The Sources of Oxygen and Nitrogen Contamination in Submerged Arc Welding Using CaO-Al₂O₃ Based Fluxes

Flux composition plays a major role in oxygen contamination but is insignificant for nitrogen pickup

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ABSTRACT. A study of the sources of oxygen and nitrogen contamination during submerged arc welding has been made using seven CaO-Al₂O₃ based fluxes of varying basicity index (B.I.). By analyzing the oxygen and nitrogen contents at the electrode tip, droplet and weld metal stages, it was demonstrated that the major source of nitrogen contamination is by reaction with the atmosphere at the electrode tip. However, oxygen contamination is associated not only with reactions with the atmosphere, but also with flux decomposition and flux entrapment. The composition of the flux is of major importance in the latter two processes, but plays no role in the nitrogen pickup. The weld metal droplets all displayed very high oxygen levels (in the range of 1400 to 3300 ppm), but the pronounced decrease in the weld metal oxygen readings pointed to extensive slag-metal reactions in all the systems. The oxygen potential of the flux provides a rough indicator as to the final oxygen level of the weld metal.

Introduction

Oxygen and nitrogen pickup during welding must be controlled to ensure adequate notch toughness and a sound

weld metal. In submerged arc welding (SAW), as in steelmaking, it is well established that lower oxygen levels usually lead to better toughness (Refs. 1-3), and until the last few years one of the goals of a successful SAW process was the attainment of a weld metal with very low oxygen values, typically less than 300 ppm. Recent research has focused on the role of non-metallic inclusions in influencing the nature of the austenite to ferrite phase transformations, and with this has come the realization that very low weld metal oxygen levels (less than 250 ppm) may be undesirable. Inclusions could play a key role in promoting the formation of acicular ferrite (which is a fine-grained product with good toughness), rather than coarse-grained polygonal or Widmanstatten ferrite. Several authors have suggested that both the size and composition of inclusions is important. Inclusions such as TiO (Ref. 4), TiN (Refs. 5-7) and VN (Ref. 7), all of which have the rock-salt structure, have been considered in this context. If this viewpoint is supported by further evidence, clearly control of both the total oxygen content and the specific chemistry of inclusions formed during welding would be desirable.

The comparison with inclusion control during steelmaking is an interesting one. The science of steelmaking has progressed to the point that both the final oxygen level and the nature of any inclusions formed by deoxidation can be predicted from equilibrium thermodynamic

arguments. Such is not the case in submerged arc welding. In part, the difficulty in making predictions relates to the unique characteristics of a welding operation; the short reaction times (of the order of a second), high metal temperatures (in excess of 2000°C/3632°F) and plasma conditions within the welding arc all conspire to cast doubt on the value of equilibrium thermodynamics for understanding gas-metal-slag reactions during welding. However, a second problem is that there have been few attempts to identify and categorize the origin of inclusions during submerged arc welding. For example, if the majority of the inclusions have their origin in phenomena related to flux entrapment, and are not related to deoxidation reactions, equilibrium thermodynamics would not be helpful in predicting either the composition or volume fraction of inclusions formed.

Lacking a sound theoretical framework, most attempts to predict the final oxygen level in submerged arc welds have relied on empirical ideas drawn loosely from steelmaking. It is generally agreed that the flux composition is important and the basicity index concept introduced by Tuliani, et al. (Ref. 1), explicitly recognized this point. The formula given by these authors,

 $\begin{array}{l} \text{B.I.} = [\text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O} + \\ \text{Li}_2\text{O} + \text{CaF}_2 + 1/2(\text{MnO} + \text{FeO})] \div \\ [\text{SiO}_2 + 1/2(\text{Al}_2\text{O}_3 + \text{TiO}_2 + \text{ZrO}_2)] \end{array}$

divided oxides into basic, amphoteric or

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Table	e 1—Com	position o	of Fluxes (wt %)						
	CaO	CaF_2	Al_2O_3	MnO	SiO ₂	TiO ₂	FeO	MgO	Na ₂ O	B.I. ^(a)
C1	46.3	9.8	3.2	0.14	36.0	_	0.2	0.36	5.1	1.6
C2	8.0	_	49.0	13.0	17.0	13.0	7.0	_		0.4
L1	72.5 ^(b)	_	26.7	_	_	_	_	8.0	-	5.5
L2	42.3	_	32.4	25.3	_	_	_	_		3.4
L3	37.1	_	32.0	_	24.7	_	*	6.2		1,1
L4	39.8	_	36.5	13.0	10.6	_	_	_		1.6
L5	96.4 ^(b)	_	_	-	_	_	_	3.6	-	_

(a)Basicity index calculated according to equation (1) in the text.

