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This document is submitted in partial fulfillment of paragraph B(1.1.1.1.9.2) of the Statement of Work, System 620A, Exhibit 620A-62-2, dated 26 January 1962, revised 1 August 1962.

U3-4071-1000

SUMMARY

The two test programs reported in this report provided basic structural data on the use of 2219-T6E46 aluminum for the X-20 cryogenic storage tanks. The following summarizes the test results:

1. Biaxial strength of 2219-T6E46 aluminum at temperatures of -395° F. and lower are 91,000 psi (min.) compared to uniaxial strengths of 88,200 psi (min.) at -423° F.

2. Ductile failures occurred in all four test tanks at temperatures of -320° F. and -395° F.

3. A low factor, prototype liquid nitrogen tank failed at a pressure of 2650 psi after 252 pressure cycles at 1000 ± 50 psi

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INTRODUCTION

A cryogenic tank development test program was instituted to provide the following basic data which did not exist at the time the Dyna Soar cryogenic tank program was initiated. These problem areas were as follows:

1. Determine biaxial strength and fracture toughness of 2219-T6E46 aluminum in a 1 : 1 stress field at cryogenic conditions.

2. Determine the burst strength of a low factor, prototype, 2219-T6E46 aluminum cryogenic tank that had been subjected to 1.5 times its operating life cycle requirements.

It had been determined that the prime considerations of any material for the Dyna Soar tanks would be:

1. High strength to weight ratio.

2. High fracture toughness at cryogenic temperatures.

3. Excellent fabrication characteristics for small tanks.

Prior to establishing the development test program, studies and tests had been conducted both at Boeing and at outside the company on potential cryogenic tank materials.

From the comparison data, the aluminum alloy, 2219, met all the above requirements and was thus selected for the Dyna Soar tanks. The -T6E46 heat treat condition of this material had been developed at Boeing for the ramjet fuel tanks on the IM-99B missile and provided a higher yield strength than the more conventional -T62 condition developed by Alcoa. All that remained, was to test this material in the actual tank configurations and to resolve the previously-mentioned problem areas.

EWA 5-749, Section 1 of this report, was initiated to resolve the biaxial strength and toughness of 2219-T6E46. Liquid hydrogen was chosen as the test media for several reasons:

1. Fracture toughness for all materials is more critical as the environment approaches absolute zero.

2. Material strengths increased as the absolute zero is approached.

3. A production liquid hydrogen storage tank is to be used in the Dyna Soar Glider.

A 17" diameter sphere was used as the test specimen because it would provide an ideal biaxial stress field and would require the same or similar fabrication processes as full-sized tanks.

EWA 5-747, Section 2 of this report, was instigated to evaluate the second problem area. As explained in Section 2.4, the design objectives of a low factor, prototype tank were met in the 16.18" diameter sphere which was designed to meet the original supercritical nitrogen storage tank requirements.

THE BOEING COMPANY

NUMBER D2-80092 MODEL NO. X-20

TITLE Section 1: EWA 5-749, "Structural Development Tests of Cryogenic Subsize Tanks"

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2-5142

EWA 5-749 LH_2 Subsize Tank Burst Tests

1.1 SUMMARY

The three 17" diameter tanks were burst tested at LH_2 temperatures. Each tank failed at calculated stresses in excess of the predicted uniaxial strength for this material. Failures were ductile, indicating that 2219 aluminum is a reliable, tough material suitable for low factor cryogenic tanks. No difficulties were found to exist in fabricating this material.

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1.3 REFERENCES

1.3.1 Engineering Work Authorization, 5-749, "Liquid Hydrogen Subsize Tank Burst Tests"

1.3.2 T2-2613, "Dyna Soar Subsize Liquid Hydrogen Tank Burst Testing"

1.3.3 Dyna Soar Unit Material and Processes Summary Report DS-SR-041-MP, October 25, 1961

1.3.4 Dyna Soar Material and Processes Unit Summary Report DS-SR-042-MP, November 6, 1961

1.3.5 BMS 7-105, "Aluminum Alloy Sheet and Plate, Bare, for Welded and Heat Treated Applications"

1.3.6 Structures Laboratories--Material Laboratory Report 62-157, "Material Properties Tests of Cryogenic Subsize Tank Components"

1.3.7 Engineering Work Authorization 5-404, "Mechanical Properties--Cryogenic Tank Materials"

1.3.8 B.A.C. Process Specification 5-602, "Heat Treatment of Aluminum Alloys"

1.3.9 B.A.C. Process Specification 5-8901, "Fusion Welding on Heat Treatable Aluminum Alloys"

1.4 INTRODUCTION

Three 17" diameter spherical tanks were fabricated from 2219 aluminum plate and tested at LH_2 temperatures. The purpose for this phase of the cryogenic tank development program was to provide information in the following problem areas:

a. Determine biaxial strengths and toughness of 2219-T6E46 at LH_2 temperatures.

b. Evaluate fabrication characteristics of 2219 Al. in a 17" diameter spherical configuration.

c. Develop design confidence in thin-walled, low factor cryogenic pressure vessels.

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1.5 TEST SPECIMEN

The three burst tanks were identical 17" diameter spherical shells fabricated from 2219 Al. sheet stock. A spherical specimen was selected to provide a 1 : 1 biaxial stress field for comparison with the uniaxial test specimen tested in reference 1.3.7 on the same material.

1.5.1 Design of Test Tanks

The test tanks were built to the dimensions of Figure 1.1. As noted, these spherical shells were a uniform .120" thick in the lower hemisphere (head) and .19" thick in the upper head through which the pressurization and instrumentation fitting was attached. The upper hemisphere was deliberately made of a thicker gage than the lower head to avoid failure near the fitting. The lower head was reinforced adjacent to the girth weld to reduce failure potential through the weld zone. The instrumentation fitting was welded to the upper hemisphere and provided a reinforcement for the 1½" diameter penetration in the tank shell. A flanged tube was attached to this fitting from which the tank could be suspended and filled during test and through which the instrumentation probe could be inserted. The No. 2 tank differed from the No. 1 and No. 3 test tanks by the integral boss built into the lower head. This boss was similar in geometry to those used in the X-20 tanks. In this area, local discontinuity stresses do occur which affect the normal hoop and meridional shell stresses. It was the purpose of this test tank to see what effect such a reinforcing boss would have on the overall integrity of the tank structure.

1.5.2 Fabrication

All upper and lower tank heads were shear spun, (See Figure 1.2), to the required 8.50" radius. The lower heads were machined to the required thickness and contour after spin forming. To the 3.0 inch diameter penetration in the upper head, a machined fitting with the flanged tube was welded in place to provide hole reinforcement. The upper and lower head subassemblies were then heat treated and aged to the 2219-T6E46 requirements of reference 1.3.8 prior to girth welding per reference 1.3.9. The girth weld was left in the "as welded" condition.

Each tank was insulated with self-adhering foam insulation after the tanks were installed in the test fixtures and all instrumentation had been attached, (see Figure 1.8).

1.6 TEST SETUP

To attain the desired environmental test conditions, liquid hydrogen was used as the test media. The use of liquid hydrogen required that the test be conducted at a remote test site. The Mechanical Propulsion Laboratory was responsible for implementing the test phase.

1.6 TEST SETUP (CONTINUED)

1.6.1 Test Site

For this test program area 35, at the Tullalip Test Site, was activated. Site preparation was required and included instrumentation, providing a test pad and control house, and installing test plumbing. Pictures of the test facility are shown in Figures 1.3 and 1.4. The test pad is approximately 300' from the control house.

1.6.2 Test Equipment

The three tank burst tests were conducted using the same basic test setup as shown in schematic in Figure 1.5. The test system as installed in the test area, is shown in Figure 1.6. The heat exchanger, consisting of a coil of 250 feet of ½" diameter stainless steel tube in a liquid nitrogen tank, is located on Pad C along with the high pressure trailer mounted helium source. The test tank was located on Pad B. The 1000 liter liquid hydrogen dewar along with purge and fill valves were located on Pad A.

The test assembly, made up of a test tank, test dome, overfill indicator tank, vent valve, and a support stand, were assembled as shown in Figure 1.7. All required instrumentation wiring was run in copper tubing for protection past the point where the assembly was to be foam insulated. Figure 1.8 shows a typical test assembly after completing the insulation.

The fill line from the dewar to the fill valve was a vacuum-insulated flexible metal line. The fill valve and the fill line from the valve to the test assembly were foam insulated.

Also included in the test setup was the control console, as shown in Figure 1.9, located in the control house. This test utilized only a small portion of the switches on the console which was built up to be used for control of the entire Area 35 liquid hydrogen system. Two different fill valves were used in this test. A ½" Annin valve with 2500 lb. ASA flanges was used for the first tank burst and the first attempt on the second burst. This valve had been purchased for use in a cold hydrogen gas system and did not incorporate a bonnet extension. After being in liquid hydrogen service for the time required to fill the test tank assembly, ice was present in the valve stem seal area and the valve would not close completely. On the first burst test it was possible to free the valve so that it sealed by pushing down on the indicating switch actuating finger. On the first attempt of the second burst a seal could not be obtained so the run was aborted. At this time the Annin valve was replaced with a ½" Pacific valve (Model G2500C-10K-ASA) incorporating a bonnet extension and originally obtained for use in liquid hydrogen service. This valve was not used in the original fill line due to unavailability of gaskets. No problems of any kind were encountered with this valve.

1.7 BURST TESTS RESULTS

All three tanks were full of LH_2 at the time of burst as indicated by temperature measurements and the nature of the burst itself. Very little scattering of tank fragments was in evidence (See Figures 1.10, 1.11, and 1.12.

The few problems that were encountered in this test program were due to the fact that this was the first test conducted in area 35 and because of the unavailability of proper test equipment.

1.7.1 Discussion

Two attempts to burst the first test tank failed due to an obstruction in the helium pressurizing line. On both attempts the initial portion of tank pressurization went satisfactorily and then no more helium would flow from the high pressure source to the test piece. In both cases the pressure remaining in the high pressure bottles was considerably more than that required to burst the tank. Operation of the pressurizing valve was satisfactory in both cases. It is believed that water was present in one of the high pressure bottles which had been hydrostatically pressure tested prior to its use in this system. This moisture most likely froze out and plugged the orifice which was in the system to control tank pressurization rate. The orifice size was increased after the first burst attempt. The maximum pressure attained on the second attempt was considerably higher on the second attempt than on the first. (1650 vs. 500 psig). The orifice size was further increased prior to the third burst attempt which was successful.

During test preparation for each test a low pressure helium purge was run on the pressurizing system during chill-down of the heat exchanger to prevent in-breathing of moisture laden air.

Chill-down and fill of the test system and test tank required approximately one and one-half hours. Chill-down of the system was accomplished with hydrogen. During chill-down, the hydrogen gas vented through the hollow instrumentation probe on the test tank until stabilized temperatures were attained. No liquid nitrogen pre-chill was used due to increased complexity of the system and the additional time required.

Pressurization was accomplished by stepping the helium pressure up using a pneumatically-controlled Minneapolis-Honeywell valve rated for 10,000 psi service. This valve was cycled open and closed with a solenoid valve in the control system. The pressurization rate was quite high in the initial portion of all three burst tests and then lower as the pressure approached the burst pressure of the tanks. The rate was manually controlled in this way so that the liquid temperature inside the tank could be held at a minimum while still maintaining a reasonable pressurization rate at the time of burst.

1.7 BURST TESTS RESULTS (CONTINUED)

1.7.1 Discussion (Continued)

The pressurization rate for the three tanks at the time of burst was as follows: (1) 2400 psi/min. (2) 2290 psi/min. (3) 1410 psi/min. The burst pressures were as follows: (1) 2620 psig, (2) 2500 psig, (3) 2330 psig. The liquid temperature in the center of the tank at the time of burst was as follows: (1) -406.4° F., (2) -401.8° F., (3) -402.6° F. In addition to the liquid temperature measurement, a tank skin temperature measurement was taken. This measurement was made by installing a carbon resistor on the outer surface of the tank approximately four inches in a circumferential direction from the weld which attaches the fitting to the tank upper hemisphere. The maximum shell temperatures at time of failure were -395° F. for tank No. 2 and -396° F. for tank No. 3.

The only problems encountered on this test were concerned with inadequate equipment and instrumentation. Several cases of failure of temperature-measuring systems and liquid level indicators occurred on this test. Most of these problems can be traced to the fact that Area 35 had just been built up and this was the first test conducted in the area. Some temporary instrumentation cables were in use at the time of this test which resulted in some difficulty.

1.7.2 Test Analysis

Based on the burst pressures recorded at the test site, nominal tank diameter (per Figure 1.1) and measured shell thicknesses, the calculated hoop stresses are presented in Table 1.1. The discontinuity stresses occurring around the integral boss of test tank No. 2 are not included. However, the combination of such stresses and normal hoop stresses would indicate a higher failure stress. Comparison of these stresses with uniaxial test data is included in Section 1.9.1.

TABLE 1.1

Test Tank	Burst Pressure, p	Shell Temperatures	Min. Shell Thickness, t	Nom. Inside Radius, Y	Calculated [1] Hoop Stresses
1	2620 psig	-399° F. [2]	.111 in.	8.50 in.	101,500 psi
2	2500	-395	.108	8.50	98,300
3	2330	-396	.108	8.50	91,100

[1] Hoop stress = pr/2t [2] Estimated shell temperature

U3-4071-1000

1.8 METALLURGICAL ANALYSIS OF FAILED TANKS

Metallurgical analysis of the first and second tanks are included in this section. The third tank was lost in transit from the Tullalip Test Site to the Development Center, thus no analysis was possible. The following data is a direct reproduction of the metallurgical test reports, (Reference 1.3.3 and 1.3.4), prepared by the Materials and Processes Unit.

1.8.1 Metallurgical Analysis of Tank No. 1

1.8.1.1 Conclusions

The tank failed in a ductile manner at an area of minimum wall thickness. No material defect was found at the point of origin of the failure. The pitting and intergranular attack on the inside of the tank did not contribute significantly to the failure but did influence the fracture path and the resultant breaking into numerous small pieces.

1.8.1.2 Procedures and Discussion

The broken pieces were re-assembled and the approximate point of origin determined. Figure 1.13 shows the parts re-assembled using the largest piece as a form. The center of the bottom is shown marked with a circle. The point of origin is marked with arrows.

The interior surface contained a heavy coating of aluminum oxide and numerous corrosion pits. Examination at low magnification showed a network of fine cracks running from pit to pit. Figure 1.14 shows the interior surface. Figure 1.15 is a view showing the extent of the intergranular attack on the interior surface. The intergranular network on the interior surface had an average depth of .005" and was general. This in effect is a decrease of 5% in effective wall thickness. Had this network been absent the tank could be expected to withstand a somewhat higher burst pressure. The cracks shown in Figure 1.14 are the opening up of this area during general yielding of the tank prior to failure. Along the fracture face at the side of the photo it will be seen that the fracture followed these cracks from one dark corrosion pit to the next. The fact that the tank failed at full calculated stress would verify that this network of cracks did not contribute significantly to the failure. However, if a tank with similar intergranular attack was subjected to either sustained or cyclic loading, the notch effect could lead to early failure. This type of surface is definitely unsatisfactory for pressure vessels. The Structural Materials Group recommended a cleaning sequence prior to heat treatment which was followed on the third tank of this series. The interior of this tank was bright after heat treatment. The material was checked microscopically after burst test to verify the absence of intergranular attack.

