BOEING

# STUDY OF
# WELDING DEFECTS
# SATURN JOINT CONFIGURATION
# FINAL REPORT

Contract NAS8-24512

D2-107012-3

THE BOEING COMPANY

AEROSPACE GROUP

Prepared by Nad M. Lowry
Nad M. Lowry

Approved by W. Evan Strohelt
W. Evan Strohelt

Approved by
Charles Johnson

CONTENTS

LIST OF FIGURES

## 1. SUMMARY

The objectives of this program were to quantitatively define porosity and weld quality resulting from variations in joint and torch configurations. These objectives were met with the conclusion that mechanical joint defects do not cause porosity in aluminum welds. This conclusion is supported by the experimental evidence that joint defects do not cause contamination from the atmosphere under normal conditions and that the components of air do not cause porosity when taken collectively.

Since this conclusion was reached early in the program the objectives were modified to include the weld joint conditions which are the suspect cause of weld porosity observed in the production of the Saturn Booster. The conclusions drawn from the experimental evidence presented here is that surface contamination resulting from normal handling is the most likely source of porosity with lower probability of contamination from tack welds and adsorption of atmospheric water. These conclusions are supported by the correlation observed between porosity and the level of hydrogen containing surface contamination produced by various shop operations.

The results of this program demonstrate that water does not cause porosity when its source is atmospheric because of the interaction with oxygen. This program does show that handling with clean gloves produces sufficient surface contamination to cause porosity.

The experience gained in this study can be applied to significantly improve weld quality and costs. The profile data show that the Linde HW-27 torch provides good shielding at moderate flow rates while the HW-13 torch does not provide reliable coverage at higher flow rates and longer torch to work distances. The HW-27 torch can be used with a helium flow rate of ca. 0.63 standard liters per second (80 SCFH) instead of the usual 0.98 standard liters per second (125SCFH). An additional 20 to 30% flow reduction is possible with modest reduction in cup to work distance. Techniques in handling could be modified to prevent touching the faying surfaces with even gloved hands, since this was found to be the largest source of contamination. Careful use of non-hydrocarbon solvent such as "Freon" 113 ($C_2 Cl_3 F_3$) can prevent porosity by removing contamination resulting from careless handling.

## 2. BACKGROUND

It has been clearly demonstrated by a great many investigators that hydrogen, in one form or another, is the cause of porosity in aluminum welds. The solubility of hydrogen in liquid aluminum changes rapidly with temperature. If hydrogen dissolves in aluminum at temperatures much above the melting point, then it may precipitate out in the form of bubbles or pores as the metal is cooled and solidified.

How does hydrogen content reach such a high level to cause porosity? The answer to this question is not well understood and has been the object of many study programs. There are primarily three sources of hydrogen: within the metal (base metal and weld wire) on the surface of the metal and from the atmosphere. Martin et. al. (1, 2) examined porosity as a function of chemical composition within the range of certain commercial alloys and concluded that the effect of variations in composition and internal hydrogen content of the materials upon weld porosity is slight. Earlier reports by Martin (4, 5), however, state that increasing hydrogen content was related to increasing weld porosity and a level of 1.8 ppm by weight caused a high level of porosity overshadowing other composition effects. Other studies (3) show that, over a wide range of composition, increasing concentration of magnesium or calcium increases the tendency toward porosity formation. Although these studies lend a great deal of insight, it is clear that much more work is necessary to determine the role of base metal composition, particularly hydrogen.

Since it seems that base metal composition plays a minor role in porosity formation, hydrogen must enter the metal from the atmosphere or surface during the welding process. The detailed mechanism of hydrogen pickup during the welding process has not been defined but many studies have shed light on the problem. Considerable experimental evidence indicates that surface hydrogen in various forms is the largest single uncontrolled factor (4, 5). Surface hydrogen may be present in many forms: adsorbed and chemically bound water, oil residue from machining processes, organic dust and other airborne material, organic material from finger prints, and so on.

Hydrogen may enter the weld metal from the atmosphere. The control of the atmosphere is considerably easier than any other source of hydrogen and thus much experimental evidence has been accumulated (4, 5). Saperstein (7) measured porosity as a function of water content of shielding gas and found that porosity increased when the dew point of the gas was above -40°C. Measurements made by Strobelt (6) showed porosity increased with either increasing hydrogen or water content of the shielding gas. Both of these studies indicated that oxygen and perhaps nitrogen reduced porosity caused by hydrogen, but this idea was not specifically investigated.

Thus, it would seem that a great deal is known about porosity but also a great deal is still unknown. NASA is sponsoring many research programs aimed at pinning down the variables of aluminum welding. Part of these programs are directed toward prevention of porosity. The work just mentioned is concerned with chemical influences but other work indicates that much can be done to influence porosity while hydrogen levels are constant. For example, the length of time at which the weld metal is in the liquid state and the rate of change of temperature will affect porosity levels. These studies have been discussed by Hasemyer (8) and show that by control of time at temperature porosity can be controlled.

Unfortunately, it is not always as easy to control the variables when making production welds as it is in the preparation of small scale experimental welds. In production welding non-uniform heat flow paths and physical restraints cause difficulty in controlling temperature-time relationships and result in metal movement and mismatch.

Gott, Clover, and Rudy (9), made an extensive investigation of metal movement and mismatch and the resulting stress build-up. It was shown that careful attention to balance of heat input and removal can reduce mismatch in many cases. However, the problem is not easily solved and, as pointed out by scientists at Marshall Space Flight Center (8, 4), it seems that some degree of mismatch will be encountered.

During fabrication of hardware for space projects NASA has encountered many of these problems and consequently funded a series of welding research programs of which this is one. The specific problem prompting this investigation is the porosity found in the horizontal weld made when joining two sections of the Saturn Booster. The time required in jigging up the entire part is about eight hours. The two parts are held by Hawthorn clamps positioned every six inches along the joint. Most of the time is spent placing and adjusting these clamps. One side of the joint has been cut away to provide room for the clamp. This cut was at first a slot but then altered by tapering the edges to prevent entrapment of contamination. When the clamps are adjusted to reduce the misfit to a minimum, a tack weld is made between each clamp one after the other as the clamps are removed. After all the clamps have been removed, the joint is welded in one continuous pass, if possible, covering all the tacks and the gaps left by the clamp slots. The resulting weld showed considerable porosity, some of which appears to be associated with the clamp slot location.

Tests welds made at NASA did not produce porosity when the same materials were used. These test welds were prepared in the same way with the exception of clamp slots, tack welds, misfit, and the lengthy handling and metal-to-metal rubbing at the joint. Thus the conclusion was reached that clamp slots, tacks, joint misfit and metal movement contribute to the observed porosity.

## 3. EXPERIMENTAL DETAILS

### Operating Thesis

If porosity is to result from joint defects, then these defects must produce perturbations of the gas shield of such a magnitude that air---carrying contaminations---can enter the critical arc zone. Then such perturbations can be readily detected mass spectrometrically by sampling a small portion of the shield gas and determining the extent of perturbation. Oxygen was selected as the most reasonable element of air to monitor since it is quite constant while water vapor varies over a wide range.

### Objectives

The objectives of this study were to define the shielding gas profiles of typical production weld torches, determine the degree of contamination introduced into the arc region as a result of joint defects, and then to correlate these with weld porosity.

### Contamination Profiles

In order to measure contamination in the shield gas a special probe was designed which could continuously sample a very small portion of the gas and deliver it to a mass spectrometer for analysis. The probe was made by silver soldering a 0.025 mm. (1 mil) stainless steel capillary with 0.15 mm. (6 mils) outside diameter into the end of a 0.79 mm (1/32") stainless steel tube. The tube was connected to a mass spectrometer as shown in Figure 1. The probe was affixed to the weld torch by means of a motor driven clamp. The probe tip and mount are shown in Figure 2. The motor used was a syncronous type geared down so that the probe travel was 1 cm./min. This drive speed provided a position resolution of 0.025 cm. since the response time was about one second (the time required for the gas to pass through the probe and into the mass spectrometer).

The mass spectrometer used for this report was a Veeco Model RG-4 residual gas analyzer. Calibration of the mass spectrometer was accomplished by passing the helium gas to be analyzed past an electrochemical cell at a known flow rate. Oxygen was generated electrochemically at a platinum electrode from dilute sulfuric acid.

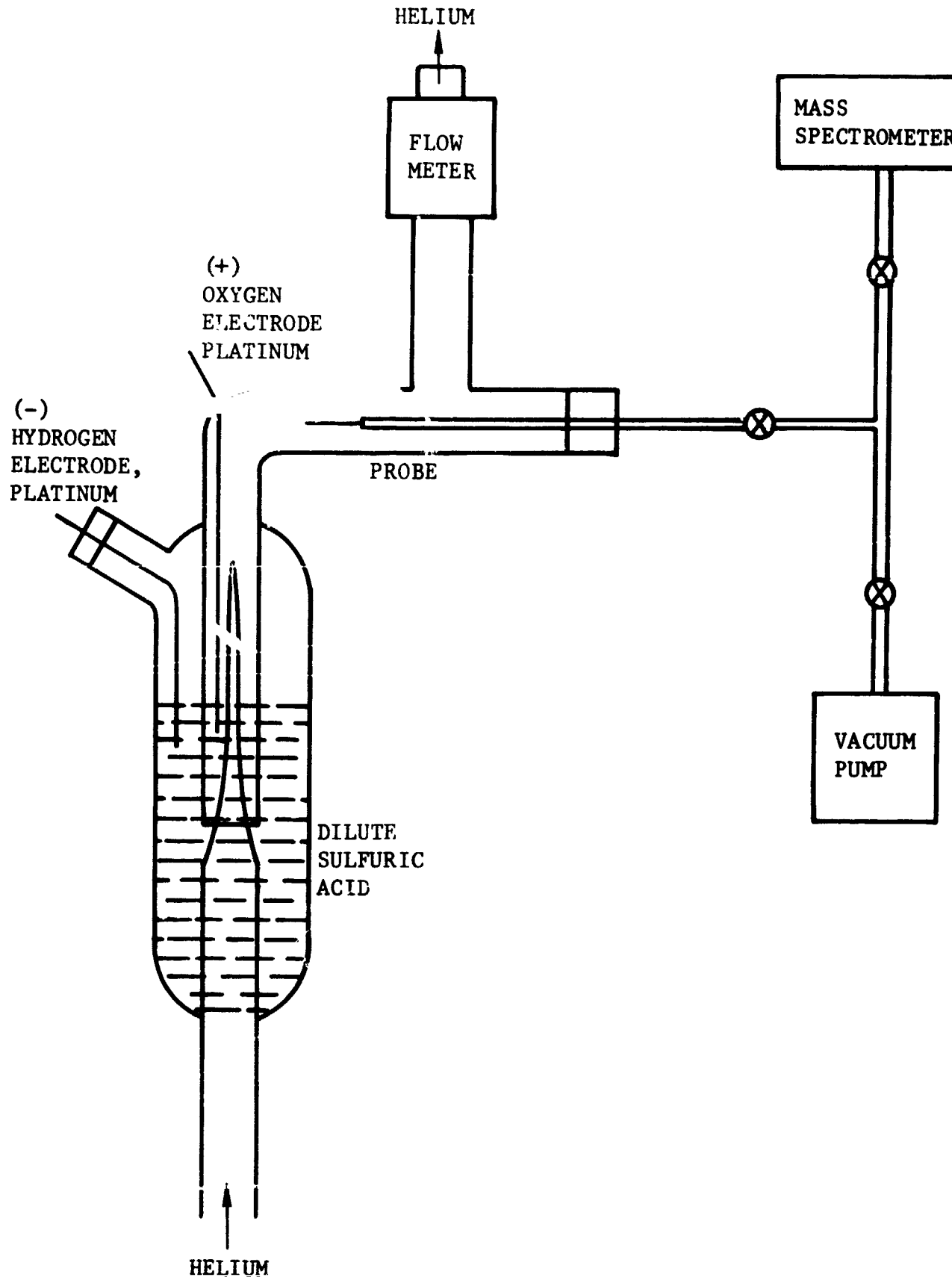
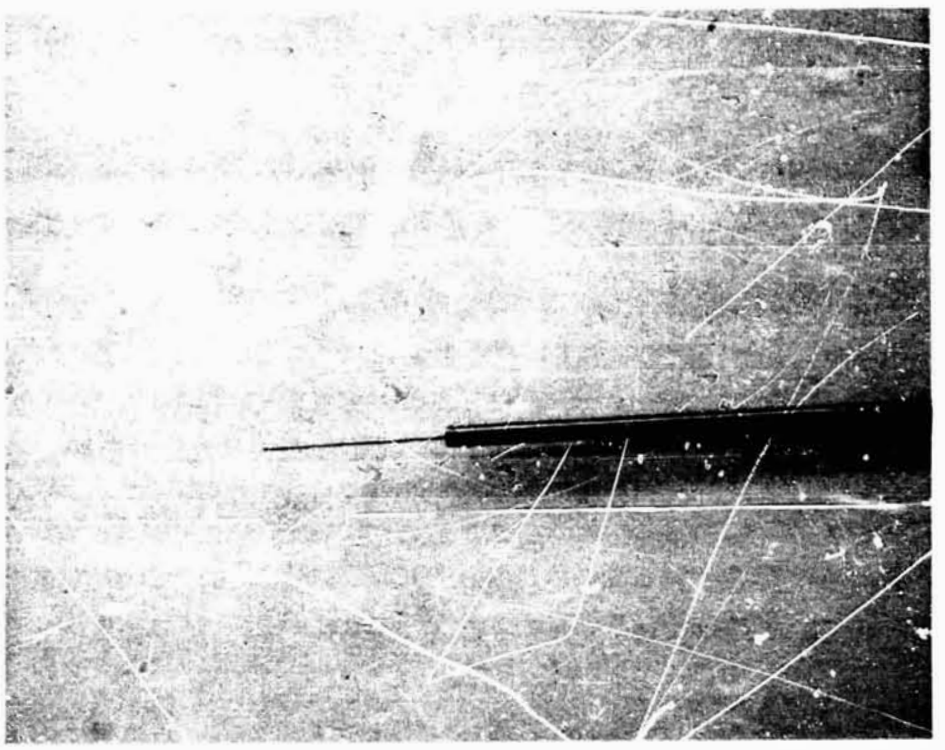
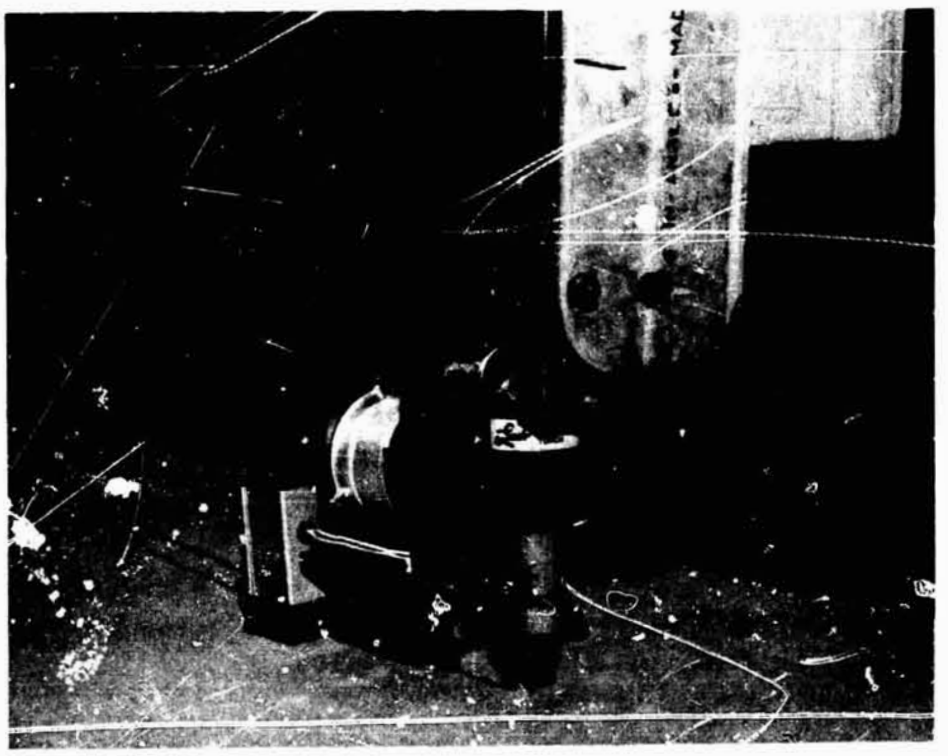



Figure 1: SCHEMATIC OF MASS SPECTROMETER AND CALIBRATION CELL



PHOTOGRAPH OF PROBE TIP
(A)



PHOTOGRAPH OF WELD TORCH, PROBE, AND CONTROL
(B)

Figure 2: MASS SPECTOMETER PROBE AND CONTROL

Under the operating conditions the sensitivity to oxygen in helium was found to be 3.15 ppm/division with an observed noise level of up to 0.3 division or an uncertainty of ca. 2 ppm oxygen.

By means of the motor driven probe it was possible to scan the gas shield and relate composition to position and to reconstruct the contamination profile. The mass spectrometer was set to continuously monitor oxygen. A typical scan is shown in Figure 3. From these scans the distances at which oxygen reached 10, 100, 1000, and 5000 ppm were recorded. Scans were made at several positions (up to twelve per profile) to define the nature of each profile. Four helium flow rates, 0.34, 0.44, 0.57, and 0.68 standard liters per second (43, 56, 72 and 86 standard cubic feet per hour), four torch to work distances 0.6, 1.0, 1.3 and 1.5 cm (1/4, 3/8, 1/2, and 19/32 inch), two torch positions horizontal and vertical, and two torches Linde HW-27 and HW-13 were used to prepare reference profiles. These profiles are reproduced in the appendix.

The oxygen contamination levels may be converted to water contamination levels but these depend upon temperature and humidity. Each oxygen contour can be converted to a water contour by multiplying by the ratio of the partial pressure of water to the partial pressure of oxygen.

At 100% relative humidity the partial pressure of water, $P(H_2O)$ is equal to the vapor pressure of water and can be found in standard handbooks. At 50% R.H. $P(H_2O)$ is one-half the vapor pressure, et cetera. At one atmosphere pressure, dry air contains 20.95% oxygen by volume, therefore the partial pressure of oxygen, $P(O_2)$, is

$$P(O_2) = 0.2095 \left[ 760 - P(H_2O) \right]$$

The ratio $P(H_2O)/P(O_2)$ is given in Table 1 for various temperatures and humidity levels that may be encountered in a production area.

