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TITANIUM-OXYGEN REACTIVITY STUDY

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ABSTRACT

A program has been conducted at Astronautics to investigate the likelihood of occurrence of the catastrophic oxidation of titanium alloy sheet under conditions which simulate certain cases of accidental failure of the metal while it is in contact with liquid or gaseous oxygen. Three methods of fracturing the metal were used; they consisted of mechanical puncture, tensile fracture of welded joints, and perforation by very high velocity particles.

The results of the tests which have been conducted provide further evidence of the reactivity of titanium with liquid and gaseous oxygen. The evidence indicates that the rapid fracturing of titanium sheet while it is in contact with oxygen initiates the catastrophic oxidation reaction. Initiation occurred when the speed of the fracture was some few feet per second, as in both the drop-weight puncture tests and the static tensile fracture tests of welded joints, as well as when the speed was several thousand feet per second, as in the simulated micrometeoroid penetration tests. The slow propagation of a crack, however, did not initiate the reaction.

It may logically be concluded that the localized frictional heat of rapid fracture and/or spontaneous oxidation (exothermic) of minute particles emanating from the fracture cause initiation of the reaction. Under conditions of slow fracture, however, the small heat generated may be adequately dissipated and the reaction is not initiated.

A portion of the study conducted consisted of investigating various means by which the reaction might be retarded or prevented. Providing a "barrier" at the titanium-oxygen interface consisting of either aluminum metal or a coating of a petroleum base corrosion inhibitor appeared to be only partially effective in retarding the reaction.

The accidental puncturing or similar rupturing of thin-walled pressurized oxygen tanks on missiles and space vehicles will usually constitute loss of function, and may sometimes cause their catastrophic destruction by explosive decompression regardless of the type of material used for their construction. In the case of tanks constructed of titanium alloys the added risk is incurred of catastrophic burning of the tanks. In view of this it is recommended that thin-walled tanks constructed of titanium alloys should not be used to contain liquid or gaseous oxygen.

TABLE OF CONTENTS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

TABLES

1 INTRODUCTION

The program described in this report has been conducted at Astronautics to study the titanium-oxygen reactivity problem with respect to the use of thin titanium alloy sheet for construction of pressurized tanks to contain liquid (and gaseous) oxygen as a rocket fuel. The work was performed under provisions of USAF Contract No. 18(600)-1775.** The total project consisted of three general types of tests, namely: diaphragm puncture tests, tensile fracture tests of welded joints, and simulated micrometeoroid high velocity penetration tests.

Significant payload advantage may be obtained through the use of strong, lightweight, thin sheet titanium alloy tank structures for containing cryogenic liquids as rocket propellants. Titanium alloys possess high strength to weight characteristics, display marked increases in strength with decreasing temperature, may be very ductile and tough in base metal and weld joint configurations at cryogenic temperatures, and are resistant to general corrosion by the principal propellants. Toughness (resistance to brittle fracture), always of major importance in cryogenic pressure vessels, is especially good in the case of high purity alpha type titanium alloys (e.g., Ti-5Al-2.5 Sn) even at -423°F. Alloys of the alpha + beta type (e.g., Ti-6Al-4V) are tough at -320°F, but the results of notched and unnotched tensile tests show that they tend to become brittle at -423°F.

Earlier work[(1)(2)(3)*] has indicated the sensitivity of titanium to violent reaction when it is impacted in the presence of liquid oxygen. Nevertheless, consideration of the unique conditions which appeared to be required in order to initiate the reaction gave rise to a tentative conclusion that titanium alloys could be used safely in contact with oxygen provided that the reaction is not started by a sudden compressive impact. The reaction is not spontaneous and requires energy to initiate it. The present work was undertaken in order to explore more fully the conditions under which the titanium-oxygen reaction will occur; and, in particular, to demonstrate whether a catastrophic reaction will result from certain specific conditions of normal or accidental occurrence when gaseous or liquid oxygen is contained in a thin-walled titanium alloy tank. That is, the tests undertaken tend to simulate conditions which could occur in service.

It is well established that oxide films form readily on the surface of reactive metals, and that such films or coatings often inhibit any further reaction. It then becomes necessary to expose a fresh surface of the metal to promote a reaction. Hence, it was deemed logical to investigate the oxygen-reactivity of titanium by tests which fracture the metal and expose a clean unoxidized surface while it is in contact with liquid or gaseous oxygen. This was accomplished by each of the three basic types of tests: (1) diaphragm puncture tests; (2) tensile fracture tests of weld joints; and (3) simulated micrometeoroid puncture tests. The first of these is described in some detail in this report. The results of the other two parts of the project were reported separately, see references 5, 6, and 7; hence, most of the details of these tests will not be included here. However, brief discussions of the results will be given in order to provide a comprehensive picture of the program.

* See list of References.

** Contract No. NAS 8-2664

2 BACKGROUND

Instances of the violent reaction of titanium alloys with oxygen date back several years; and these occurrences prompted a number of test programs within the missile industry and by associated organizations. Most of the early investigations concerned "LOX impact sensitivity" which is determined by compressive impact of a flat-face striker on the material in the presence of liquid oxygen. Such tests were conducted by Astronautics as well as by other companies,[8] including Aerojet-General, Battelle Memorial Institute, Army Ballistic Missile Agency, Martin-Denver, Wright Air Development Center, North American-Rocketdyne, and Reaction Motors, Inc. A high incidence of reaction between titanium and liquid oxygen was obtained by all of these organizations with the standard test involving 70 ft-lb. of impact energy. Under lighter impacts most of the investigators found that reactions also occurred but with less frequency. In one series of such tests conducted at Astronautics, however, a reaction occurred in each instance (Table VII), at least as low as the 30 ft.-lb. level. The same series of tests showed an aluminum alloy to be sensitive to LOX impact reaction, but to a considerably lesser degree than in the case of titanium.

Because of the high interest on the part of so many in the problem of oxygen-reaction sensitivity of titanium the Defense Metals Information Center has attempted to make available the latest information as it becomes known to them. Several DMIC reports [1,2,4,8] have been issued which summarize the results of titanium-oxygen tests. In addition, the investigations conducting LOX sensitivity work at Battelle under USAF contracts have reported[9,11] on their work which is aimed at understanding the mechanism of the reaction.

The results of the LOX-sensitivity compressive impact tests clearly indicated that titanium alloys are sensitive to reaction when impacted at energy levels lower than that considered acceptable for materials to be used in LOX systems, i.e., no reactions should occur in 20 impacts at 70 ft-lb. impact energy when a flat faced striker impacts the test material immersed in a cup of liquid oxygen.

It appears that a unique set of conditions occurs in the compressive impact test which initiates the reaction with LOX. The reactants are suddenly and forcefully brought together by the blow and the reaction appears to be initiated by the frictional heat of the impact. A clean unoxidized surface may be generated by the blow, and sparks can occur (minute metal particles which are readily oxidized).

The physical properties of titanium alloys are such as to explain, in part at least, their higher sensitivity to the oxygen-reaction. Titanium has (1) low thermal conductivity and low heat capacity on a volume basis, resulting in the development of a high temperature and slow heat dissapation for a given heat input; (2) it has a low ignition temperature in an oxygen atmosphere, (3) the titanium-oxygen reaction is highly exothermic, thus ample heat is generated to sustain the reaction, and (4) titanium oxides, the products of the reaction, are highly soluble in the molten metal at the reacting interface, thereby maintaining sufficient contact of unprotected titanium metal with oxygen to allow the reaction to proceed with little or no retarding effect of the oxide layer.

The conditions which occur in the compressive impact test are not representative of service conditions as missile tanks. Hence, results of these tests should not be the sole criterion for designation of "LOX-compatible" materials for missile structures. This view was held both by Astronautics personnel and by others concerned with the problem. Therefore, a variety of tests have been conducted which tended to simulate in various degrees the conditions of service as thin-wall missile propellant tanks. Specifically, tests which involve fracture of the metal while in contact with oxygen were deemed necessary. For example, a series of tests were performed at GD/A in which sheet specimens were punctured by a cone or chisel-shaped tool while they were totally immersed in liquid oxygen.[12] A photograph of the fixture used is shown in Figure 20. A reaction did not occur in any of these tests. Twenty specimens were punctured of each of the materials. These consisted of Type 301 stainless steel, aluminum alloys 2024-0 and 6061-T6, K-monel, and titanium alloys Ti-6Al-4V, Ti-5Al-2.5 Sn, and Ti-75A. Gaseous oxyten pressure-surge tests[12] conducted by Astronautics also resulted in no reaction.

Other investigators reported that reactions did occur in some instances when titanium was fractured under LOX[9]. Menasco Mfg. Co. reported that a 1/4" diameter test bar which was fractured while immersed in LOX showed some evidence of burning on the fracture surfaces and on the threaded grip-ends. A similar bar fractured in the gaseous oxygen atmosphere over LOX did not react. Martin Co. reported that a flash of light occurred when 0.063 x 0.375" titanium test bars were fractured in LOX but no evidence of burning was observed on the surfaces. Both Titanium Metals Co. and Aerojet-General ruptured titanium sheet while it was immersed in LOX under pressure without occurrence of a reaction. The latter company also fractured end-supported titanium specimens by center-point loading under LOX. They reported that one out of ten specimens ignited.

In the work conducted at Battelle Memorial Institute[9] fresh titanium surfaces were made by fracturing or gauging the metal under LOX. In only a few instances was there evidence of a reaction at the fractured surfaces. Reaction did occur at pin-grip holes on the specimens due to compressive impact as the specimen halves rebounded against the pins. In tensile fracture tests in high pressure gaseous oxygen[11] they found that reaction occurred at the fracture surfaces. Occurrence of the reaction appeared to be dependent upon both pressure and temperature. They obtained no reactions below 75 psig between -300 and +75°F. They concluded that the reaction occurs only when the oxygen is in the gaseous state and is above some threshold pressure which is dependent on its temperature. Thus, according to the hypothesis, heat must be generated at a local spot to gasify LOX in order to initiate a reaction.

In recent work conducted by NASA, Marshall Space Flight Center, stainless steel, aluminum, and titanium alloy sheet specimens were placed in contact with LOX and detonated by primacord or other explosive materials. A variety of test configurations were used. Some of these subjected the reactants only to a shock wave, while others created mechanical rupture. The test results indicated that both the titanium and aluminum alloys reacted with oxygen when the reaction was initiated by the explosive; the titanium however, reacting with much greater frequency than the aluminum alloys.

3 DESCRIPTION OF DIAPHRAGM PUNCTURE TESTS

3.1 TEST EQUIPMENT AND PROCEDURE

The diaphragm puncture tests simulated the occurrence of an accidental puncture of a pressurized propellant tank, e.g., the puncture of a tank containing liquid or gaseous oxygen by a falling tool or other sharp object. A drop-weight type of apparatus, shown in Figure 1, was available for conducting the tests. The falling weight was equipped with puncture tools of various configurations such as a conical point or flat chisels of desired size or shape. The test vessel consisted of a vertical 4" diameter x 6" high heavy-wall stainless steel chamber to which the thin sheet diaphragm test specimen was attached with a bolt-on flange-ring, see Figures 2 and 3. The diaphragm was positioned at an angle in an attempt to promote the condition of maintaining liquid oxygen against the inner surface of the diaphragm until the moment of puncture. Filling, pressurization, and relief of the vessel was accomplished through insulated lines and valves. A temporary test site, isolated from routine operations because of the hazard involved in handling liquid oxygen, was set up for conducting the tests. A view of the site is shown in Figure 4.

In conducting the tests care was taken to ensure that dirt, grease, or other foreign matter was removed from the diaphragm specimen, the puncture tool, and other parts of the apparatus before each test. The cleaning procedure consisted of wiping the parts vigorously with clean cheesecloth soaked in either methyl ethyl ketone or oxylene and was followed by wiping with a clean dry cheesecloth. Specimens were stored in clean plastic bags and were handled only with clean cloth gloves. The cleaned specimen was bolted onto the test tank; a pressure-tight seal was accomplished with a stainless steel "o"-ring. After filling the tank with gaseous or liquid oxygen to the desired pressure the weighted penetrator was released from a latch actuated with a solenoid. The falling penetrator was permitted to puncture through the diaphragm and was arrested by a heavy chain.

For conducting the tests with liquid oxygen the latter was transferred to the test tank through insulated copper lines by pressurizing a small dewar. Sufficient liquid was permitted to exhaust through an elevated line to ensure cool-down of the tank before closing the system. In each case the puncture of the diaphragm occurred within 5 to 15 seconds after the system was closed. It is assumed that the boil-off was small during this time. However, the pressure was permitted to rise to 30 psig before puncturing the diaphragm. It is possible that a film of gaseous oxygen existed at the inside surface of the diaphragm, even though the tank may have been nominally "full" of liquid oxygen to the top of the diaphragm at the moment of puncture. Thermocouples attached to the exhaust line at the test tank indicated a temperature of approximately -298°F at the time the diaphragm was punctured.

The gaseous oxygen tests were conducted at ambient temperature. Type K pressure bottles were used to supply the oxygen to the test tank.

Puncture tools made of steel or of beryllium-copper were used in the tests. They consisted of chisel or cone-shapes as shown in the sketches, Figures 5, 6, and 7. The beryllium-copper alloy was selected to eliminate sparking which could initiate the titanium-oxygen reaction. It was desired to ascertain if penetration of tanks by non-sparking tools would lessen or completely eliminate the reaction hazard.

3.2 TEST PROGRAM AND RESULTS

The principal objective of this part of the program was to determine under what conditions the rapid puncture of a thin-wall titanium tank will cause reaction with liquid or gaseous oxygen. An additional objective of the puncture tests was to compare the oxygen-reactivity behavior of the titanium alloys with that of aluminum and stainless steel alloys. Thus, for each type of test described diaphragm specimens were tested which were cut from titanium alloy sheet as well as from aluminum alloy 2024-T3 and from Type 301 stainless steel sheet. Factors which were varied in order to note their effect upon the reactivity included the kind, size, and shape of the puncture tool (see Figures 5, 6, and 7), the pressure within the test chamber, as well as the type and thickness of the test diaphragm. In addition, some puncture tests were conducted on titanium alloy diaphragms which had been coated with various materials in order to determine whether they may retard or eliminate the susceptibility to reaction. Mixtures of helium and gaseous oxygen also were used for some tests in an attempt to note the limiting condition for reaction.

A total of 339 puncture tests were performed using gaseous oxygen as the test medium. A log of the conditions for each of these tests is given in Table I. Liquid oxygen was the test medium in 52 tests as shown in Table II. Summaries of the results of the puncture tests of uncoated diaphragms in the presence of gaseous oxygen and liquid oxygen are shown in Tables III and IV, respectively. Tables V and VI contain the corresponding information for the tests conducted on coated diaphragms.

Compressive impact tests made previously on a drop-weight apparatus using a flat-face striker on titanium alloy sheet specimens resulted in positive reactions in a large percentage of the tests; see Table VII. Tests of this type were also performed during this investigation using titanium alloy sheet specimens which had been coated on both surfaces with either mineral oil or with the corrosion inhibitor WD-40. The results of these tests are shown in Table VIII.

4. DISCUSSION OF PUNCTURE TEST RESULTS

It will be noted by an examination of the data shown in Tables III and IV that neither aluminum alloy 2024-T3 nor stainless steel 301-XFH reacted with liquid or gaseous oxygen when they were punctured. The titanium alloy diaphragm specimens did react, however, in a large percentage of the tests. For reasons which are not evident the results of the titanium tests do not appear to be entirely consistent; repetition of a given test did not always produce the same result. Nevertheless, the pyrophoric reaction of titanium did occur in these puncture tests with sufficient frequency to show clearly that a similar puncture of a titanium missile tank containing liquid or gaseous oxygen would be very likely to result in its catastrophic destruction. The type of spectacular burning which ensues is illustrated by the sequence photographs of the drop-weight puncture tests shown in Figures 8, 9, and 10. The photographs in Figures 11 through 14 show the extent of damage in test No. 22-L in which Ti-5Al-2.5 Sn was punctured. In this test the container was filled with LOX; however, the rapid heat input through the diaphragm due to the ambient temperature may have produced a layer of oxygen at the inside surface. In many tests the diaphragm was only partially consumed as shown by the photographs in Figures 15 through 29. Among other factors, undoubtedly, the quantity of gaseous oxygen available (pressure) will affect the extent of the burning. Thus a correlation was expected between the pressure and the incidence of reaction. The data of Table III does not show such a correlation for the tests employing a conical penetrator. However, in the tests in which the chisel penetrators were used the frequency of severe burning reactions appeared to be increased by increasing the gaseous oxygen pressure in the chamber. A threshold pressure below which the reaction does not occur was not found. Punctures made while the gaseous oxygen in the chamber was at atmospheric pressure caused reaction in 3 out of 6 tests (Test Nos. 52 through 57). Tests in which liquid oxygen was used were conducted at a uniform pressure, 30 psig.

The frequency of a reaction characterized by severe burning appeared to be greater when liquid oxygen rather than gaseous oxygen was used. This conclusion would appear to be contrary to that reached at Battelle. If, however, an initial layer of gaseous oxygen did occur at the inside surface of our diaphragm in the LOX tests, as mentioned earlier, then the greater frequency of severe reactions may be attributable to the larger quantity of oxygen available as the liquid is changed to gas by the heat of the reaction.

In an effort to gain further knowledge about how the reaction is initiated by the rapid puncture, tests,nos. 109 through 122,were run to determine whether a greater sharpness of the chisel-edge influenced the frequency of initiating a reaction. The results appear inconclusive as to this point.

The conical and chisel-type penetrators referred to thus far were made of hardened steel. In addition. 18 puncture tests (nos. 197-214) were run in which either conical or chisel-edge penetrators made of beryllium copper (non-sparking) were used. Of these, 5 resulted in only slight reaction and 10 tests produced no reaction at all (see Figures 15 and 17). Three punctures by a beryllium copper penetrator initiated a positive reaction. Thus, while it appears that sparks generated by the puncturing tool probably assist in initiating the reaction this is not an absolutely essential or controlling factor.

Eight tests were performed to determine the approximate extent to which dilution of the gaseous oxygen by helium is effective in retarding the reactivity; see tests nos. 218 through 226. In three tests in which the proportion of oxygen to helium was 7 to 1 only one resulted in a reaction while two did not. Proportions of helium in the mixture equal to or greater than 25% by volume appeared to prevent occurrence of a reaction.

Tests were also conducted in which gaseous hydrogen was used in the chamber at pressures as high as 55 psig. No reaction was noted in 10 tests using diaphragms made of 301 stainless steel, aluminum 2024-T3 or Ti-5Al-2.5 Sn. The sequence photographs of test no. 152, Figure 21, provide a clear view of the puncture operation. It is interesting to note that the penetrator rebounds clear of the punctured diaphragm. It is not known to what extent the friction between the penetrator and the edges of the puncture contributes to initiation of the reaction.

A large number of the tests were conducted in order to determine whether the pyrophoric reaction could be retarded or prevented by some suitable method. A number of coatings or cover materials were tried. Sprayed or wiped-on coatings of two commercial corrosion inhibitors, WD-40 and CRC 3.36, appeared to retard the severity of the pyrophoric reaction, see data in Table V, but they had little or no effect upon the rate of incidence of the reaction. Figure 22 shows sequence photographs of one of the tests in which no reaction was initiated. Figure 23 is a close-up view of the test chamber after the diaphragm was punctured. It appears that the corrosion inhibitor may tend to remove heat and thereby retard the extent of the burning. Two other liquid materials, mineral oil and duPont 703 pump oil, were wiped onto the surface of titanium alloy test diaphragms as a thin film. Based on the relatively few tests conducted (3 tests with each oil) these materials appeared to have no effect upon the initiation or propagation of the reaction.

As a further check on the influence which coatings of WD-40 and mineral oil have on the titanium-oxygen reaction, an additional series of drop-weight compressive impact tests were performed. A flat-face striker was used. The test results are shown in Table VIII. From these data it appears that one coat of WD-40 or of mineral oil has no effect. However, using three coats of WD-40 appears to retard the incidence of the reaction.

It was hypothesized that metallic coatings may serve to limit the extent of the pyrophoric reaction by abstracting heat. That is, materials having higher thermal conductivity and higher specific heat than that possessed by titanium may provide a quenching action at the point where the reaction is initiated. Accordingly, several types of metallic coatings were applied by various methods to titanium diaphragms for puncture testing. Most of these consisted of aluminum applied by dip-coating or of aluminum foil attached either by diffusion bonding, by an organic adhesive, or by simply pressing the foil in contact with the diaphragm without a bond. A total of 45 tests were conducted on aluminum coated specimens under conditions which otherwise generally resulted in severe burning of the diaphragm. Of these, 22 diaphragms burned extensively and 22 burned only slightly or not at all. Figure 17 shows typical results of these tests. The evidence indicates that aluminum in some appreciable thickness (e.g., greater than 0.001") is at least partially effective in retarding the reaction. Good contact with the titanium is probably required, but actual bonding did not appear to be necessary.

A very thin but adherent aluminum coating produced by vapor deposition proved ineffective. Thin electrodeposited coatings of copper, nickel, gold, and silver also did not limit the reaction; see Figure 16.

Seven tests were conducted using a composite diaphragm consisting of 0.005" stainless steel sheets placed on one or both sides of a 0.035" Ti-5Al-2.5 Sn diaphragm but not bonded to it. The results of these tests seem to indicate that a "barrier" of stainless sheet was at least partially effective in reducing the incidence of reaction. Of the 5 tests in which the stainless sheet was between the titanium and the oxygen when the composite was punctured only two provided a reaction. Two tests conducted with the stainless sheet on the outside only (i.e., titanium was in contact with oxygen) resulted in reactions in both cases.

As a final observation on the puncture tests, attention should be directed to the fact that sheet specimens made of three titanium alloys were employed; namely, Ti-5Al-2.5 Sn, Ti-6Al-4V, and commercially pure titanium. Furthermore, several different gages of Ti-5Al-2.5 Sn were used, ranging from 0.010" to 0.050". Upon examining the limited amount of test data as a function of these factors there does not appear to be a definite pattern. There were no clear or significant differences in the reactivities of the three alloys used. All of the titanium diaphragms used may be considered sensitive to reaction regardless of the kind or thickness of the alloy when they are punctured while in contact with liquid or gaseous oxygen.

5 DISCUSSION OF SIMULATED MICROMETEOROID PENETRATION TESTS AT GD/ASTRONAUTICS

In the tests described by Reference 6 a six-inch diameter by six-inch long pressurized cylinder was equipped with replaceable diaphragms of titanium alloy, aluminum alloy, or stainless steel. The diaphragms were subjected to penetration by 0.1 to 0.2 gram steel projectiles traveling at 10,000 to 15,000 ft/sec. An explosive charge, C-4, was used to propel the steel slugs through the diaphragms. The horizontal cylinder was filled with either gaseous or liquid oxygen prior to firing the projectile. Photographs of the test site are shown in Figures 24 and 25.

Since the projectile traveled at a high velocity in air prior to penetrating the sheet specimens it probably attained some elevated temperature due to aerodynamic heating. Thus, these particles might well be expected to initiate the oxidation reaction even more readily than puncture tests performed at lower velocities with a tool at ambient temperature. In the tests conducted this prediction was substantiated.

The tests in which the projectile perforated titanium alloy sheet in contact with either liquid or gaseous oxygen under pressure resulted in deflagration. Aluminum alloy or stainless steel sheets did not react. The burning of the titanium sheet was sometimes observed to be more extensive on either the forward or the rear diaphragm. However, no pattern of this behavior was established. No reaction occurred when the diaphragm was not punctured. The diaphragms shown in Figure 26 show the results typical of perforating the titanium alloys.

In all of the high velocity puncture tests it was noted that perforation of the diaphragm by the projectile was accompanied by oxidation of the edges of the hole. That is, the hot particle always burned the edges of the hole regardless of whether the sheet material was titanium stainless steel, or aluminum alloy. Nevertheless, only the titanium sheet proceeded to react by catastrophic oxidation. It is probably safe to assume that the hot steel pellet itself reacts to some degree with the oxygen, causing more heat. This may account for the oxidation at the edges of the holes.

The practical significance of the high velocity puncture tests is directly related to the degree to which they simulate the puncturing of a pressurized space vehicle tank by micrometeoroids. The data for the tests conducted indicate that micrometeoroid perforation of a titanium alloy tank while it contains liquid or gaseous oxygen under pressure will be likely to result in a reaction and catastrophic destruction. On the other hand, some of the tests showed that similar perforation by micrometeoroids of a tank made of stainless steel or aluminum alloy may also result in catastrophic destruction due to explosive decompression. That is, a few of the diaphragms in these tests, including some made of stainless and aluminum, were evidently punctured in such a manner that the conditions of critical crack length were exceeded and the diaphragms were ripped by explosive force.

Some of the high velocity puncture tests were performed on diaphragms which had been coated with the corrosion inhibitor, WD-40. This coating appeared to be at least partially effective in reducing the incidence of the reaction with titanium diaphragms.

6 DISCUSSION OF SIMULATED MICROMETEOROID PENETRATION TESTS CONDUCTED AT UTAH RESEARCH & DEVELOPMENT CO.

Several series of hypervelocity particle puncture tests were conducted by Utah Research & Development Co., Salt Lake City, Utah, under contract to General Dynamics/Astronautics. This work is described in Reference 7. A principal difference with respect to the procedure in the Utah tests and in those conducted by Astronautics is the fact that the high velocity particles were shot in a vacuum tank at Utah. Thus, it is assumed that the projectile was not heated by air friction.