1.8 METALLURGICAL ANALYSIS OF FAILED TANKS (CONTINUED)

1.8.1 Metallurgical Analysis of Tank No. 1 (Continued)

1.8.1.2 Procedures and Discussion (Continued)

The point of origin of the failure was approximately 10° up from the bottom of the tank (or 6.5" down from the girth weld). Figure 1.16 shows the fracture face at the point of origin. The arrows indicate the location of growth rings or hesitation points in the growth. Beyond the outer arrows, growth was catastrophic. Critical crack length (area of slow growth) was .100" at the surface and .200" at the center of the wall thickness.

1.8.2 Metallurgical Analysis of Tank No. 2

1.8.2.1 Conclusions:

The tank failed in a ductile manner in an area where minimum wall thickness was combined with a change in contour. No material defect was found at the point of origin of the failure. Both surfaces of the tank were free of oxide coating. There was no intergranular attack found on either surface.

1.8.2.2 Procedures and Discussion

Figure 1.17 shows the broken tank after reconstruction. The point of origin was found to be 2.5" from the center of the boss. From this point in toward the boss the shell thickness increased abruptly. Thickness at the origin of failure was .108".

The outside contour in this region was a uniform sphere. The increase in wall thickness around the boss resulted in a flattening of the interior contour. It was at this change of contour that the failure originated. Critical crack length (area of slow growth) was .100" at the surface and .200" at the center of the wall thickness. Figure 1.18 shows the fracture with the point of origin bracketed.

The interior of the tank was bright. There was no evidence of oxide coating, pits, or intergranular attack. Figure 1.19 is a cross section taken near the point of origin.

1.9 UNIAXIAL TENSILE TESTING

To verify the calculated burst stress of the tanks, six specimens were cut from each of the two failed tanks and tested at LH_2, LN_2 & room temperatures. In this section the uniaxial test results are included and compared with the biaxial burst test data.

1.9 UNIAXIAL TENSILE TESTING (CONTINUED)

1.9.1 Test Specimen

The nine specimen blanks were cut from the .19" thick upper hemisphere of the No. 1 and No. 2 test tanks. The blanks were cut in the following directions from each head (See Figure 1.20); five each in the meridional direction; two each in the hoop direction; and two each at a 45° diagonal. These blanks were cut out, straightened, and machined without subsequent heat treatment. Blank size was limited to the smallest feasible size to minimize induced strains incurred during the straightening operation. A Boeing test specimen, Drawing No. 23-5131, was used for these tests. This is a 1.00" Gage Length Specimen and required a 4.00" x 1.00" blank. Gage in the test section was a nominal .23".

1.9.2 Test Results

The results of the tensile tests are tabulated in Table 1.2. Room temperature tests were conducted as control specimen for comparison with the specimen tested in Reference 1.3.7.

Figure 1.21 is plot of the base metal tests obtained in Reference 1.3.7 and the data obtained in this test program as summarized in Reference 1.3.6. In addition, the calculated burst stresses from Table 1.7.1 are also indicated. The plot of data indicates that the tanks burst at stresses equal to or higher than the uniaxial test specimen.

1.9 UNIAXIAL TENSILE TESTING (CONTINUED)

1.9.2 Test Results (Continued)

TABLE 1.2
UNIAXIAL SPECIMEN TENSILE TEST DATA

Test Tank No.	Test [1] Specimen No.	Test Temp. (°F.)	Ultimate Stress (K.S.I.)	Yield Stress (K.S.I.)	Elongation in 1.00" %
1	7R1	70	61.3	45.6	9
	7T1	70	63.9	47.8	8
	7-45-1	70	63.9	42.8	8
2	9R1	70	68.1	48.7	11
	9T1	70	68.8	50.5	9
	9-45-1	70	67.8	49.0	11
1	7R2	-423	93.6	64.2	10
	7T2	-423	89.9	64.9	9
	7-45-2	-423	91.4	65.4	11
2	9R2	-423	96.0	61.8	16
	9T2	-423	91.4	65.2	12
	9-45-2	-423	91.9	64.4	14
1	7R3	-320	68.6	48.7	10
	7R4	-320	70.5	49.5	12
	7R5	-320	77.4	53.5	12
2	9R3	-423	93.6	64.3	15
	9R4	-423	88.2	62.1	22
	9R5	-423	98.7	64.7	19

[1] Specimen No. indicates orientation of blank:
7R1 - Meridional, 7T1 - Hoop, & 7-45-1 Diagonal Specimen

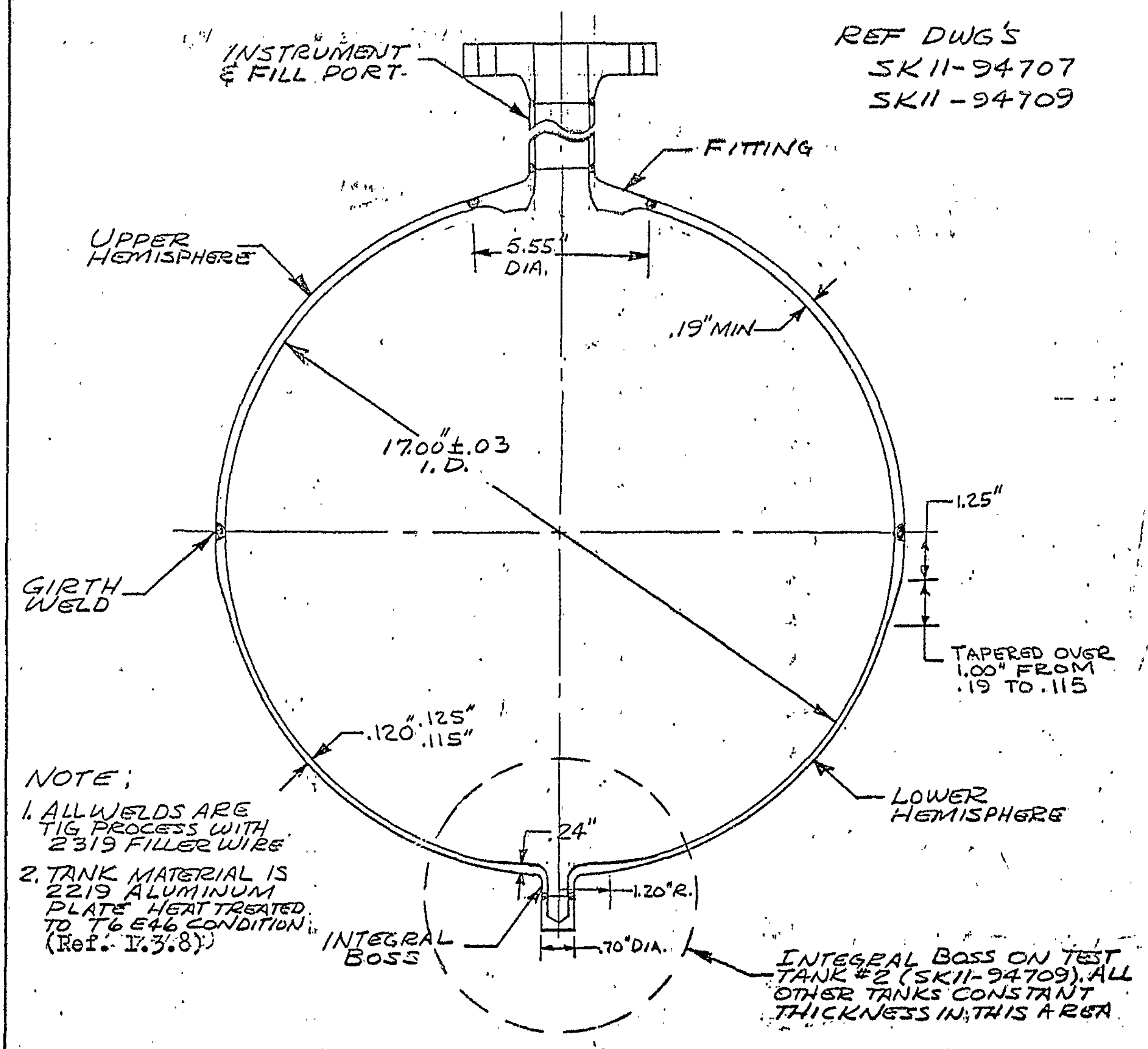


FIGURE 1.1

LH$_2$ BURST TEST TANKS

DS-I - SPINNING CRYOGENIC TANK COMPONENTS 2A91027
INTERMITTENT THICKNESS TANK HEADS, MAT'L.
10-20-61

FIG. 1.2 SPINNING LH_2 TEST TANK HEMISPHERES

U3-4071-1000 (was BAC 1546-L-R3)

