NUREG/CR-3911
PNL-5181
Vol. 1

Evaluation of Welded and Repair-Welded Stainless Steel for LWR-Service

Quarterly Report
January-March 1984

Prepared by D. G. Atteridge, S. M. Bruemmer, R. E. Page

Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory Commission

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NUREG/CR-3911
PNL-5181
Vol. 1
R5

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Manuscript Completed: October 1984
Date Published: November 1984

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NRC FIN B2449

ABSTRACT

The Division of Engineering Technology, U.S. Nuclear Regulatory Commission, is sponsoring a program at Pacific Northwest Laboratory to evaluate welded and repair-welded stainless steel piping for light-water reactor (LWR) service. Stainless steels often become sensitized, or less resistant to stress corrosion cracking (SCC), after undergoing heating and cooling cycles such as those encountered in welding. The weld heat-affected zone (HAZ) is often the site of crack initiation. This program will therefore measure and model the development of a sensitized microstructure and its resultant resistance to SCC in welded and repair-welded stainless steel pipe. The result will be a method to assess the effects of welding variables on the SCC susceptibility of component-specific nuclear reactor welds/repairs.

The progress achieved toward this objective during January - March 1984 is described in this report.

SUMMARY

The Division of Engineering Technology, U.S. Nuclear Regulatory Commission, is sponsoring a program at Pacific Northwest Laboratory (PNL) to evaluate welded and repair-welded stainless steel (SS) piping for light-water reactor (LWR) service. Stainless steels often become sensitized, or less resistant to stress corrosion cracking (SCC), after undergoing heating and cooling cycles such as those encountered in welding. Once sensitization occurs, an area known as the heat-affected zone (HAZ) of the weld is often the site of crack initiation. This program, therefore, will measure and model the development of a sensitized microstructure and its resultant resistance to SCC in welded and repair-welded SS pipe. The degree of sensitization (DOS) of the weld HAZ will be predicted from a model based on experimental data, and then an empirical correlation between DOS and susceptibility to SCC will be determined using constant extension rate tests (CERTs). The result will be a method to assess the effects of welding variables on the SCC susceptibility of component-specific nuclear reactor welds/repairs.

The PNL program is divided into three experimental tasks. Task I will identify and measure the welding and weld-induced parameters that have a major effect on resultant DOS. A method to predict the thermomechanical (TM) history of the HAZ in contact with the coolant environment will be developed under Task I. Task II will assess and model the influence of material composition and TM history on a steel's susceptibility to IGSCC. Task III will use the data bases generated in the first two tasks to predict SCC from component-specific TM histories of weld/repair HAZs.

This report is an account of the work performed toward meeting the program objectives during the January - March 1984 quarter. Significant goals for this reporting period include the redesign of the attachment stud for the clip gage used to measure the TM history of the experimental welds, the design and fabrication of a prototype unit for operating a gas tungsten arc welder without generating radio frequency during arc starting which interferes with the computer system used in weld data collection, and the preparation of a working draft of a review report which discusses compositional effects on sensitization of SS pipe.

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INTRODUCTION

Pacific Northwest Laboratory (PNL)[a] and the Division of Engineering Technology of the U.S. Nuclear Regulatory Commission (NRC) are conducting a program to determine a method for evaluating welded and repair-welded stainless steel (SS) piping for light-water reactor (LWR) service. Validated models, based on experimental data, will be developed to predict the degree of sensitization (DOS) and the stress corrosion cracking (SCC) susceptibility in the heat-affected zone (HAZ) of SS weldments. The cumulative effects of material composition, past fabrication procedures, past service exposure, weldment thermomechanical (TM) history, and projected post-repair component life will be considered.

Austenitic SS components of commercial boiling-water (BWR) and pressurized water (PWR) reactors have experienced intergranular (IG) SCC in the HAZ of in-service SS welds. Although only a few instances of such cracking have been observed, their potential for causing serious component failure should not be underestimated. IGSCC is caused by a combination of a sensitized microstructure, an aggressive environment, and tensile stress. Control of any of these three factors can eliminate IGSCC in most practical situations.

This program will measure and model the development of a sensitized microstructure as it pertains to welded and repair-welded SS pipe. An empirical correlation between a material's DOS and its susceptibility to IGSCC will be determined using constant extension rate tests (CERTs). The successful completion of these tasks will result in a method for assessing the effects of welding/repairing parameters on the SCC susceptibility of component-specific nuclear reactor welds/repairs. The test matrix will include various Type 304, 304L, 304NG, 316, 316L, and 316NG SS materials used in nuclear reactor piping systems.

The progress achieved toward the program objectives during the January - March 1984 quarter is presented in the following sections.

(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute.

TASK I: WELD THERMOMECHANICAL HISTORY DETERMINATION AND PREDICTION

Task Leader: R. E. Page

The objective of this task is to develop a method for predicting weld/repair HAZ histories on the inside surface of pipe welds. A weld/repair HAZ is subject to a complicated strain history superimposed over the heating and cooling cycle. Recent work indicates that this strain cycle increases the resultant sensitization of the HAZ over that predicted from strain-free isothermal data or that measured in specimens subjected to a similar but strain-free heating and cooling cycle. It is therefore necessary to precisely determine the strain/temperature history of a HAZ. The HAZ strain history is more complex in a multipass weld/repair than in a single-pass weld/repair. Strain history is also more complex in a pipe weld/repair than in a plate weld/repair; stresses can be relieved by plate bending, while circumferential restraint restricts metal movement in a pipe weld.

A major goal of this task is therefore to identify and measure the pipe welding and repair-welding variables that have a major effect on resultant DOS, and to assess the ability to predict HAZ TM histories analytically. The initial work will be oriented toward experimentally determining HAZ TM histories of welds/repairs as a function of pipe size and heat input. These data will then be used to assess analytical methods for predicting TM histories of generic pipe welds/repairs and the effect of specific welding and repair-welding variables on the resultant TM history.

The focus of the current experimental work is on developing the instrumentation needed to determine the TM history of a thin layer of material on the inside surface of 24-in.-dia. pipe, as it is this region that controls IGSCC initiation. The placement of strain measurement devices and thermocouples on this surface will allow real-time TM history measurement.

TECHNICAL PROGRESS

Instrumentation of SS Pipe. Strain-sensing devices and thermocouple attachment techniques are being developed in preparation for recording strain and temperature histories of welded pipe HAZs as a function of arc-on time and distance from the fusion line. The instrument development is being carried out on a flat plate feasibility weld. A section of Schedule 80 Type 304 SS pipe (24-in.-dia.) has been prepared for welding and the TM history recording devices will be installed as soon as use feasibility has been determined.

Two major instrumentation problems were addressed this quarter: the development of a method for attaching the surface strain-measurement devices to the pipe surface, and the development of an arc-starting method that does not employ high-frequency voltage.

Attachment of the Surface Strain-Sensing Devices. Thermally insulated MTS crack-opening displacement clip gages will be used to measure surface strains.

The thermal insulation is achieved by attaching ceramic leg extensions to the clip gage. Clip gage attachment studs are welded to the surface of the plate and attachment "feet" are connected to the tops of the studs. The ceramic extension legs of the clip gage have notches on the outside surface of the legs similar to those in the standard MTS clip gage legs. The attachment feet contain knife edges that fit into the clip gage leg notches. The clip gage legs fit between the attachment feet as shown in Figure 1.

The surface strain-measurement devices will be attached to the pipe counterbore surface and a thermocouple will be welded to the pipe midway between the attachment studs. This will allow simultaneous measurement of strain and temperature at a given distance from the weld centerline. The feasibility of using this type of a strain-measurement device was determined using the flat plate weld shown in Figure 2. A typical strain-sensor output as a function of arc-on time is shown in Figure 3; the corresponding surface temperature is also indicated. There is essentially no change in strain until the heat from the arc arrives, at which time the surface first goes into compression and then into tension. The data indicate that a permanent plastic strain is present after welding.

A series of remelt passes were made on the flat plate feasibility weld and a discrepancy was found between the manually measured strain induced in the plate and the strain change indicated by the strain-measuring devices. The manual strain measurements showed essentially no movement, while the strain-measuring devices indicated that up to 0.010 in. of movement had taken place. An investigation showed that the attachment studs deformed during the welding cycle due to the applied stress from the legs of the strain-measuring devices.