Two types of tests were conducted. In each instance a pressurized tank similar to those used at Astronautics was equipped with sheet specimen diaphragms at both ends. The horizontal cylinder was filled with either liquid or gaseous oxygen under pressure. The high velocity particles were propelled by various means so as to impinge upon or perforate the diaphragms.

In the first series of tests high velocity particles which simulated micrometeoroids were produced by a spray technique. A primary particle or pellet was fired into a steel target at approximately 10,000 ft/sec. Micro particles emerge from the primary impact in a spray pattern. These particles, whose velocities approximate 30,000 to 45,000 ft/sec., were 5 to 15 microns in size. When permitted to impact against the pressurized test diaphragms these particles did not penetrate the 0.014" thick Ti-5Al-2.5 Sn sheet and no damage resulted.

Larger micrometeoroids were simulated using either a light gas gun or a powder gun as launching devices. Both devices employed a projectile consisting of a 1/16" diameter steel sphere which was shot directly at the diaphragm. Velocities ranged from 12,000 to 20,000 ft/sec. in this series of tests.

The results of the tests were similar to those obtained at Astronautics. They are illustrated by the photographs shown in Figures 27, 28, and 29. The titanium alloy diaphragms burned in each instance in which they were perforated by the projectile. None of the stainless steel or aluminum alloy diaphragms reacted with the oxygen. However, damage was sustained by explosive decompression when the pressurized diaphragms were punctured.

If the assumption is correct that the projectiles fired in vacuo in the Utah tests were not heated by their flight prior to penetration of the diaphragm then these tests may be said to demonstrate that the titanium-oxygen reaction will be initiated by high velocity puncture alone. Initiation does not require puncture by a hot particle.

7 DISCUSSION - STATIC TENSION AND FATIGUE FRACTURE TESTS OF WELD JOINTS

Two accidental in-service conditions which are important in respect to the possible initiation of a titanium-oxygen reaction are the failure of the metal while in contact with liquid or gaseous oxygen by (a) static tensile fracture (i.e., rapid fracture) and (b) by progressive fracture of welded joints due to cyclic stressing (i.e., initiation and slow propagation of fatigue cracks). These conditions became the basis for the third phase of the work at Astronautics.

It was shown by the work conducted by Battelle[11] that the reaction could sometimes be initiated by tensile fracture of a titanium specimen in gaseous oxygen at 75 psi and -250°F. Reactions did not occur at lower pressures. However, it was concluded that at lower pressures initiation would probably occur if higher temperatures were used. In the tests conducted by Astronautics ( ) it was desired to determine whether the reaction is initiated when titanium alloy weld joint specimens are fractured rapidly by a static tensile load or slowly by a cyclic stressing in the presence of either liquid or gaseous oxygen at 30 psig. This pressure corresponds approximately to the service condition. The gaseous oxygen tests were conducted at ambient temperature, a condition that is considered to be somewhat more severe.

Two types of weld joint specimens were fractured; a 1" wide fusion butt joint with a sharp center-notch in the weld, and a 1" wide spot welded lap joint consisting of two spotwelds in tandem. For each of the test conditions a comparison was made between the behavior of weld joints in titanium alloy Ti-5Al-2.5Sn and that of similar joints in aluminum alloy 2014-T6 and stainless steel 301XFH. The number of replicate tests conducted (from one to five) was severely limited by the available facilities. The design of the cryostatic testing chamber did not allow for ready replacement or repair of damage.

Static tensile fracture of both types of welded joints in titanium resulted in reaction with gaseous oxygen at 30 psig. Out of two spot welded joints tested one initiated a reaction; out of five tests of the notched butt welded joint one reaction resulted. In the lone static tensile test of a butt welded titanium joint in contact with liquid oxygen a reaction was obtained. The spot welded joint was not tested in liquid oxygen, since the equipment had been damaged by prior tests. In the comparison tests five specimens each of the aluminum and stainless steel alloys were fractured in either liquid or gaseous oxygen without any evidence of a reaction having occurred.

In the low cycle-high stress fatigue testing in liquid and gaseous oxygen it was desirable to cause slow progression of a crack without final rupture. Therefore, specimens were examined after each 50 load cycle and the test was stopped after a fatigue crack had developed between 0.05" and 0.10". Reactions were not initiated by the development of fatigue cracks in welded joints in either titanium, aluminum, or stainless steel alloys.

Based on the limited amount of tensile fracture and fatigue crack testing described the following was concluded: (a) rapid fracture can sometimes initiate a titanium-oxygen reaction in gaseous oxygen at 30 psig and ambient temperature or in liquid oxygen at 30 psig and -297°F; (b) slow progression of a crack in titanium is not sufficient to cause reaction. Thus, it appears that the simple presentation of a clean, unoxidized surface of titanium to liquid or gaseous oxygen at 30 psig will not cause reaction. This result conforms to the previously held theory concerning initiation of the reaction; namely, the reaction of solid titanium with oxygen is not spontaneous but must be initiated by input of energy (e.g., heat energy due to friction, compression, etc.). The rapid fracture which occurs in the static tension test undoubtedly creates some frictional heat at the fracture surface. Furthermore, rapid fracture should be more prone to cause separation of very minute metal particles at the fracture surface. Such particles would oxidize spontaneously causing a further evolution of heat.

8 SUMMARY AND CONCLUSIONS

Based on the results of the tests discussed in the foregoing section, the following conclusions may be set forth:

1. In puncture tests in which titanium alloy sheet specimens were rapidly pierced by a sharp penetrator while the sheet was in contact with gaseous oxygen a catastrophic combustion reaction usually occurred. A reaction did not occur in those cases in which the sheet specimen was made of aluminum alloy 2024-T3 or Type 301-XFH stainless steel.

2. Similar puncture tests in which liquid oxygen was placed in back of the titanium sheet likewise resulted in the spectacular oxidation reaction. The reaction did not occur when either aluminum 2024-T3 or 301 XFH stainless were substituted for the titanium.

3. The rate of incidence of severe burning reactions when titanium alloy sheet is punctured while in contact with oxygen appears to increase directly with increasing pressure of the oxygen; but a minimum threshold pressure below which the reaction was not initiated was not found.

4. Use of a non-sparking beryllium-copper puncture tool instead of hardened steel appears to decrease the probability of the occurrence of a reaction, but some reactions still occur.

5. The incidence of reaction was decreased by substituting a helium plus oxygen gas mixture for pure oxygen in the puncture test. Proportions of helium in the mixture equal to or greater than 25% by volume appeared to prevent occurrence of a reaction.

6. A reaction did not occur when either titanium, aluminum, or stainless steel sheet was punctured while it was in contact with gaseous hydrogen.

7. Coating the titanium sheet with a corrosion inhibitor, WD-40, appears to retard the severity of the pyrophoric reaction in the puncture test, probably by absorbing some heat; but it does not decrease the rate of incidence of the reaction in this test. When three coats of WD-40 were applied to flat-face compressive impact test specimens, however, the rate of reaction incidence was retarded.

8. Coating the titanium sheet with aluminum foil or with an aluminum dip-coat appears to be at least partially effective in retarding the severity but not the rate of incidence of the reaction. A thin vapor deposit of aluminum and electrodeposited coatings of either copper, nickel, gold, or silver are ineffective. A stainless steel sheet, 0.005" thick, placed between the titanium and the oxygen appears to be at least partially effective in reducing the incidence of reaction.

9. There does not appear to be significant differences in the oxygen reactivity among the three titanium alloys used in the puncture tests.

10. In tests in which very small steel projectiles traveling at high velocities so as to simulate micrometeoroids in space were caused to perforate titanium sheet diaphragms acting as a part of the wall of a pressurized, oxygen-filled vessel the catastrophic oxidation reaction was initiated. This was true regardless of whether the vessel contained gaseous or liquid oxygen. No reaction occurred when the diaphragm was not penetrated by the impinging particles. Perforation of aluminum alloy or stainless steel diaphragms under the same conditions did not cause a reaction.

11. The burning reaction was initiated when titanium diaphragms were punctured by high velocity particles regardless of whether the particles traveled in air or in vacuo before penetrating the sheet.

12. The hazard to pressurized space vehicles due to possible puncture by micrometeoroid particles consists of both (a) the catastrophic deflagration (i.e., the case of reaction of titanium tankage with liquid or gaseous oxygen contained in the tanks), and (b) explosive decompression (i.e., the violet ripping apart of the tank regardless of the kind of metal of which it is constructed. The latter occurrence is a possibility if the puncture exceeds the conditions of critical crack propagation.

13. Initiation of the titanium-oxygen reaction by perforating with high velocity particles appeared to be retarded to some degree by coating the sheet specimens with WD-40 corrosion inhibitor. This was true in the case of contact with gaseous oxygen but was not true when liquid oxygen was in contact with the diaphragm specimens.

14. The titanium-oxygen reaction may be initiated by the relative rapid fracturing of welded joints by static tensile loading. Both resistance spot welds and Heliarc butt welds reacted some of the time in the limited number of tests in gaseous oxygen (1 out of 2 spot welds, 1 out of 5 butt welds).

15. Slow propagation of a crack in Heliarc butt welded joints in titanium do not initiate the titanium oxygen reaction.

16. Neither rapid fracture nor slow propagation of cracks in welded joints in aluminum or stainless steel alloys will initiate a metal-oxygen reaction.

17. In view of the high incidence of the titanium-oxygen reaction obtained in the tests conducted it is recommended that thin-walled tanks constructed of titanium alloys should not be used to contain liquid or gaseous oxygen.

ACKNOWLEDGEMENT

The authors with to acknowledge the valuable assistance given by S. Naber, R. Neie, J. Whitehead and H. Anderson of the Engineering Test Support Department of Astronautics in conducting the tests described. Special thanks are also due A. Hurlich, Chief, Materials Research Group for counsel and helpful comment throughout the program.

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11. J. D. Jackson, et al., "A Study of the Mechanism of the Titanium - Liquid Oxygen Explosive Reaction", ASD-TR-61-479, 8-31-61.

12. J. Hertz, "Modified LO_2 Impact Tests", GD/A Report MRG-207, Jan. 10, 1961.

FIGURE 1. DROP-WEIGHT APPARATUS USED TO PUNCTURE PRESSURIZED DIAPHRAGMS. The camera in the foreground automatically recorded rapid sequence photographs of the burning diaphragm.

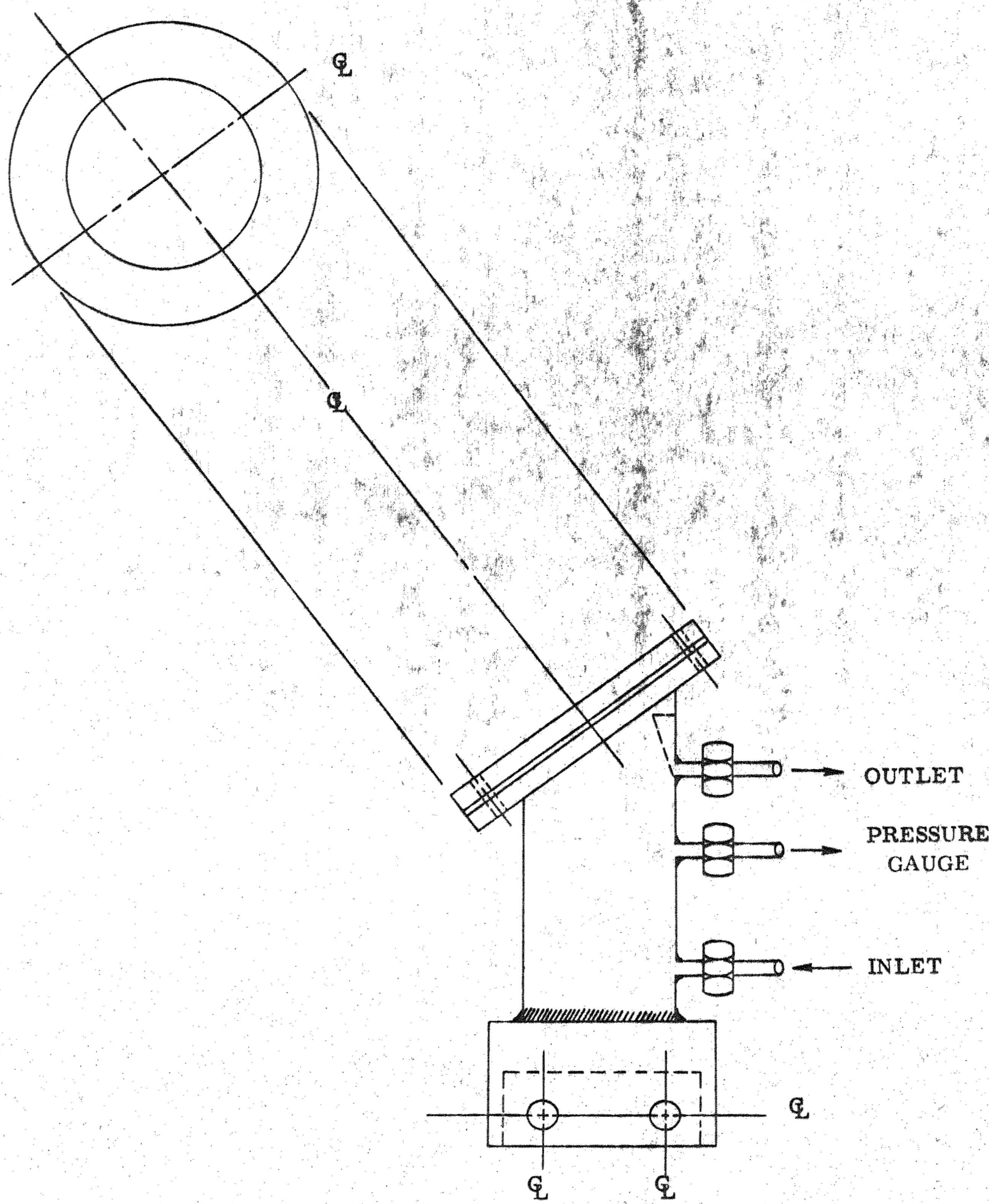


FIGURE 2. DIAGRAM OF PUNCTURE TEST TANK.

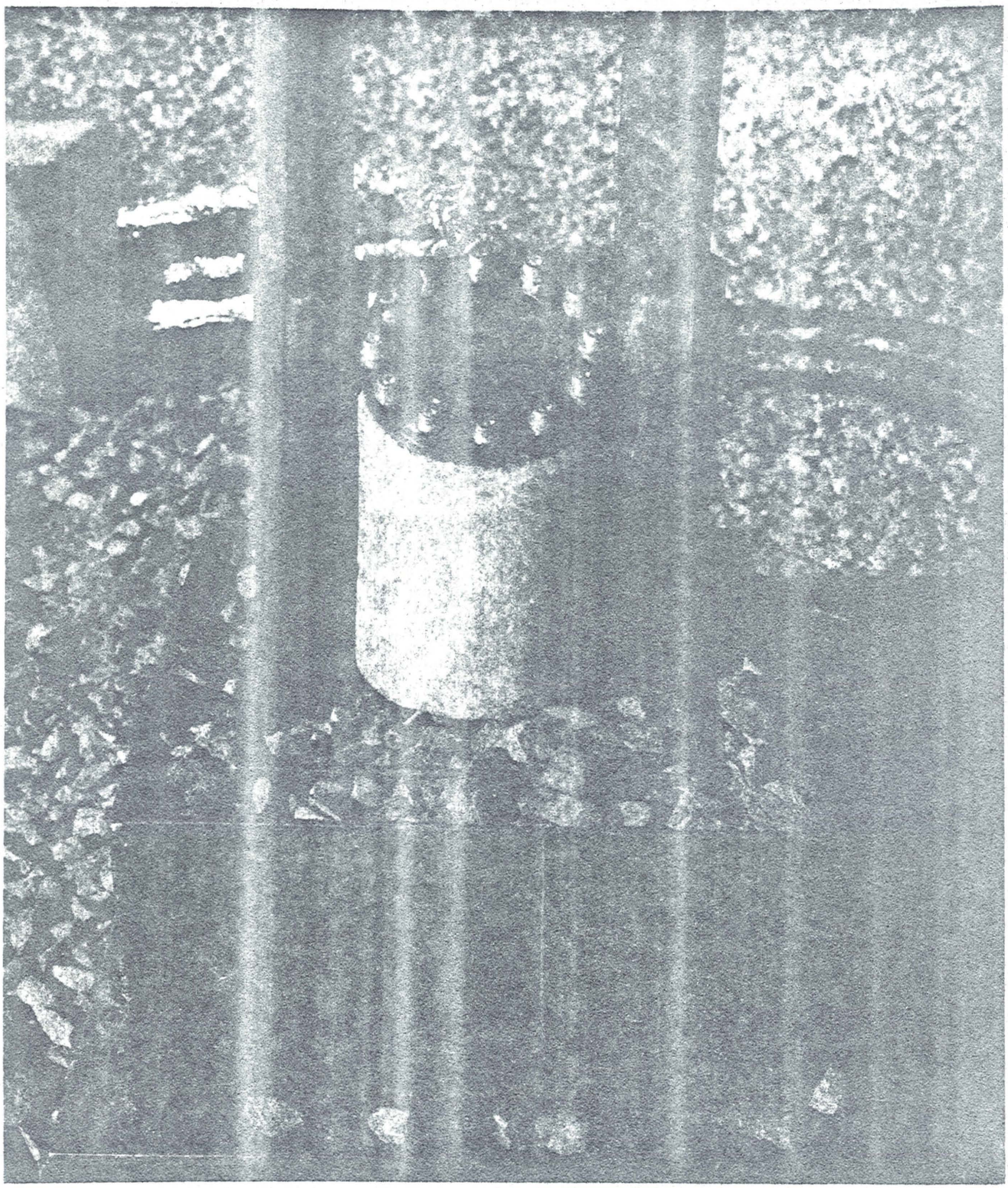


FIGURE 3. CLOSE-UP PHOTOGRAPH OF TEST TANK IN THE PUNCTURE APPARATUS. Note that foam insulation was used on the tank to limit the rate of boil-off

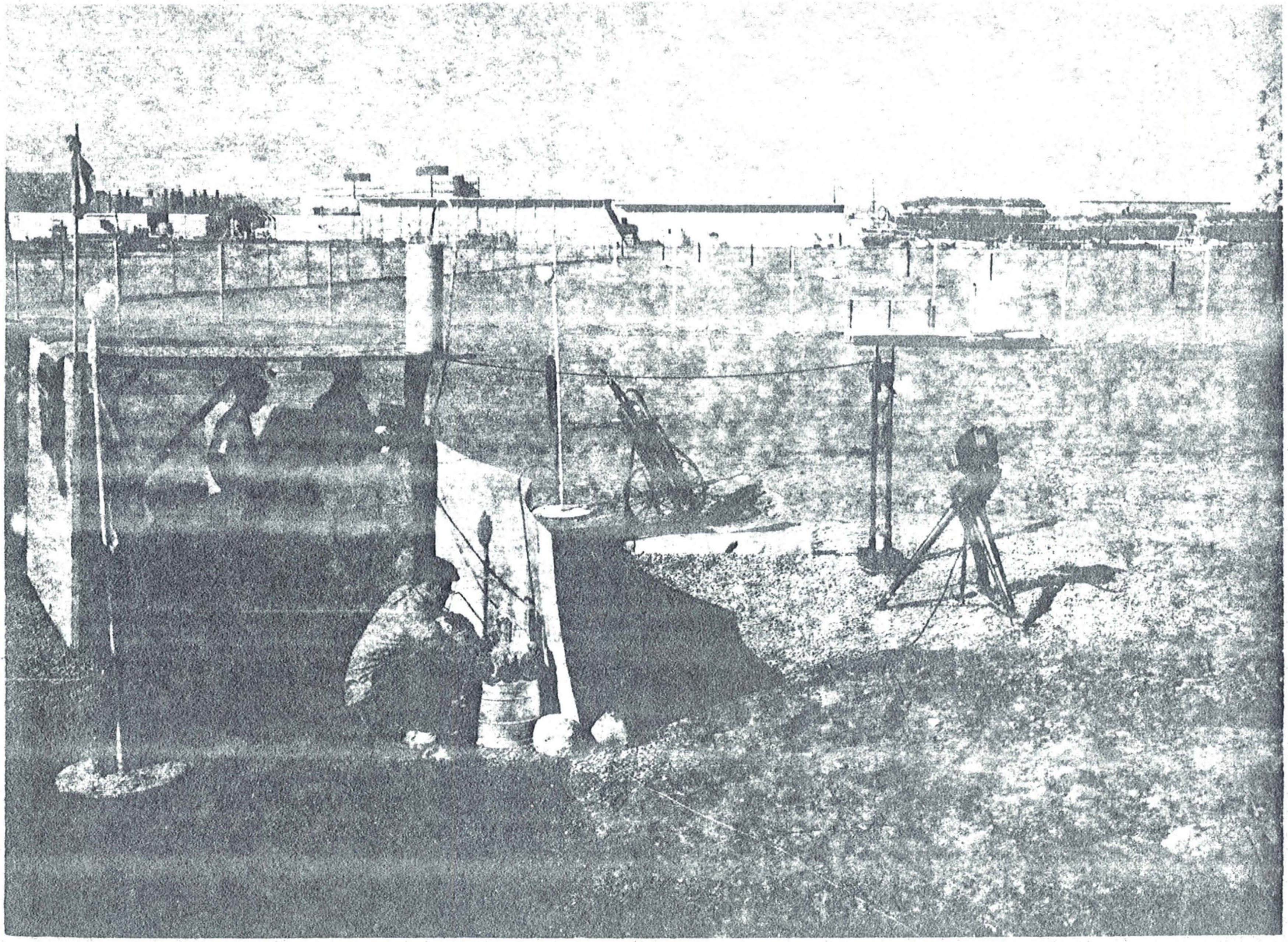


FIGURE 4. TEMPORARY LIQUID OXYGEN TEST SITE USED FOR PUNCTURE TESTS OF PRESSURIZED DIAPHRAGMS.

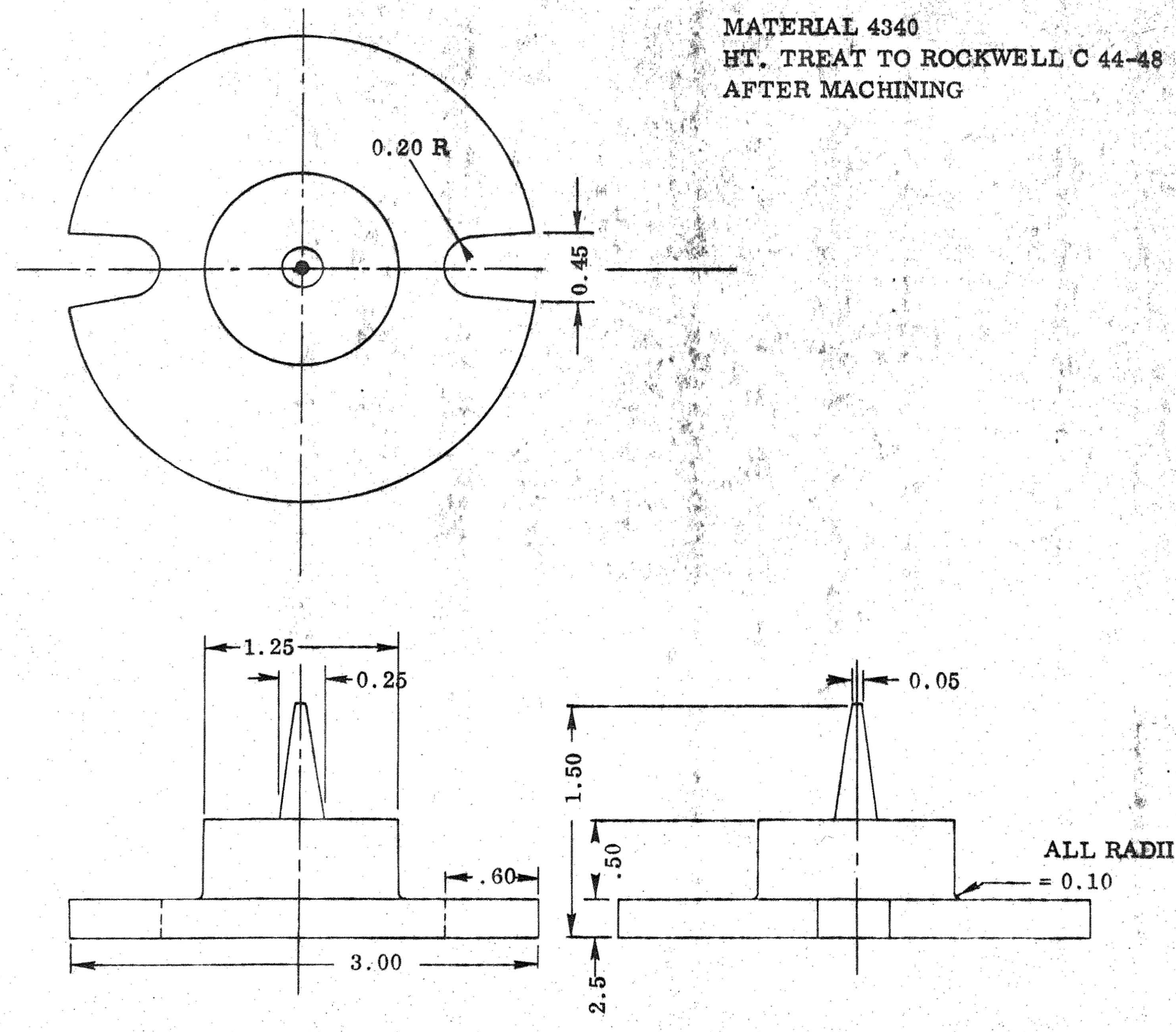


FIGURE 5. CONICAL PLUNGER - MRG D 35.