TULALIP AREA 35 LOOKING WEST FROM CONTROL ROOM TO PADS SHOWING INSTRUMENTATION INSTL 1-8-61 2A94118

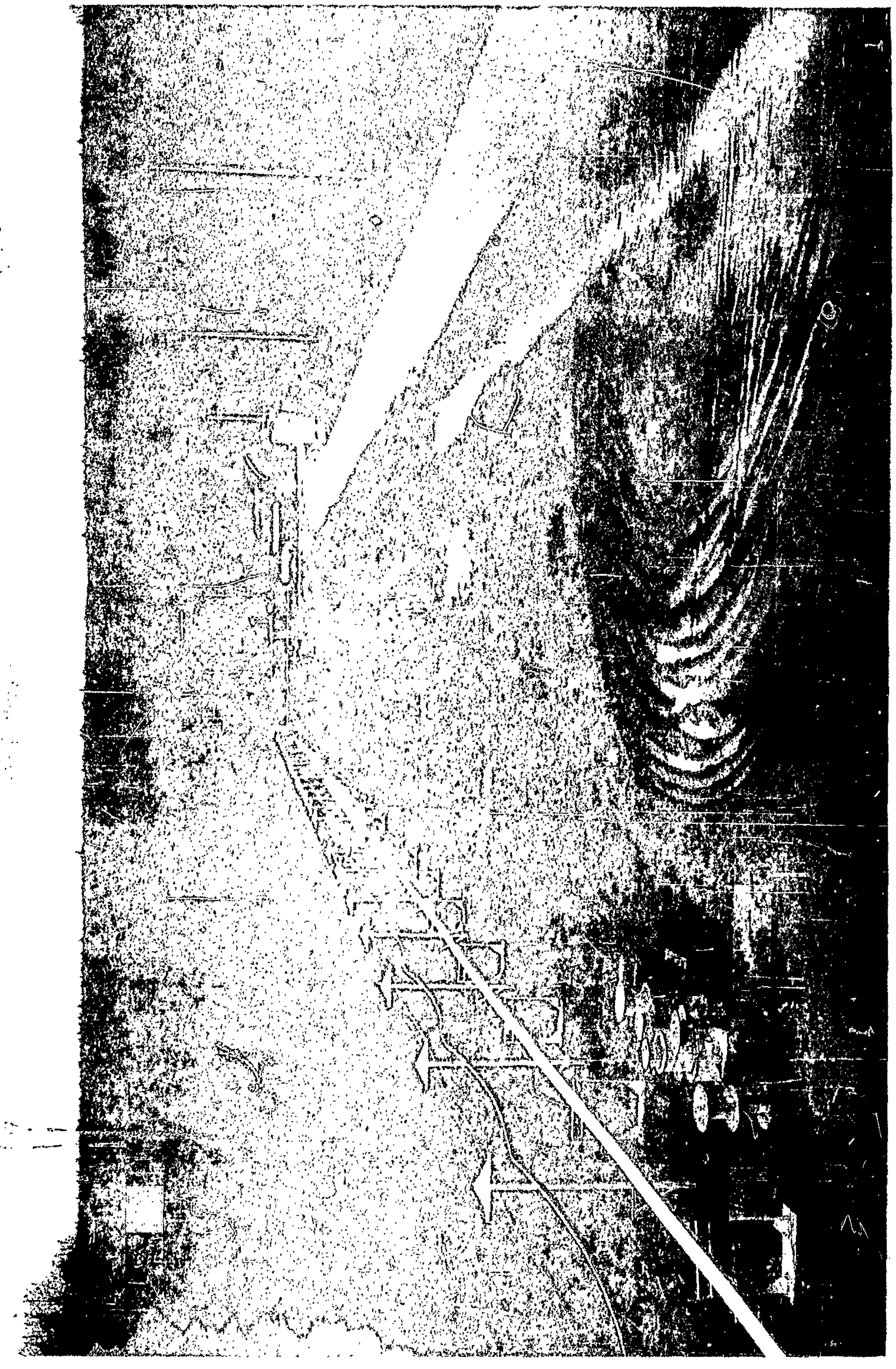


FIG. 1.3 TULLALIP [illegible] TEST AREA

TULALIP AREA 35 CONTROL HOUSE
12-8-62

2A94119

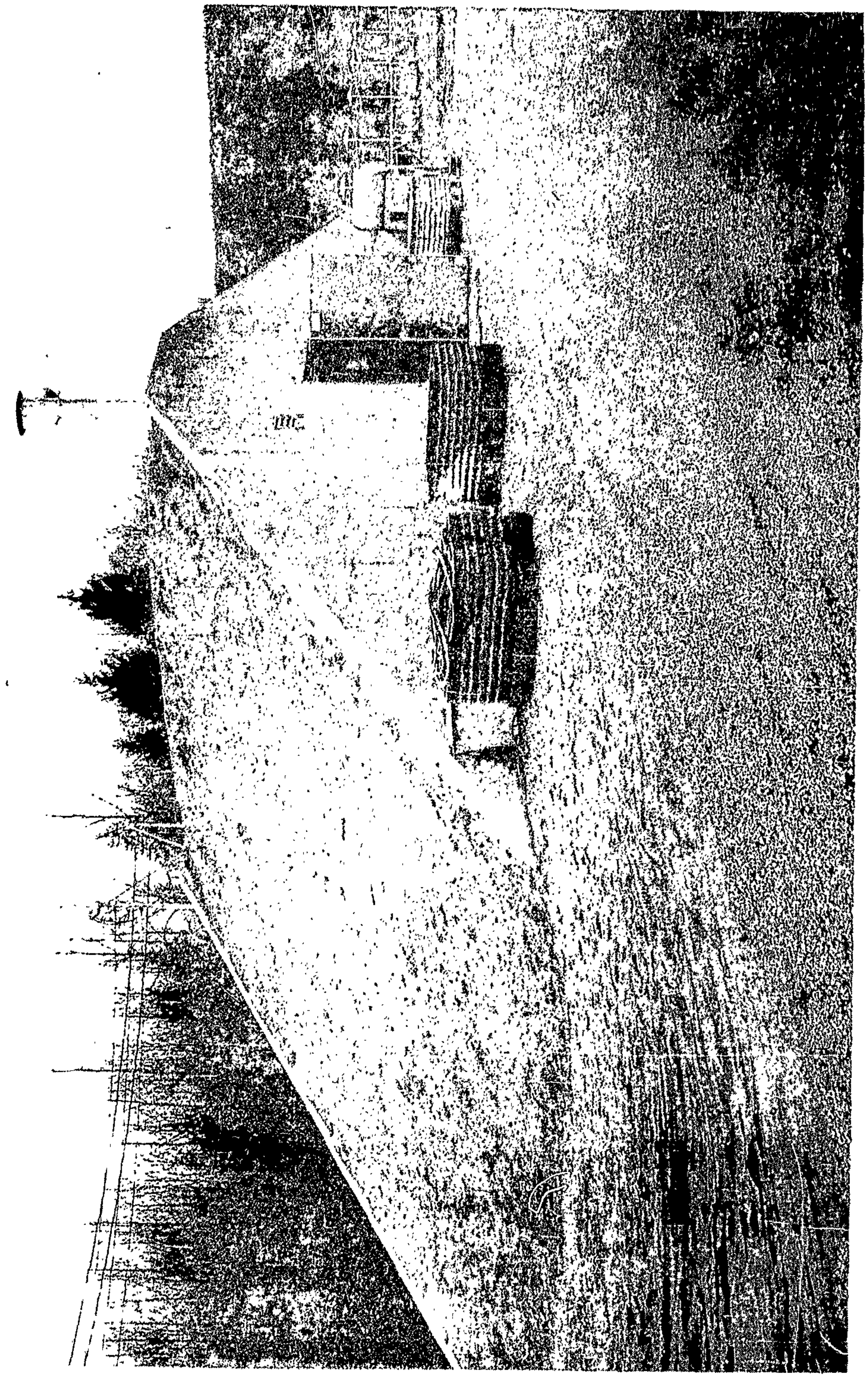
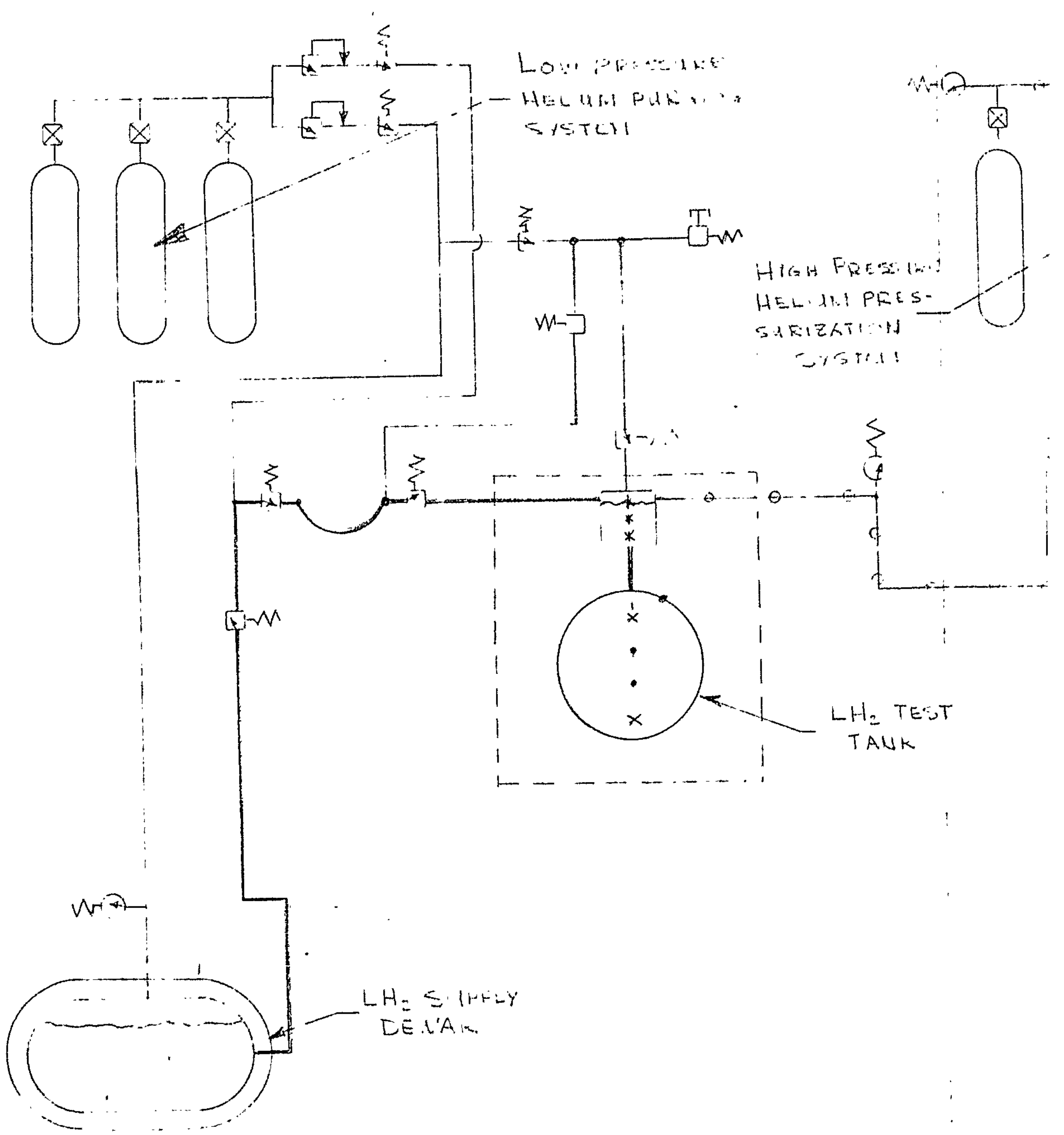
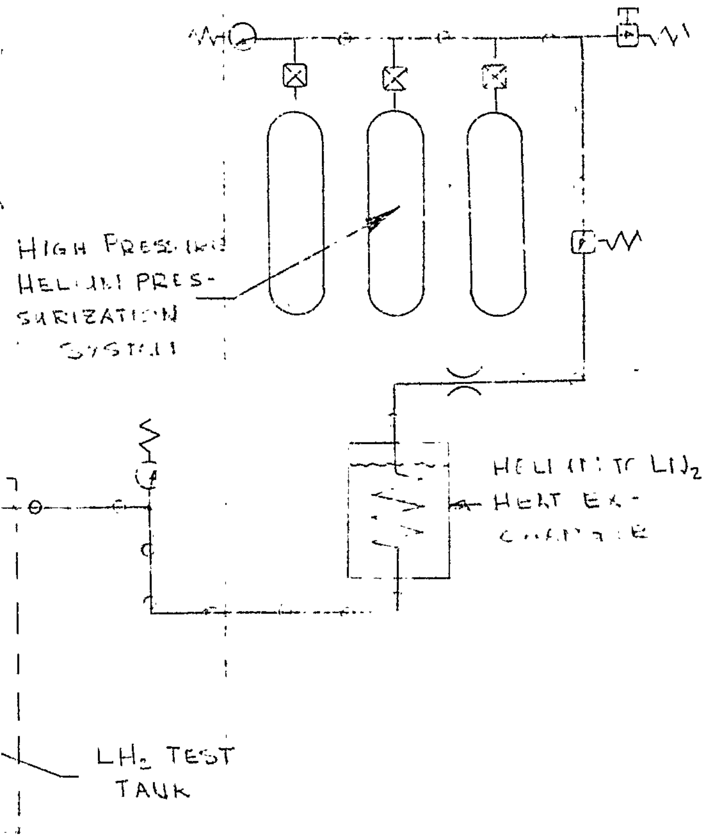


FIG 1.4 TULLALIP SITE 35 CONTROL HOUSE



U3 4038 9000 (WAS BAC 1017 B)

1



SYMBOLS

- ORFICE, FIXED
- MANUALLY CONTROLLED VALVE
- REMOTELY OPERATED VALVE
- PRESSURE RELIEF VALVE
- PRESSURE REGULATOR
- REMOTELY READ PRESSURE GAGE
- CARBON RESISTOR FILL INDICATOR
- THERMOCOUPLE
- VACUUM INSULATED FLEXIBLE LINE
- LH_2 FILL LINE
- HI-PRESSURE HELIUM PRESSURIZATION LINE
- LOW-PRESSURE HELIUM PURGE LINE

2

		REVISED	DATE	FIG 1.5 SYSTEM SCHEMATIC ~ LH_2 SUBSIZE TANK BURST TEST FACILITY	D2-80092
~~DATE~~ DWN L.L.M	4/4/62				DS-1
CHECK					
APR					
APR				BOEING AIRPLANE COMPANY	PAGE 1-18

LIQUID HYDROGEN BURST TESTS - DS-I SUBSIZE 2A90589
CRYOGENIC TANKS RUN #2 - OVERALL AREA BEFORE
BURST 10-13-61

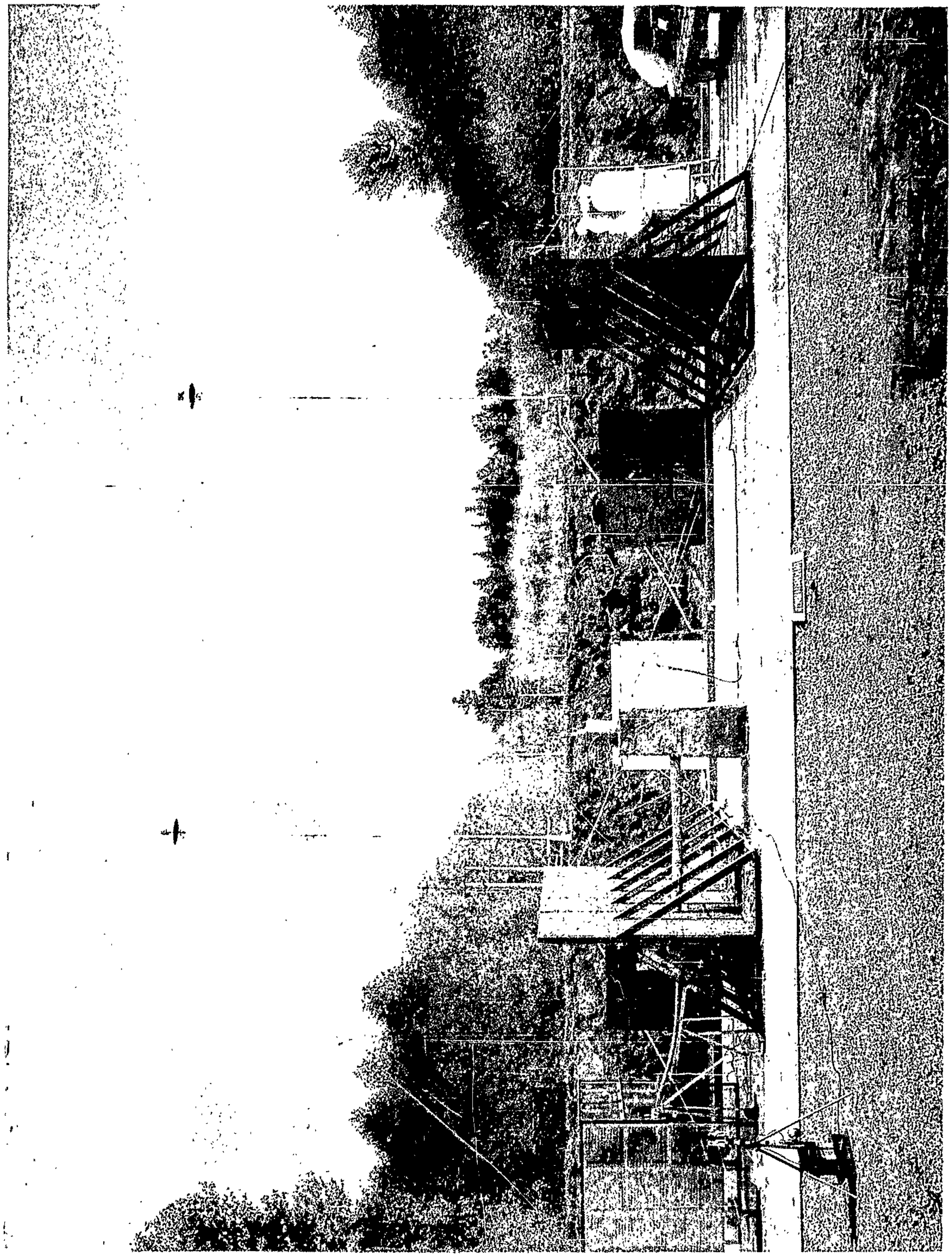


FIG 1.6 TULLALIP SITE 35 TEST PAD

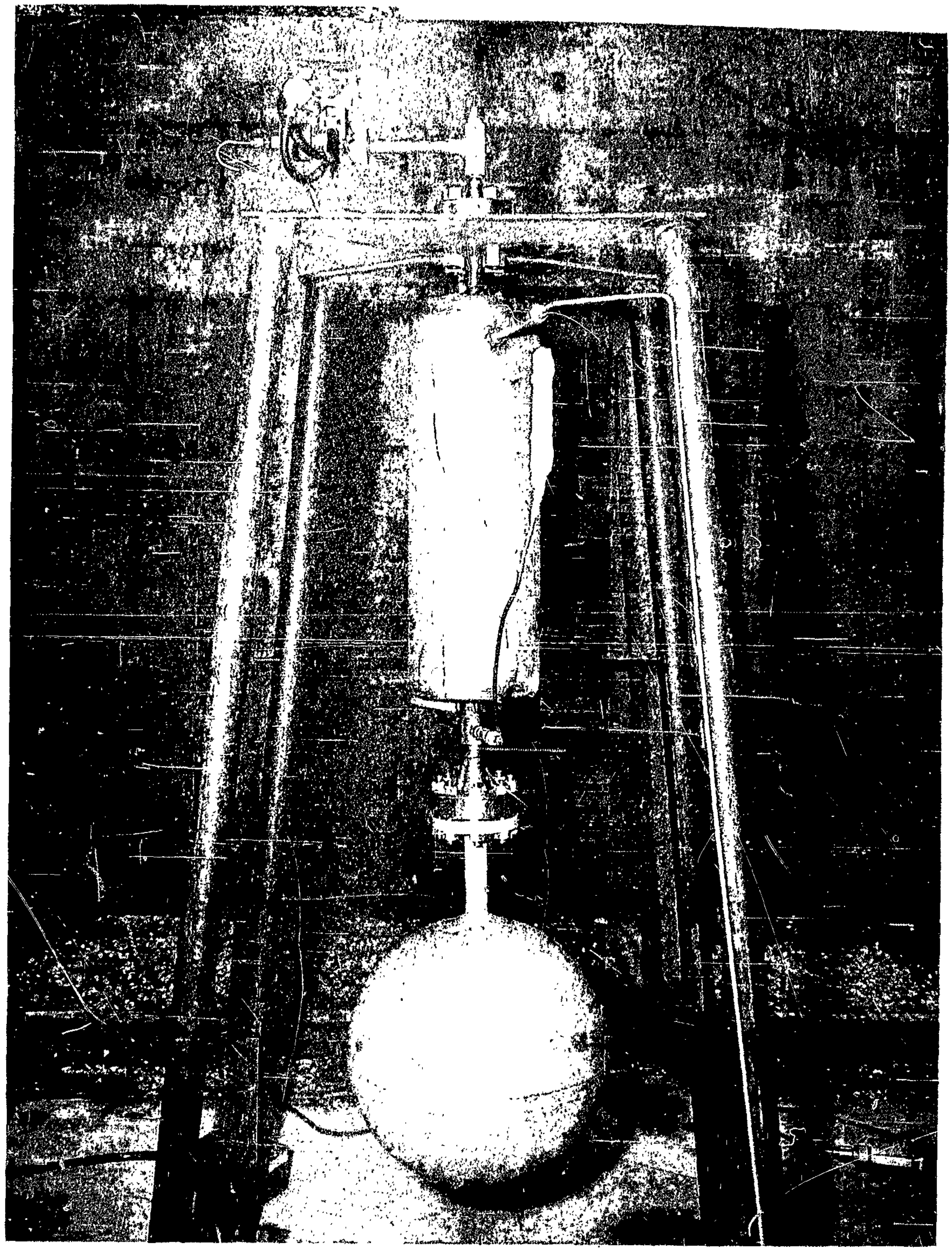


FIG. 1.7 TEST TANK INSTALLATION-UNINSULATED

DS-I SUB-SIZE CRYOGENIC TANK - LH_2 BURST TEST 2A89573
LH_2 FILL TANK & BURST TANK 10-5-61

U3-4071-1000 (was BAC 1546-L-R3)

