# PALO VERDE
# NUCLEAR GENERATING STATION

## UNITS 1, 2&3

# QUALIFICATION OF AN ALTERNATIVE ELECTRODE CONTROL PROGRAM FOR AWS D1.1



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ARIZONA PUBLIC SERVICE COMPANY
PROJECT MANAGER AND OPERATING AGENT

# QUALIFICATION OF AN ALTERNATIVE ELECTRODE CONTROL PROGRAM FOR AWS D1.1

FOR THE

ARIZONA NUCLEAR POWER PROJECT

PALO VERDE NUCLEAR GENERATING STATION

UNITS 1, 2, AND 3

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CONTENTS

CONTENTS (continued)

## 1. INTRODUCTION

Weld rod control as specified in AWS D1.1 is overly restrictive for welding mild steel with E7018 electrodes. For welding at the Palo Verde Nuclear Generating Station (PVNGS), NRC Inspection and Enforcement has required that the project strictly enforce the 4-hour out-of-oven time specified in AWS D1.1. In addition, to mitigate concern resulting from inconsistencies with other codes (e.g., ASME Section III Div 1), the NRC requires that the more conservative AWS D1.1 requirement be applied to all welding at the site.

### 1.1 OBJECTIVE

This report provides information which enables Arizona Public Service Company (APS) through its Engineer, Bechtel Power Corporation (Bechtel), to qualify an alternative electrode control procedure to that presented in AWS D1.1. This alternative electrode control procedure allows a 12-hour out-of-oven time. This time limit applies to the welding of all mild and austenitic stainless steels and nickel base materials.

### 1.2 SCOPE

The compilation of information and data presented in this report is intended to provide the necessary technical justification for this alternative electrode control procedure. To assure proper documentation for qualification and acceptance by the Engineer in accordance with AWS D1.1, the qualification program includes the following key elements which are described in this report:

A. Literature search

B. Industry practice and experience

C. PVNGS Test Program

D. MIT Test Program

E. Independent consultant review

## 2. SUMMARY

The American Welding Society's Structural Welding Code, AWS D1.1, is frequently referenced as a standard governing structural welding. However, D1.1 is relatively restrictive regarding the requirements for storage and issue of low hydrogen electrodes (E7018) when used to weld mild steel base metals.

This report states and reviews the problem, outlines the project history, and discusses a literature survey and the historical basis for alternative electrode controls. Information is provided on some of the current industry practices and on high humidity tests which have been conducted to

show weld quality. Commentary is provided from three independent consultants on various aspects of acceptable longer out-of-oven time including review of test data.

The conclusion reached from the program is that the AWS D1.1 controls on storage and issue of electrodes are unnecessarily conservative for welding mild steel, and that a specific alternative electrode program which allows out-of-oven time up to 12 hours is qualified under AWS D1.1, paragraph 5.2.

## 3. CONCLUSIONS

A. The historic concerns for short out-of-oven times are not justfied for the welding of mild steel when E7018 electrodes are controlled in accordance with the requirements of Bechtel Standard WFMC-1, Revision 6 (WFMC-1 is included as part of Appendix C). The essential control elements of WFMC-1 include storage in 200F minimum ovens, issue to the welder in individually identified containers, and controlled retrieval at shift end or 12 hours, whichever comes first. Low alloy electrode controls were not investigated and no change should be made in control of low alloy electrodes based on this data.

B. The principal conclusion regarding the adequacy of WFMC-1, Revision 6, is supported by the literature, by the results of the MIT testing, by the experience of fabricators, the Navy, shipyards and heavy construction projects and, most specifically, by the results of the PVNGS tests which qualified the alternative electrode control program to the requirements of AWS D1.1.

C. The 12-hour maximum out-of-oven time is a conservative requirement when compared to the test results that included exposure to 100-percent humidity for periods of 15 and 20 hours.

D. Independent review by three consultants experienced and knowledgeable in welding and welding metallurgy have substantiated the test results and have provided agreement with the alternative electrode control procedure permitting a maximum 12-hour out-of-oven time for E7018 electrodes for mild steel welding applications.