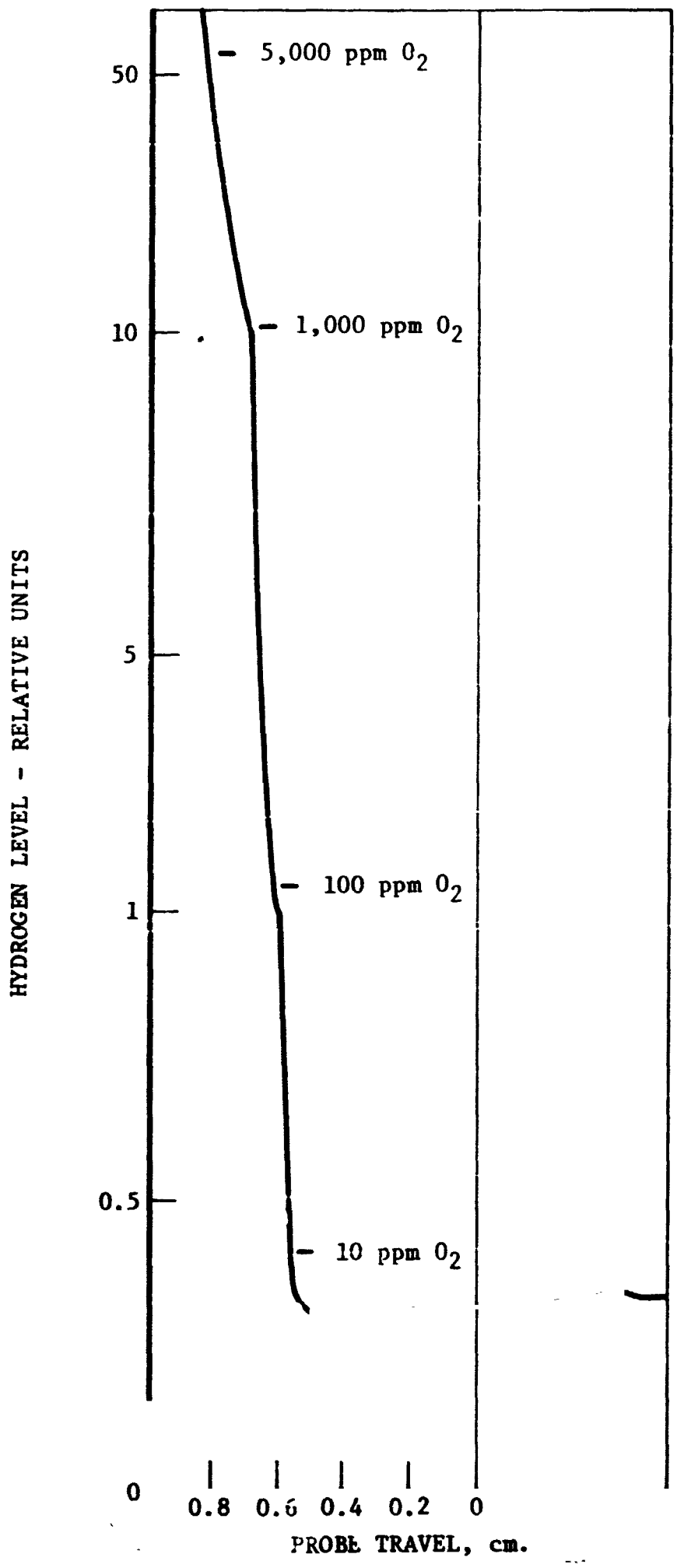



Figure 3: TYPICAL SCAN FOR GAS PROFILE

TABLE 1

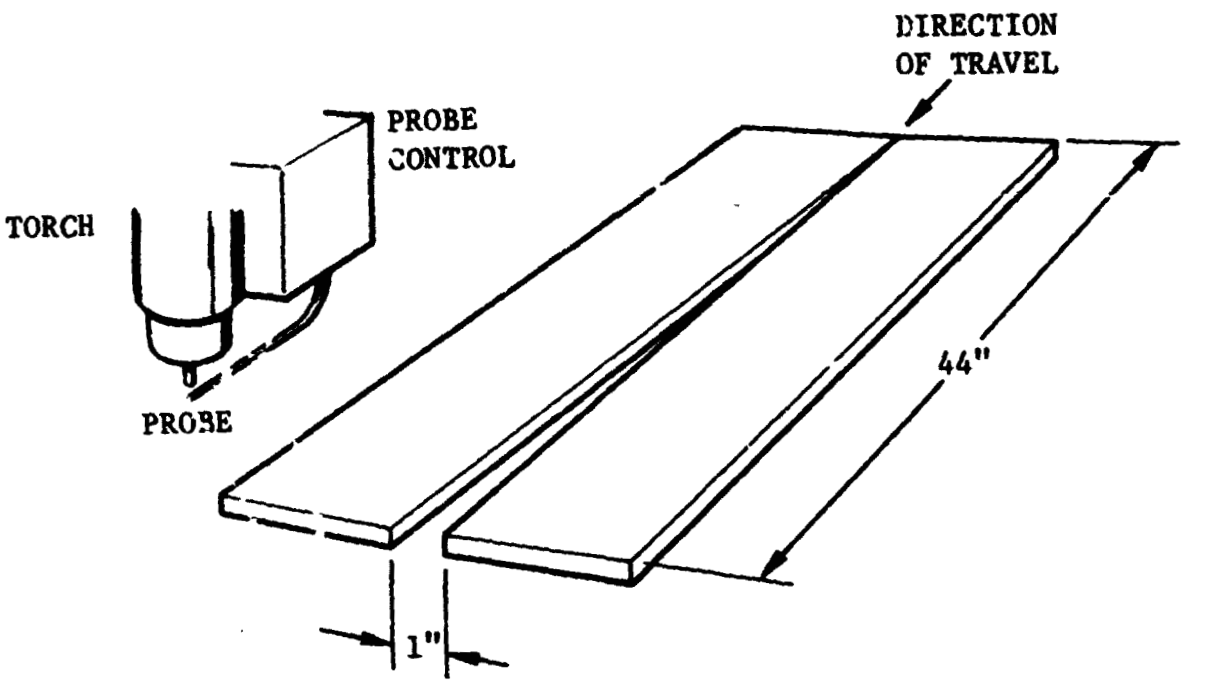
| Temperature | | $P(H_2O)/P(O_2)$ | |
|---|---|---|---|
| °C | °F | 50% R.H. | 100% R.H. |
| 20 | 68 | .056 | .112 |
| 25 | 77 | .076 | .154 |
| 30 | 86 | .102 | .209 |
| 35 | 95 | .136 | .280 |

These data indicate that a ratio of 0.1 to 0.2 covers the range encountered in most shop environments. If we assume a value of 250 ppm water in the gas shield is necessary to produce significant porosity (6), then it is necessary to introduce a contamination level of something greater than 1000 ppm oxygen from shop air. This represents a rather large contamination level and therefore should be easy to detect.

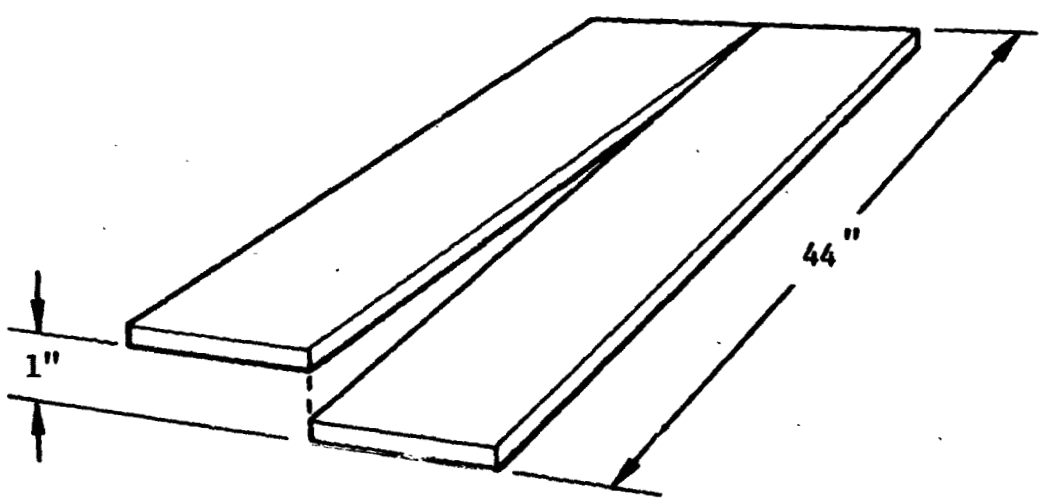
Joint Defects

In order to determine the influence of joint defects on contamination profiles a few key experiments were set-up. These experiments were designed to indicate the minimum size defect that results in contamination in the critical arc zone. Gaps were selected for the first experiment. Flow rates were selected which represent minimum coverage and thus the easiest to perturb.

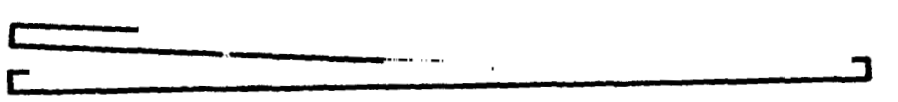
The following experiment was conducted: The mass spectrometer probe was set directly below the electrode tip at the surface of the aluminum panel. The joint was adjusted so that a gap of 2.54 cm (one inch) existed at one end and no gap at the other end. The joint was made up from two pieces of 0.63 cm (0.25 inch) by 1.118 m (44 inches) long. The weld torch was moved along the joint starting at zero gap at various speeds. (See Figure 4.) The gap size at which the contamination level changed was recorded and is listed in Table 2.




GAPS




MISFITS



SIDE VIEW

Figure 4: GAPS AND MISFITS

TABLE 2

Gap Size Necessary to Cause
Contamination Changes in Gas Shield

o Torch: Linde, HW-13

| Position | Flat | | | | | |
|---|---|---|---|---|---|---|
| Helium Flow Rate | 0.44 1/s | | | 0.57 1/s | | |
| Torch Travel Rate cm/min | 29.5 | 51.6 | 73.1 | 29.5 | 51.6 | 73.1 |
| Gap Size where contamination level changes (cm) | 1.52 | 1.9 | 1.75 | 2.21 | 2.34 | * |

| Position | Horizontal | | | | | |
|---|---|---|---|---|---|---|
| Helium Flow Rate | 0.44 1/3 | | | 0.57 1/s | | |
| Torch Travel Rate cm/min | 29.5 | 51.6 | 73.1 | 29.5 | 51.6 | 73.1 |
| Gap Size where contamination level changes (cm) | * | * | * | * | * | * |

o Torch: Linde, HW-27

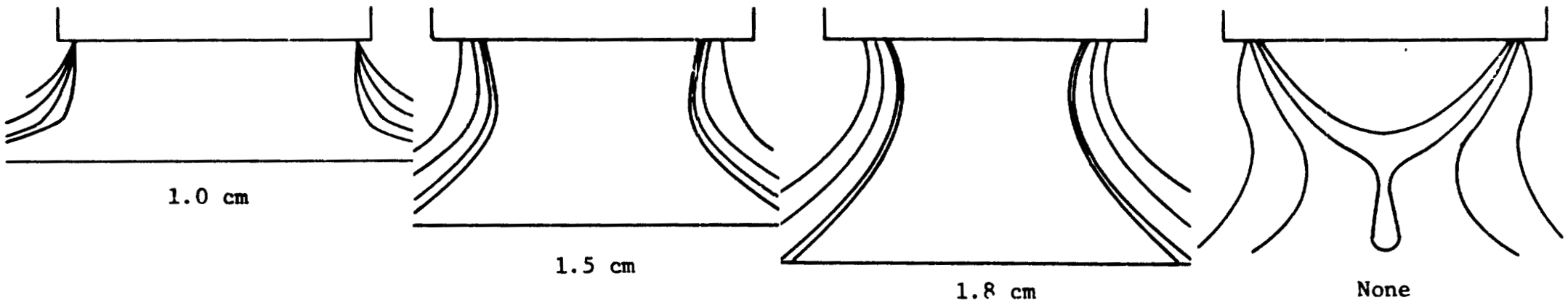
| Position | Horizontal | | | | | |
|---|---|---|---|---|---|---|
| Helium Flow Rate | 0.44 1/3 | | | 0.57 1/s | | |
| Torch Travel | 29.5 | 51.6 | 73.1 | 29.5 | 51.6 | 73.1 |
| Gap Size | * | * | * | * | * | * |

* No change was noted in the contamination level.

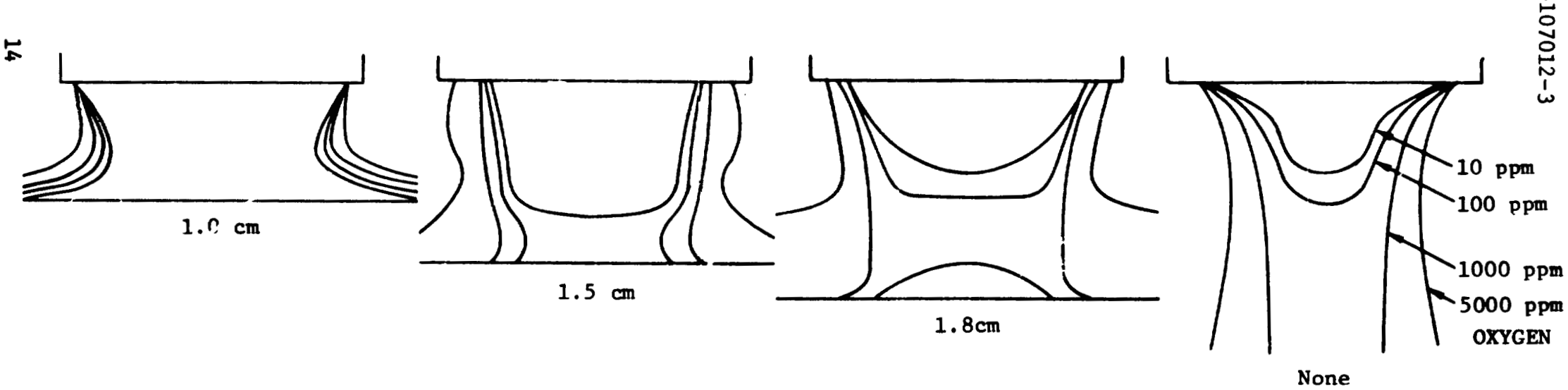
These data indicate that only gaps of very large size allow contamination to enter the critical zone. The gas flow rate was lowered to the point where coverage was just barely adequate and the experiment repeated. With this lower flow rate it was impossible to prevent even the slightest draft from disturbing the gas shield despite extensive shielding. The movement of the torch was enough to cause contamination of the gas shield. The results of these tests may be summed up as follows: If shielding gas flow rate is adequate, gaps do not perturb the contamination profile but if flow rates are reduced to where gaps may cause contamination, then movement of the torch and other slight drafts disturb the shielding gas enough to completely overshadow any effect of the gap. This condition was also found to exist for misfits (Figure 4), i.e., either no change in the profile was found or drafts overshadow the effect. In order to properly interpret these results, it is necessary to compare the contamination profiles for constant gas flow by changing torch to work distances. To supplement the profiles in the appendix it was necessary to determine profiles for the case of no work present. This series is shown in Figure 5. A helium flow rate that is adequate for short torch to work distance becomes inadequate at longer distances. When carried to extreme, the region of zero contamination decreases to a small cone. At the shorter torch to work distances the work forces the shield gas out, thus there is adequate coverage. When a gap is encountered, the profile exhibits a transition to that observed with no work present, when the gap is large enough.

This transition is dependent upon helium flow rate. At a flow rate high enough to provide adequate coverage the transition occurs at a large gap. At lower flow rates the gas shield is unstable with respect to slight air movement and the transition cannot be seen.

These data indicate that joint variations may have very little influence on shielding. Therefore, certain experimental welds are indicated to establish the amount of porosity that would result from maximum atmospheric contamination.