DS-1 SUB-SIZE CRYOGENIC TANK - LH_2 BURST TEST 2A89565
TANK BEFORE BURST 10-5-61

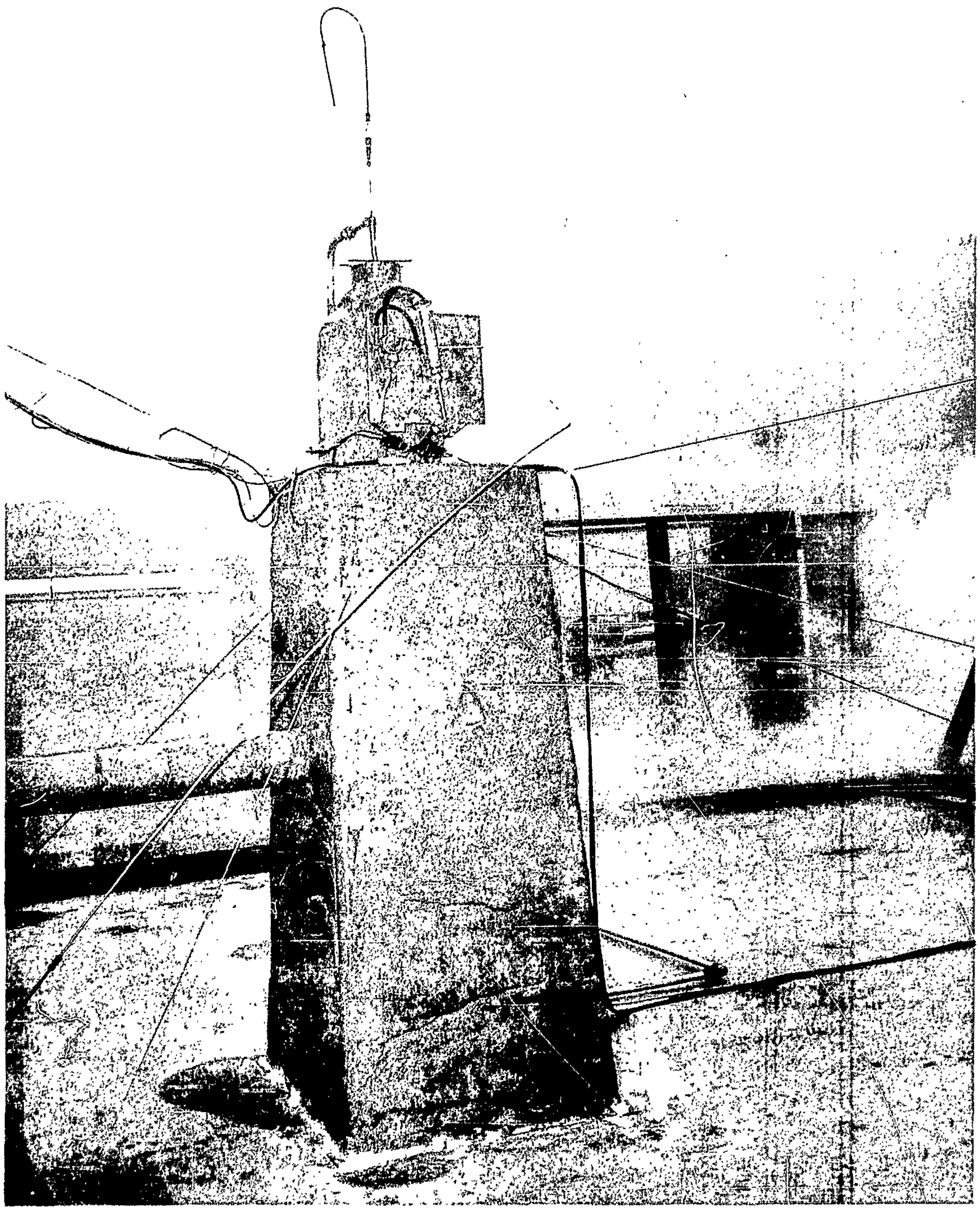


FIG. 1.8 TEST TANK INSTALLATION ~ INSULATED

DS-I SUB-SIZE CRYOGENIC TANK - LH_2 BURST TEST 2A89572
CONTROL PANEL 10-5-61

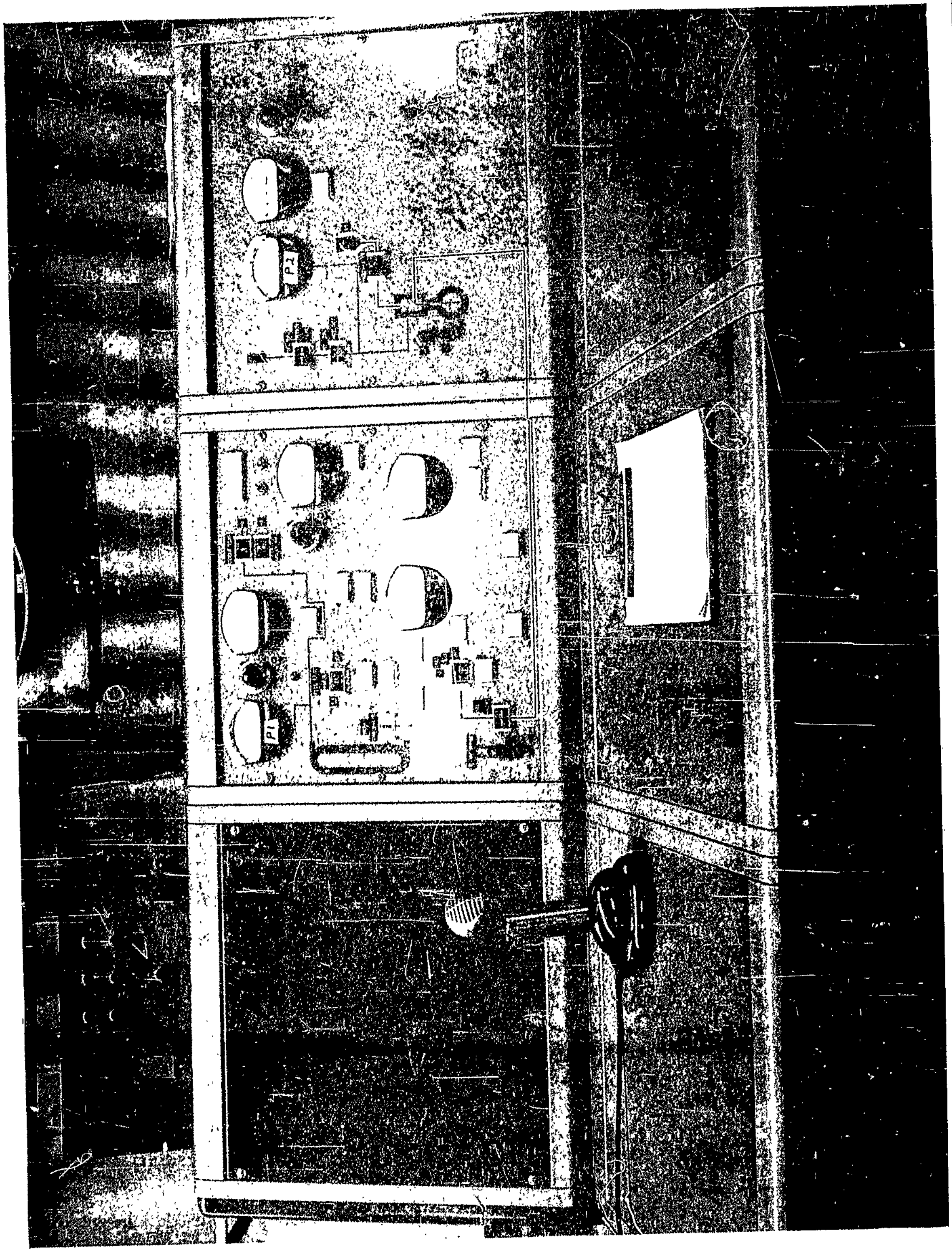


FIG. 1.9 TULLALIP SITE 35 CONTROL PANEL

DS-I SUB-SIZE CRYOGENIC TANK - LH_2 BURST TEST 2A89554
PARTS OF TANK AFTER BURST
10-5-61

FIG. 1.10 TANK NO. 1 AFTER BURST

U3-4071-1000 (was BAC 1546-L-R3)

ID HYDROGEN BURST TESTS - DS-1 SUBSIZE 2A9G564
CRYOGENIC TANKS NO. 2 - TANK PIECES AFTER
BURST 10-1?-61

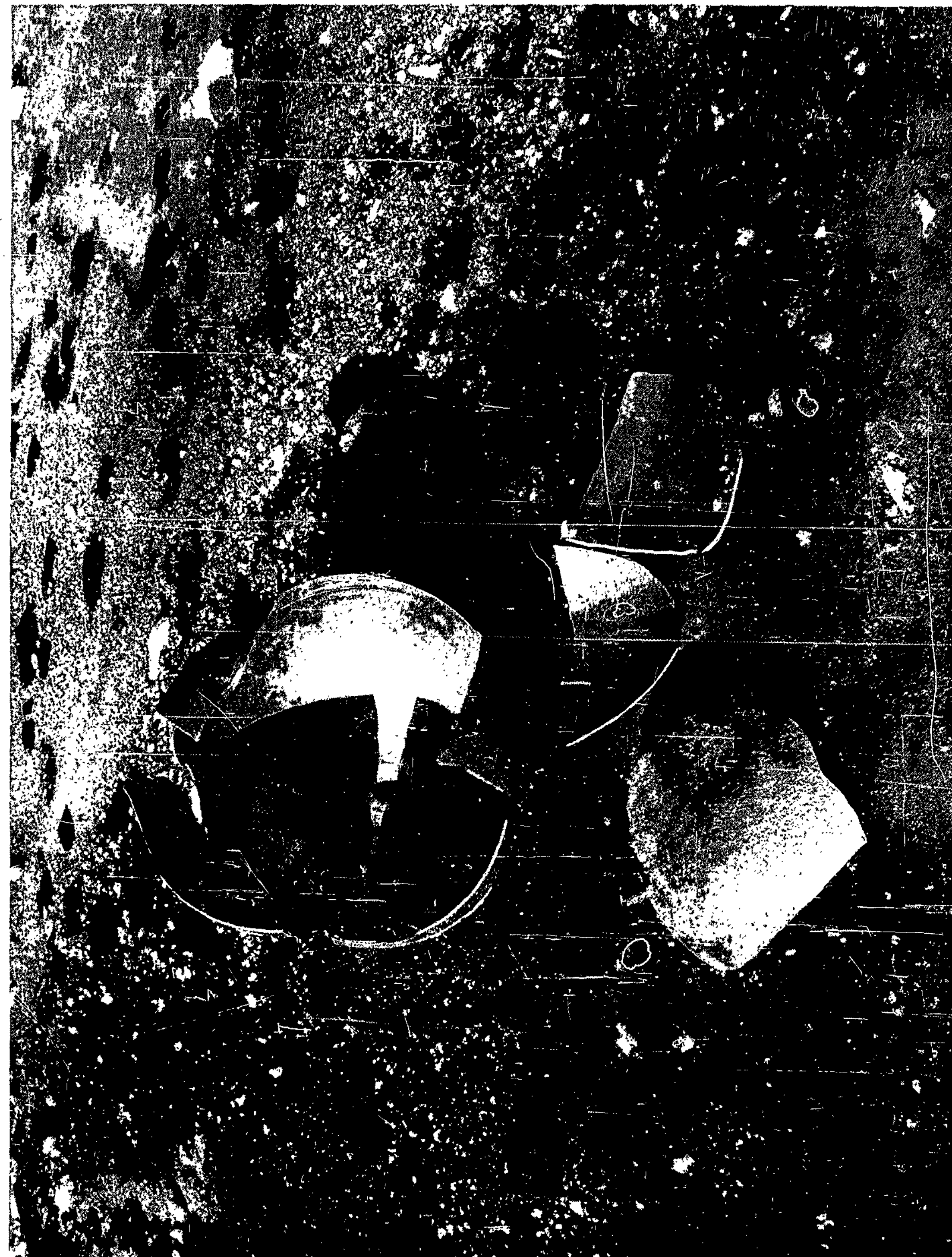


FIG. 1.11 TANK NO 2 AFTER BURST

U3-4071-1000 (was BAC 1546-L-R3)

