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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA APOLLO PROGRAM WORKING PAPER NO. 1333

AN INVESTIGATION OF APOLLO TITANIUM PRESSURE VESSEL WELDS MADE WIT'I COMMERICALLY PURE FILLER WIRE

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
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AN INVESTIGATION OF APOLLO TITANIUM PRESSURE VESSEL WELDS MADE WITH COMMERCIALLY PURE FILLER WIRE

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AN INVESTIGATION OF APOLLO TITANIUM PRESSURE VESSEL WELDS MADE WITH COMMERCIALLY PURE FILLER WIRE

By Glenn M. Ecord

SUMMARY

The explosion of the Saturn IVB-503 booster in March 1967 was tentatively attributed to the failure of a 6Al-4V titanium alloy gaseous helium vessel which had inadvertently been welded with commercially pure weld wire instead of the 6Al-4V titanium alloy wire specified for the Saturn vessel. The weld exhibited severe titanium hydride banding. This condition in the Saturn vessel caused concern over the integrity of those Apollo titanium alloy pressure vessels which are welded, by specification, with commercially pure wire. A metallurgical investigation was undertaken by the Structures and Mechanics Division to determine whether Apollo welds made with commercially pure wire exhibit hydrides and to determine the conditions under which titanium hydrides would form and precipitate a structural problem. The occurrence of hydride banding or agglomeration was not observed in Apollo production welds or in welds repaired by any of the methods in use. Attempts to produce the hydride banding in the Apollo commercially pure wire welds were successful only when hydrogen was charged into the material from an external source.

The investigation has shown that the occurrence of hydride banding is not an inherent or inevitable condition when 6Al-4V titanium alloy is welded with unalloyed titanium filler metal. It is concluded that a titanium hydride problem does not exist for Apollo titanium 6Al-4V pressure vessels welded with commercially pure wire.

INTRODUCTION

A prime suspect as the cause of the explosion of the Saturn IVB-503 (S-IVB) booster in March 1967 was identified as a 6Al-4V titanium alloy pressure vessel (see appendix). The S-IVB contains nine ambient temperature, spherical, gaseous helium vessels, which operate at 3200 psi pressure, located around the thrust cone. Halves of three gaseous helium vessels, which had separated at the girth weld in a brittle manner, were recovered at the Saturn test site. In addition, a small fragment not traceable to a particular vessel was found which exhibited brittle fracture at the weld. Subsequent investigation showed that the separated vessels and the fragment were inadvertently welded with commercially pure (CP) titanium weld wire instead of the specified 6Al-4V titanium alloy weld wire. A screening of helium bottles in other boosters, using an eddy current technique, identified five additional vessels which had been welded using CP wire but which had not failed.

Laboratory examination of the failed vessels revealed hydrogen content in localized areas in the welds to be from 600 to 1600 parts per million (ppm). Normal hydrogen content is considered to be less than 140 ppm. Banding of titanium hydrides was discovered on the weld metal side of the weld-parent metal fusion line. The hydrides were identified by visual and electron diffraction techniques. The fracture of the helium vessels appeared to occur along the banded hydrides.

Investigators of the Saturn failure postulated that the low alloy content welds on helium vessels inadvertently made with CP weld wire were subject to the formation of the titanium hydrides which degraded the weld and ultimately resulted in failure of the vessels. There has been no known occurrence of hydride banding in welds made with 6Al-4V titanium alloy weld wire. Metallurgical conditions in the higher alloy content welds are not conducive to the gross formation or selective precipitation of hydrides. The relatively abrupt change in hydrogen solubility between 6Al-4V titanium parent material and a titanium rich weld made with CP weld wire provides a metallurgical condition where hydride formation can occur. For the Saturn vessels, it was suggested that hydrogen migrated due to stress conditions from a region of high solubility (alloy parent material) to a region of low solubility (relatively unalloyed weld) and precipitated as titanium hydrides upon reaching this zone.

The presence of hydride bands in the welds of the failed S-IVB helium vessels generated concern over the integrity of the Apollo titanium 6Al-4V pressure vessels which are welded with CP weld wire by specification. As a result of this concern, an investigation of Apollo welds was initiated to determine whether hydride formation was occurring and the conditions required for hydride formation or associated problems.

Electron-microprobe analyses of the Apollo weldments were made to determine alloy content variations, and metallographic examinations were made of the welds to identify alloy structure and to determine the presence of titanium hydrides. Samples of all available Apollo CP weldments were investigated. These samples were taken from vessels with varying service histories, including sustained operating pressures for as long as 80 days. The samples consisted of unrepaired welds and welds which had been repaired by the various methods used in the Apollo Program.

Comparisons were made between Apollo and Saturn welds to identify differences which could relate to the formation of titanium hydrides.

APPROACH

In order to assess the integrity of Apollo pressure vessel welds made with CP filler wire, a program was initiated to examine as complete a sampling as possible of representative welds. Apollo contractors were requested to furnish the Manned Spacecraft Center (MSC) Structures and Mechanics Division (SMD) with weld data, photographs, and all available weld samples. Several weld samples available within SMD from destructed vessels were also collected. This sampling plan was considered to be the only workable method for obtaining welds for evaluation, since the welds in whole pressure vessels could not be metallurgically investigated without destroying the vessels.

Each weld was analyzed for aluminum and vanadium composition using an electron-microprobe technique and examined metallographically for alloy structure and for the presence of hydrides. The composition and microstructure evaluation was conducted to determine whether a hydride problem existed in any of the Apollo welds and to correlate weld composition with the presence of hydrides. The results of the evaluation on each weld were compared with the results of a similar evaluation made on a weld, furnished by NASA-Marshall Space Flight Center (MSFC), representative of the failed Saturn pressure vessel. The comparisons were made to establish the differences between the Apollo and Saturn welds that could be significant to the presence or absence of a hydride problem.

After determination of the general characteristics of Apollo welds, an eddy current nondestructive technique was evaluated for comparing the investigated welds with welds on existing pressure vessels. The feasibility and limitations of the technique were established for measuring the alloy content of Apollo welds.

Attempts were made to produce hydride banding in Apollo welds to gain an understanding of the stress, time, and environment factors which are conducive to hydride agglomeration or banding in these welds.

In addition, the performances of qualification vessels and special test vessels were examined in light of hydride problems. These vessels contained both unrepaired welds and repaired welds which would be expected to have low alloy contents. Samples of many of these welds were examined during the investigation.

The approach used in the investigation of Apollo welds, as described above, provided a realistic evaluation which generated data believed applicable to the CP wire welds on Apollo titanium vessels.

WELD SAMPLES

The Apollo weld samples evaluated during the investigation for titanium hydrides are listed in table I. The samples are identified as to vessel, location, type of weld, and vessel history.

The welds examined were made by the two principal Apollo titanium pressure vessel manufacturers who use CP filler wire: (1) Allison Division of General Motors (service propulsion system and lunar module descent propellant vessels), and (2) Aerojet General Corporation (lunar module ascent propellant vessels). Figure 1 presents detailed characteristics of Apollo welds, weld configurations, and dimensions. The welding methods used by the two vendors are outlined in figures 2 and 3 and are summarized as follows:

1. Allison — (Allison Weld Specification EPS R-14635-11). Allison vessels are welded from both the inside diameter and the outside diameter with local inert shielding. The initial weld pass is a fusion pass made on the outside diameter of the vessel. The fusion pass is followed by a filler metal pass which completes the outside diameter weld. The inside diameter is routed according to specification requirements and a fusion pass made from the inside diameter side. The inside diameter fusion pass is followed by an inside diameter filler pass which completes the weld.

2. Aerojet — (Weld Specification AGC-51097/2). Aerojet vessels are welded from the outside diameter only, in an inert chamber. The initial weld pass is a fusion pass at the root of the weld. This pass is followed by a second fusion pass. A single pass of filler metal completes the weld.

Vessels made by other vendors are welded in a manner similar to one of the above methods. Welds which are not satisfactory may be repaired by a number of standard methods. In general, the following descriptions summarize the repair procedures:

Method 1 — An additional 360-degree fusion pass is made. This method is usually employed to correct undercuts or shallow surface irregularities.

Method 2 — The weld to be repaired is routed 360 degrees to a specified depth. A fusion pass is made and new filler metal is added in a subsequent weld pass. This method is usually employed to remove deep porosity, inclusions, or other irregularities where a method 1 repair is not applicable. A variation of this method is employed when the rout and fill are localized and not made around the entire 360-degree weld. A local rout and fill may be followed by a 360-degree fusion pass.

Method 3 — The weld is machined to the original detail dimensions and a new detail is welded to the previously welded edge. This method is employed in the event of damage to one of the details or when it is determined that a method 1 or 2 repair is not applicable.

The repair procedures are illustrated in some detail in figure 4.

Welds repaired by routing and refilling with CP wire would be expected to have a lower alloy content than the original weld. Welds repaired by fusion only may have a higher alloy content. Samples of repaired welds from destructed vessels were examined and the certification programs and results for repair welds were reviewed. Table II lists the performance histories of a group of Apollo vessels having a variety of weld repairs.

CHEMICAL COMPOSITION OF WELDS

The alloy content of welds is considered a major factor in the susceptibility of a weld to hydride formation or banding. Hydrogen solubility is low in unalloyed titanium. It is not uncommon to observe scattered hydrides in the unalloyed material. As alloy content increases, the occurrence of hydrides decreases. As the alloy content of the weld approaches the content of the parent material, the hydrogen solubility (for all practical purposes) becomes constant through the parent material and the weld. Under these conditions hydride banding or agglomeration is highly unlikely.

The electron microprobe method of analysis was selected as the most expeditious means of determining weld composition. The technique is exacting and allows traverses to be made across the weld which can identify variations in alloy content. Any part of a weld can be analyzed, and direct comparisons between corresponding areas of different welds are possible.

Electron microprobe traverses were made on all Apollo welds examined during the investigation. The summary data for these welds are presented in figures 5 through 8. The compositions and variations within Apollo welds were compared to the composition of the Saturn weld which failed on the S-IVB stage.

Figure 5 illustrates the comparative chemical analysis of Apollo and Saturn welds. The alloy content of the Saturn weld drops sharply just inside the fusion line to approximately 1 percent aluminum as opposed to an average 6 percent aluminum in the parent metal. It is in this area that the hydride formation occurred in the Saturn weld. A hydrogen analysis made in the area of hydride formation showed the hydrogen content to range between 600 and 1600 ppm. This high hydrogen content was present although the hydrogen content of the parent material, the weld bead, and the wire used in fabricating the Saturn welds was less than 70 ppm.

Figures 6, 7, and 8 show the average and minimum compositions of the Apollo welds and weld repairs as determined by electron probe traverses. Hydrogen analyses of Apollo welds show the content to be less than 70 ppm in all cases examined.