HW-27 TORCH, 0.57 1/SEC (72 SCFH) AT VARIOUS TORCH TO WORK DISTANCES, TWICE ACTUAL SIZE




HW-13 TORCH, 0.68 1/SEC (86 SCFH), AT VARIOUS TORCH TO WIRK DISTANCES, TWICE ACTUAL SIZE

Figure 5: EFFECT OF TORCH TO WORK DISTANCE ON CONTAMINATION PROFILES



D2-107012-3

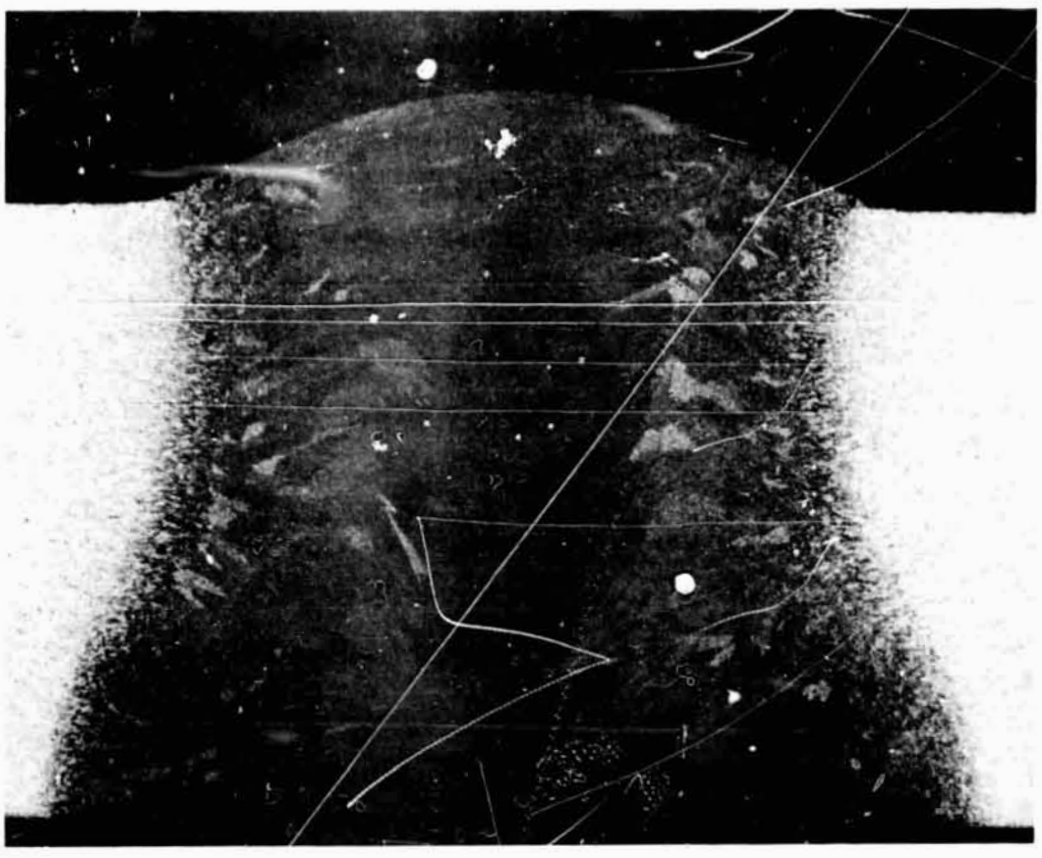
The following welds were made: HW-27 torch, 0.64 cm. (0.25 in.) thick 2014-T6 aluminum alloy, water added was in the form of saturated air, 100% relative humidity.

| JOINT | HELIUM FLOW | WATER ADDED | POROSITY |
|---|---|---|---|
| 1. Bead on Plate | 0.63 1/sec (80 SCFH) | None | None |
| 2. Bead on Plate | 0.63 1/sec (80 SCFH) | 125 ppm | None |
| 3. Bead on Plate | 0.63 1/sec (80 SCFH) | 250 ppm | None |
| 4. Butt Joint | 0.63 1/sec (80 SCFH) | None | None |
| 5. Butt Joint | 0.32 1/sec (40 SCFH) | None* | None |
| 6. Butt Joint | 0.63 1/sec (80 SCFH) | 250 ppm | None |
| 7. Butt Joint | 0.63 1/sec (80 SCFH) | 500 ppm | None |
| 8. Gap 0-.64 cm. (.25 in.) | 0.63 1/sec (80 SCFH) | None | None |
| 9. Gap 0-.64 cm. (.25 in.) | 0.36 1/sec (45 SCFH) | None* | None |
| 10. Misfit 0-.64 (.25 in.) | 0.63 1/sec (80 SCFH) | None | None |
| 11. Misfit 0-.64 (.25 in.) | 0.36 1/sec (45 SCFH) | None* | None |

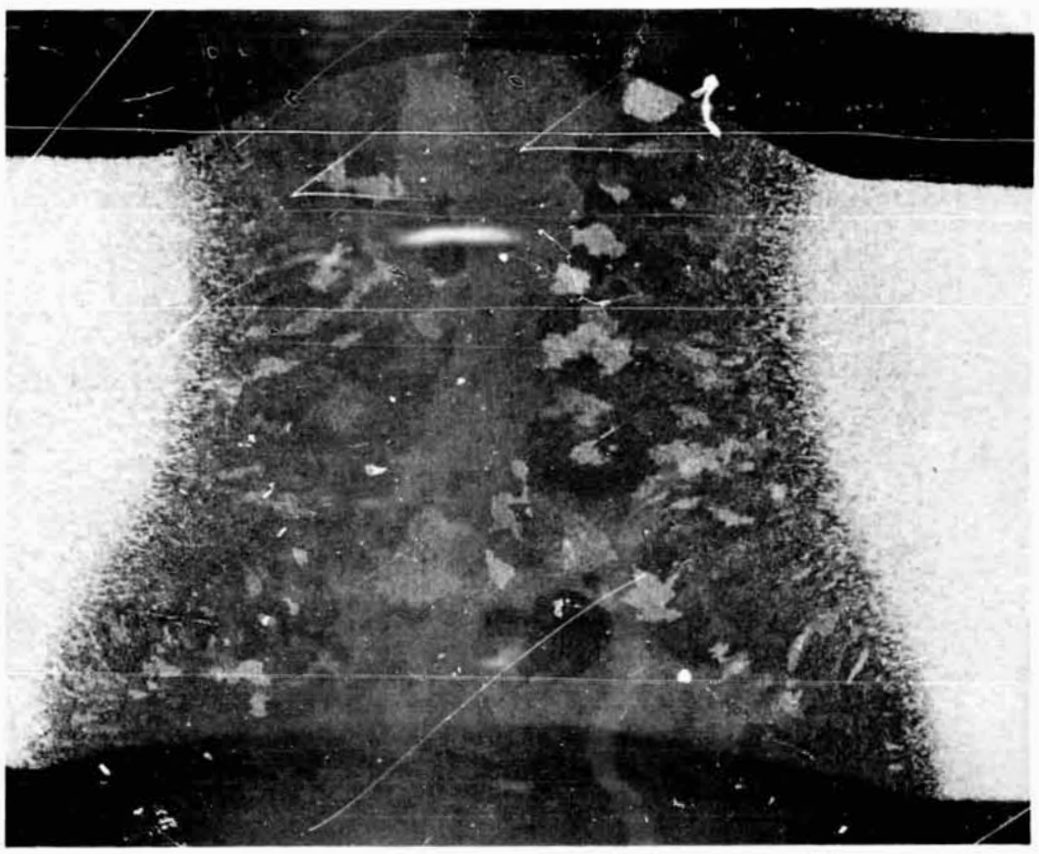
* Profiles indicate considerable atmospheric contamination at this flow rate.

Cross sections of welds 4, 5, 6 and 7, shown in Figures 6 and 7, indicate no change in microporosity. The lack of porosity in those welds where excessive water contamination was introduced is most likely due to the presence of oxygen. This is consistent with observations of other workers (6, 7) and the fact that oxygen is sometimes added to the shielding gas to reduce porosity in aluminum welding.

The data presented so far strongly suggests that mechanical joint defects do not lead to porosity. That is, mechanical joint defects do not easily produce poor shielding and if they could, atmospheric contamination, particularly moist air, cannot enter the arc region in sufficient quantities to produce porosity in aluminum even under the most adverse production conditions.

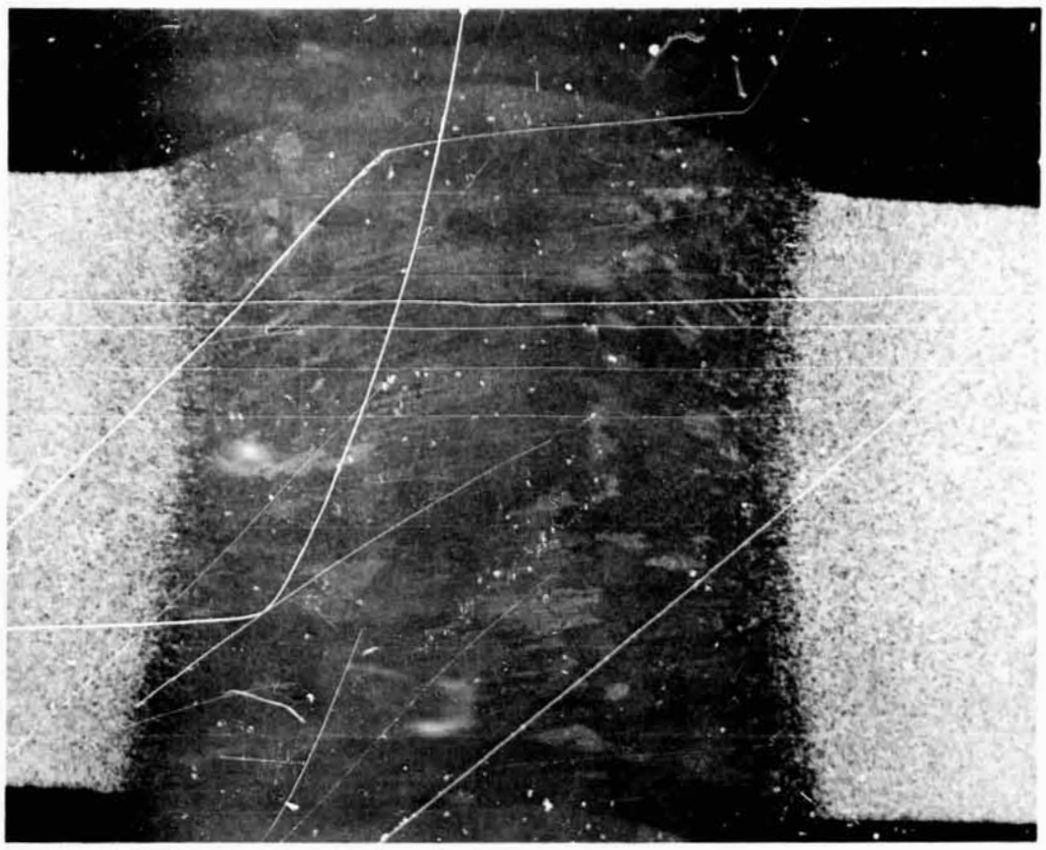


NO. 4

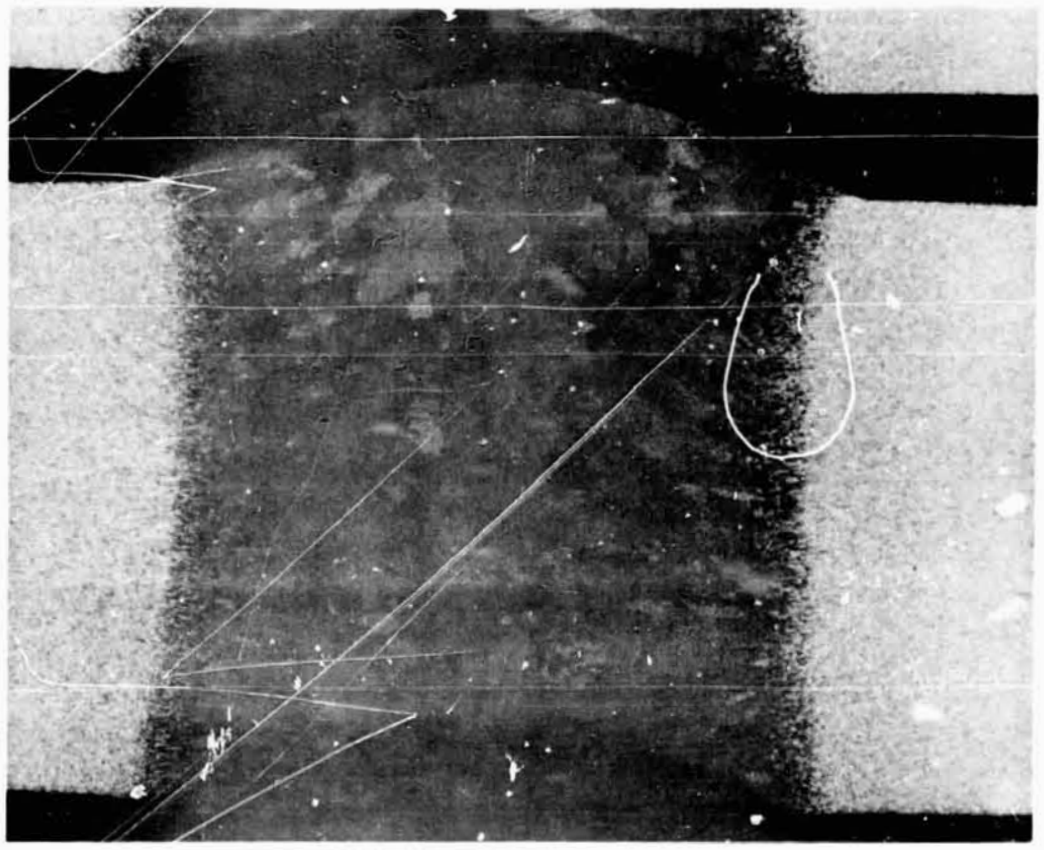


NO. 5

Figure 6: PHOTOMICROGRAPH OF WELDS 4 AND 5



NO. 6



NO. 7

Figure 7: PHOTOMICROGRAPH OF WELDS 6 AND 7

## Other Causes of Porosity

The Saturn booster welds that show porosity include additional variables not yet included in this report. The significant differences between the Saturn welds exhibiting porosity and the test welds are: First, the large amount of handling of the surface in preparing Saturn weldments. Second, tack welds are known to produce surface contamination that can lead to porosity. Third, considerable rubbing and abrading of faying surfaces during set-up.

These conditions result in chemical changes in the surface, changes that could involve hydrogen and, therefore, could produce porosity. Even though white gloves are worn the time period is long enough for severe contamination to occur. Tack welds could result in a porosity forming surface deposit. Whenever two aluminum surfaces are rubbed enough to cause galling, the new metal exposed can react with water present in the air. If sufficient moisture is present, the galled metal can be pockets of high hydrogen concentration and thus lead to porosity during weldings. These considerations led to a series of tests utilizing the measurement of surface hydrogen.

## 4. SURFACE HYDROGEN ANALYSIS

### Description of Experimental Set-up

The surface analysis was carried out using a very sensitive hydrogen detector recently developed by Das and Strobelt (9) under an in-house company-funded R&D program. The instrument is capable of detecting bulk as well as surface hydrogen in metals and has a detection sensitivity of as low as a few parts per billion in a gas stream. Besides having a high sensitivity this instrument is unique from the point of view of simplicity of handling and low cost investment. It is simple enough to be used for an on-line or in-process inspection on a continuous basis in a manufacturing operation, or used for defining procedures for a specific manufacturing process.

A schematic of the surface hydrogen analyzer is shown in Figure 8. The plate under test is fastened securely on a spark chamber and sealed by means of an "O" ring. This apparatus is shown in Figure 9. The spark used to extract hydrogen is low energy, supplied by a high voltage, high impedance direct current power supply. The energy supplied (ca. 5 watts) is not enough to vaporize a measurable amount of metal. The hydrogen thus liberated is directed to an activated palladium barrier under a positive pressure of [illegible]rity argon (carrier gas). The palladium barrier lets only hydrogen permeate through it while impermeable to argon. On the other side of the barrier is a 1 l/sec. ion pump. Thus, the palladium barrier has a high vacuum on one side of it and one atmosphere pressure on the other side. The vacuum in the ion pump chamber is measured by the current through the pump and is recorded on a strip chart recorder. Once the pump has reached its base vacuum any diffusion of hydrogen through the palladium barrier will result in an increase in current. The current through the pump is directly proportional to the pressure, which establishes a relationship between the amount of hydrogen in the gas stream and the pump current. This makes it possible to estimate the amount of hydrogen in a gas stream from an unknown source.