SUBSIZE CRYOGENIC TANKS - LH2 BURST TESTS - TEST NO. 3 - TANK PIECES AFTER BURST 10-18-61 2A90821

FIG. 1.12 TANK NO. 3 AFTER BURST

FIG. 1.13

TEST TANK No. 1 REASSEMBLED
WITH FAILURE AREA NOTED

DS-I REASSEMBLY OF #1 CRYOGENIC BURST TANK 2450355
10-10-61

FIG. 1.14 5X WALL CROSS SECTION ~ TANK NO. 1

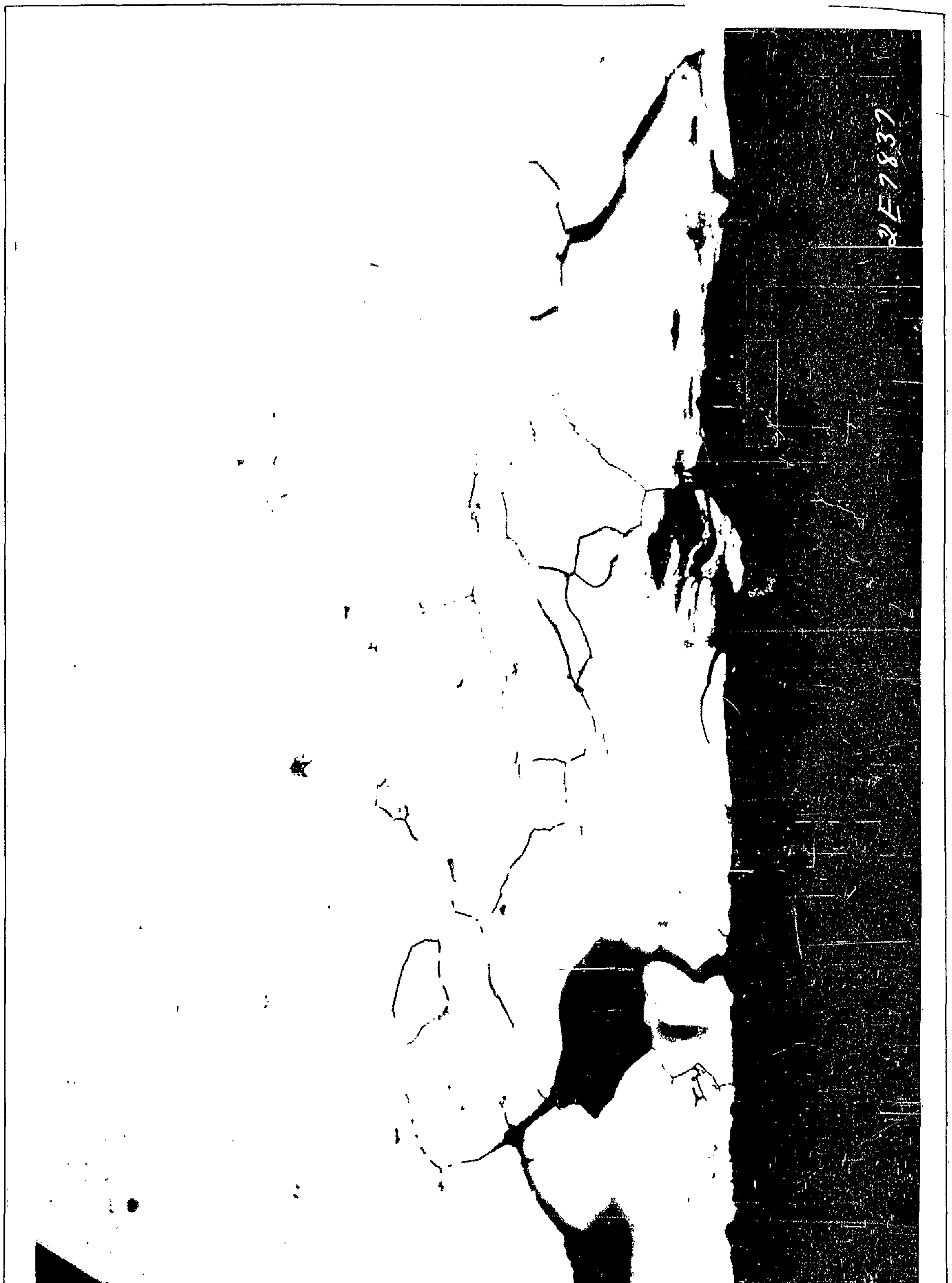


FIG 1.15 250X CROSS SECTION ~ TANK NO. 1

FIG. 1.16 6X VIEW AT POINT OF FRACTURE ~ TANK NO. 1

34

U3-4071-1000 (was BAC 1546-L-R3)

FIG. 1.17
TEST TANK NO. 2 REASSEMBLED WITH FAILURE AREA NOTED

DS-... 10-24-... D 17" CRYOGENIC BURST TEST 2A91303

35

U3-4071-1000 (was BAC 1546-L-R3)

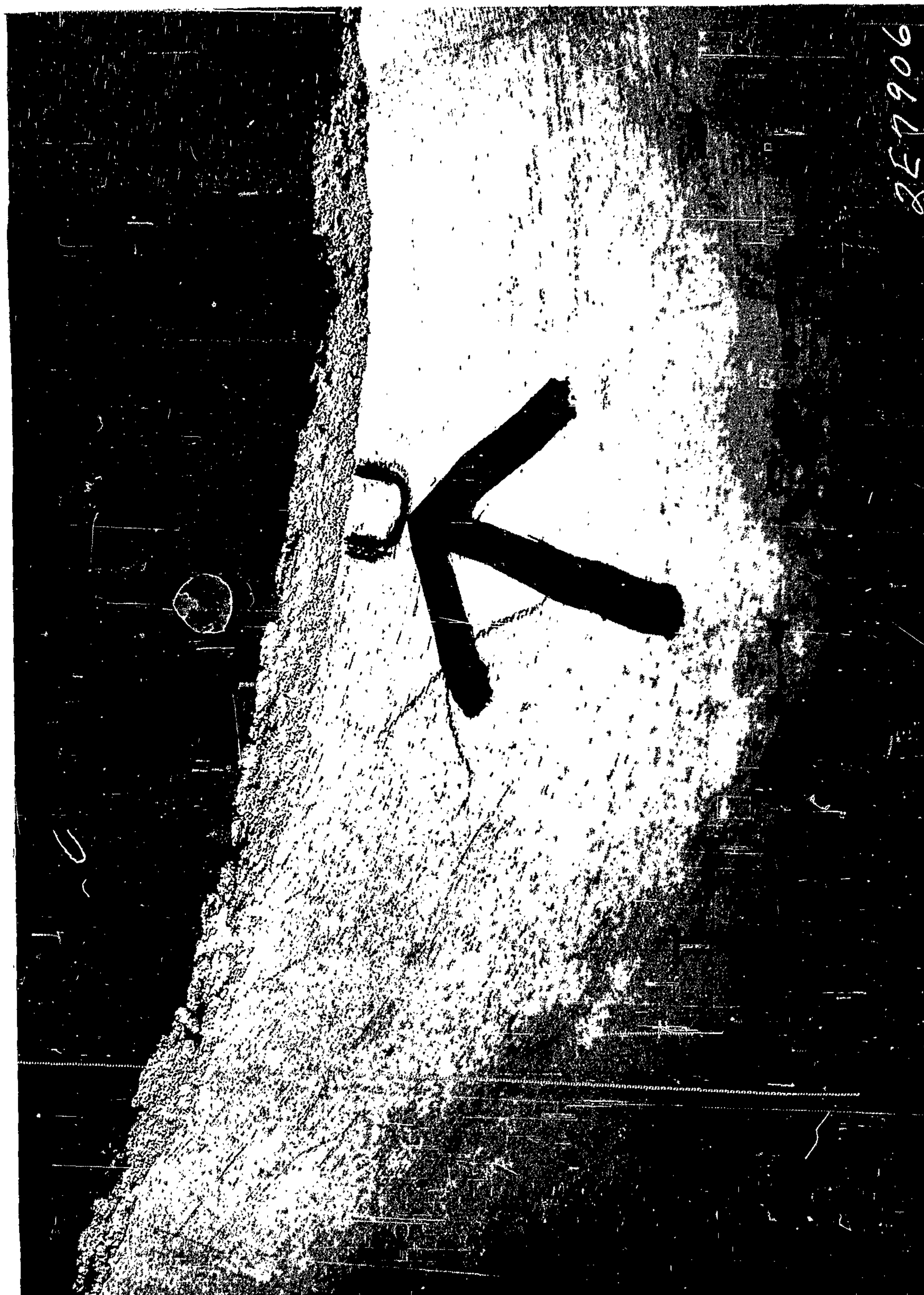


FIG 1.18 4X OUTER SHELL VIEW ~ TANK NO. 2

U3-4071-1000 (was BAC 1546-L-R3)

FIG. 1.19 250X CROSS SECTION ~ TANK NO. 2

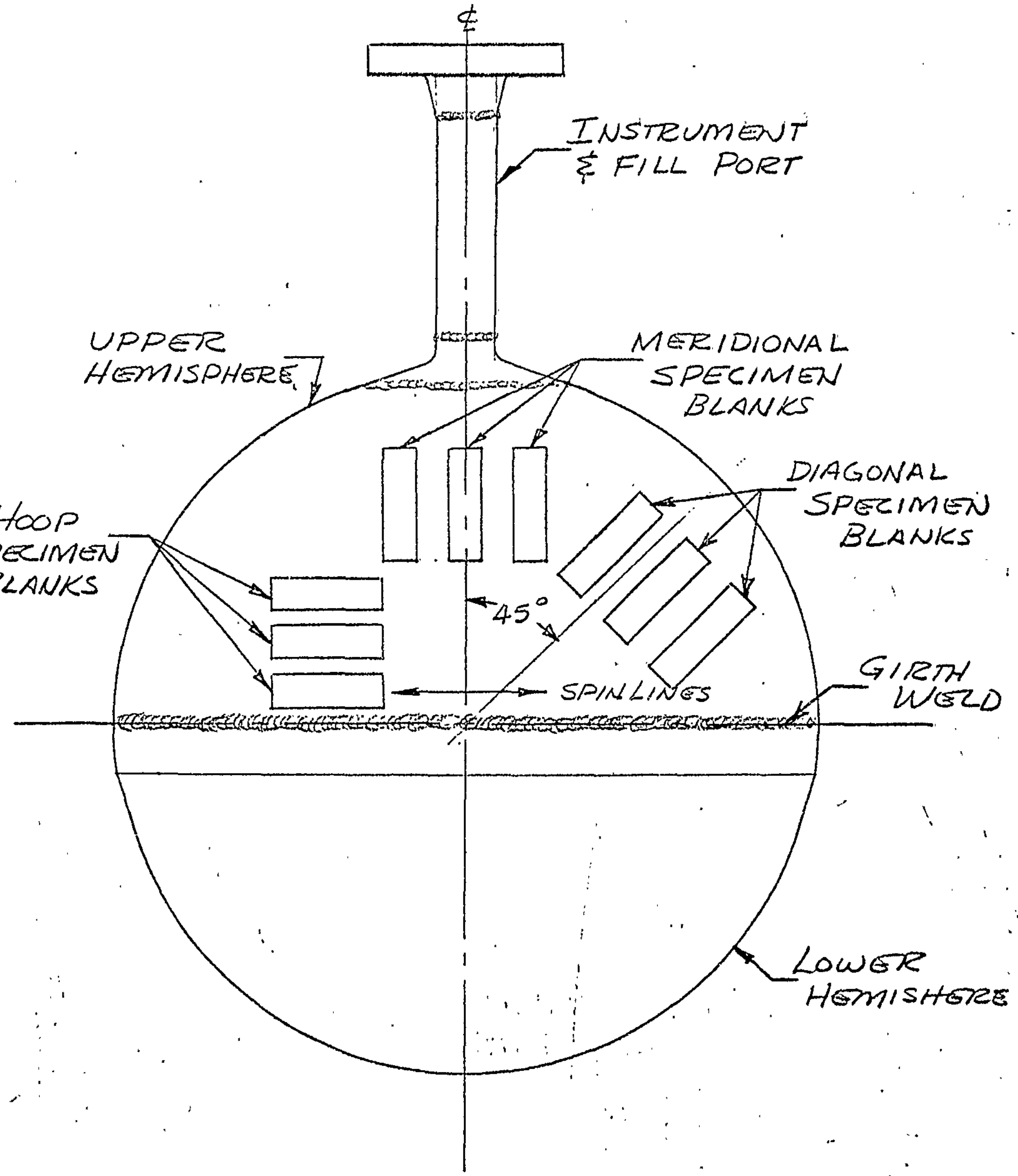
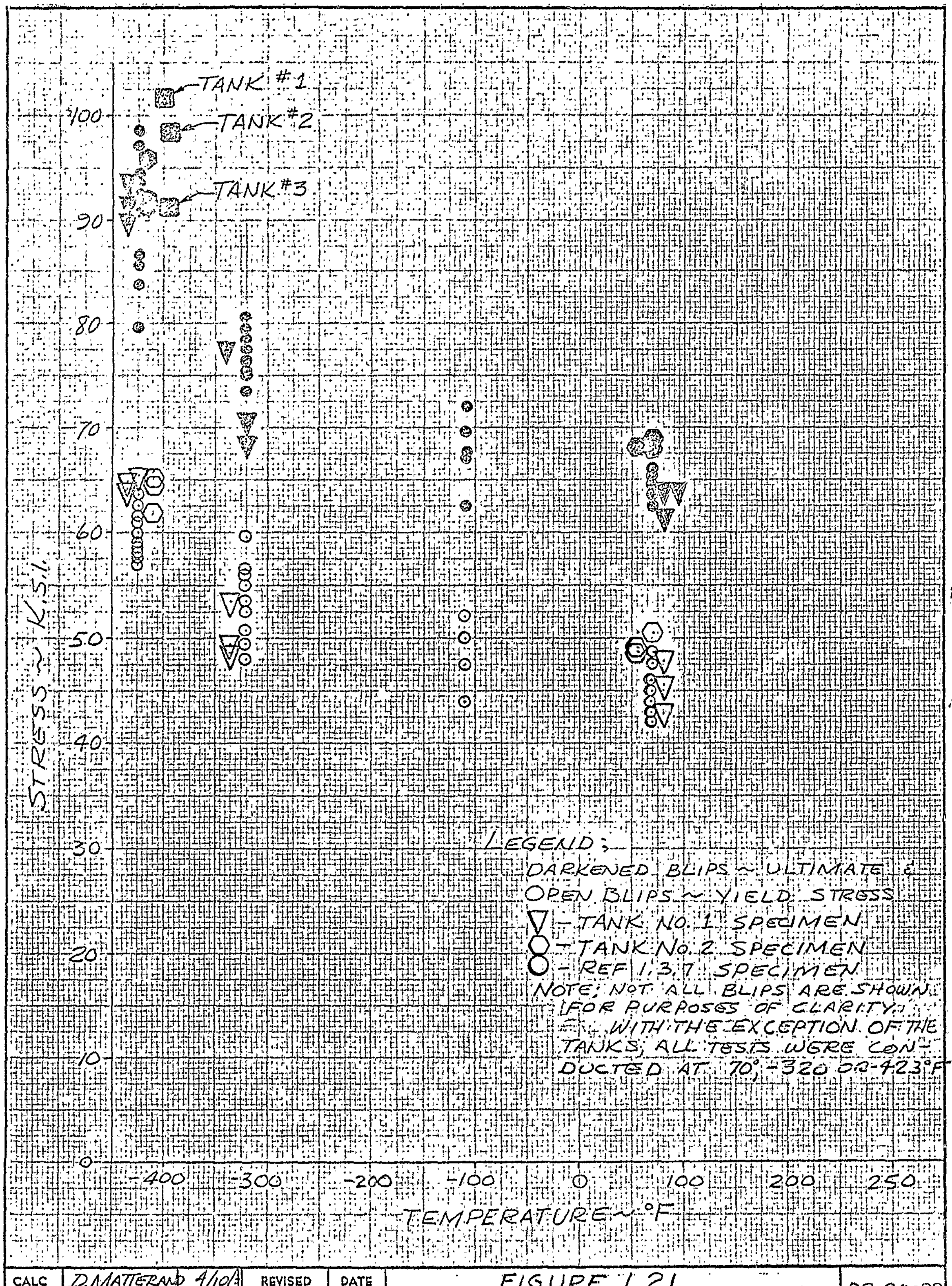


FIGURE 1.20

ORIENTATION OF UNIAXIAL TEST SPECIMEN



CALC	D. MATTERAND	4/10/	REVISED	DATE	FIGURE 1.21 2219-T6E46 ALUMINUM PLATE TEST RESULTS	D2-80092
CHECK						
APR						
APR					THE BOEING COMPANY	PAGE 1-34

THE BOEING COMPANY

NUMBER D2-80092 MODEL NO. X-20

TITLE Section 2: EWA 5-747, "Liquid Nitrogen Tank Structural Integrity Tests"

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RELIABILITY APPROVAL

(DATE)

CONTRACT NO. CHARGE NUMBER

2-5142 SECTION TITLE PAGE U3 4288 0000 REV. 2/61

2.1 SUMMARY

One uninsulated 2219 aluminum liquid nitrogen tank was pressure cycled and burst at -320° F. The tank completed 252 pressure cycles before bursting in excess of design requirements. The failure was of a ductile nature.