An eddy current device was tested on welds of known alloy composition to determine whether readings could be used to indicate alloy content. Using this technique the Saturn-type welds made with alloy or with CP wire are easily distinguished. The technique is also applicable to Apollo welds; however, Apollo welds are much smaller, have comparatively pronounced crowns, and are of compositions between pure titanium and the 6Al-4V titanium alloy. The tests show that eddy current techniques can be used to measure alloy content of Apollo welds when due consideration is given to weld geometries and weld type.

METALLOGRAPHIC EXAMINATION OF WELDS

All of the welds evaluated during the investigation for hydrides were sectioned and examined under magnification. Several photomicrographs of welds considered pertinent to the investigation are presented in figures 9 through 15. The principal reason for the microscopic examination was the detection of titanium hydrides in the weld. There is no known nondestructive method for detection of hydrides. In addition, the general metallographic characteristics of Apollo welds were identified.

The weld metal structure of Apollo vessels differs markedly from the structure observed in the Saturn weld. Although both are predominantly alpha phase titanium, the alloy content difference causes a definite distinction in phase morphology.

A second significant difference in the welds is noted at the fusion line between weld metal and parent metal. The Saturn weld exhibits a very sharp, distinct fusion line while the Apollo welds do not. The absence of sharpness is indicative of the dissolution and higher alloy content in the Apollo welds. Figures 9, 10, and 11 show the Apollo and Saturn weld structures, respectively. Examination of the "worst case" Apollo weld repair (a double method 2 repair) where the alloy content would be expected to be the lowest, showed no banding or agglomeration of hydrides. One zone in the weld was analyzed to be nearly unalloyed titanium (see fig. 7, S/N 066) and contained a relatively large amount of small scattered titanium hydrides. Figure 12 shows the weld section. An enlargement of the low alloy portion is also shown which exhibits indications of slight hydride banding and lack of fusion. The condition in no way approaches the severity of hydrides found in the Saturn weld.

During the course of this investigation, a problem with CP wire welds was experienced by an Apollo vendor. Metallographic examination revealed hydrides at the fusion zone of a weld repair as shown in figure 13. This condition closely resembles the banding discovered in the Saturn weld. Subsequent investigation disclosed that the affected welds had inadvertently been heat-treated in a hydrogen contaminated atmosphere. The hydrogen introduced externally had selectively precipitated at the fusion line area of the low alloy weld repair. Similar weld repairs not exposed to the hydrogen atmosphere heat-treatment did not exhibit hydride banding. Figure 14 shows the effect on an Apollo weld from introduction of hydrogen by electrochemical action.

OCCURRENCE AND REPRODUCTION OF HYDRIDE BANDING

It has been suggested that time under stress and age of the weld are significant factors in the occurrence of titanium hydrides. The Saturn welds were made in 1965 and had been under stress for an accumulated period of at least 100 hours and possibly more than 800 hours. Any effect of time under stress and age of the weld on hydride formation and agglomeration appears to be negligible for Apollo welds. This observation is supported by the normal appearance of the structure and absence of hydrides in welds taken from an Apollo propellant vessel (S/N 002) which had been pressurized at maximum operating pressure for 80 days. This vessel was built in late 1963 and burst tested in mid-1966. The photomicrographs from each of the five welds on the vessel are shown in figure 15. Two of the welds on this vessel were repaired. One was repaired by a method 3 repair followed by a method 1 repair. The other weld was repaired by a method 2 repair with two extra filler metal passes for a total of four filler passes. Reference to the microprobe analyses for the repaired welds on the vessel (fig. 7, S/N 002) shows that aluminum content falls below 2 percent in the weld. These welds, however, survived the 80-day pressure test and showed no hydride agglomeration or banding. Examination of a weld from a lunar module propellant vessel which had been pressurized for 75 days also showed a normal structure.

Attempts by Douglas and MSFC to reproduce the hydride banding found in the Saturn vessels have been generally unsuccessful. Attempts by SMD to produce hydride banding or agglomeration in Apollo welds have been unsuccessful except where hydrogen is charged from an external source. Success with external charging by SMD combined with the generation of agglomerated hydrides in a production weld through inadvertent external hydrogen charging at an Apollo vendor suggests that hydride banding can be expected in a weld made with CP w[illegible] when excessive hydrogen is introduced. A special heat-treatment devised by Douglas is reportedly successful in producing agglomerated hydrides in regions of stress concentration. However, it is difficult to visualize that such a schedule of temperatures and times could be inadvertently applied to Apollo vessels.

RESULTS AND DISCUSSION

Many welds on Apollo 6Al-4V titanium alloy pressure vessels are made with CP filler wire according to specification requirements. After the Saturn vessel failure the Apollo welds were immediately reviewed since the Saturn vessel hydride problems were attributed to the use of CP filler wire for the welds. The investigation described in this report was conducted to evaluate Apollo welds made using CP filler wire.

The investigation did not detect the presence of agglomerated or banded titanium hydrides in any of the Apollo welds examined, but it did establish a significant difference between the Apollo and Saturn welds. The Apollo welds are much higher in alloy content, even in the repaired condition, and exhibit considerably more parent metal dissolution at the weld-parent metal fusion line.

Attempts to reproduce the hydride banding in Saturn type CP welds have been generally unsuccessful. Some success has been experienced when hydrogen is externally introduced or when the welds are given a specific heat treatment. Attempts by SMD to produce hydride banding in Apollo welds by heat treatment or sustained stress were unsuccessful. When hydrogen was charged into the welds by an electrochemical process, hydride banding was observed at the weld-parent metal fusion line. During the course of the investigation, an Apollo vendor experienced a hydride problem in a pressure vessel welded with CP filler wire. The cause of the problem was traced to inadvertent heat-treatment of the vessel in a hydrogen-containing atmosphere. Titanium hydrides were observed banded at the weld-parent metal fusion line.

Weld repairs generally result in lower alloy content welds making these welds theoretically more subject to hydride formation. A qualification propellant vessel (S/N 004) contained a weld repaired by a method 2 technique followed by a method 3 and then a second method 2 repair. This weld would be expected to have a very low alloy content. The vessel survived a full qualification test which included the following:

1. Leak test 1

2. Shock test (1.10g to 2.98g)

3. Leak test 2

4. Proof pressure (3 min)

5. Proof pressure (30 min)

6. Vertical structural load test at operating pressure

7. Leak test 3

8. Creep test (30 days at maximum operating pressure)

9. Burst test (burst in dome at a pressure above design burst pressure)

The average and the minimum analysis for 14 Apollo service propulsion system (SPS) propellant vessel welds are shown graphically in figure 6. It is noted that the analysis for any one of the welds did not go lower than 2 percent aluminum. Based on the 14 analyses, it was decided that 2 percent aluminum could be considered an arbitrary lower limit for aluminum content in Apollo welds. The lower limit was arbitrarily established because anything below this limit would be generally considered as abnormal for the Apollo weld.

CONCLUDING REMARKS

It is concluded that Apollo welds made or repaired according to specification requirements are not affected by hydride agglomeration or banding. An exception is a double method 2 repair where the second repair was made off-center to the first. A zone of very low alloy content, less than 1 percent Al, was detected in this repair with evidence of slight hydride agglomeration within this zone. The necessity for a double repair of this type may indicate a serious process problem with the particular weld. For this reason and the fact that the double method 2 repair is a "worst case" repair, considering alloy content, vessels containing such repairs have been removed from use in the Apollo Program. It has been pointed out, however, that an Apollo propellant vessel with two welds repaired by combinations of methods resulting in a low alloy content survived an 80-day sustained load test at maximum operating pressure and subsequently was burst above design burst pressure. Examination of the unrepaired and repaired welds from this vessel showed no hydride agglomeration or banding.

The results of the investigation of various Apollo welds for hydrides, combined with knowledge of the histories of Apollo vessels, lead to the overall conclusion that the CP filler wire welds in the Apollo Program are satisfactory for unrestricted use within the design limits and environment constraints of the pressure vessels.

APPENDIX

SUMMARY OF SATURN WELD FAILURE

The Saturn IVB contains nine ambient temperature, 3200 psi spherical gaseous helium bottles located around the thrust cone. Halves of three different bottles S/N 65, 66, and 69 (two tops and one bottom) which had separated at the girth weld in a brittle manner were recovered at the Saturn test site. In addition, a small fragment, designated fragment no. 888, was found which showed brittle fracture at the weld.

Fragment no. 888 could not be traced to a particular bottle but it was definitely from one of the ambient helium bottles and inadvertently had been welded using commercially pure (CP) titanium weld wire. Three other bursted tanks were also determined to have been welded with CP titanium weld rod as well as one tank found intact. Subsequent screening of helium bottles in other boosters using a Douglas developed eddy current device recovered five additional bottles welded using CP wire. All other helium bottles checked had been welded using 6Al-4V titanium alloy weld rod.

Metallographic examination revealed vessel fracture occurred through a semicontinuous phase (identified as titanium hydride). Besides metallographic appearance, two other methods were used to identify the hydrides. Filings from the fracture surface of the tank halves were collected as well as filings from the fracture surface of fragment no. 888. Vacuum fusion analysis of the collected filings at four different locations gave from 600 to 1600 parts per million hydrogen. The hydrides were also identified by electron diffraction techniques.

The titanium hydride was present from the face of the weld to the root but was not present in the material melted by the first fusion weld pass. The hydride was also located on both sides of the weld bead.

Wet chemical analysis of the weld bead showed approximately 1 percent aluminum and 1/2 percent vanadium as compared to 6.3 percent aluminum and 4 percent vanadium in the parent metal.

A microprobe scan of the S-IVB titanium tank weld set on aluminum showed a constant aluminum content in the parent material, a gradual decrease as the fusion line was crossed which continued for approximately 800 microns, and a leveling out at the aluminum content in the weld. The low aluminum content (equivalent to approximately 1 percent) remained constant all the way across the weld. The 800-micron transition zone compares to approximately a 50-micron transition zone for an Apollo weld as determined using the same technique.

Analysis of the weld bead (away from the hydride band) and the parent metal of fragment no. 888 is compared to the analysis of the commercially pure titanium weld rod inadvertently used as follows:

Element	Fragment no. 888		Bundle no. 975
	Weld	Parent metal	Weld wire
Fe	0.12 percent	0.079 percent	0.103 percent
N	0.019 percent	0.016 percent	0.013 percent
V	0.79 percent	3.98 percent	Less than 0.1 percent
Al	1.37 percent	6.33 percent	Less than 0.05 percent
O	0.22 percent	0.171 percent	0.22 percent
C	0.58 percent	0.030 percent	
H	40 ppm	70 ppm	15.5 ppm and 45 ppm[a]

[a]Two analyses at two different locations.