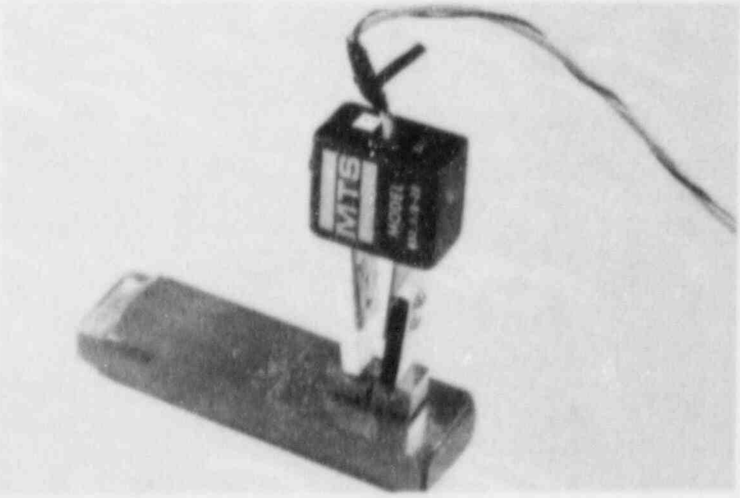


FIGURE 1. MTS Clip Gage Adapted for High-Temperature Use. Gage is in place between attachment feet that are connected by studs to the surface of the SS block.

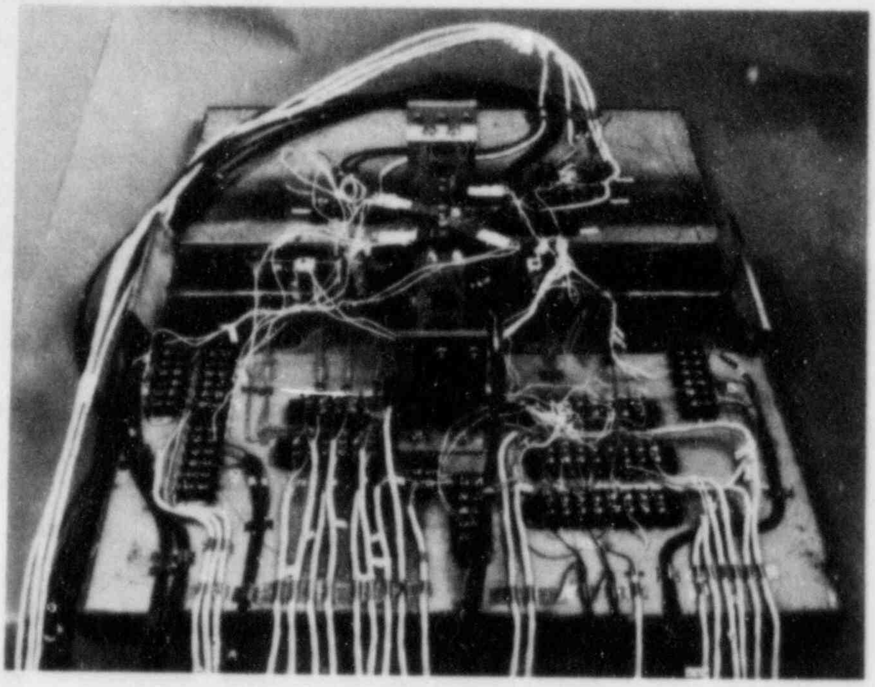


FIGURE 2. Flat Plate Feasibility Weld Showing Instrument Domain, Thermocouple, and Surface Movement Marker Layout

It was experimentally determined that the clip gages applied a maximum load of 4 lb to the feet. Cantilever beam bending equations were used to estimate the stress at the outside fiber of the beam where it attached to the pipe. The beam length was defined as the distance between the point of applied load and the pipe surface. The results of these calculations are shown in Figure 4 as a series of curves of moment arm as a function of maximum outer fiber stress. The curves yield the maximum outer fiber stress to which the attachment studs are subjected at the point of attachment as a function of stud diameter and applied moment.

The maximum outer fiber stress can be compared with the yield stress of the Type 304 SS stud as a function of temperature (the dashed curve in Figure 4) to determine the minimum stud diameter that will not yield at a given temperature and moment. It was decided to use a stud diameter of 0.125 in. and a moment of 1.2 in.-lb (a load of 4 lb at 0.3 in.) as the stud and feet attachment criteria. These criteria resulted in a stud capable of withstanding temperatures approaching 1000°C.

Surface strain-measurement devices with attachment stud diameters of 0.125 in. were tested on the flat plate weld. The test results indicated that the extraneous plastic deformation was substantially decreased but may not have been completely eliminated. This was difficult to determine, however, because the strain-measuring devices were much more sensitive than the manual method for determining stud movement. Therefore, an external spring was developed that reacted on the attachment feet with a force that was equal but opposite to

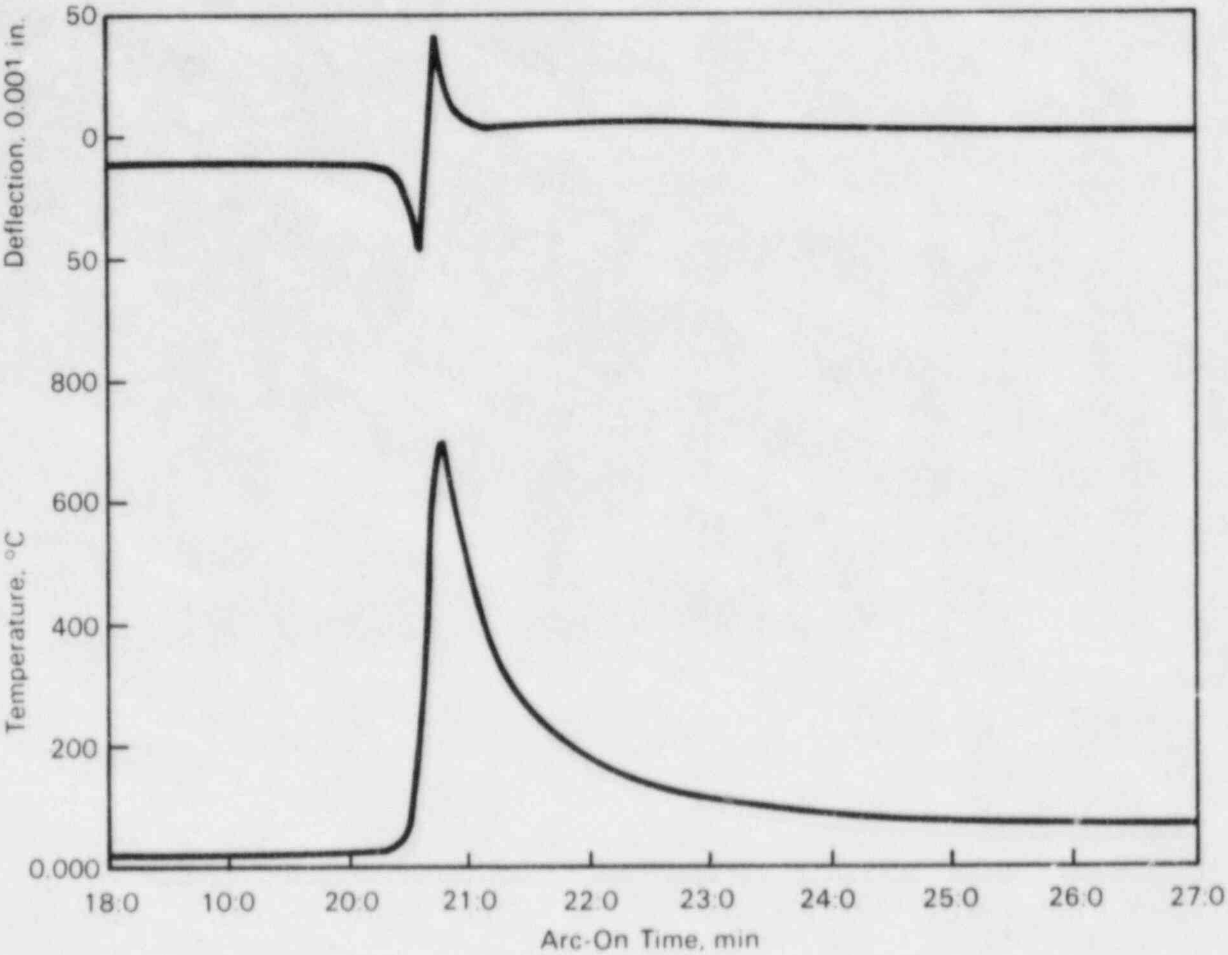


FIGURE 3. Typical Strain and Temperature Measurements as a Function of Arc-on Time

that applied by the clip gages. The use of this spring eliminated all traces of extraneous strain. This surface strain-measurement system (Figure 5) is currently being installed on the 24-in.-dia. pipe.