2.2 TABLE OF CONTENTS

Contents

LIST OF FIGURES

2.3 REFERENCES

2.3.1 Engineering Work Authorization 5-747, "Liquid Nitrogen Tanks Structural Integrity Tests"

2.3.2 Drawing 25-80337, "Tank Assembly - Supercritical Nitrogen (Test Only)"

2.3.3 Dyna Soar Materials and Process Unit Summary Report, DS-SR-079 MP, April 4, 1962

2.3.4 Structures Laboratories Test Progress Report, SLDL 62-56, March 21, 1962

2.3.5 MIL-T-5208A, "Tanks, Removable, Liquid Propellant Rocket Engine, General Specification for", dated July 5, 1955

2.3.6 D-5000, Book 89, "Design Manual"

2.4 INTRODUCTION

One 16.18" diameter spherical tank was fabricated from 2219 aluminum plate and tested at liquid nitrogen temperatures. The purpose of this phase of the cryogenic tank development program was to substantiate the ultimate strength of the tank after being subjected to operational life pressure cycle requirements.

Two more tanks had been included in this test program. One tank would have been burst tested to substantiate the ultimate strength of the inner shell; the second would have been subjected to external environment testing to determine the structural integrity under dynamic loads. Several reasons were apparent for not completing this phase of the program. They were:

(a) The tank configuration no longer resembled production liquid nitrogen or liquid oxygen tankage.

(b) Availability of the test data would have been too late to support production tank drawing releases.

(c) The pressure cycle and burst tank failed well above the static burst pressure requirements.

2.5 TEST SPECIMEN

The test specimen is shown in Figure 2.1 and comprises the -7 inner tank assembly of reference 2.3.2. Basically, the inner shell is a 16.18" diameter sphere with two inlet-outlet penetrations and two trunnion support fittings, all parts being made of 2219 aluminum.

2.5.1 Design of Specimen

The design of this tank was based on the original requirements for a storage vessel capable of containing 1.27 cubic feet of supercritical liquid nitrogen at an operating pressure of 1000 ± 50 psig and with a 167 pressure cycle capability. In addition to these requirements were the requirements of low weight, minimum volume, fill and venting in two different attitudes and structural support with low heat gain.

2219 aluminum in the T6E46 heat treat condition (See reference 1.3.8) had been selected as the tank material primarily because of its excellent low temperature strength, toughness, formability, and weldability. This material had demonstrated these characteristics in the first phases of the structural development program in reference 1.3.1, 1.3.7, and in the IM-99B ram jet fuel tanks. Allowable stress for this material was provided in reference 2.3.6.

To satisfy manned safety requirements, factors of 1.5 at proof pressure, (at which no permanent deformation could occur) and 2.0 at burst pressure, (under which no failure could occur), were applied. The foundation for these factors are based on reference 2.3.5, paragraphs 3.10.1 and 4.8.11.3. In addition to these requirements, a factor of 1.5 is applied to the life cycle requirements. Using the above criteria, the inner tank shell would be required to provide 2.0 factor burst strength, (2100 psi), at the end of 252, (1.5 x 168) operational pressure cycles.

To satisfy these requirements the tank design shown in Figure 2.5.1 resulted. Two trunnion fittings provided external support for the tank. At each of these support points, an integral pad is provided through which loads could be uniformly distributed into the shell. Two fill and vent fittings are also provided with integrally reinforced penetrations in the tanks shells to accommodate the local discontinuity stresses. Where the two hemispheres are girth welded together, a reinforcing band is provided in each hemisphere to provide the additional strength in the "as welded" zone.

2.5.2 Construction of Specimen

The two tank hemispheres were formed by shear spinning. Each head progressed in several stages from a ½" thick, 36" x 36" 2219 aluminum plate to the 16.18 I.D. hemispherical shape. The material was annealed during the spinning operation to preclude the possibility of tearing due to work hardening.

2.5 TEST SPECIMEN (CONTINUED)

2.5.2 Construction of Specimen (Continued)

Following spinning, the reinforcing pads for the vent and fill fittings were indented into each head. The outer surface of each hemisphere was machined to the contour indicated in reference 2.3.2. Prior to welding the fill and vent fitting to the tank, the nozzle was punched out in the center of the reinforcing boss. This technique provided an integrally reinforced penetration without requiring a "weld-in" fitting. The oversize trunnion fittings were butt welded to the apex of each hemisphere to provide the support points for the tank. Each head subassembly was heat treated and aged to the T6E46 condition, (See reference 1.3.8), prior to the final girth weld per reference 1.3.9. Final machining was done to each trunnion fitting to true their axis to the center line of the tank.

2.6 TEST SETUP

The schematic sketch of the test setup is shown in Figure 2.2. The test was conducted in the Structures Laboratories Hazardous Test Cell by the Development Lab Unit.

The test tank was immersed in a LN_2 bath to maintain a constant -320° F. test temperature. Pressure was applied by a 10,000 psig, 5 g.p.m. Cosmodyne cryogenic pump. Control of the system was by manually-controlled valves operated outside of the test cell. Test pressures were recorded by a Sanborn Strip Chart Recorder. Testing was performed on schedule with no delays due to malfunctioning equipment. Photos of the test equipment and facility are included in Figures 2.3, 2.4, and 2.5.

2.7 TEST OBSERVATION

Pressurization of the test tank started after the temperatures had stabilized in the immersion tank and in the pressurization loop. This was visually confirmed by checking the boil-off rate in the system and ice build-up on the supply lines. The test pressure of 1000 ± 50 psig was attained in 30 seconds, held for 30 seconds, and then depressurized in 30 seconds. This was repeated 252 times at which time pressure was steadily increased until burst occurred at 2650 psi.

Burst occurred as a mild detonation due to two factors. (1) There was no fragmentation, and (2) the burst energy was absorbed by the immersion liquid. Figure 2.6 is a photo of the test specimen after failure. As is noted, the failure occurred as a clean circumferential break adjacent to the girth weld neatly separating the tank into halves.

2.7 TEST OBSERVATION (CONTINUED)

The burst stresses were determined in both the heat treated shell and the "as welded" girth weld where failure occurred. The effect of stress raisers were ignored and only membrane stresses are considered. From the hoop stress equation, $S = pr/2t$, the following stresses were calculated:

Base Metal Burst Stress

p = burst pressure = 2650 psig

$r = 8.09 + .15/2 = 8.165$ in.

t = shell thickness = .15 in. (min.)

$$s = \frac{2650 \times 8.165}{2 \times .15} = 72{,}000 \text{ psi}$$

Girth Weld Stress

p = 2650 psig

$r = 8.09 + .168 = 8.258$ in.

t = .336 in.

$$s = \frac{2650 \times 8.258}{2 \times .336} = 32{,}500 \text{ psi}$$

These stresses can be compared with reference 2.3.6 allowable stresses at -320° F. They are:

F_{TU} = 68,200 psi (base metal, pg. 82.5.5.1-11)

F_{TU} = 29,300 psi ("as welded" butt joints, pg. 82.5.9.3)

2.8 METALLURGICAL ANALYSIS

The following data is based on information provided in reference 2.3.3 by the Materials and Process Unit. The failure occurred along the girth weld. The arrows in Figure 2.6 and 2.7 indicate the origin of failure which corresponded with a deep, sharp weld undercut on the outer surface of the tank. Figure 2.8 is a cross section through the weld showing the .0055" deep undercut with a root radius of .012". This undercut was evident on both sides of the weld and varied in depth from .005" to .006".

The radius of the weld underbead drop-through is .028". The weld itself was found to be of uniform quality with no porosity or slag

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U3-4071-1000

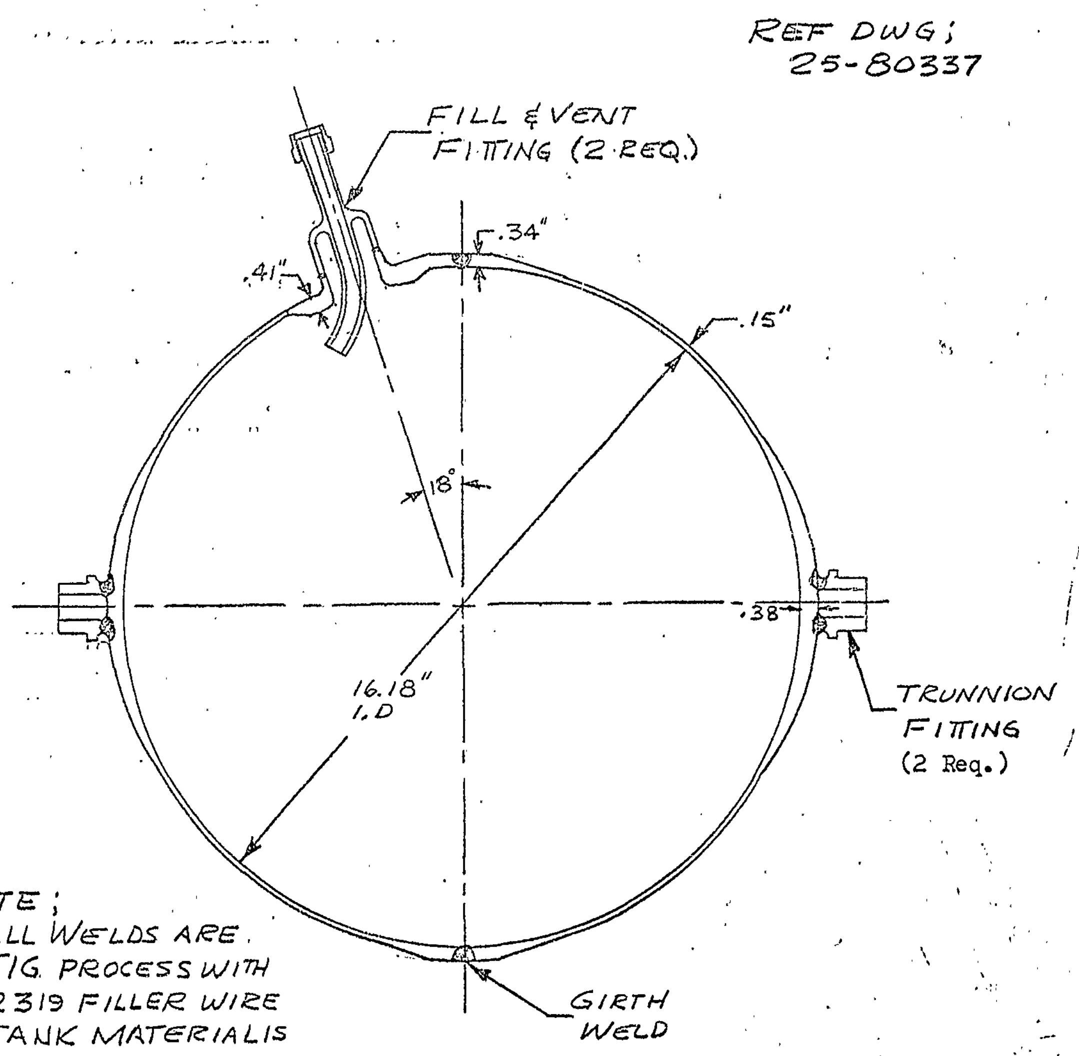
2.8 METALLURGICAL ANALYSIS (CONTINUED)

inclusions. The microhardness readings, converted to Rockwell E, were 87.5 in the weld metal, 87.0 to 99.0 in the heat-affected zone, and 97.0 in the base metal. These readings are normal for an "as welded" joint in 2219 T6E46 aluminum.

In conclusion it can be stated that the notch effects at the weld undercut and the underbead drop-through acted as stress risers and caused failure in that zone.

Production tanks will not have "as welded" joints in the shells, nor will such obvious stress raiser be tolerated.

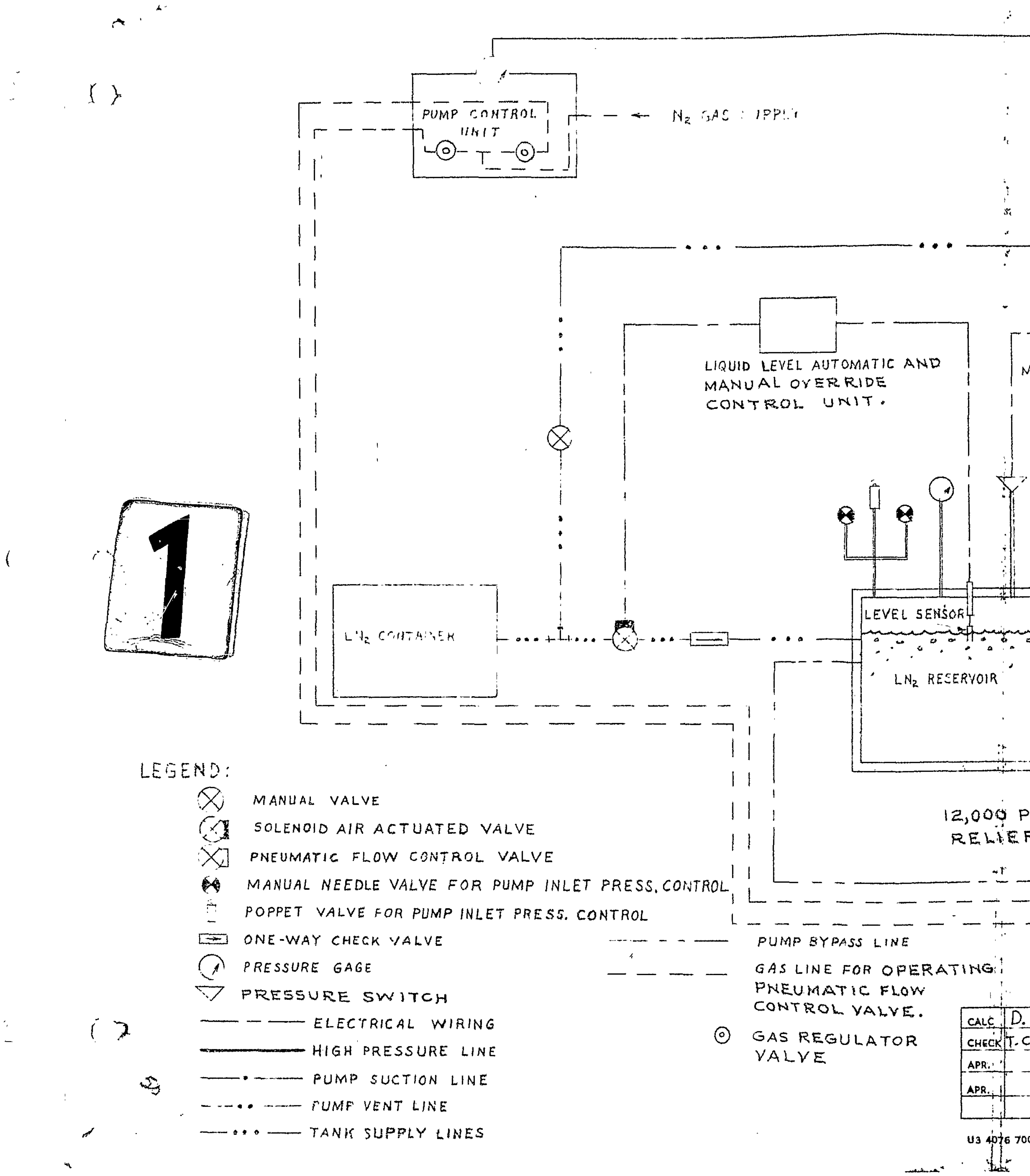
U3-4071-1000



NOTE;
1. ALL WELDS ARE TIG PROCESS WITH 2319 FILLER WIRE
2. TANK MATERIAL IS 2219 ALUMINUM PLATE (BMS7-105)

FIGURE 2.1
INNER LN_2 TANK SHELL

U3 4038 8000 REV. 12-62 2-5142-2


PUMP CONTROL UNIT
N_2 GAS
LIQUID LEVEL AUTOMATIC AND MANUAL OVERRIDE CONTROL UNIT.
LN_2 CONTAINER
LEVEL SENSOR
LN_2 RESERVOIR
12,000 P
RELIEF
LEGEND:
MANUAL VALVE
SOLENOID AIR ACTUATED VALVE
PNEUMATIC FLOW CONTROL VALVE
MANUAL NEEDLE VALVE FOR PUMP INLET PRESS. CONTROL
POPPET VALVE FOR PUMP INLET PRESS. CONTROL
ONE-WAY CHECK VALVE
PRESSURE GAGE
PRESSURE SWITCH
ELECTRICAL WIRING
HIGH PRESSURE LINE
PUMP SUCTION LINE
PUMP VENT LINE
TANK SUPPLY LINES
PUMP BYPASS LINE
GAS LINE FOR OPERATING PNEUMATIC FLOW CONTROL VALVE.
GAS REGULATOR VALVE
CALC
CHECK
APR.
APR.

