that the reaction was complete.

b. The results of these tests of Zircaloy-2 are also presented in Table I.

5. Testing of Aluminum

a. Two tests were made with 150-gram samples of molten aluminum (99.0% min. Al, with Si and Fe as impurities) without blasting caps. The primary purpose of these tests was to obtain high-speed motion pictures of the metal blob falling into the water. A glass-sided water tank was used. The motion pictures showed that the main blob of aluminum was approximately 1 in. in diameter and 3 in. long, comprising 65 to 70% of the total sample. The rest of the metal, in smaller blobs, followed close behind. A steam cavity was seen to form around the sample as it entered the water, collapsing as the steam and metal chilled as it fell toward the bottom of the tank. Figure 15 shows the residue.

b. One test was made with a blasting cap, using the glass-sided tank and high-speed photography. The film records showed that approximately 85% of the sample was in the water when the blasting cap was energized. The residue from a run similar to this is shown in Figure 16. Little or no reaction occurred.

c. Six other tests were made on aluminum using the regular setup with a blasting cap. Fine metallic granules were formed but no violent reactions occurred.

d. The results of the tests of aluminum are also presented in Table I.

6. Testing of Pure Magnesium

a. Two tests were made with commercially pure magnesium (99.7% min. Mg, 0.1% Cu, 0.2% Al+Cu+Si+Ni) using a blasting cap for dispersion. A sharp blast and a shower of white sparks resulted in both tests. No damage was done, but the flocculent white precipitate, magnesium hydroxide, was

evident. Some of the magnesium burned (in air) on the floor of the test bay and around the crucible lid. Some metallic residue was found. It was difficult to estimate the quantity of magnesium which actually reacted with the water in the container.

b. The results of these tests of magnesium are shown in Table I.

7. Testing of Stainless Steel

a. Two tests were made with Type 321 stainless steel (18.0% Cr, 9.5% Ni, 0.4% Ti, 0.08% C, 2.0% Mn, 1.0% Si, remainder Fe). The blasting cap failed to detonate on both of these tests due to faulty circuitry. Some oxidation took place but the reaction was not vigorous.

b. These results are also presented in Table I.

C. DISCUSSION AND CONCLUSIONS

1. The destructive power of reacting systems is often estimated by comparing their "characteristic product." This is obtained by multiplying the volume of the products of the explosion (at STP) by the heat of the explosion. Berthelot considered this to be a measure of the mechanical work performed by the explosion. The gas volume, the heat of reaction, and the product of these values for several reacting systems are listed in Table II for comparison. The conclusion that can be drawn from the tabulated values is that the metal-water reactions are potentially powerful and could cause severe damage if the reaction time is short. The reaction time depends on the reactivity of the metal and on the dispersion or droplet size.

2. Particle-size analyses have been performed on the residue from two tests, one using aluminum and the other using nickel. In both tests the blasting cap functioned properly, but little or no reaction of the metal occurred. The results of the sieve analyses are listed below.

Mesh Size	Nickel % Through	Aluminum % Through
- 4	86.7	81.0
- 10	46.4	63.5
- 16	30.6	47.5
- 100	0.65	4.8
- 200	0.26	1.7
- 325	0.15	0.62
Recovery	99.4	99.5

From these values and from the photographs of residue included in this report, it can be concluded that the average particle size produced by the action of the blasting cap is not small for metal powders, and a number of processes can be visualized which would produce particles fine enough to cause self-sustaining reactions.

3. In the Alcoa tests on molten aluminum (see "Introduction," paragraph I,B,4), dispersion sufficient to cause self-sustaining violent reactions probably was produced as follows:

a. The large molten blob fell through the water and came to rest on the bottom of the tank, trapping some water between the blob and the tank.

b. The entrapped water was flashed into steam by the molten metal. The steam, being restrained by the inertia of the blob, was superheated and expanded further.

c. The blob finally gave way under the pressure of the steam pocket and was broken into small particles thus exposing fresh, unprotected metallic surfaces to the steam. These clean, oxide-free surfaces were readily attacked by the steam, generating heat and liberating hydrogen.

d. If the exposed surface was great, sufficient heat and gas would be generated to further break up the metal, exposing new surfaces. This then would be a self-sustaining reaction.

The conditions which must be met in order to produce this sequence of events are: (1) the molten blob must be large enough to trap a pocket of water and afford some confinement, and (2), the molten metal must reach the bottom with a sufficient reserve of heat to generate a quantity of steam and still remain in the molten state.

4. According to the pressure-time trace in Figure 11, the reaction time for zirconium was approximately 1 milliseconds, and the expansion of the steam and hydrogen gas to atmospheric pressure took 4 milliseconds. Observation of the damage done to the water container indicates that the mechanism of the reaction of metals with water is a low-order detonation.

5. If a metal oxide film is impervious and firmly attached to the metal, as is the case with aluminum oxide, then corrosion or reaction ceases or is greatly retarded as soon as the oxide film forms. It appears that this may be true for molten metals as well as for solid metals, judging from the passivity of pure molten aluminum in the tests made in this study. Because beryllium also exhibits a protective, tenacious oxide film, it has been suggested that zirconium and uranium alloys containing small percentages of beryllium be tested in the hope that their reactivity would be lessened. Time did not permit these alloys to be made and tested.

D. RECOMMENDATIONS

1. It is recommended that the drop-test work be continued. Alloys on hand which should be tested, both with and without the blasting cap for dispersion, are Zircaloy-B, uranium-molybdenum, uranium, and uranium-zirconium-niobium.

2. Any other alloys which are of special interest to the Commission should also be tested as described above. This work should include the testing of alloys containing small quantities of beryllium.

3. It is recommended that the instrumentation system for measuring explosion pressure vs time be refined to the point where reliable records are obtained in each test. Calibration should be made with a known weight of standard explosive (TNT).

4. It is recommended that attempts be made to correlate, using both analytical means and laboratory tests, the passivity of certain metals with their physical properties. Much of this work would be centered around the study of the protective value of the oxide film.

5. It is recommended that the degree of dispersion of each of the molten metals be varied through a wide range. By correlating the extent of reaction in each case with the approximate particle size, it may be possible to obtain a fairly reliable estimate of the minimum particle size necessary in order that self-sustaining reactions will occur.

6. It is recommended that new methods of testing the reactivity of molten metals be devised which will be economical to perform. Such a setup could be used to augment the work done on the drop tests. An attempt would be made to correlate the results of the different tests.

III. METAL-WATER SLURRY REACTION TESTS

A. EXPERIMENTAL EQUIPMENT AND PROCEDURE

1. Equipment

a. The gap-test apparatus, which has been used extensively at Aerojet to measure the sensitivity of propellants and explosives to shock, was used to test the explosibility of metal-water slurries. In the gap test, as originally proposed by the Explosives Research and Development Establishment, Essex, England, the explosive force from a standard booster charge was attenuated by penetrating through a stack of paper cards before acting on the test sample. The thickness of the stack of cards, called the "gap" required to prevent initiation of explosion in 50% of the tests, was adopted as the sensitivity measurement. A 1/16-in.-thick target plate suspended above the sample was used to determine whether an explosion occurred.

b. The gap test, as finally adopted at Aerojet, employed the apparatus shown in Figure 17, which comprises the following parts: A sample cup (18) fabricated from a 3-in. length of 1-in. standard steel pipe sealed by a disc (20) of 0.002-in. brass shim stock, soft-soldered across one end; a stack of cellulose acetate discs (12) 1-9/16 in. in diameter, and 0.01-in. thick, which make up the "gap" (these were not used in the slurry tests); a 50-g tetryl booster charge (24), compressed to a cylinder 1.5 in. in diameter and having a minimum density of 1.56 g/cc (U.S. Army Ordnance Dept. Piece Mk. 82-3-591C, or equivalent); one No. 6 electrical blasting cap (26); a 4 x 4 x 3/8 in. cold-rolled steel blast plate (16); a cap holder fabricated from wood (10), 1.56 in. in diameter, 1.0 in. thick, with a 9/32-in. hole drilled longitudinally through the center; and an assembly of cardboard tubes (6, 8, 14, and 22) mounted on a steel pedestal (2 and 4) for the purpose of holding the components in a vertical line.

c. In order to reduce the noise produced in these tests, they were performed with the gap-test assembly contained in a muffle. The complete installation in the test bay is shown in Figure 18.

2. Procedure

a. The test slurries were prepared by weighing the ingredients and mixing them in a small beaker. The slurry was then poured into the cup and the components were assembled as shown in Figure 17. The gap-test assembly was then placed on the muffle platform, the muffle hood was lowered into place, and the blasting cap was fired. The apparatus was then opened, and inspection of the blast plate indicated whether or not the materials under investigation had reacted violently.

b. In Figure 19 the damage done to the blast plate when a high explosive detonates is shown, compared with the absence of damage when little or no reaction occurs. It can be seen that this is strictly a "go" or "no go" type of test when testing high explosives. When less brisant materials are tested, their relative powers can be gaged by the extent of deformation of the blast plate.

c. A calibration test was made using a mixture of dry aluminum and potassium perchlorate powders. This mixture was chosen because it is somewhat similar to the slurries being investigated and because it is known to be explosive.

d. When an explosion did result in a slurry test, an attempt was made to compare its power (taking into account the noise, the effect on the blast plate, and the total weight of reactants) with that obtained in the calibration shot.

B. RESULTS

1. Calibration Shot

a. Twenty-one grams of dry pyrotechnic powder, as described above, was used. Inspection of the blast plate revealed that a depression 1 in. in diameter and 1/8 in. deep had resulted from the explosion. The plate (3/8 x 4 x 4 in.) was bowed approximately 1/2 in. corner to corner.

b. The results of this test and of other slurry tests are presented in Table III.

2. Tests of Magnesium Slurries

a. The magnesium used in all tests was Baker & Adamson Reagent Grade powder.

b. Five tests were made using a 50-50 slurry of magnesium and distilled water. Only one explosion was obtained and this did not involve all the sample. The explosion, however, appeared to be approximately twice as powerful as the calibration shot (see data in Table III).

c. One test was made with a 40-60 mixture, and an explosion resulted. Again only a partial reaction was obtained; however the explosion was the most powerful obtained from any mixture tested, being about four times as powerful as the calibration shot.

d. One test was made with a 35-65 mixture of magnesium and water. A partial reaction resulted.

e. One test was made with a mixture of 60% magnesium and 40% methanol. The explosion which resulted was approximately three times as powerful as the calibration test.

3. Tests of Aluminum Slurries

a. The aluminum used in all tests was Alcoa No. 606 flake pyrotechnic powder.

b. Three tests were made on 50-50 mixtures of aluminum and distilled water. No explosion resulted and little or no evidence of reaction could be found.

c. Two tests were made using 50-50 mixtures of aluminum and methanol. No explosion was indicated (see Table III).

d. One test was made using a mixture of 25% Al, 25% Mg, and 50% methanol. No explosion resulted.

4. Tests of Zirconium Slurries

a. The zirconium metal used in these tests was Grade "EE" powder, manufactured by the Zirconium Metals Corporation of America.

b. Two tests were made using a 50-50 mixture of zirconium powder and water, no explosion resulted (see Table III).

C. DISCUSSION AND CONCLUSIONS

1. This series of metal-water slurry tests was undertaken in order to expand upon the work done by Shidlovskiy (Ref. 6). The intention was to test the reaction characteristics of water slurries of zirconium, Zircaloy-B, U-Mo, and Zr-Si. The three alloys could not be obtained as powders, however.

2. Shidlovskiy showed that mixtures of aluminum and water, magnesium and water, and magnesium and methanol (and other hydrocarbons) were capable of explosive decomposition. The Al-H_2O could not be initiated in the test setup, and it is assumed that the initial impulse was not sufficiently strong. It can be theorized that, given a strong initial impulse, both Al-H_2O and Zr-H_2O would react explosively.

3. According to Shidlovskiy, the basic conditions which guarantee a reliable initiation of an explosion are:

a. The use of large charges (50-100 grams) of the mixtures being tested. (From 20 to 42 grams were used in the Aerojet tests.)

b. The use of a powerful initial impulse, i.e., 8-12 grams of tetryl. (50 grams were used.)

c. The presence of a strong outer shell surrounding the charge, such as a 3-in. OD x 1.5-in.-ID lead beaker. (Standard 1-in. pipe was used.)

Apparently the much larger booster charge used was not sufficient to offset the smaller sample size and the lesser degree of confinement.

4. The tests show that a greater initiating impulse is required to cause water slurries of zirconium and aluminum to react explosively than is required to explode magnesium-water slurries. It is thought that the gap-test, with suitable modifications, could be utilized to classify various metal-water slurries according to their relative sensitivity. The gap test would be an economical way to study the value of various alloying ingredients as explosion inhibitors.

D. RECOMMENDATIONS

1. It is recommended that the gap test be modified to the extent that explosive reactions may be obtained with metal-water slurries whose specific products (see Table II) are greater than approximately 50,000.

2. It is recommended that the alloy-water slurries of interest be tested to determine the minimum initiating impulse of each by varying the gap.

3. It is recommended that the explosion-inhibiting effect of various alloying agents be tested by obtaining relative values of minimum initiating impulse, as described above.

4. It is recommended that the inhibiting effect of small quantities of oil or other substances be determined in the metal-water slurries.

IV. LOW-PRESSURE CORROSION-RATE TESTS

A. EXPERIMENTAL EQUIPMENT AND PROCEDURE

1. Equipment

a. The test apparatus used for the corrosion-rate tests (see Figure 20) was patterned after the setup used by Bostrom (Ref. 10). The corrosion sample, mounted within a heat-resistant, glass (Vycor) tube, was heated by induction. A 4000-ml graduated burette was connected above the sample section. Below, a Pyrex tube was extended to a reservoir of water. The entire system was filled with water.

b. The high-frequency power for heating the sample was supplied by the Ajax equipment described in Part I. The induction coil, constructed from 1/8-in.-dia copper tubing, was wound directly on the Vycor tube and was water-cooled.

c. The samples were ring-shaped, 11/16 to 3/4 in. OD, 5/16 in. ID, and 1/2 in. high. They were held in place in the induction field by means of the carbon holder shown in Figure 21. The large end was a snug fit in the Vycor tube and contained three longitudinal slots to permit free circulation of the water. The samples were threaded on the 1/4-in.-dia carbon rod.

d. Temperature measurements were made with an optical pyrometer, sighted on the side of the sample through the induction coil. These measurements were corrected by calibration with a standard bulb to allow for intensity losses in the Vycor tube, in the 2-1/8-in.-thick safety-glass shield, and in the reflecting mirror. By repeated observations over the range from 1800°F to 3200°F, it was determined that temperature measurements were accurate to within ± 60°F.

e. The burette was calibrated in increments of 100 ml. Additional markers were placed at the 250-ml increment positions. Oscillation of the water surface due to the hydrogen bubbles may have caused readings of gas volume to be in error by as much as ±10 ml.

f. The primary measure of corrosion rate was the amount of hydrogen which was liberated in the metal-water reaction. The gas, liberated at the sample, collects in the graduated burette. The corrosion rate (referred to the original surface area of the sample) is determined from measurements of the time required to collect successive 250-ml quantities of hydrogen. The observed volume is corrected to standard temperature and pressure. The time was measured by means of a 10-sec-sweep stop watch. The calculations assume that the metal goes to the specified oxide and that no hydrogen is absorbed by the water or the sample.

g. A measure of total corrosion was obtained by examination of the thickness of the oxide layer formed on the sample. Whenever possible, measurements of scale thickness were made using a microscope and/or a micrometer. The equivalent metal thickness was calculated, assuming that the oxide was of the theoretical density. This method gave a close approximation only when the oxide scale adhered to the sample or when it did not flake off until the end of the test.

h. The gain in weight of the sample was also used as an indication of total corrosion. The samples (and the pieces of oxide which flaked off in some tests) were weighed to the nearest tenth of a milligram, using an analytical balance. The equivalent metal thickness was calculated on the assumption that the specified oxide had formed.

i. Corrosion measurements based on hydrogen evolution are believed to give the most accurate data in this test.

2. Procedure

a. The corrosion sample was installed and the glassware was assembled. The reservoir was filled with distilled water. The vacuum pump was operated, drawing water up until the system was completely flooded. The stopcock at the top of the burette was closed to hold the water, and the vacuum pump was removed.

b. The power was turned on at the maximum setting to promote rapid heating of the sample. When the desired operating temperature was reached, the power was reduced to hold conditions steady. In most tests the sample temperature remained constant without further adjustments of power. Figure 22 shows the test section in operation. The U-Mo sample is at 1190°C.

c. As the successive 250-ml volumes of hydrogen were accumulated, the times and sample temperatures were also recorded.

d. After the test the sample was removed and the pieces of oxide scale which had cracked off during the test (if any) were recovered from the reservoir. The measurements described earlier were made.

B. RESULTS

1. Corrosion of Zirconium

a. Two tests were made on Grade 1 zirconium at temperatures of 1470 and 1500°C. The corrosion rate, as calculated from the hydrogen liberated, is shown in Figure 23. Because temperature measurements are accurate only to ±30°C, no significance should be attached to the fact that the corrosion rate is greater for the lower-temperature run. Also shown for comparison is a curve for Zircaloy-2.

b. The results of all the low-pressure corrosion-rate tests are presented in Table IV. The average corrosion rate (the total thickness of metal consumed divided by the duration of the test) is tabulated. This is an approximate value which is intended primarily for comparison. The numbers can be applied as a rough approximation but should not be extrapolated too far because of the non-linearity of the relationship.

c. Figure 24 shows a zirconium sample after 933 sec at 1470°C. A piece of the oxide scale was removed to show the formation.

2. Corrosion of Uranium-Molybdenum Alloy

a. Five tests were made on an alloy of 88% uranium and 12% molybdenum. The data from four of these tests are plotted in Figure 25. The average corrosion rates are given in Table IV.

b. Some pitting of the samples occurred in each test of the U-Mo alloy. After Test No. 2, at 1190°C, one large pit was observed which was estimated to have increased the surface area of the sample by 15% (see Figure 26). After Test No. 8, at 1250-1270°C, a smaller pit and a shallow groove were observed (see Figure 27). After Test No. 7, at 1260°C, a multitude of small pits was seen (see Figure 28). At the end of Test No. 6 (1050°C), the sample was purposely melted in order to obtain a rough measure of the reaction rate of the molten metal with water. Although the reaction was vigorous, no unusual violence was observed. The residue from this test is shown in Figure 29. During Test No. 3 (1100°C), which is not plotted in Figure 25, the sample was cracked completely through. This failure may have occurred because the sample was heated, cooled, then reheated rapidly in the course of the test.