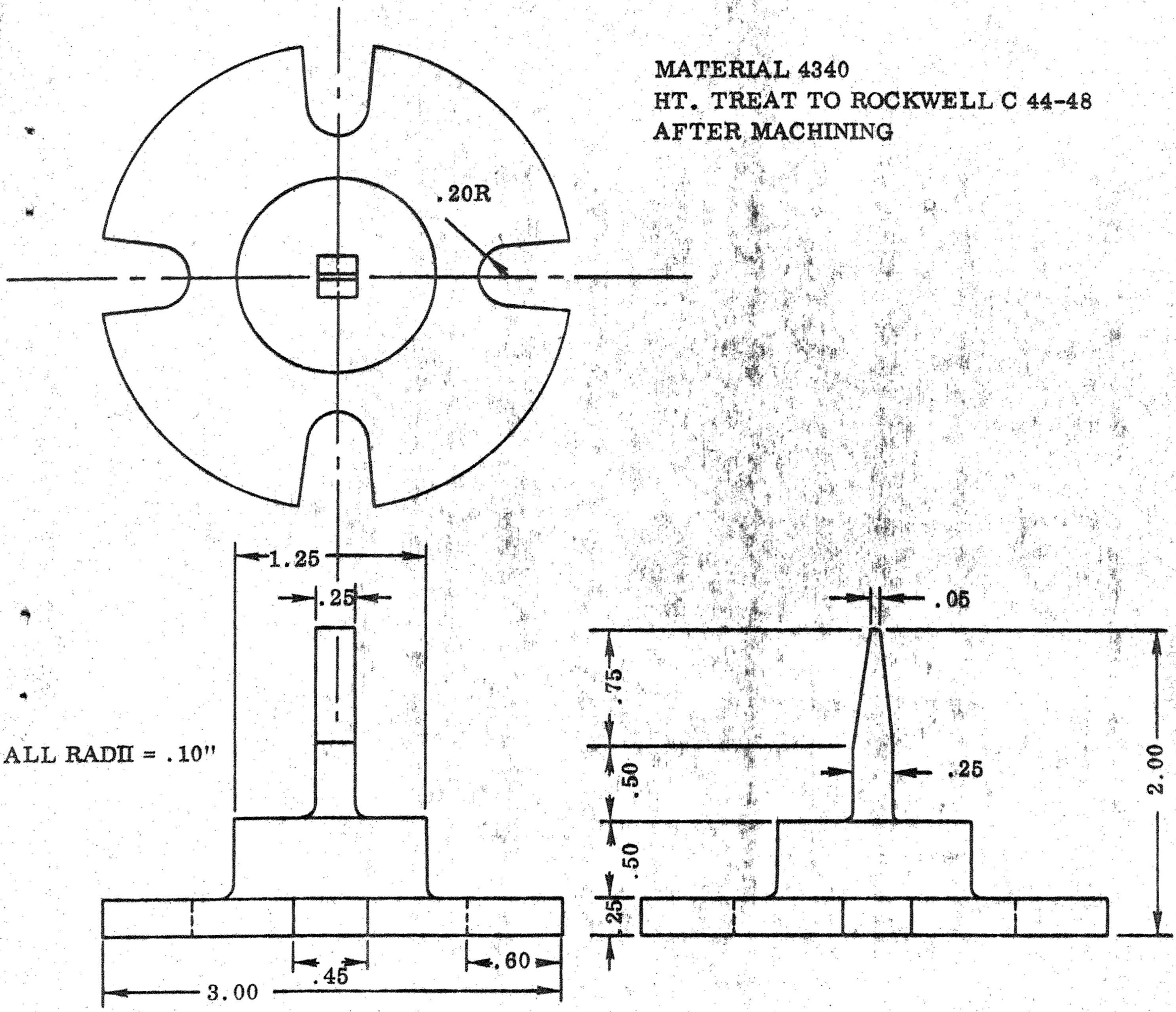


FIGURE 6. 1/4" CHISEL PLUNGER - MRG D 37.

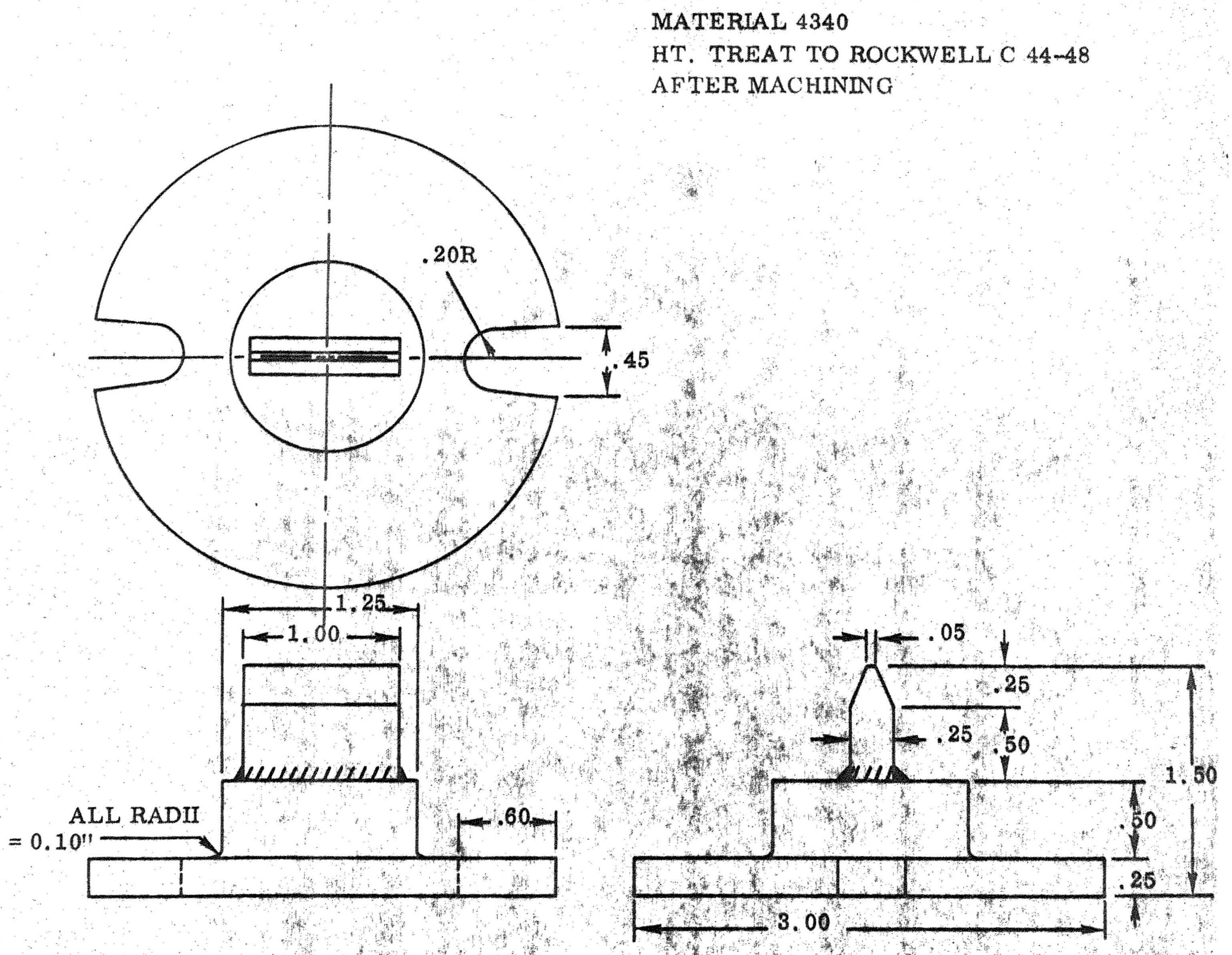


FIGURE 7. 1" CHISEL PLUNGER - MRG D 34.

Test No.	100
Material	0.016" Ti-6Al-4V
Test Medium	GOX
Pressure	30 psig
Puncture Tool	1" Steel Chisel
Puncture Energy	45 ft. lbs

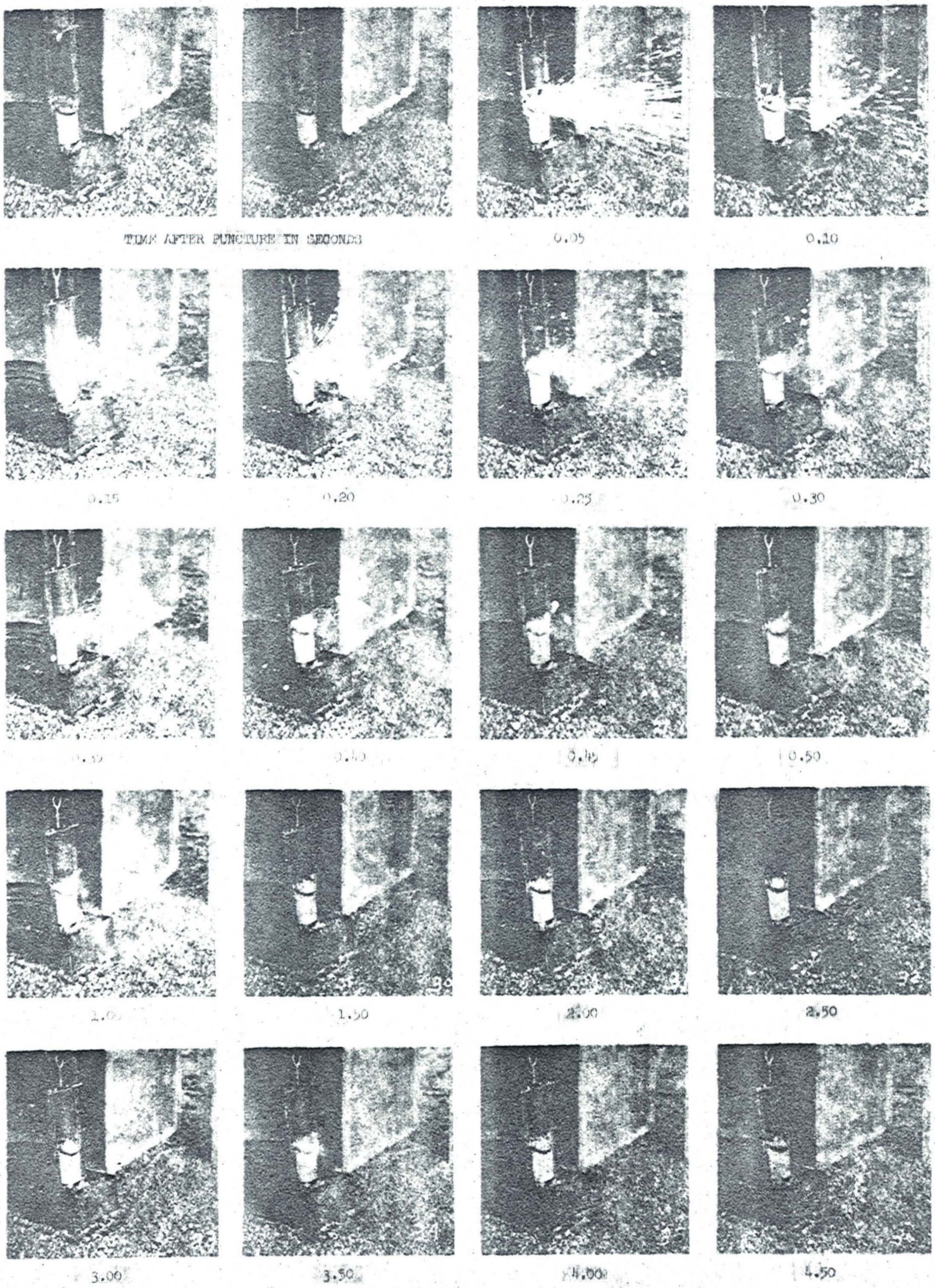
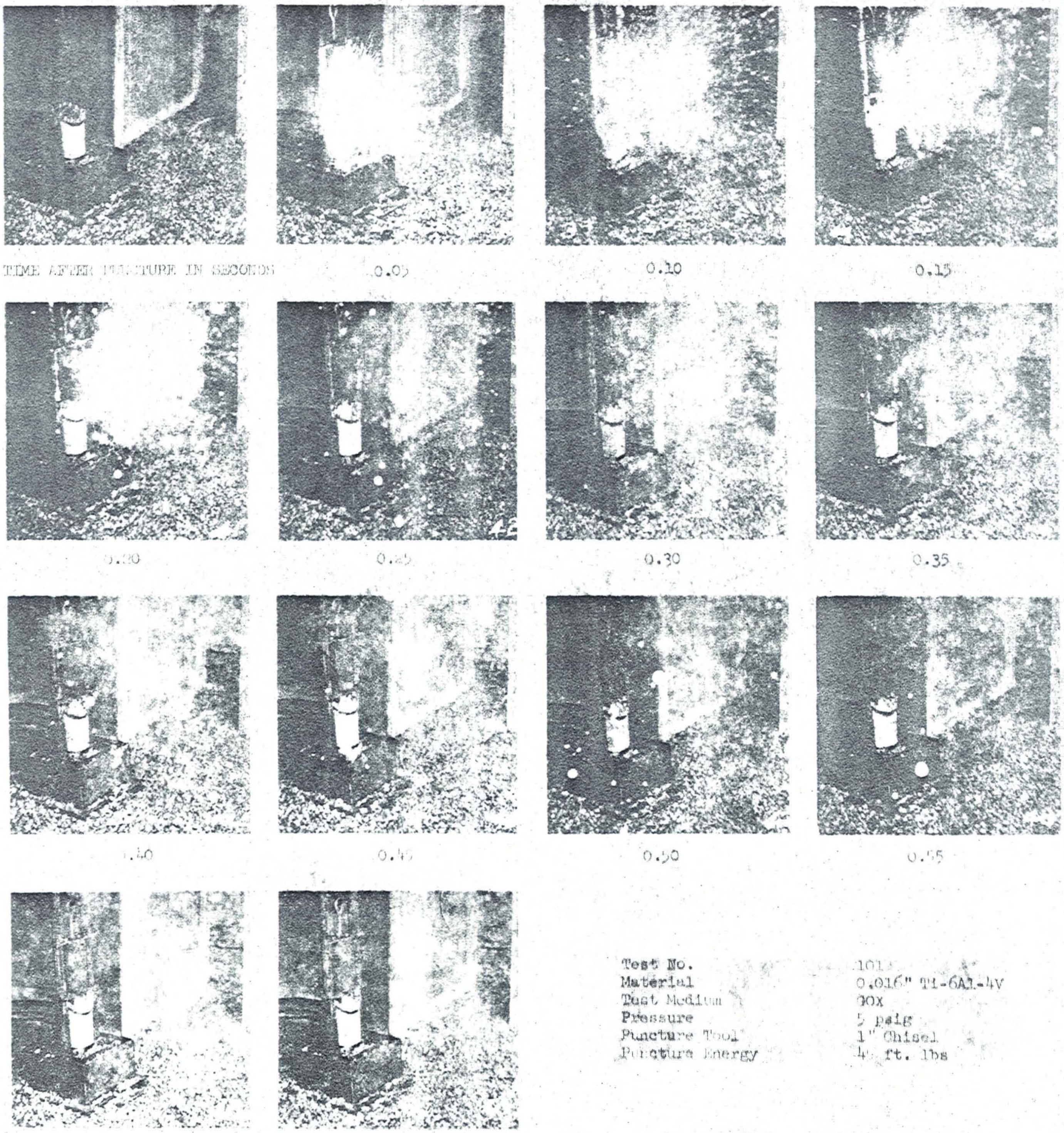


FIGURE 8. SEQUENCE PHOTOGRAPHS OF DROP-WEIGHT PUNCTURE TEST OF TI-6AL-4V DIAPHRAGM IN CONTACT WITH GASEOUS OXYGEN AT 30 PSIG. TEST NO. 100.



Test No.	101
Material	0.016" Ti-6Al-4V
Test Medium	GOX
Pressure	5 psig
Puncture Tool	1" Chisel
Puncture Energy	4[illegible] ft. lbs

FIGURE 9. SEQUENCE PHOTOGRAPHS OF DROP-WEIGHT PUNCTURE TEST OF TI-6AL-4V DIAPHRAGM IN CONTACT WITH GASEOUS OXYGEN AT 5 PSIG. TEST NO. 101.

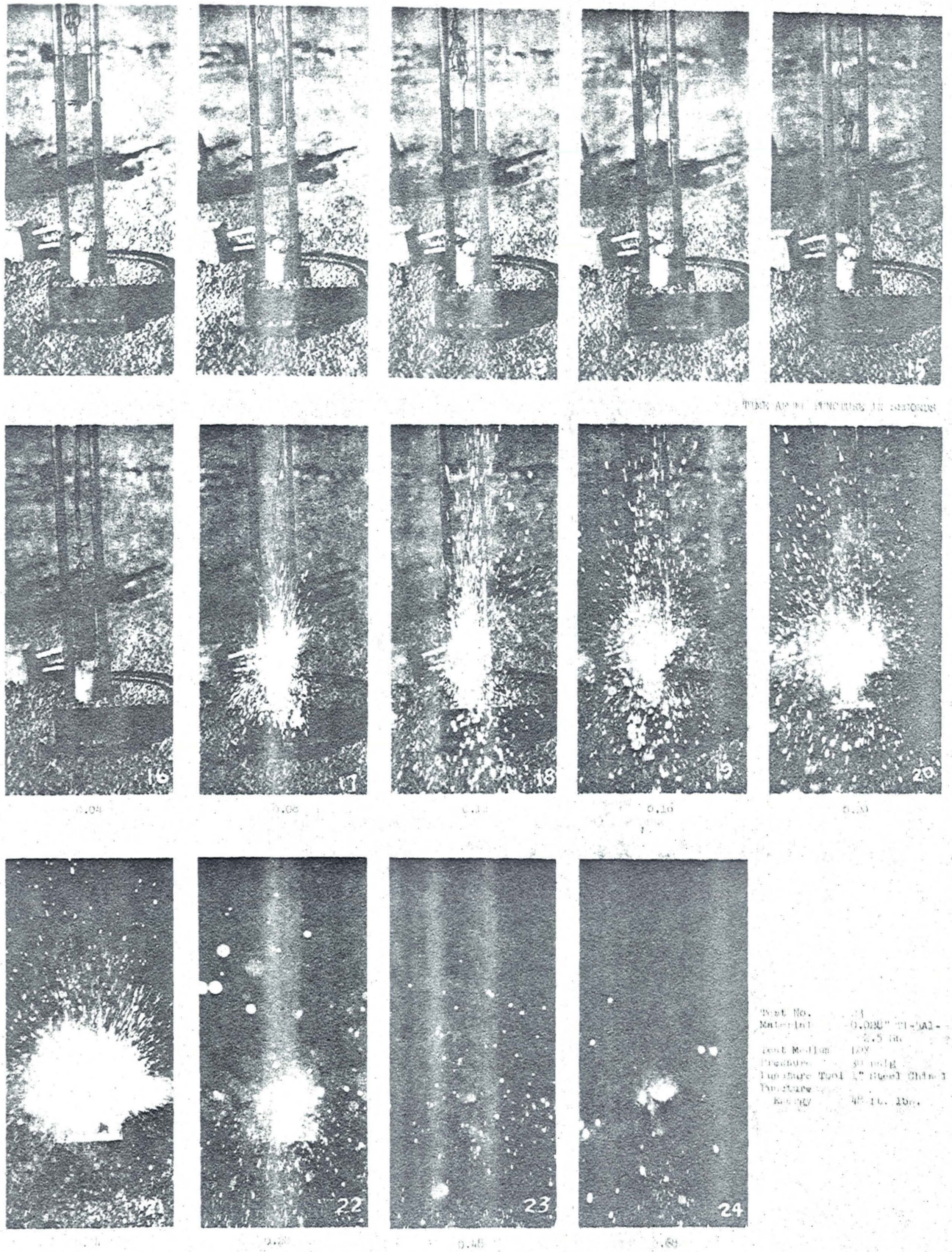


FIGURE 10. SEQUENCE PHOTOGRAPHS OF DROP-WEIGHT PUNCTURE TEST OF TI-5AL-2.5Sn DIAPHRAGM IN CONTACT WITH LIQUID OXYGEN AT 30 PSIG. TEST NO. 23.

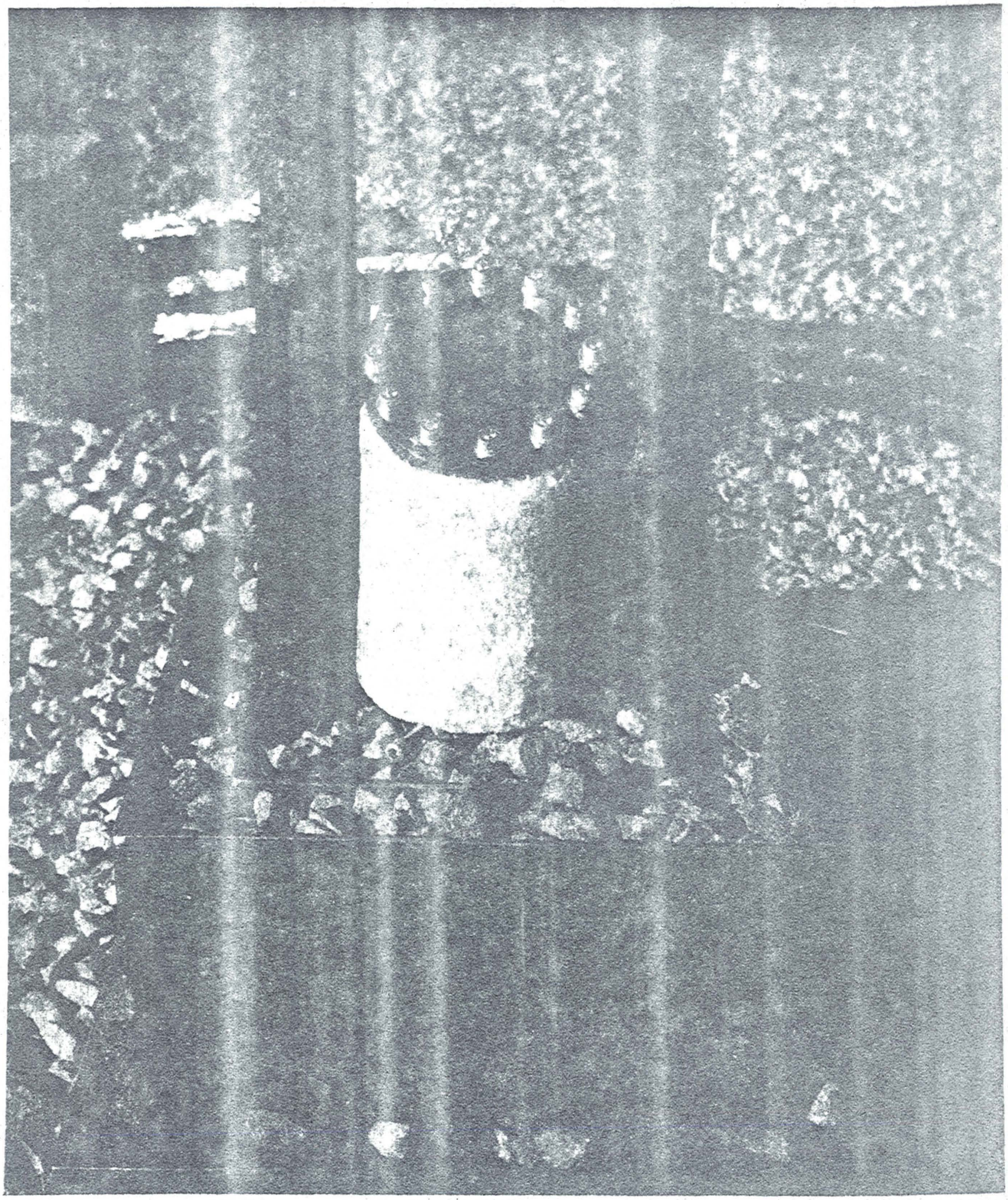


FIGURE 11. 0.028" TI-5AL-2.5Sn TARGET ATTACHED TO TEST CHAMBER. TEST NO. 22-L.