(b)Only Ca was determined by x-ray fluorescence analysis. Flux L1 contained 37.5 wt % CaO, 25 wt % CaF2 and 37.5 wt % Al₂O₃ while flux L5 contained 25 wt % CaO, 75 wt % CaF2 prior to melting

acidic groups. Acidic fluxes (B.I. less than 1) usually give high oxygen levels in the weld metal, which can be in excess of 1000 ppm, while basic fluxes (B.I. greater than 1) lead to much lower oxygen levels, typically in the range of 200-400 ppm. The concept of a basicity index has been vigorously criticized in some quarters because it fails to address the fundamental question as to how oxygen is transferred from flux to weld metal. Later authors have proposed that the oxygen potential of the flux (Ref. 8) or the concentration of a particular flux component, e.g., SiO_2 in acidic fluxes (Ref. 9), provides a better measure of the correlation between oxygen in the weld metal and the flux composition. Other work has suggested that the atmosphere composition can be an important factor in submerged arc welding (Ref. 9).

Nitrogen differs from oxygen because it can show appreciable solid solubility in steel, depending on the other alloying elements present. Interstitial nitrogen is thought to have a detrimental effect on toughness (Ref. 10), and the improvements observed on adding strong nitride formers such as Ti and B to weld metal were partly attributed to the removal of free N (Ref. 4). As noted earlier, an additional contribution could come from the favorable influence on the rate of acicular ferrite formation (Refs. 5-7) if TiN promotes the nucleation of ferrite. Nitrogen pickup is usually not considered to be a problem in submerged arc welding as a typical flux contains no nitrogen compounds, and the only important source is air trapped among the flux particles (Ref. 11). However, if a high dilution welding process such as submerged arc welding is used on a base plate containing high nitrogen levels, the total N (and free N) level in the final weldment could play an important role in determining the toughness of the weld.

In this paper we examine the effects of flux composition, welding current and gas atmosphere on the absorption of nitrogen and oxygen in weld metals. Particular attention is paid to identifying the sources of oxygen and nitrogen contamination.

Experimental Procedure

Welding Consumable

For this study, two commercial fluxes and five laboratory fluxes were used -Table 1. The commercial fluxes (C1, C2) were chosen to be representative of a basic flux (C1) and an alumina-based acidic flux (C2). The laboratory fluxes were prepared by mixing reagent-grade chemicals and melting in an arc furnace lined with an MgO refractory. There was some reaction between the flux and refractory accounting for the MgO pickup for fluxes L1, L3 and L5. The melts were crushed to an appropriate size for welding and then baked at 500°C (932°F) for 24 hours to avoid carbon contamination from electrodes and drive off any absorbed moisture. The compositions of laboratory-prepared fluxes were determined by x-ray fluorescence analysis. The major constituent in all of them was CaO (or CaF₂), with varying amounts of Al₂O₃, MnO or SiO₂ to give basicity ratios that ranged from 1 (L3) to 5.5 (L1). Fluxes L1 and L5 contained CaF2 with nominal CaF₂/CaO ratios of 0.67 and 3, respectively. The fluorescence analysis could not distinguish between CaO and CaF2, so the total Ca content in Table 1 for these two fluxes assumes that all the Ca is present as the oxide. As flux L5 contained only CaO, MgO and CaF2, no value can be assigned for a basicity index

Two wires and one base plate (having a chemistry suitable for an X65-grade line pipe application) were used. Their compositions are listed in Table 2. Samples of the base plate, $250 \times 150 \times 18$ mm $(9.8 \times 5.9 \times 0.71 \text{ in.})$ in dimension, were prepared for welding by machining a 6 mm (0.24 in.) deep groove, included angle 60 deg, along the center line of the plate. This simulates a typical edge preparation of plates for submerged arc welding and typically leads to a weld with a 50% base plate dilution factor.

Welding Procedure

For a fixed welding current, flux and wire combination, the oxygen and nitrogen levels were analyzed at the electrode tip, droplet and weld metal stages. The duration of the electrode tip stage is limited by the reaction time available from the first melting of the electrode tip to the detachment of the molten metal droplet. The mean reaction time has been estimated to vary from 0.1 to 0.35 s for current values of 400 to 850 A (Ref. 12). Electrode tips were collected by stopping the arc during the welding process; after a stable arc was established, the electrode was pulled away from the weld pool, extinguishing the arc.