3. Corrosion of Stainless Steel

a. Two tests were made on Type 321 stainless steel. Corrosion data, based on hydrogen evolution, are presented in Figure 30. Here again, excessive pitting with the resultant increase in surface area exaggerates the reported rate of corrosion. This is particularly true for Test No. 4 (1200°C), in which two fissures developed in the sample and severed the ring. This sample is shown in Figure 31.

b. No valid data could be derived from scale thickness, weight change, or dimension change because of the spotty, apparently selective nature of the corrosion.

4. Miscellaneous Tests

Attempts were made to test the corrosion rate of Zircaloy-B (sheet), uranium (flat bar), and Zircaloy-clad U-Mo rods. The design of the induction coil was found to be unsuited to heating these odd, small shapes, and because time did not permit the construction of a suitable coil, work on these alloys was discontinued.

C. DISCUSSION AND CONCLUSIONS

1. Zirconium

a. The corrosion rate of zirconium at 1500°C in water appears to be nearly twice as great as that of Zircaloy-2.

b. The corrosion rate of zirconium at 1500°C in water is rapid but not excessively violent or explosive.

c. The corrosion of zirconium at 1500°C in water is great in the early stages but gradually decreases as the oxide film thickens. The relationship of corrosion, w (mg/cm^2), vs time, t (sec), at 1500°C may be expressed in the parabolic form as $w = 1.54\ t^{0.832}$. The deviation from the true parabolic law (with an exponent of 0.5) is evident.

d. At the temperatures tested, the zirconium oxide scale builds up uniformly and does not spall. It is white to grey in color, with a measured density of 6.01, indicating the presence of metallic zirconium. This scale offers some protection from attack.

e. All the zirconium samples increased in dimensions. This was associated with the alpha-beta transformation volume change.

2. Uranium-Molybdenum

a. The oxide scale for this alloy is black and flakes off as the corrosion proceeds. Pits and grooves tend to form, at the temperatures tested, making the exact corrosion rate indeterminate.

b. Logarithmic plots of corrosion rate, w, vs time, t, for the U-Mo alloys showed that the corrosion followed a modified parabolic law as shown below.

Temperature	$w = kt^n$
1050°C	$w = 1.36\ t^{0.62}$
1190	$w = 0.70\ t^{0.93}$
1260	$w = 0.35\ t^{0.99}$
1270	$w = 0.42\ t^{1.00}$

It is seen that as the temperatures approach (and exceed) the melting point of the alloy, the exponent, n, approaches unity and the corrosion then follows the linear law. Thus, at the higher temperatures, the oxide scale offers virtually no protection from attack.

c. The corrosion of U-Mo at temperatures near its melting point is rapid but not explosive. Even when the molten alloy is poured through water the reaction, though vigorous, is not explosive or self-sustaining.

d. On Tests No. 7 and 8, the reported sample temperatures are greater than the melting point of the alloy. The appearance of the corrosion sample after Test No. 7 (Figure 28) indicated that the alloy had been in a semi-fluid state.

D. RECOMMENDATIONS

1. Because these tests can be made quickly and economically, it is recommended that additional work be done on U-Mo in order to accumulate a consistent set of data.

2. It is recommended that the necessary changes be made in the induction coil to permit the testing of the clad rods which are on hand.

3. Pure uranium and Zircaloy-B should be tested. It is recommended that sample stock of more suitable size and shape than that on hand be obtained. This will ensure more uniform heating of the sample, and hence more reliable data.

4. Other alloys which are of interest to the Commission should be tested while the equipment is set up.

V. HIGH-PRESSURE CORROSION-RATE TESTS

A. EXPERIMENTAL EQUIPMENT AND PROCEDURE

1. Equipment

a. The objective of these tests was to determine the corrosion rate of metals at temperatures up to their melting points, in 2000-psi steam. A small, pressure tank (4 in. ID x 6 in. long) was modified for this test. Two insulated electrical conductors were added, forming terminal posts inside the tank, across which the wire sample could be connected. Between these conductors was installed a 1-in.-thick, Vycor window in order to permit temperatures to be read. Other openings in the tank were provided to facilitate filling, evacuating, and bleeding. Taps for pressure and temperature measurements were also provided.

b. Two 1250-w Calrod heaters were wrapped around the tank to bring the water up to the desired temperature and pressure. One of the Calrods was controlled by a variable transformer, making it possible to maintain steady-state conditions.

c. A cooling coil was also provided to expedite cooling of the tank after a run. Thermal insulation was installed for the heating portion of the run. This was removed after the run to facilitate rapid cooling.

d. The water temperature was obtained by means of an iron-constantan thermocouple and recorded on a Brown Electronik circular-chart recorder. Pressure was indicated on a 3000-psi gage. Time was measured by means of a stop watch.

e. The corrosion samples were in wire form, 30 mils in diameter for the zirconium and 38 mils for the uranium. The wire sample was secured to the electric terminals and current was passed through it heating a length of 2.12 in. Power for heating the samples was supplied through a variable transformer. Adjustments were made to hold the temperature of the sample constant.

f. The measurement of corrosion was attempted in three ways: (1) measurement of volume of hydrogen, (2) measurement of weight gain (if oxide adhered) or loss (if oxide flaked off), and (3) by measurement of scale thickness (or diameter of metallic wire remaining). The measurement of the volume of gas liberated was not considered to be satisfactory because the total quantity of gas was small and any small leaks in the system or failure to purge 100% of the gas would introduce large errors. The wire samples were weighed before and after the test to the nearest tenth of a milligram, using an analytical balance. For direct measurements, the samples were sectioned and observed under a microscope.

g. Temperature measurements were made by means of an optical pyrometer. Because of the short duration of the tests, the small sample size, the fact that the sample was hotter in the middle than at the ends, and because of the general difficulty in seeing, it is believed that the temperatures reported may be in error by as much as $\pm 100^{\circ}C$.

2. Procedure

a. The corrosion sample was fastened to the terminals, and distilled water was poured into the tank to a depth of approximately $1\frac{1}{2}$ in. The lid was placed on the tank and it was evacuated to remove the air and degas the water. The Calrod heaters were turned on, and when the water temperature indicated $250^{\circ}F$, the tank vent valve was cracked permitting steam to exhaust for approximately 2 min. in order to purge any last trace of air from the chamber. The valve was closed and the temperature and pressure were allowed to increase to the desired values.

b. When the proper steam conditions had been established, the temperature of the wire sample was increased quickly to the desired value and held steady for the test period. Cooling water was turned on, and when the tank temperature returned to ambient, the hydrogen gas was forced into a water-filled graduate by filling the tank with water. A leveling bulb was used to equalize pressure and the volume was read.

c. The tank was opened, and the measurements were made on the wire sample as described previously.

B. RESULTS

1. Table V lists the results of all the high-pressure, high-temperature corrosion-rate tests.

2. One test was made on zirconium, with the steam pressure being 600 psig and the sample temperature $1000^{\circ}C$. Fair agreement is shown between the thickness of metal consumed, based on weight gain, and the thickness, based on microscopic observation.

3. Two tests were made on uranium. In the first, the temperature fluctuated and appeared to reach $1400^{\circ}C$ just before the wire corroded (or melted) through and stopped the test. Because the corrosion rates of 4.8 to 6.5 mils are extremely high for the length of the test, it is assumed that the sample melted (mp = $1140^{\circ}C$) and a portion of it was not recovered, thus making the calculated values high.

4. In the second uranium test, the sample was purposely melted in the presence of water vapor as a qualitative test of the reaction rate. The reaction was not self-sustaining and ceased when the wire melted in two.

C. DISCUSSION AND CONCLUSIONS

1. Further testing was not done because the equipment was found to possess several shortcomings. The test samples were too small, being limited by the controllable power available for heating the wires. A transformer which would correct this was ordered, but time did not permit its installation and use. The pressure tank was slow in coming up to temperature and slow in cooling, causing the testing to proceed slowly. Overheating of the tank seals caused leaks, limiting the maximum operating pressure.

2. Too few tests were made to permit positive statements to be made concerning the corrosion rate at high pressure compared with that at low pressure. However, the high-pressure corrosion data of zirconium obtained agrees well with data extrapolated from the work done by Bostrom (Ref. 10). Thus, it might be concluded that the corrosion rate at 600 psi is similar to that at atmospheric pressure.

3. In each test, the corrosion was seen to be greater at the center of the sample than at the ends. This was caused by uneven heating of the wire sample.

D. RECOMMENDATIONS

1. It is recommended that the high-temperature, high-pressure corrosion studies be continued. The equipment should be improved in order that the desired conditions can be duplicated and so that reliable, accurate data can be obtained. This would involve using larger-diameter, longer samples, installing a more rapid system to heat the chamber, and providing satisfactory pressure seals.

2. It is recommended that the following metals be tested: zirconium, Zircaloy-2, Zircaloy-B, uranium-molybdenum, and uranium.

REFERENCES

1. C. A. Zapffe, Preprint, Trans. Am. Soc. Met. (1947).

2. R. Fricke et al., Z. Physical Chemistry, B-37 60-74 (1937).

3. R. Fricke et al., Z. Electrochem., 47 487-500 (1941).

4. W. G. Guldner, Trans. Electrochem. Soc., 93, No. 6, 223 (1948).

5. A. S. Russell, Metal Progress, 59, 228-31 (1951).

6. A. A. Shidlovskiy, "Explosive Methyl Alcohol-Water Mixtures with Magnesium and Aluminum," Zhur. Prik. Khim., 19 371-7 (1946).

7. W. C. Ruebsamen, F. J. Shon, and J. B. Chrisney, "Chemical Reaction Between Water and Rapidly Heated Metals," NAA-SR-197, October 27, 1952.

8. H. M. Kindsvater, "Investigation of Rate of Reaction Between Water-Reactive Metals and Water," Aerojet Research Lab. Note No. 50, 8 August 1946.

9. R. B. Cox, H. M. Higgins, and E. G. Lucken, "Research, Development and Testing of Underwater Propulsion Devices," Aerojet Report No. 464, 31 July 1950.

10. W. A. Bostrom, "The High Temperature Oxidation of Zircaloy in Water," WAPD-104, March 19, 1954.

11. J. M. West and J. T. Weills, ANL-4549, December 29, 1950, pp. 5-6 and 10-23.

12. A. S. Russell, "Aluminum-Water Explosions" (Memorandum), Aluminum Company of America, April 14, 1950.

TABLE I

RESULTS OF MOLTEN-METAL DROP TESTS

Run No.	Metal	Wt, gm	Blast Cap	Violent	Approx. % Reacted	Remarks
16	95% Al - 5% Li	25.6	No	No	--	Some smoke on water.
17		62	No	No	50	Orange flame observed.
18		150	No	No	--	Flame seen, popping heard.
21		150	No	No	10	Flame seen, popping heard.
24		150	No	No	10	Some smoke seen.
25		150	No	No	5	
27		150	No	No	10	Little reaction, no flame.
30		50	No	No	--	Little or no reaction.
32		100	No	No	--	Little or no reaction.
29		150	Yes	Yes	100	Some damage to setup.
31		100	Yes	Yes	70	Little damage to setup
33		150	Yes	Yes	90	Little damage done.
34		150	Yes	Yes	100	Terrific blast, much damage.
3	Pure nickel	454	No	No	--	Steam formation caused thump.
4		454	No	No	--	
5		454	No	No	<5	No water blown out of container.
39		454	Yes	No	15	Some oxide formed.
40		454	Yes	No	15	No exceptional noise.
41		454	Yes	No	--	Very fine residue.
12	Pure zirconium	454	No	No	--	Oxide film formed, steam bubbles.
15		454	No	No	16	Oxide film formed, steam bubbles.
42		454	Yes	Yes	--	Loud blast, shower of sparks.
43		454	Yes	Yes	--	Loud blast.
44		454	Yes	Yes	100	Violent blast, extensive damage.
45	Zircaloy-2	227	Yes	Yes	--	Sharp blast.
46	Zircaloy-2	227	Yes	Yes	100	Loud blast, extensive damage.
53	Pure aluminum	150	No	No	<5	Oxide film formed.
54		150	No	No	<5	Oxide film formed.
35		150	Yes	No	--	Small reaction.
36		150	Yes	No	<10	Fine metalic granules resulted.
38		150	Yes	No	--	Fine metalic granules resulted.
50		150	Yes	No	--	Oxide film formed.
51		150	Yes	No	--	Oxide film formed.
52		150	Yes	No	--	Oxide film formed.
55		150	Yes	No	--	Oxide film formed.
56	Pure magnesium	100	Yes	Yes	70	Sharp blast, no damage.
57	Pure magnesium	150	Yes	Yes	80	White flash accompanied blast.
47	Type 321 S.	227	No	No	--	Some oxide formed.
48	Type 321 S.	225	No	No	--	Some oxide formed.

TABLE II

CERTAIN PROPERTIES OF SOME REACTING SYSTEMS

	Specific Volume		Heat of Reaction		Characteristic Product	
	cc/gm*	cc/gm**	cal/gm*	cal/gm**	*	**
Nitroglycerin	712	712	1580	1580	1,130,000	1,130,000
Black powder	285	285	685	685	195,000	195,000
$Li \longrightarrow LiOH$	4615	1280	6960	1940	11,200,000	2,480,000
$Na \longrightarrow NaOH$	487	273	1900	1065	925,000	291,000
$Al \longrightarrow Al_2O_3$	1240	620	3550	1775	4,400,000	1,100,000
$Mg \longrightarrow MgO$	922	527	3190	1820	2,940,000	958,000
$Zr \longrightarrow ZrO_2$	492	327	470	312	231,000	104,000
$U \longrightarrow U_3O_8$	250	208	437	363	109,000	75,000

* For the metal-water reactions these values are based on the weight of metal only.

** These values are based on the total weight of reactants.

TABLE III

RESULTS OF METAL-WATER SLURRY TESTS

Mixture	Total Weight of Reactant gm.	No. of Tests	No. of Violent Reactions	Relative Severity	Remarks
35% Al - 65% $KClO_4$	21	1	1	1	Calibration shot, made depression in blast plate 1 in. dia x 1/8 in. deep, buckled plate.
50% Mg - 50% H_2O	21	5	1	2	Partial reaction, plate buckled.
40% Mg - 60% H_2O	20	1	1	4	Partial reaction obtained.
35% Mg - 65% H_2O	19	1	1	1	Partial reaction.
60% Mg - 40% CH_3OH	19	1	1	3	Partial reaction.
50% Al - 50% H_2O	32	3	0	--	No indication of reaction.
50% Al - 50% CH_3OH	29	2	0	--	No indication of reaction.
25% Mg - 25% Al - 50% CH_3OH	25	1	0	--	No indication of reaction.
50% Zr - 50% H_2O	42	2	0	--	No indication of reaction.

TABLE IV

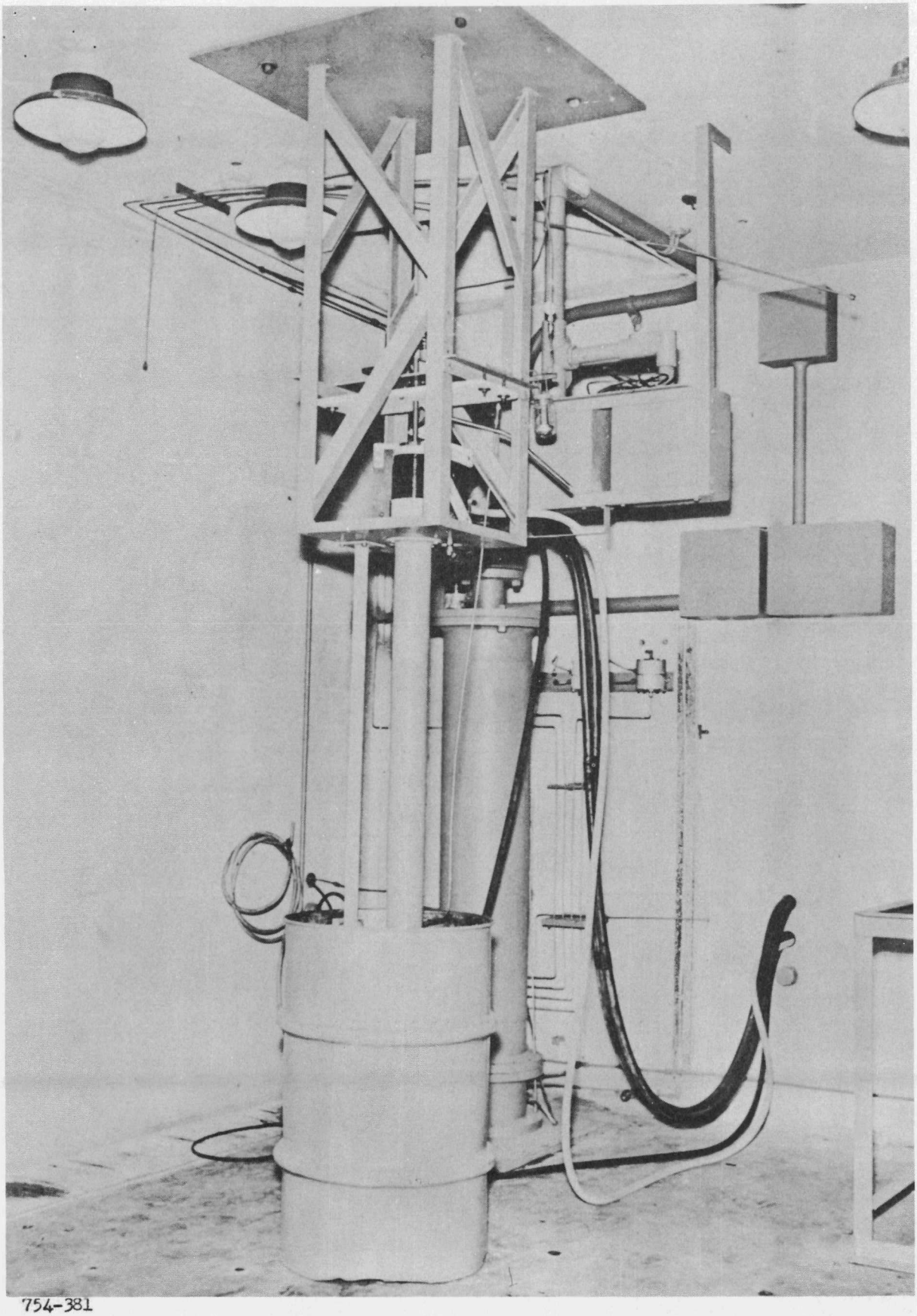
RESULTS OF LOW-PRESSURE CORROSION-RATE TESTS

Run No.	Metal	Temp. °C	Time sec	Av. Corrosion Rate, mils/hr, Based on Hydrogen Evolution	Scale Thickness	Weight Gain
1	100% zirconium	1470	933	118	74	87
12	100% zirconium	1500	850	109	72	--
2	88% U + 12% Mo	1190	1115	35	23	17
6	88% U + 12% Mo	1050	1120	--	--	--
7	88% U + 12% Mo	1260	1135	27	25	11
8	88% U + 12% Mo	1270	1116	33	24	24
4	Type 321 S. S.	1200	164	--	--	--
5	Type 321 S. S.	1260	380	--	--	--