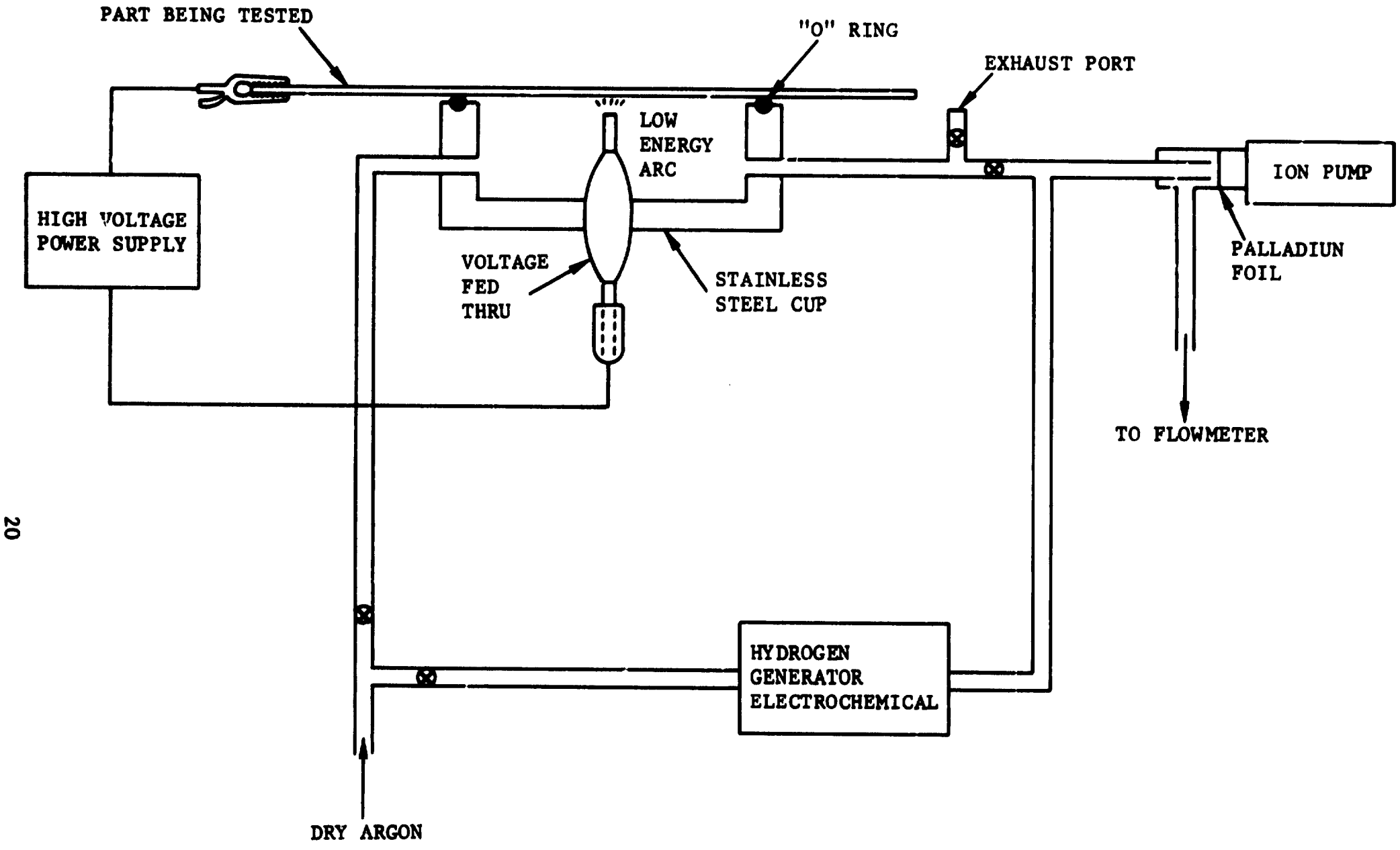



FIGURE 8: SCHEMATIC OF SURFACE HYDROGEN MEASUREMENT EQUIPMENT

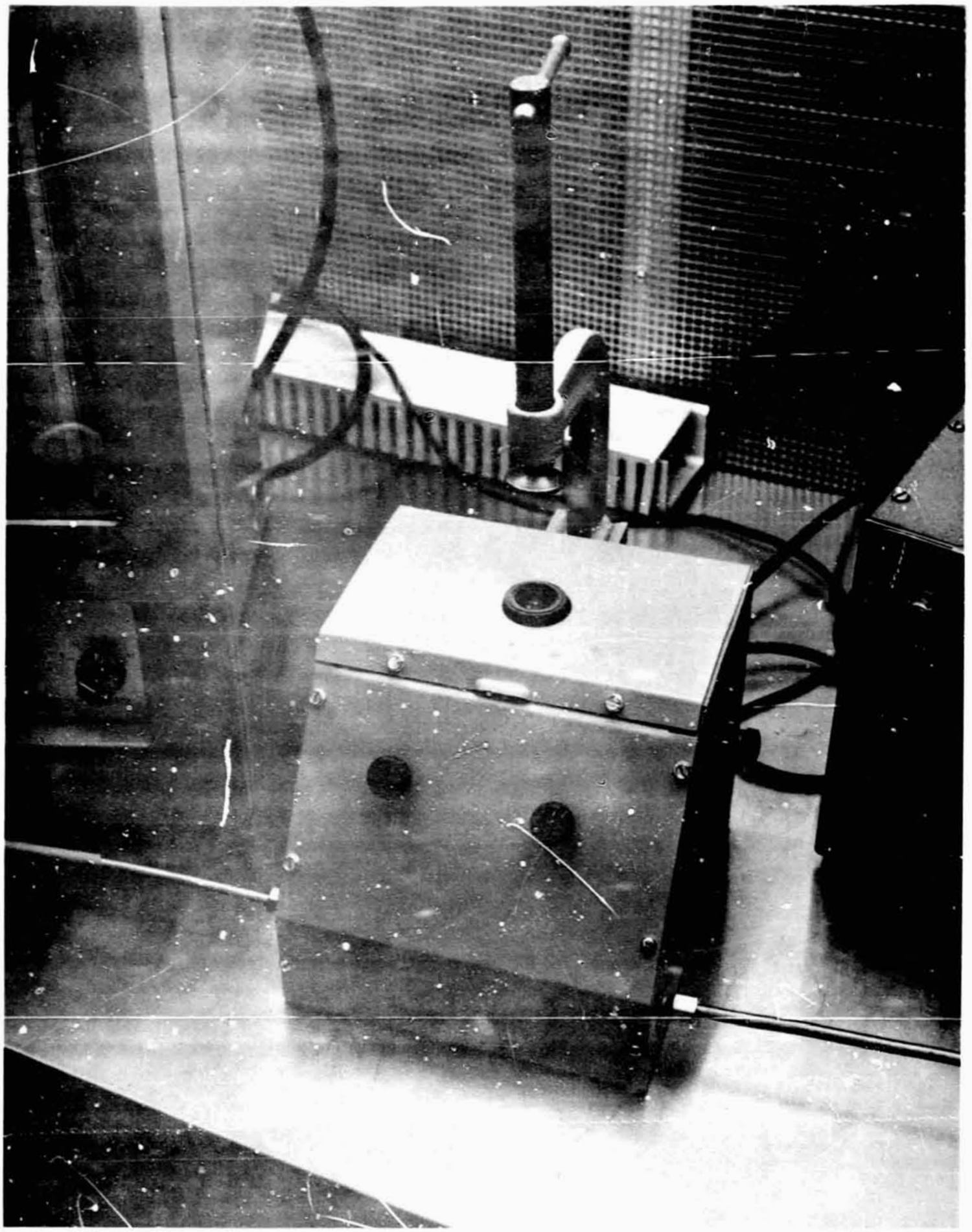


Figure 9: SPARK CHAMBER FOR SURFACE HYDROGEN ANALYSIS

In the present case such a calibration is performed by using an electrolysis cell to generate known amounts of hyd gen.

The electrolyte used is a saturated solution of potassium hydroxide. Upon electrolysis, water decomposes into oxygen and hydrogen according to the following chemical reaction:

$$2H_2O \longrightarrow 2H_2 + O_2$$

As per Faraday's Law, 96501 coulombs (amp-seconds) are required to evolve 1 gram equivalent of hydrogen. In the reaction given above 2 X 96501 coulombs are required to give one mole of hydrogen. Since one mole occupies 22400 cc at STP, 0.1275 cc of hydrogen are generated per amp-sec. input at 300°K (room temperature).

The hydrogen thus generated is mixed with pure argon and directed towards the palladium foil. A carrier gas flow of 100 cc/min. was used throughout these tests. The temperature of the palladium foil is maintained at about 560°C for adequate diffusion of hydrogen through the foil. By varying the current in the electrolysis cell the response of the ion pump can be calibrated.

For example:

Under steady state conditions with a carrier gas flow of 100 cc/min., the ratio between electrolytically generated hydrogen and carrier gas (argon) is as follows:

$$\frac{H2}{H_2+Ar} \simeq \frac{H_2}{Ar} = \frac{0.1275 \text{ cc of } H_2/\text{amp. sec.}}{100 \text{ cc of Ar/min.}} = 0.0765 \text{ parts/amp.}$$

Expressed otherwise, 76.5 parts per million of hydrogen are carried through in the gas stream at a flow of 100 cc/min per d.c. milliampere through the cell. Once the detector is calibrated in this manner, it is a simple matter to estimate quantitative amounts of hydrogen in the gas stream from an unknown source.

Figure 10 shows the calibration curve for the detector as obtained under the conditions given below:

Total flow rate (50 cc/min. through the electrolytic cell and 50 cc/min. through the spark chamber) of argon = 100 cc/min.
Palladium disc temperature = 560°C.

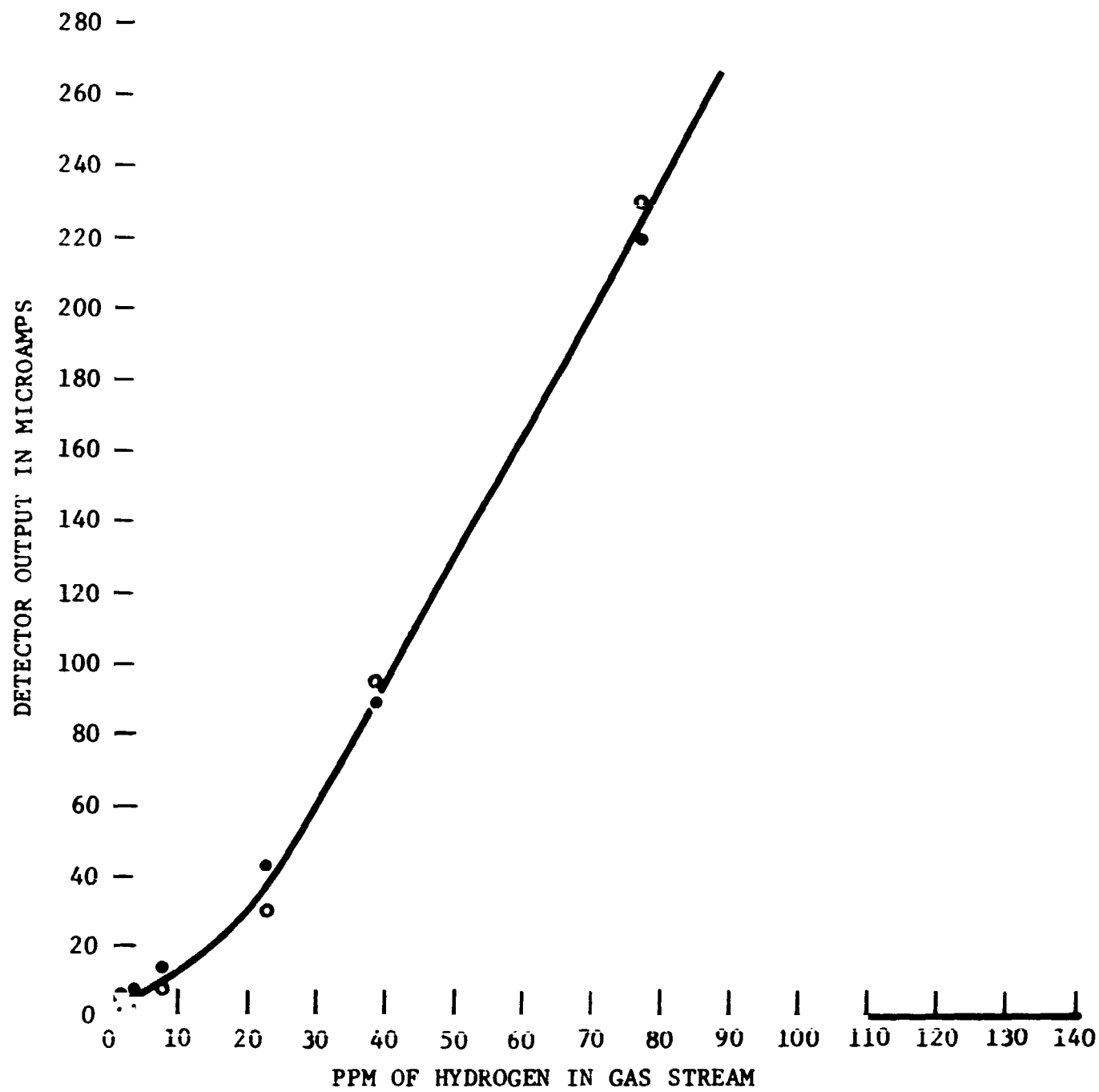



Figure 10: CALIBRATION OF HYDROGEN DETECTOR

Electrolyte = Potassium hydroxide.

The calibration curve shows the detector response in microamperes as a function of hydrogen concentration of ppm in the carrier gas stream as generated by the electrolysis cell. It is observed that below 20 ppm of hydrogen concentration in the gas stream the curve deviates slightly from linearity. This is because the efficiency of the ion pump for hydrogen at such low concentration levels is reduced. Since the data in the entire calibration range is quite repeatable, the non-linearity does not affect the surface hydrogen analysis.

Once the calibration of the detector was performed extreme care was exercised to maintain the same conditions of palladium disc temperature and argon gas flow to insure consistent results. When surface analysis was carried out, it was necessary to have a constant background of .05 ma through the electrolytic cell (4 ppm) to maintain detector sensitivity. Argon was supplied from a bottle of high purity liquid argon. Since the temperature of liquid argon is -193°C there is very little water present, significantly less than one part per million. All surface measurements were made on bare 7075 - T6 aluminum alloy samples prepared by vapor degreasing and alkaline cleaning.

Figure 11 shows a typical result. Within a few seconds after turning on the power to the spark source, an initial peak is noted. After about 3 to 5 minutes of continuous arcing the curve begins to fall off. Within 30 minutes it reaches a constant level and further arcing produces no change in the curve. It is believed that the initial high hydrogen peak is due to surface contamination. The portion of the curve after the peak should then be representative of a clean surface. When the power is shut off, the signal level is observed to drop back to the original background level. If the power is subsequently turned on, no large initial increase in the hydrogen level was observed, thereby further indicating that surface contamination was removed by the initial power application. It is further observed that the signal level after the peak is considerably higher than the background level. This suggests that some hydrogen is being extracted from the interior of the metal. The difference between the peak

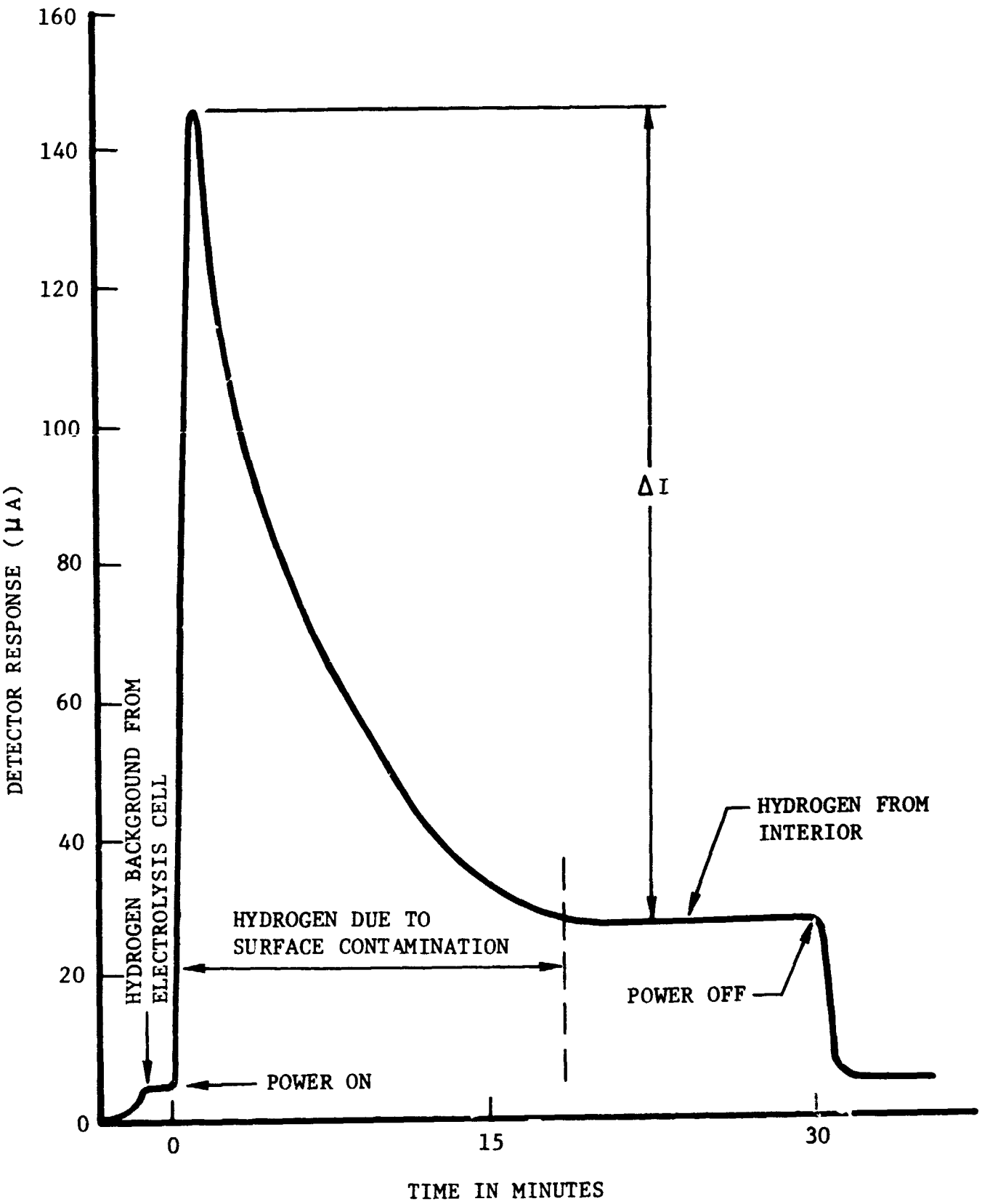



Figure 11: TYPICAL RESULT OF ARCING ALUMINUM ALLOY SURFACE

current and the current at 30 minutes (ΔI) is used as a first approximation of the surface hydrogen detected. A more exact value would be obtained from the increase in area under the curve, measured on a cleaned surface.

The value of ΔI for cleaned aluminum was found to be 93 ± 32. This is an average of 15 measurements on separate pieces of the same alloy. Although all samples were cleaned the same way at one time, there was a variation in the observed value of ΔI from one sample to the next. This variation could be due to the complex relationship between adsorbed water and oxide film. Some of the curves are shown in Figure 12.

All measurements were started within one minute after the test sample was mounted on the spark chamber and argon flow adjusted. This was done to prevent a change in surface due to the effect of dry argon found to occur after 30 minutes of exposure.

Water as a Source of Surface Hydrogen

Figure 13 shows the detector response of an aluminum plate with adsorbed water. The plate was flooded with distilled water and air dried until the visible traces of water disappeared. This was accomplished in about 90 seconds. When the plate was allowed to dry for longer periods of time the value of ΔI drops to that obtained with an untreated plate. The ΔI value for the untreated plate was 155 while after drying in air for 1, 1.5, and 3 hours the values were 85, 60, and 170 respectively (equal within experimental error).

This series of measurements demonstrates the relative speed at which wet aluminum dries and reaches equilibrium with moisture in the air. The atmosphere of the laboratory in which these measurements were made is controlled to 50% relative humidity and 21°C temperature.