A typical time cycle pressure history for the S-IVB tanks for each vehicle cycle is as follows:

Description of test	Pressure, psi	Time, hr	Number of cycles
Preliminary helium leak check	1900	0.50	1
	2250	0.25	1
	1450	16.00	1
	1450	4.00	1
Final helium leak check	1450	4.00	1
	1450	6.00	1
	1450	1.50	2
	1450	0.50	1
Simulated static firing	1450	8.33	1
	1450	5.00	1
	3000	3.33	1
Total		49.41	

Since S-IVB-503 was recycled at least once (failure occurred during the 300 psi test), the titanium tanks were exposed under pressure for at least 100 hours.

TABLE I.- APOLLO PRESSURE VESSEL WELD SAMPLES EXAMINED FOR TITANIUM HYDRIDES

Vessel	Serial number	Weld location	Repair history	Number of samples	Remarks
SPS	016 016 016	G-1 G-2 G-3	None None None	1 2 1	35 + hours at vessel pressures from normal to maximum operation pressure
SPS	023	G-3	None	2	35 + hours at pressures from normal to maximum operation pressure
SPS	054 054 054	G-1 G-2 G-3	None None None	3 4 2	Developed leak in cylinder during cold flow test with methyl alcohol
SPS	066	G-1	M2 + M2	1	Vessel rejected during fabrication
SPS	053 053 053	G-1 G-2 G-3	M2A None None	1 1 1	Block II qual vibration + 1500 cycles + 30 day creep + burst
SPS	023 023	G-1 G-2	None None	1 2	35 + hours at pressures from normal pressure to maximum operation + stress wave acoustical technique evaluation

NOTE: G = Girth weld, numbered from top to bottom as installed in spacecraft.
SPS = Service propulsion system.
M = Method.

TABLE I.- APOLLO PRESSURE VESSEL WELD SAMPLES EXAMINED

FOR TITANIUM HYDRIDES - Concluded

Vessel	Serial number	Weld location	Repair history	Number of samples	Remarks
SPS	002 002 002 002 002	G-1 G-2 G-5 G-3 G-4	None None M2 + two filler passes M3 + M1 None	1 1 1 1	Vessel held 80 days at maximum operating pressure at 105° F
SPS	055	G-3	M2A + M1 + M1 + M1	1	Dome subsequently scrapped
LM ascent	--- --- ---	--- --- ---	M1 M2 M2 + M2	2 2 2	Weld certification ring samples
LM ascent	LAD 9 LAD 17	Girth Girth	None None	1 1	500 cycles 0-maximum operation pressure: held 10 days at maximum operation pressure and burst above design burst pressure
LM ascent	TAY 4 TAY 6	Girth Girth	None None	1 1	Reproduction vessels held 75 days at 77 percent of design burst pressure
SPS	003 003 003	G-2 G-3 G-4	None None M2	1 1 1	Ruptured during hold tests with white nitrogen tetroxide

NOTE: G = Girth weld, numbered from top to bottom as installed in spacecraft.
SPS = Service propulsion system.
LM = Lunar module
M = Method.

TABLE II.- HISTORICAL SUMMARY OF APOLLO PROPELLANT

VESSELS HAVING WELD REPAIRS

Tank serial number	Repair (location)	Test history	Remarks
001 (SPS 45 in.)	Meth 3 (G4) Meth 1 (G5)	Block I qual test (proof, leak, burst 465 psig)	Welds not available for examination
005 (SPS 45 in.)	Meth 1 (G5)	Block I qual test (vibration 1500 cycles proof, leak, burst 441 psig)	Welds not available for examination
001 (SPS 51 in.)	Meth 1 (G2)	Block I qual test (proof, leak, burst 442 psig)	Welds not available for examination
002 (SPS 51 in.)	Meth 3 + meth 1 (G3) meth 2 + two filler passes (G5)	Delta block I qual test (80-day green N_2O_4 hold at 240 psig, burst 435 psig)	No hydride banding observed in welds
004 (SPS 51 in.)	Meth 1 (G1) Meth 1 (G2) Meth 2 + meth 3 + meth 2 (G3)	Block I qual test (shock, 30-day creep, proof, leak, burst 447 psig)	Welds not available for examination
005 (SPS 51 in.)	Meth 2 (G2)	Block I qual test (vibration, 1500 cycles, proof, leak, burst 435 psig)	Welds not available for examination
006 (SPS 51 in.)	Meth 3 (G2)	Block I qual test (vibration, 1500 cycles, shock, 30-day creep, proof, leak, burst 425 psig)	Welds not available for examination
053 (SPS 51 in.)	Meth 2A (G1)	Block II qual test (vibration, 1500 cycles, 28-day creep, proof, leak, burst 413 psig)	No hydride banding observed in welds

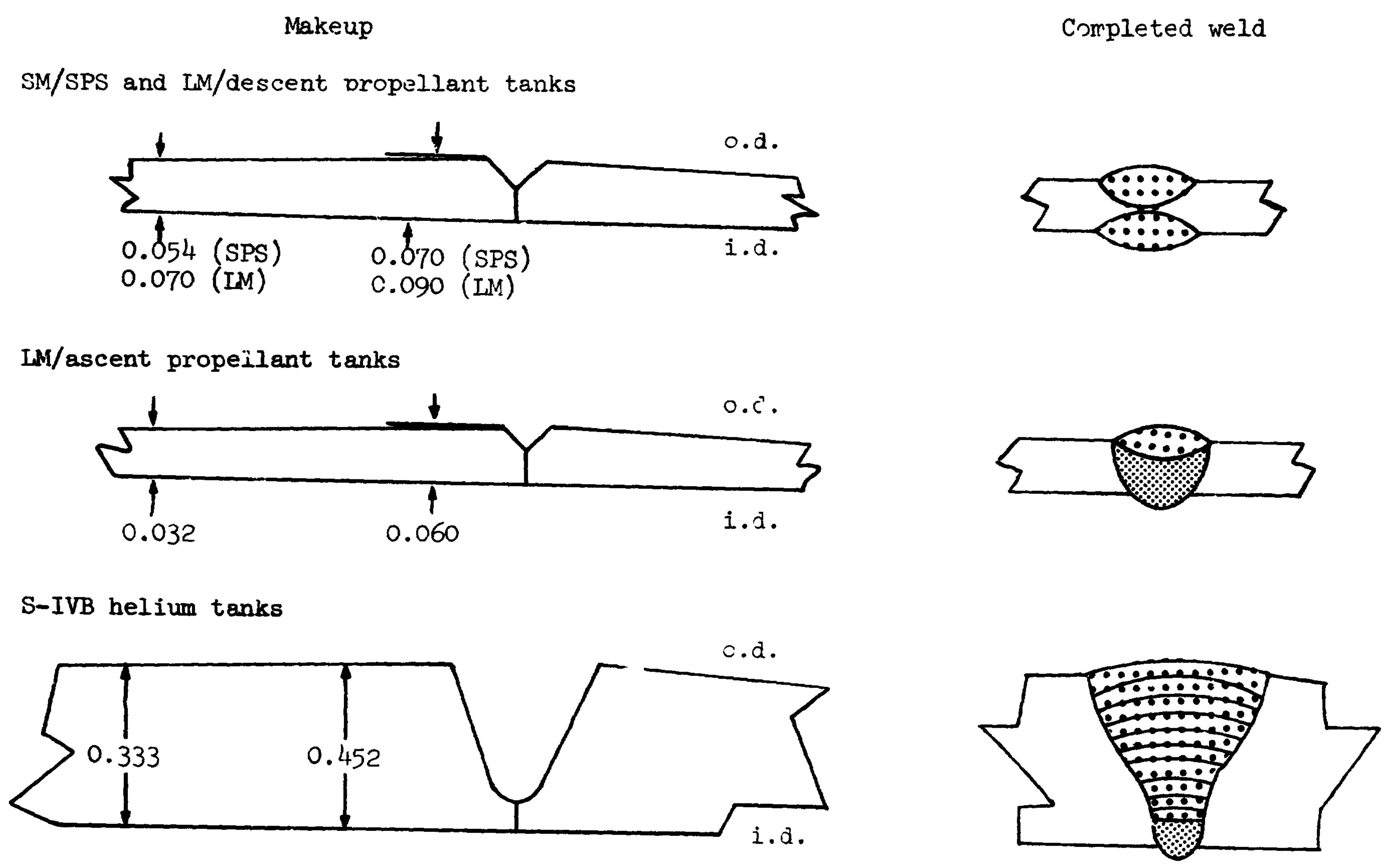
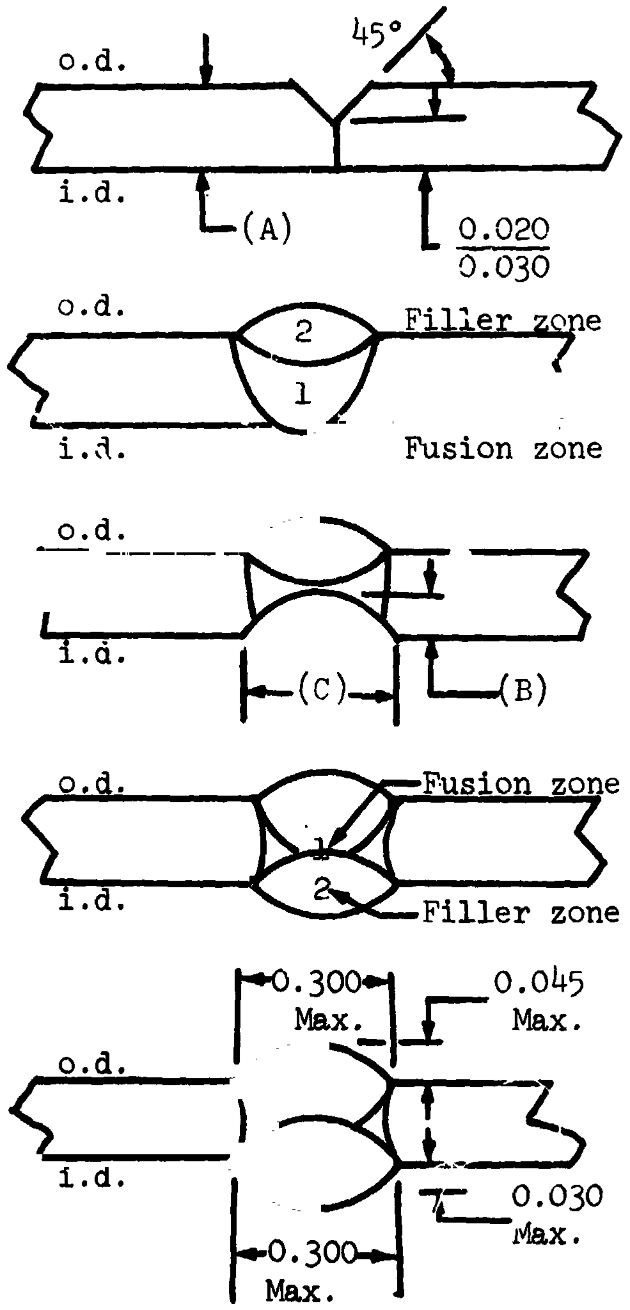


Figure 1.- Comparison of weld configuration (Apollo-Saturn).