Data Retrieval and Analysis System (DRAS). The DRAS now records up to 50 channels of data as a function of test time, and will soon be expanded to 66 channels. Its capabilities are adequate for recording and collecting welding data. However, severe radio frequency interference (RFI) was induced in the computer portion of the DRAS by the mechanized gas tungsten arc welder during arc starting. This RFI caused the computer-controlled system to lock up and/or damaged the DRAS command disk. Methods of RF-free arc starting were therefore investigated, as described below.

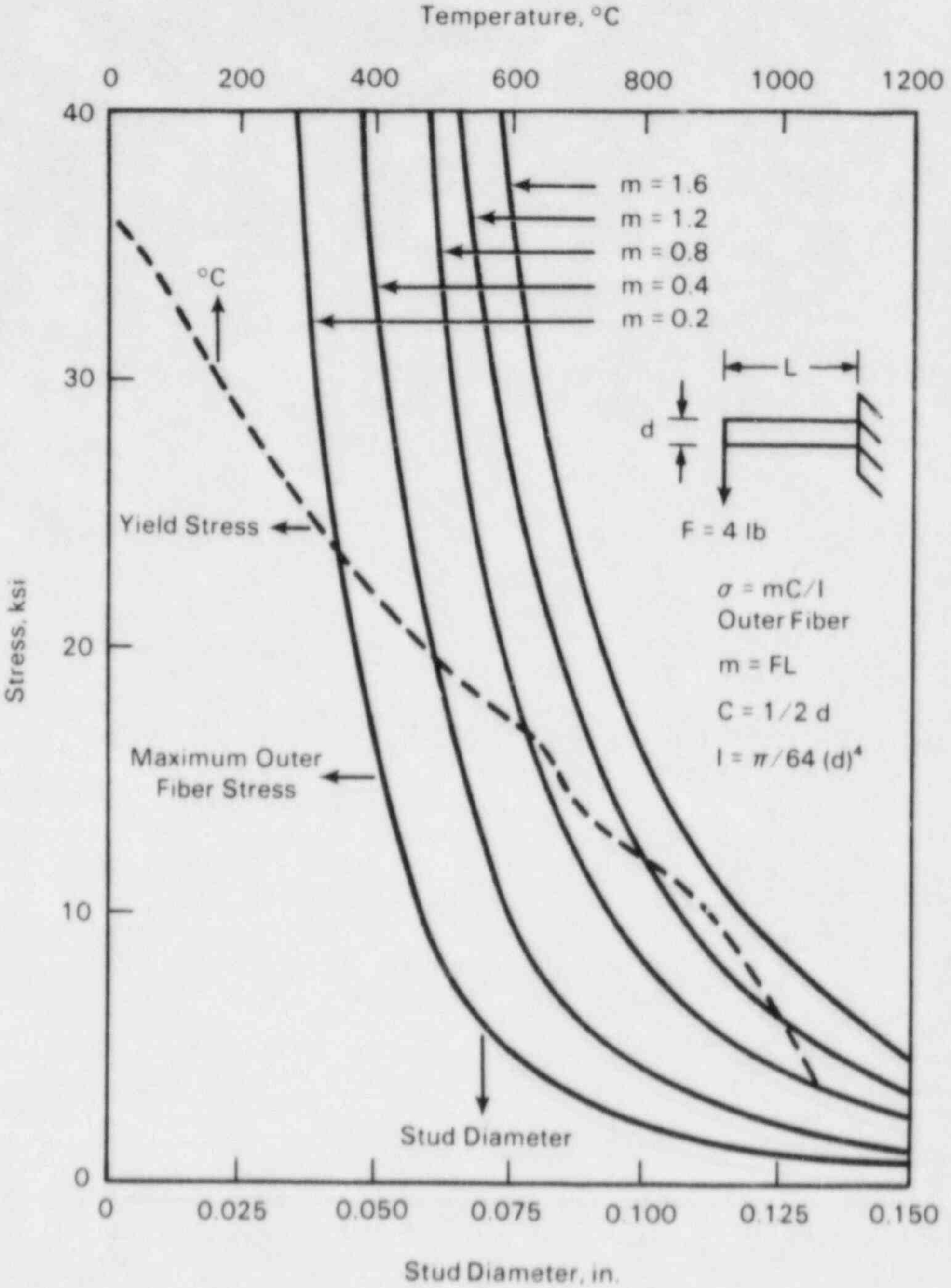


FIGURE 4. Type 304 SS Yield Strength Versus Temperature Plotted over Maximum Outer Fiber Stress as a Function of Stud Diameter and Moment Arm

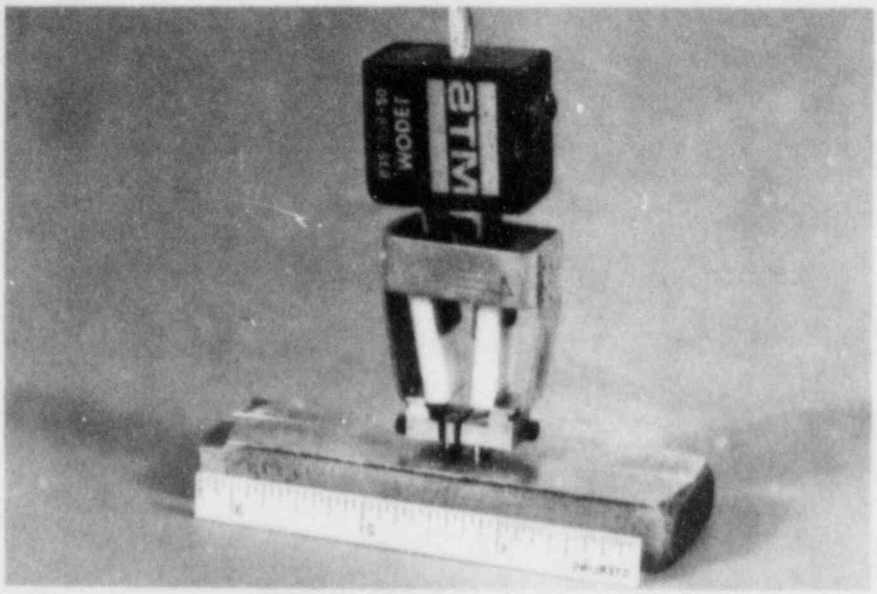


FIGURE 5. Surface Strain-Measurement Device Attached to SS Surface

Investigation of Arc-Starting Techniques. Electrical RF signals generated during gas tungsten arc welding (GTAW) arc starting were found to interfere with the operation of the DRAS. The RFI was capable of "locking up" the analog-to-digital signal conversion unit, requiring a system shutdown and restart before data collection could be continued. RFI was also capable of scrambling information on the main Winchester hard disk, requiring reprogramming of the disk before data collection could continue. The proposed solutions to this problem were to attempt to shield the complete system from the RFI or to eliminate the RFI by not using the commercially supplied RFI generating arc-starting unit supplied with the Astro-arc welding power supply. It did not appear feasible to completely shield the system from RFI; thus a study of alternative arc-starting methods was initiated.

Two important factors considered in selecting an alternative arc-starting method, in addition to RFI elimination, were operating safety and weld quality. A system was judged safe to operate if 1) the operator could simultaneously touch the work piece and the starting electrode without getting an electrical shock and 2) the starting electrode could come in contact with the work piece without initiating an arc. Weld quality criteria included the absence of contamination on the weld or the electrode. The arc-starting methods investigated in this study are listed in Table 1, along with the criteria used to evaluate them. Only the auxiliary electrode arc-starting method with the single thoriated tungsten electrode connected to the welding power supply gave no electrode or weld metal contamination and was a safe operating system.

It was decided that the auxiliary arc energized by the welding power supply was most suited to the program's welding application. This system uses an auxiliary gas-shielded tungsten torch connected to the welding power supply

TABLE 1. Evaluation of Alternative Arc-Starting Techniques

	Contamination		Operating
	Electrode	Weld	Safety
Scratch-starting methods			
With welding electrode	yes	yes	ok
With auxiliary electrode	none	yes	no(a)
Auxiliary electrode arc-starting methods			
Single thoriated tungsten electrode			
With auxiliary power supply	none	none	no
With welding power supply	none	none	ok
Twin thoriated tungsten electrodes	none	none	no
Plasma needle arc	none	none	no

(a) System presents a risk of operator shock and/or accidental arc starts.

ground for arc starting. The auxiliary electrode is brought into contact with the welding electrode as a first step in arc starting. A "touch-start" arc ignites between electrodes because of the voltage potential between the two electrodes supplied by the welding power supply. The auxiliary electrode is then withdrawn from the welding electrode. The starting arc elongates between electrodes during this process until it is more energetically favorable for it to arc down to the work piece. An arc is then formed between the welding electrode and the work piece. The arc between the welding and auxiliary electrodes is extinguished at this time and welding is initiated.