E. The Engineer, as defined by AWS D1.1, has reviewed test and other pertinent data. This comprehensive review and the conclusive test data presented provides a technically sound base for the Engineer to accept WFMC-1, Revision 6, as qualified in accordance with paragraph 5.2 of AWS D1.1.

F. In the interest of consistency and ease in administrating a single electrode control procedure, the 12-hour maximum out-of-oven time should be applicable to welding on all safety related systems and structures utilizing mild and austenitic stainless steels and nickel base materials regardless of which code or standard is applicable.

## 4. BACKGROUND

In 1975, after extensive review by Bechtel of the literature, a compilation of industrial practice and world wide construction experience, it was determined that portable rod warmers were technically not required for E7018 electrodes used to weld mild steel for out-of-oven times of up to 12 hours. During February, 1976, the filler metal control procedure being used to weld mild steel, austenitic stainless steel, and nickel base materials for ASME applications on nuclear projects, was changed to reflect the results of this evaluation.

In late 1976 and early 1977, it became apparent that the AWS D1.1 paragraph 4.9.2 restriction on exposure time for the alloyed electrodes of Specification AWS/SFA 5.5 was being interpreted as applying to the E7018 mild steel electrodes of Specification AWS/SFA 5.1. In addition to the difficulties in interpretation between the requirements of AWS D1.1 and the several AWS/SFA specifications, inconsistencies in the requirements for electrode moisture control between codes governing structural, liner plate, and ASME piping applications have further complicated the issue.

### 4.1 AWS D1.1

AWS D1.1 has evolved as a consensus standard representing good practice. It is generally a non-mandatory code used for mutual convenience and by mutual agreement. AWS D1.1 is a conservative code in many regards, such that manufacturers and installers meeting all stated requirements need neither qualify nor demonstrate the adequacy of fabrication and installation procedures. One of the conservative AWS D1.1 requirements is stated in paragraph 4.9.2, which, in part, deals with moisture control of E7018 electrodes. However, AWS D1.1 in paragraph 5.2 makes provisions for alternative procedures and assigns the responsibility for acceptance of any alternative to the Engineer. Acceptance by the Engineer of an alternative electrode control procedure is clearly permitted as stated by AWS in correspondence included in Appendix A.

#### 4.1.1 AWS D1.1, Paragraph 4.9.2-Electrode Storage and Issue

Paragraph 4.9.2 requires that:

> "All electrodes having low hydrogen coatings conforming to Specification AWS/SFA 5.1 shall be purchased in hermetically sealed containers or shall be dried for at least 2 hours between 450F (230C) and 500F (260C) before they are used. Electrodes having low hydrogen coatings conforming to Specification AWS/SFA 5.5 shall be purchased in hermetically sealed containers or shall be dried at least 1 hour at temperatures between 700F (370C) and 900F (403C) before use. Electrodes shall be dried prior to use if the hermetically sealed containers show evidence of damage. Immediately after the opening of the hermetically sealed container or removal of the electrodes from drying ovens, electrodes shall be stored in ovens held at a temperature of at least 250F (120C). E70XX electrodes

that are not used within 4 hours, E80XX within 2 hours, E90XX within 1 hour, E100XX and E110XX within one-half hour after the opening of the hermetically sealed container or removal of the electrodes from a drying or storage oven shall be redried before use. Electrodes that have been wet shall not be used."

4.1.2 AWS D1.1, Paragraph 5.2 - Qualification of Other Procedures

In part AWS D1.1 provides that welding procedures which conform in all respects to the provisions for Design, Workmanship, and Technique (including electrode storage and issue) shall be deemed prequalified and are exempt from tests or qualifications. Fabricators and installers need not demonstrate the adequacy of procedures conforming in all respects with AWS D1.1. Paragraph 5.2 of AWS D1.1 makes provisions for other procedures, as follows:

> "Except for the procedures exempted in 5.1, joint welding procedures which are to be employed in executing contract work under this Code shall be qualified prior to use, to the satisfaction of the Engineer, by tests as prescribed in Part B of this section. The Engineer, at his discretion, may accept evidence of previous qualification of the joint welding procedures to be employed."