TABLE V

RESULTS OF HIGH-PRESSURE CORROSION-RATE TESTS

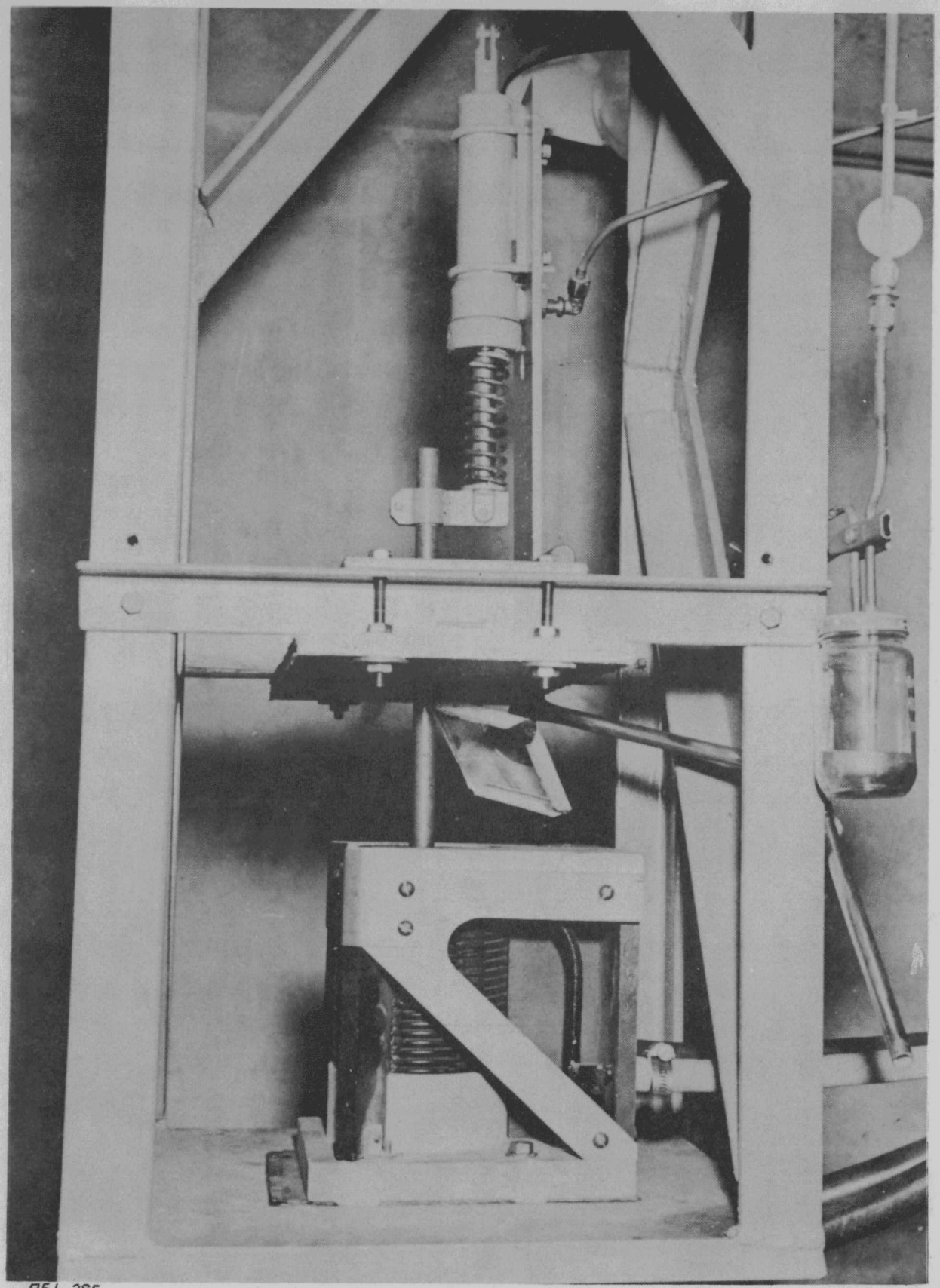
Run No.	Metal	Metal Temp. °C	H_2O Press. psig	Wt. Metal Consumed mg	Metal Consumed mg/cm^2	Duration of Test sec	Calc. Thick. of Metal Consumed mils	Meas. Thick. of Metal Consumed mils
1	Zr	1000	600	11.1	9.75	200	0.6	0.45
2	U	1400	250	313	228	22.4	4.8	6.5
3	U	Molten	600	---	---	---	---	---