Scraping the Clean Surface

Since scraping the surface is a common method used in preparation for welding, it is necessary to measure the amount of surface water before and after scraping. The results of three different plates showed no difference between scraped and unscraped surface hydrogen levels. The ΔI values were 119 and 135, 59 and 105, 90 and 73 representing

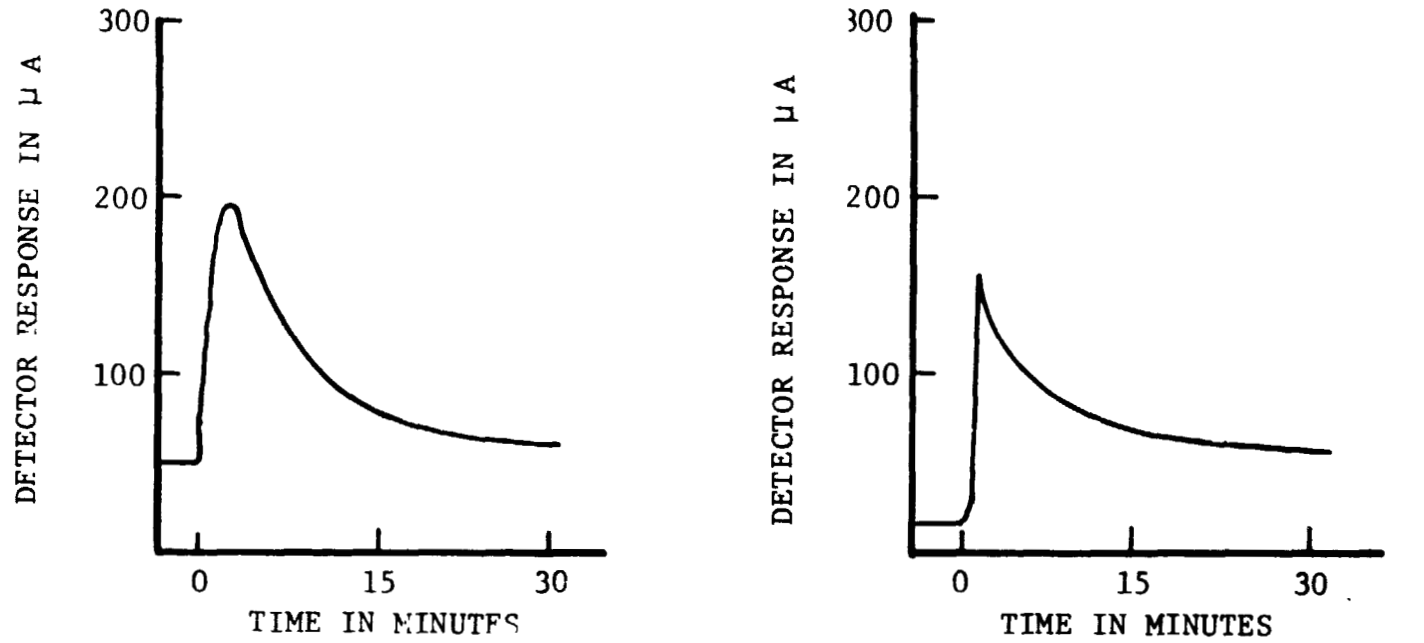



Figure 12: TYPICAL CURVES FOR CLEANED ALUMINUM SURFACES

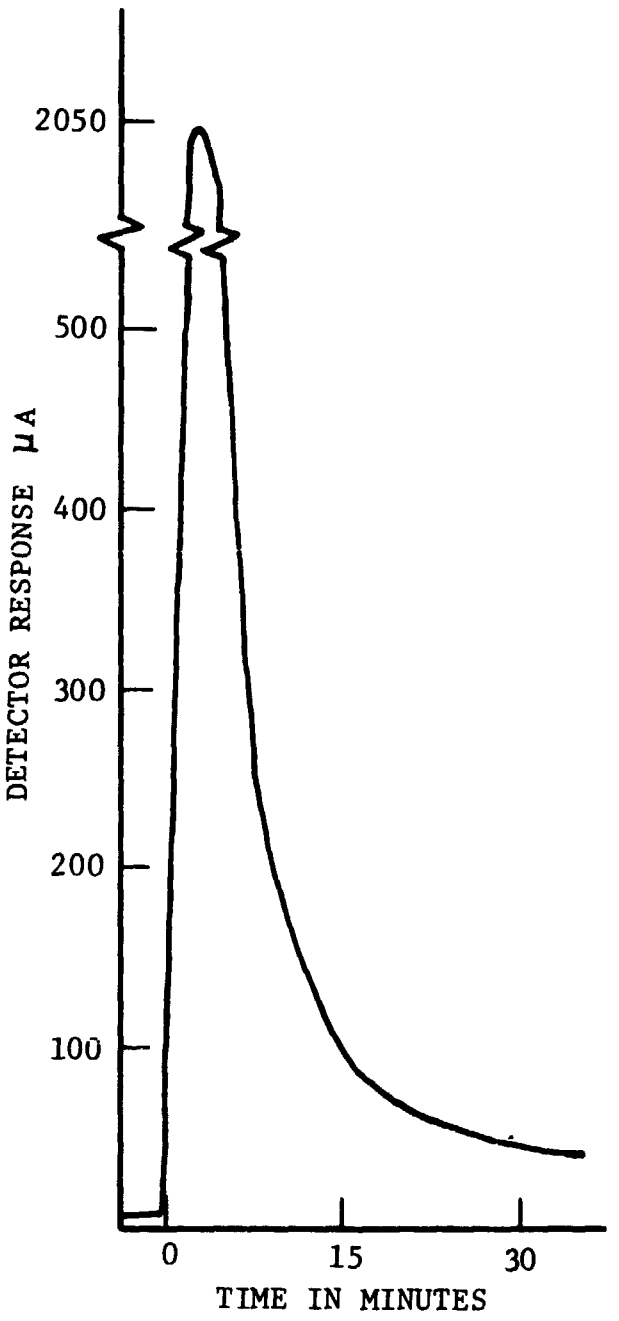



Figure 13: HYDROGEN RESULTING FROM SURFACE WATER

before and after scraping respectively. These are all within experimental error of the same value.

These two experiments demonstrate the rapidity with which water adsorbed on aluminum reaches equilibrium with water in the atmosphere. These values could be affected to a limited extent by changes in humidity, however, it appears that adsorbed water is not a potentially severe problem.

Tack Welds as a Source of Surface Contamination

Tack welds were prepared using a hand held torch wi .i helium shield gas. The measurements were made 4.5 minutes after welding. The following ΔI values were obtained:

Alternating current with filler wire..... 195 μa
direct current with filler wire..... 65 μa
direct current without filler wire..... 80 μa
direct repeat..... 85 μa

The ΔI value of 195 for an a.c. tack weld represents a contamination level above that found for an untreated surface. However, the other three values do not represent an increase in contamination. The fact that the one tack weld showed a slight increase in contamination suggests a possible problem but perhaps not a serious one under the conditions of these tests. Other conditions may produce problems but would require considerably more experimentation to determine if a problem does exist.

Handling as a Source of Surface Contamination

With the surface hydrogen detector, it is possible to measure small amounts of hydrogen or hydrogen containing material such as oil and grease deposited as a result of handling. In this series of experiments measurements of surface contamination were made of fingerprints, clean glove prints and used glove prints.

Finger prints made by two different subjects were measured with the following results:

| | | |
|---|---|---|
| Subject A | ΔI = | 1455 μa |
| Subject A, repeat | ΔI = | 1570 μa |
| Subject B | ΔI = | 975 μa |

The hands of subject A were relatively clean and dry, a normal condition, while the hands of subject B were washed with a detergent, rinsed thoroughly with distilled water, and dried with a clean towel before making the finger print.

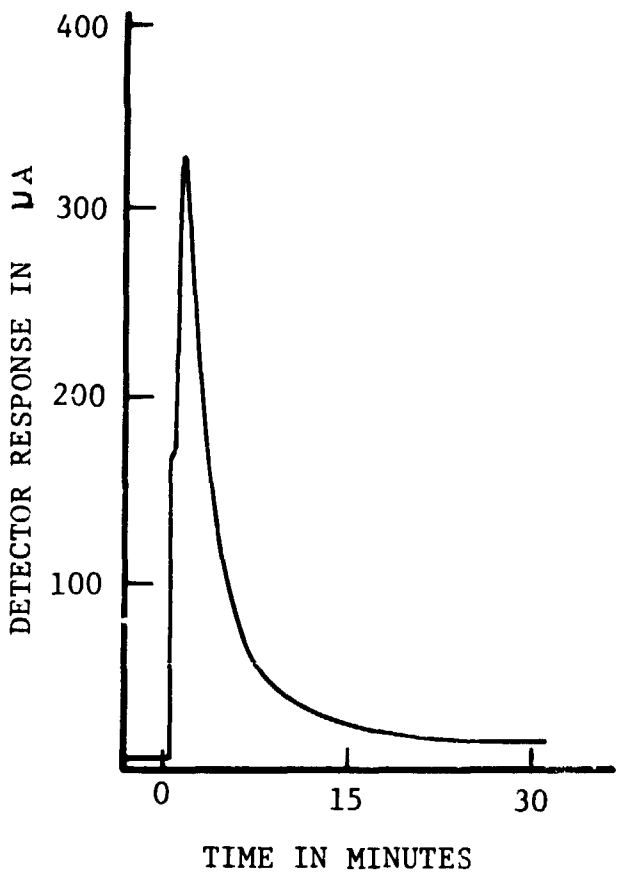
Since the normal procedure for shop work is to use white cotton gloves when handling material for critical welds, surface contamination measurements were made of fingerprints using white cotton gloves. The fingerprints were made with new clean gloves and gloves that had been worn for various lengths of time. These tests were made by subject B:

| | | |
|---|---|---|
| New, clean glove., pair A | $\Delta I$ = | 200 μa |
| another pair new gloves, pair B | $\Delta I$ = | 335 μa |
| glove worn for 0.5 hours, pair C | $\Delta I$ = | 360 μa |
| 1.0 hours, pair A | $\Delta I$ = | 455 μa |
| 1.5 hours, pair B | $\Delta I$ = | 435 μa |
| glove worn for 2.0 hours, pair B | $\Delta I$ = | 420 μa |
| Undetermined time, pair D | $\Delta I$ = | 425 μa |

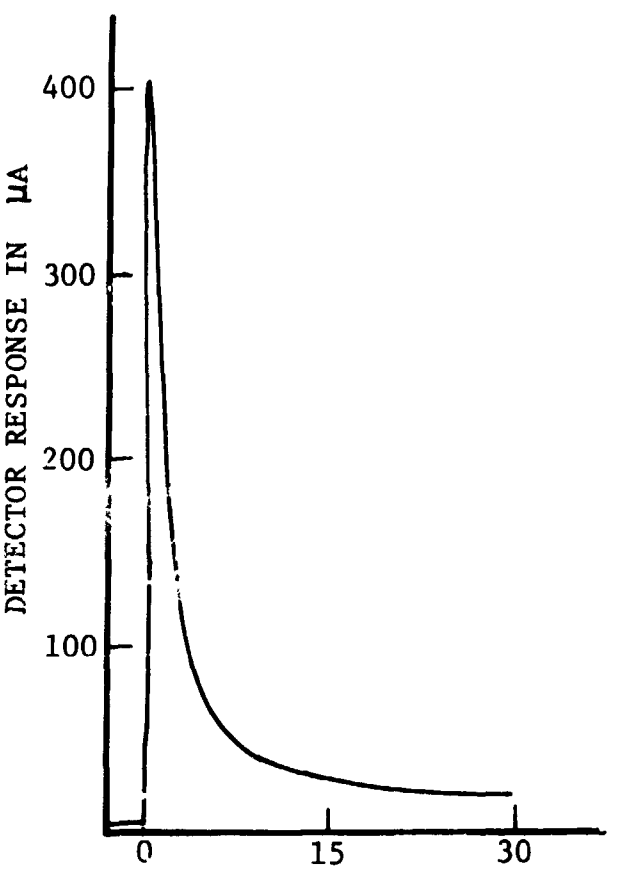
These gloves were worn in the laboratory under normal working conditions, no effort was made to either keep them especially clean or to contaminate them with grease or oil. These data clearly show that contamination cannot be avoided even through the use of white cotton gloves. While cotton gloves reduce the level of contamination by a substantial amount, the contamination level resulting from even new gloves indicates a severe potential for porosity if the faying surface has been touched.

The Use of a Solvent to Remove Contamination

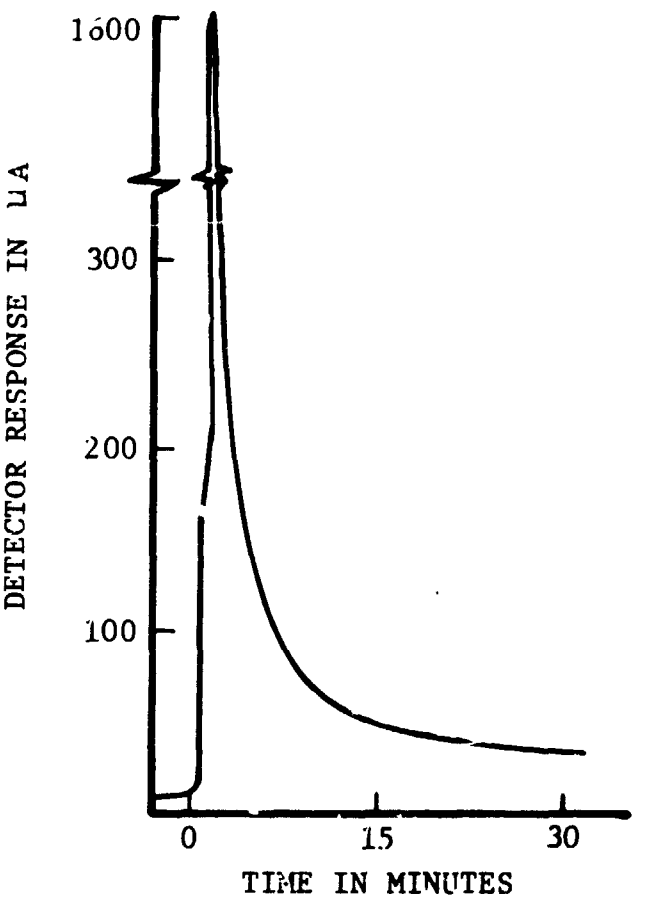
Since the most likely source of surface hydrogen appears to be organic rather than adsorbed water, a cleaning method involving a solvent rinse might be in order. A likely choice for solvent is "Freon" 113 ($C_2$ $Cl_3$ $F_3$) since it does not contain hydrogen and is a good general solvent. In order to demonstrate that no problem would be encountered in using "Freon" 113, several measurements were made of the contamination remaining after use. "Freon" used for this series of tests had been distilled to ensure no hydrocarbon contamination. The test sample was flooded with "Freon" as might be done in washing a part




Finger print impression with new clean cotton gloves




Finger print impression after wearing gloves continuously for 2 hrs.




Finger print impression of subject A

Figure 14: HYDROGEN RESULTING FROM FINGERPRINTS WITH AND WITHOUT COTTON GLOVES.

in preparation for welding. The "Freon" was not, however, wiped on as is sometimes done since contamination is not as easily removed by this method. Two measurements of ΔI after washing with "Freon" 113 gave values of 35 and 60, experimentally equal to the value of ΔI before treatment.

"Freon" 113 prepared by distillation in the same way, was used to wash weld joints (described below) prior to welding. In order to properly wash the joint a polyethylene squeeze bottle was used to direct the stream of "Freon" into the weld joint. After the bottle was in use for about a week the surface contamination was again checked. This time a ΔI value of 3735 μa was found indicating a severely contaminated surface. It was apparent that the "Freon" had become contaminated from the polyethylene bottle even though the bottle was new. To check this conclusion the bottle was rinsed several times with "Freon", then let stand for about 4 days. This "Freon" was compared to the original "Freon" with a Beckman IR-12 infrared spectrophotometer. The original "Freon" contained no hydrocarbons while that stored in the polyethylene bottle contained 154 ppm. These data clearly demonstrate the need for careful handling of "Freon" or any other solvent for this use. A metal container with no organic parts would be required to prevent contamination of this nature.

Significance of ΔI Values

It is possible to make an estimate of the amount of hydrogen from the observed value of ΔI. The area under the curve is related to total amount of hydrogen removed from the surface by the following equations:

$$\frac{it}{2} \times \frac{E}{96,500} = w$$

$$\frac{W}{2} \times 22,400 = v$$

The area of a triangular peak is it/2 and has the units of coulombs when i is in amperes and t in seconds. Coulombs divided by 96,500 and multiplied by equivalent weight (1.00 for hydrogen) gives weight in grams of material. When this is multiplied by E, efficiency of

the pump and paladium foil (100 in this experiment) the weight of hydrogen present in the gas stream at any one instant is obtained. Dividing the weight by the molecular weight (2.00 for hydrogen) and 22,400 the volume of hydrogen in cubic centimeters at standard temperature and pressure is obtained. For a $\Delta I$ value of 1000 this calculation gives 1.4 cc. This value of 1.4 cc. depends on the shape of the current-time curve and could be much larger for the same value of $\Delta I$.

In a like manner the amount of hydrogen deposited from a single fingerprint while wearing a new cotton glove is 0.4 cc. This is pure hydrogen; it it were distributed through one liter, it would be 400 ppm. This calculation clearly shows that any type of handling of the weld metal whether gloves are worn or not, will produce enough contamination to result in weld porosity.

## 5. WELDS FOR CORRELATION WITH SURFACE CONTAMINATION

As mentioned previously, the construction of the Saturn booster involves variables not associated with mechanical joint defects. The following variables have been treated in this study for correlation of weld porosity with surface contamination: tack welds, rubbing, storage, slots, and handling. In addition, the possibility of cleaning contaminated weldments prior to welding to prevent porosity was examined.

Table 3 contains a summary of the treatment and results of the series of welds for correlation with surface contamination. The treatment of the panels are as follows:

a. Plates 10 x 70 x 0.64 cm. (4 x 28 x 1/4 inches) were cut from 2014-T651 and 2219-T87. All plates were vapor degreased, alkaline cleaned and scraped prior to welding.

b. Those with slots were prepared by cutting the slots in the bottom panel .05 cm (.020 in.) deep, separated by 15 cm (6 in.). Those marked "Square" had square corners and those marked "Sine" had beveled corners.

c. Those stored were left 24 hours after scraping in open shop atmosphere (ca. 50% RH and 21°C).

d. Handling was done with white cotton gloves never more than 4 hours old.

e. Tacking was done with hand held d.c. torch, one tack weld was made every 15 cm. (6 inches).

f. Brushing was done with a new steel brush.

g. Rubbing was done by movement of the faying surface with ca. 0.7 kg/cm$^2$ (10 psi) force until galling was apparent.

h. Cleaning was accomplished by flooding the joint with "Freon" 113. A polyethylene squirt bottle was used to direct the stream of solvent into the weld joint. The bottle was rinsed with "Freon" 113 before each application. Cleaning was done after weldments were secured and immediately before welding.