Tank material — 6Al-4V titanium alloy
Filler wire — commercially pure titanium
Weld process — tig automatic

Dimensional requirements

Tank	(A) +005 -0	(B)	(C) ±030
SM/SPS (BLKI - fuel)	0.070	0.015 / 0.030	0.140
SM/SPS (BLKI - oxidizer)	0.078	0.015 / 0.030	0.140
SM/SPS-45 in. DIA (BLK II)	0.062	0.015 / 0.025	0.140
SM/SPS-51 in. DIA (BLK II)	0.070	0.015 / 0.030	0.140
LM/descent	0.087	0.020 / 0.040	0.080



Weld sequence

A. Joint configuration

B. o.d. Weld:
(1) fusion pass
(2) filler pass

C. Machine rout i.d.

D. i.d. Weld:
(1) fusion pass
(2) filler pass

E. Completed weld
(NOTE: Max. specified dimensions shown)

Figure 2.- Normal weld procedure for Apollo service propulsion system propellant vessels.

Tank material — 6Al-4V titanium alloy
Filler wire — commercially pure titanium
Weld process — tig automatic

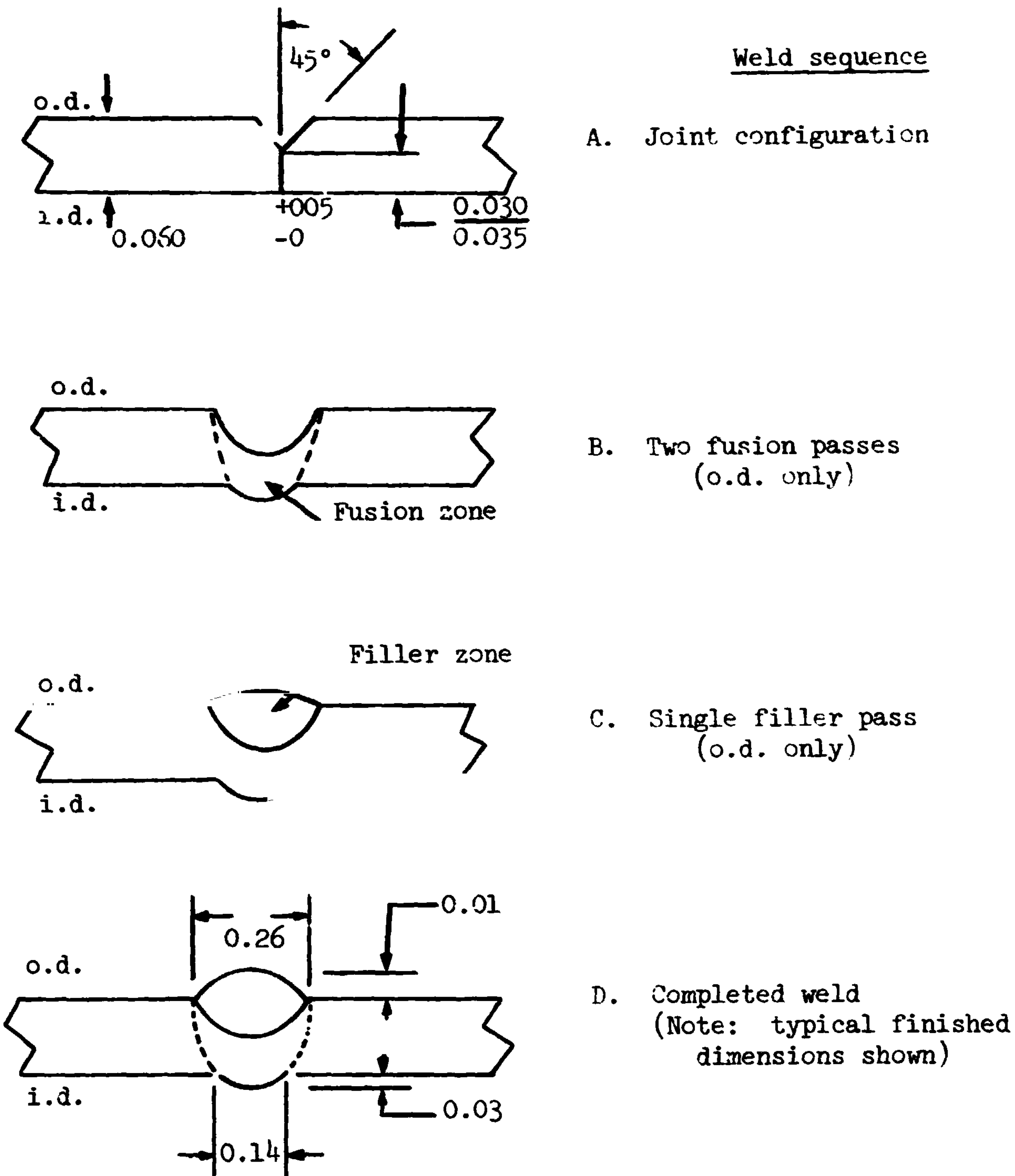


Figure 3.- Normal weld procedure for Apollo lunar module/ascent propulsion system propellant vessels.

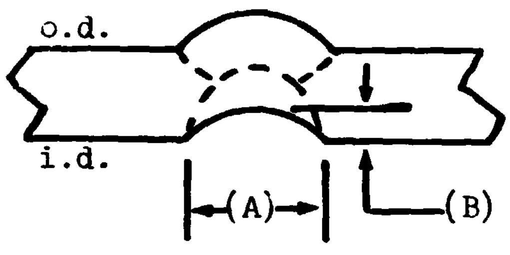
Tank material — 6Al-4V titanium alloy
Filler wire — commercially pure titanium
Weld process — tig automatic

Dimensional requirements

Tank	Repair	(A)	(B)
SM/SPS	o.d. or i.d.	0.225 Max	0.015 0.030
LM/descent	o.d.	0.190 0.200	0.040 0.050
LM/descent	i.d.	0.200 0.210	0.040 0.050

Method 1 repair:

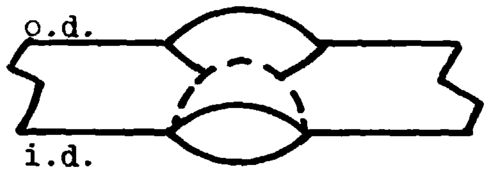
A. 360° fusion pass, o.d. or i.d.
B. Two repairs allowed per weld



MACHINE ROUT

Method 2 repair:

A. 360° machine rout, o.d. or i.d.
B. Verify defect removal (X-ray)
C. Local hand rout, if required:
   (1) 0.015 in. depth max.
   (2) 12 in. max. total rout length
   (3) 4 in. max. single rout length
   (4) 4 in. min. space between routs
D. 360° fusion pass
E. 360° filler pass
F. One repair allowed per weld

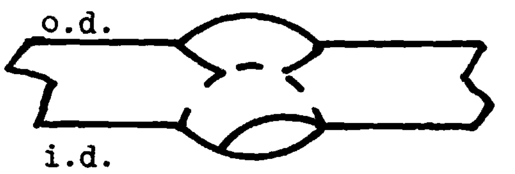


Completed method 2 repair

Method 2A repair:

A. Local rout to remove defect(s):
   (1) 1.5 in. max. rout length
   (2) Depth and width same as method 2
   (3) Two local routs per weld (max.)

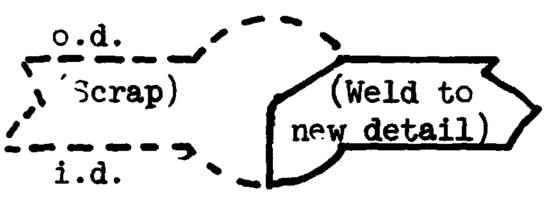
B. Add filler to rout areas
C. 360° fusion pass
D. One repair allowed per weld



Completed method 2A repair

Method 3 repair:

A. Machine off defective tank detail to original joint location and dimension
B. Weld on new detail as normal weld



NOTE: Completed repair weld dimensions (max.) same as normal weld (see fig. 1).

Figure 4.- Weld repair procedure for Apollo SM/SPS and LM/descent vessels.

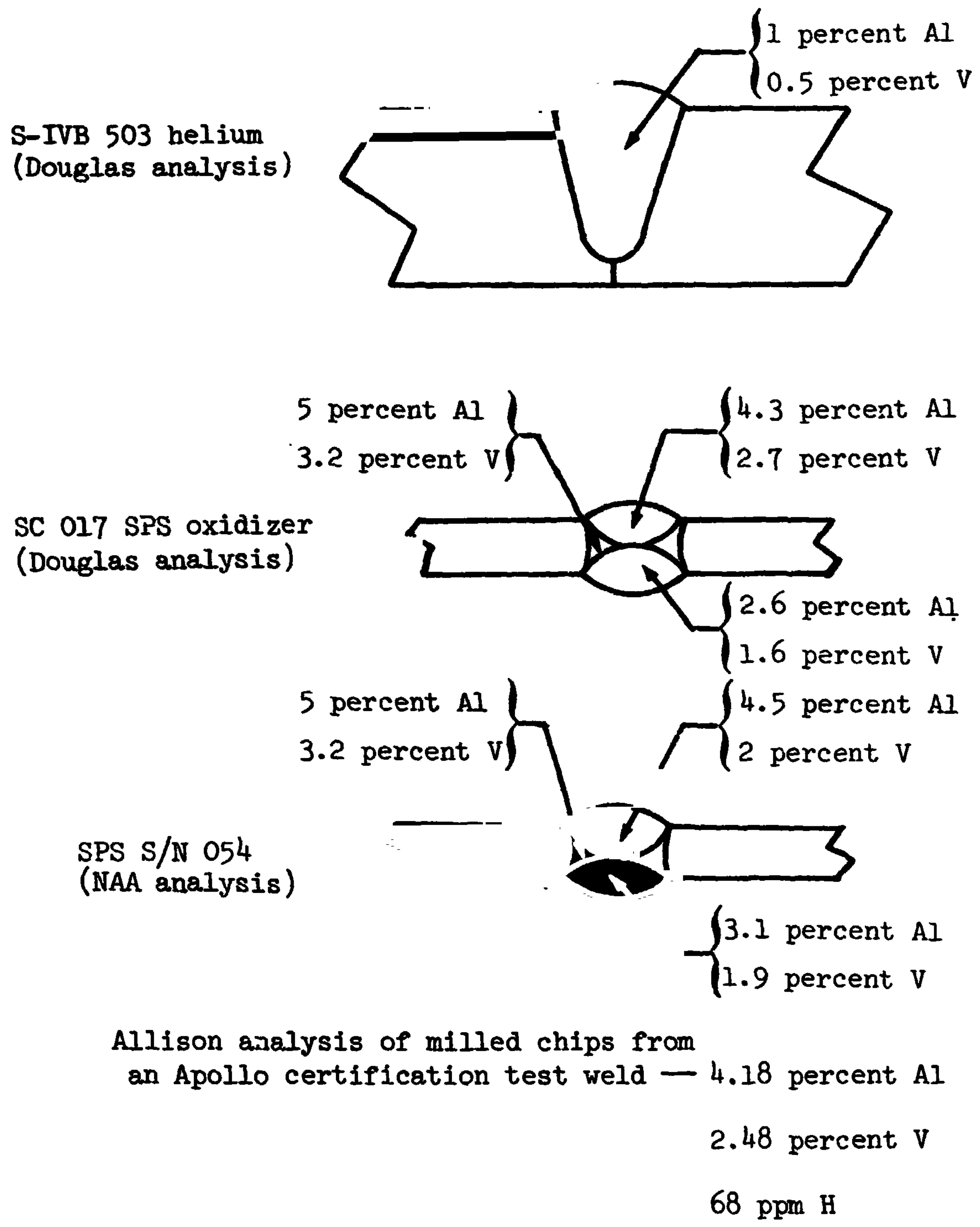


Figure 5.- Comparative chemical analyses of Apollo and Saturn welds.