754-381

Drop-Test Apparatus

Figure 1

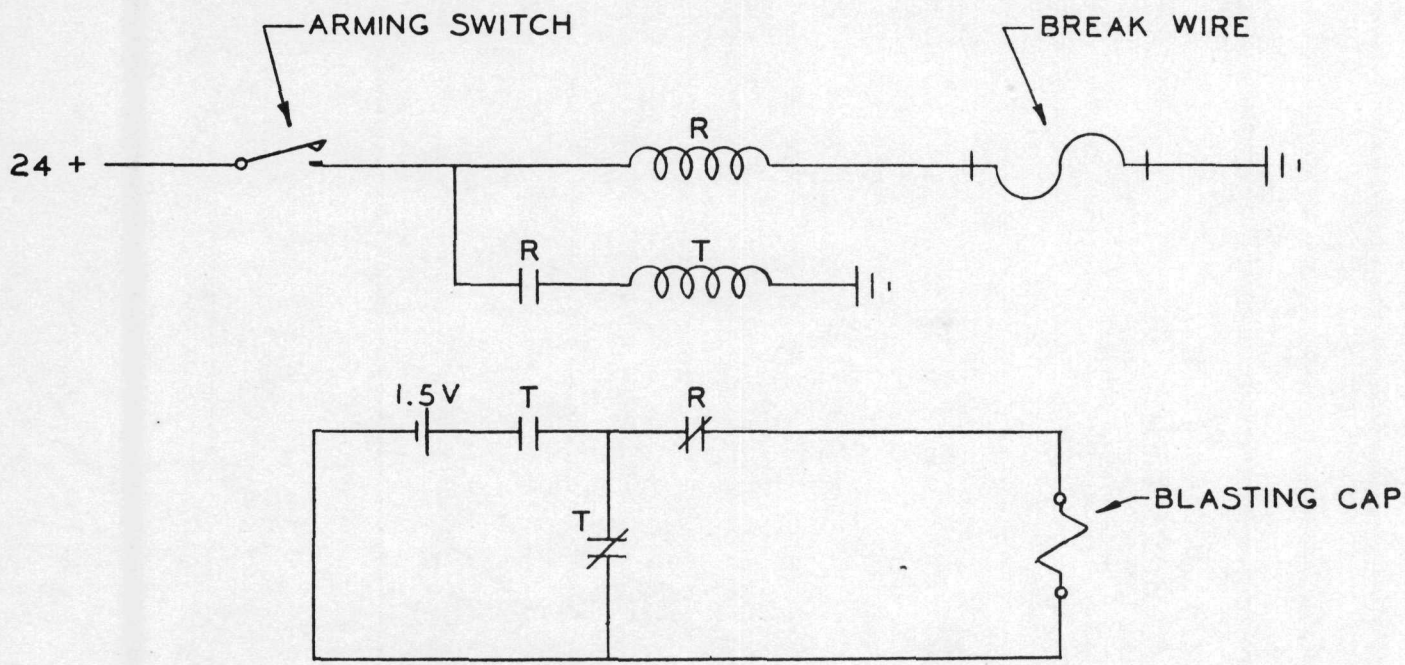


754-385

Furnace Assembly

Figure 2

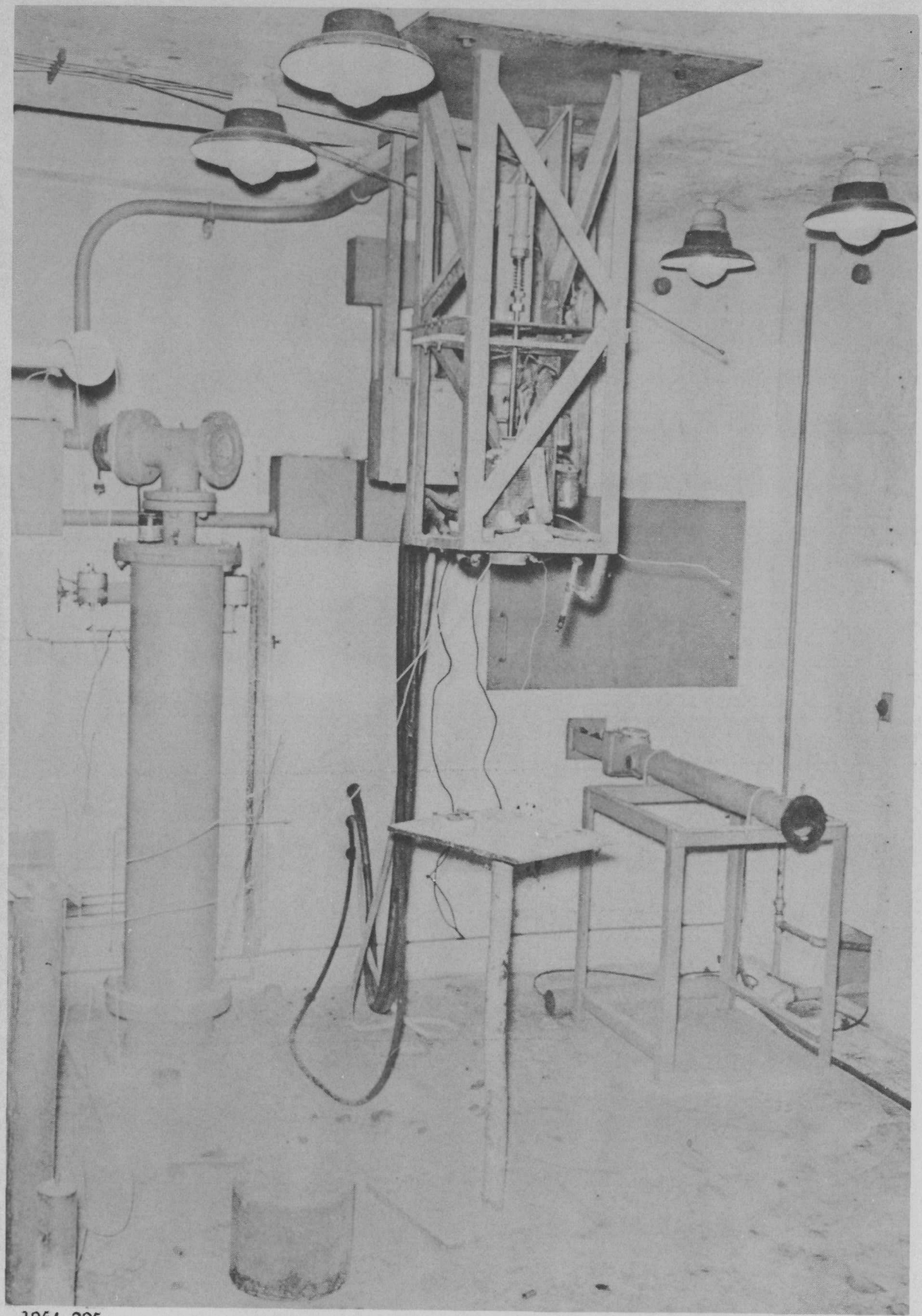
Fig-3



'R'-ADVANCE RELAY #K160A
'T'-G.E. RELAY SLUG TYPE
DELAYED OPENING

DIAGRAM OF BLASTING-CAP CIRCUIT

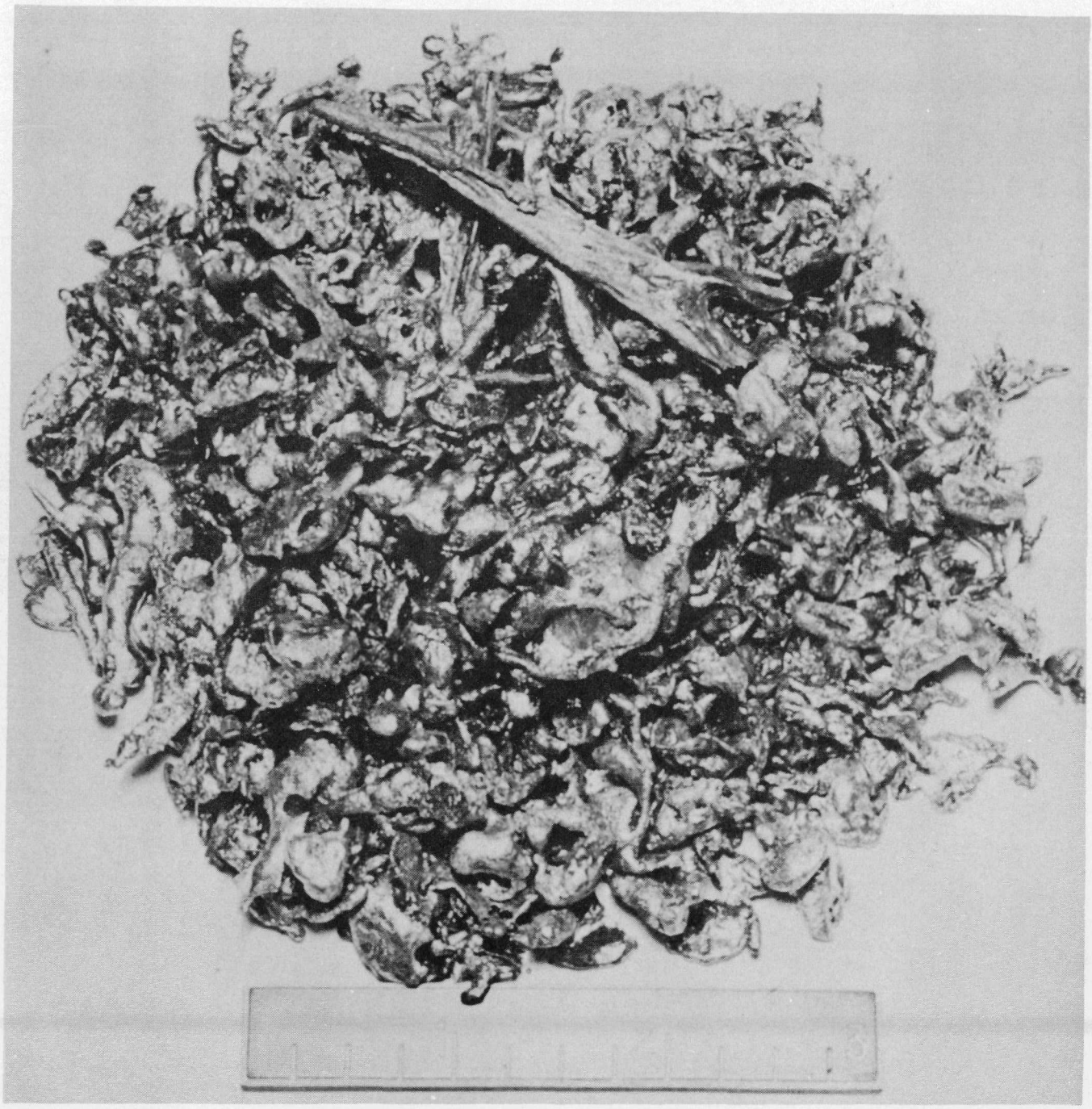
Figure 3
31



1054-295

Apparatus Following Test No. 34

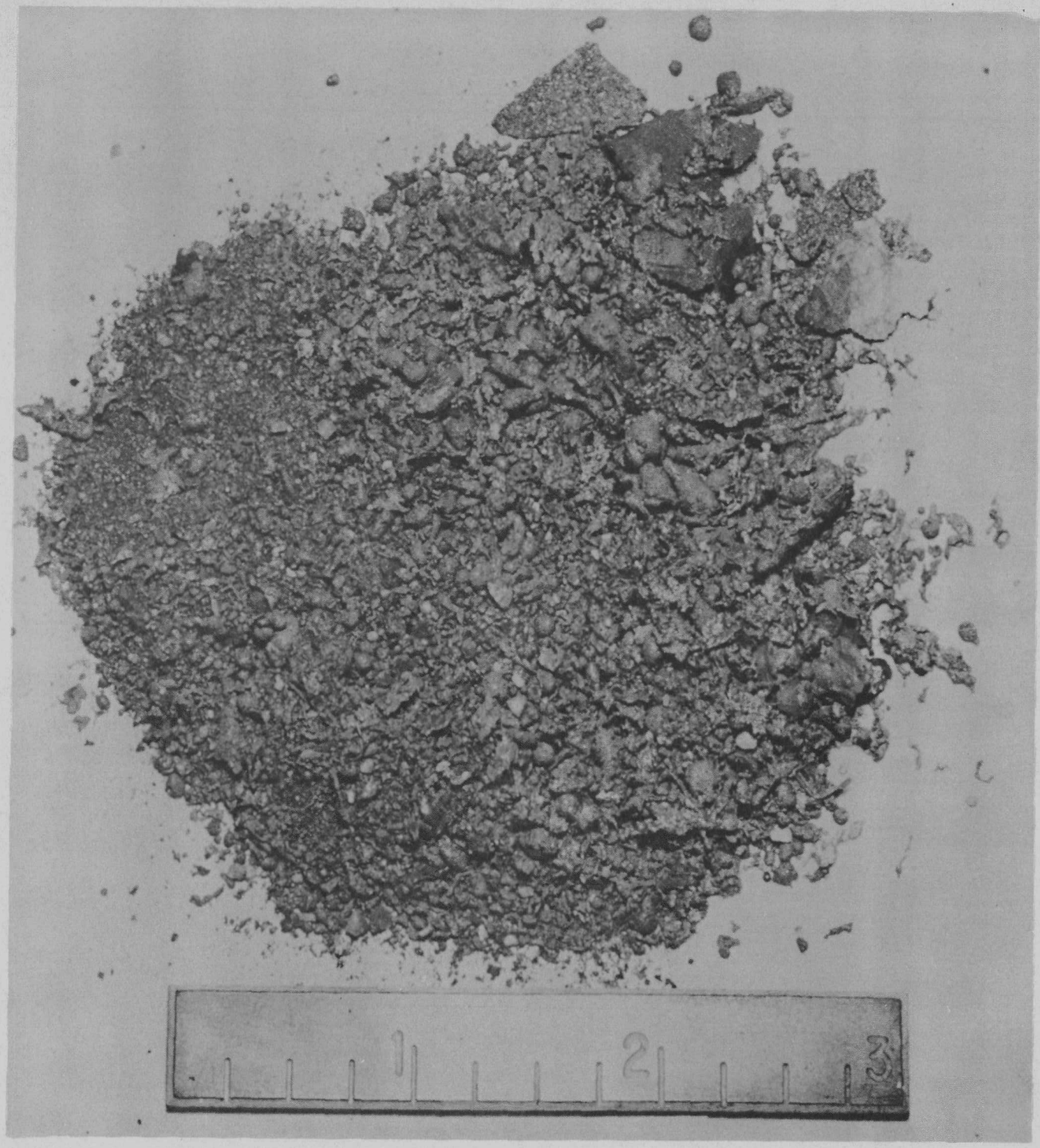
Figure 4



1254-608

Drop Test No. 5, Pure Nickel

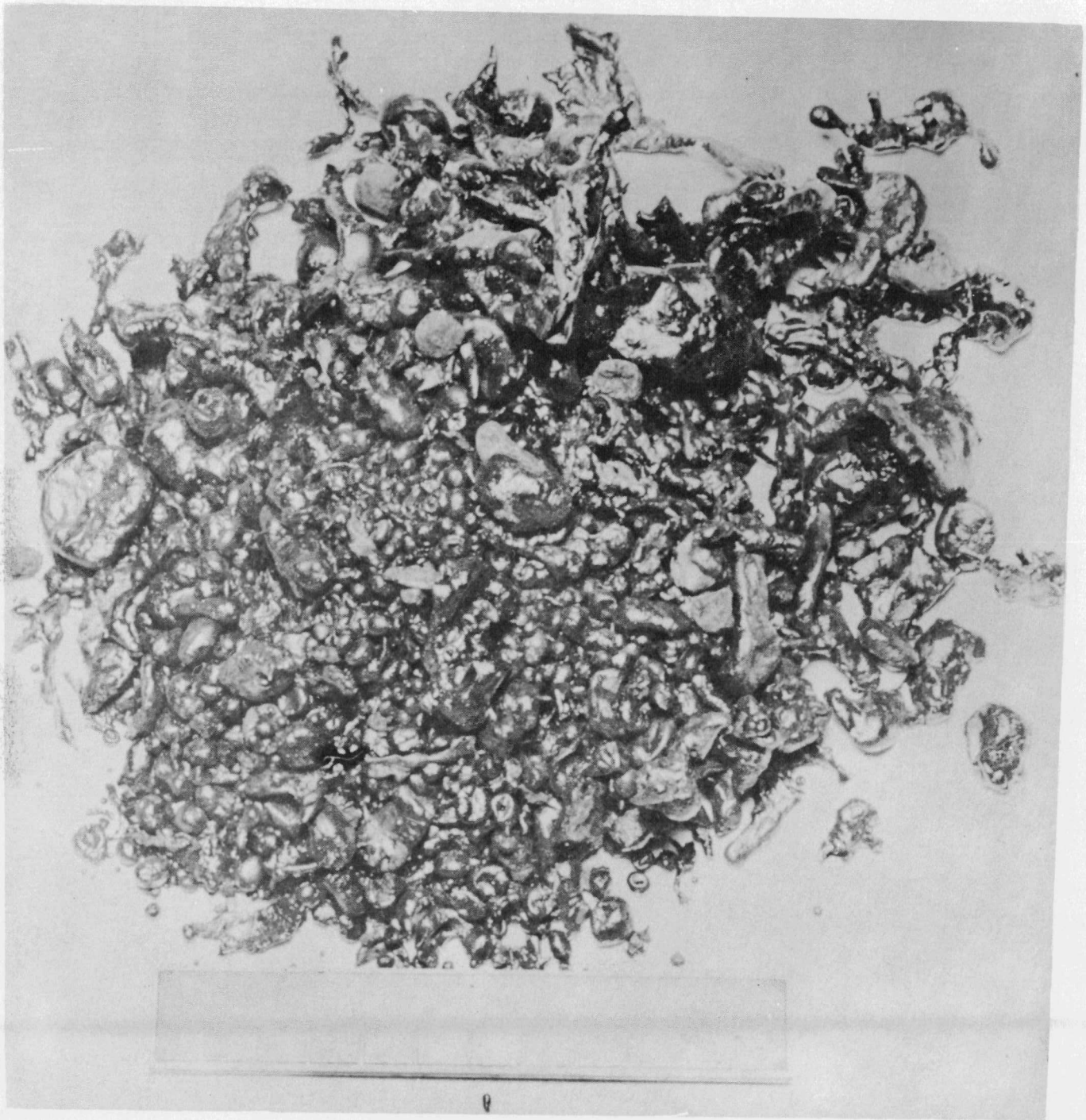
Figure 5



1254-609

Drop Test No. 39, Pure Nickel

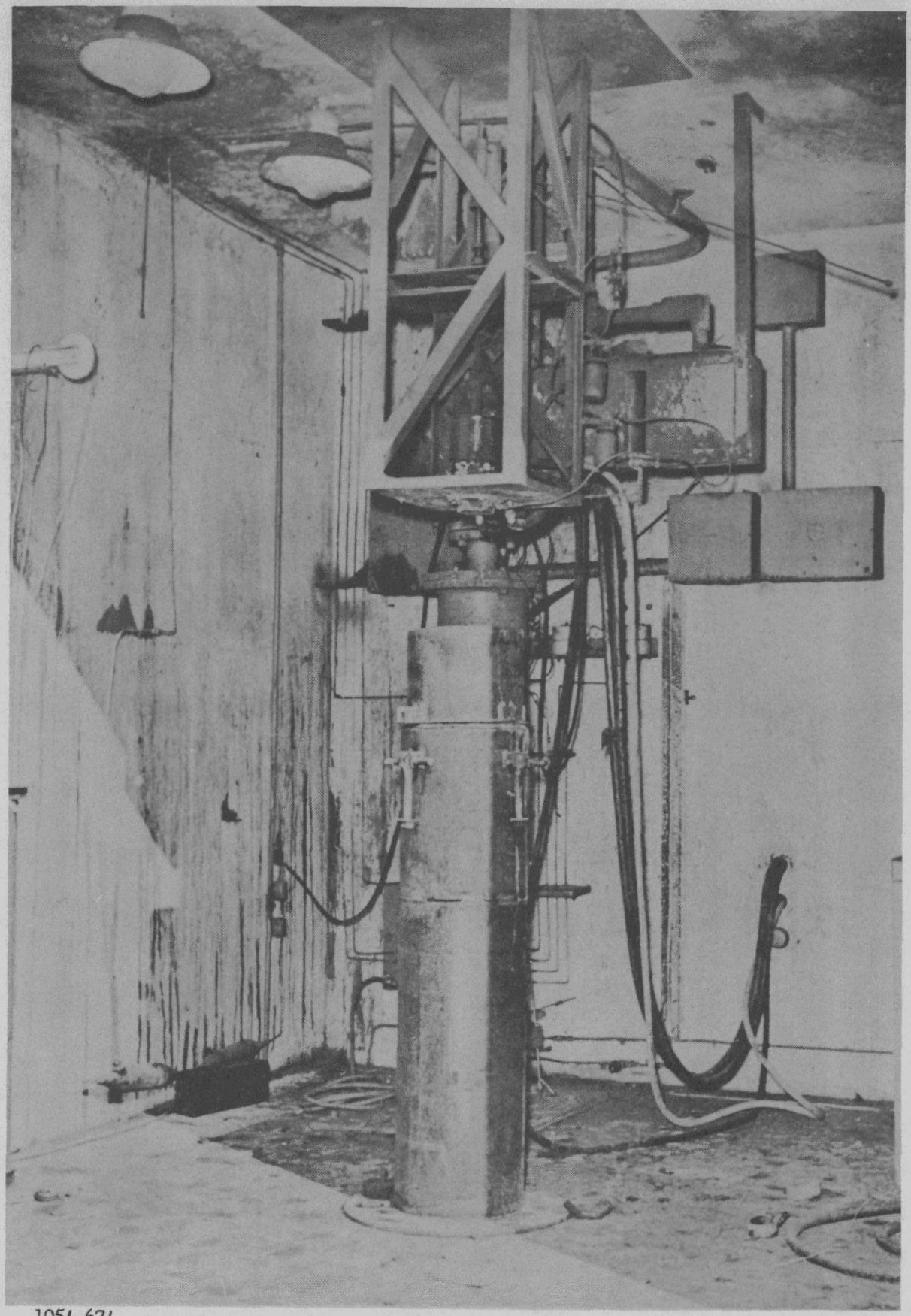
Figure 6