TABLE 3 SUMMARY OF WELD RESULTS

| WELD | ALLOY | Slots | Store | Hdl | Clean | Tack | Brush | Rub. | Hdl | Clean | Porosity and Defects* | Associated with slot or Tack |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2014 | | | | | X | X | | | | 1 | No |
| 2 | | | | X | | X | | | X | | 3 | No |
| 3 | | | | | | X | | | X | | 2 | No |
| 4 | | | | | | X | | | | | 1 | No |
| 5 | | | | X | | X | | | | | 3 | No |
| 6 | | | X | | | | | | | | 0 | |
| 7 | | | X | X | | | | | | | 1 | |
| 8 | | | X | | | | | X | | | 1 | |
| 9 | | | | X | | | | X | | | 4 | |
| 10 | | Square | | | | | | X | | | 1 | No |
| 11 | | Sine | | | | | | X | | | 1 | No |
| 12 | | Square | | X | | | | | | | 2 | Half |
| 13 | | Sine | | X | | | | | | | 2 | Half |
| 14 | | Square | | | | | | | | | 1 | No |
| 15 | | Sine | | | | | | | | | 0 | No |
| 34 | | | | | | | | | | X | 1 | |
| 35 | | | | X | | X | | | | X | 1 | Half |
| 36 | | | | X | | | | | | X | 1 | |
| 37 | | | | | | X | | | | | 1 | No |
| 22 | 2219 | Sine | | X | X | X | | | | X | 0 | No |
| 23 | | Square | | X | X | X | | | | X | 1 | No |
| 26 | 2219 | | | | | | | | | | 0 | |
| 27 | | | X | | | | | X | | | 1 | |
| 29 | | | | | | X | | | | | 0 | No |
| 30 | | | | X | | X | | | | | 2 | No |
| 38 | | | | X | | | | | | X | 0 | |
| 39 | | | | X | | X | | | | X | 1 | No |
| 40 | | | | | | | | | | X | 4 | |
| 41 | | | | X | X | X | | | | X | 2 | Half |

*KEY 0 - No defects 1 - Very minor 2 - Minor 3 - Moderate 4 - Significant

i. Welding conditions: all welds were made in the horizontal position using a Line HW-27 torch and helium flow rate of 0.63 standard liters per second (80 SCFH). 2014 alloy was welded at 167 amperes and 11.5 volts with a torch travel of 15 cm./min. (6 in./min.). 4043 aluminum filler wire was used at a feed rate of 38 cm./min. (15 in./min.). 2219 alloy was welded at 160 amperes and 11.5 volts and 2319 aluminum wire with torch and wire feed rate as above.

Correlations Between Surface Hydrogen and Weld Porosity

None of the experimental welds showed serious porosity but some solid trends were established.

Tack Welds: Those welds made over tack welds showed no increase in porosity when no other variable was included cf. welds 1, 4, 29. This agrees with surface hydrogen analysis which shows no contamination due to d.c. tack welds.

Slots: When clamp slots are welded over there is a possibility of trapped contaminants, however, there was none observed relating to slots alone cf. welds 10, 11, 14, 15. The possibility of contamination from the atmosphere because of lack of shielding was dealt with in section 1 and eliminated as a source of porosity.

Rubbing: If rubbing of the faying surfaces caused galling then there is the possibility of an accumulation of oxide and adsorbed moisture. This was not demonstrated in welds as shown by welds 8, 10, 11, 27. Under adverse conditions such as high humidity and long times porosity may develop where galling occurs, but the tests made here do not cover that humidity range.

Handling: In nearly all cases where handling was done without subsequent cleaning there was a significant increase in weld defects. These are welds 2, 5, 7, 9, 12, 13, and 30 in Table 3. Only one of these, #7, showed low porosity, whereas the other six had more porosity than welds treated in other ways. This demonstrates the contamination possible from handling even though white gloves are worn, and demonstrates the correlation between surface hydrogen analysis and weld porosity.

Cleaning: The results of welding after cleaning dramatically demonstrates the role of surface contamination in porosity formation and ease of removal by the proper use of solvents. Welds 22, 23, 35, 38, 39, and 41 were handled and then cleaned with porosity in only one of the six welds. This handling process without cleaning resulted in measurable porosity (cf. 2, 5, 7, 9, 12, 13 and 30). The welds made after cleaning but not handling (welds 34, 37 and 40) help substantiate the correlation between surface hydrogen measurements and porosity. Only two welds of ten showed porosity after treatment with the "Freon". Welds 16, 17, 18, 19, 20, 21, 24, and 25 have been excluded from the table because all were cleaned with "Freon" 113 contaminated with unknown amounts of hydrocarbons from the polyethylene bottle. No statements can be made about the correlation of porosity and various factors when the over-riding factor is uncontrolled. It was demonstrated that "Freon" picked up hydrocarbons from polyethylene but no metal container was available so polyethylene was used with a rinse prior to cleaning. This does not appear to be adequate. Nevertheless, the fact that five welds of six showed no porosity after cleaning, when they were treated in a manner that produced porosity, demonstrates that porosity of this nature can be avoided. These conclusions are summarized in Table 4.

TABLE 4

Summary of Porosity vs. Surface Hydrogen

| Surface Condition | ΔI, μa (± 32) | Porosity |
|---|---|---|
| Untreated | 93 | --- |
| Scraped | 104 | No porosity |
| Tack weld | 77 | No porosity |
| Handling with gloves | 376 | Measurable porosity |
| Hydrocarbon contamination | 3735 | Significant porosity |

The relationship of porosity and the surface contamination index, ΔI, can easily be seen. Scraped and tack welded surfaces show the same level of contamination and no porosity, while surface

contamination and porosity both increase when the surface is touched with a gloved hand. This demonstrates that the surface contamination index, $\Delta I$, can be used to predict porosity.

## 6. PROGRAM BENEFITS

In a broad sense the purpose of programs such as this is to determine ways of making better welds. Information gained during this program can be used to improve quality and cost of aluminum welding. The profile data show that the Linde HW-27 torch provides good shielding at moderate flow rates while the HW-13 torch does not provide reliable coverage at these flow rates and especially at longer torch to work distances. The HW-27 torch can be used with a helium flow rate of ca. 0.63 standard liters per second (80 SCFH) instead of the usual 0.98 standard liters per second (125 SCFH). An additional 20 to 30% flow reductions is possible with modest reduction in cup to work distances. This can significantly reduce the cost of helium shield gas.

The conclusions drawn from the experimental evidence presented here is that surface contamination resulting from normal handling is the most likely source of porosity with much lower probability of contamination from tack welds and adsorption of atmospheric water. These conclusions are supported by the correlation observed between porosity and the level of hydrogen containing surface contamination produced by various shop operations. It was shown that contamination from handling can be removed by careful use of a solvent such as "Freon" 113 thus eliminating the major source of porosity.

As a result of this study the following related programs are suggested: They have a significant potential for solving or controlling the production porosity problem in welding aluminum and are listed in order of priority:

a. Develop surface hydrogen analyzer for use in the shop to inspect surface cleanliness and as a Manufacturing Development tool to define the optimum manufacturing procedures necessary for low porosity welds.

b. Determine the quantitative relationship between porosity and surface contamination and define tolerable limits.

c. Determine the feasibility of adding oxygen to the shield gas to eliminate porosity in aluminum welds caused by surface contamination. Once feasibility is established a quantitative relationship between oxygen content, surface contamination level, and weld porosity should be determined.

d. Determine the conditons where tack welds cause porosity and explore methods of cleaning tack welds to eliminate porosity.

e. Define a reliable solvent for cleaning weldments, available from the vendor without further purification.

## 7. REFERENCES


1. Cheever, D. L., Monroe, R. E., Martin, D. C., Welding Research Supplement 35 (1) 1-s (1970).

2. Cheever, D. L., Kammer, P. A., Monroe, R. E., and Martin, D. C., Welding Research Supplement 48 (8), 348-s (1969).

3. Kozlarski, J., The Welding Journal, 32 (1), 973 (1953).

4. Masubuchi, K., Integration of NASA Sponsored Studies on Aluminum Welding, RSIC-670, Redstone Scientific Information Center, Ala., September 28, 1967.

5. Meister, R. P., and Martin, D. C., Welding of Aluminum and Aluminum Alloys, DMIC Report 236, April 1, 1967.

6. Strobelt, W. E., Inert Gas Weldment Effects Study, Phase I Report (January 1966-June 1966) on Contract NAS8-21068 from Aerospace Group, Quality Control Research Section, The Boeing Company.

7. Saperstein, Z. P., Prescott, G. R. and Monroe, E. W., Welding Research Supplement 43 (10) 443-s (1964).

8. Hasemeyer, Earl A., Weld Imperfections, Addison-Wesley Publ. Co., 1968, pp. 209.

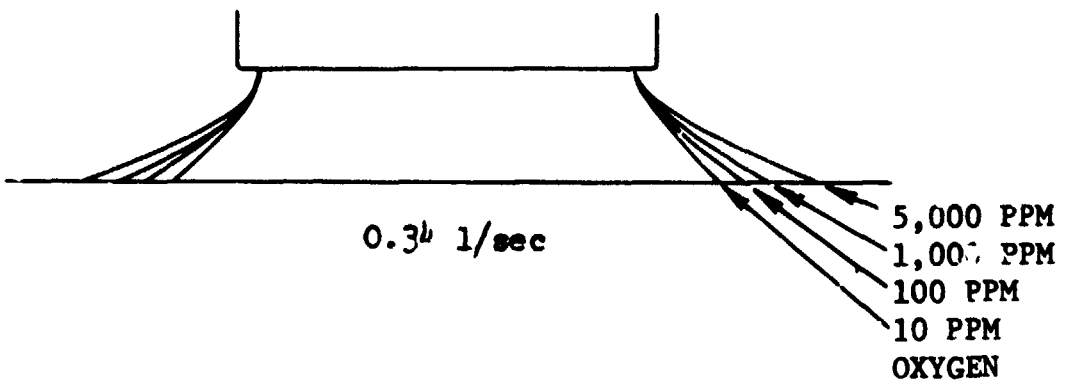
9. Das, K. B., and Strobelt, W. E., Patent Application (Disclosure #69-442), 1969.

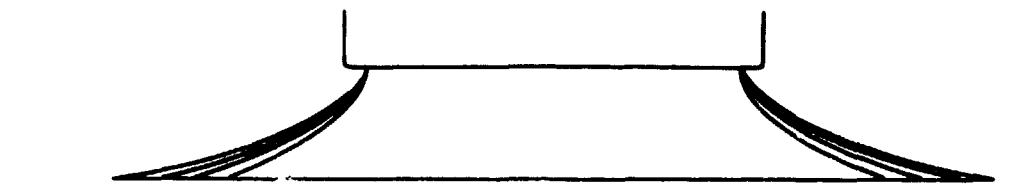
## 8. APPENDIX

Figures 1 through 15, Contamination Profiles

Contours indicate constant contamination levels on a plane intersecting the centerline of the torch. In the case of horizontal torch position the plane is vertical. The four contour lines indicate 10, 100, 1000, and 5000 ppm (parts per million) oxygen. The mass spectrometer was calibrated for oxygen in helium by electrochemical generation of oxygen from dilute sulfuric acid. The flow rates have been corrected by comparison against a calibrated flow meter and are noted for each profile. In all figures, the top of the page is up. Drawings are twice actual size.

Most of the profiles are straight forward and clearly indicate the flow rate where adequate coverage occurs. However, the Linde HW-13 torch at a torch to work distance of 1.5 cm (19/32 inch) does not provide adequate coverage over the flow range studied for two reasons. First, at lower flow rates 0.34 and 0.44 standard liters per second (43 and 56 SCFH) there is inadequate coverage because of the low flow rate. Second, the higher flow rates with this torch in combination with the longer torch to work distances produces a focusing of shield gas as in a light beam. This has the effect of pinching the column of helium to a point. This effect produces turbulence in the critical arc zone and therefore contamination. This pinching effect occurs at the higher flow rates with the HW-13 torch but not with the HW-27.



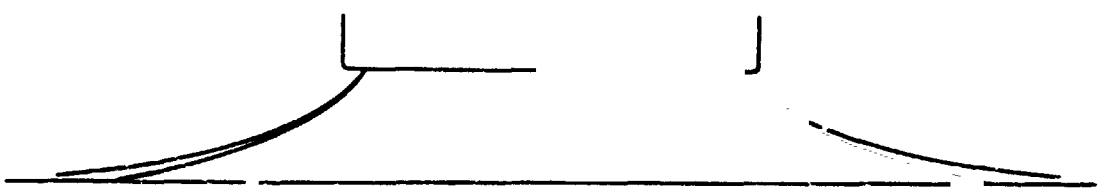
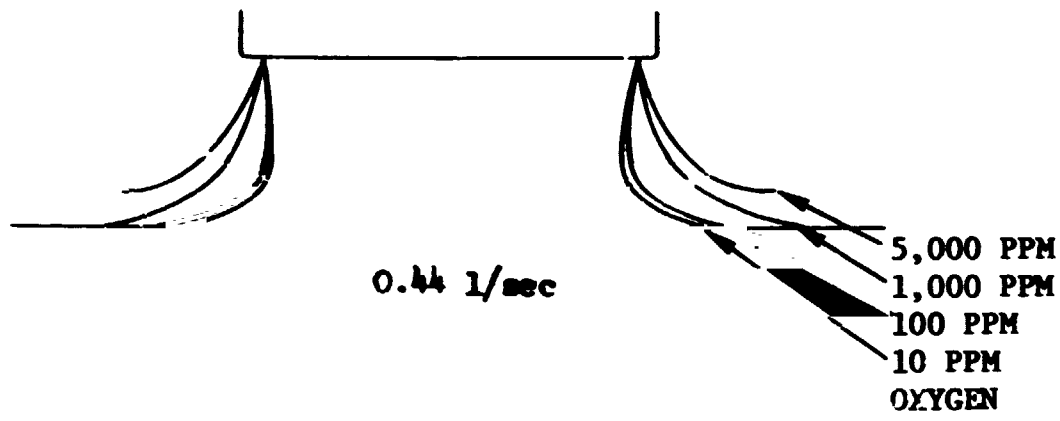
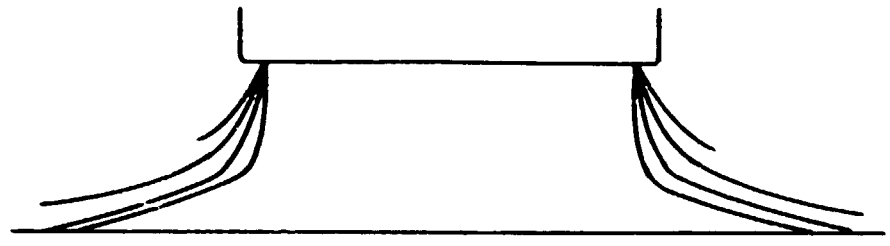




Figure 1: Contamination Profiles For HW-27 In Flat Position At 0.6 cm.

0.34 1/sec

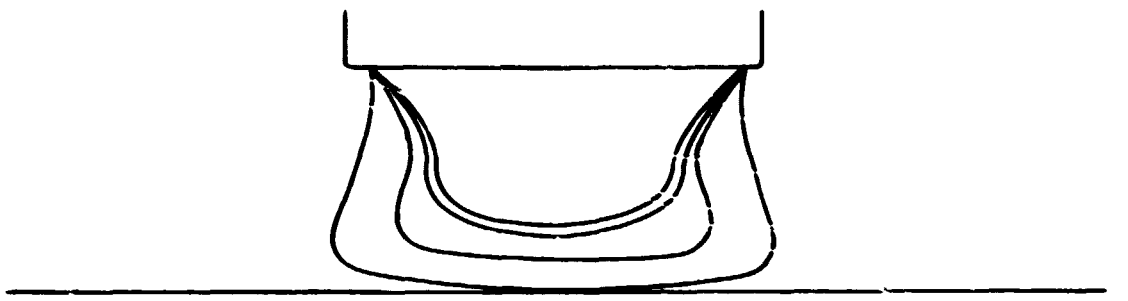



0.44 1/sec

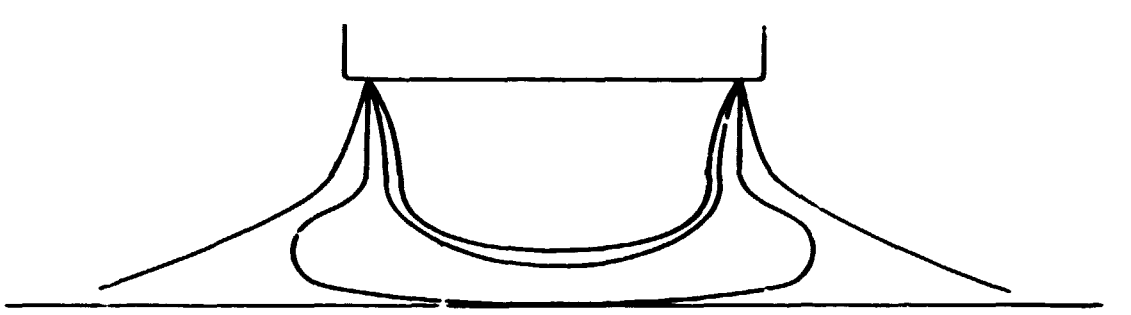


0.57 1/sec

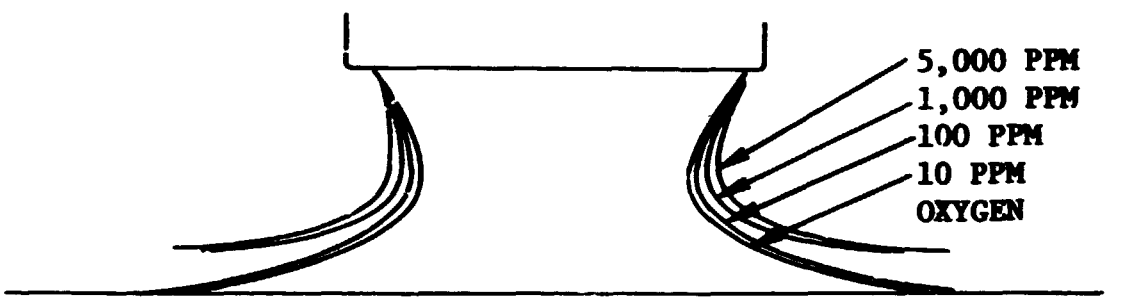
Figure 2: Contamination Profiles for HW-27 in Flat Position at 1.0 cm.



0.34 l/sec



0.44 l/sec




0.57 l/sec

Figure 3: Contamination Profiles for HW-27 in Flat Position at 1.3 cm.