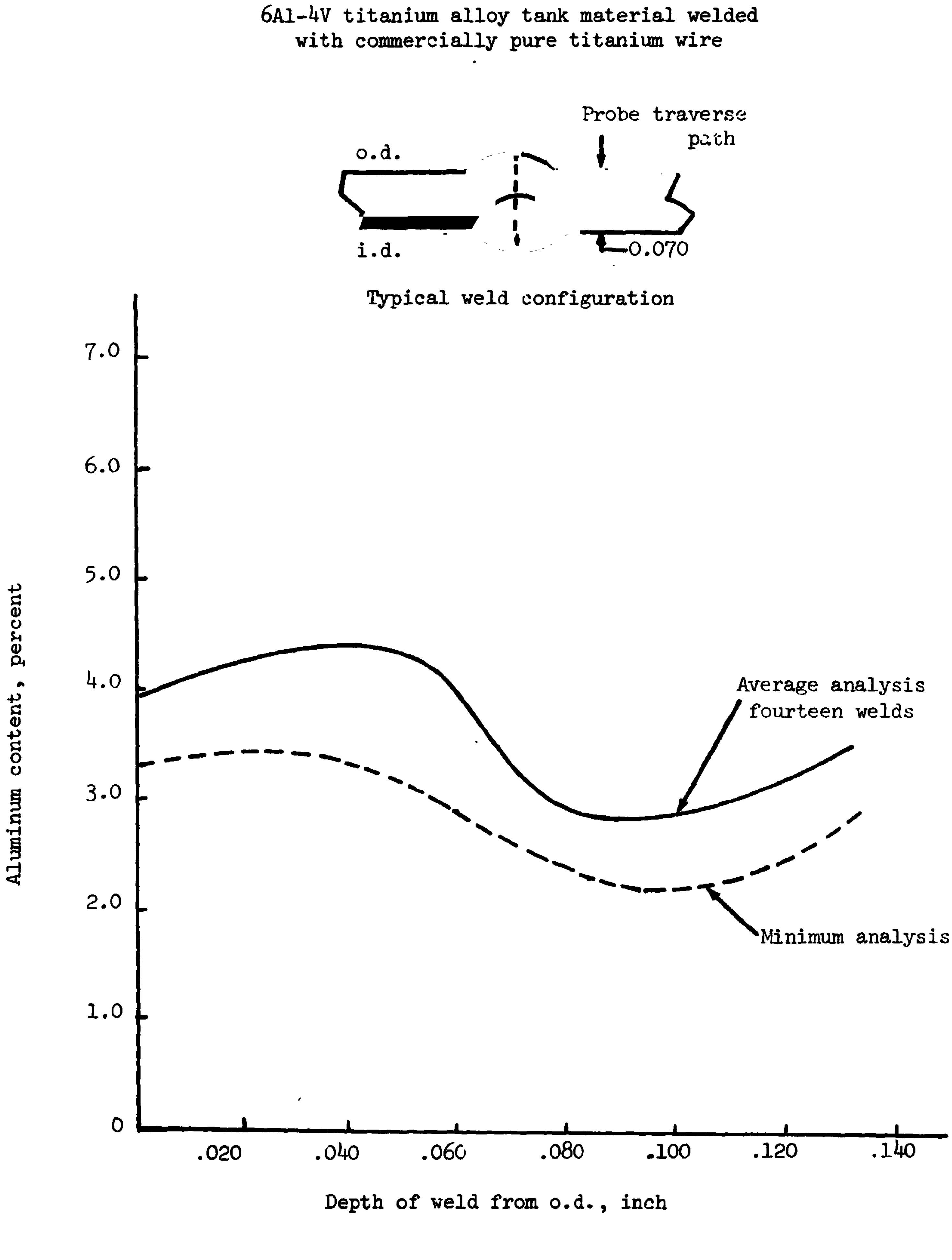


Figure 6.- Aluminum content of Apollo SM/SPS propellant vessel welds.

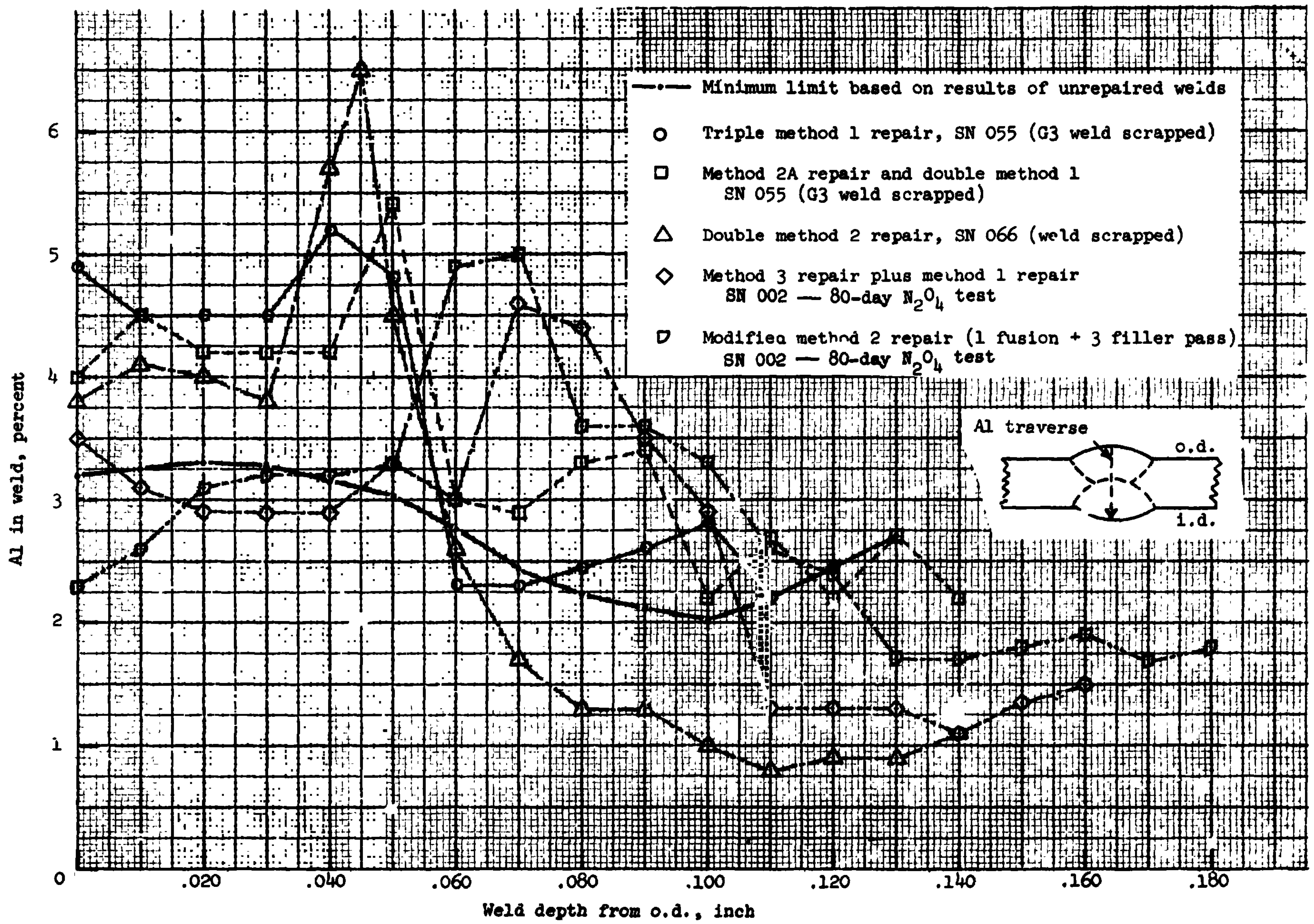


Figure 7.- Comparison of aluminum analysis in unrepaired and worst case repaired welds of SM/SPS propellant vessels.