The AWS Committee has advised that these provisions may be used to qualify alternative electrode control procedures to those requirements in paragraph 4.9.2. Refer to Appendix A.

## 4.2 PROJECT HISTORY

In response to a finding resulting from the difference between the control program being implemented for ASME E7018 electrodes used at the PVNGS jobsite and the AWS D1.1 requirements for storage and issue of these same type mild steel electrodes to weld structural steel, APS requested an informal hearing with the NRC I & E regional office at Walnut Creek to review the basis for the alternate ASME filler metal control procedures. This meeting was held June 1, 1977, and the points considered are outlined in Appendix B.

In November, 1977, the NRC's Metallurgy Section of the Materials Engineering Branch developed an evaluation and position which was forwarded to APS in December, 1977. This position recognized that hydrogen underbead cracking had not been reported in plain carbon (mild) steels and indicated a slight modification in the AWS D1.1 requirement for welding mild steel with E7018 electrodes could be permitted. However, the use of portable rod warmers or a 4-hour maximum out-of-oven time was still required.

Since the requirement for a 4-hour out-of-oven time or the use of rod warmers for E7018 electrodes when welding mild steel did not appear to be technically justifiable, in late January 1978, APS requested Bechtel to develop data for longer out-of-oven times and elimination of E7018 portable rod warmers. Rod warmers for low alloy steel electrodes would continue to be used. The data was to provide the qualification of an alternative procedure in compliance with AWS D1.1, paragraph 5.2.

In early February, Bechtel began a test program for several brands of E7018 electrodes (including those used at the PVNGS jobsite) in order to provide the qualification test report. At this same time, Chemetron, the principal PVNGS jobsite supplier of E7018 electrodes, was authorized under Bechtel direction to conduct an independent parallel program for confirmation of results using their products.

On February 14, 1978, the Bechtel test program was expanded to include repeated exposures to 100-percent humidity and the addition of circular patch test coupons. On February 15, 1978, Chemetron was commissioned to conduct a parallel expanded scope program. The Bechtel test program and data are reported in Appendix C. The Chemetron reports are included in Appendix D as is the Bechtel Commentary to the Chemetron reports. It is also intended that test results will be submitted to AWS D1.1 for consideration in revision of paragraph 4.9.2 in time for the next meeting to be held in October of 1978.

## 5. LITERATURE SURVEY AND PRELIMINARY EVALUATION

During 1975, an extensive review of the technical literature was performed to determine the technical justification, if any, for E7018 4-hour out-of-oven time or use of portable rod warmers when welding mild steel. The review has been expanded and kept current. Efforts have also been directed toward determining the basis for the AWS D1.1 electrode control requirements. These reviews and efforts were prompted by the NRC I&E requirement on all projects that E7018 electrode out-of-oven time not exceed 4 hours.

### 5.1 BASIS FOR 4-HOUR MAXIMUM EXPOSURE REQUIREMENT IN AWS D1.1

In 1966, AWS D1.1 (D1.0 and D2.0 at that time) imposed 4-hour requirements on storage and issue of all low hydrogen electrodes. In 1969, the requirements were modified, with separate statements being made for AWS/SFA 5.1 electrodes and more restrictive statements made for the AWS/SFA 5.5 electrodes. It appears that the 4-hour exposure limit in D1.1 paragraph 4.9.2 is based upon avoidance of porosity with the worst of the six electrodes tested by D.C. Smith in 1956. The D.C. Smith Welding Research Council (WRC) report is included in Appendix E.

Recent inquiry was made to Mr. T. G. Ferrell, current Chairman of the D1.1 Subcommittee having jurisdiction over paragraph 4.9.2, as to the basis for the requirement. It was indicated by Mr. Ferrell that this was based on electrode manufacturer recommendations, and that the most conservative or worst case was used as the AWS D1.1 basis. It appears that U.S. Steel test data for AWS/SFA 5.5 low alloy electrodes was also considered by the Subcommittee. Mr. Ferrell did not recall if the restrictions in paragraph 4.9.2 were originally intended to apply to unalloyed mild steel electrodes, as well as to alloyed electrodes. He indicated that the paragraph is not clearly written. He also indicated that AWS D1.1 is considering changes to the paragraph to allow longer times based upon fabricators' or installers' tests. Mr. Ferrell agreed that the 4-hour limit applied to E7018 electrodes when welding mild steel was conservative.