1254-606

Drop Test No. 15, Pure Zirconium

Figure 7



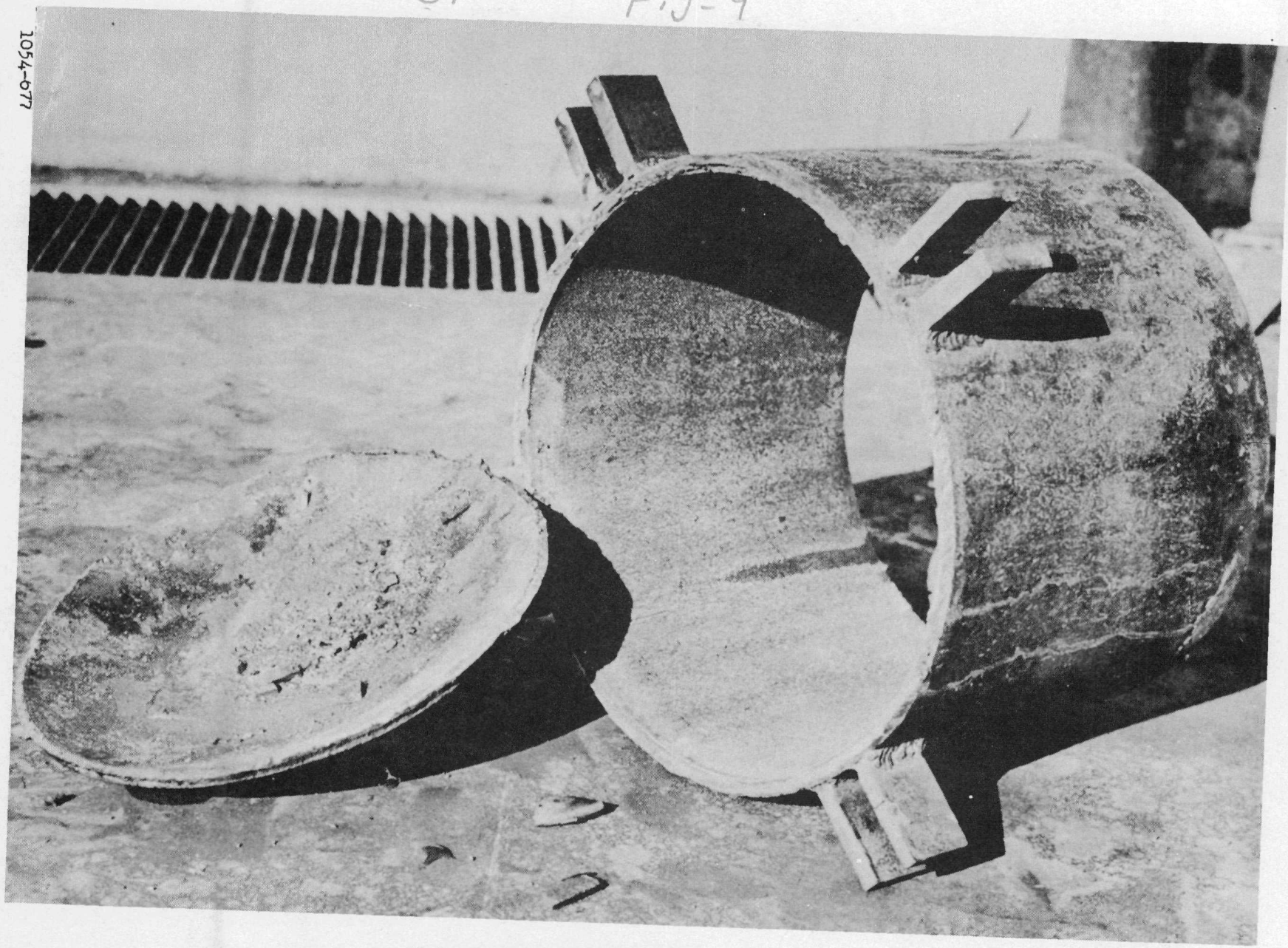
1054-674

Apparatus Following Test No. 44

Figure 8

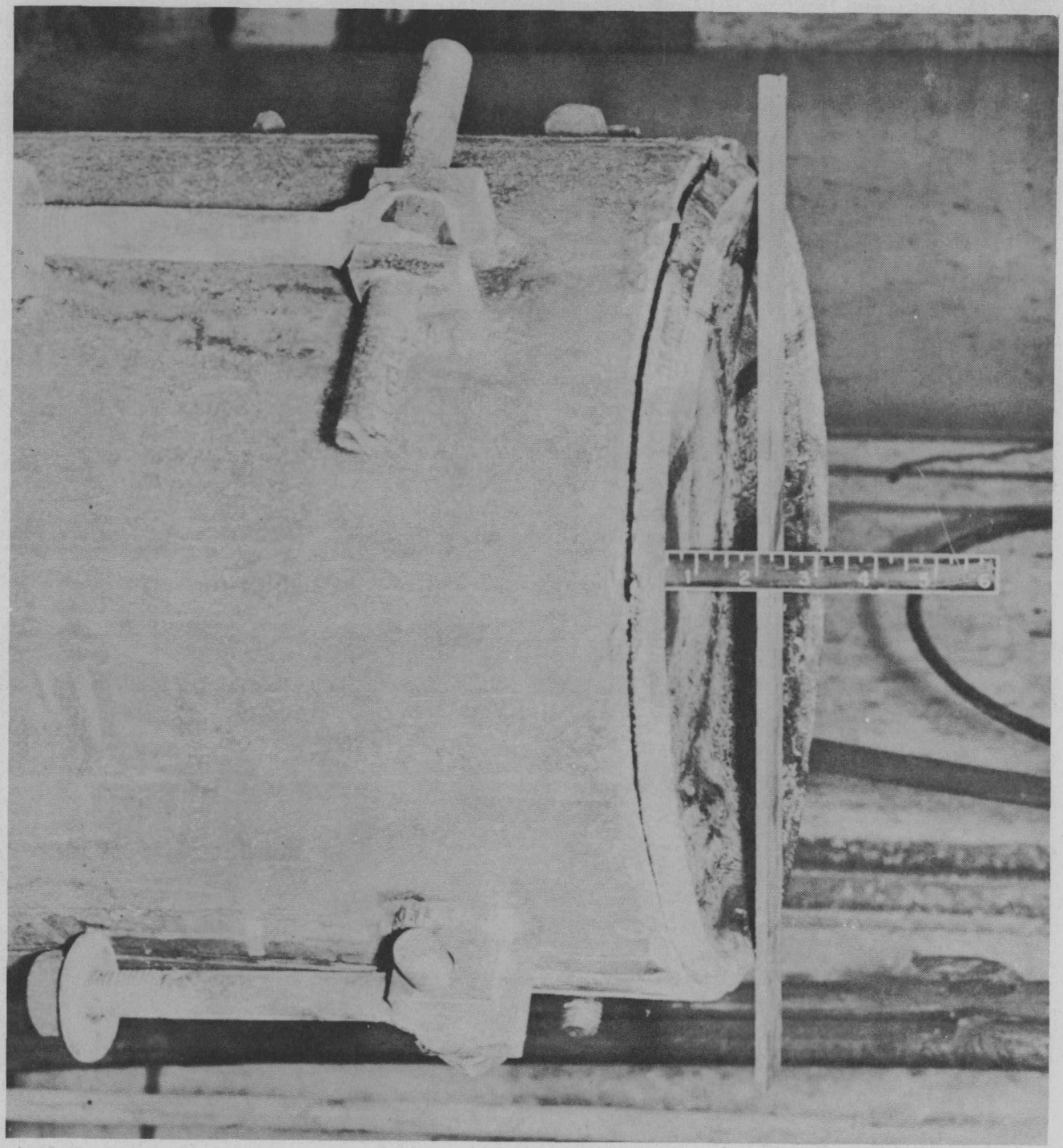
Fig-9

1054-677



Water Container After Test No. 44

Figure 9

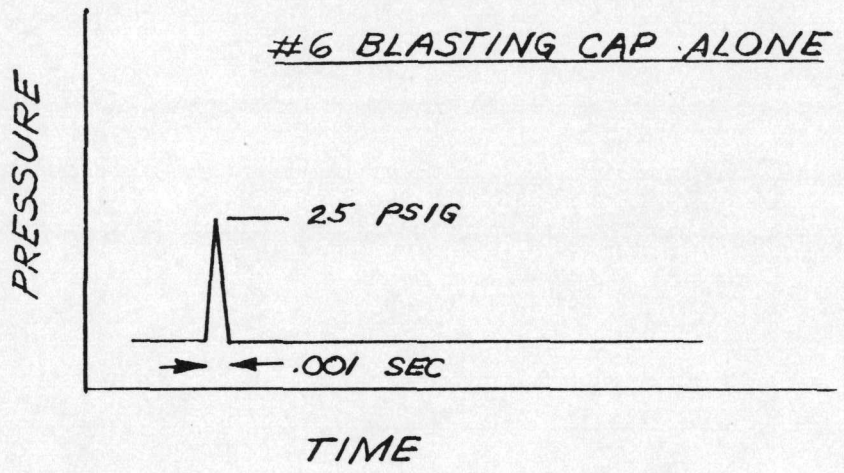


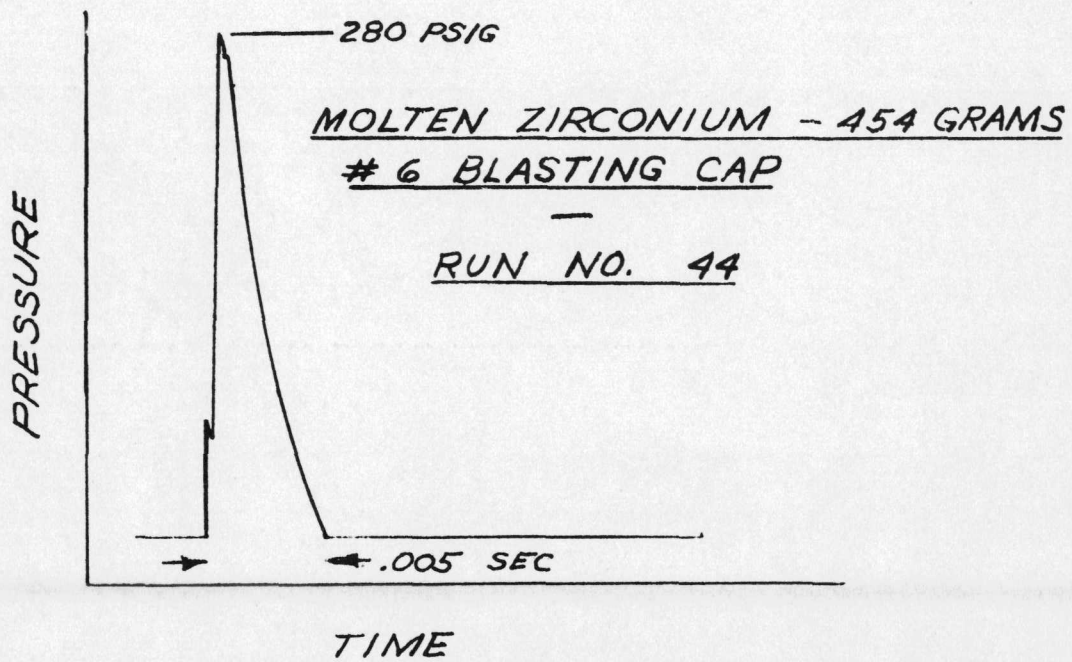
Pedestal After Test No. 44

Figure 10

H.M. HIGGINS

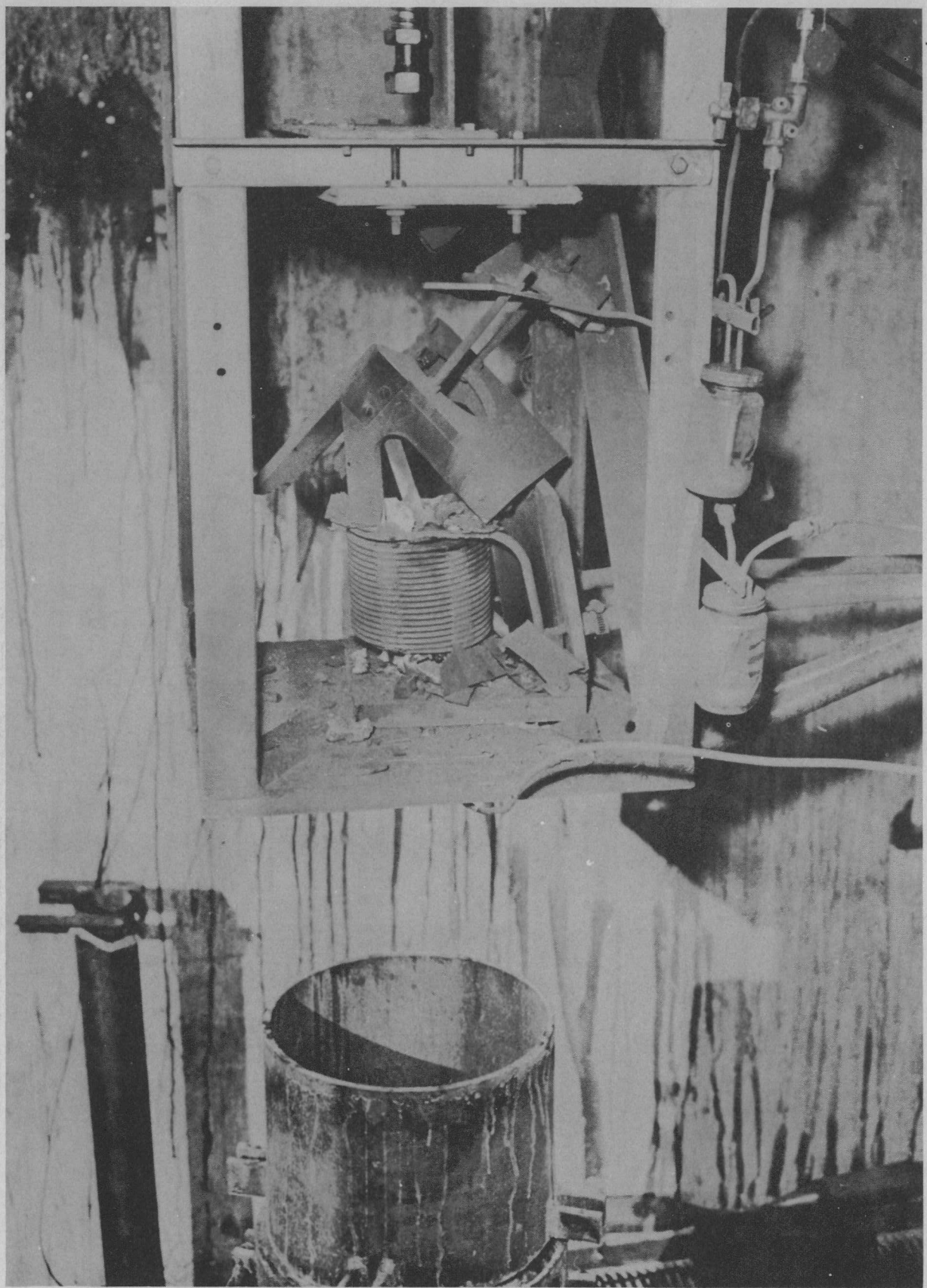
C-4317 12-28-54





TYPICAL PRESSURE-TIME RECORDS

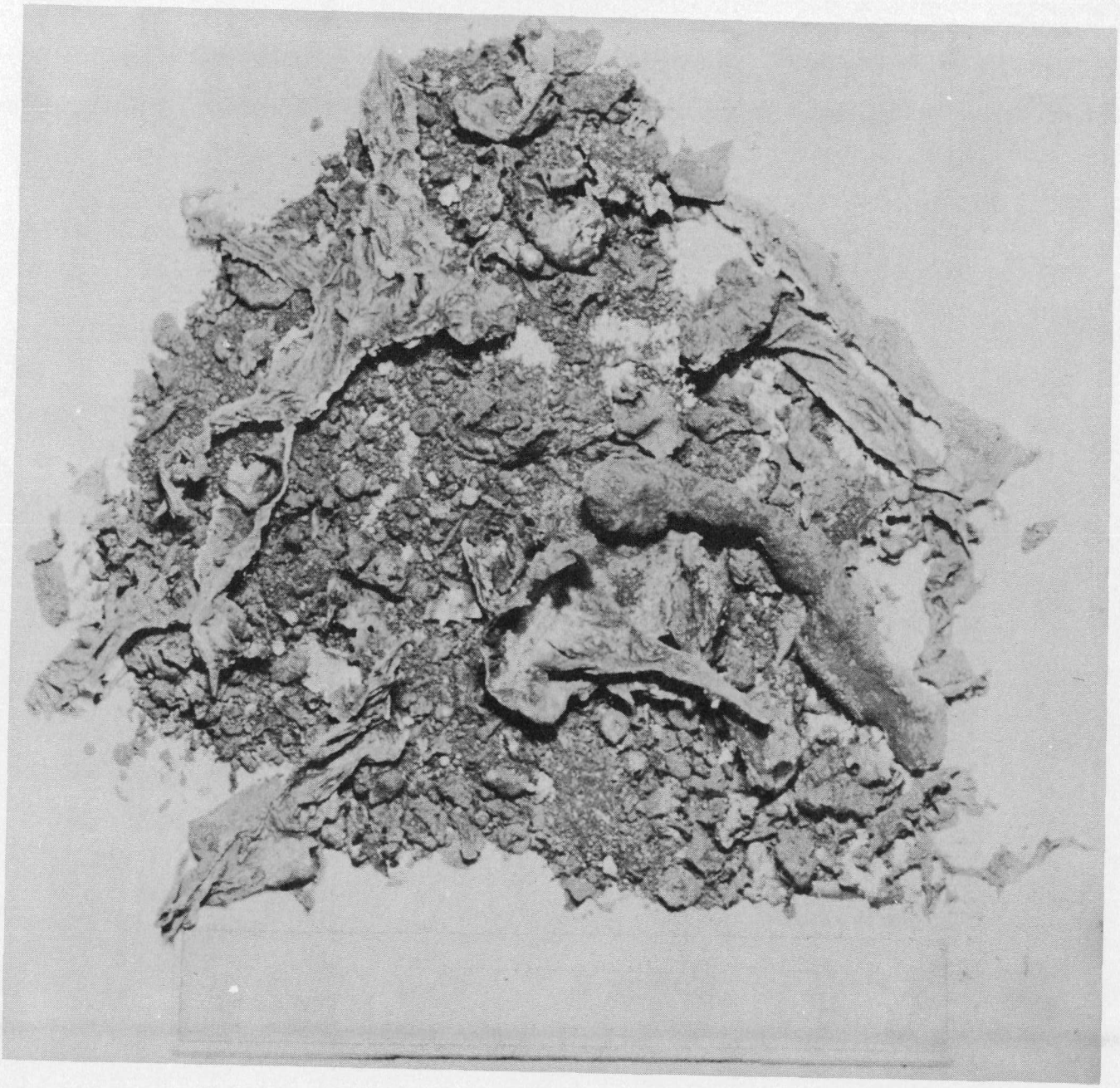
Figure 11



1054-675

Furnace Assembly After Test No. 44