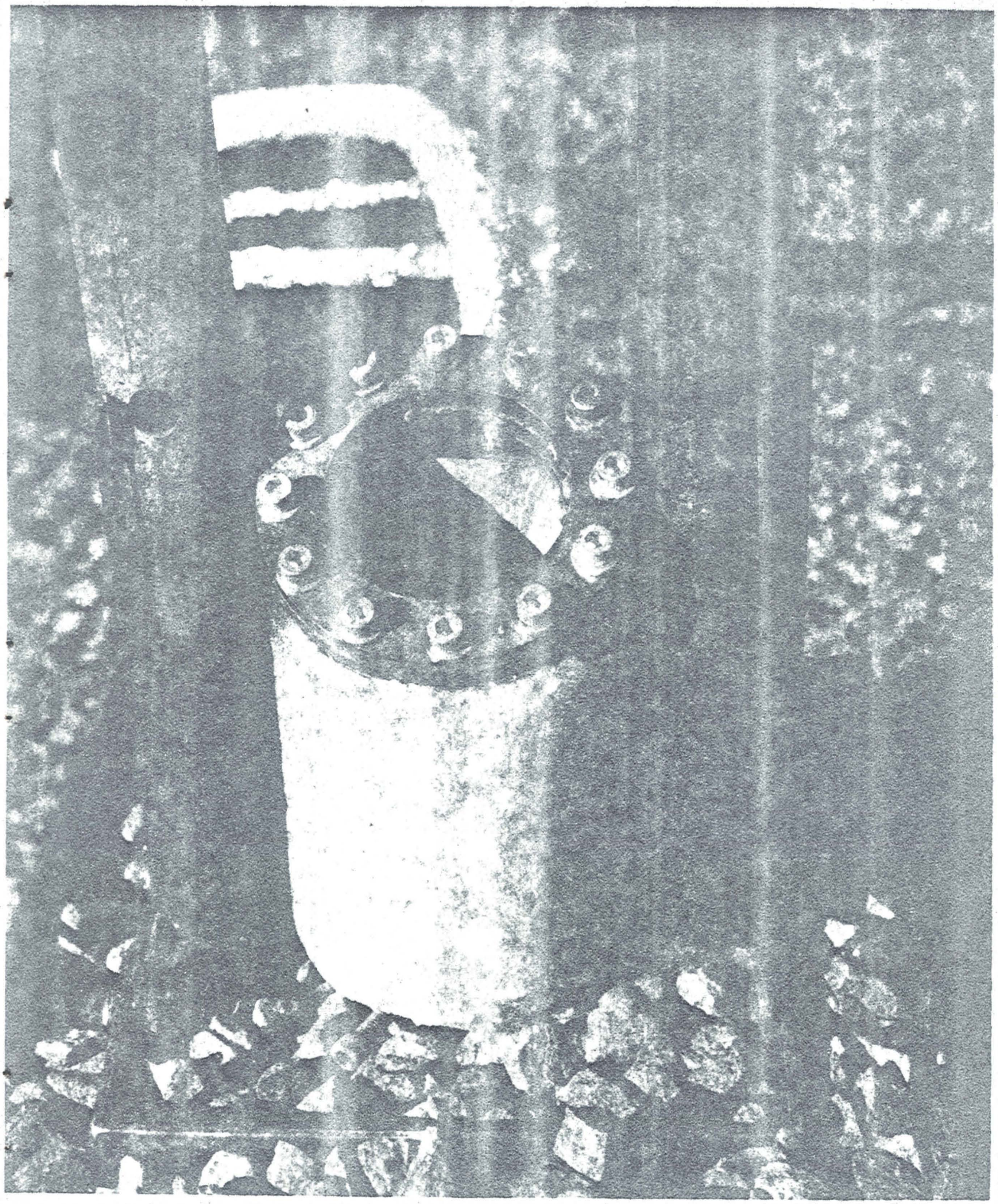


FIGURE 12. 0.028" TI-5AL-2.5Sn TARGET AFTER PENETRATION WITH 1" CHISEL IN A LOX TEST MEDIUM. PRESSURE 30 PSIG. TEST NO. 22-L.

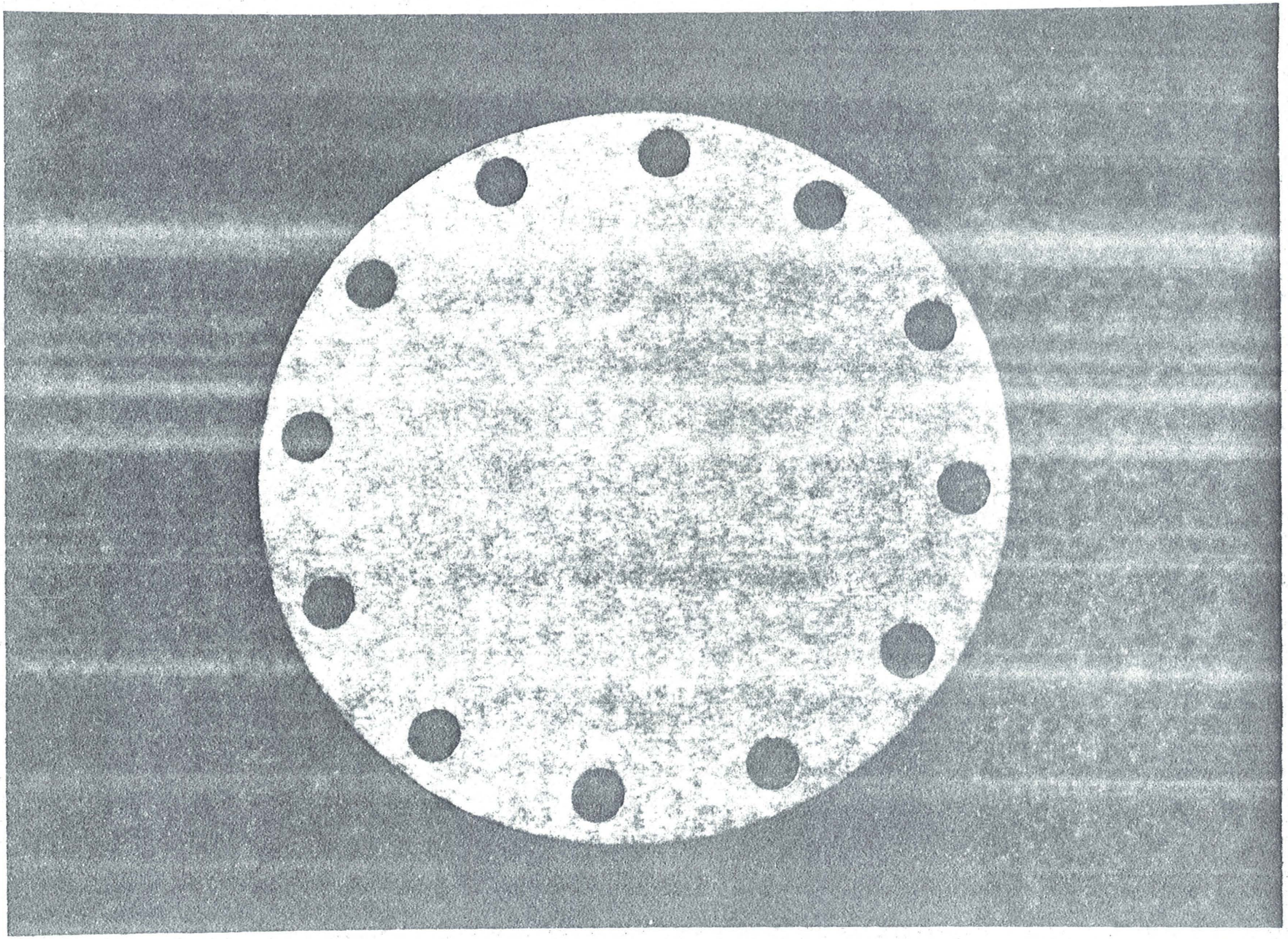


FIGURE 13. 0.028" TI-5AL-2.5Sn TARGET READY FOR TESTING.
TEST NO. 22-L.

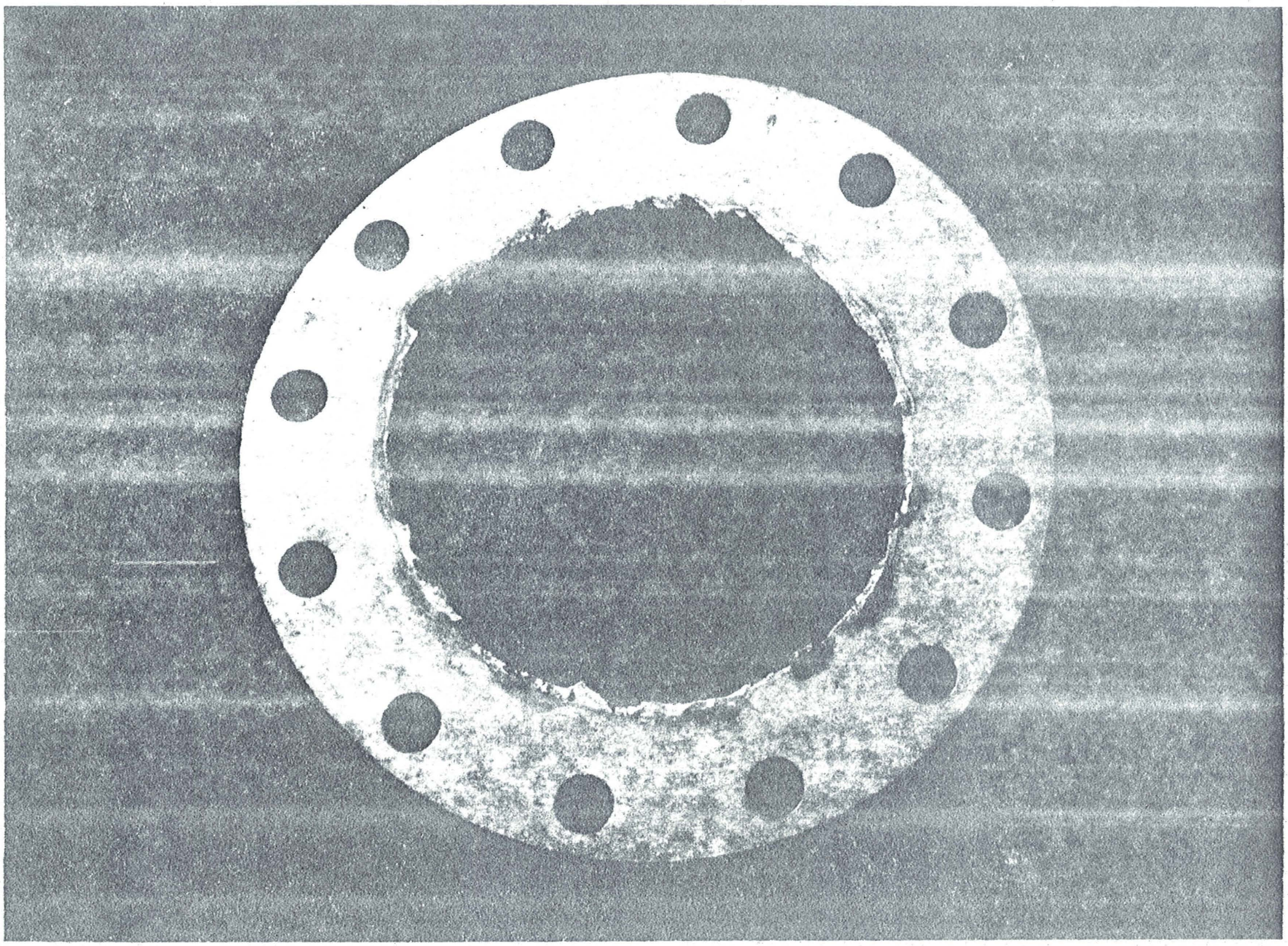


FIGURE 14. REMAINS OF 0.028" TI-5AL-2.5Sn TARGET AFTER PENETRATION WITH 1" CHISEL IN LOX TEST MEDIUM. PRESSURE 30 PSIG. TEST NO. 22-L.

Test No. 122. 0.028" Ti-5Al-2.5 Sn alloy sheet backed by 40 psig gaseous oxygen at at 75° F. Penetrated by 1" chisel penetrator with 46.5 ft. lbs. energy. Severe burning.

Test No. 131. 0.050" Ti-5Al-2.5 Sn alloy sheet backed by 40 psig gaseous oxygen at 75°F. Penetrated by 1/4" chisel penetrator with 45.7 ft. lbs. energy. Severe burning.

Test No. 197. 0.035" Ti-5Al-2.5 Sn alloy sheet backed by 40 psig gaseous oxygen at 75°F. Penetrated by conical beryllium-copper penetrator with 47.8 ft. lbs. energy. No reaction.

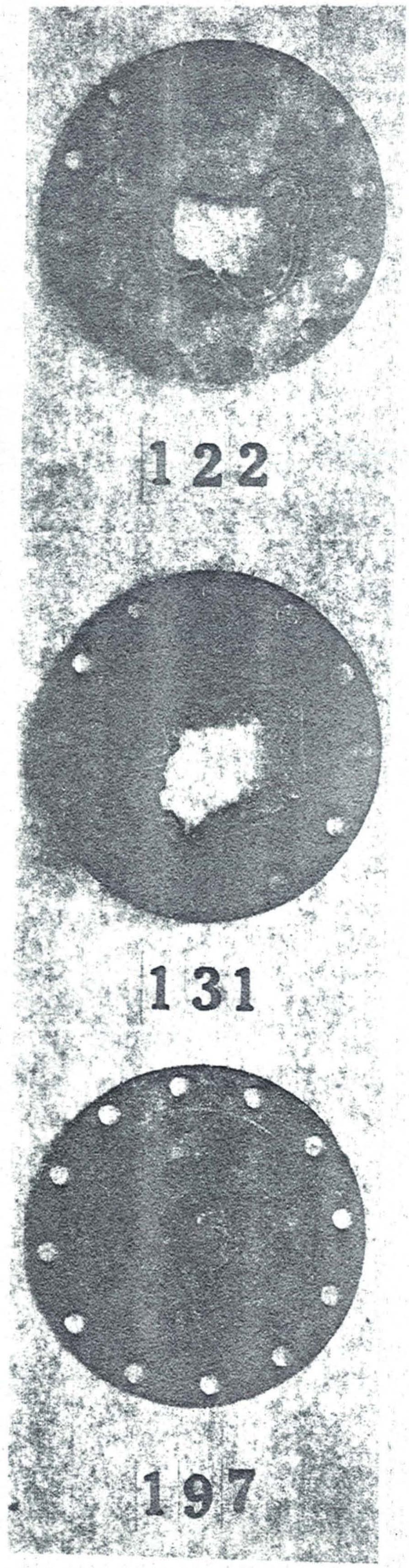


FIGURE 15. PHOTOGRAPH OF TEST DIAPHRAGMS AFTER BEING PUNCTURED.

Test No. 57. 0.016" Ti-6Al-4V alloy sheet backed by 0 psig gaseous oxygen at 75°F. Penetrated by 1/4" chisel penetrator with 47.8 ft. lbs. energy. No reaction.

Test No. 60. 0.016" Ti-6Al-4V alloy sheet backed by 30 psig gaseous oxygen at 75°F. Penetrated by 1/4" chisel penetrator with 47.8 ft. lbs. energy. Severe burning.

Test No. 129. 0.050" Ti-5Al-2.5 Sn alloy sheet with electrodeposited nickel and silver on both surfaces. Backed by 40 psig gaseous oxygen at 75°F and penetrated by 1" chisel penetrator with 45.7 ft. lbs. energy. Severe burning.

Test No. 135. 0.016" Ti-6Al-4V alloy with electrodeposited nickel on both surfaces. Backed by 40 psig gaseous oxygen at 75°F and penetrated by 1/4" chisel penetrator with 45.7 ft. lbs. energy. Severe burning.

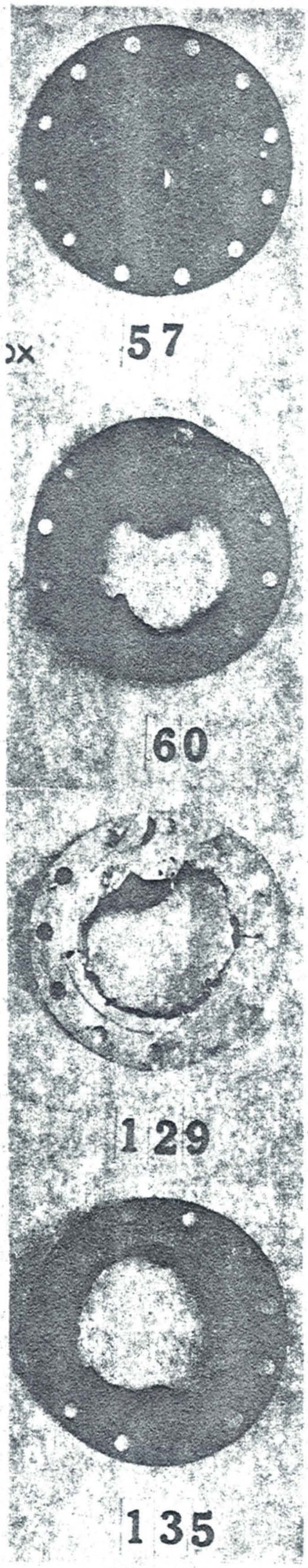


FIGURE 16. PHOTOGRAPH OF TEST DIAPHRAGMS AFTER BEING PUNCTURED.

Test No. 140. 0.025" Ti-5Al-2.5 Sn Alloy sheet with 0.001" aluminum foil diffusion bonded to side in contact with gaseous oxygen at 40 psig and 75°F. Penetrated by 1/4" chisel penetrator with 44.5 ft. lbs. energy. Very slight burning reaction at edges of penetration.

Test No. 142. 0.028" Ti-5Al-2.5 Sn alloy sheet with 0.001" aluminum foil diffusion bonded to side in contract with gaseous oxygen at 40 psig and 75°F. Penetrated by 1/4" chisel penetrator with 44.5 ft. lbs. energy. Very slight burning reaction at edges of penetration.

Test No. 209. 0.035" Ti-5Al-2.5 Sn alloy sheet covered by aluminum foil backed by 40 psig gaseous oxygen at 75°F. Penetrated by 3/8" knife edge beryllium-copper penetrator with 47.8 ft. lbs. energy. No reaction.

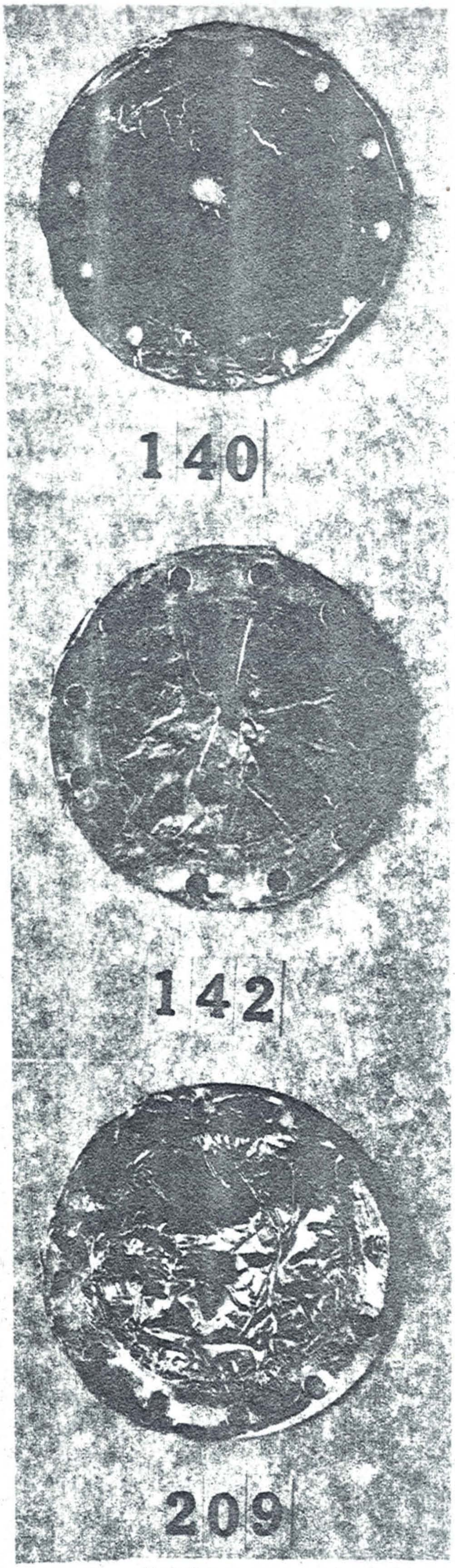


FIGURE 17. PHOTOGRAPH OF TEST DIAPHRAGMS AFTER BEING PUNCTURED.

Test No. 49. 0.016" 2024-T3 aluminum alloy sheet backed by 55 psig gaseous oxygen at 75°F. Penetrated by 1/4" chisel penetrator with 50.4 ft. lbs. energy. No reaction.

Test No. 171. 0.016" 2024-T3 aluminum alloy sheet backed by 55 psig gaseous oxygen at 75°F. Penetrated by conical penetrator with 43.9 ft. lbs. energy. No reaction.

Test No. 172. 0.016" 2024-T3 aluminum alloy sheet backed by 55 psig gaseous oxygen at 75°F. Penetrated by 1" chisel penetrator with 43.9 ft. lbs. energy. No reaction.

Test No. 182. 0.010" Type 301 stainless steel sheet (extra full hard) backed by 55 psig gaseous oxygen at 75°F. Penetrated by 1" chisel penetrator with 43.9 ft. lbs. energy.
No reaction; large tear in sheet.

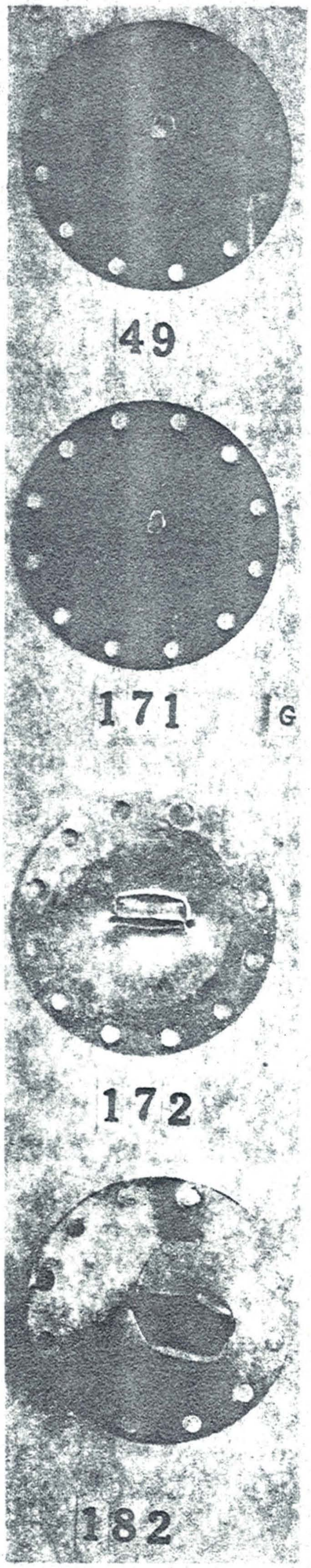


FIGURE 18. PHOTOGRAPH OF TEST DIAPHRAGMS AFTER BEING PUNCTURED.

Test No. 58. 0.010" Type 301 extra full hard stainless steel sheet backed by 55 psig gaseous oxygen at 75°F. Penetrated by 1/4" chisel penetrator with 47.8 ft. lbs. energy. No reaction, but sparks were generated.

Test No. 167. 0.010" Type 301 extra full hard stainless steel sheet backed by 55 psig gaseous oxygen at 75°F. Penetrated by conical penetrator with 43.9 ft. lbs. energy. No reaction.

Test No. 181. 0.010" Type 301 extra full hard stainless steel sheet backed by 55 psig gaseous oxygen at 75°F. Penetrated by 1" chisel penetrator with 43.9 ft. lbs. energy. No reaction.

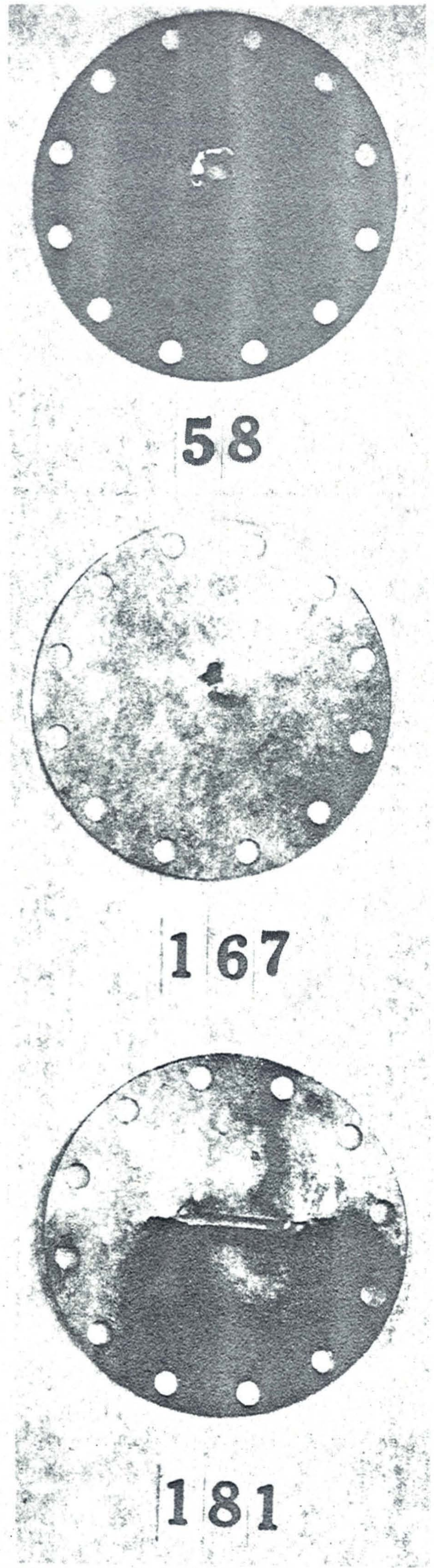


FIGURE 19. PHOTOGRAPH OF TEST DIAPHRAGMS AFTER BEING PUNCTURED.