There is no operator shock potential in this method, as the auxiliary electrode is connected to the welding power supply ground lead. Nor is there a potential for unwanted arcing to the work piece as the auxiliary electrode is at the same potential as the work piece. A schematic of this arc-starting technique is presented in Figure 6. A detailed drawing of the arc-starting system fabricated for this program is shown in Figure 7.

FUTURE WORK

The Schedule 80, 24-in.-dia., 304 SS pipe will be ready for welding once the strain-sensing devices have been installed. All thermocouples and sensing-device studs will be welded down. The DRAS system will be expanded to accept 66 channels of data, and the various data output instruments to be used on the 24-in.-dia. pipe weld will be calibrated. Final thermocouple calibration will include an experimental error analysis.

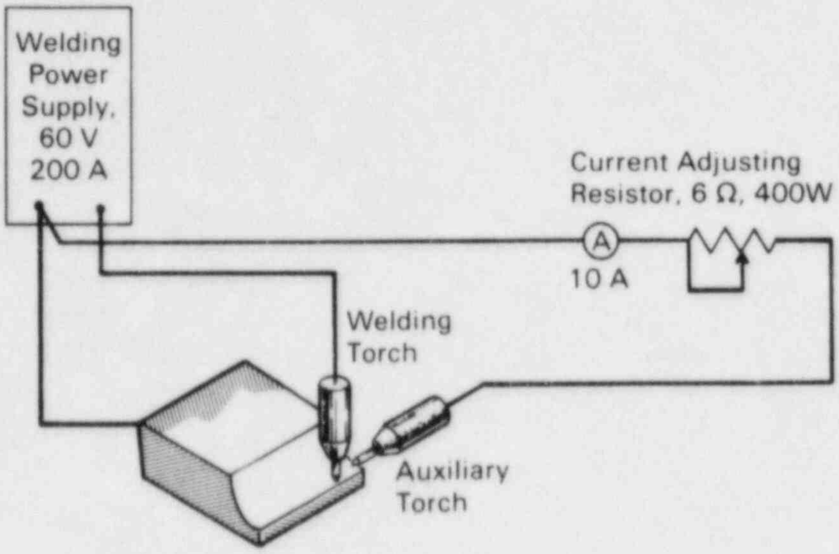
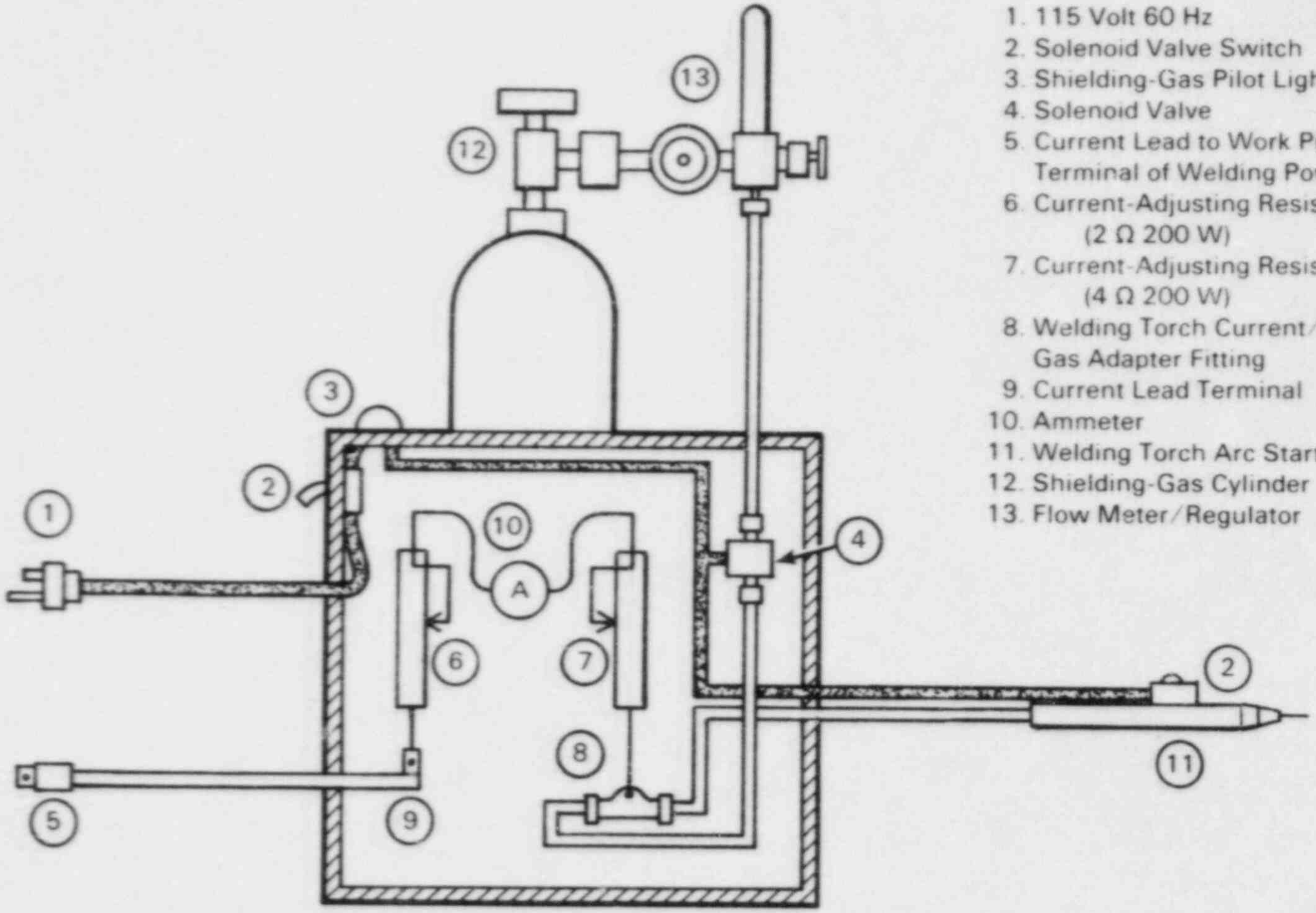


FIGURE 6. Auxiliary Arc-Starting Method Energized by the Welding Power Supply

A report reviewing the various solutions considered in solving the RFI induced in the computer portion of the DRAS during arc starting will be prepared.

Thermal history will be monitored during the welding of 14-in.-dia. Schedule 160 304 SS. Four pipe welds will be monitored for thermal history on a pass-by-pass basis; strain history monitoring will be attempted on a limited basis on the final pipe weld. The pipe welds will be used to test the DRAS functions in a pipe welding application and to assess heat input variations on a series of welds fabricated at nominally the same weld parameters and groove geometry. They will also be used to test out the EPR field cell techniques developed to determine DOS gradients in the 24-in-dia. weld. Post-weld EPR measurements as a function of distance from the fusion line will be taken. Data analyses will include a comparison of the measured DOS profiles with those predicted from the measured thermal histories.



1. 115 Volt 60 Hz
2. Solenoid Valve Switch
3. Shielding-Gas Pilot Light
4. Solenoid Valve
5. Current Lead to Work Piece or Positive Terminal of Welding Power Supply
6. Current-Adjusting Resistor (2 Ω 200 W)
7. Current-Adjusting Resistor (4 Ω 200 W)
8. Welding Torch Current/Shielding-Gas Adapter Fitting
9. Current Lead Terminal
10. Ammeter
11. Welding Torch Arc Starter
12. Shielding-Gas Cylinder
13. Flow Meter/Regulator

FIGURE 7. RFI-Free Gas Tungsten Arc Welder Arc-Starting System

TASK II. INFLUENCE OF COMPOSITION AND THERMOMECHANICAL HISTORY ON DOS AND IGSCC

Task Leader: S. M. Bruemmer

Austenitic SS may become sensitized and thus susceptible to IGSCC when chromium-rich carbides precipitate at grain interfaces, causing a chromium depletion of the adjacent matrix. This phenomenon is controlled by the thermodynamics of carbide formation and the kinetics of chromium diffusion. In a temperature regime in which chromium carbide precipitation is thermodynamically stable (<800°C) and chromium diffusion is sufficiently rapid (>500°C), a SS can become sensitized in a relatively short time.