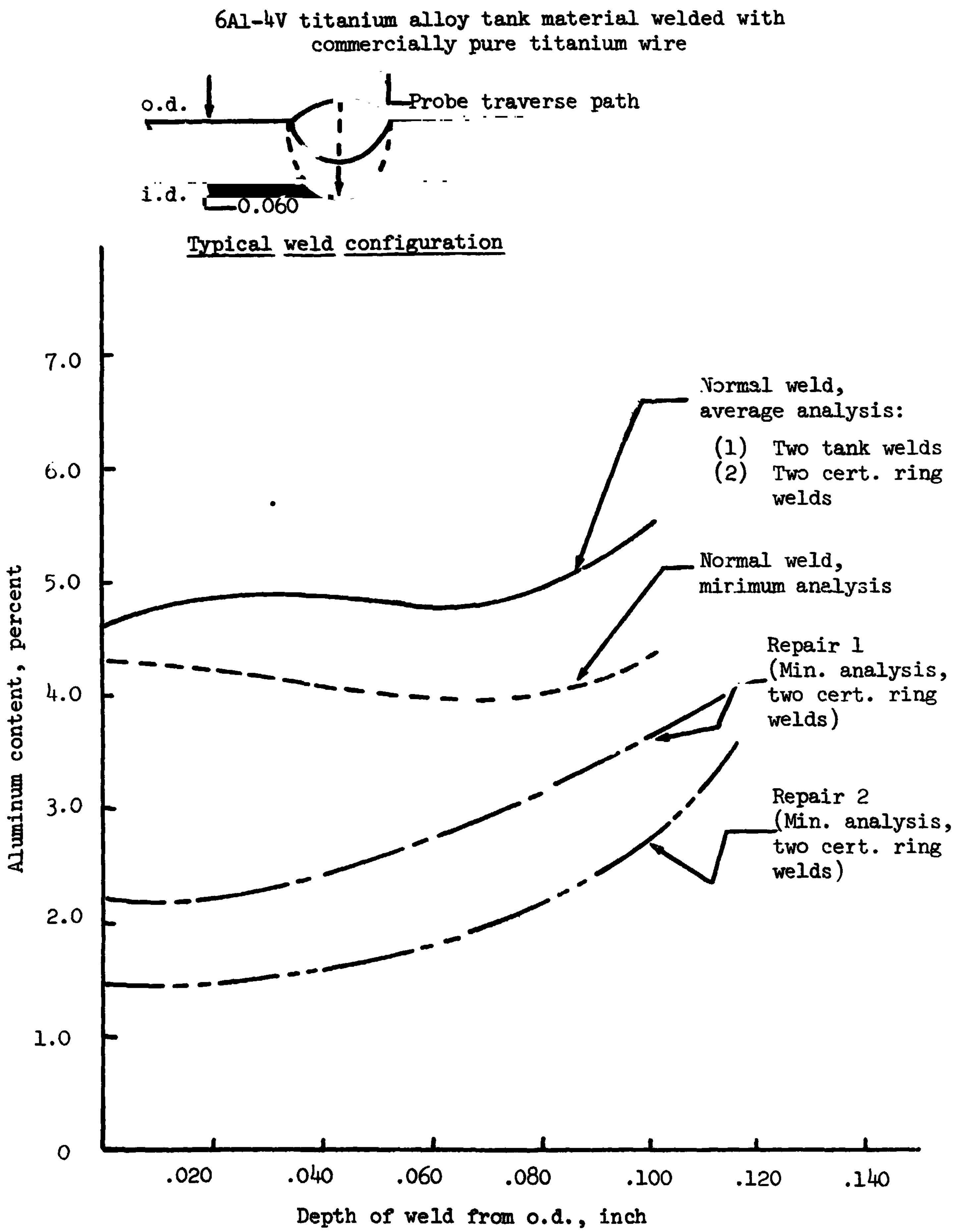


Figure 8.- Aluminum content of Apollo LM/ascent propellant vessel welds.

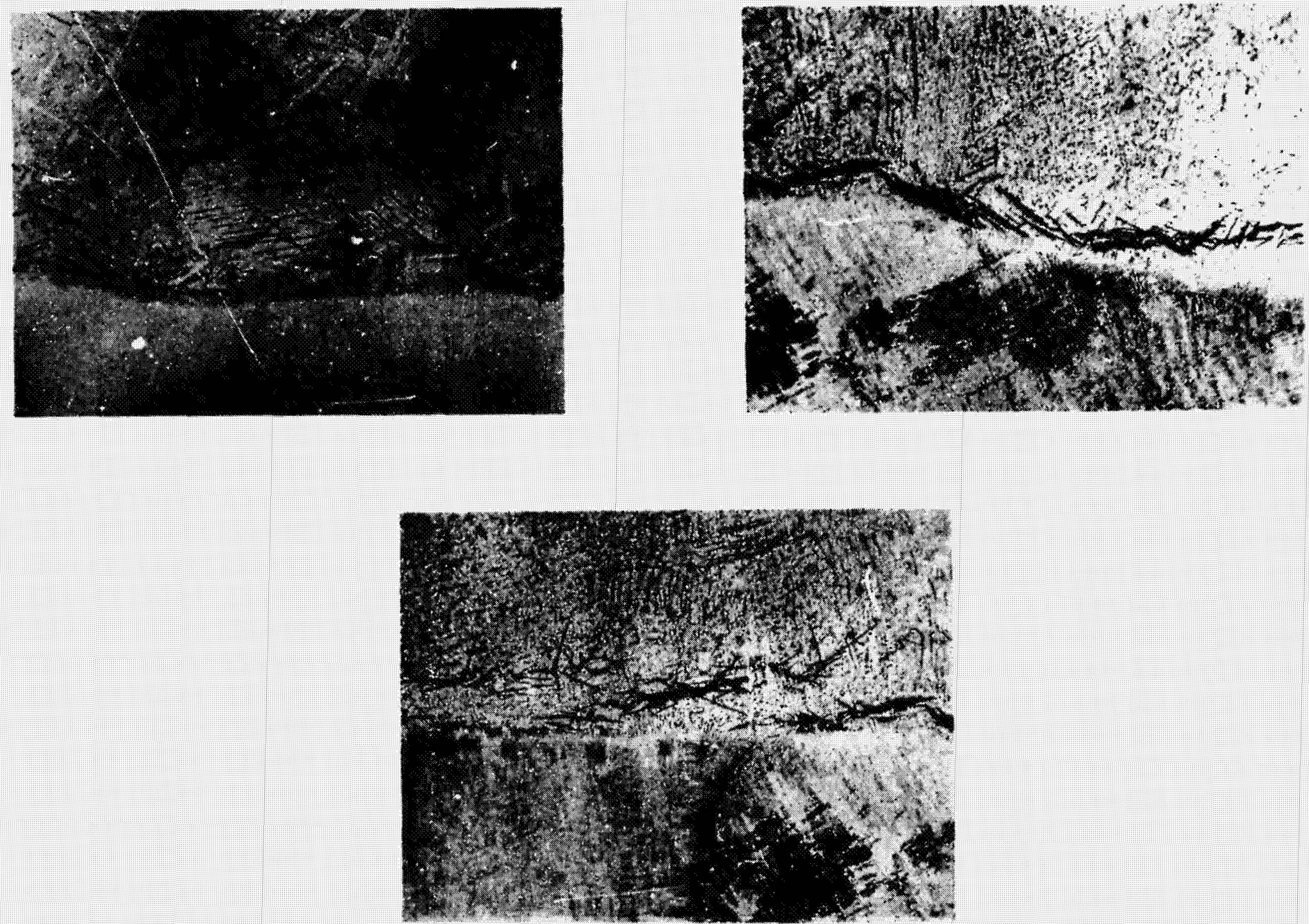
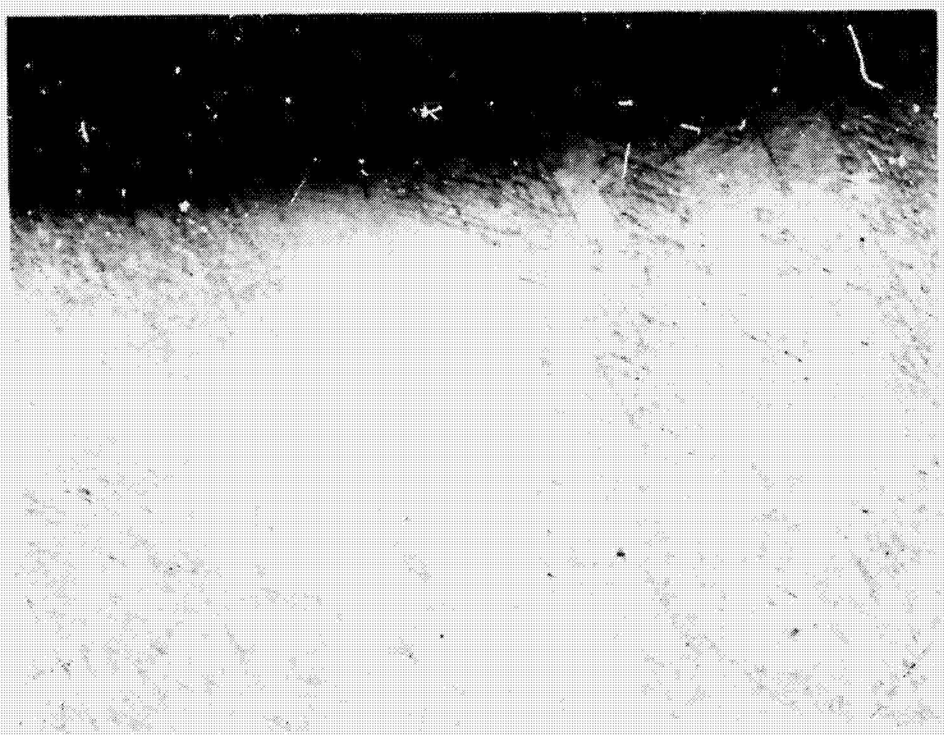


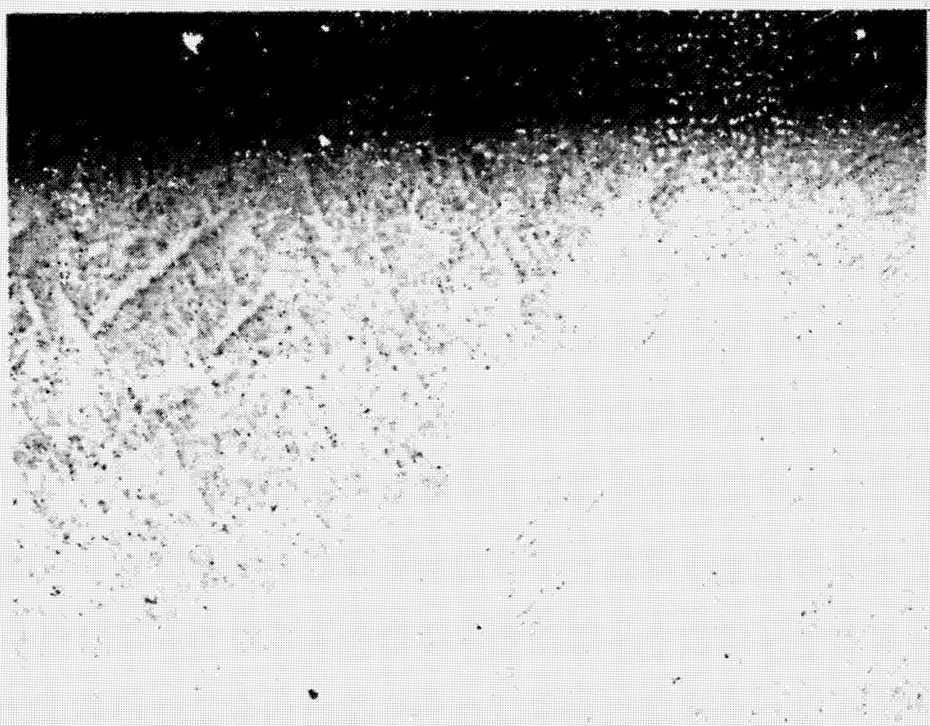
Figure 9.- Photomicrographs of Saturn weld (fragment 888) showing titanium hydride bands (X100). Weld metal — parent metal fusion line.