Test No.	152
Material	0.0[illegible]" TI-5Al-2.5 Sn
Test Medium	H_2 GAS
Pressure	35 psig
Puncture Tool	1/4" Steel [illegible]
[illegible] Energy	44 ft. lbs.

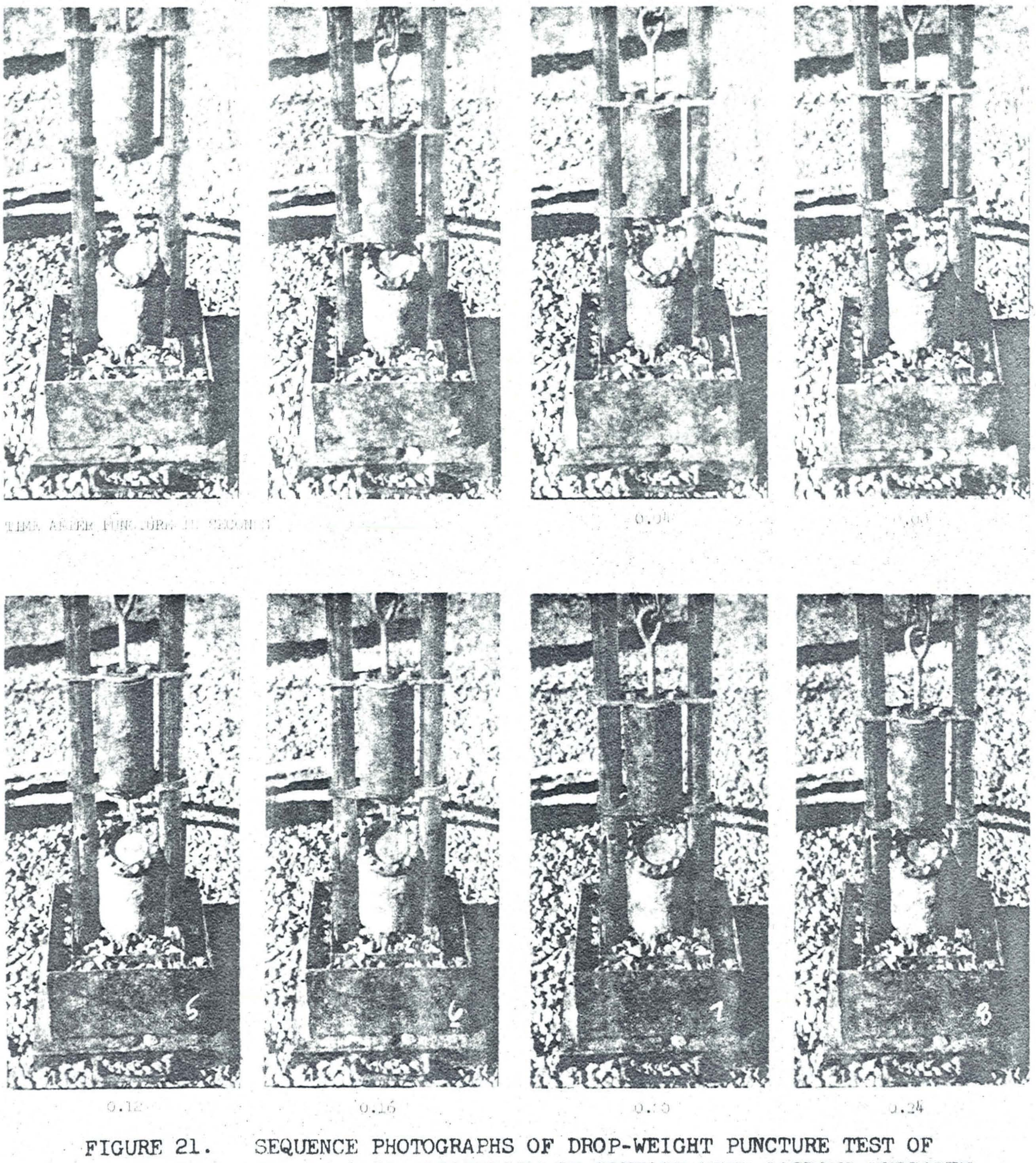
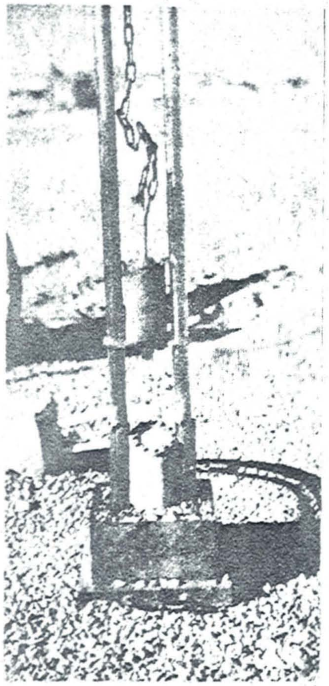
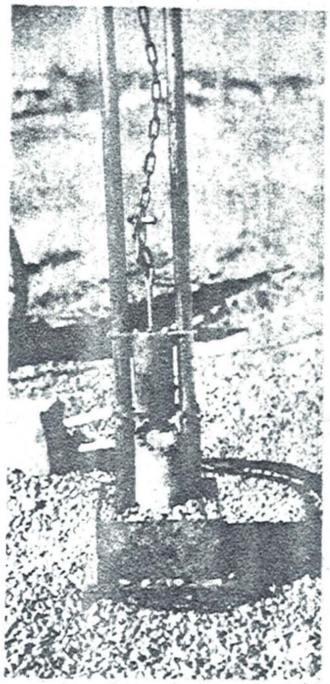
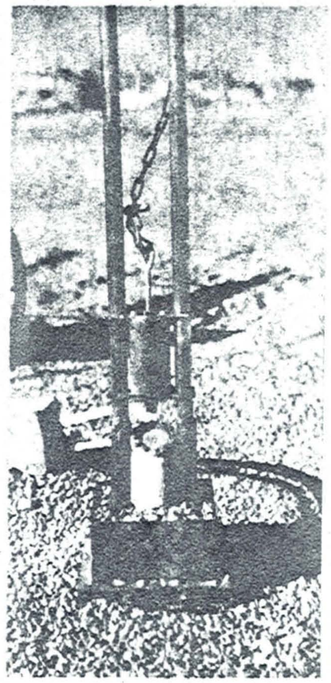
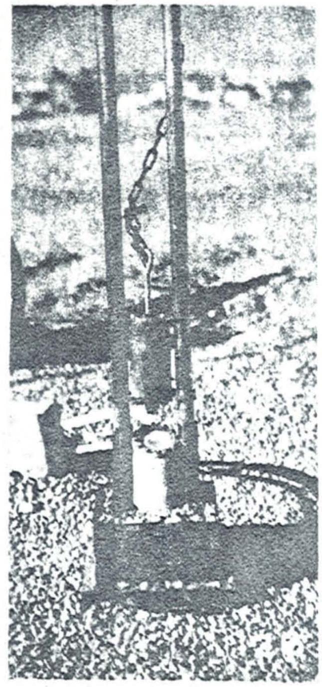


FIGURE 21. SEQUENCE PHOTOGRAPHS OF DROP-WEIGHT PUNCTURE TEST OF TI-5AL-2.5Sn DIAPHRAGM IN CONTACT WITH GASEOUS HYDROGEN. TEST NO. 152.

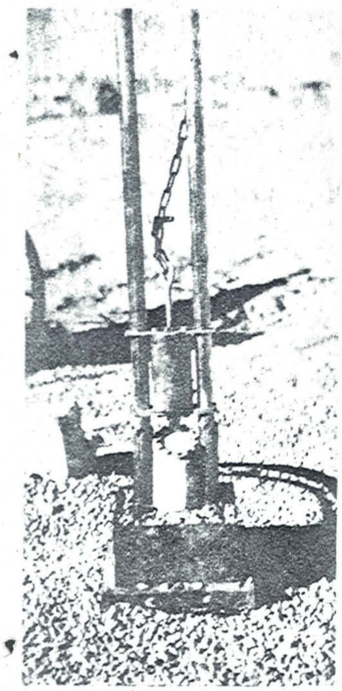


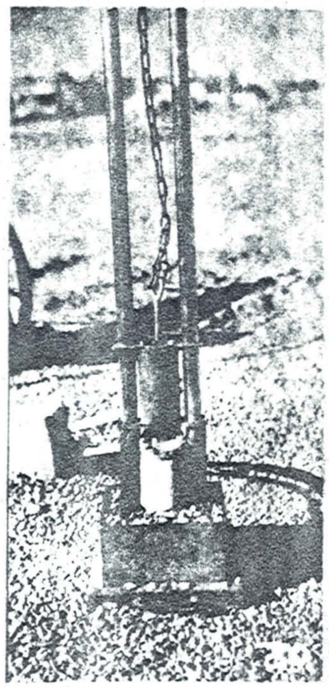






TIME AFTER PUNCTURE IN SECONDS   0.04   0.08   0.12





[illegible]   0.20

Test No.	24
Material	0.0[illegible]8" TI-5Al-2.5 Sn 1 coat of WD-40
Test Medium	LOX
Pressure	30 psig
Puncture Tool	1" Steel Chisel
Puncture Energy	48 ft. lbs.

FIGURE 22. SEQUENCE PHOTOGRAPHS OF DROP-WEIGHT PUNCTURE TEST OF TI-5AL-2.5Sn DIAPHRAGM WHICH HAD BEEN COATED WITH WD-40 CORROSION INHIBITOR. TEST NO. 24-L.

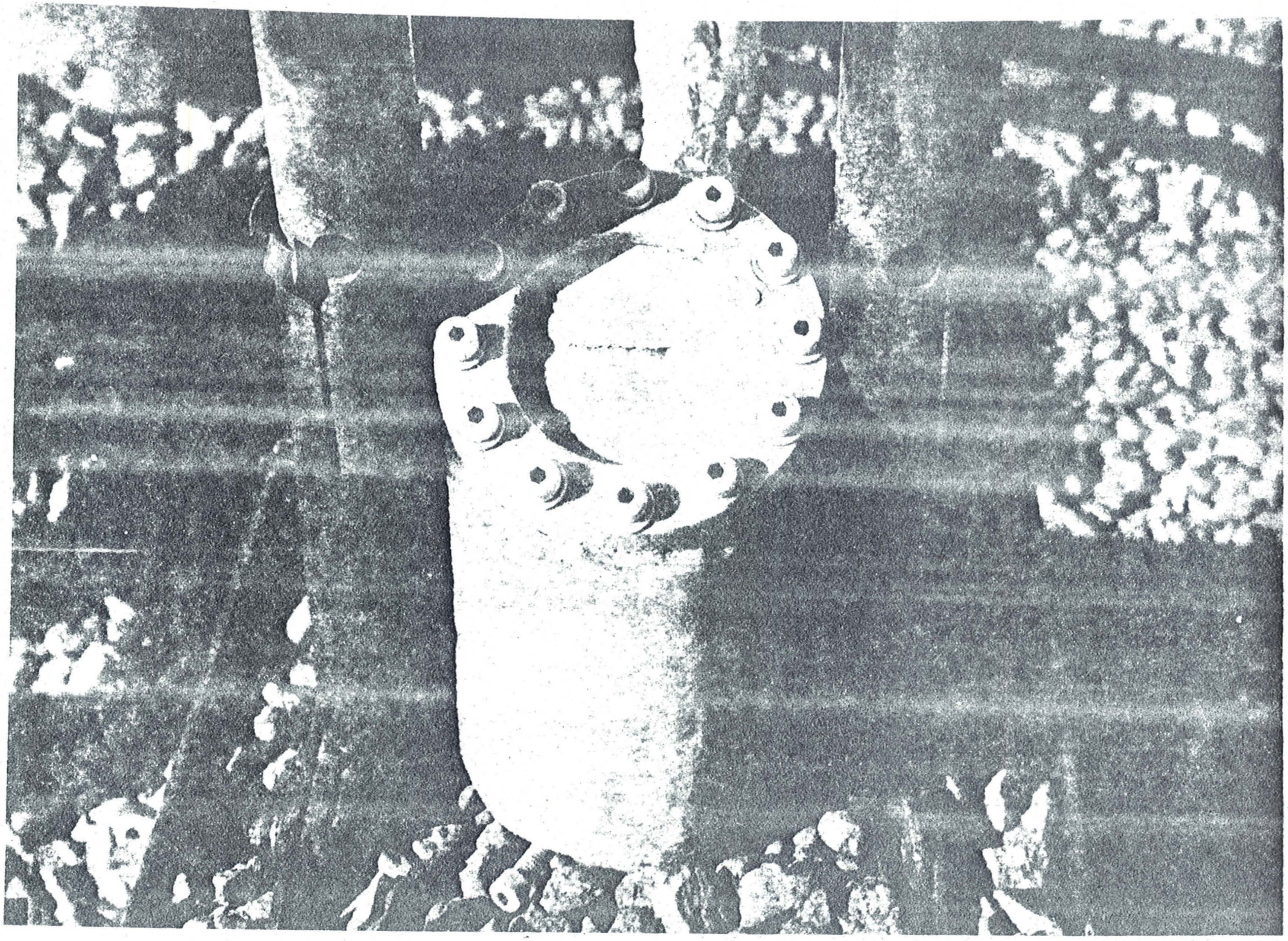


FIGURE 23. 0.028" TI-5AL-2.5Sn TARGET COATED WITH ONE COAT OF WD-40 AFTER PENETRATION WITH 1" CHISEL IN LOX TESTING MEDIUM. TEST NO. 24-L.

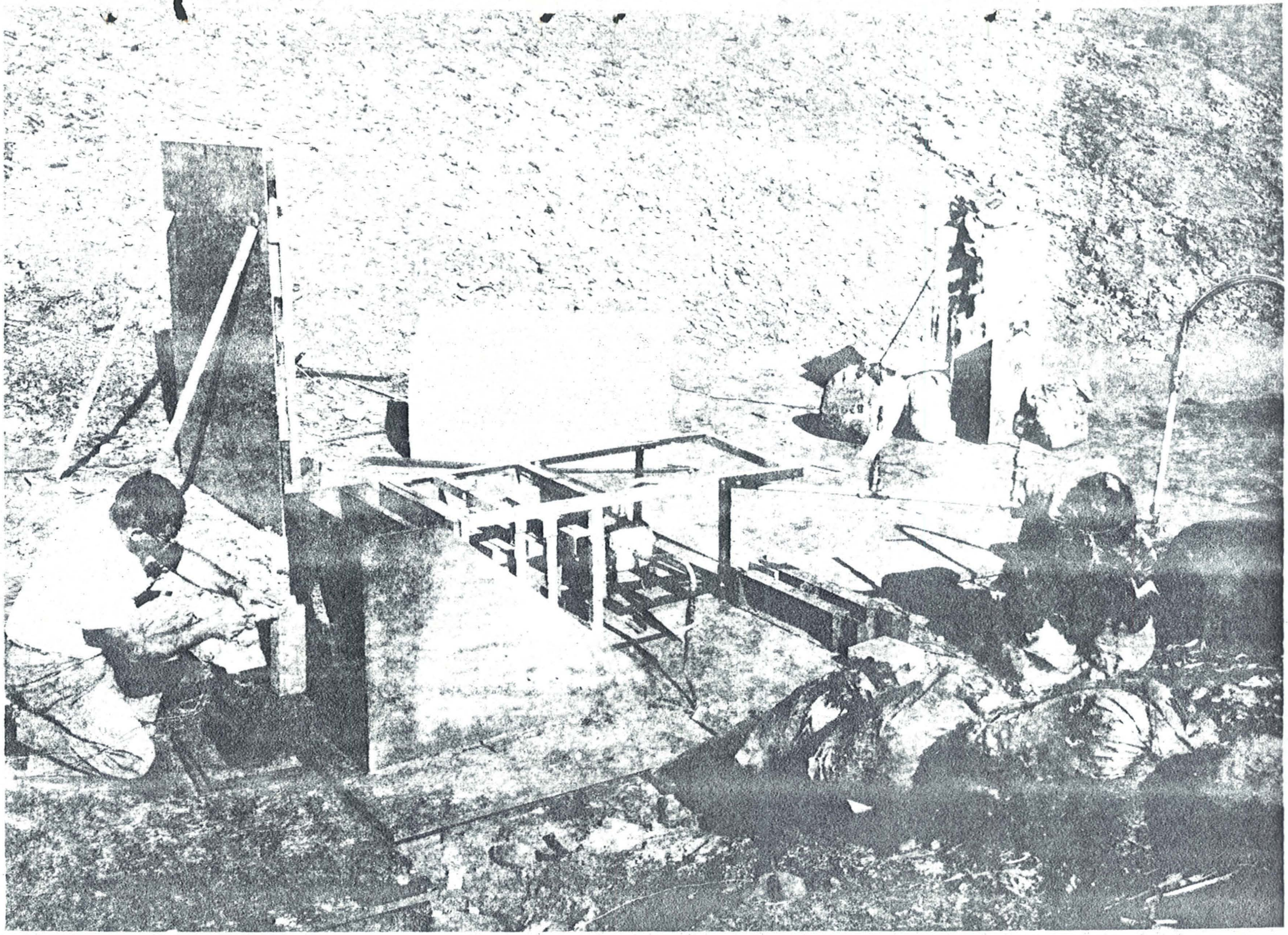


FIGURE 24. HYPERVELOCITY PENETRATION TEST FACILITIES AT GD/A.
The detonating primer is being placed in the explosive charge.

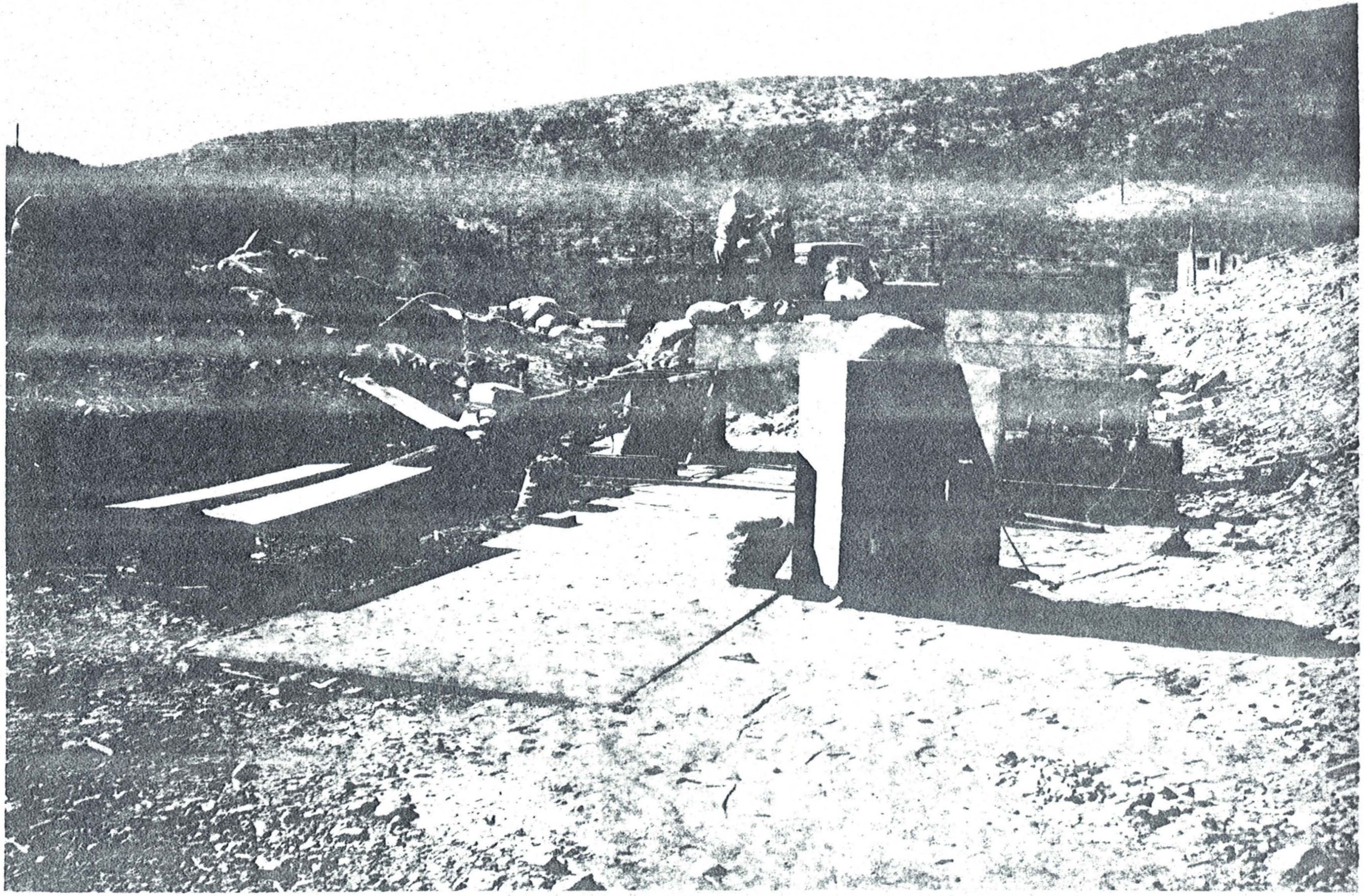


FIGURE 25. HYPERVELOCITY PENETRATION TEST FACILITIES SHOWING THE TEST CHAMBER BEING LOADED WITH LIQUID OXYGEN.

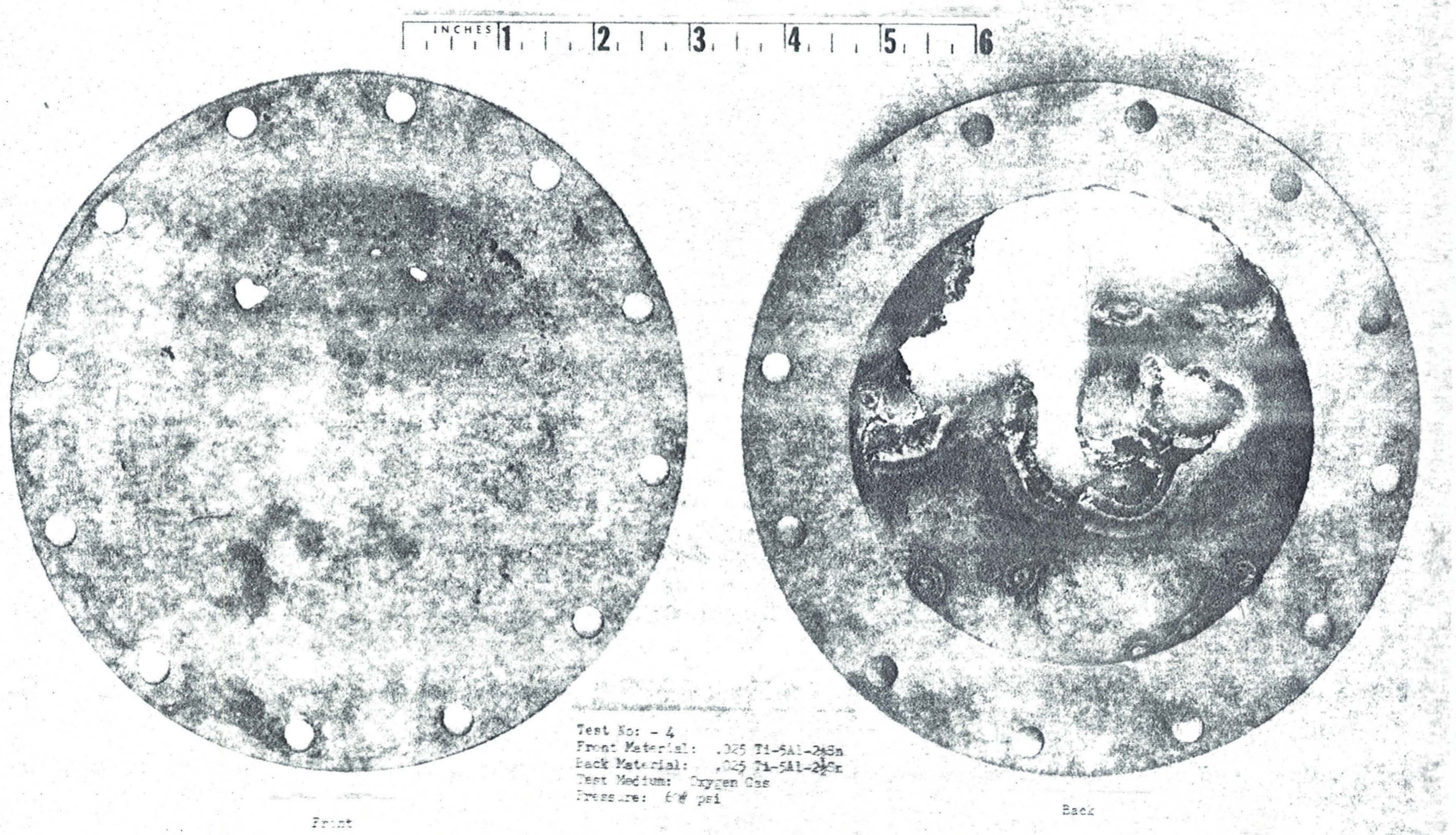


FIGURE 26. TITANIUM ALLOY DIAPHRAGMS AFTER TYPICAL HIGH VELOCITY PUNCTURE IN TESTS CONDUCTED AT GD/ASTRONAUTICS.