Stress corrosion cracking of SS has been studied extensively for more than 20 years. However, much of the data that have been generated cannot be directly applied to the understanding and prediction of weld-induced sensitization. The development of a sensitized microstructure depends on a material's bulk composition and TM history. Neither of these factors, nor their effect on IGSCC, is sufficiently understood for accurate predictive modeling.

The primary objective of this task, therefore, is to develop a sufficient data base to predict DOS and IGSCC susceptibility as a function of TM history and material composition. All data will be used in developing a DOS prediction methodology based on thermodynamic and kinetic models. An empirical correlation between DOS and IGSCC susceptibility will be determined in specific reactor-relevant environments, providing a basis for IGSCC susceptibility prediction methodology. The electrochemical potentiokinetic reactivation (EPR) test will be used as a quantitative measure of DOS.

TECHNICAL PROGRESS

Materials. Fourteen heats of Types 304 and 316 SS pipe have been obtained. All pipe heats are 4 in. outside diameter (OD) and either Schedule 40 or 80. This brings the total number of program heats to 24. A purchase requisition for additional Type 316L and 316LN SS heats are out for bid. The total matrix of program heats will allow statistical evaluation of alloying (e.g., molybdenum, nickel, and chromium) and impurity (e.g., nitrogen, phosphorus, and sulfur) elements on sensitization development and SCC resistance. Independent chemical analysis is being performed on all heats; preliminary compositions are listed in Table 2.

EPR Testing. Electrochemical potentiokinetic reactivation (EPR) testing has been completed on Type 304 SS - carbon series specimens. As expected, bulk carbon content was a controlling factor for a heat's sensitization propensity. An example of the effect of bulk carbon on sensitization development is shown in Figure 8 for four Type 304 SS heats. The time required for significant sensitization (EPR-DOS values $\geq 5\ C/cm^2$) at temperatures between 550 and 750°C can be seen to decrease sharply as the bulk carbon content is increased from

TABLE 2. Program Material

			Pipe	Composition, wt%							
Lable	Type	Heat #	Sch.	C	Cr	Ni	Mo	Mn	Si	P	S
SS 1	304L	3406001	40	0.013	18.22	10.05		1.44	0.62	0.031	0.005
SS 2	304L	09947	80	0.013	18.09	10.31	0.27	1.86	0.49	0.020	0.027
C 1	304L	49105		0.015	18.6	9.0	0.13	1.8	0.45	0.019	0.003
SS 3	304L	M59116	80	0.019	18.17	10.18		1.41	0.48	0.028	0.003
C 2	304L	V80575		0.020	18.4	9.0	0.23	1.7	0.50	0.033	0.009
C 3	304	F91156		0.035	18.2	8.7	0.28	1.7	0.60	0.022	0.009
SS 4	304	39590-03	40	0.04	18.13	8.38		1.59	0.60	0.033	0.002
SS 5	304	SD 232	80	0.04	18.31	9.1	0.32	1.50	0.39	0.030	0.002
C 4	304	39232		0.045	18.2	8.4	0.19	1.7	0.75	0.022	0.005
SS 6	304	TV 7041	40	0.047	18.63	8.78		1.81	0.40	0.030	0.005
C 5	304	49145		0.050	18.5	8.9	0.16	1.8	0.60	0.021	0.007
C 6	304	5101A		0.062	18.4	8.7		1.8	0.40	0.015	0.013
SS 7	304	A 11473	40	0.07	19.17	9.32		1.30	0.47	0.023	0.013
C 7	304	159340	40	0.072	18.5	9.3	0.43	1.7	0.46	0.046	0.017
SS 10	316L	39379-04	40	0.013	17.35	12.21	2.05	1.40	0.66	0.033	0.003
SS 11	316L	2S0329H	40	0.015	17.26	12.28	2.08	0.97	0.70	0.031	0.007
SS 12	316L	1S1517D	40	0.016	17.70	12.22	2.17	0.97	0.65	0.030	0.011
SS 13	316	TV 9142	80	0.02	16.56	12.28	2.14	1.69	0.40	0.028	0.003
SS 14	316	837853	40	0.021	17.38	11.40	2.13	1.70	0.60	0.031	0.022
C 10	316	15893		0.054	17.4	12.5	2.17	1.8	0.66	0.032	0.018
SS 15	316	TV 4572	40	0.058	16.78	11.43	2.07	1.74	0.42	0.029	0.005
SS 16	316	01379	80	0.064	16.75	11.10	2.06	1.49	0.24	0.031	0.022
C 11	316			0.08	17.2	11.8	2.05	1.3	0.60	0.031	0.020

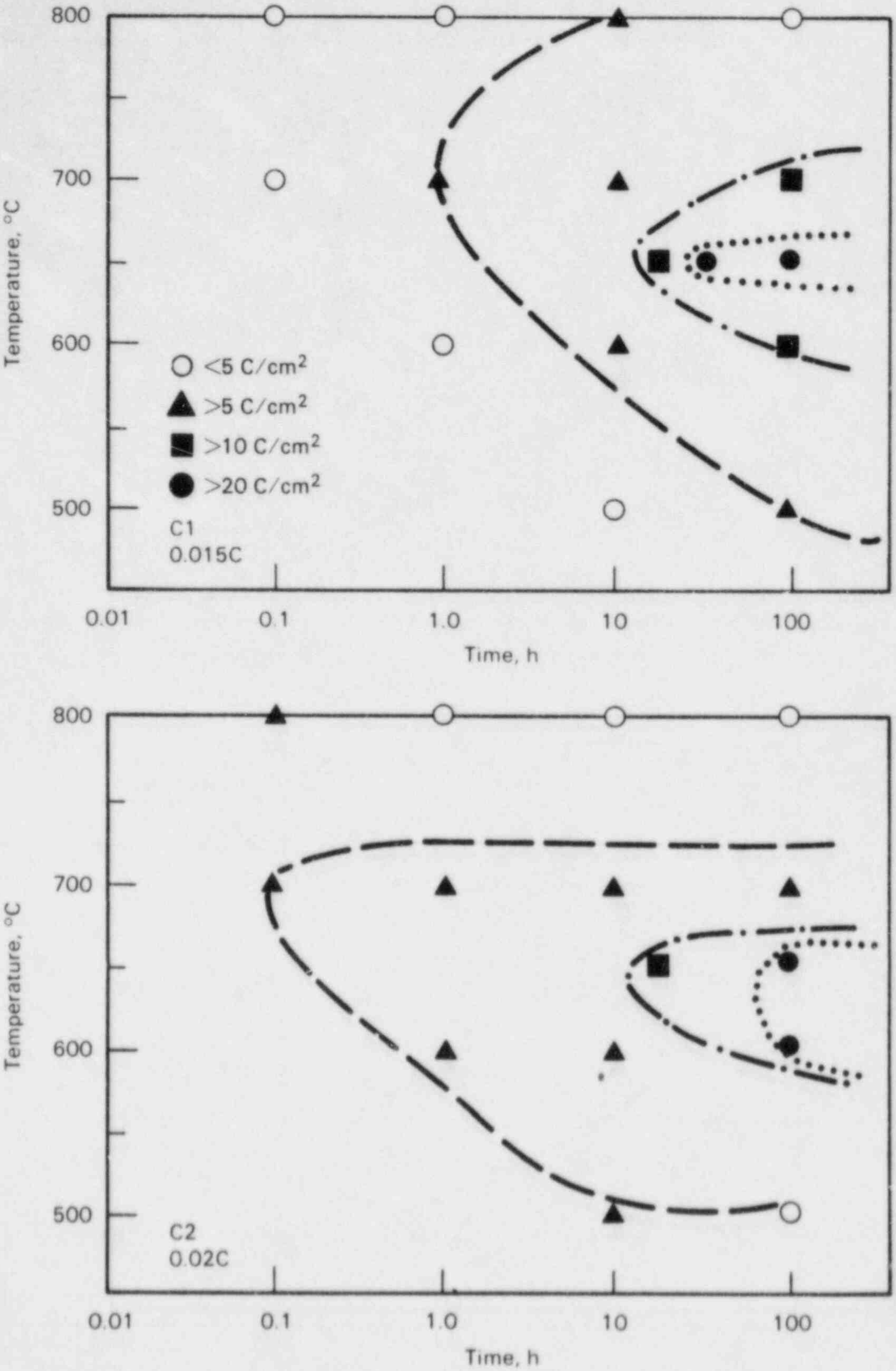
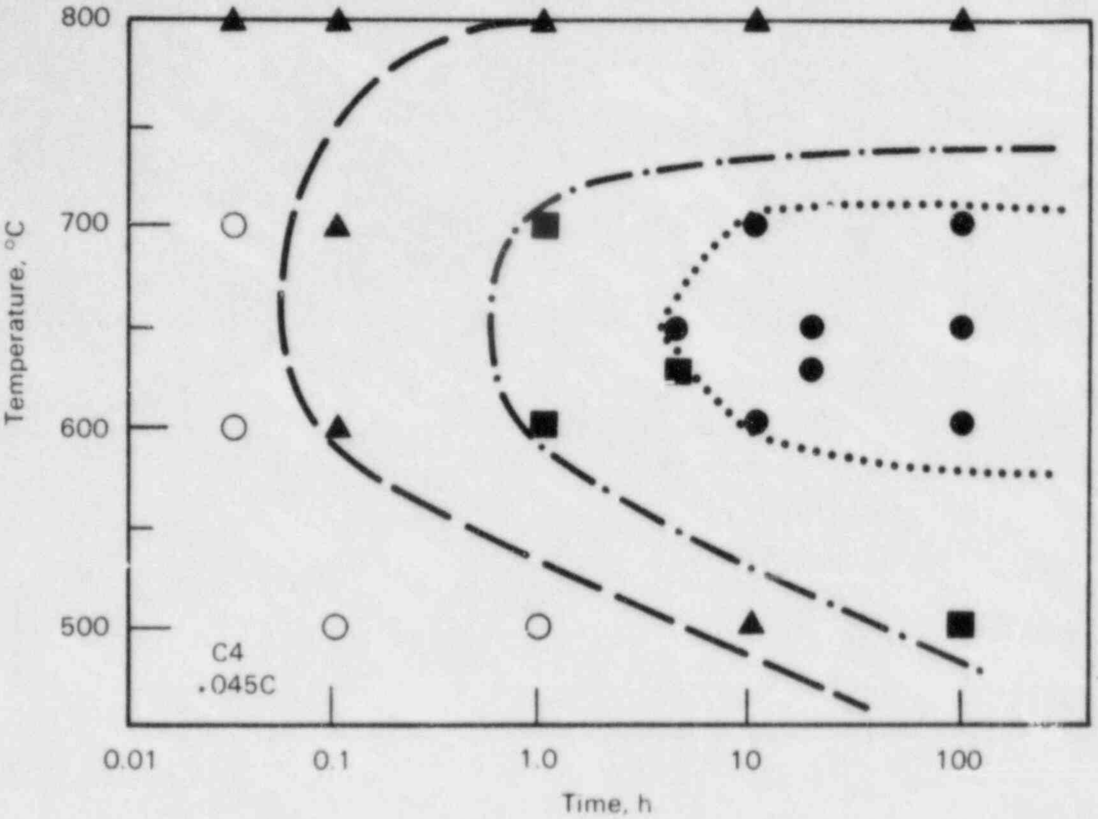