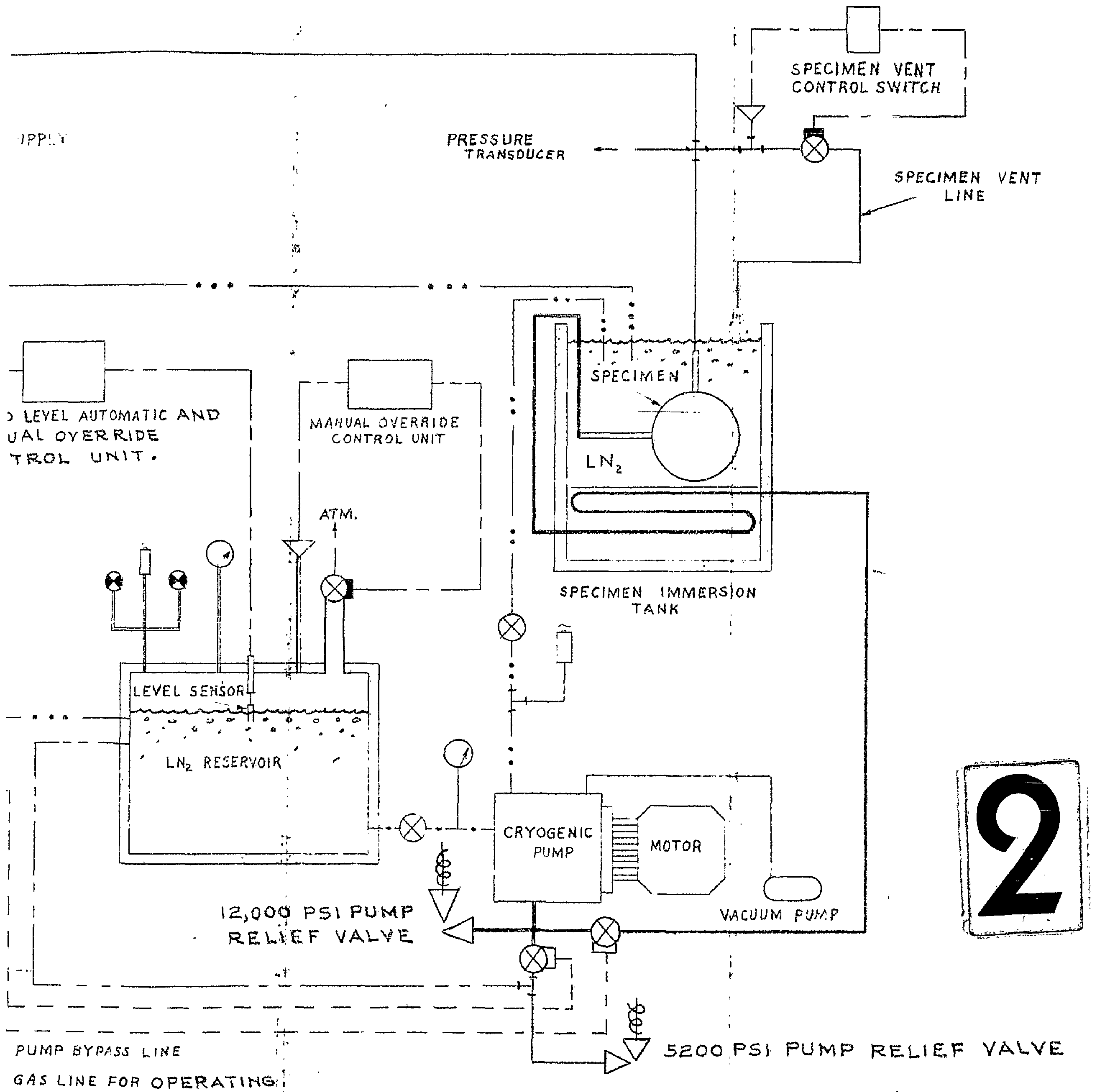


FIG. 2.2

CALC	D. JONES	3·20·2	REVISED	DATE	SCHEMATIC SKETCH CRYOGENIC PRESSURE TEST SETUP DYNA-SOAR LN_2 TANKS	D2-80092
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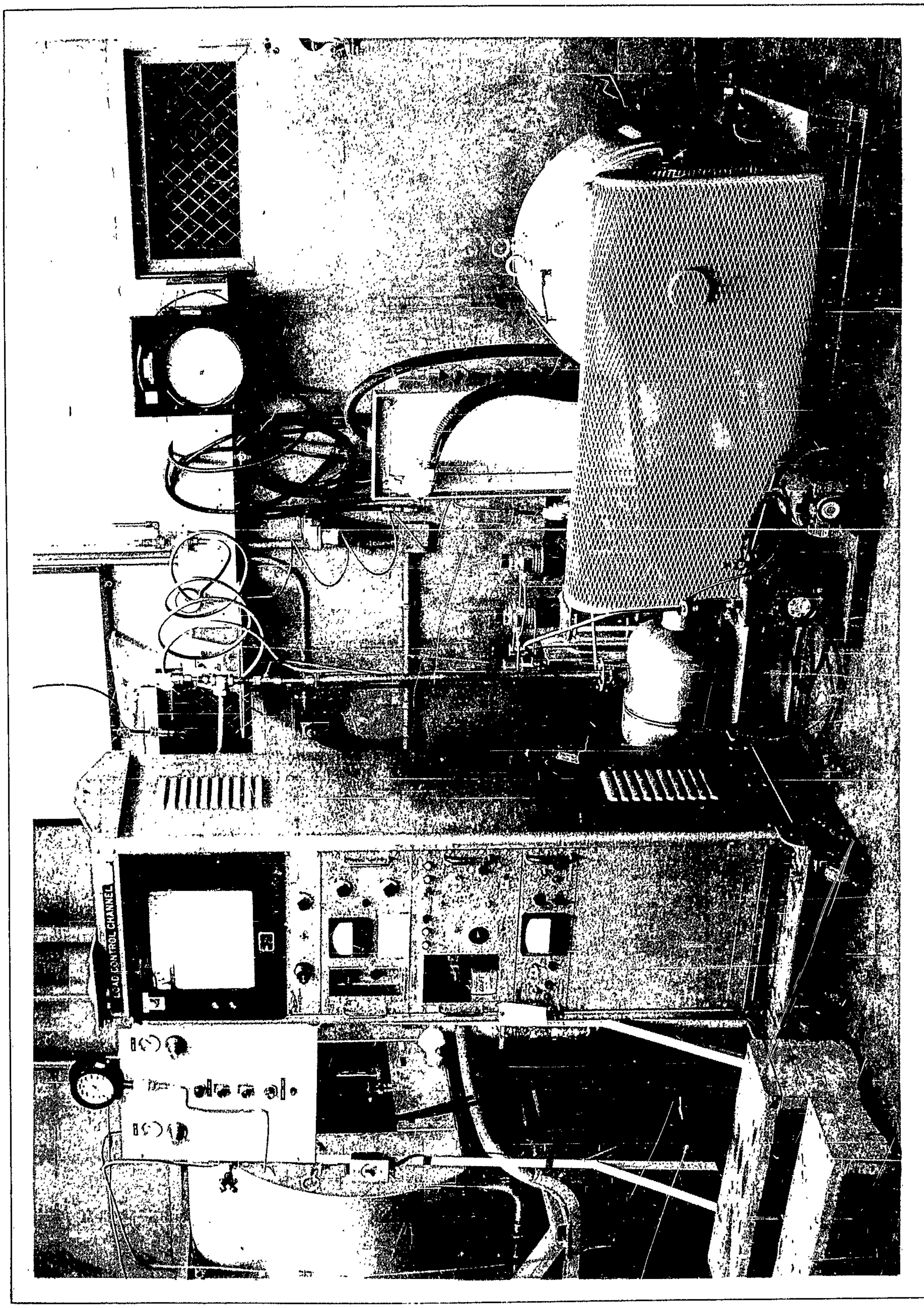
APR.						

U3 4076 7000 (WAS BAC 1656-R2)

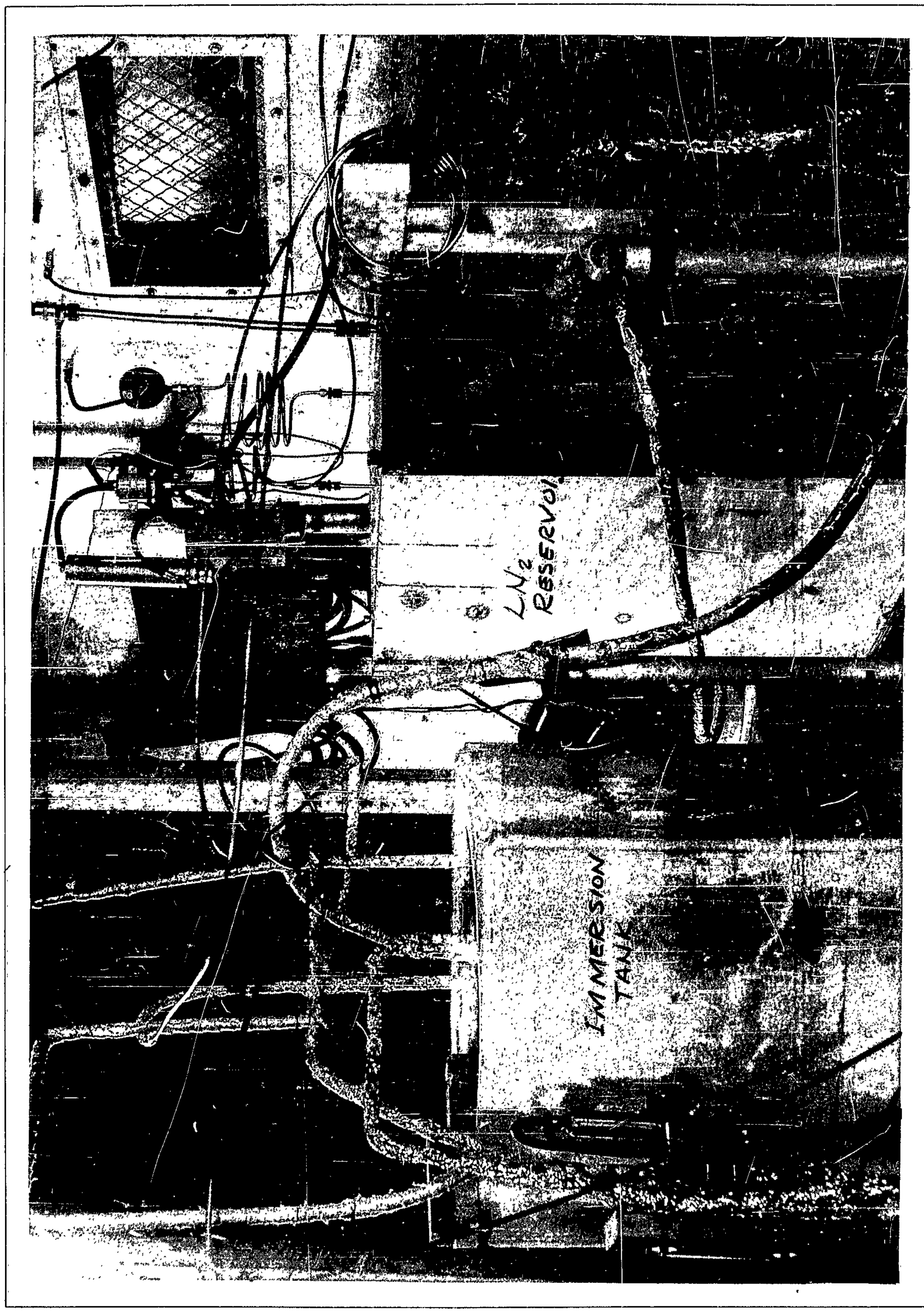


ST SETUP CYCLING AND BURST TESTING 2A104453
WITH ... OF DS-I LIQUID NITROGEN 3-16-62

51

U3-4071-1000 (was BAC 1546-L-R3)