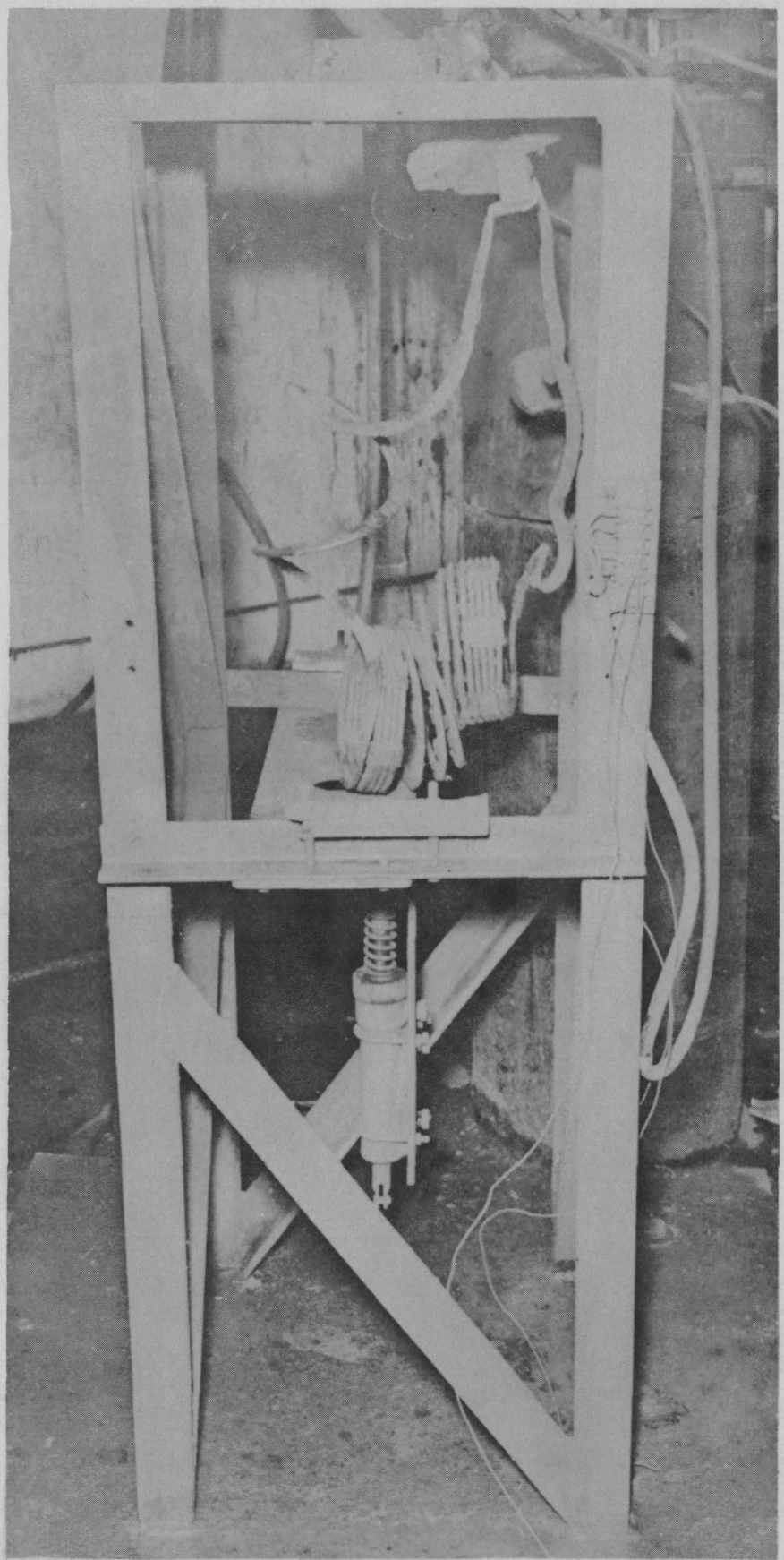
Figure 12



1254-607

Drop Test No. 42, Zirconium Residue

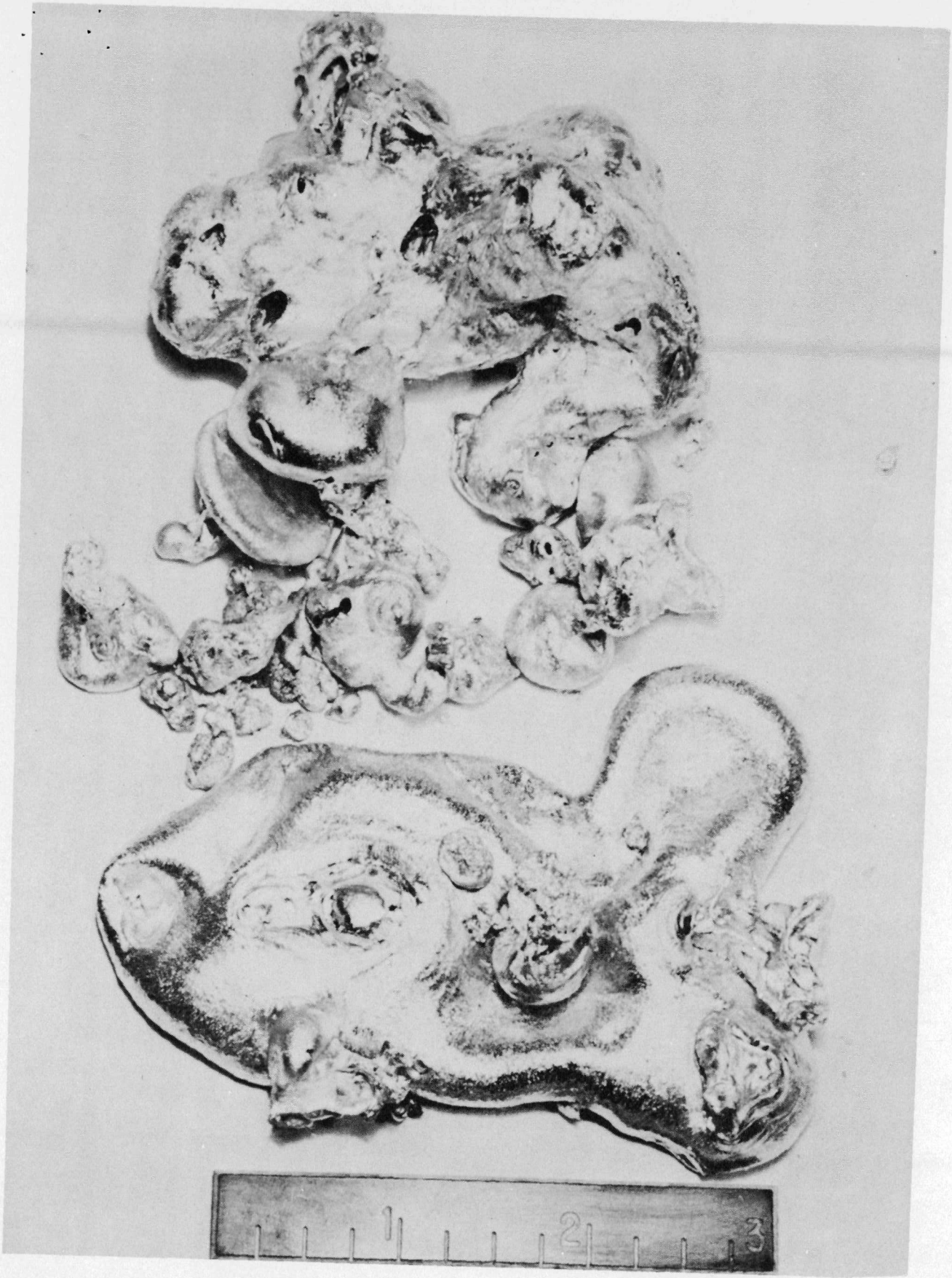
Figure 13



1054-850

Furnace Assembly After Test No. 46

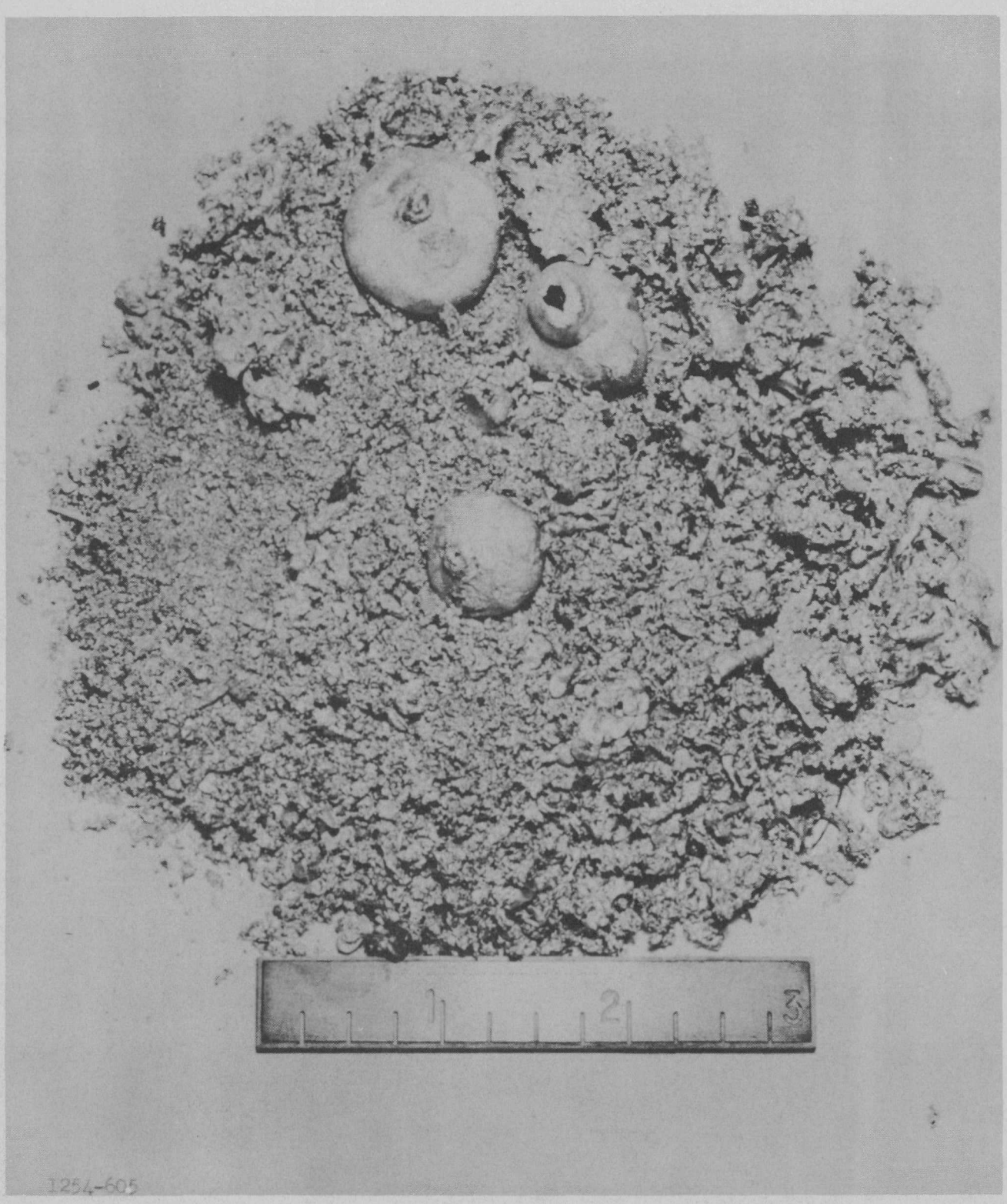
Figure 14



I254-610

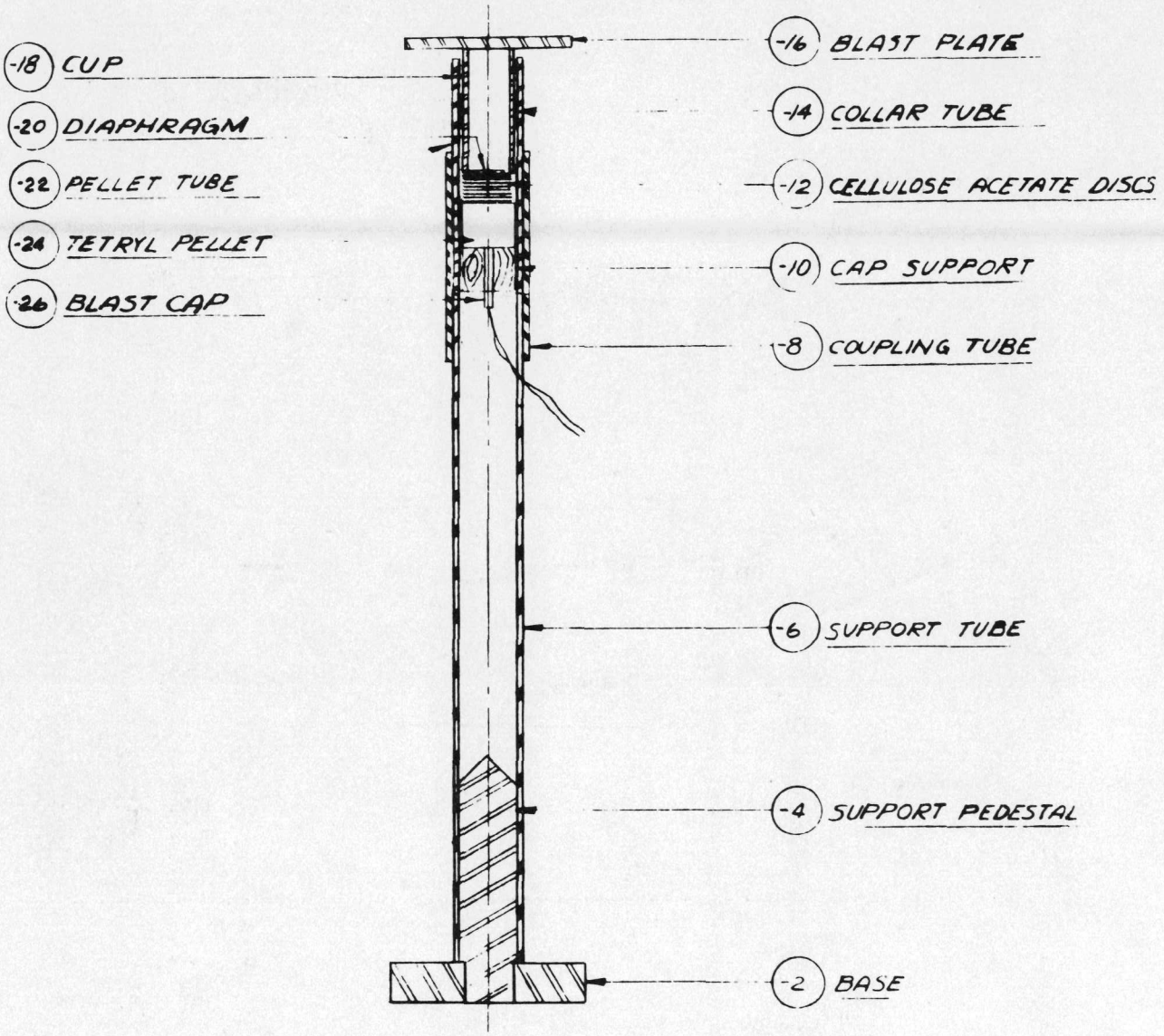
Drop Test No. 54, Pure Aluminum

Figure 15



Drop Test No. 52, Pure Aluminum

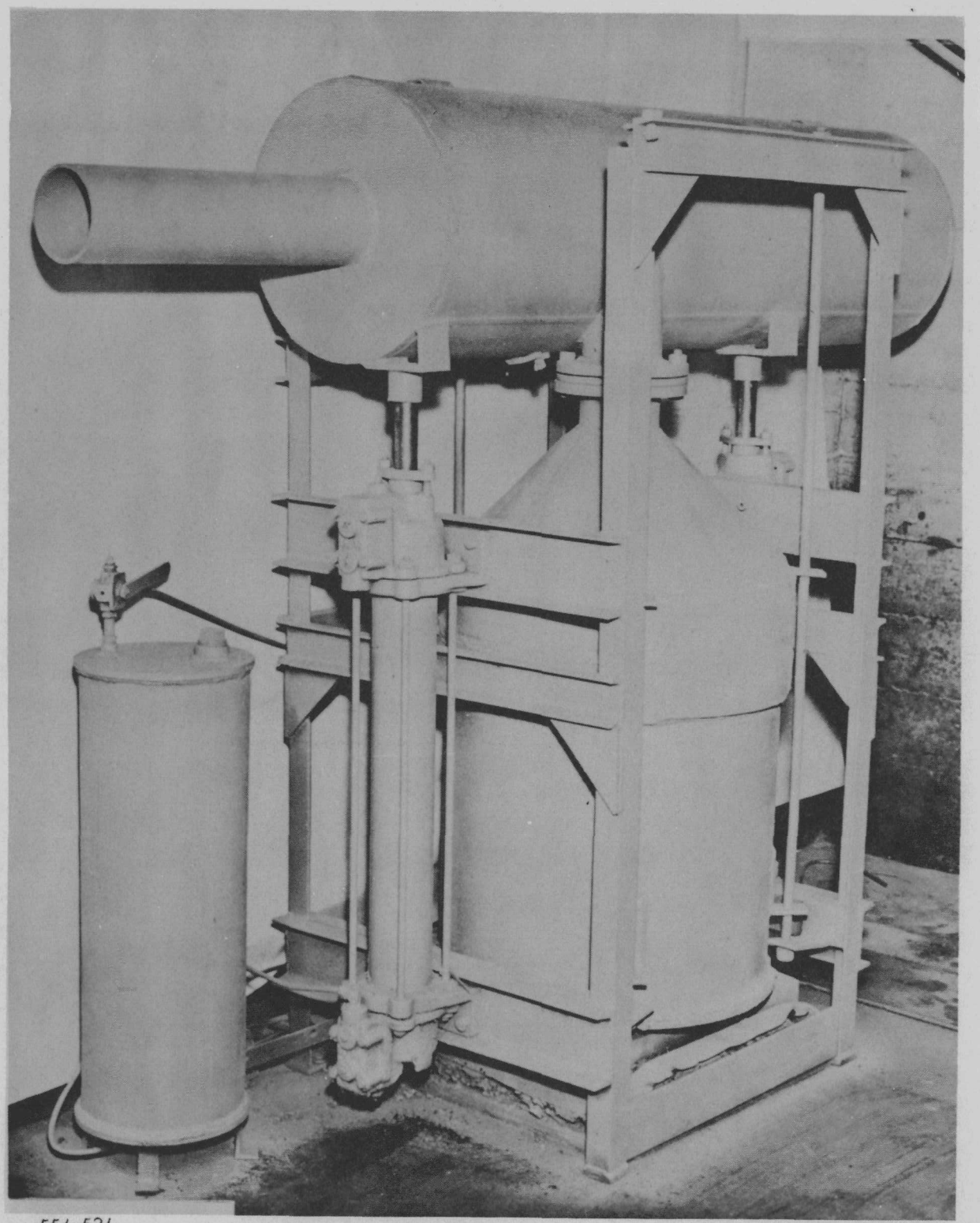
Figure 16



454-777

Gap-Test Assembly

Figure 17



554-524

Complete Gap-Test Installation

Figure 18

47 Fig-19

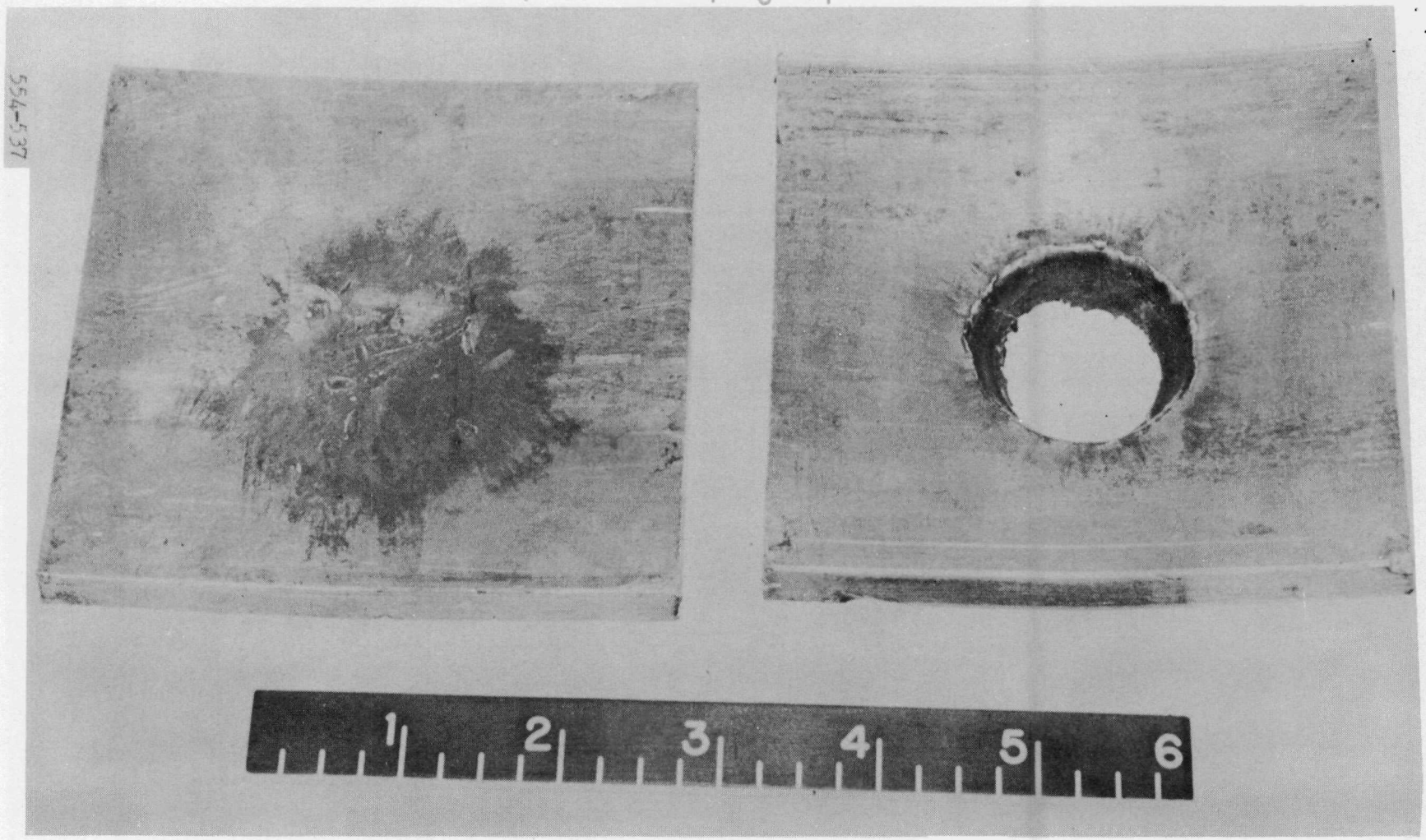
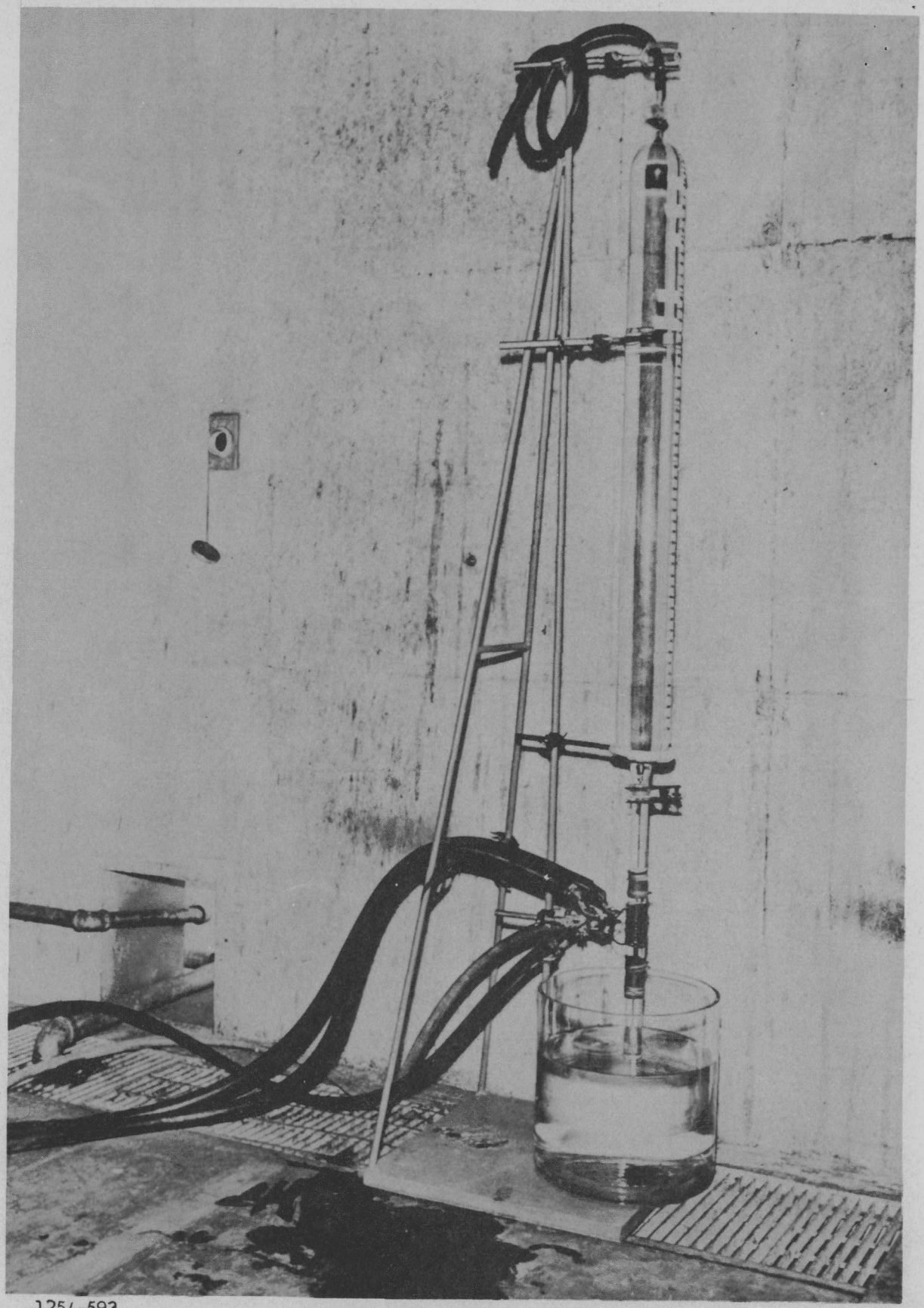