Similar inquiry was made of A. J. Julicher, long standing member of the AWS D1.1 Main Committee, and Dr. A. Lesnewich, Director of Research at Airco Welding Products and President-Elect of AWS. These gentlemen were in agreement that the historic basis of the 4-hour requirement resulted from the most conservative of the electrode manufacturers' recommendations. There was also agreement that the 4 hours was conservative when applied to E7018 electrodes when welding mild steel and was probably intended for those cases when E7018 electrodes would be applied to alloy steel. Further details on the evolution of this requirement in AWS D1.1 is provided in the Commentary by A. J. Julicher (Appendix H).

The Commentary on the Structural Welding Code, AWS D1.2, was issued by the AWS in 1977. The Commentary on AWS D1.1, paragraph 4.9.2 deals mostly with alloy electrodes and the case when lower strength electrodes (E7018) were used to weld A514 and A517 steels (100,000 psi yield strength materials). The last two paragraphs in the AWS Commentary dealing with this subject confirm that the moisture control requirements are based upon the moisture absorption of the worst case electrodes and that the requirements are conservative.

The last AWS Commentary paragraph on this subject states:

> "The time restrictions on the use of electrodes after removal from a storage oven may seem overly conservative to some users. The rate of moisture absorption in areas of low humidity is lower than that encountered in areas of high humidity. The Code covers the most restrictive situations."

### 5.1.1 Base Materials

Most grades and types of structural steels used in nuclear power plant construction do not require the use of low hydrogen electrodes. The structural and piping steels for the most part are 38,000 psi yield strength or less. AWS D1.1 permits the use of non-low hydrogen electrodes for mild steels and does not impose storage or issuance restrictions on the non low hydrogen electrodes. As AWS D1.1 would permit the entire mild steel structural fabrication to be made without low hydrogen electrodes, it is extremely conservative, if not contradictory, to impose restrictions on the E7018 low hydrogen electrodes used to weld mild steel. Appendix B contains further discussion of this subject including the reasons why low hydrogen E7018 electrodes are selected. The reasons for E7018 selection relate to welder appeal and usability. The AWS D1.1 requirements appear to assume that fabricators or installers will use E7018 electrodes only as required by the Code and further assume that E7018 electrodes will not be used unless required. These are not valid assumptions.

### 5.1.2 Other Codes

Other AWS codes and specifications do not provide specific restrictions on electrode storage and issuance. Some of these are discussed in Appendix B. The Specification for Welding Industrial and Mill Cranes, AWS D14.1, is mute on the subject of electrode control. The responsibility for procedures

and practice will result in weld joints meeting specification requirements is assigned to the manufacturer. This approach allows fabricators and installers to develop appropriate electrode controls for each application. Similar practices are followed by ANSI B31.1 for power piping and ASME Section III, Division 1.

## 5.2 EVALUATION OF THE LITERATURE

The data presented and discussed in Appendix E represents a great deal of the information on moisture absorption by low hydrogen electrode coatings. Four of the references (4, 5, 6 and 7[a] which are reproduced in Appendix E) relate to the specific percentages of moisture gained or lost by electrodes and the significance of this moisture gain is interpolated to effects on porosity or underbead cracking.

At this point, it should be re-emphasized that the various investigators of electrode moisture and hydrogen cracking have generally produced what is best described as negative data or indirect evidence for the welding of mild steel with E7018 electrodes. The data which has been published relates primarily to those materials which are susceptible to the phenomenon of hydrogen embrittlement and underbead cracking. Thus, the data on cracking presented in Appendix E and the enclosed references is not relevant to power plant construction using mild steels because the base materials tested represented higher carbon contents, higher alloy content, or higher strength levels. The data presented in Appendix E is valid as regards porosity since porosity is not related to base material hardenability or restraint. Investigators have used alloy materials because these steels have sufficient hardenability to develop the microstructures susceptible to underbead cracking.