FIGURE 8. Time/Temperature/Sensitization Curves Determined by EPR Tests on Type 304 SS Alloys of Variable Carbon Contents



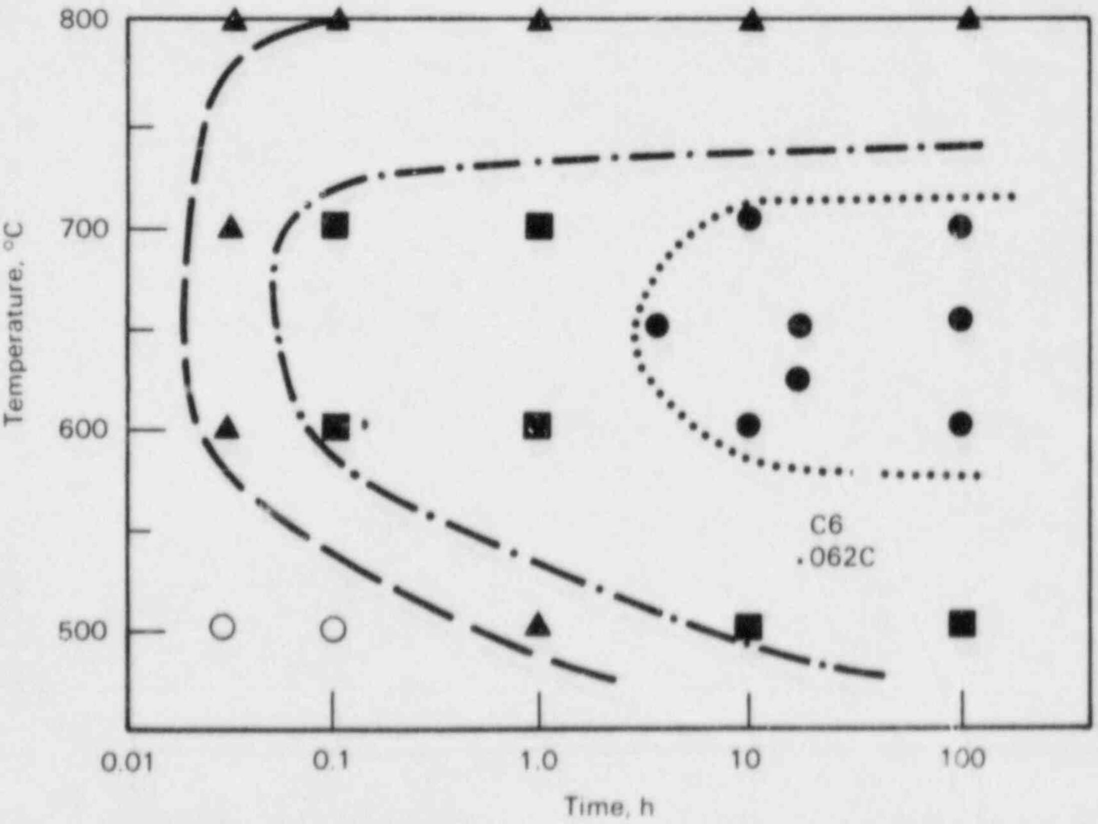


FIGURE 8. (contd)

0.015 to 0.062 wt%. Data of this type will be used to examine and quantify the effects of alloying and impurity elements on sensitization.

Data analysis on the full carbon series is continuing and a comparable test matrix is under way on Type 316 SS heats. The resultant data base on sensitization development will be correlated to initial model predictions.

An additive isothermal heat treatment series of experiments has been completed and the specimens are being prepared for EPR analysis. The modeling of the additive isothermal sensitization is the first step in predicting additive effects in the HAZ during welding. The data from these tests will also provide the data base for determining the effect of strain during isothermal and variable heating/cooling tests.

Compositional Effects. An initial draft of a review report entitled "Compositional Effects on the Sensitization of Austenitic Stainless Steels" has been completed. As part of this review, isothermal time/temperature/sensitization data have been used to statistically estimate "factors of improvement" in sensitization resistance for the individual elements present in SS. These factors are based on the change in time-to-sensitize as a function of bulk material composition.

Sensitization refers to the loss of corrosion resistance after heat treatment in, or slow cooling through, a particular temperature regime. This susceptibility to corrosion results from a change in the local composition at grain boundaries. Basic understanding of the sensitization phenomenon is developed by examination of the thermodynamics of carbide precipitation and the kinetics of chromium depletion. The primary composition change that occurs is the precipitation of chromium-rich carbides and an associated depletion of chromium in the adjacent region (Figure 9). Experimental measurements have indicated that the chromium-depleted zone is, in most cases, directly responsible for the loss in intergranular corrosion (and stress corrosion) resistance.

Bulk carbon content is the dominant factor controlling sensitization. Reducing the carbon concentration significantly decreases the steel's susceptibility to sensitization and IGSCC. Low ($\leq$0.02 wt%) carbon stainless steels are extremely resistant to sensitization during proper welding practices. The importance of carbon is illustrated in Figure 10, comparing time-to-sensitize data to bulk carbon contents for Types 304 and 316 SS. Other alloying elements, such as molybdenum, chromium, and nickel, have a strong effect on carbon and chromium activities and thereby on sensitization. These elements must be taken into account when assessing a material's resistance to sensitization.