Figure 19

Typical Results Using High Explosives



1254-593

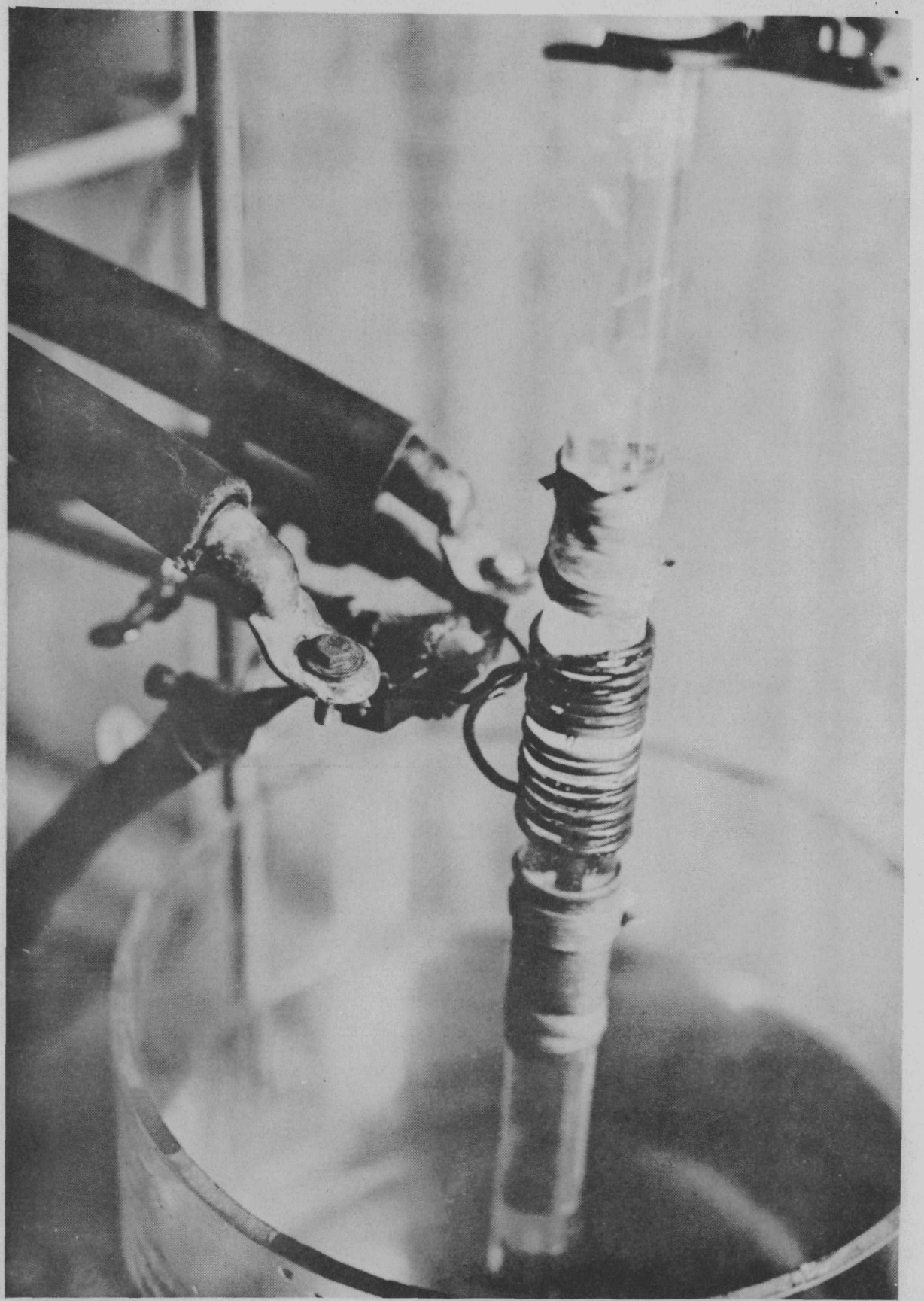
Low-Pressure Corrosion-Rate Apparatus

Figure 20

49 Fig-21

1254-595

Figure 21



1254-594

Corrosion Test in Progress

Figure 22

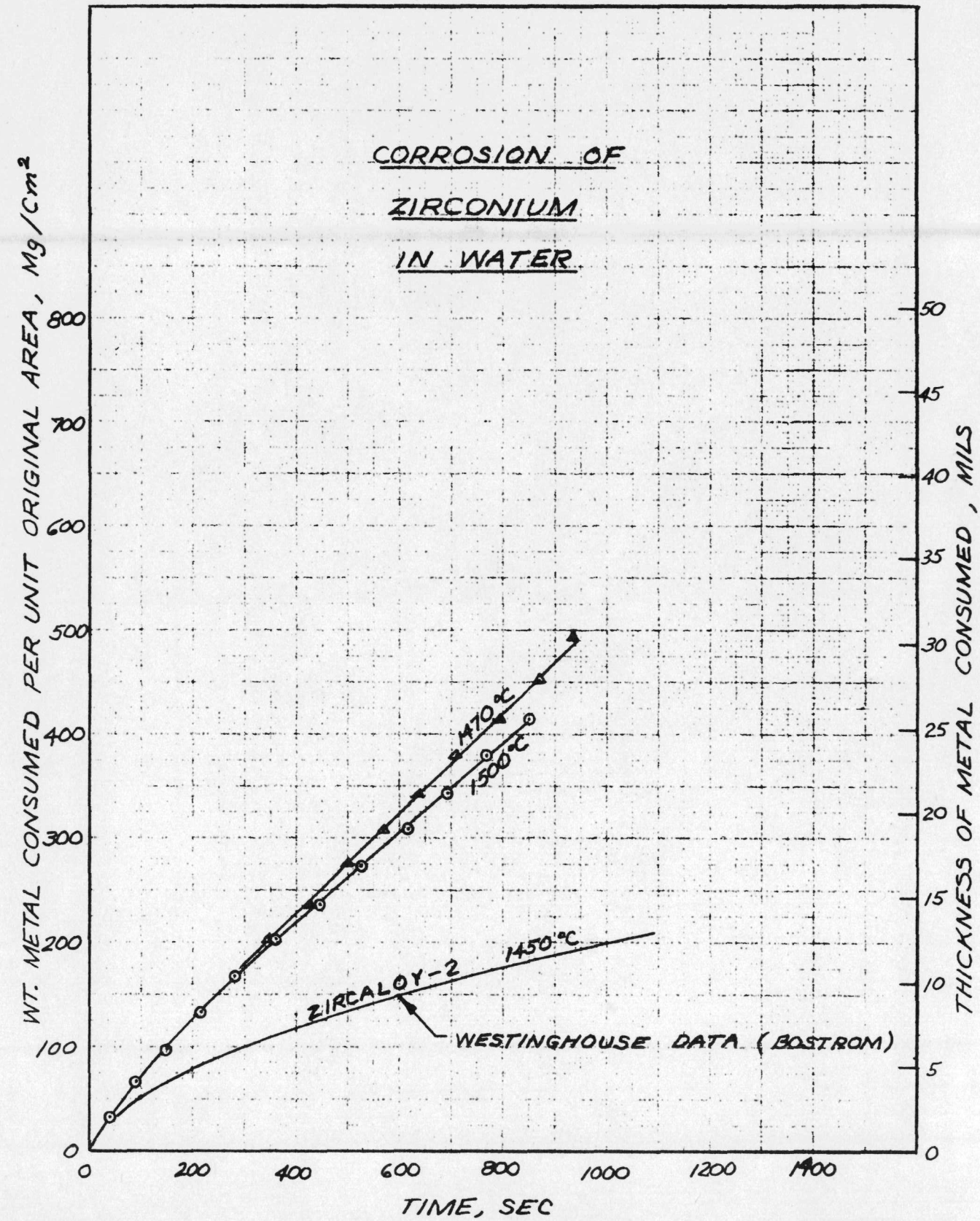

CORROSION OF
ZIRCONIUM
IN WATER
H.M. HIGGINS
C 4346 1-5-55
WT. METAL CONSUMED PER UNIT ORIGINAL AREA, Mg/Cm²
THICKNESS OF METAL CONSUMED, MILS
TIME, SEC
0
100
200
300
400
500
600
700
800
0
5
10
15
20
25
30
35
40
45
50
0
200
400
600
800
1000
1200
1400
1470°C
1500°C
1450°C
ZIRCALOY-2
WESTINGHOUSE DATA (BOSTROM)

Figure 23

155-377

Corrosion Test No. 1, Zirconium

Figure 24

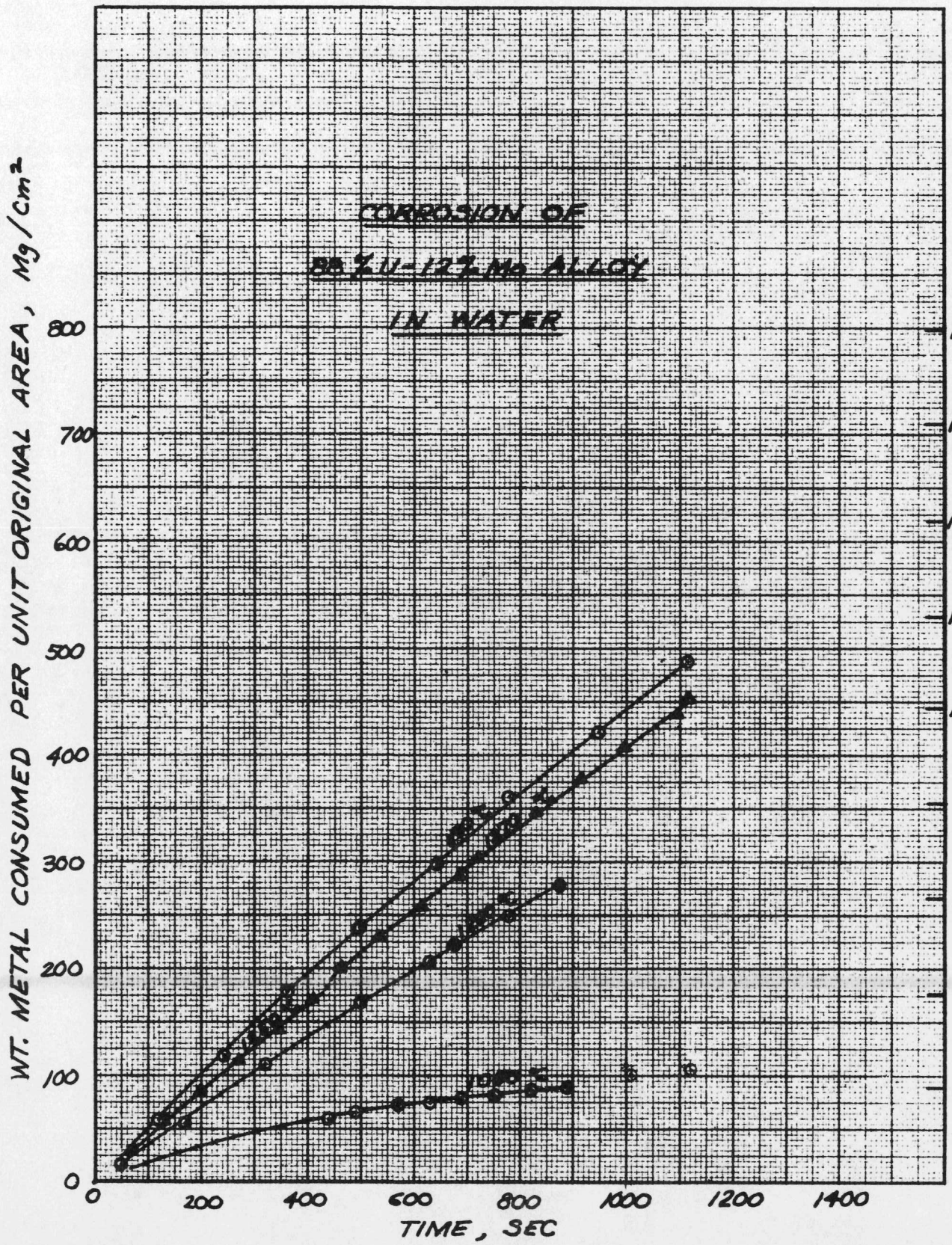
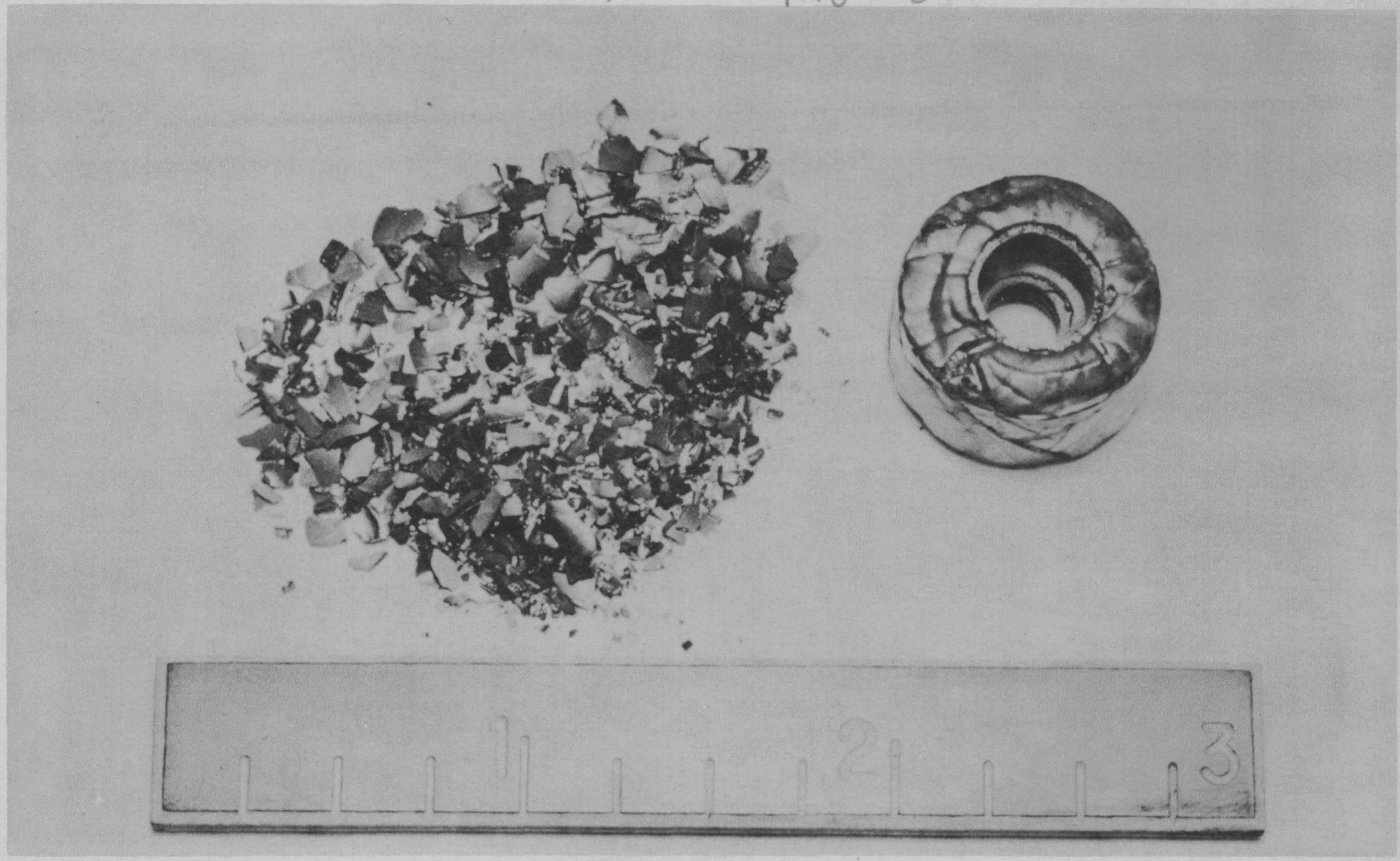

CORROSION OF
88 % U-12 % Mo ALLOY
IN WATER
H.M. HIGGINS
C 4347 1-5-55
WT. METAL CONSUMED PER UNIT ORIGINAL AREA, Mg/Cm²
THICKNESS OF METAL CONSUMED, MILS
TIME, SEC
0
100
200
300
400
500
600
700
800
2
4
6
8
10
12
14
16
18
200
400
600
800
1000
1200
1400