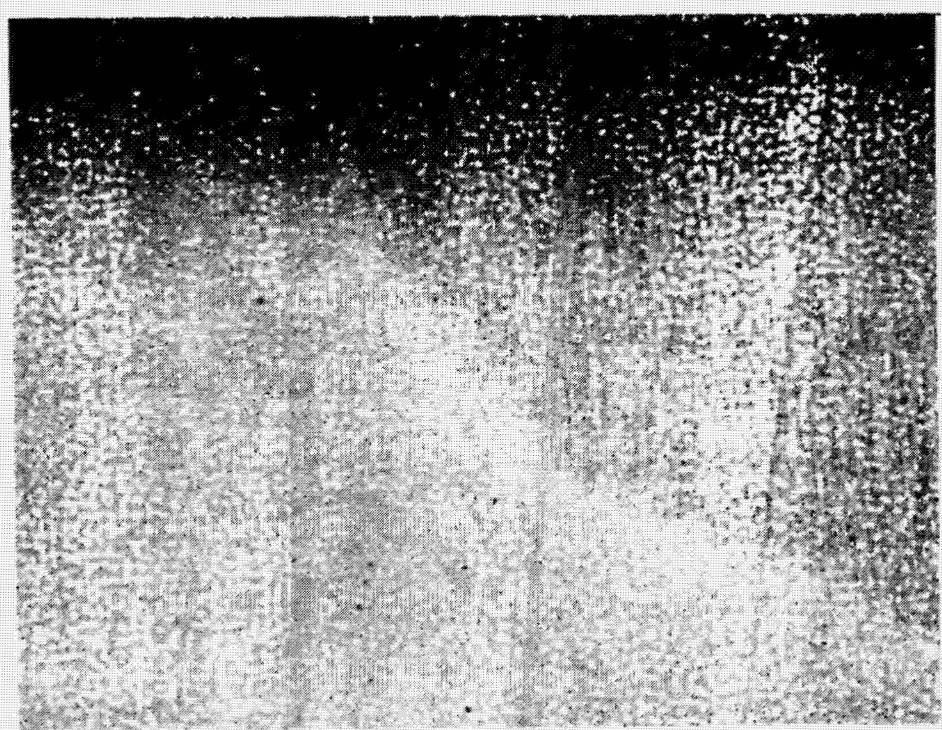
(a) SC 101 (fuel tank) G3 weld bottom (X150).

(b) SC 101 (fuel tank) G2 weld middle (X150).

Figure 10.- Photomicrographs of typical Apollo welds made with CP weld wire. Weld metal — parent metal fusion line.

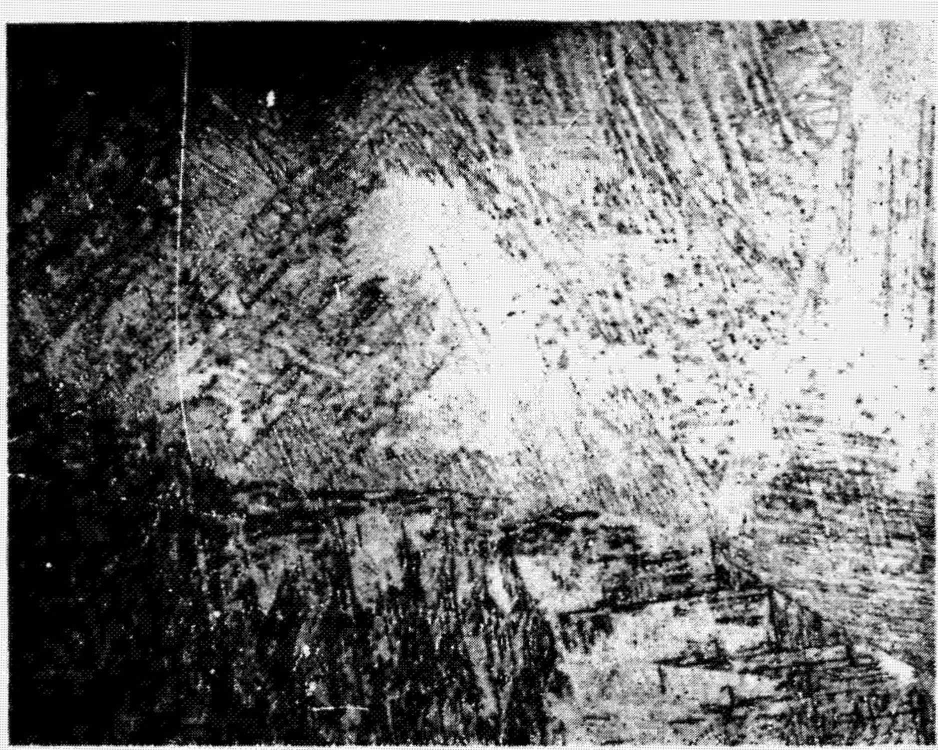


(c) SC 101 (fuel tank) G1 weld top (X150).



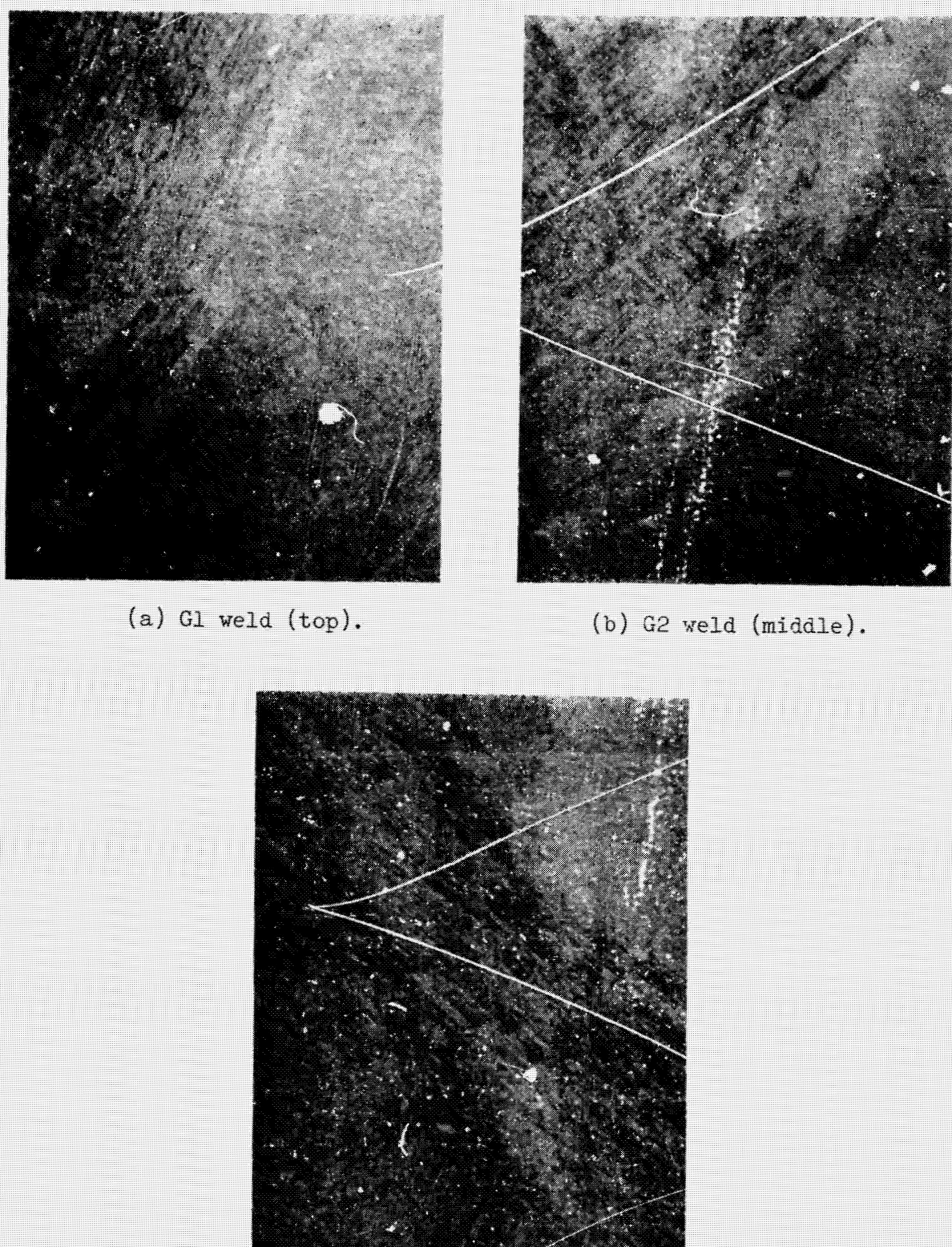
(d) SC 017 (oxidizer tank) weld bottom (X150).

Figure 10.- Continued.



(e) SC 017 (oxidizer tank) G2 weld middle (X150).

Figure 10.- Concluded.