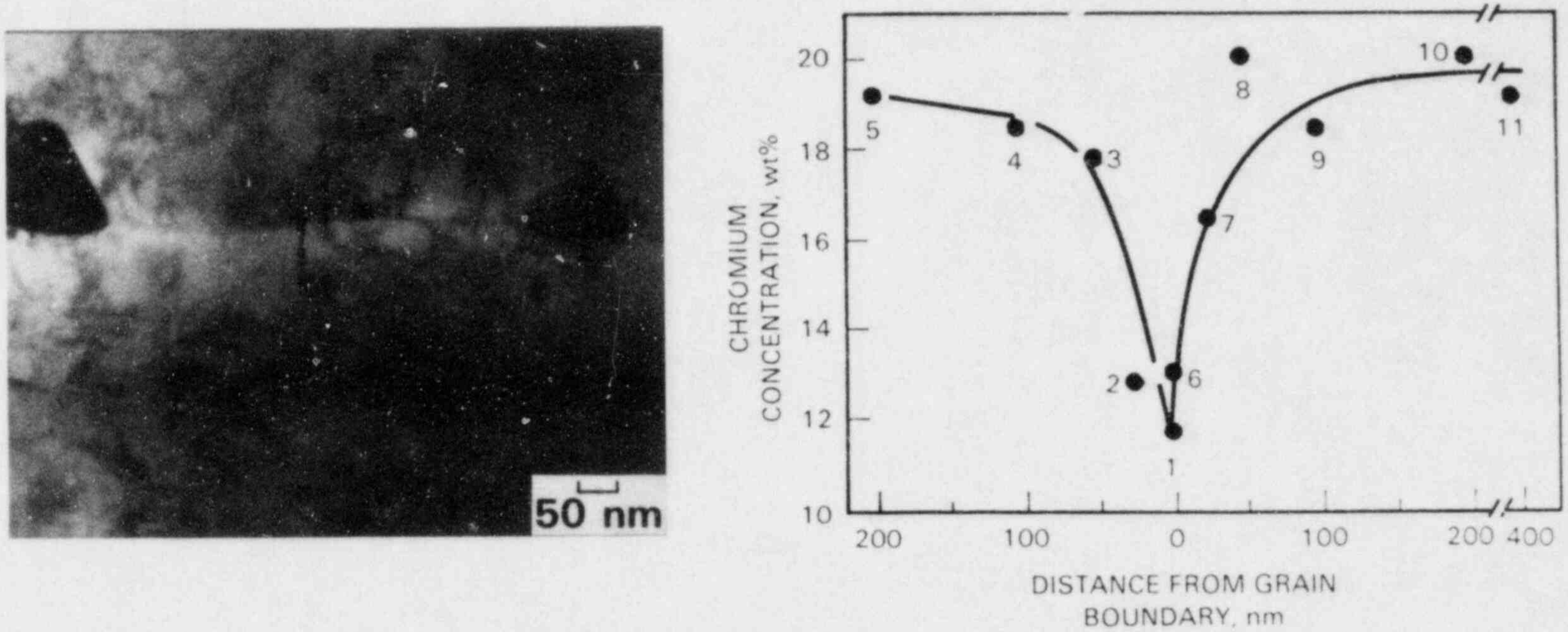


FIGURE 9. Chromium Depletion Profile Across Grain Boundary in Sensitized Type 304 SS

Methods to determine the relative sensitization resistance of particular stainless steel heats as a function of bulk composition have been reviewed and compared to a large data base. The best predictive capability was obtained by normalizing the chromium content as a function of molybdenum, nickel, and carbon contents to calculate a composite chromium (Cr*) value:

$$Cr^* = Cr + 1.6\ Mo - 0.2\ Ni - 100\ C$$

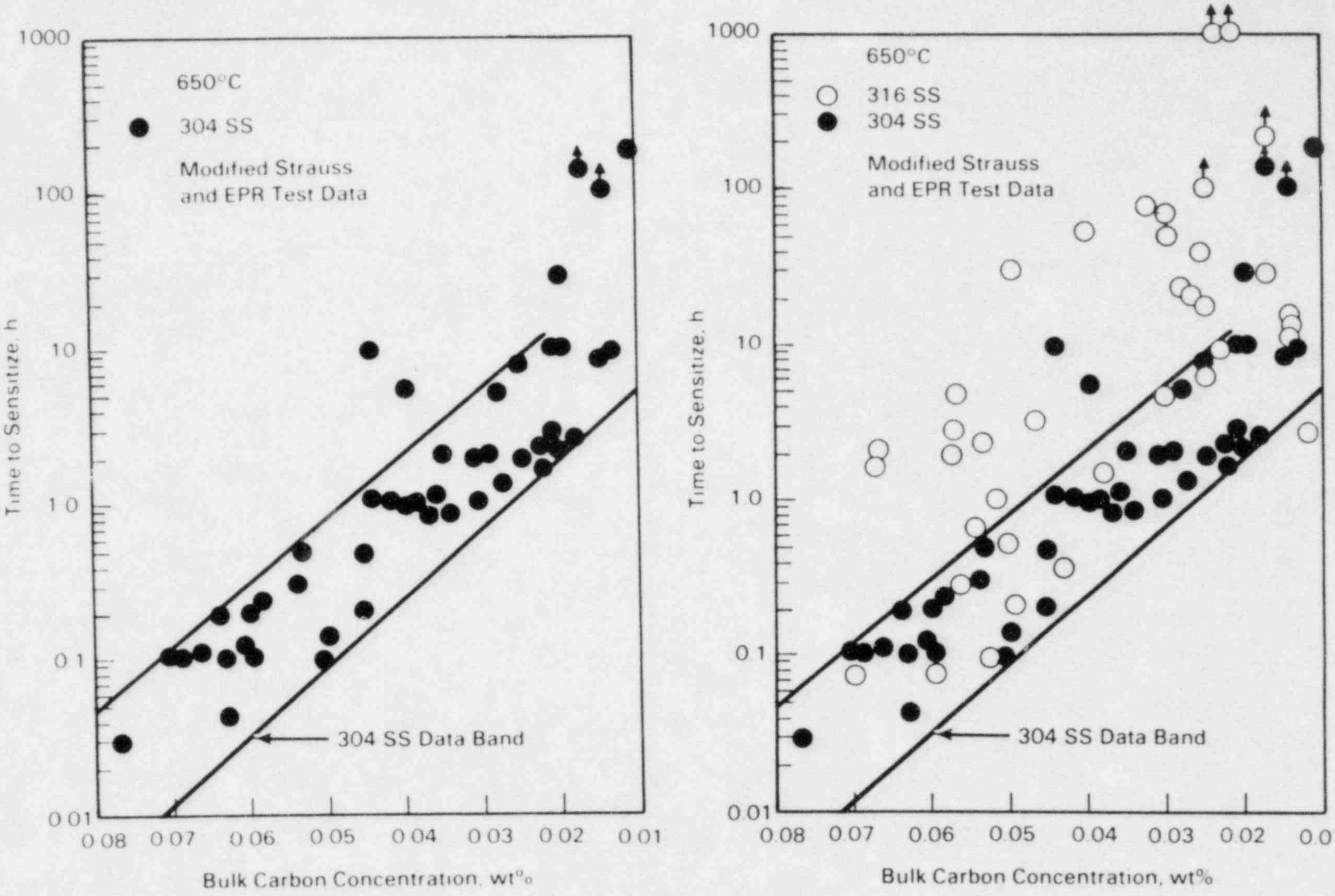
where the elements listed represent their bulk concentration in weight percent. Other elements such as manganese, silicon, and nitrogen were evaluated but did not significantly improve the predictive capability.

A positive correlation between prediction and experimental data has been documented (Figure 11), allowing estimation of improvement factors based on time required for sensitization to occur. A simple method to determine factors of improvement is proposed based on this correlation. These factors allow materials to be compared and assessed in reference to their expected sensitization resistance based on bulk composition information. A factor of improvement of approximately 20 times is predicted comparing nuclear grade Type 316 SS to a standard Type 304 SS.

Classical sensitization resulting from grain boundary chromium depletion is the primary, but not the only, reason for a stainless steel's susceptibility to intergranular corrosion and SCC. Phosphorus, sulfur, and silicon can promote intergranular attack in certain environments and may contribute to IGSCC. Impurity elements such as sulfur and phosphorus enrich grain boundary regions by factors more than 10^4 times their bulk concentration. Nitrogen and boron also strongly segregate to grain boundaries and may also have a significant effect on corrosion and SCC susceptibility. Lowering the bulk carbon concentration in alloys such as the nuclear grade stainless steels may increase the importance of impurity elements, because the potential for sensitization is significantly reduced. Additional understanding of impurity element effects is required to determine whether the nuclear grade alloys are immune to IGSCC in BWR environments.