A significant fact frequently overlooked is that Mallet and Reippel at Battelle, (Appendix E, Reference 4) in a first test series did not find underbead cracking with low hydrogen electrodes which had been steamed to produce 6-percent moisture in the coating. Non-low hydrogen electrodes produced significant cracking in other test series using an unspecified alloy steel. The other test series used a higher alloy content plate that was more crack sensitive. This data is significant because it shows that moisture absorption alone is not a determining factor in developing underbead cracking and demonstrates the importance of the alloyed base metal in developing underbead cracking.

Reference 4 in Appendix E clearly indicates that the absorbed moisture is converted by the arc energy to molecular hydrogen (H) and is dissolved in the molten weld metal in direct relation to the square root of its partial pressure. H dissolved in weld metal will be lower if the partial pressures of CO, O, or $CO_2$ from limestone in the coating are increased in the arc atmosphere. Again Appendix E, Reference 4 indicates the significance of crack sensitive steels.

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a. Reference numbers are as shown in Appendix E on the last page of "Further Information on Eliminating the Use of Portable Rod Warmers," by G. R. Schmidt dated July 30, 1976.

Stout and Doty in Weldability of Steels, page 165, indicates that an essential feature for underbead cracking is the transformation of austenite to martensite. Weldability of Steels is referenced by Appendix E, but is not included. The formation of martensite is dependent on base metal alloy composition and cooling rates from austenitic temperatures. Plain carbon steels are not sufficiently alloyed or hardenable to form martensite with the cooling rates associated with shielded metal arc welding.

Cooling rate effects are clearly shown in Appendix E, Reference 2, Figure 12 which was developed by Burdekin, et al of the British Welding Research Association. The area labeled NO CRACKING SUSCEPTIBILITY represents the mild steels and the welding conditions of interest. The steels are shown by the abscissa (carbon equivalent), and the cooling rates of interest for shielded metal arc welding are shown by the ordinate rates (five degrees C per second or less). This figure shows that for the materials of interest there is a wide safety margin in cooling rates before cracking susceptibility is reached. Appendix E, Reference 2 also stresses the importance of the martensitic structure in developing susceptibility to hydrogen cracking. This author is somewhat critical of other investigators (such as those in Appendix E, Reference 3) for developing formulas applicable to a relatively limited range of steel compositions which are useful for laboratory comparisons of steels, electrodes, and procedures, but not useful for specification or acceptance purposes.

The criticism of Reference 3 and many similar articles is valid for the reasons given and because experience of 30 years has shown the results of Reference 3 to be ultraconservative for mild steel. The results have validity limited to low alloy materials similar to those used in the data base. Reference 3 has taken an interesting theoretical approach to quantifying preheat and energy input for various welding processes grouped by hydrogen potential. The theory is composed of two basic assumptions: first, that a hardness level can be determined below which cracking will not be present even in restrained joints, and second, that this hardness level can be related to a critical cooling rate. The approach breaks down because it fails to recognize the importance of microstructure, as distinguished from hardness, and does not properly address the influence of alloying on hardness or microstructure at a given cooling rate.

On the second point, shown in Figure 3C of Reference 3, the hardness data for very low alloy steels and mild steels did not fit the theoretical curve based on alloy steel so that authors developed a correction factor. It is these points on which this theoretical approach breaks down and results in overly conservative results and conclusions. The authors recognized that welding engineers have tended to consider the resultant diagram overly conservative and discussed several additional reasons for this opinion, but overlooked the error of extrapolating alloy steel data to mild steel applications.