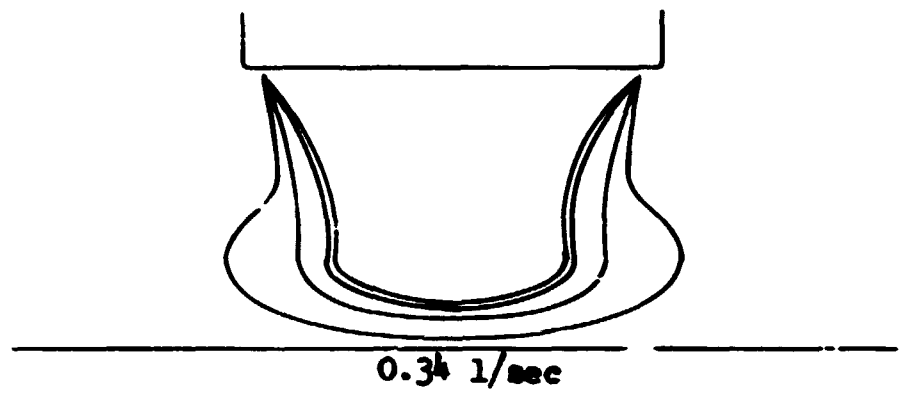
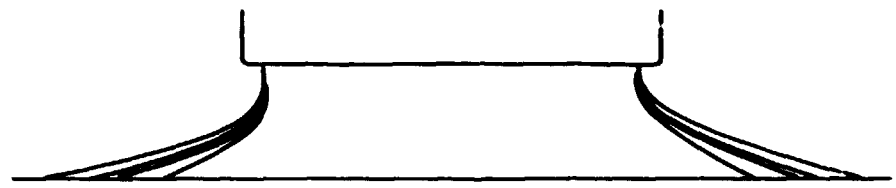
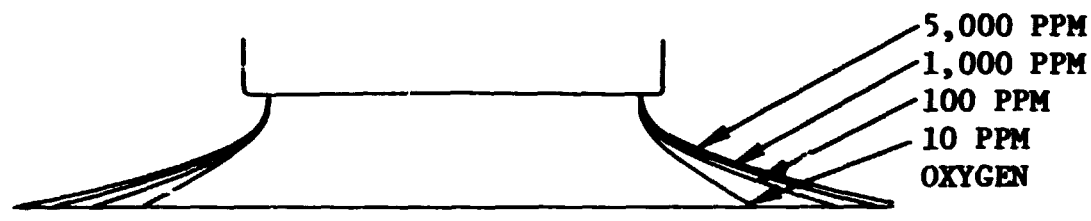



Figure 4: Contamination Profiles for HW-27 in Flat Position at 1.5 cm.

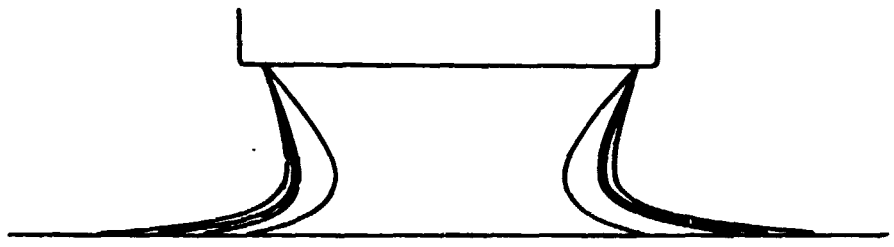


0.34 l/sec

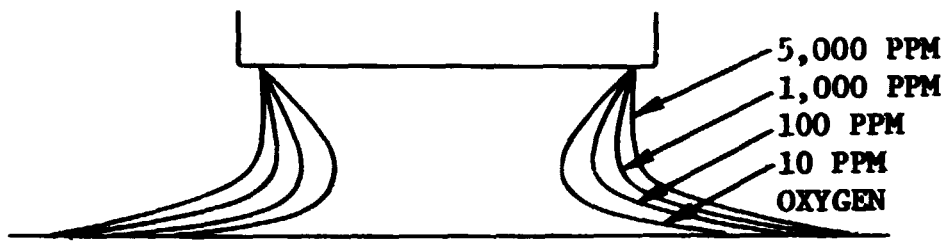



0.44 l/sec

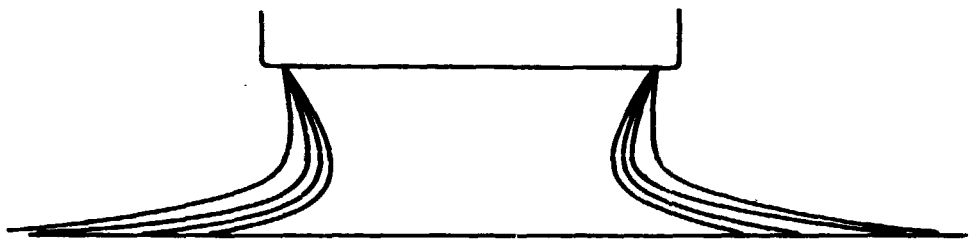
Figure 5: Contamination Profiles for HY-13 in Flat Position at 0.6 cm.



0.34 l/sec

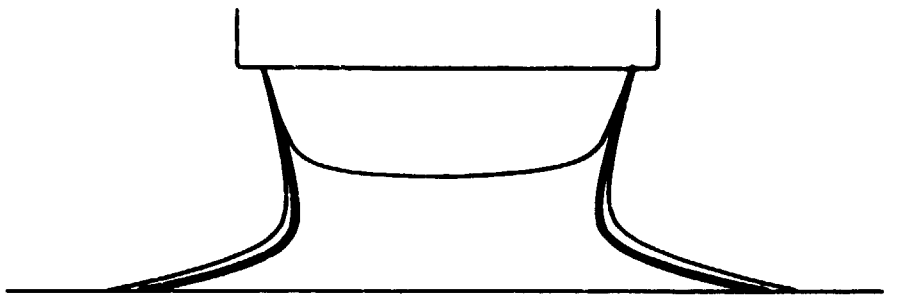



0.44 l/sec

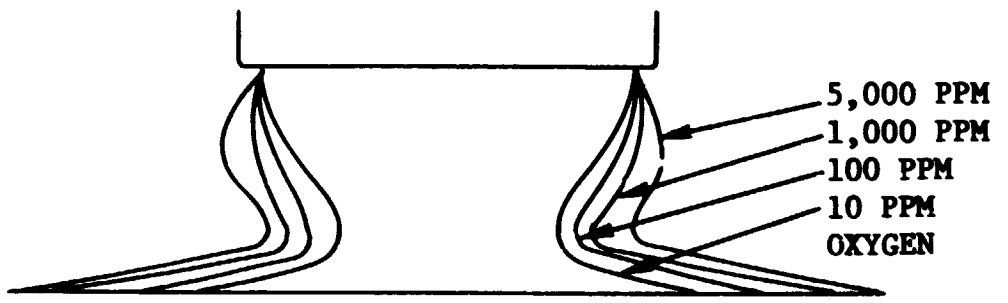


0.57 l/sec

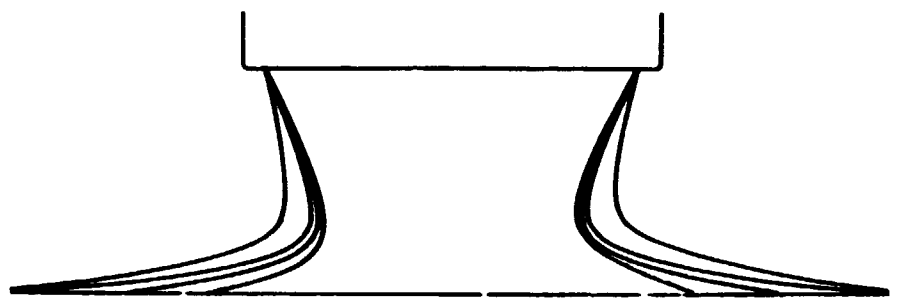
Figure 6: Contamination Profiles for HW-13 in Flat Position at 1.0 cm.



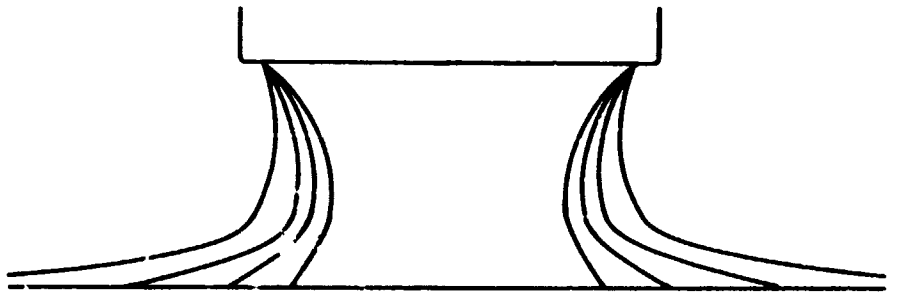
0.34 l/sec




0.44 l/sec



0.57 l/sec



0.68 l/sec

Figure 7: Contamination Profiles for HW-13 in Flat Position at 1.3 cm.

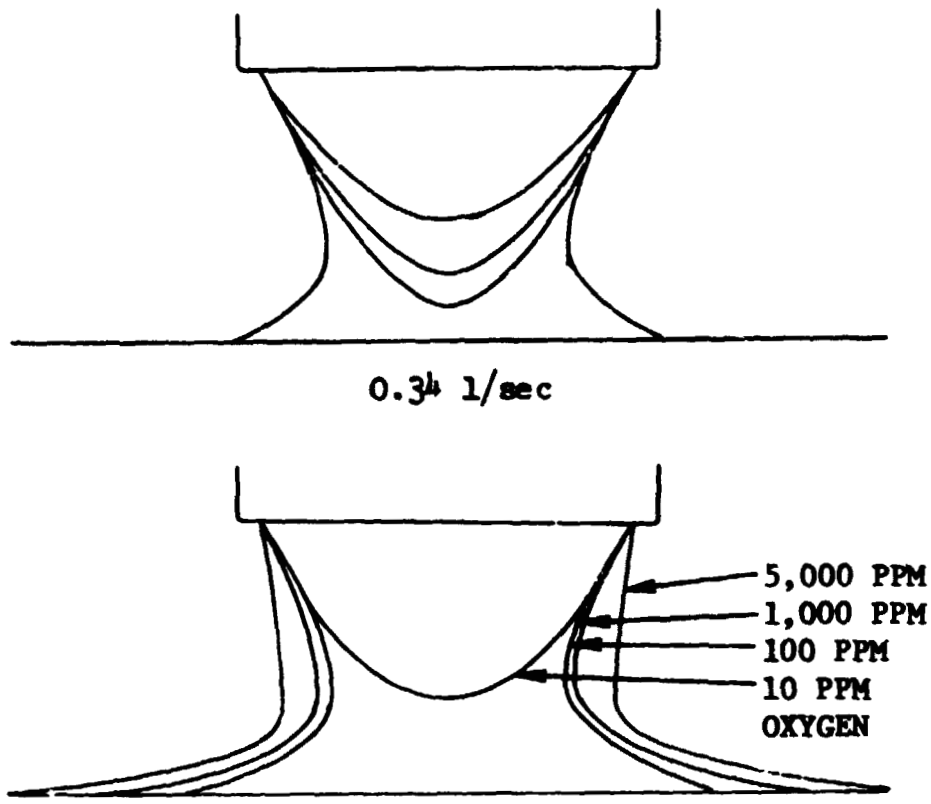



Figure 8: Contamination Profiles for HW-13 in Flat Position at 1.5 cm.

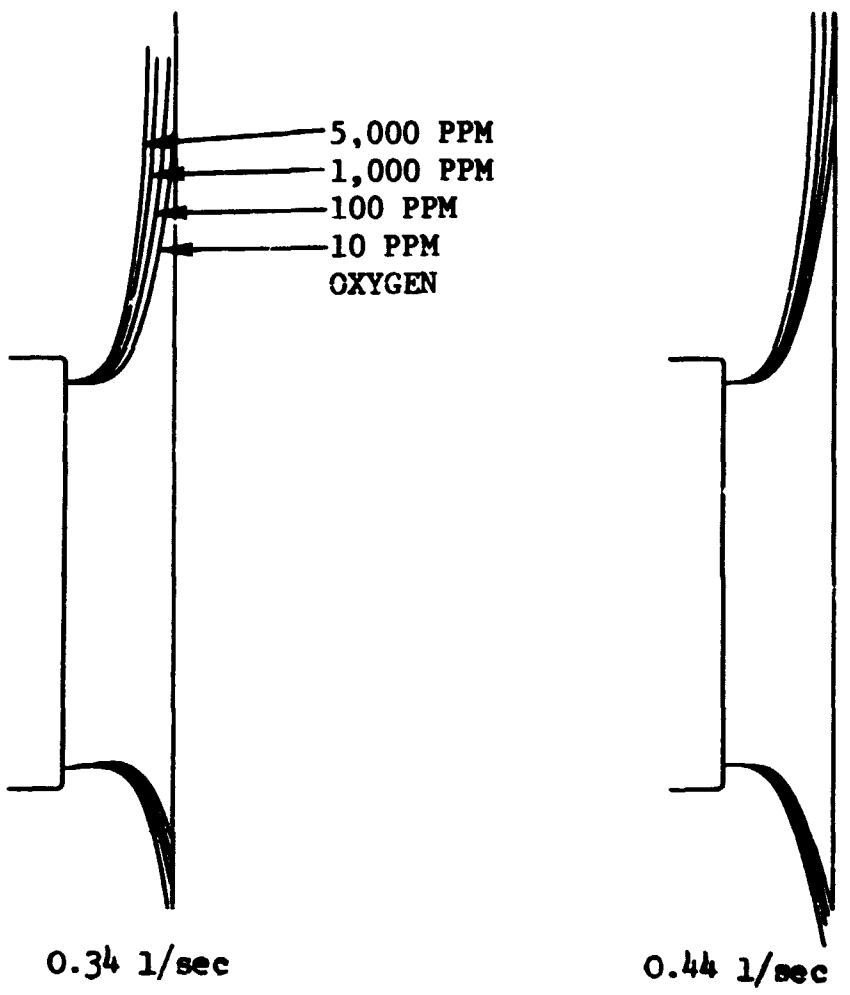
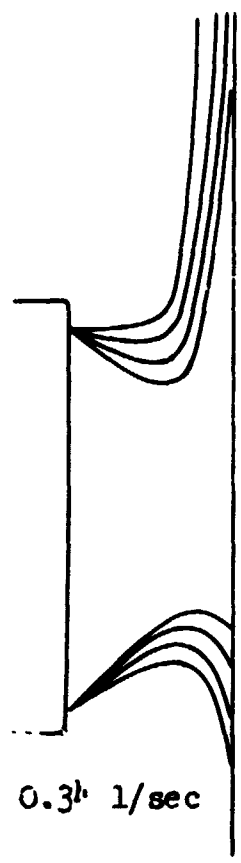
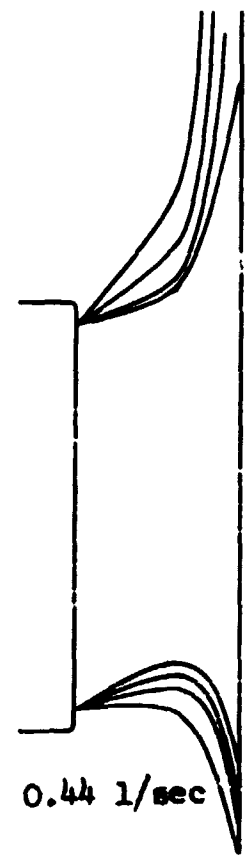



Figure 9: Contamination Profiles for HW-27 in Horizontal Position at 0.6 cm.



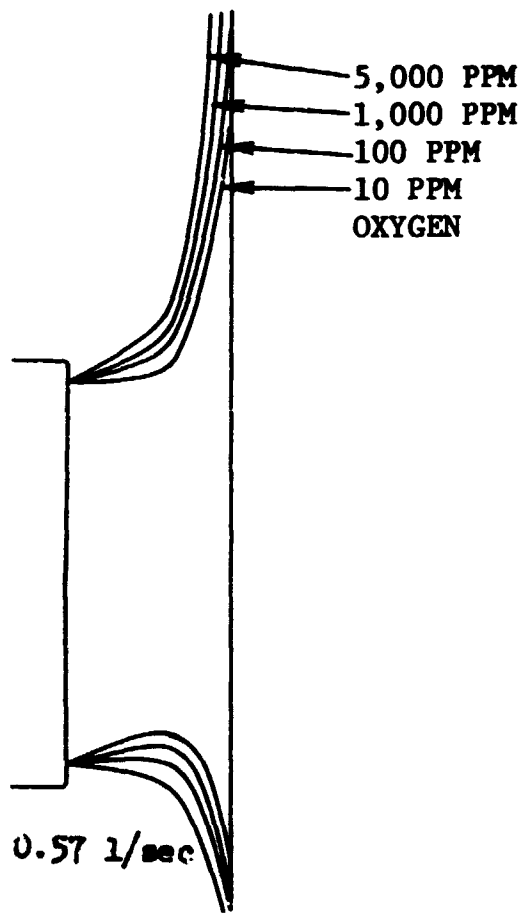
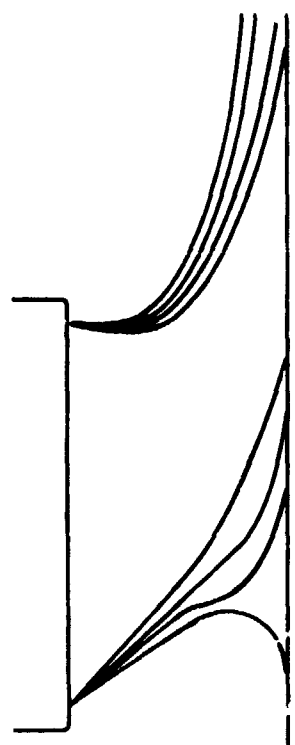
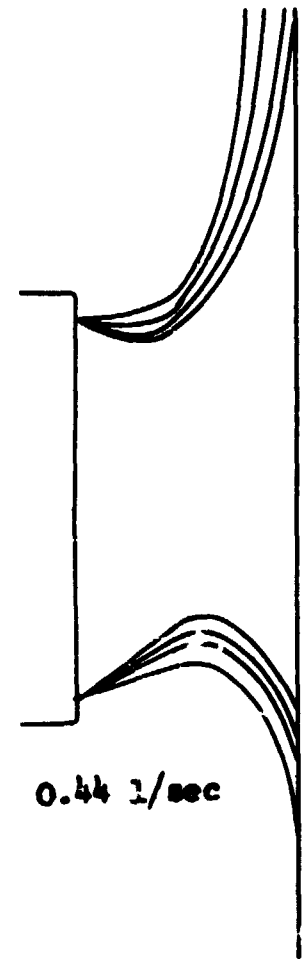




Figure 10: Contamination Profiles for HW-27 in Horizontal Position at 1.0 cm.