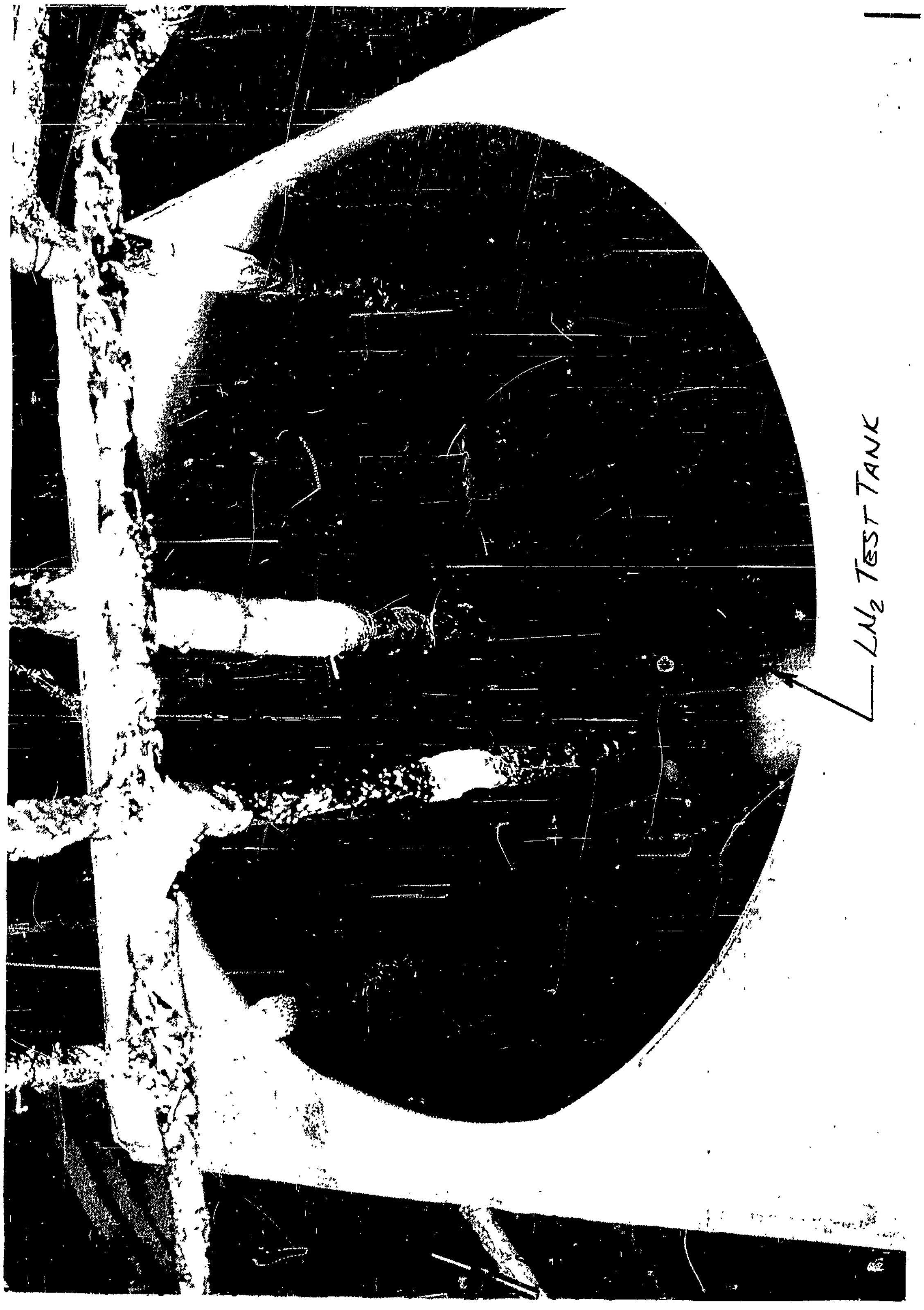
FIG. 2.3
LN_2 TANK TEST
EQUIPMENT



DS-I - TEST SETUP FOR CY... TESTING WITH LN2 OF PS-I LIQUID NITROGEN 3-16-62

U3-4071-1000 (was BAC 1546-L-R3)

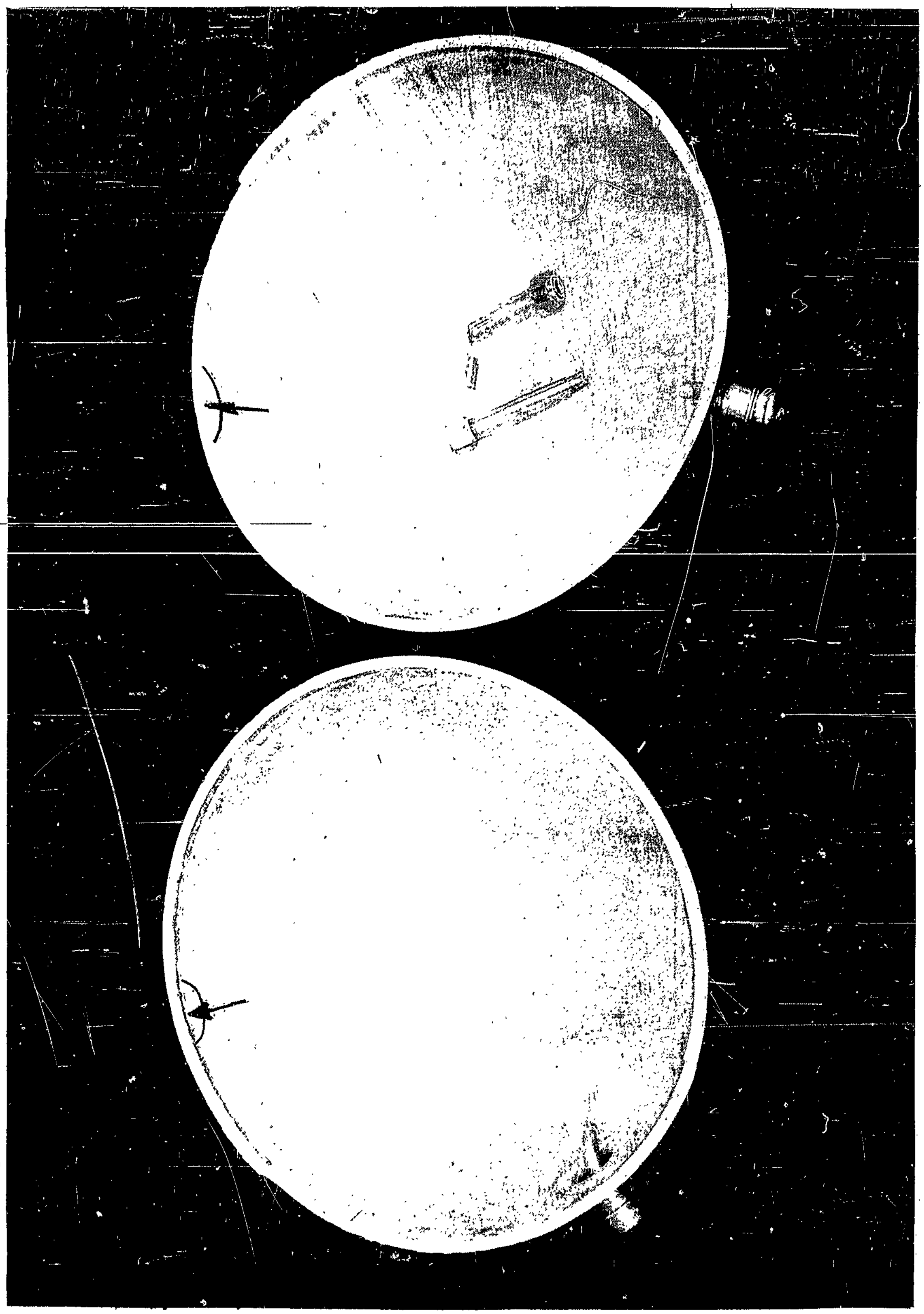
FIG 2.4
LN_2 TANK TEST SETUP
IN HAZARDOUS TEST CELL



DS-I -- TEST SETUP FOR CYCLING AND BURST 2A104455
TESTING WITH LN^2 OF DS-I LIQUID NITROGEN TANK
3-16-62

U3-4071-1000 (was BAC 1546-L-R3)

FIG. 2.5
LN_2 TANK IN IMMERSION TANK



DS- .D NITROGEN TANK BURST TEST - 2A104623
3-21-62

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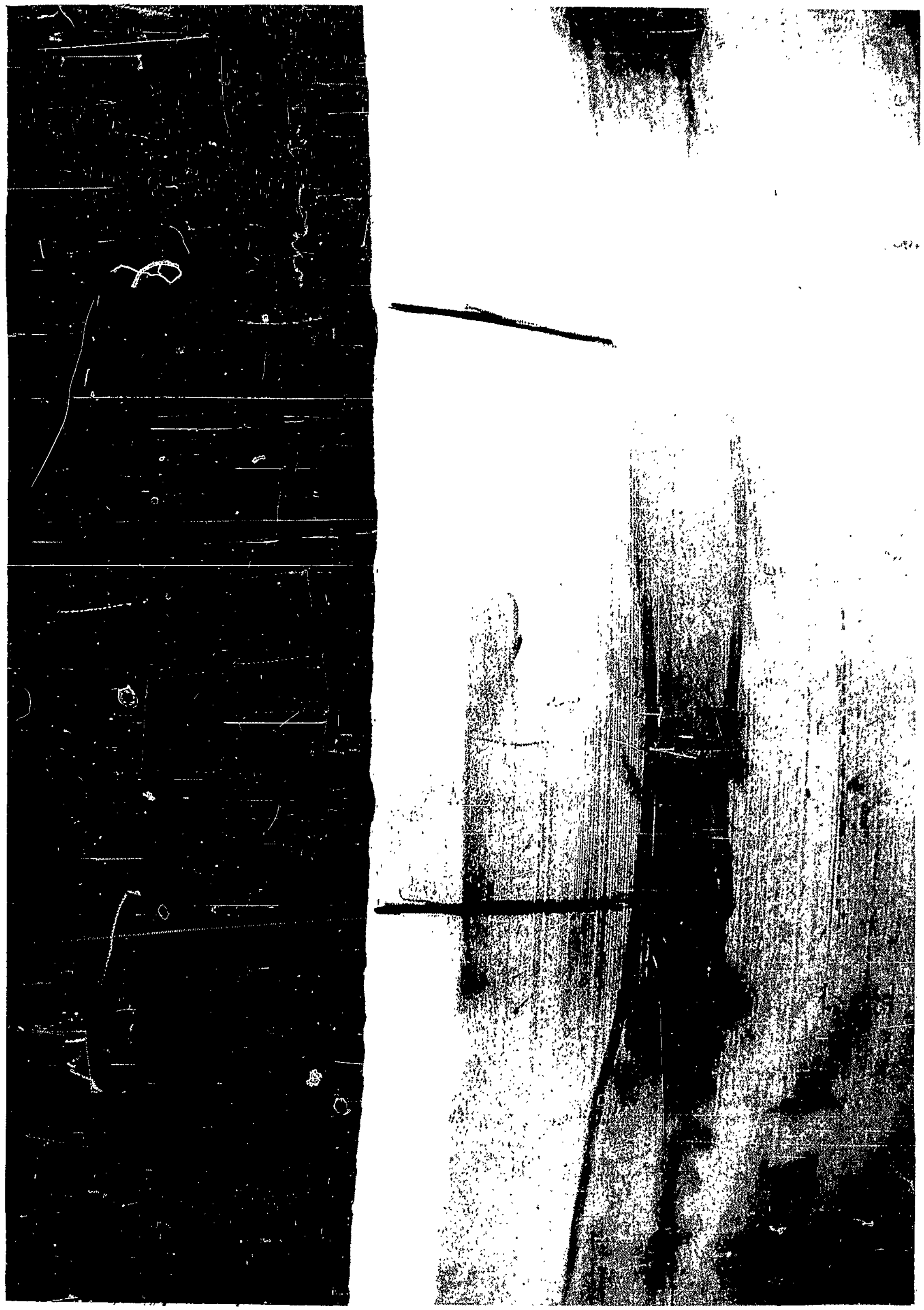
U3-4071-1000 (was BAC 1546-L-R3)

FIG 2.6
LN_2 TANK INNER SHELL
AFTER BURST



U3-4071-1000 (was BAC 1546-L-R3)

FIG. 2.7
FAILURE ZONE VIEWED
FROM OUTER SURFACE

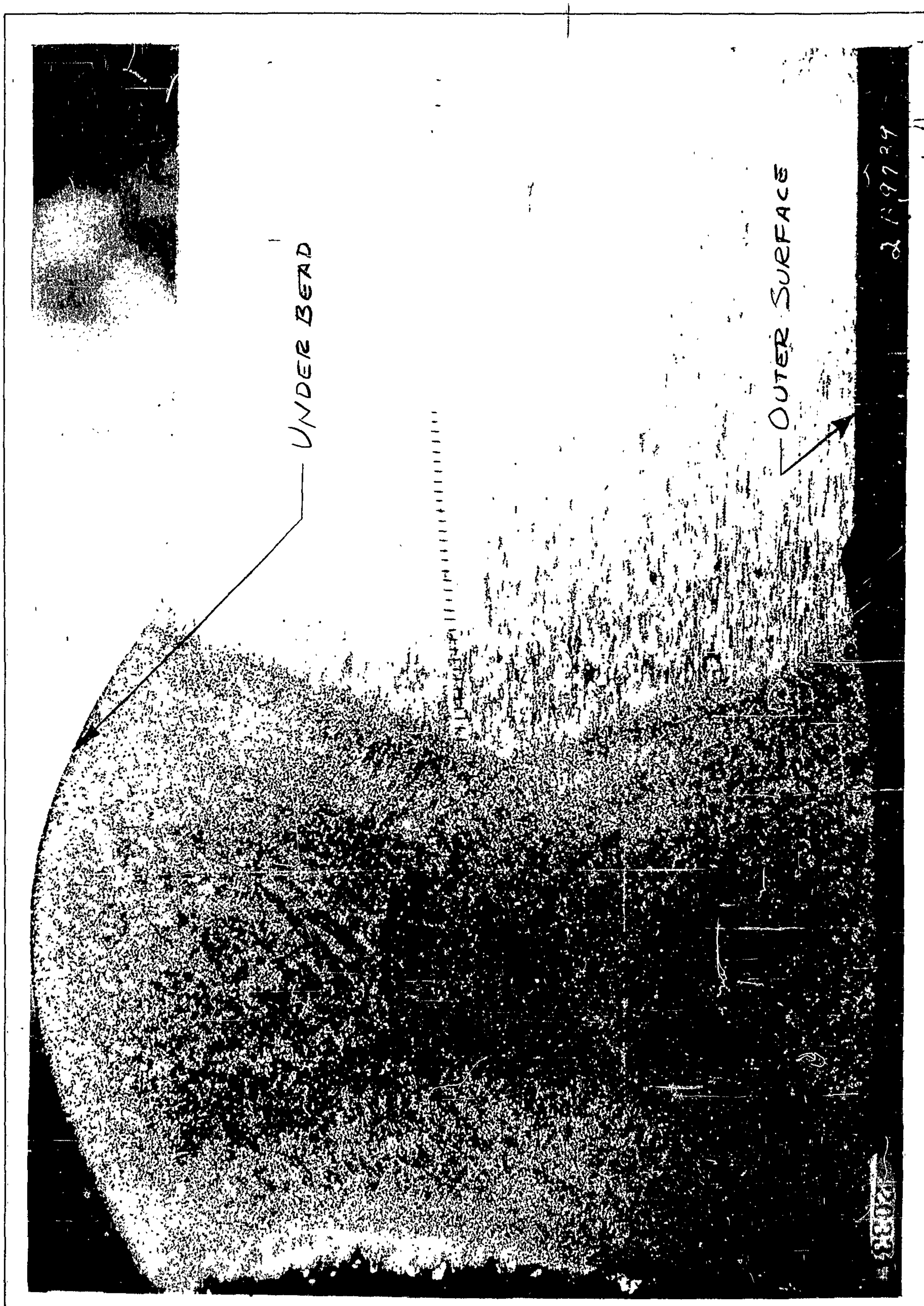


FIG. 2.8
GIRTH WELD CROSS
SECTION (5X)