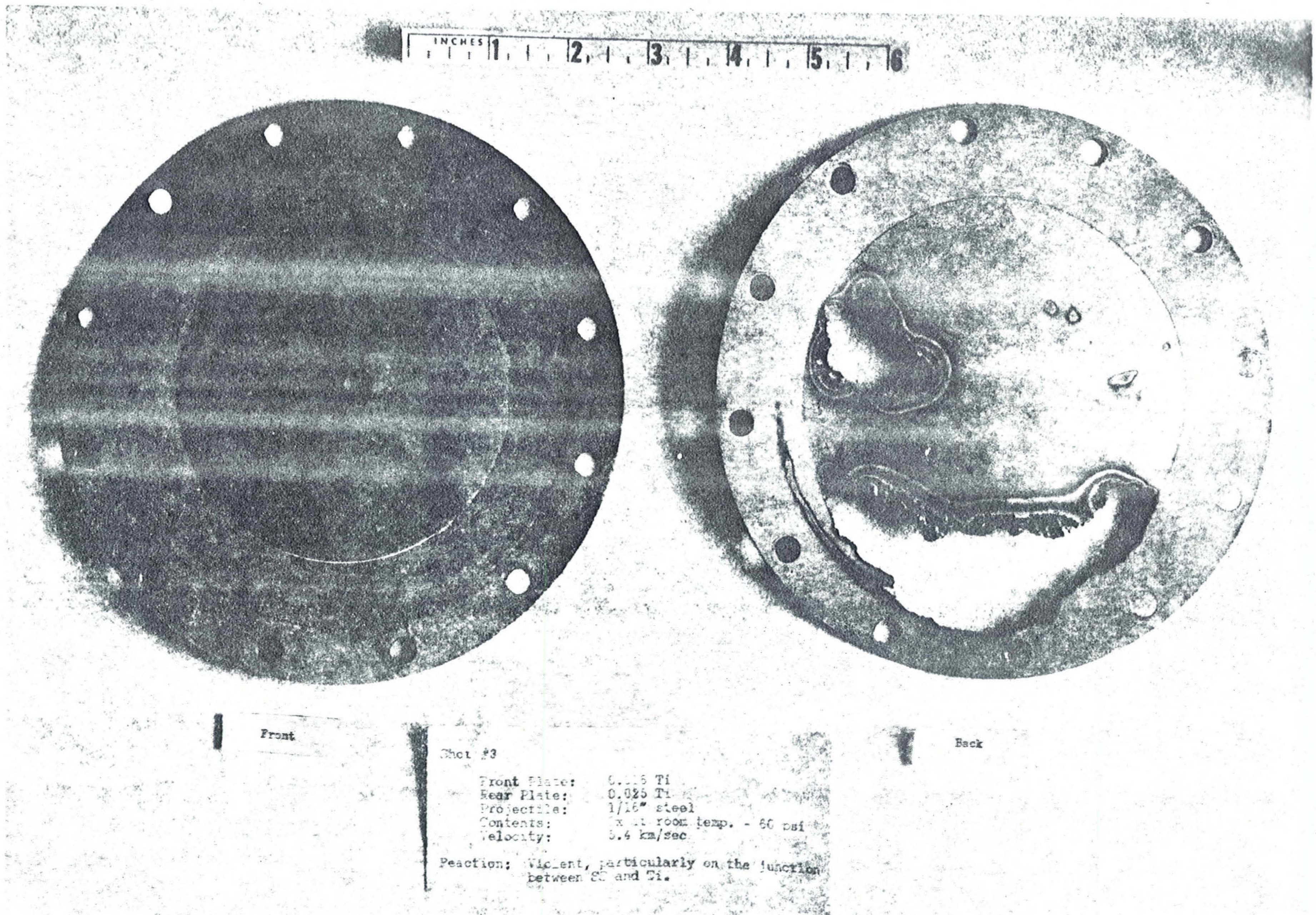


FIGURE 27. TITANIUM ALLOY DIAPHRAGMS AFTER TYPICAL HIGH VELOCITY PUNCTURE IN TESTS CONDUCTED AT UTAH RESEARCH AND DEVELOPMENT CO.

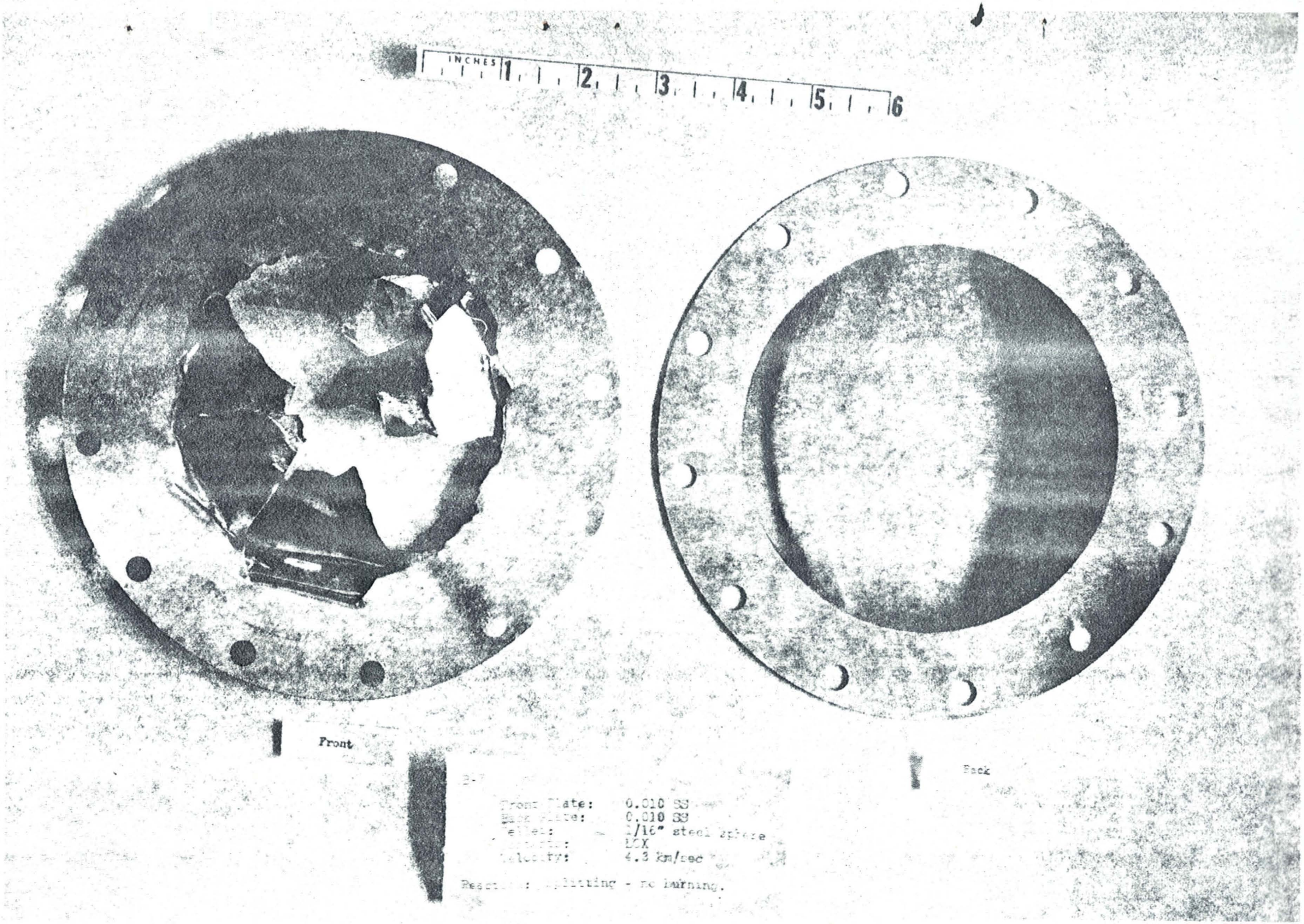


FIGURE 28. STAINLESS STEEL DIAPHRAGMS AFTER HIGH VELOCITY PUNCTURE TEST.

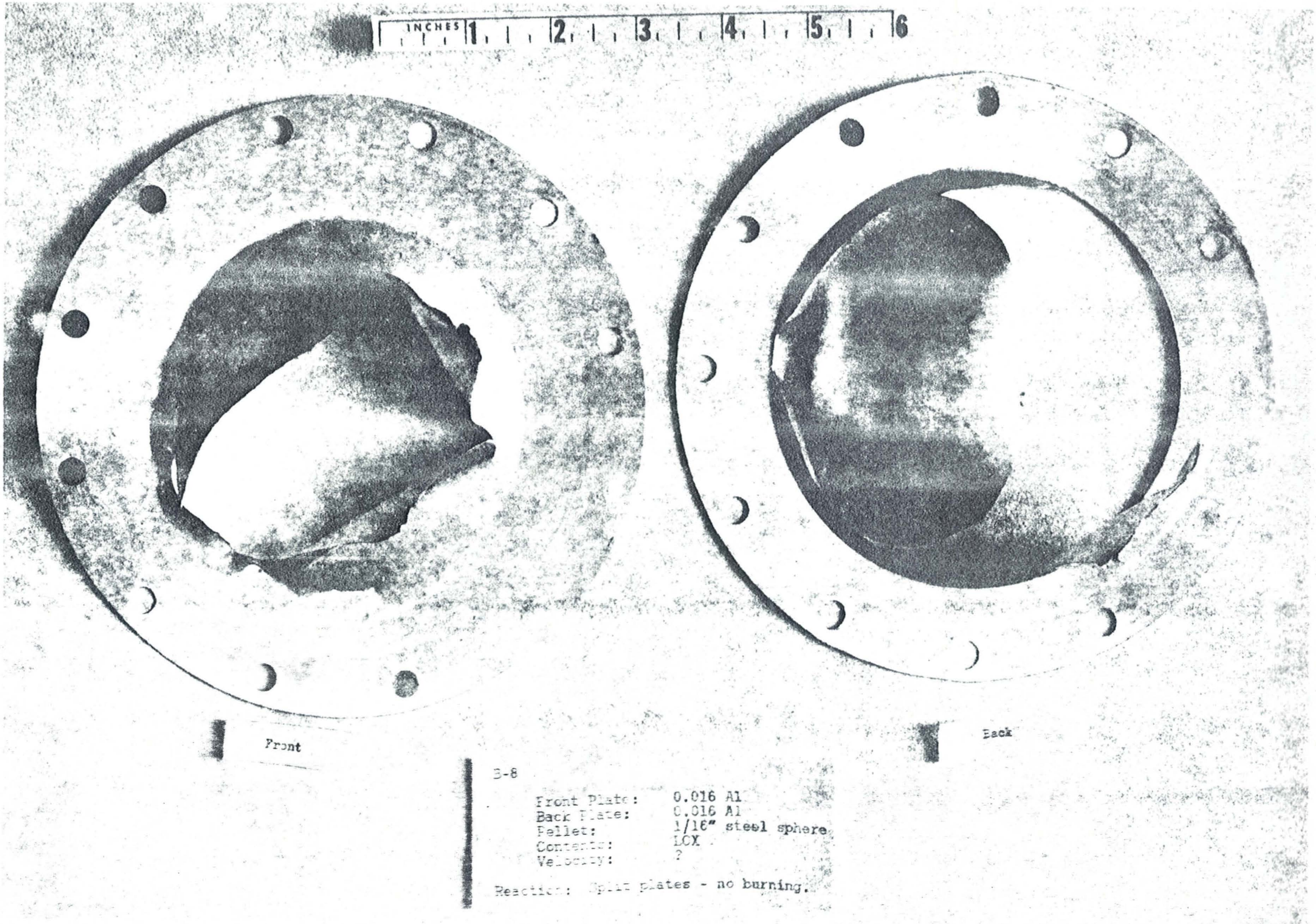
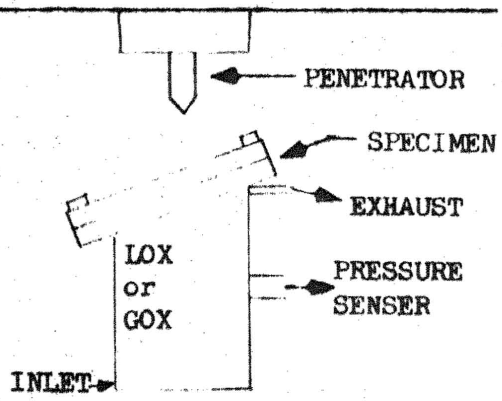


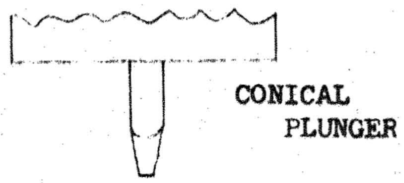
FIGURE 29. ALUMINUM ALLOY DIAPHRAGMS AFTER HIGH VELOCITY PUNCTURE TEST.

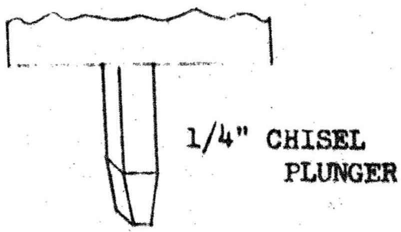
I REACTIVITY TESTS - GASEOUS OXYGEN

OF RATOR	GOX	LOX	OTHER	IMPACT ENERGY	REMARKS
isel	X			51.3 ft lbs	No Reaction
isel	X			"	No Reaction
isel	X			"	No Reaction
isel	X			"	No Reaction
isel	X			"	No Reaction
isel	X			"	No Reaction
isel	X			"	No Reaction
isel	X			"	No Reaction
isel	X			"	No Reaction
isel	X			"	No Reaction
isel	X			"	Sparks
isel	X			"	No Reaction
isel	X			"	50% Burned
isel	X			"	75% Burned
sel	X			"	75% Burned
sel	X			"	Positive Reaction
sel	X			"	Positive Reaction
l	X			"	Sparks
r					
	X			"	Positive Reaction
	X			"	Positive Reaction
,	X			"	No Reaction
	X			"	Sparks
	X			"	Positive Reaction
	X			"	No Reaction
	X			"	No Reaction
	X			"	Sparks
	X			"	Sparks
	X			"	Positive Reaction
	X			"	Positive Reaction
	X			"	Slight Burning
	X			"	Positive Reaction
	X			"	No Reaction
	X			"	No Reaction
	X			"	No Reaction
	X			"	Sparks
	X			"	Positive Reaction
	X			"	Positive Reaction
	X			"	Positive Reaction
	X			"	Positive Reaction
l					
l	X			"	Slight Burning
	X			"	Positive Reaction
	X			"	Positive Reaction
sel	X			50.4 ft lbs	Positive Reaction
	X			"	Positive Reaction
	X			"	Positive Reaction
	X			"	No Reaction
	X			"	No Reaction
	X			"	No Reaction

CONFIGURATION







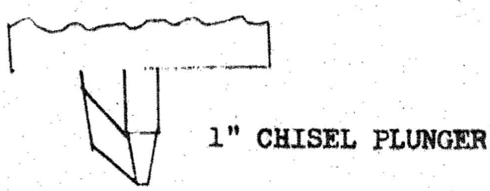


TABLE I. LOG OF TITANIUM-OXY

TEST NO.	DATE	TIME	HUMIDITY %	TEMP °F	ATMOS PRESS in Hg	TEST TANK PRESS	SPEC. MATERIAL	SPEC. THICK	TY PE
1	12/9/61	11:00am				30psig	301SS	0.014"	1"
2	12/9/61	11:30am				30psig	301SS	0.014"	1"
3	12/9/61	12:30pm				30 psig	301SS	0.014"	1"
4	12/9/61	1:00pm				30 psig	301SS	0.014"	1"
5	12/9/61	1:30pm				30 psig	301SS	0.014"	1"
6	12/9/61	2:00pm				30 psig	2024-T-3	0.016"	1"
7	12/9/61	2:30pm				30 psig	" Al	0.016"	1"
8	12/9/61	3:00pm				30 psig	"	0.016"	1"
9	12/11/61	9:00am				50 psig	"	0.016"	1"
10	12/11/61	9:30am				50 psig	"	0.016"	1"
11	12/11/61	10:00am				30 psig	Ti-6Al-	0.016"	1"
12	12/11/61	10:30am				30 psig	" 4A	0.016"	1"
13	12/11/61	10:50am				50 psig	"	0.016"	1"
14	12/11/61	11:20am				45 psig	"	0.016"	1"
15	12/11/61	12:30pm				40 psig	"	0.016"	1"
16	12/11/61	1:00pm				30 psig	"	0.016"	1"
17	12/11/61	1:30pm				30 psig	"	0.016"	1"
18	12/11/61	2:00pm				40 psig	"	0.016"	Co Pl
19	12/11/61	2:30pm				40 psig	"	0.016"	
20	12/11/61	3:00pm				30 psig	"	0.016"	
21	12/11/61	3:30pm				10 psig	"	0.016"	
22	12/12/61	12:45pm				20 psig	"	0.016"	
23	12/12/61	1:20pm				20 psig	"	0.016"	
24	12/12/61	2:00pm				50 psig	2024-T-3	0.016"	
25	12/12/61	2:25pm				55 psig	" Al	0.016"	
26	12/12/61	3:00pm				55 psig	301SS	0.014"	
27	12/12/61	3:30pm				55 psig	301SS	0.010"	
28	12/13/61	9:00am				50 psig	Ti-6Al-4V	0.016"	
29	12/13/61	9:30am				20 psig	"	0.016"	
30	12/13/61	10:00am				15 psig	"	0.016"	
31	12/13/61	10:30am				15 psig	"	0.016"	
32	12/13/61	11:00am				55 psig	301SS	0.014"	
33	12/13/61	11:30am				10 psig	Ti-6Al-4V	0.016"	
34	12/13/61	12:00pm				50 psig	2024 T-3	0.016"	
35	12/13/61	12:45pm				10 psig	Ti-6Al-4V	0.016"	
36	12/13/61	1:30pm				13 psig	"	0.016"	
37	12/13/61	2:00pm				11 psig	"	0.016"	
38	12/13/61	2:45pm				10 psig	"	0.016"	
39	12/13/61	3:30pm				10 psig	"	0.016	
40	12/14/61	9:25am				10 psig	"	0.016"	C
41	12/14/61	9:45am				30 psig	"	0.016"	
42	12/14/61	10:05am				10 psig	"	0.016"	
43	12/14/61	10:20am				10 psig	"	0.016"	[illegible]
44	12/14/61	10:50am				30 psig	"	0.016"	
45	12/14/61	11:10am				5 psig	"	0.016"	
46	12/14/61	11:35am				50 psig	2024 T-3	0.016"	
47	12/14/61	11:55am				55 psig	"	0.016"	
48	12/14/61	12:45 pm				55 psig	"	0.016"	

OXYGEN REACTIVITY TESTS - GASEOUS OXYGEN (Continued)

TYPE OF PENETRATOR	GOX	LOX	OTHER	IMPACT ENERGY	REMARKS	CONFIGURATION
¼ Chisel	X			50.4 ft lbs	No Reaction	
"	X			47.8 ft lbs	Positive Reaction	
"	X			"	Positive Reaction	
"	X			"	No Reaction	
"	X			"	No Reaction	
"	X			"	Positive Reaction	
"	X			"	Positive Reaction	
"	X			"	Positive Reaction	
"	X			"	No Reaction	
"	X			"	Sparks	
"	X			"	No Reaction	
"	X			"	Positive Reaction	
"	X			"	Positive Reaction	
"	X			"	No Reaction	
Conical Chisel	X			46.1 ft lbs	No Reaction	
"	X			"	No Reaction	
"	X			"	No Reaction	
"	X			"	No Reaction	
"	X			"	No Reaction	
"	X			50.8 ft.lbs	No Reaction	
"	X			"	Positive Reaction	
"	X			"	Positive Reaction	
"	X			"	No Reaction	
"	X			"	No Reaction	
"	X			"	Positive Reaction	
"	X			"	No Reaction	
"	X			"	No Reaction	
"	X			"	Sparks	
"	X			"	No Reaction	
"	X			"	No Reaction	
"	X			"	No Reaction	
Conical Plunger	X			"	No Reaction	
"	X			"	No Reaction	
"	X			"	No Reaction	
"	X			"	No Reaction	
"	X			"	Positive Reaction	
"	X			"	Positive Reaction	
"	X			"	Positive Reaction	
"	X			"	Positive Reaction	
"	X			"	Positive Reaction	
¼" Chisel	X			47.8 ft lbs	Positive Reaction	
"	X			"	No Reaction	
"	X			"	No Reaction	
"	X			"	Positive Reaction	

TABLE I. LOG OF TITANI

TEST NO.	DATE	TIME	HUMIDITY %	TEMP °F	ATMOS PRESS in Hg	TEST TANK PRESS	SPEC. MATERIAL	SPEC. THICK
49	12/14/61	1:10am				55 psig	2024 T-3	0.016"
50	12/14/61	1:40am				5 psig	Ti-6Al-4V	0.016"
51	12/14/61	2:00pm				5 psig	"	0.016"
52	12/14/61	2:25pm				0 psig	"	0.016"
53	12/14/61	3:00pm				0 psig	"	0.016"
54	12/14/61	3:20pm				0 psig	"	0.016"
55	12/14/61	3:55pm				0 psig	"	0.016"
56	12/15/61	9:35am				0 psig	"	0.016"
57	12/15/61	10:00am				0 psig	"	0.016"
58	12/15/61	10:20am				55 psig	301SS	0.010"
59	12/15/61	10:55am				55 psig	"	0.014"
60	12/15/61	11:20am				30 psig	Ti-6Al-4V	0.016"
61	12/15/61	11:55am				10 psig	"	0.016"
62	12/15/61	12:50am				55 psig	301 SS	0.014"
63	12/15/61	1:25am				10 psig	Ti-6Al-4V	0.016"
64	12/15/61	1:45am				30 psig	"	0.016"
65	12/15/61	2:10am				10 psig	"	0.016"
66	12/15/61	2:30am				10 psig	"	0.016"
67	12/15/61	2:50am				30 psig	"	0.016"
68	12/15/61	3:10am				30 psig	"	0.016"
69	12/15/61	3:30am				50 psig	"	0.016"
70	12/15/61	3:45am				30 psig	"	0.016"
71	12/15/61	4:00am				10 psig	"	0.016"
72	12/16/61	9:00am				10 psig	"	0.016"
73	12/16/61	9:15am				10 psig	"	0.016"
74	12/16/61	9:30am				10 psig	"	0.016"
75	12/16/61	9:45am				10 psig	"	0.016"
76	12/16/61	10:00am				15 psig	"	0.016"
77	12/16/61	10:15am				20 psig	"	0.016"
78	12/16/61	10:30am				20 psig	"	0.016"
79	12/16/61	10:45am				30 psig	"	0.016"
80	12/16/61	11:00am				30 psig	"	0.016"
81	12/16/61	11:15am				30 psig	"	0.016"
82	12/16/61	11:30am				40 psig	"	0.016"
83	12/16/61	12:00pm				40 psig	"	0.016"
84	12/16/61	1:00pm				40 psig	"	0.016"
85	12/16/61	1:15pm				40 psig	"	0.016"
86	12/16/61	1:30pm				40 psig	"	0.016"
87	12/16/61	1:45pm				40 psig	"	0.016"
88	12/16/61	2:00pm				40 psig	"	0.016"
89	12/16/61	2:15pm				5 psig	"	0.016"
90	12/16/61	2:30pm				5 psig	"	0.016"
91	12/16/61	2:45pm				10 psig	"	0.016"
92	12/16/61	3:00pm				10 psig	"	0.016"