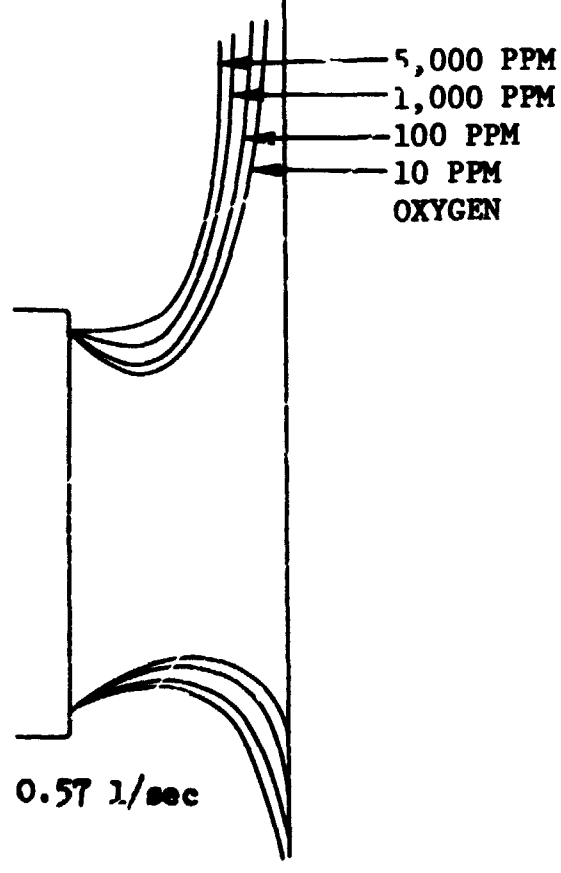
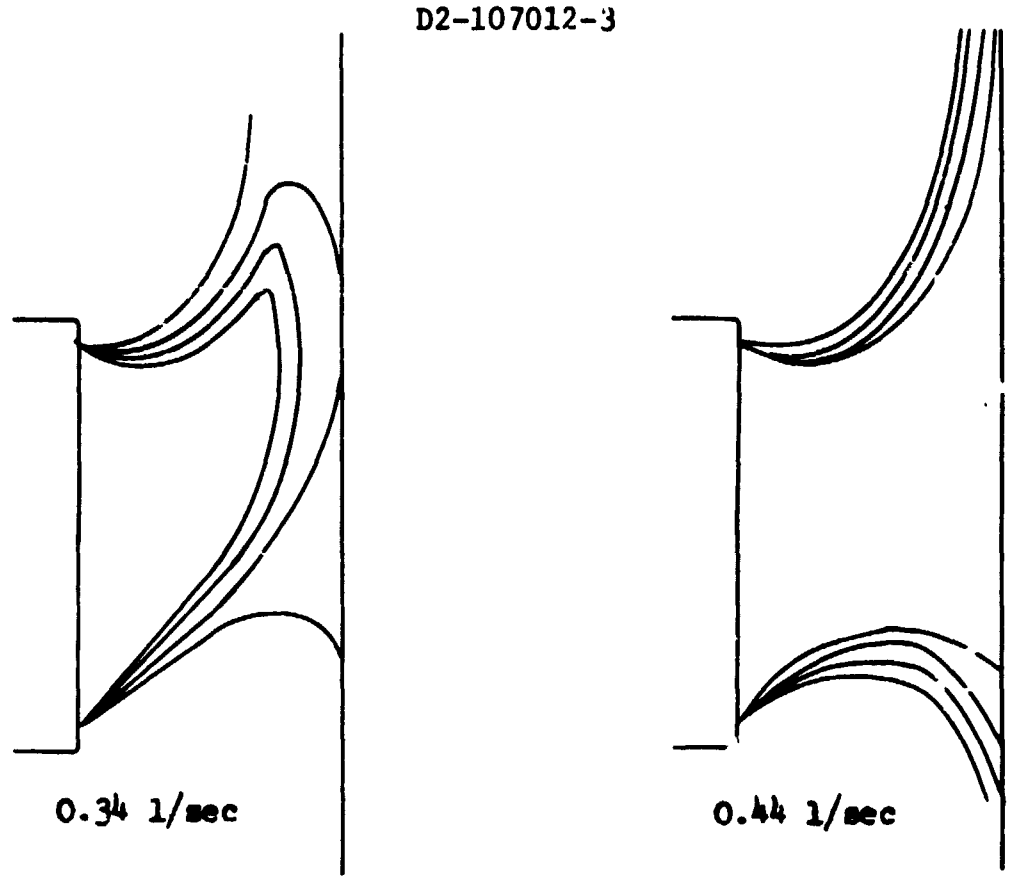




Figure 11: Contamination Profiles for FW-27 in Horizontal Position at 1.3 cm.



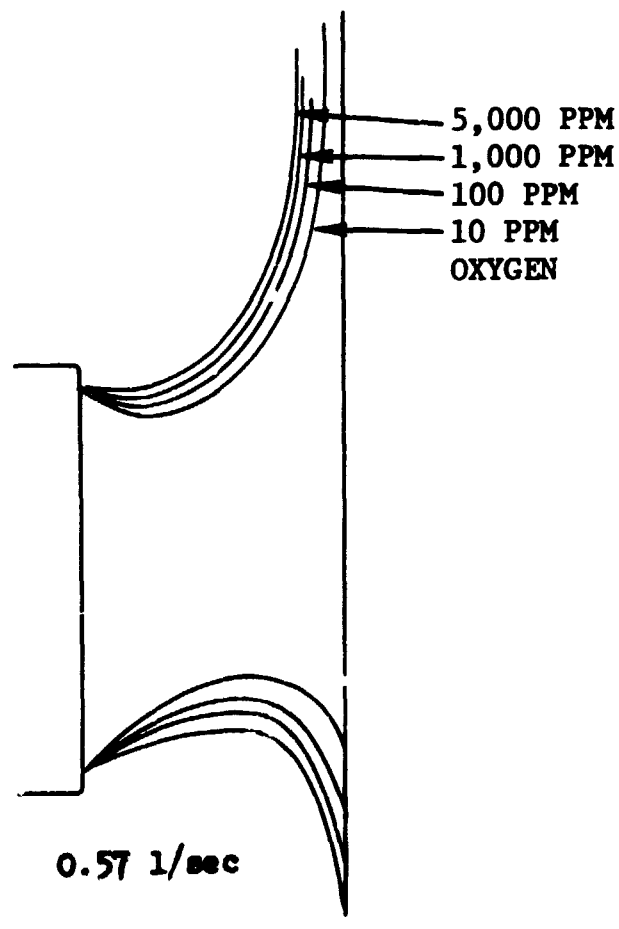
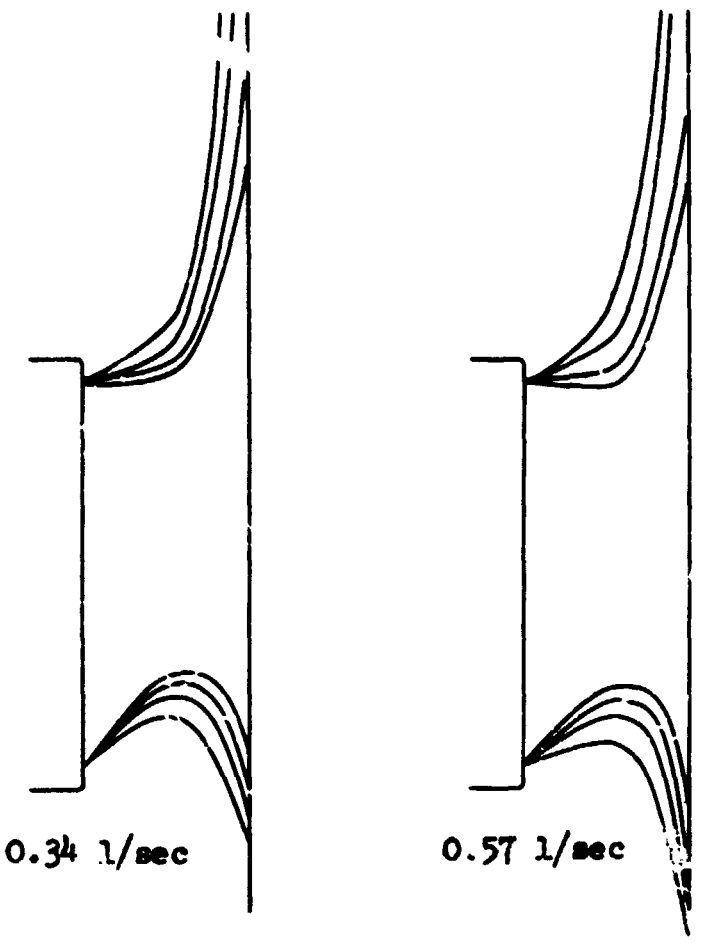




Figure 12: Contamination Profiles for HW-27 in Horizontal Position at 1.5 cm.



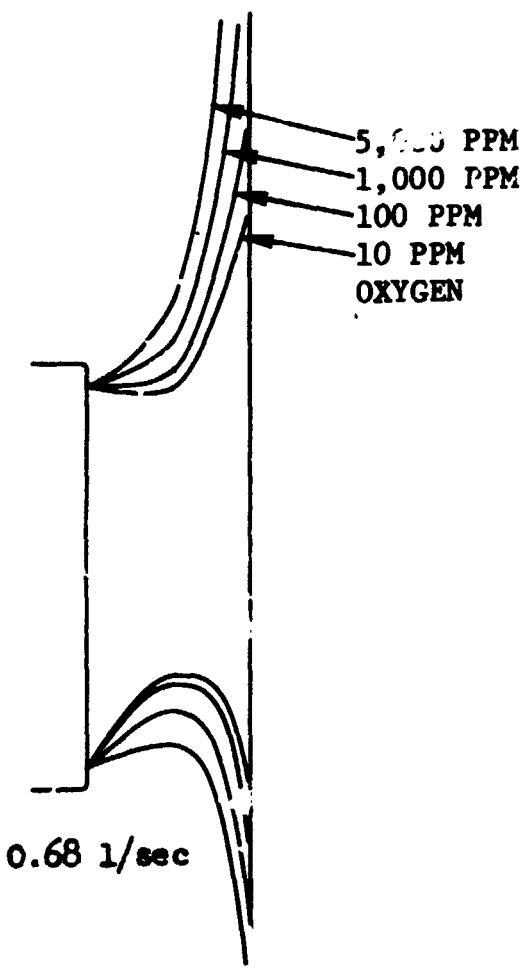




Figure 13: Contamination Profiles for HW-13 in Horizontal Position at 1.0 cm.

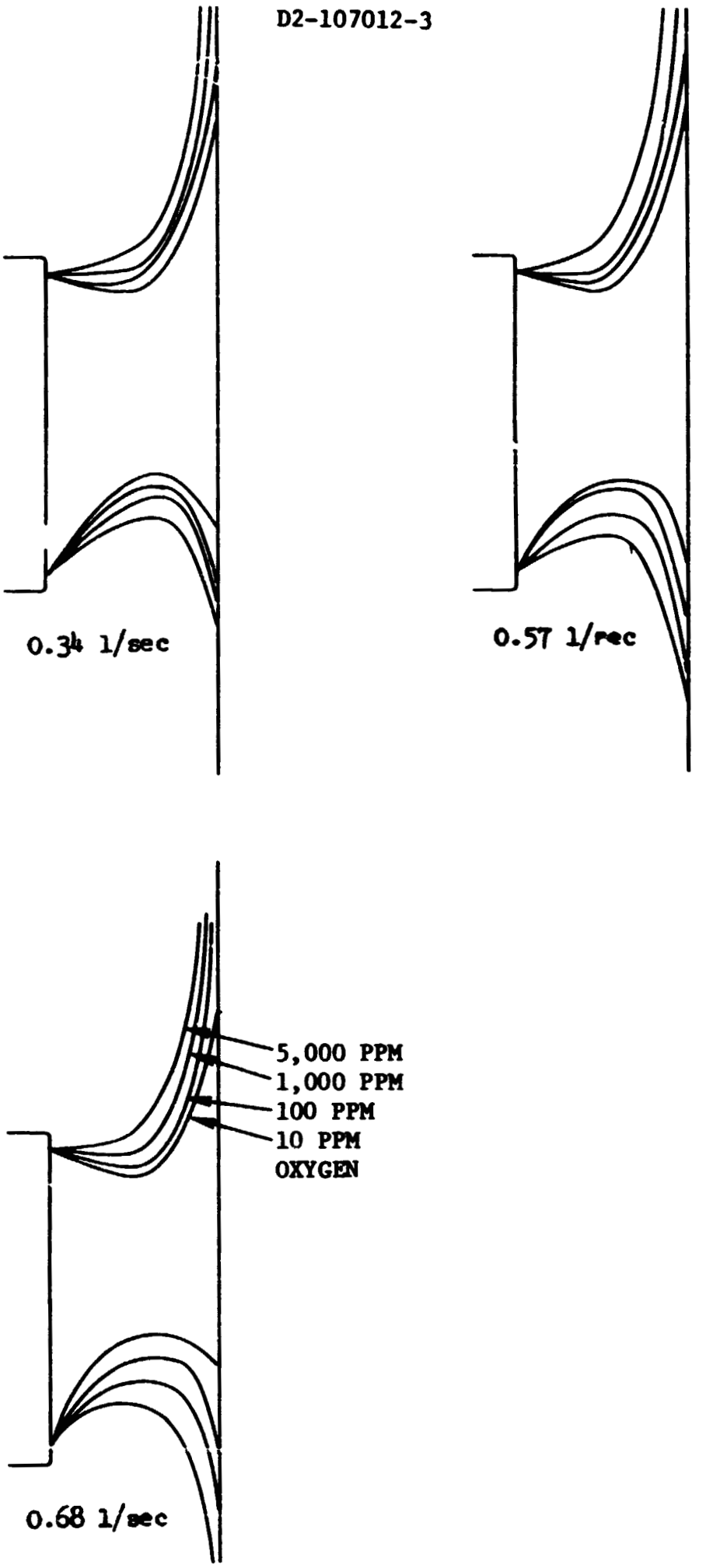



Figure 14: Contamination Profiles for HW-13 in Horizontal Position at 1.3 cm.

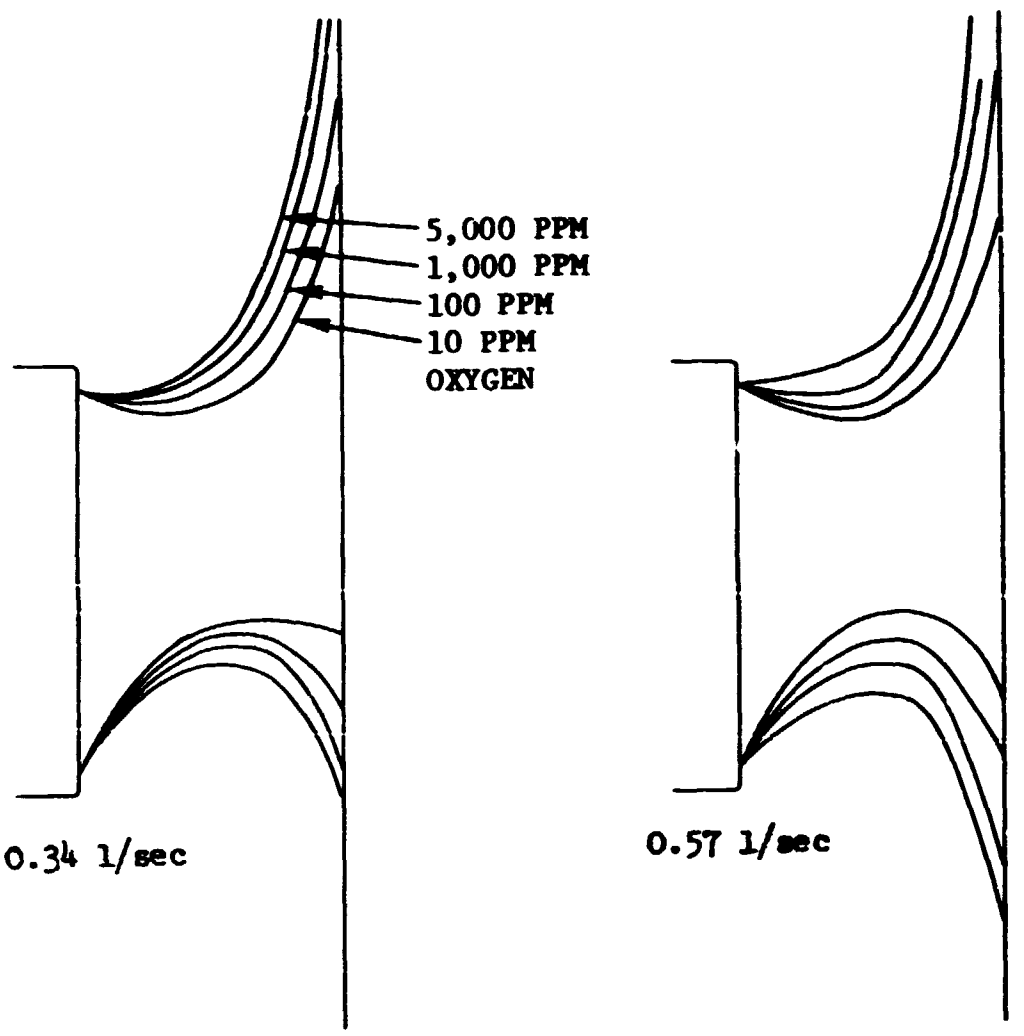



Figure 15: Contamination Profiles for HW-13 in Horizontal Position at 1.5 cm.