5.3 ALTERNATE PROCEDURES

Recognition of the difficulty in converting laboratory data and technical reports to meaningful results in practical situations led to the development of Appendix B, a brief summary of industrial experience, requirements of various codes and standards, and an explanation of why low hydrogen electrodes are used in power plant installation even though such

electrodes are not metallurgically necessary for mild steel welding. Appendix B calls attention to the Specification for Mild Steel Electrodes, AWS/SFA 5.1, to explain the original purpose of E7018 electrodes. These electrodes were developed for welding higher strength, high carbon or alloy steels in which electrodes other than low hydrogen electrodes produced underbead cracking. Although these cracks do not occur in mild steels they may occur whenever a non-low hydrogen electrode is used on high strength steels.

5.4 WRC BULLETIN 216

This bulletin, published in 1976, is a definitive study of the hydrogen cracking problem and, while not directly addressing structural steels or mild steel welding, does provide guidance on the conditions necessary for the cracking phenomenon. This bulletin is included as part of Appendix F. Four conditions are required for hydrogen induced cracking. The conditions are a source of hydrogen, tensile stress, a susceptible microstructure, and low temperature. At least two of the required conditions are not obtainable in mild steels. It is not possible to develop the required residual tensile stress in material of 38,000 yield strength or less. Additionally, it is not possible to develop the required martensitic structure in mild steels welded with E7018 electrodes because the cooling rates are insufficient. Any preheat application essentially eliminates the low temperature requirement as hydrogen rapidly diffuses from preheated joints. Thus, two or three of the four requisite conditions necessary for hydrogen induced cracking are not present in mild steel weldments.

## 6. <u>INDUSTRY PRACTICE AND EXPERIENCE</u>

Industry practice and experience vary over a wide spectrum from almost no control to the very tight controls found in some fabrication shops and shipyards welding low alloy quenched and tempered steels. Some of the practices and experiences of alternative electrode control for structural applications, Navy and shipyard practices, and heavy construction projects are summarized in Appendix G.

6.1 SUMMARY OF INDUSTRIAL EXPERIENCE

Bechtel and others have demonstrated that alternative E7018 electrode controls may be successfully implemented in severe environments.

Successful implementation has several common features. These common features are:

A. The electrodes are issued for a shift and retrieved at the end of shift.

B. The electrodes are stored in heated storage ovens with minimum temperatures of 150F.

C. Outdoor applications involved electrodes issued in containers and n rod warmers.

D. The applications are on mild steel.

It has become apparent that 30 years of successful alternative industrial practice with E7018 electrodes when combined with the data reported in the literature has substantiated that there need be no concern for hydrogen cracking in mild steels when E7018 electrodes are used.

## 7. RECENT TEST PROGRAMS

Several recent test programs have been conducted to demonstrate the effects of exposure to high humidity on the usability of E7018 electrodes and the metallurgical acceptability of the resultant weld joints. These test programs have directly addressed the two concerns regarding E7018 electrodes used on mild steel weldments after exposure to high humidity: these are hydrogen embrittlement, especially underbead cracking, and weld metal porosity.

### 7.1 PVNGS TEST PROGRAM

A test program was conducted by Bechtel to justify the alternative electrode control program at the PVNGS jobsite, under the worst anticipated conditions of exposure by qualifying an alternative electrode control procedure in accordance with AWS .1, Paragraph 5.2 (refer to Appendix A). The test program was expanded to include data in excess of that required by AWS D1.1 for qualification, in order to produce conclusive and conservative data for the worst conditions of humidity, exposure time, restraint and relevant base metal. This program is reported in Appendix C. The program was designed to evaluate the net effects of exposure time and percent humidity on the usability of E7018 electrodes based on the metallurgical and radiographic acceptability of completed mild steel weld joints. Similarly, Chemetron Corporation was commissioned to conduct a parallel program to that of Bechtel using their electrodes to provide support and confirmation of the Bechtel data. The results of this program are reported in Appendix D. The test results reported in Appendices C and D conclusively demonstrate that even under the most severe conditions of exposure to humidity and restraint that a 12 hour minimum out-of-oven time is technically justified and fully qualified to the requirements of Paragraph 5.2 of AWS D1.1.