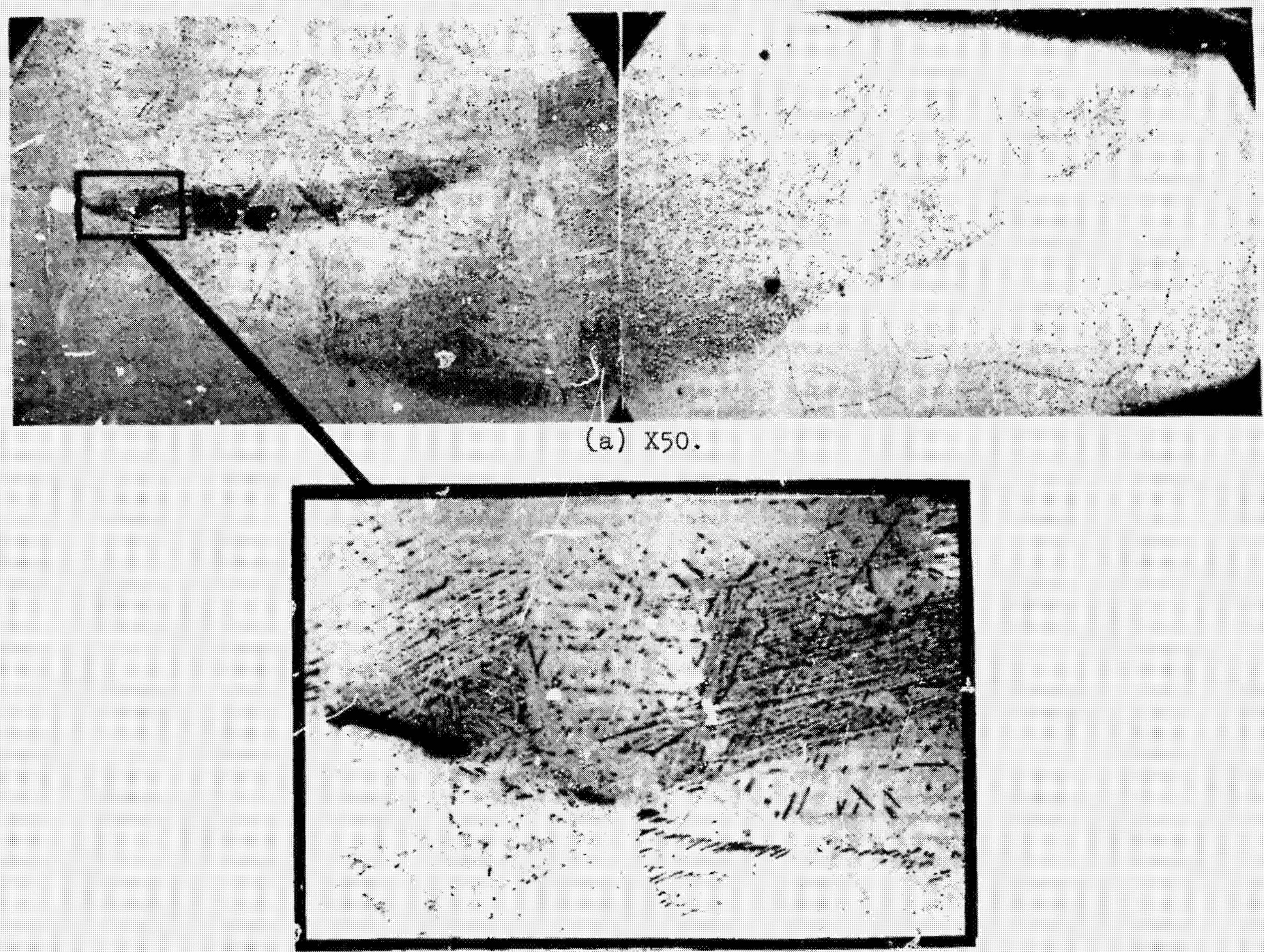


(a) G1 weld (top).

(b) G2 weld (middle).

(c) G3 weld (bottom).

Figure 11.- Photomicrographs of welds from SC 017 fuel tank S/N 023 (X150). Weld metal — parent metal fusion line.



(a) X50.

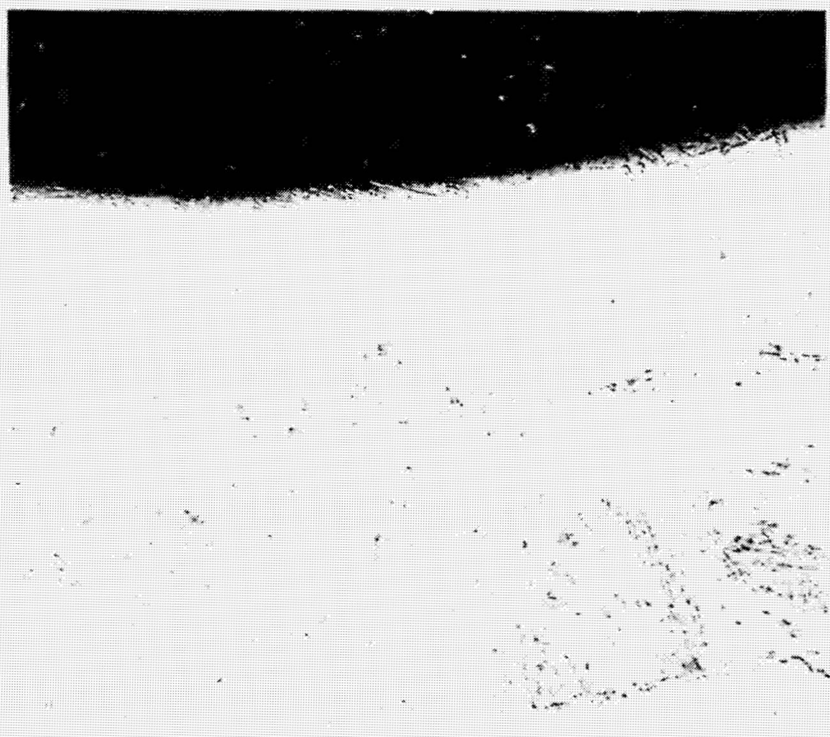
(b) X200.

Figure 12.- Photomicrographs of an Apollo double method 2 weld repair, tank S/N 066.

NOTE: The weld repair is contaminated by a known hydrogen atmosphere.

Figure 13.- Photomicrographs showing hydride agglomeration at a fusion line in an Apollo weld (X250).

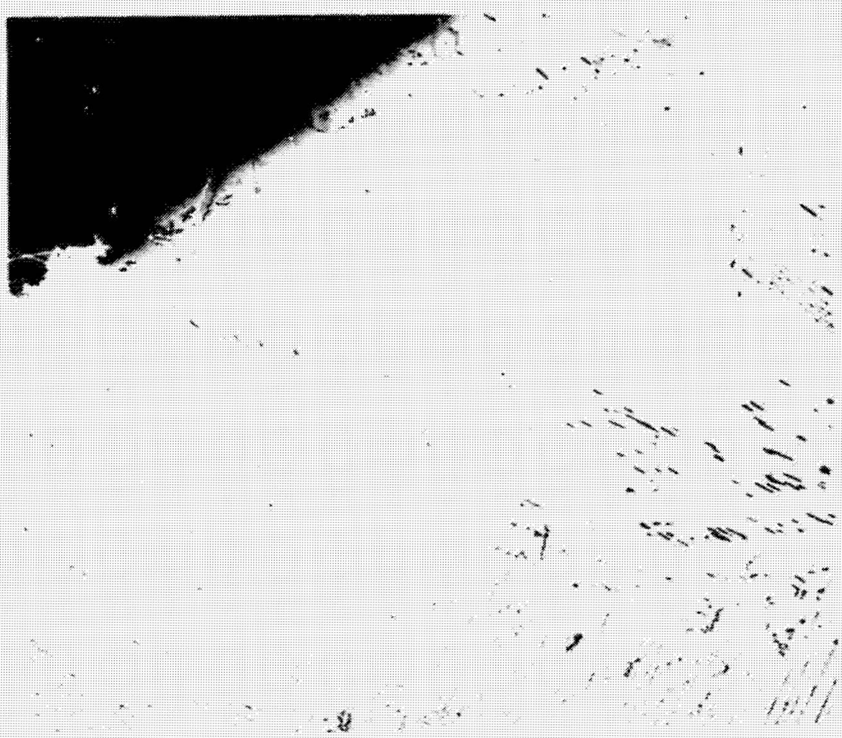
Figure 14.- Photomicrograph of an Apollo weld hydrogenated by electrochemical action (X150).



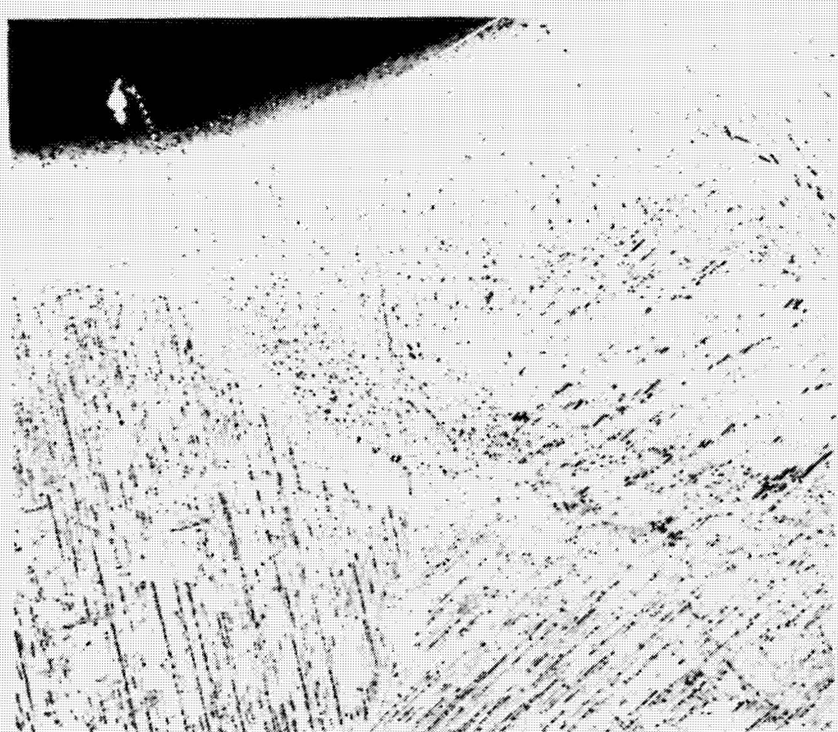
(a) G1 weld (no repair).

(b) G2 weld (no repair).

Figure 15.- Photomicrographs of Apollo vessel welds taken from a vessel pressurized for 80 days. Weld metal — parent metal fusion line (X150).

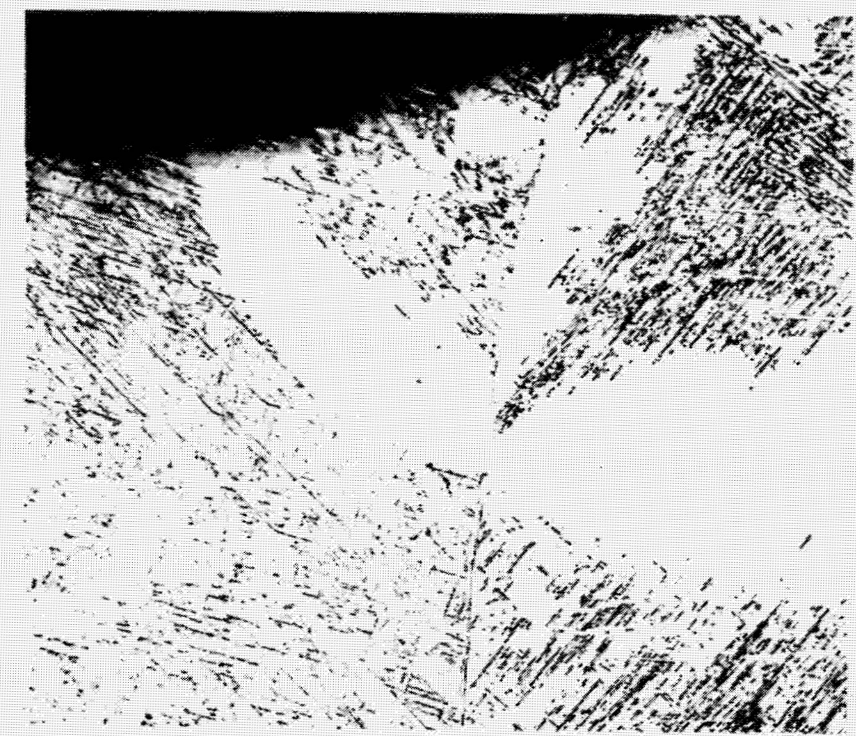


(c) G3 weld (method 3 plus method 1 repair).



(d) G4 weld (no repair).

Figure 15.- Continued.



(e) G5 weld (method 2 repair plus two filler passes).

Figure 15.- Concluded.