FUTURE WORK

The second draft of the report Compositional Effects on the Sensitization of Austenitic Stainless Steels will be completed and submitted to the NRC technical monitor. This report will review individual element effects on carbide precipitation and sensitization in Types 304 and 316 SS. Elements that do not directly effect sensitization, but that may have an effect on IGSCC resistance (e.g., sulfur, phosphorus, and silicon), will be discussed. In addition, a method to determine factors of improvement in sensitization resistance will be proposed based on time-to-sensitize data from the literature.



(a)

(b)

FIGURE 10. Time-to-Sensitize Data as (a) a Function of Bulk Carbon Content for (a) Type 304 SS and (b) with Data for Type 316 SS Included

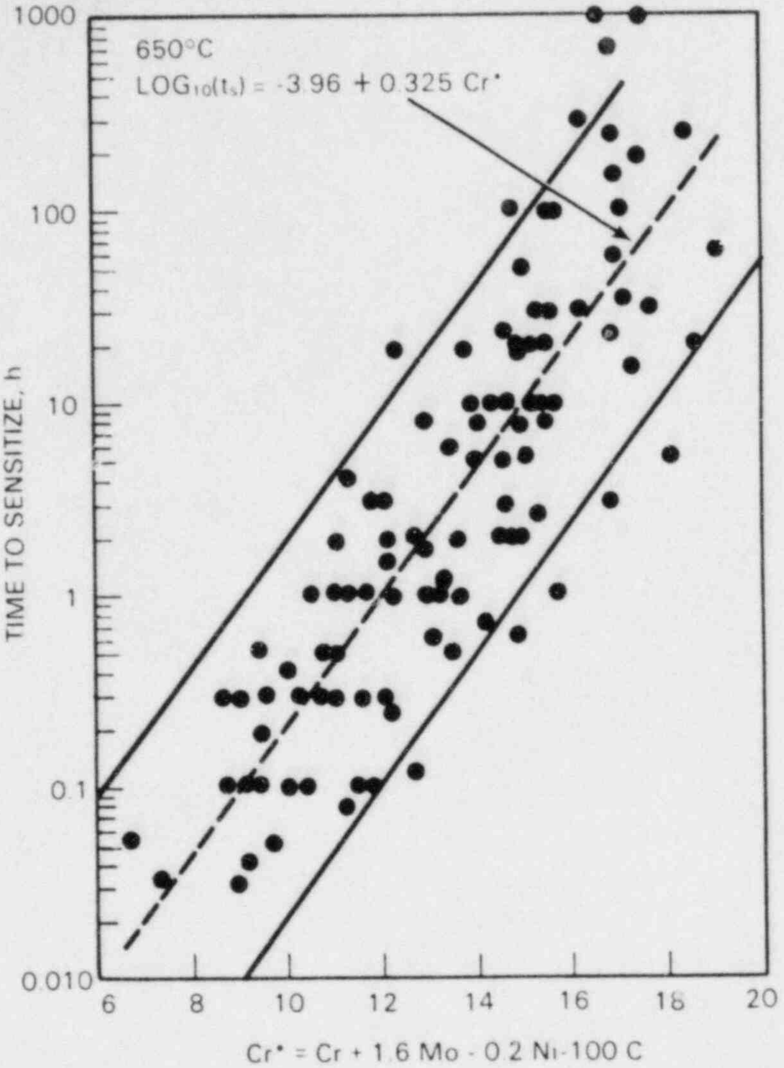


FIGURE 11. Correlation Between Composition Normalization Parameter, Cr*, and Experimentally Measured Time-to-Sensitize Data

Isothermal and additive isothermal sensitization experiments will continue on Types 304 and 316 SS. Preliminary experiments on the effect of simultaneous strain on sensitization development will be initiated. Sensitization will be determined using the EPR test technique in all cases.

The second elemental effects on sensitization series will examine a range of nitrogen contents in low-carbon Type 316 SS. Materials will be located and purchased which have bulk levels of nitrogen up to about 0.2 wt%. An extensive matrix of low-carbon Type 316 SS will be obtained, with more than 15 heats with carbon levels of 0.02 wt% or less.

An initial model will be set up to predict material sensitization as a function of bulk composition, initial material condition, and thermomechanical history. The model will be capable of predicting isothermal, additive isothermal, continuous cooling, and additive continuous cooling sensitization. Comparison of model predictions and program data will be initiated.

TASK III: IGSCC PREDICTION METHODOLOGY FROM COMPONENT-SPECIFIC THERMOMECHANICAL HISTORIES

Task Leader: D. G. Atteridge

Austenitic SS components of commercial BWRs and PWRs have experienced IGSCC in the HAZ of stainless steel welds in service. This type of cracking phenomenon, although it has been rarely observed, can result in serious component failure. Extensive research over the last several decades has defined the factors controlling the IGSCC phenomena: sensitized microstructure, tensile stress, and an aggressive environment. However, at present, IGSCC susceptibility of in-service weldments can be predicted only qualitatively.

The objective of this task is to develop and validate a methodology to quantitatively predict the IGSCC susceptibility of HAZ regions in austenitic SS weldments. The basic methodology will include:

- TM history prediction from welding and/or repair welding parameters, component size, and weld groove configuration
- DOS prediction from TM history, material composition, and initial condition
- IGSCC susceptibility prediction from DOS measurements.

Each of these steps will be assessed by direct comparison to the experimental data base generated in Tasks I and II. Existing models will be evaluated, modified (where appropriate), and combined.

TECHNICAL PROGRESS

Initial program modeling efforts have been directed toward prediction of sensitization on weld simulation specimens. As a result, these efforts have been conducted within the framework of Task II and are discussed in that section of this report. Thermomechanical history modeling efforts will begin once 24-in.-dia. pipe welding is initiated. This work will be carried out under Task I. Task III incorporates the results from Tasks I and II in an effort to develop a unified DOS/SCC prediction capability.

FUTURE WORK

Heat-affected zone DOS as a function of distance from the fusion line will be predicted for the 14-in.-dia. Schedule 160 SS pipe welds that will be monitored under Task I in the next quarter. These initial DOS predictions will be based on the current thermal history DOS prediction model developed in Task II and the actual HAZ thermal histories recorded in Task I. The DOS development will be predicted on a pass-by-pass basis and post-weld HAZ DOS predictions will be compared with measured EPR-DOS HAZ profiles.

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PNL-5181-1
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NRC FORM 335
(11-81)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-3911, Vol. 1
PNL-5181

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
EVALUATION OF WELDED AND REPAIR-WELDED STAINLESS STEEL FOR LWR SERVICE: QUARTERLY REPORT, JANUARY-MARCH 1984

5. DATE REPORT COMPLETED
MONTH October | YEAR 1984

6. *(Leave blank)*

7. AUTHOR(S)
D.G. Atteridge, S.M. Bruemmer, R.E. Page

8. *(Leave blank)*

DATE REPORT ISSUED
MONTH November | YEAR 1984

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Pacific Northwest Laboratory
P. O. Box 999
Richland, Washington 99352

10. PROJECT/TASK/WORK UNIT NO.

11. FIN NO.
B2449

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

13. TYPE OF REPORT
Quarterly

PERIOD COVERED *(Inclusive dates)*
January-March 1984

14. *(Leave blank)*

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(200 words or less)*

The Division of Engineering Technology, U.S. Nuclear Regulatory Commission, is sponsoring a program at Pacific Northwest Laboratory to evaluate welded and repair-welded stainless steel piping for light-water reactor (LWR) service. Stainless steels often become sensitized, or less resistant to stress corrosion cracking (SCC), after undergoing heating and cooling cycles such as those encountered in welding. The weld heat-affected zone (HAZ) is often the site of crack initiation. This program will therefore measure and model the development of a sensitized microstructure and its resultant resistance to SCC in welded and repair-welded stainless steel pipe. The result will be a method to assess the effects of welding variables on the SCC susceptibility of component-specific nuclear reactor welds/repairs.

The progress achieved toward this objective during January - March 1984 is described in this report.

17. KEY WORDS AND DOCUMENT ANALYSIS
welded and repair-welded stainless steel
stress corrosion cracking
degree of sensitization
light-water reactor

17a. DESCRIPTORS
heat-affected zone
chromium-depleted zone

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited

19. SECURITY CLASS *(This report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES

22. PRICE
$

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

NUREG/CR-3911, Vol. 1

EVALUATION OF WELDED AND REPAIR-WELDED STAINLESS STEEL
FOR LWR-SERVICE

NOVEMBER 1984

120555078877 1 1AN1R5
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