TABLE I. LOG OF TITANIUM-OXY

TEST NO.	DATE	TIME	HUMIDITY %	TEMP °F	ATMOS PRESS in Hg	TEST TANK PRESS	SPEC. MATERIAL	SPEC. THICK	TY PR
93	12/16/61	3.15pm				10 psig	Ti-6Al-4V	0.016"	¼"
94	12/16/61	3:30pm				30 psig	"	0.016"	
95	12/16/61	3:45pm				30 psig	"	0.016"	
96	12/18/61	9:00am				30 psig	"	0.016"	
97	12/18/61	9:30am				20 psig	"	0.016"	
98	12/18/61	10:15am				20 psig	"	0.016"	
99	12/18/61	11:00am				5 psig	"	0.016"	
100	12/18/61	11:10am				30 psig	"	0.016"	1"
101	12/18/61	11:25am				5 psig	"	0.016"	
102	12/18/61	11:45am				5 psig	"	0.016"	
103	12/18/61	12:00N				5 psig	"	0.016"	
104	12/18/61	1:00pm	75	66	79.4	5 psig	"	0.016"	
105	12/18/61	1:30pm				5 psig	"	0.016"	
106	12/18/61	2:15pm				0 psig	"	0.016"	
107	12/18/61	3:00pm	74	63	29.4	10 psig	"	0.016"	
108	12/21/61	8:50am	69	61	29.6	10 psig	Ti-5Al-2.5Sn	0.014"	Sh C
109	12/21/61	9:00am				10 psig	"	0.028"	
110	12/21/61	9:15am				10 psig	"	0.028"	
111	12/21/61	9:25am				10 psig	"	0.028"	
112	12/21/61	9:45am				20 psig	"	0.028"	
113	12/21/61	10:00am	62	68	29.6	20 psig	"	0.028"	
114	12/21/61	10:10am				20 psig	"	0.028"	
115	12/21/61	10:20am				20 psig	"	0.028"	
116	12/21/61	10:35am				20 psig	"	0.028"	
117	12/21/61	10:50am				30 psig	"	0.028"	
118	12/21/61	11:05am				30 psig	"	0.028"	
119	12/21/61	11:15am				30 psig	"	0.028"	Sh C
120	12/21/61	11:30am				30 psig	"	0.028"	
121	12/21/61	11:40am	42	86	29.6	40 psig	"	0.028"	
122	12/21/61	12:50pm				40 psig	"	0.028"	
123	12/21/61	1:15pm				30 psig	"	0.028"	1"
124	12/21/61	1:30pm				30 psig	"	0.035"	
125	12/21/61	1:40pm				40 psig	"	0.028"	
126	12/21/61	1:50pm				40 psig	"	0.028"	
127	12/21/61	2:00pm	48	82	29.6	40 psig	"	0.028"	
128	12/21/61	2:20pm				40 psig	"	0.050"	
129	12/21/61	2:40pm				40 psig	" 1		
130	12/21/61	3:00pm				40 psig	" 2	0.028"	
131	12/21/61	3:20pm				40 psig	"	0.050"	1/
132	12/21/61	3:40pm				40 psig	"	0.028"	
133	12/21/61	4:00pm	62	68	29.6	40 psig	Ti-6Al-4V 3	0.016"	1"
134	12/21/61	4:15pm				40 psig	3	0.016"	

1 - Ni & Ag plated
2 - Vapor Deposited Al
3 - Ni Plated

REACTIVITY TESTS - GASEOUS OXYGEN (Continued)

F ... RATOR	GOX	LOX	OTHER	IMPACT ENERGY	REMARKS	CONFIGURATION
isel	X			47.8 ft lbs	No Reaction	
	X			"	Positive Reaction	
	X			"	Positive Reaction	
	X			"	Positive Reaction	
	X			"	Positive Reaction	
	X			"	Positive Reaction	
	X			"	No Reaction	
isel	X			45.3 ft lbs	Positive Reaction	
	X			"	Positive Reaction	
	X			"	No Reaction	
	X			"	No Reaction	
	X			"	No Reaction	
	X			"	No Reaction	
	X			"	No Reaction	
	X			"	Sparks	
1" el	X			"	No Reaction	
	X			46.5		
	X			ft lbs	Sparks	
	X			"	No Reaction	
	X			"	No Reaction	
	X			"	Positive Reaction	
	X			"	Slight Burning	
	X			"	No Reaction	
	X			"	No Reaction	
	X			"	Slight Burning	
	X			"	Slight Burning	
1/4" el	X			"	Slight Burning	
	X			"	No Reaction	
	X			"	Positive Reaction	
	X			"	Positive Reaction	
isel	X			"	Positive Reaction	
	X			45.7 ft.lbs	No Reaction	
	X			"	Positive Reaction	
	X			"	Positive Reaction	
	X			"	No Reaction	
	X			"	Could not Cut	
	X			"	Positive Reaction	
	X			"	Positive Reaction	
isel	X			"	Positive Reaction	
	X			"	Positive Reaction	
sel	X			"	Slight Burning	
	X			"	Positive Reaction	

- GASEOUS OXYGEN (continued)

GOX	OTHER	IMPACT ENERGY	REMARKS	CONFIGURATION
X		45.7 ft.lbs.	Positive Reaction	
X		44.5 ft.lbs.	Slight Burning	
X		"	Sparks	
X		"	Very Slight Burning	
X		"	Very Slight Burning	
X		"	Very Slight Burning	
X		"	100% Burned	
X		"	Very Slight Burning	
X		"	Positive Reaction	
X		"	Very Slight Burning	
X		"	Positive Reaction	
X		"	Positive Reaction	
X		"	No Reaction	
X		"	No Reaction	
X		"	No Reaction	
X	H_2 Gas	"	No Reaction	
	"	"	No Reaction	
	"	43.9 ft.lbs	No Reaction	
	"	"	No Reaction	
	"	"	No Reaction	
	"	"	No Reaction	
	"	"	No Reaction	
	"	"	No Reaction	
	"	"	No Reaction	
X		"	No Reaction	
X		"	No Reaction	
X		"	No Reaction	
X		"	No Reaction	
X		"	Positive Reaction	
X		"	Positive Reaction	
X		"	Positive Reaction	
X		"	No Reaction	
X		"	No Reaction	
X		"	No Reaction	
X		"	No Reaction	
X		"	No Reaction	
X		"	No Reaction	
X		"	No Reaction	
X		"	No Reaction	
X		"	No Reaction	

:h GOX.
:h GOX.

TABLE I. LOG OF TITANIUM-OXYGEN REACTIVITY T

TEST NO.	DATE	TIME	HUMIDITY %	TEMP °F	ATMOS PRESS in Hg	TEST TANK PRESS	SPEC. MATERIAL	SPEC. THICK	TYPE OF PENETRA
135	12/21/61	4:35pm	69	60	29.6	40 psig	Ti-6Al-4V[3]	0.016"	1" Chis
136 [a]	12/22/61	9:15am	69	61	29.5	30 psig	Ti-5Al-2.5Sn	0.028"	1/4" Ch
137 [a]	12/22/61	9:45am				30 psig	"	0.028"	"
138 [b]	12/22/61	10:00am	74	62	29.5	30 psig	"	0.028"	"
139 [b]	12/22/61	10:30am				30 psig	"	0.028"	"
140 [b]	12/22/61	11:00am				40 psig	"	0.028"	"
141	12/22/61	11:35am	42	88	29.6	40 psig	"	0.028"	"
142 [b]	12/22/61	1:20pm				40 psig	"	0.028"	"
143 [c]	12/22/61	2:00pm	54	80	29.6	30 psig	"	0.028"	"
144 [b]	12/22/61	2:15pm				40 psig	"	0.028"	"
145 [b]	12/22/61	2:45pm				50 psig	"	0.028"	"
146	12/22/61	3:05pm				40 psig	"[1]	0.028"	"
147	12/22/61	3:30pm				40 psig	Ti-4901 A.N.	0.010"	Conical Plunge
148	12/22/61	4:00pm	62	68	29.6	55 psig	301 SS	0.008"	"
149	12/22/61	4:20pm				55 psig	"	0.008"	"
150	12/27/61	9:00am	57	73	29.6	30 psig	"	0.010"	1/4"Chi
151	12/27/61	9:15am				30 psig	"	0.010"	"
152	12/27/61	9:40am				30 psig	Ti-5Al-2.5Sn	0.028"	"
153	12/27/61	10:00am	48	82	29.6	55 psig	301 SS	0.014"	"
154	12/27/61	10:15am				30 psig	2024T-3 Al	0.016"	"
155	12/27/61	10:30am				55 psig	"	0.016"	"
156	12/27/61	10:50am				55 psig	"	0.016"	"
157	12/27/61	11:20am				55 psig	Ti-5Al-2.5Sn	0.028"	"
158	12/27/61	11:40am	34	90	29.6	55 psig	"	0.035"	"
159	12/27/61	1:00pm				55 psig	2024-T3-Al	0.016"	"
160	12/27/61	1:20pm				55 psig	"	0.016"	"
161	12/27/61	1:45pm				55 psig	301 SS	0.010"	"
162	12/27/61	2:00pm	47	79	29.6	55 psig	"	0.014"	"
163	12/27/61	2:10pm				20 psig	Ti-5Al-2.5Sn	0.028"	"
164	12/27/61	2:30pm				20 psig	"	0.035"	"
165	12/27/61	2:45pm				20 psig	"	0.035"	"
166	12/27/61	3:05pm				55 psig	301 SS	0.014"	Conical Plung
167	12/27/61	3:35pm				55 psig	"	0.010"	"
168	12/27/61	3:50pm				55 psig	"	0.010"	"
169	12/27/61	4:00pm	49	72	29.6	55 psig	2024 T-3-Al	0.016"	"
170	12/27/61	4:15pm				55 psig	"	0.016"	"
171	12/27/61	4:30pm				55 psig	"	0.016"	"
172	12/28/61	8:50am	50	62	29.5	55 psig	"	0.016"	1" Chis
173	12/28/61	9:00am				55 psig	"	0.016"	"
174	12/28/61	9:15am				55 psig	"	0.016"	"

1 - Ag Plated
3 - Ni Plated

a - 0.001" Al foil bonded by diffusion on both sides of Ti membrane
b - 0.001" Al foil bonded by diffusion on one side of Ti membrane. Al foil in contact
c - 0.001" Al foil bonded by diffusion on one side of Ti membrane. Ti foil in contact

TABLE I. LOG OF TITANIUM-OXYGEN REACTIVITY TES

TEST NO.	DATE	TIME	HUMIDITY %	TEMP. °F	ATMOS PRESS in Hg	TEST TANK PRESS	SPEC. MATERIAL	SPEC. THICK	TYPE OF PENETRAT
175 [d]	12/28/61	9:30am				30 psig	Ti-5Al-2.5 Sn	0.035"	1/4"Chis
176	12/28/61	9:45am				55 psig	2024 T-3Al	0.016"	1" Chise
177	12/28/61	10:00am	34	69	29.6	55 psig	"	0.016"	"
178	12/28/61	10:20am				55 psig	301 SS	0.010"	"
179	12/28/61	10:35am				55 psig	"	0.014"	"
180	12/28/61	10:50am				55 psig	"	0.010"	"
181	12/28/61	11:00am				55 psig	"	0.010"	"
182	12/28/61	11:20am				55 psig	"	0.010"	"
183	12/28/61	11:40am				30 psig	Ti-5Al-2.5Sn[1]	0.028"	"
184	12/28/61	12:00N	31	76	29.6	30 psig	"[2]	0.028"	1/4"Chis
185[d]	12/28/61	1:05pm				30 psig	"	0.035"	1" Chise
186[d]	12/28/61	1:20pm				30 psig	"	0.035"	"
187[e]	12/28/61	1:35pm				30 psig	"	0.035"	"
188[e]	12/28/61	1:50pm				50 psig	"	0.050"	Conical
189[f]	12/28/61	2:00pm	25	82	29.6	40 psig	"	0.028"	1" Chis
190[f]	12/28/61	2:20pm				30 psig	"	0.028"	"
191	12/28/61	2:40pm				50 psig	Ti-4901-AM	0.010"	"
192[e]	12/28/61	3:05pm				30 psig	Ti-5Al-2.5Sn	0.028"	"
193	12/28/61	3:30pm				40 psig	Ti-4901-AM	0.010"	"
194	12/28/61	3:55pm	60	78	29.6	30 psig	"	0.010"	"
195	12/28/61	4:10pm				20 psig	"	0.010"	"
196	12/28/61	4:40pm				10 psig	"	0.010"	"
197	12/29/61	9:10am	34	73	29.5	40 psig	Ti-5Al-2.5Sn	0.035"	Be-Cu Co
198	12/29/61	9:30am				50 psig	"	0.035"	"
199	12/29/61	9:45am				55 psig	"	0.028"	"
200[g]	12/29/61	10:00am	25	83	29.6	40 psig	"	0.028"	Be-Cu Ch
201[g]	12/29/61	10:30am				50 psig	"	0.028"	"
202[g]	12/29/61	10:50am				50 psig	"	0.028"	"
203[g]	12/29/61	11:15am				45 psig	"	0.035"	"
204[g]	12/29/61	11:30am				40 psig	"	0.028"	"
205	12/29/61	11:45am	26	89	29.6	40 psig	"	0.028"	"
206	12/29/61	1:15pm				40 psig	"	0.035"	"
207	12/29/61	1:40pm				40 psig	"	0.035"	"
208	12/29/61	2:15pm	30	82		40 psig	"	0.050"	"
209	12/29/61	2:40pm				40 psig	Covered by Al. foil	0.035"	"

d - 2 thin 0.005" 301 S.S. sheets on each side of the Ti-5Al-2.5Sn membrane

e - 1 thin 0.005" 301 S.S. sheet on one side of the Ti-5Al-2.5Sn membrane. 301 S.S. sh

f - 1 thin 0.005" 301 S.S. sheet on one side of the Ti-5Al-2.5Sn membrane. 301 S.S. sh

g - Be-Cu chisel acting as a knife cutting through the membrane

1. Ag Plated
2. Au Plated

GASEOUS OXYGEN (Continued)

	GOX	OTHER	IMPACT ENERGY	REMARKS	CONFIGURATION
	X		44.5 ft.lbs	Positive Reaction	
	X		43.9 ft.lbs	No Reaction	
	X		"	No Reaction	
	*X		"	No Reaction	
	X		"	No Reaction	
	X		"	No Reaction	
	*X		"	No Reaction	
	X		"	No Reaction	
	X		50.6 ft.lbs.	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	No Reaction	
	X		"	No Reaction	
ıger			43.9 ft.lbs.	No Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		50.6 ft.lbs.	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
ıl	*X		47.8 ft.lbs.	No Reaction	
	X		"	No Reaction	
	X		"	No Reaction	
-K	*X		"	No Reaction	
	X		"	Trace of Burning	
	X		"	Trace of Burning	
	X		"	Trace of Burning	
	X		"	No Reaction	
	X		"	Slight Burning	
	X		"	No Reaction	
	X		"	Slight Burning	
	X		"	No Reaction	
	X		"	No Reaction	

in contact with GOX
in contact with atmosphere.

- GASEOUS OXYGEN (Continued)

	GOX	OTHER	IMPACT ENERGY	REMARKS	CONFIGURATION
L	X		47.8 ft.lbs.	Positive Reaction	
	X		"	No Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
:r	X		"	No Reaction	
	X		41 ft.lbs.	Positive Reaction	
	X		20.5 ft.lbs	Positive Reaction	
	X		"	Positive Reaction	
	25%	75%He	47.8 ft.lbs.	No Reaction	
	"	"	"	No Reaction	
	75%	25% He	"	No Reaction	
	"	"	"	No Reaction	
	X		"	Positive Reaction	
	87.5%	12.5% He	"	No Reaction	
	87.5%	"	"	Positive Reaction	
	75%	25% He	"	No Reaction	
	87.5%	12.5% He	"	No Reaction	
	X		"	Sparks & Slight Burning	
	X		"	Sparks but no burning	
	X		"	No Reaction	
	X		"	No Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Slight Burning	
	X		"	Positive Reaction	
	X		"	No Reaction	
	X		"	Sparks & Slight Burning	
	X			No Reaction	
	X			Sparks & Trace of Burning	
	X			Sparks & Slight Burning	
	X			Positive Reaction	
	X		47.8 ft.lbs.	Sparks & Slight Burning	

TABLE I. LOG OF TITANIUM-OXYGEN REACTIVITY TES

TEST NO.	DATE	TIME	HUMIDITY %	TEMP. °F	ATMOS PRESS in Hg	TEST TANK PRESS	SPEC. MATERIAL	SPEC. THICK	TYPE OF PENETRA
210	12/29/61	3:20pm				50 psig	Ti-5Al-2.5Sn	0.035"	Be-Cu Ch K
211	12/29/61	3:40pm				40 psig	"	0.050"	"
212	12/29/61	4:00pm	29	80	29.6	40 psig	"	0.035"	"
213	12/29/61	4:15pm				30 psig	"	0.035"	"
214	12/29/61	4:35pm				55 psig	"	0.035"	Be-Cu Po
215	1/3/62	9:45am				30 psig	"	0.028"	1" Chis
216	1/3/62	10:00am				30 psig	"	0.028"	"
217	1/3/62	10:20am				30 psig	"	0.028"	"
218	1/3/62	10:40am				40 psig	"	0.028"	"
219	1/3/62	11:00am				40 psig	"	0.028"	"
220	1/3/62	11:15am				40 psig	"	0.028"	"
221	1/3/62	11:30am				40 psig	"	0.028"	"
222	1/3/62	11:45am				40 psig	"	0.028"	"
223	1/3/62	1:00pm				40 psig	"	0.028"	"
224	1/3/62	1:40pm				40 psig	"	0.028"	"
225	1/3/62	1:55pm				40 psig	"	0.028"	"
226	1/3/62	2:10pm				40 psig	"	0.028"	"
227	1/3/62	2:25pm				40 psig	"	0.028"	"
228	1/3/62	2:45pm				40 psig	1 coat of WD-40 Ti-5Al-2.5Sn	0.028"	"
229[1]	1/4/62	1:00pm				50 psig	1 coat of WD-40 Ti-5Al-2.5Sn	0.028"	"
230[1]	1/4/62	1:20pm				50 psig	"	0.028"	"
231[1]	1/4/62	1:40pm				50 psig	"	0.028"	"
232[1]	1/4/62	2:00pm				50 psig	"	0.028"	"
233[1]	1/4/62	2:20pm				50 psig	"	0.028"	"
234[1]	1/4/62	2:40pm				50 psig	"	0.028"	"
235[1]	1/4/62	3:00pm				50 psig	"	0.028"	"
236[1]	1/4/62	3:20pm				50 psig	"	0.028"	"
237[1]	1/4/62	3:40pm				50 psig	"	0.028"	"
238[1]	1/4/62	3:55pm				50 psig	"	0.028"	"
239[2]	1/4/62	4:10pm				50 psig	"	0.028"	"
240[2]	1/5/62	11:00am				50 psig	"	0.028"	"
241[2]	1/5/62	11:15am				50 psig	"	0.028"	"
242[2]	1/5/62	11:30am				50 psig	"	0.028"	"
243[2]	1/5/62	11:45am				50 psig	"	0.028"	"
244[2]	1/5/62	11:55am				50 psig	"	0.012"	"
245[2]	1/5/62	12:55pm				50 psig	"	0.014"	"

1. Sized Al tape in contact with GOX and Ti-5Al-2.5Sn membrane
2. One coat WD-40 sprayed and wiped off and set 3 hours or more

TS - GASEOUS OXYGEN (Continued)

TOR	GOX	OTHER	IMPACT ENERGY	REMARKS	CONFIGURATION
el	X		47.8 ft.lbs.	No Reaction	
	X		"	No Reaction	
	X		"	No Puncture	
*	X		"	Positive Reaction	
	X		"	No Reaction	
	X		"	Sparks & Slight Burning	
*	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	No Reaction	
	X			Positive Reaction	
	X			Positive Reaction	
nter	X			No Reaction	
	X		47.8 ft.lbs.	Positive Reaction	
	X		"	Sparks & Slight Burning	
	X		"	Sparks & Slight Burning	
	X		"	No Reaction	
	X		"	Positive Reaction	
el	X		"	Slight Burning	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
*	X		"	No Reaction	
	X		"	Very slight burning around puncture	
*	X		"	Slight burning around puncture	
	X		"	Slight burning around puncture	
	X		"	Positive Reaction	
	X		"	Slight burning around puncture	
	X		"	Slight burning around puncture	
	X		"	Slight burning around puncture	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	No Reaction	
l	X		"	Positive Reaction 3/8" to 1/2" Depth of Puncture	
	X		"	Positive Reaction 3/8" to 1/2" Depth of Puncture	
	X		"	Positive Reaction 3/8" to 1/2" Depth of Puncture	

* WD-40.

TABLE I. LOG OF TITANIUM-OXYGEN REACTIVITY T

TEST NO.	DATE	TIME	HUMIDITY %	TEMP. °F	ATMOS PRESS in Hg	TEST TANK PRESS	SPEC. MATERIAL	SPEC. THICK	TYPE PENET
246 [2]	1/5/62	1:05pm				50 psig	Ti-5Al-2.5Sn	0.035"	1" Ch
247 [2]	1/5/62	1:15pm				50 psig	"	0.028"	"
248 [3]	1/5/62	1:30pm				50 psig	"	0.050"	"
249 [3]	1/5/62	1:45pm				50 psig	"	0.028"	"
250 [3]	1/5/62	2:00pm				50 psig	"	0.035"	"
251 [3]	1/5/62	2:10pm				50 psig	"	0.028"	"
252 [3]	1/5/62	2:20pm				50 psig	"	0.028"	"
253 [3]	1/5/62	2:30pm				50 psig	"	0.028"	"
254 [3]	1/5/62	2:40pm				50 psig	"	0.035"	"
255 [3]	1/5/62	2:50pm				50 psig	"	0.028"	"
256 [3]	1/5/62	3:00pm				50 psig	"	0.028"	"
257 [3]	1/5/62	3:10pm				50 psig	"	0.050"	Be-Cu
258 [4]	1/8/62	8:00am	32%	84	29.4	50 psig	Ti-6Al-4V	0.016"	1"Chi
259 [4]	1/8/62	8:20am				50 psig	"	0.016"	"
260 [4]	1/8/62	8:30am				50 psig	"	0.016"	"
261 [4]	1/8/62	8:45am				50 psig	"	0.016"	"
262 [4]	1/8/62	9:05am				50 psig	"	0.016"	"
263 [4]	1/8/62	9:35am				50 psig	"	0.016"	3/8"C
264 [4]	1/8/62	9:55am				50 psig	"	0.016"	"
265 [4]	1/8/62	10:05am	35	88	29.6	50 psig	"	0.016"	"
266 [4]	1/8/62	10:20am				50 psig	"	0.016"	"
267 [4]	1/8/62	10:40am				50 psig	"	0.016"	"
268 [2]	1/8/62	10:50am				50 psig	"	0.016"	"
269 [2]	1/8/62	11:00am				50 psig	"	0.016"	"
270 [2]	1/8/62	11:20am				50 psig	"	0.016"	"
271 [2]	1/8/62	12:30pm	30	87	29.5	50 psig	"	0.016"	"
272 [2]	1/8/62	12:45pm				50 psig	"	0.016"	"
273 [2]	1/8/62	1:00pm				50 psig	"	0.016"	"
274 [2]	1/8/62	1:15pm				50 psig	"	0.016"	"
275 [2]	1/9/62	1:30pm				50 psig	"	0.016"	"
276 [2]	1/8/62	1:50pm				50 psig	"	0.016"	"
277 [2]	1/8/62	2:10pm	28	82	29.4	50 psig	Ti-5Al-2.5Sn	0.050"	"
278 [2]	1/8/62	2:30pm				50 psig	Ti-6Al-4V	0.016"	1" Ch
279 [2]	1/8/62	2:40pm				50 psig	"	0.016"	"
280 [2]	1/8/62	3:00pm				50 psig	"	0.016"	"

2. One coat WD-40 sprayed and wiped off and set 3 hours or more.
3. Three coats of WD-40 sprayed and wiped and allowed to set 3 hours or more between coat
4. 0.002" Al foil in contact with GOX and Ti-6Al-4V.