Weld metal droplets were collected by running the arc at high speed over a chilled copper plate with a protective layer of flux covering the welding head and metal droplets. The duration of the droplet stage is determined by the time of flight after detachment of the droplet till it impinges the weld pool. This time is of the order of 0.01 to 0.0035 s (Ref. 12). The average diameter of the droplets was in the range of 3-4 mm (0.12-0.16 in.), slightly larger than the wire diameter of 2.4 mm (3/2 in.). Both the electrode tips and droplets were collected at welding current settings of 300, 400, 500 and 600 A when the commercial fluxes were used, and at 300 and 600 A for the laboratory-prepared fluxes.

A constant nominal heat input of 3.54 kJ/mm (90 kJ/in.) was used for all the welding runs. The voltage as measured at the power source was kept constant at 35 V, and changes in the current (300 and 600 A) were accommodated by varying the speed of the welding head. As noted in the results presented in Tables 3 and 4, many of the experiments were done under an argon atmosphere, which supplemented the shielding provided by the normal flux covering. The high purity argon atmosphere (less than 10 ppm O_2 , 25 ppm N₂) was introduced into a plastic container that enclosed the welding head and workpiece. This container was flushed for 5 min with argon prior to welding, and a positive argon pressure was maintained throughout the welding procedure.

Table 2—Composition of Wires and Base Plate (wt %)

	С	Mn	Si	S	Р	Mo	Cr	Ni	Αl	O	Ν
Wire 2	0.11	1.06	0.27	0.017	0.006 0.0025 0.008	_	_	_	0.006	0.016	N.D.

Table 3—Nitrogen Levels (ppm) at Various Stages of Welding with Commercial Fluxes as a Function of the Welding Current^(a)

		Welding	Current	
Location	300A	400A	500A	600A
Wire 1, Flux C1				
Tip	57 (40)	48 (42)	60 (42)	63 (43)
Droplet	58 (38)	59	60	61 (39)
Weld metal	75 (59)	70	68	64 (55)
Wire 1, Flux C2				
Tip	59 (29)	59	61	63 (36)
Droplet	60 (27)	58 (25)	61 (24)	60 (24)
Weld metal	68 (60)	67	65	62 (59)

⁽a) The numbers in parentheses are those obtained when welding under an argon atmosphere.

Nitrogen and Oxygen Analysis

Nitrogen and oxygen contents of metal samples were determined by inert gas fusion analysis. For all fluxes (with the exception of flux L5) the layer of slag that enclosed the electrode tips and droplets could be readily detached. For flux L5, the samples were covered by a blue-colored film. This was ground away prior to analysis. Several individual electrode tips or droplets were required for each determination to obtain the recommended mass of about 1 g (0.03 oz) for the inert gas fusion analysis.

Results

Nitrogen Analyses

The results of the nitrogen analyses of samples collected using wire 1 (starting N level = 21 ppm) and two commercial fluxes at current levels ranging from 300 to 600 A are presented in Table 3. The effects of welding under a protective argon atmosphere on the nitrogen levels at the different stages of welding are also shown in Table 3. Each number is the average of five analyses; the spread in the values in any one group was less than 10 ppm. For the weld metal, samples were taken from the central region as

well as the edge region of the weld section, but no significant differences were observed with the location of the sample.

Flux composition had no significant effect on the pickup of nitrogen, but the use of an argon atmosphere led to a marked decrease in the rate of nitrogen pickup at the electrode tip. In all cases, reaction at the electrode tip stage resulted in an increase in the nitrogen level. There was no further change at the droplet stage, and this was followed by a small increase in the weld metal readings. However, when the base plate dilution factor of about 50% is accounted for, there is in fact a small decrease in the weld metal nitrogen levels, particularly at the higher currents.

Oxygen Analyses

The results of the oxygen analyses are summarized in Tables 4 and 5. For the commercial fluxes, readings were taken at 300, 400, 500 and 600 A, again with and without argon shielding. For the five laboratory fluxes, all the readings were obtained without argon at two current values, 300 and 600 A. For the weld metal studies using the commercial fluxes, oxygen levels were again measured at

the central and edge locations in the cross-section of the weldment. In this case, the location had a significant effect, the values at the center being 60–80 ppm higher than those at the edge — Table 4. For the laboratory-made flux experiments, all the weld metal values were obtained from the central portions of the section.

The oxygen values shown in Tables 4 and 5 are again the average of five separate readings. The scatter observed was significantly higher than that found with the nitrogen analyses, 200–300 ppm for the electrode tips, 500 ppm for the droplets, and 100 ppm for the weld metal.