Figure 25

54 Fig-26

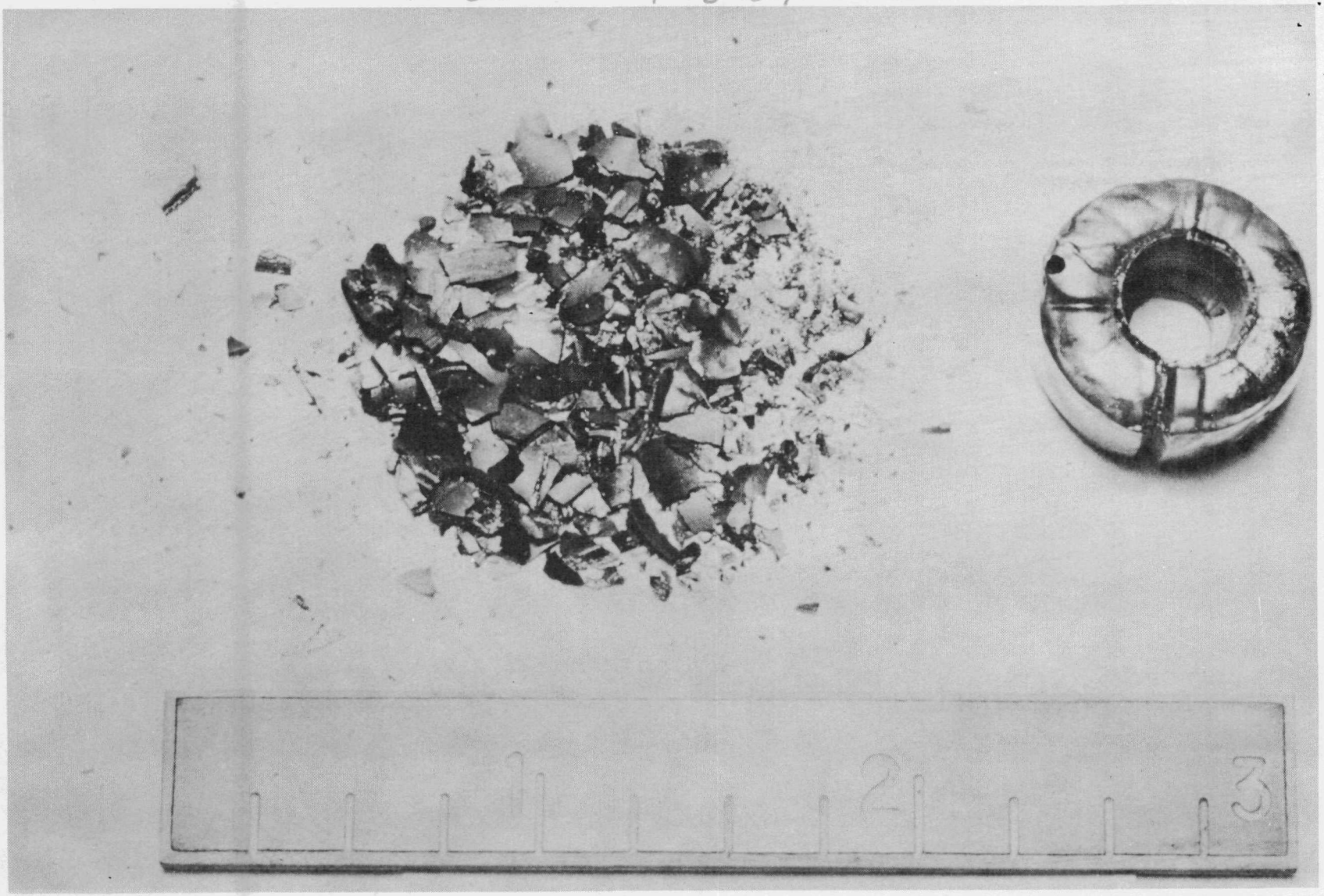


1254-599

Corrosion Test No. 2, U-Mo Alloy

Figure 26
54

55 F+9-27

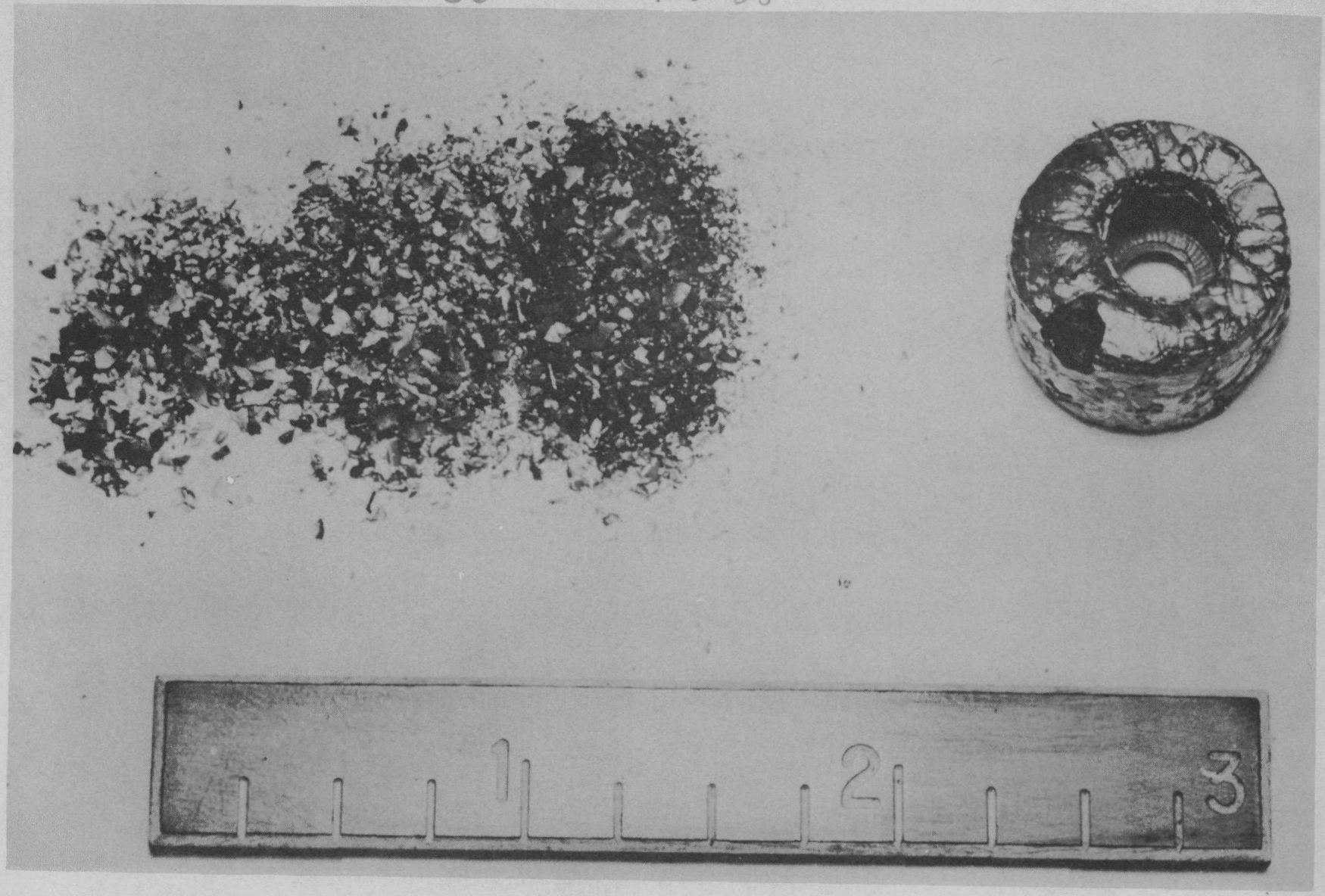


Corrosion Test No. 8, U-Mo Alloy

1254-602

Figure 27
55

1254-596

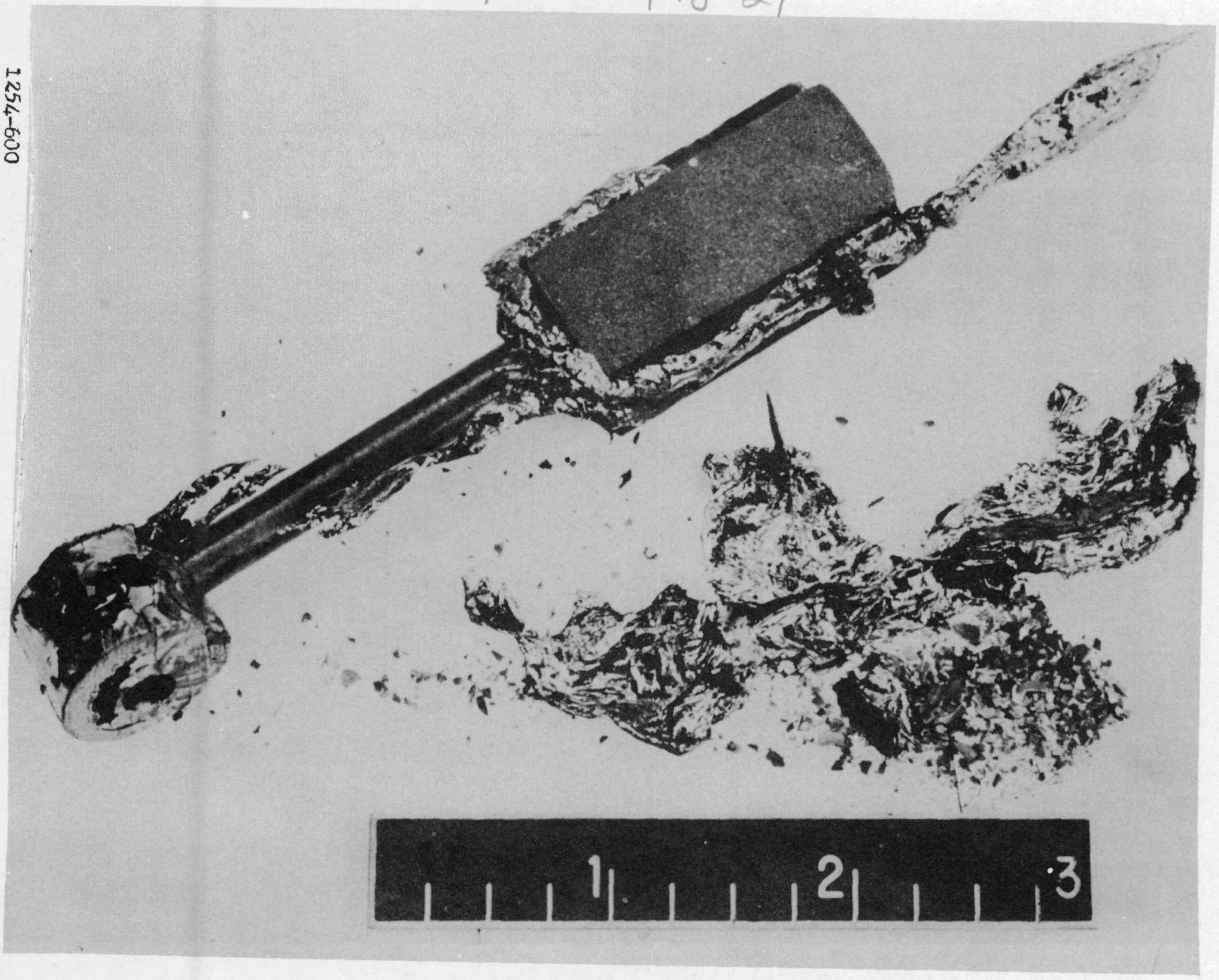


Corrosion Test No. 7, U-Mo Alloy

Figure 28

57 Fig-29

1254-600



Corrosion Test No. 6, U-Mo Alloy

Figure 29

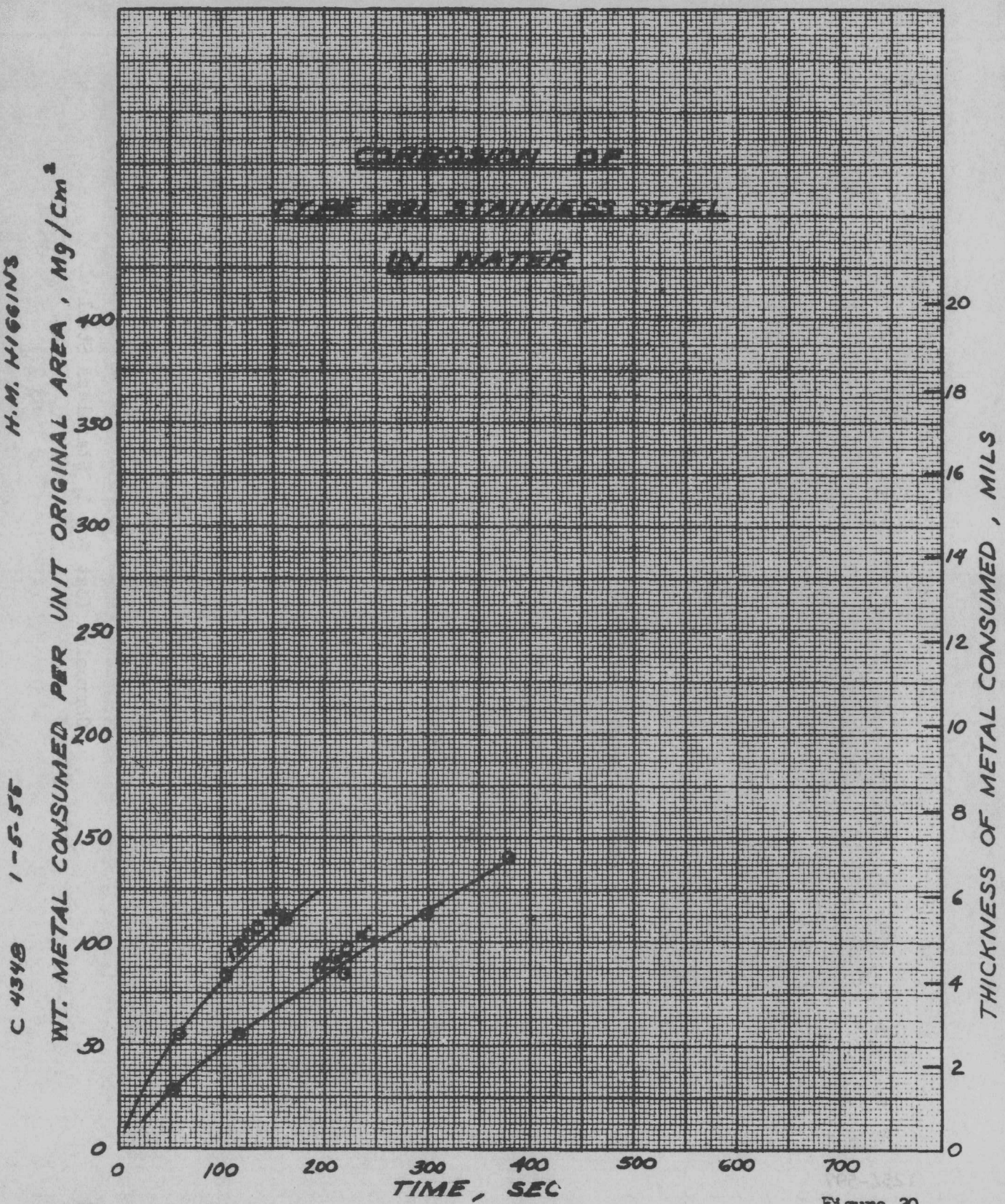
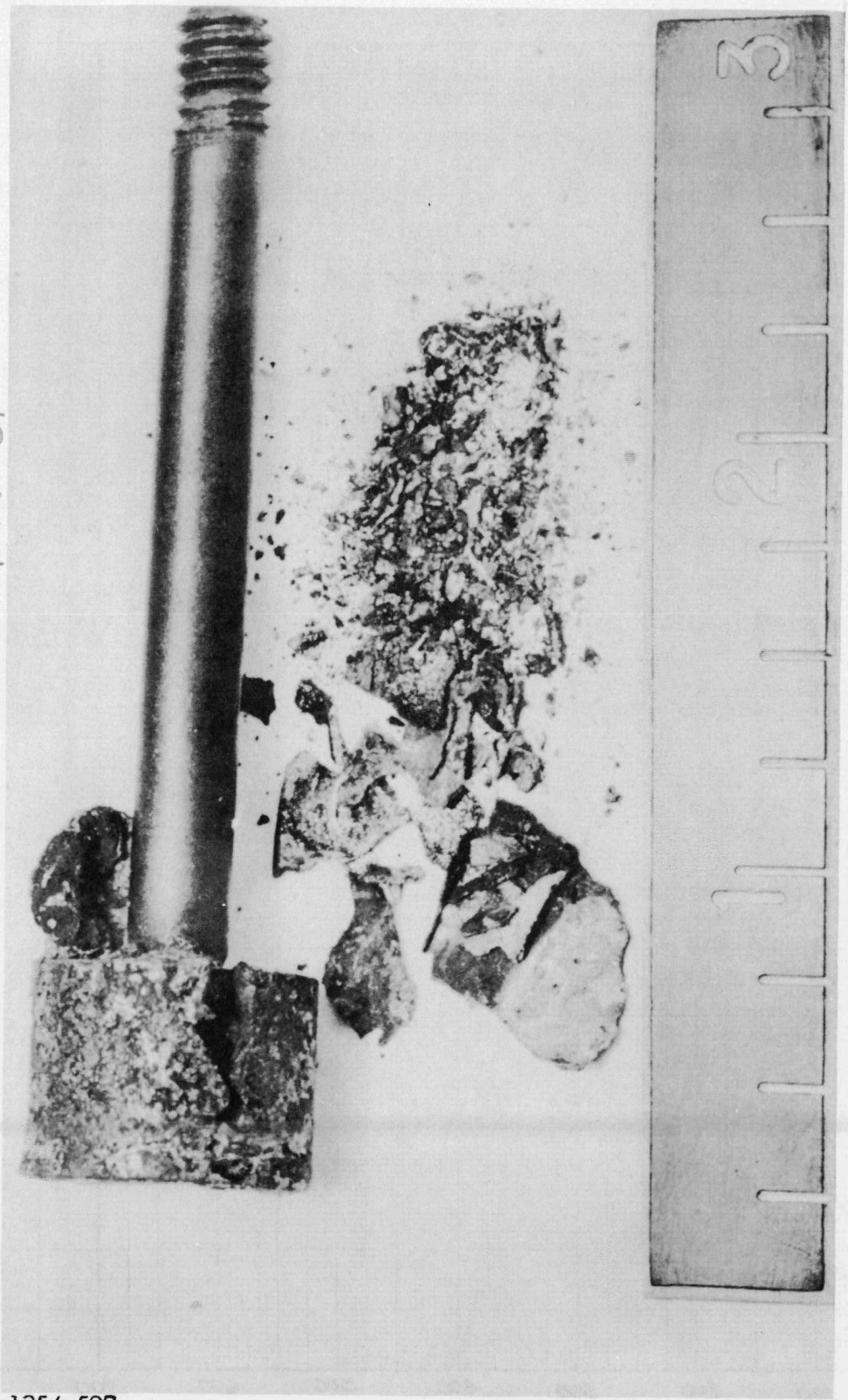

CORROSION OF
TYPE 321 STAINLESS STEEL
IN WATER
H.M. HIGGINS
C 4348 1-5-56
WT. METAL CONSUMED PER UNIT ORIGINAL AREA, Mg/Cm²
THICKNESS OF METAL CONSUMED, MILS
TIME, SEC
0
50
100
150
200
250
300
350
400
0
2
4
6
8
10
12
14
16
18
20
0
100
200
300
400
500
600
700

Figure 30



Corrosion Test No. 4, Stainless Steel

Figure 31