The electrodes tested were from manufacturers presently being used at PVNGS from other potential sources. Electrodes were exposed to 100 percent humidity prior to welding. This represents a saturated condition at which condensate will form on cooler surfaces. The saturated condition represents the worst possible humidity situation. Electrodes were exposed to 100 percent humidity for repetitions of 20-hour periods. In addition, higher strength mild steel materials were tested. The A516, Grade 70 material with 70 ksi minimum ultimate strength represents the upper end of the mild steels in terms of hardenability and susceptibility to underbead cracking. Using circular patch tests, an extreme degree of restraint was developed. The diameter of the patch, in relation to coupon size was selected to assure weld strength level residual stresses (Welding Metallurgy, Volume 2, 3rd Edition, page 636, by Linnert).

The usability evaluation was based upon weld metal porosity. The ASME Section III radiographic acceptance standard was used since this is the criterion required for most construction weld joints, and is as severe or more severe than the AWS D1.1 criterion. Arc stability and slag characteristics for welder appeal were evaluated by the test welder.

The metallurgical acceptability was based upon mechanical tests and metallography. The transverse mechanical tests were chosen in place of all weld metal specimens so that the heat affected zone (HAZ) could also be evaluated. Bend specimens were selected because the test loading rate is more appropriate to show potential hydrogen embrittlement. Also, HAZ impact test results would be more dependent upon base metal characteristics rather than electrode characteristics.

The radiographic acceptability of all tests coupons including the root layer welded without preheat on cold plate deserves special emphasis, as it demonstrates that the 300F interpass temperature which was subsequently developed for the later fill and cap passes was not a controlling or limiting factor on the program results.

The test program fully qualified the weld filler metal control procedure WFMC-1, Revision 6, and showed that hydrogen embrittlement or underbead cracking will not occur when implementing this procedure on mild steel weldments and that porosity will not be a problem or result in unacceptable welds when implementing this procedure.

## 7.2 MIT TEST PROGRAM

A U.S. government sponsored study at the Massachusetts Institute of Technology has investigated hydrogen cracking in underwater steel welds. This study has shown no observable hydrogen cracks in either underwater or surface welding of mild steel. The data indicates that at least a 50,000 psi yield strength steel was required to induce hydrogen cracking in underwater welding applications. This data is significant because of the ultimate moisture present in the underwater environment on both the base metal and in the electrode coatings, and because of the extremely rapid cool rates achieved due to water quenching. E7018 electrodes were included in these conclusions. This was reported in the August, 1977, Welding Journal and is included in Appendix F.

These underwater welds were conducted on the severe Y-slit self-restrained cracking test coupon. This coupon is severe because of the presence of a geometric notch in addition to restraint. The water environment presented an unlimited hydrogen potential to the weld joint from the arc atmosphere by reduction of the liquid phase . Various coating types and waterproofings were studied and found to have little effect on results. The water environment at 70F provided a large heat sink capable of quenching the weld metal and heat affected zones. Figure 3 of this reference shows the E7018 weld metal and adjacent heat affected zones to be crackfree.

Figure 4 of the reference shows the mild steel heat affected zone to have a Widmanstatten structure, not martensite, and not susceptible to underbead cracking even when water quenched. The validity of the test procedure was demonstrated by the cracking obtained when higher strength or alloy materials were welded underwater. Duplicate Y-slit restrained tests welded in air on mild steel and alloy steel base metal confirmed that mild steels are not susceptible to underbead cracking.

## 8. CONSULTANTS REVIEW AND COMMENTARY

Three independent consultants of varied professional welding backgrounds were utilized to provide impartial and experienced evaluation of the test program and its results. One of the consultants, C. B. Robinson, was also asked to act as a witness to monitor the Bechtel portion of the PVNGS test program to assure that performance was as described in the various reports. The commentary of each consultant is contained in Appendix H.

### 8.1 BIOGRAPHIC SKETCH OF CONSULTANTS

C. B. Robinson has more than 40 years practical experience, first with the U. S. Navy, and then with private industry. He is currently an active consultant to several Bay Area fabricators and a commercial shipyard.

A. J. Julicher is a member of the AWS D1.1 committee and has served on that committee for many years. Formerly associated with the National Bureau of Standards, he is an active consultant to many organizations including the U.S. Air Force.