S - GASEOUS OXYGEN (Continued)

TOR	GOX	OTHER	IMPACT THEORY	REMARKS	CONFIGURATION
el	X		47.8 ft.lbs.	Positive Reaction 3/8" to 1/2" Depth of Puncture	
	X		"	Positive Reaction 3/8" to 1/2" Depth of Puncture	
	X		"	Positive Reaction 3/8" to 1/2" Depth of Puncture	
	X		"	Positive Reaction 3/8" to 1/2" Depth of Puncture	
	X		"	Trace of Burning 1/8" Depth of Puncture	
	X		"	Trace of Burning 1/8" Depth of Puncture	
	X		"	Positive Reaction 3/8" to 1/2" Depth of Puncture	
sel	X		48 ft.lbs.	Positive Reaction	
	X		"	10% of Membrane Burned	
	X		"	Sparks & Slight Burning	
	X		"	Slight Burning	
	X		"	10% of Membrane Burned	
	X		"	Positive Reaction	
	X		"	10% of Membrane Burned	
	X		"	Positive Reaction	
	X		"	Slight Burning	
	X		"	10% of Membrane Burned	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	

TABLE I. LOG OF TITANIUM-OXYGEN REACTIVITY T

TEST NO.	DATE	TIME	HUMIDITY %	TEMP. °F	ATMOS PRESS in Hg	TEST TANK PRESS	SPEC. MATERIAL	SPEC. THICK	TYPE PENE
281 [2]	1/8/62	3:20pm				50 psig	Ti-6Al-4V	0.016"	1" C
282 [2]	1/8/62	3:40pm	23%	86	29.6	50 psig	"	0.016"	"
283 [2]	1/8/62	4:35pm				50 psig	"	0.016"	"
284 [2]	1/8/62	4:45pm				50 psig	"	0.016"	"
285 [2]	1/8/62	5:00pm	70	76	29.6	50 psig	"	0.016"	"
286 [2]	1/8/62	5:15pm				50 psig	"	0.016"	"
287 [2]	1/8/62	5:30pm				50 psig	"	0.016"	"
288	1/10/62	10:00am	29	81	29.6	10 psig	"	0.016"	1/4"
289 [1]	1/10/62	10:30am				50 psig	"	0.016"	"
290 [1]	1/10/62	11:00am				50 psig	"	0.016"	"
291 [1]	1/10/62	11:30am				50 psig	"	0.016"	"
292 [1]	1/10/62	12:00am	26	91	29.6	50 psig	"	0.016"	"
293 [1]	1/10/62	1:00pm				50 psig	"	0.016"	"
294 [1]	1/10/62	1:20pm				50 psig	"	0.016"	"
295 [1]	1/10/62	1:40pm				50 psig	"	0.016"	"
296 [1]	1/10/62	2:00pm	23	86	29.6	50 psig	"	0.016"	"
297 [1]	1/10/62	2:20pm				50 psig	"	0.016"	"
298 [1]	1/10/62	2:40pm				50 psig	"	0.016"	"
299 [4]	1/10/62	3:00pm				50 psig	"	0.016"	"
300 [4]	1/10/62	3:20pm				50 psig	"	0.016"	"
301 [4]	1/10/62	3:40pm				50 psig	"	0.016"	"
302 [5]	1/10/62	4:00pm	44	66	29.6	50 psig	"	0.016"	"
303 [4]	1/10/62	4:20pm				50 psig	"	0.016"	"
304 [4]	1/10/62	4:40pm				50 psig	"	0.016"	"
305 [6]	1/10/62	5:00pm	26	65	29.6	50 psig	"	0.016"	"
306 [6]	1/10/62	5:20pm				50 psig	"	0.016"	"

2. - 1 coat of WD-40 applied to Ti-6Al-4V. The WD-40 was allowed to dry for 3 hours or mo
1. - Sized Al Tape in contact with GOX and Ti-6Al-4V membrane.
4. - Ni Plated
5. - Cu Plated
6. - Al Foil on both sides of the Ti-6Al-4V membrane.

TS - GASEOUS OXYGEN (Concluded)

TOR	GOX	OTHER	IMPACT THEORY	REMARKS
isel	X		50.8 ft.lbs.	Sparks & Very Slight Burning
	X		"	Sparks & Very Slight Burning
	X		"	Sparks & Very Slight Burning
	X		"	Sparks and very slight burning
	X		"	Sparks & very slight burning
	X		"	No reaction
	X		"	Sparks & very slight burning
	X		"	Sparks & very slight burning
	X		"	Sparks
	X		"	Positive reaction
sel	X		"	Positive reaction
isel	X		"	Sparks & very slight burning
	X		"	Sparks & very slight burning
	X		"	Sparks & very slight burning
	X		"	Sparks & very slight burning
	X		"	Sparks & very slight burning
	X		"	Sparks & a trace of burning
	X		"	Sparks & a trace of burning
	X		"	Sparks & a trace of burning
	X		"	Sparks & a trace of burning
	X		"	Sparks & very slight burning
	X		"	Positive reaction
	X		"	Sparks & very slight burning
	X		"	Positive reaction
	X		"	Positive reaction
	X		"	Positive reaction
	X		"	Positive reaction
	X		"	Sparks & very slight burning
	X		"	Sparks & very slight burning
	X		"	Sparks & very slight burning
sel	X		"	No reaction
	X		"	Positive reaction
	X		"	Positive reaction

TABLE I. LOG OF TITANIUM-OXYGEN REACTIVIT

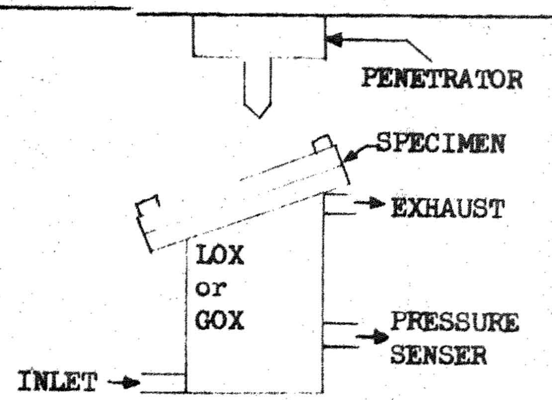
TEST NO.		DATE	TIME	HUMIDITY %	TEMP. °F	ATMOS PRESS in Hg	TEST TANK PRESS	SPEC. MATERIAL	SPEC. THICK	TY PE
307	2	1/11/62	8:00am				50 psig	Ti-6Al-4V	0.016"	1/
308	2	1/11/62	8:20am	32	66	29.7	50 psig	"	0.016"	
309	2	1/11/62	8:40am				50 psig	"	0.016"	
310	2	1/11/62	9:00am				50 psig	"	0.016"	
311	2	1/11/62	9:20am				50 psig	"	0.016"	
312	2	1/11/62	9:40am				50 psig	"	0.016"	
313	2	1/11/62	10:00am	56	78	29.8	50 psig	"	0.016"	
314	2	1/11/62	10:20am				50 psig	"	0.016"	
315	2	1/11/62	10:40am				50 psig	"	0.016"	
316	2	1/11/62	11:00am				50 psig	"	0.016"	
317	2	1/11/62	11:20am				50 psig	"	0.016"	1"
318	5	1/11/62	11:40am				50 psig	"	0.016"	1/
319	5	1/11/62	12:00pm	25	76	29.8	50 psig	"	0.016"	
320	5	1/11/62	12:45pm				50 psig	"	0.016"	
321	5	1/11/62	1:00pm				50 psig	"	0.016"	
322	5	1/11/62	1:15pm				50 psig	"	0.016"	
323	9	1/11/62	1:30pm				50 psig	"	0.016"	
324	9	1/11/62	1:45pm				50 psig	"	0.016"	
325	9	1/11/62	2:00pm	31	69	29.7	50 psig	Ti-5Al-2.5Sn	0.025"	
326	9	1/11/62	2:15pm				50psig	Ti-6Al-4V	0.016"	
327	7	1/11/62	2:30pm				50 psig	"	0.016"	
328	7	1/11/62	2:45pm				50 psig	"	0.016"	
329	7	1/11/62	3:00am				50 psig	"	0.016"	
330	8	1/11/62	3:15am				50 psig	"	0.016"	
331	8	1/11/62	3:30pm				50 psig	"	0.016"	
332	8	1/11/62	3:45pm				50 psig	"	0.016"	
333		1/11/62	4:00pm	36	66	29.8	50 psig	"	0.016"	
334	6	1/11/62	4:15pm				50 psig	"	0.016"	
335	6	1/11/62	4:30pm				50 psig	"	0.016"	
336	6	1/11/62	4:45pm				50 psig	"	0.016"	
337	7	1/11/62	5:00pm	46	58	29.6	50 psig	"	0.016"	1"
338	7	1/11/62	5:15pm				50 psig	"	0.016"	
339	7	1/11/62	5:30pm				50 psig	"	0.016"	

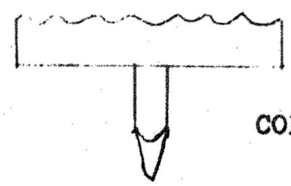
6 - One coat of CRC 3.36 rust inhibitor on both sides of titanium target
2 - One coat of WD-40 on both sides of titanium target
5 - One coat of WD-40 on the outside of the titanium target
9 - Titanium target dipped in molten aluminum
7 - One coat of mineral oil on both sides of titanium target
8 - One coat of DuPont 703 Vacuum pump fluid on both sides of titanium target.

TS - LIQUID OXYGEN

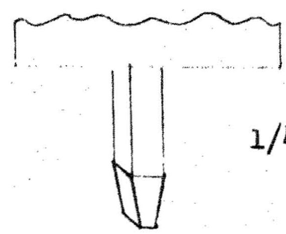
OF TRATOR	GOX	OTHER	IMPACT THEORY	REMARKS
al er	X		43.0 ft.lbs	No Reaction
*	X		43.9 ft.lbs.	No Reaction
	X		"	Positive Reaction
	X		"	No Reaction
*	X		"	No Reaction
	X		44.5 ft.lbs.	Positive Reaction
hisel	X		50.8 ft.lbs.	Positive Reaction
	X		"	Positive Reaction
	X		46.5 ft.lbs.	No Reaction
	X		44.5 ft.lbs.	No Reaction
	X		"	No Reaction
	X		"	No Reaction
	X		"	No Reaction
sel	X		"	No Reaction
	X		"	No Reaction
	X		47.8 ft.lbs.	No Reaction
	X		"	No Reaction
	X		"	No Reaction
	X		"	No Reaction
*	X		"	No Reaction
	X		"	No Reaction
	X		"	Positive Reaction
	X		"	Positive Reaction
*	X		"	No Reaction
hisel	X		"	No Reaction
	X		"	No Reaction
	X		"	No Reaction
	X		"	No Reaction
	X		"	No Reaction
	X		"	No Reaction
	X		"	No Reaction
	X		"	No Reaction
	X		"	No Reaction
	X		"	No Reaction
*				
*				

CONFIGURATION

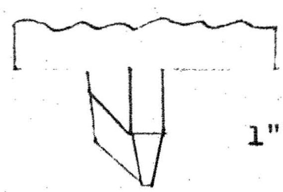




CONICAL PLUNGER



1/4" CHISEL PLUNGEI



1" CHISEL PLUNGER

TABLE II. LOG OF TITANIUM-OXYGEN REACTIVITY

TEST NO.	DATE	TIME	HUMIDITY %	TEMP °F	ATMOS PRESS in Hg	TEST TANK PRESS	SPEC. MATERIAL	SPEC THICK	T P
1	12/19/61	10:30am	55	80	29.6	30 psig	301 SS		Co Pl
2	12/19/61	10:50am				30 psig	"		
3	12/19/61	11:10am				30 psig	Ti-5Al-2.5Sn		
4 [a]	12/19/61	1:00pm				30 psig	"		
5 [a]	12/19/61	1:35pm				30 psig	"		
6	12/19/61	2:15pm	54	80	29.6	30 psig	"		
7	12/19/61	3:00pm				30 psig	"		1/4
8	12/19/61	3:50pm	62	68	29.5	30 psig	"		
9	12/20/61	10:50am	70	66	29.6	11 psig	2024-T3 Al		
10	12/20/61	11:40am	42	82	29.6	30 psig	"		
11	12/20/61	1:00pm				30 psig	"		
12	12/20/61	1:30pm	39	83	29.6	30 psig	"		
13	12/20/61	3:00pm				30 psig	"		
14	12/20/61	3:30pm				30 psig	"		1"
15	12/20/61	4:00pm	48	82	29.6	30 psig	"		
16	1/3/62	3:25pm				30 psig	301 SS	0.014"	
17	1/3/62	3:45pm				30 psig	"	0.013"	
18	1/4/62	10:00am				30 psig	"	0.013"	
19	1/4/62	10:22am				30 psig	"	0.013"	
20	1/4/62	10:50am				30 psig	"	0.013"	
21	1/4/62	11:50am				30 psig	2024-T3	0.016"	
22	1/5/62	9:30am				30 psig	Ti-5Al-2.5Sn	0.028"	
23	1/5/62	10:00am				30 psig	"	0.028"	
24	1/5/62	10:30am				30 psig	"	0.028"	
25	1/9/62	8:40am	61	66	29.4	30 psig	2024-T3	0.016"	1/
26	1/9/62	9:00am				30 psig	"	0.016"	
27	1/9/62	9:30am				30 psig	"	0.016"	
28	1/9/62	10:00am	41	80	29.6	30 psig	"	0.016"	
29	1/9/62	10:15am				30 psig	"	0.016"	
30	1/9/62	10:30am				30 psig	301 SS	0.014"	
31	1/9/62	11:00am				30 psig	"	0.014"	
32	1/9/62	11:20am				30 psig	"	0.014"	
33	1/9/62	11:40am				30 psig	"	0.014"	
34	1/9/62	12:20pm	42	86	29.6	30 psig	"	0.014"	

a. Puncture of membrane very slight

IQUID OXYGEN (Continued)

)F RATOR	GOX	OTHER	IMPACT THEORY	REMARKS	CONFIGURATION
Chisel	X		47.8 ft.lbs.	No Reaction	
	X		"	Positive Reaction	
	X		"	Sparks	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Positive Reaction	
	X		"	Sparks & slight burning	
"	X		"	Positive Reaction	
nisel	X		"	No Reaction	
"	X		48 ft.lbs.	No Reaction	
"	X		"	No Reaction	
"	X		"	Positive Reaction	
"	X		"	Positive Reaction	

Al foil attached. The Al foil was in contact

TABLE II. LOG OF TITANIUM-OXYGEN REACTIVITY TESTS

TEST NO.	DATE	TIME	HUMIDITY %	TEMP. °F	ATMOS PRESS in Hg	TEST TANK PRESS	SPEC MATERIAL	SPEC THICK	T F
35 [1]	1/9/62	12:50pm				30 psig	Ti-6Al-4V	0.016"	1
36 [1]	1/9/62	1:25pm				30 psig	"	0.016"	
37 [1]	1/9/62	1:45pm				30 psig	"	0.016"	
38 [1]	1/9/62	2:00pm	30	82	29.4	30 psig	"	0.016"	
39 [1]	1/9/62	2:15pm				30 psig	"	0.016"	
40	1/9/62	2:30pm				30 psig	"	0.016"	
41	1/9/62	2:50pm				30 psig	"	0.016"	
42	1/9/62	3:10pm				30 psig	"	0.016"	
43 [2]	1/9/62	3:30pm				30 psig	"	0.016"	
44 [2]	1/9/62	3:45pm				30 psig	"	0.016"	
45 [2]	1/9/62	4:00pm	30	82	29.6	30 psig	"	0.016"	
46 [2]	1/9/62	4:15pm				30 psig	"	0.016"	
47 [2]	1/9/62	4:40pm				30 psig	"	0.016"	
48	1/9/62	5:00pm	74	62	29.6	30 psig	2024-T3	0.016"	1
49	1/10/62	8:00am	42	64	29.6	30 psig	"	0.016"	
50	1/10/62	8:30am				30 psig	Ti-6Al-4V	0.016"	
51	1/10/62	9:00am				30 psig	"	0.016"	
52	1/10/62	9:30am				30 psig	"	0.016"	

1 - One coat of WD-40 allowed to dry 16 hours or more

2 - One coat of WD-40 on side of membrane in contact with atmosphere and oppostie side wi
with the Ti membrane and the LOX.

TABLE III. SUMMARY OF TITANIUM - GASEOUS OXYGEN REACTIVITY TES
PRESSURIZED TITANIUM DIAPHRAGMS IMPACTED BY DROP- W

PRESSURE PSIG	CONICAL PENETRATOR NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
10	15	9	1	5
15	5	0	1	4
20	5	2	1	2
30	10	6	1	3
40	9	3	0	6
50	2	0	0	2
TOTAL	46	20	4	22

57% of tests resulted in reaction.
40% of tests resulted in severe burning.

PRESSURE PSIG	NO. OF TESTS
0	6
5	7
10	5
20	5
30	6
40	1
TOTAL	30

70% of

PRESSURE PSIG	CONICAL PENETRATOR NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	2	2	0	0
55	5	5	0	0

PRESSURE PSIG	NO. OF TESTS
50	1
55	5

No reacti

PRESSURE PSIG	CONICAL PENETRATOR NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
55	5	3	2*	0

*Sparks genereated, but no burning

PRESSURE PSIG	NO. OF TESTS
55	5

Steel showing some
or surface oxidatio

PENETRATORS

TITANIUM

1/4" CHISEL PENETRATOR

ACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
3	0	3
3	0	4
2	0	3
0	0	5
1	0	5
0	0	1
9	0	21

resulted in severe burning.

1" CHISEL PENETRATOR

PRESSURE PSIG	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
0	1	1	0	0
5	5	4	0	1
10	6	3	2	1
20	6	3	0	3
30	12	3	1	8
40	7	1	0	6
50	2	0	0	2
TOTAL	39	15	3	21

62% of tests resulted in reaction.
54% of tests resulted in severe burning

LUMINUM (2024-T3 Alloy)

O REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
1	0	0
5	0	0

any tests with aluminum.

1" CHISEL PENETRATOR

PRESSURE PSIG	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNIN
30	3	3	0	0
50	2	2	0	0
55	5	5	0	0

STAINLESS STEEL

HISEL PENETRATION

O ACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
4	1*	0

ng when impacted but no burning
rred in any tests.

1" CHISEL PENETRATOR

PRESSURE PSIG	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING	SEVERE BURNI
50	5	5	0	0

TRATORS

IUM

PENETRATOR

SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
0	5

1" CHISEL PENETRATOR

PRESSURE PSIG	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
30	5	1	0	4

1 (2024-T3 ALLOY)

ISEL PENETRATOR

SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
0	0

1" CHISEL PENETRATOR

PRESSURE PSIG	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
30	5	5	0	0

EEL (301 XFH)

PENETRATOR

SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
0	0

1" CHISEL PENETRATOR

PRESSURE PSIG	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
30	5	5	0	0

TABLE IV. SUMMARY OF LIQUID OXYGEN REACTIVITY TESTS
PRESSURIZED DIAPHRAGMS IMPACTED BY DROP-WEIGHT I

TI

CONICAL PENETRATOR

PRESSURE PSIG	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
30	5	2	0	3

1/4" CHI

PRESSURE PSIG	NO. OF TESTS	NO REACTIONS
30	5	0

ALUM

1/4"

PRESSURE PSIG	NO. OF TESTS	NO. REACTION
30	9	9

STAINLESS

1/4" CHIS

PRESSURE PSIG	NO. OF TESTS	NO REACTION
30	5	5

/8" CHISEL PENETRATOR

ACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
1	6	3

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
50	20	4	6	10

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
50	5	0	0	5

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
50	10	4	1	5

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
50	3	0	1	2

TABLE V. SUMMARY OF COATED TITANIUM - GASEOUS OXYGEN REACTIVITY T
OF PRESSURIZED DIAPHRAGMS IMPACTED BY DROP-WEIGHT PENETRA

ONE COAT OF WD-40 APPLIED TO BOTH SIDES OF TITANIUM TARGET

1/4" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
50	10	1	8	1

PRESS. (PSIG)	NO. OF TESTS
50	10

ONE COAT OF WD-40 APPLIED TO OUTSIDE OF TITANIUM TARGET

1/4" CHISEL PENETRATION

PRESS (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	5	0	5	0

3 COATS OF WD-30 APPLIED TO BOTH SIDES OF TITANIUM TARGET

1/4" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
50	10	0	7	3

NI PLATED

1/4" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
50	4	0	0	4

/8" CHISEL PENETRATOR

ACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
1	6	3

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	20	4	6	10

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	5	0	0	5

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	10	4	1	5

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	3	0	1	2

50	10	1	8	1	50	10

ONE COAT OF WD-40 APPLIED TO OUTSIDE OF TITANIUM TARGET

1/4" CHISEL PENETRATION

PRESS (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	5	0	5	0

3 COATS OF WD-30 APPLIED TO BOTH SIDES OF TITANIUM TARGET

1/4" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	10	0	7	3

NI PLATED

1/4" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	4	0	0	4

5

/8" CHISEL PENETRATOR

ACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
1	6	3

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	20	4	6	10

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	5	0	0	5

0

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	10	4	1	5

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	3	0	1	2

0

TABLE V. SUMMARY OF COATED TITANIUM - GASEOUS OXYGEN REACTIVITY TE
OF PRESSURIZED DIAPHRAGMS IMPACTED BY DROP-WEIGHT PENETRA

ONE COAT OF WD-40 APPLIED TO BOTH SIDES OF TITANIUM TARGET

1/4" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	10	1	8	1

PRESS. (PSIG)	NO. OF TESTS
50	10

ONE COAT OF WD-40 APPLIED TO OUTSIDE OF TITANIUM TARGET

1/4" CHISEL PENETRATION

PRESS (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	5	0	5	0

3 COATS OF WD-30 APPLIED TO BOTH SIDES OF TITANIUM TARGET

1/4" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	10	0	7	3

NI PLATED

1/4" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	4	0	0	4

S

/8" CHISEL PENETRATOR

ACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
1	6	3

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
50	20	4	6	10

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
50	5	0	0	5

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
50	10	4	1	5

1" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURN-ING OF EDGES	SEVERE BURNING
50	3	0	1	2

TABLE V. SUMMARY OF COATED TITANIUM - GASEOUS OXYGEN REACTIVITY T
OF PRESSURIZED DIAPHRAGMS IMPACTED BY DROP-WEIGHT PENETR

ONE COAT OF WD-40 APPLIED TO BOTH SIDES OF TITANIUM TARGET

1/4" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	10	1	8	1

PRESS. (PSIG)	NO. OF TESTS
50	10

ONE COAT OF WD-40 APPLIED TO OUTSIDE OF TITANIUM TARGET

1/4" CHISEL PENETRATION

PRESS (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	5	0	5	0

3 COATS OF WD-30 APPLIED TO BOTH SIDES OF TITANIUM TARGET

1/4" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	10	0	7	3

NI PLATED

1/4" CHISEL PENETRATOR

PRESS. (PSIG)	NO. OF TESTS	NO REACTION	SPARKS AND SLIGHT BURNING OF EDGES	SEVERE BURNING
50	4	0	0	4

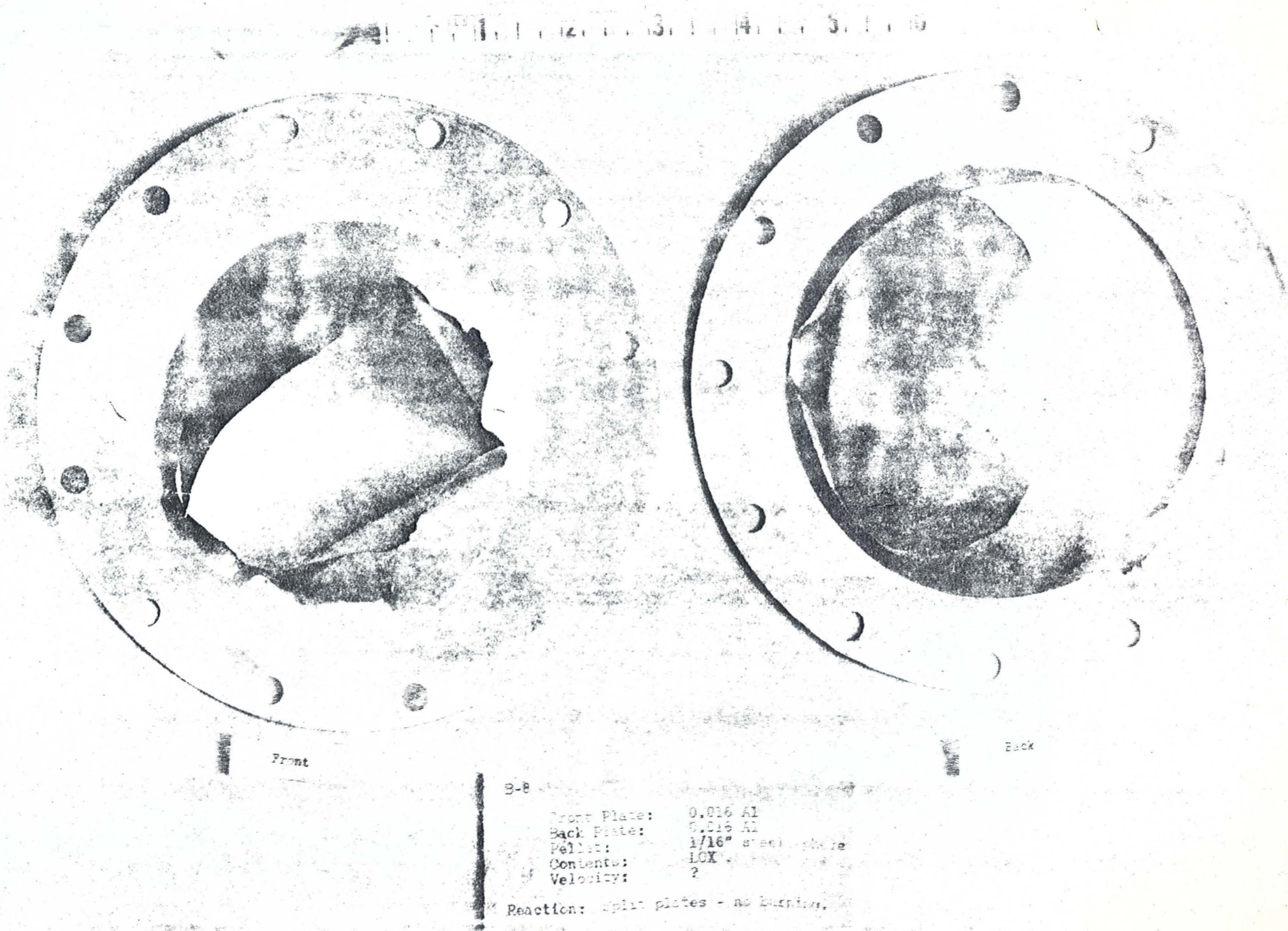


FIGURE 29. ALUMINUM ALLOY DIAPHRAGMS AFTER HIGH VELOCITY PUNCTURE TEST.