The welding current and flux type had a marked influence on the oxygen levels at all three locations. Oxygen pickup at the electrode tips from starting values of 130 ppm to values in the range of 1000–2000 ppm occurred for the two commercial fluxes; the corresponding increase for the laboratory fluxes was from 160 ppm (the starting level in wire 2) to 900–1700 ppm. A further increase (50–100%) in oxygen levels occurred for all flux/current combinations in the droplets, but the oxygen levels then dropped dramatically at the weld metal stage. Even allowing for the 50% dilution factor from the

Table 4—Oxygen Levels (ppm) at Various Stages of Welding with Commercial Fluxes as a Function of the Welding Current^(a)

		Welding	g Current	
Location	300A	400A	500A	600A
Wire 1, Flux C1				
Tip	975 (844)	1097 (938)	1344 (1051)	1475 (1201)
Droplet	2012 (1913)	2275 (2044)	2516 (2319)	2925 (2681)
Weld Metal (1)(b)	409 (370)	450	572	618 (559)
(2) ^(b)	343 (272)	396	510	560 (485)
(3) ^(c)	376 (321)	423	537	589 (522)
Wire 1, Flux C2				
Tip	1150	1573 (1368)	1861	2075 (1943)
Droplet	2725	2887 (2534)	2970	3275 (2987)
Weld Metal (1) ^(b)	775	850 (784)	1089	1137 (1068)
(2) ^(b)	715	782 (720)	1015	1057 (1009)
(3) ^(c)	745	816 (752)	1052	1097 (1039)

⁽e)The numbers in brackets are those obtained when welding under an argon atmosphere.

(a)(3) is the mean of (1) and (2).

⁽b)(1) and (2) are average values determined from samples removed from the central and edge sections of the weld metal

base plate, there was a net loss of oxygen at the weld metal stage (in comparison to the droplet measurements). The use of argon shielding had a small but consistent effect in reducing the oxygen readings at all three stages.

Discussion

Nitrogen Reactions at the Electrode Tip

With both commercial fluxes, the major source of nitrogen absorption appears to be associated with reactions at the electrode tip stage. Flux type had little or no effect on the amount of nitrogen pickup, but argon shielding had a marked effect (e.g., at 300 A, argon shielding reduced the pickup from 36 to 19 ppm with flux C1 and from 38 to 8 ppm with flux C2). It is concluded that the major source of nitrogen contamination is the atmosphere. Argon shielding is only partly successful in eliminating N pickup because of difficulties associated with displacing all of the air that is trapped in the rather porous flux particles. The differences in N pickup between fluxes C1 and C2 with argon shielding are attributed to the much coarser particle sizes of the latter flux, which made flushing with argon more effective in removing entrapped air. Flux consumption rate increases with higher currents (Refs. 13, 14), and this would induce a larger amount of air into the arc column, leading to the slightly higher nitrogen levels observed at these current values (both with and without argon shielding).

Nitrogen Reactions within the Arc Column

Reactions in the arc column could lead to either desorption or further absorption of nitrogen, and can be influenced by the polarity of the electrode in DC welding (Ref. 15). The smaller total nitrogen absorption when welding with the electrode negative has been attributed to the net effect of both enhanced nitrogen absorption effects (as nitrogen ions) in the cathode drop region (Refs. 15, 16) and nitrogen desorption in the arc column (Ref. 17). In the present study no significant change was noted between the electrode tip and weld metal droplet stages when welding in air, but a small decrease was found with argon shielding, most notably with flux C2 at 600 A (from 36 ppm to 24 ppm N).

Nitrogen Reactions within the Weld Metal

As noted earlier, when the base plate dilution factor is taken into account there is either little change or a small net decrease in nitrogen from the droplet to weld metal stages. The end result is an overall slight decrease in nitrogen levels as the welding current increases. Similar

Table 5—Oxygen Levels (ppm) at Various Stages of Welding with Laboratory-Made Fluxes(a)

	Location	
300A		
Tip	Droplet	Weld Metal
880	1405	261
1433	2445	616
984	1740	565
1421	2192	513
925	2468	361
600A		
999	1496	273
1565	2647	722
1168	1816	543
1659	2199	580
	880 1433 984 1421 925 600A 999 1565 1168	300A Tip Droplet 880 1405 1433 2445 984 1740 1421 2192 925 2468 600A 999 1496 1565 2647 1168 1816

(a)Wire 2 was used for all these tests

trends have been noted by Kobayashi, et al. (Ref. 18), and Miller and Salter (Ref. 19) in gas shielded metal arc welding. They suggested that this was due to the faster transfer rates of metal droplets at higher currents, limiting the time available for nitrogen absorption. This cannot explain the present results because the weld metal droplet measurements were independent of welding current. Flux/weld metal interactions and the freezing time of the weld are variables which could influence this behavior in a submerged arc welding operation. At the weld pool stage, nitrogen desorption continues and a longer freezing time at higher current results in a lower nitrogen level.