Dr. A. Lesnewich is Director of Research, Airco Welding Products, and President-Elect of the AWS for 1978-1979. He is a recognized authority in welding, metallurgy and welding electrodes.

### 8.2 SUMMARY OF CONSULTANTS COMMENTARY

The commentary of all three consultants indicates agreement with the test results and with the soundness of the conclusion that a maximum 12-hour out-of-oven time for E7018 electrodes used for welding mild steel is technically justified.

#### 8.2.1 Commentary of C. B. Robinson

The commentary of C. B. Robinson indicates the Bechtel and Chemetron test results show that even under the severe condition of 100-percent humidity exposure for as long as 12 hours, E7018 electrodes are acceptable in welding mild steel. This conclusion is reinforced and emphasized by C. R. Robinson's witnessing and monitoring of the Bechtel test program.

The commentary discusses the acceptable mechanical and bend test results. It is noted that the radiographic examination revealed acceptable film clarity and there is a lack of evidence of underbead cracking. He commented on the single cluster of porosity found in one of the 86-percent humidity coupons and indicated that metallographic examination showed no cracking even in the highly restrained circular patch coupons.

The commentary then discusses the need to distribute low hydrogen electrodes in controlled containers, although they need not be heated, for periods of as long as 12 hours. The point is made that unused electrodes should be returned to holding ovens and, if exposed for more than 12 hours, the electrodes should be reconditioned in accordance with manufacturer's recommendations or discarded.

The commentary concludes that the 12-hour limit on exposure and the requirement to issue electrodes in unheated containers is acceptable and that test results qualify WFMC-1, Revision 6 as an alternative electrode control procedure as permitted by paragraph 5.2 of AWS D1.1.

### 8.2.2 Commentary of A. J. Julicher

The commentary of A. J. Julicher begins with a statement of the thoroughness and completeness of the Bechtel and Chemetron tests and results. Based on the test results, it is concluded that WFMC-1, Revision 6 has been qualified as an alternative electrode control procedure. It is also noted that WFMC-1, Revision 6 with the 12-hour exposure limit is conservative in terms of the 20-hour test data, and incorporates issue of electrodes in identified containers with provisions for retrieval of unused electrodes.

The commentary provides a rather lengthy discussion of the evolution of electrode moisture requirement in AWS D1.1. This information may be of interest to those wishing some insight into the history of this requirement. The history does indicate, however, that the AWS D1.1 Committee has had some difficulty in deciding how or if to state electrode moisture requirements and that the trend has been to adopt the most conservative approach.

The commentary concludes with the recommendation that the Bechtel and Chemetrom test results be submitted to AWS D1.1 for use in modifying the E7018 electrode moisture control requirements and suggests that additional testing be conducted on higher strength low hydrogen electrodes and higher strength steels. Current test data will be submitted to AWS 1.1 with a request to modify present electrode moisture control requirements.

### 8.2.3 Commentary of Dr. A. Lesnewich

The commentary of Dr. Lesnewich starts with agreement with conclusions of the Bechtel and Chemetron reports that E7018 electrodes can be exposed to moist air for extended times without resulting in either porosity or delayed cracking in weldments of structural grades of carbon steels. After discussing the amount of moisture that can be expected to be absorbed by E7018 electrodes and relating this to Airco Products, the important point is made that hydrogen induced cracking also requires high stresses, susceptible microstructures and time, in addition to the presence of hydrogen.

The commentary continues by emphasizing the importance of microstructure and residual stresses. It is noted that residual stresses are probably below 70 ksi; however, it should be remembered that circular patch tests were conducted and that these tests are among the most highly restrained yet devised. Also mentioned is the 300F interpass temperature and the benefits that result in mitigating hydrogen induced cracking. This observation is correct, but it should be pointed out that the interpass temperature is a requirement of AWS/ASME 5.2 and is used in all testing of fill material to this specification.

The commentary concludes that based on review of the Bechtel and Chemetron data, as well as other published information, Dr. Lesnewich is in agreement that E7018 electrodes can be exposed for at least 12 hours without resulting in defects in mild steel weldments.