Oxygen Absorption

The results of the oxygen analyses of the droplets and electrode tips showed a considerable scatter. This must reflect the variability of conditions at the electrode tip and in the arc column. Since the electrode tips were simply collected by stopping the arc at random intervals, the extent of development (and hence the period for reaction) of the droplet at the electrode tip would be quite variable. In the arc, flux dissociation and/or entrapment and the mode of droplet transfer could all account for the large spread in the oxygen values in the droplets.

Part of the variability of the oxygen readings in the weld metal data (Table 4) is associated with segregation effects during solidification. This produces a greater density of inclusions and thus higher oxygen contents at the center of the welds (Ref. 20). Similar observations have been reported by Iwamoto, et al. (Ref. 21). However, part of the scatter at the weld metal stage must also be inherent in the welding process itself. In light of the great variability found in the droplet oxygen readings, this large scatter is not unexpected.

The nitrogen absorption data considered earlier clearly demonstrated that the atmosphere is the most probable source

of nitrogen contamination during SAW. The influence of argon on the rate of oxygen pickup (Table 4) shows that the atmosphere also plays a role in determining the oxygen levels in the electrode tips and droplets, although the decrease observed at these two stages is only approximately 20% and 10%. The smaller change at the droplet stage and the 50-100% increase in oxygen levels from the tip to droplet stage emphasizes the importance of flux decomposition and/ or flux entrapment on the reactions occurring in the arc column. This is in accord with the observation that there was little or no change in the nitrogen levels from electrode tip to droplet.

A precise figure for the relative contributions of the flux and atmosphere cannot be given because of the incomplete flushing of air from the flux particles, but the following argument illustrates the magnitude of the effect that might be expected. For welding at 300 A, the weight of flux consumed was measured to be 2.6 g per g (0.09 oz/oz) electrode, in good agreement with the values given by Renwick and Patchett (Ref. 22). Knowing the density of the flux, the weight of air per unit weight of flux consumed can be estimated. Assuming that all this air is available as a potential source of oxygen, the weight of oxygen per unit weight of melted wire is 190 ppm. If all the air trapped in the flux particles could be replaced by argon containing 10 ppm O₂, the corresponding weight of oxygen would be 0.01 ppm. For fluxes L1 and L5, which contain only relatively stable oxides, the major sources of oxygen at the electrode tip stage would be the atmosphere as well as flux entrapment. For the other laboratory fluxes, flux decomposition or flux entrapment would be important. However, flux entrapment is not the most important mechanism at all the stages concerned.

The much lower oxygen content of the weld metal (observed both with and without argon shielding) compared to the droplet measurements strongly suggests that further reactions take place in the weld pool. Removal of inclusions to the slag phase and slag-metal reactions prior to freezing both play a part in determin-

ing the final oxygen levels.

The oxygen values at the tip and droplet stages increase with increasing weld current for both the commercial and laboratory fluxes. At the electrode tip stage, this can be partly explained by the higher rate of flux consumption, as discussed in connection with nitrogen absorption. A second factor which can affect oxygen absorption is the arc temperature. Milner, et al. (Ref. 20), have shown that the temperature of an argon-shielded tungsten arc increases at higher currents, and the same trend is expected in SAW. At higher arc temperatures, the decomposition of flux components such as MnO, SiO₂, etc., would be favored, increasing the driving force for oxygen transfer to the electrode tips and droplets. Again the time of flight does not seem to be a limiting factor in oxygen pickup. At a current of 600 A, where the time available for reaction inside the arc column is shorter, there is considerably more oxygen pickup than at 300 A. The shorter reaction time is more than compensated for by the greater surfaceto-volume ratio of the smaller droplets and higher arc temperatures expected as the welding current increases.

The flux composition strongly influenced the final weld metal oxygen values, but the results illustrate the limitations of the basicity index approach to this problem (Ref. 1). For example, flux L2, with a B.I. value of 3.4, gave higher weld metal oxygen values than flux L3, with a B.I. of 1.1. Better agreement is found by ranking the fluxes according to their oxygen potentials (Refs. 8, 23). The oxygen potentials of the laboratory-prepared fluxes can be arranged in descending order, viz. L2, L4, L3, L1 and L5. This arrangement is based simply on the relative stabilities and proportions of the oxides MnO, SiO₂, Al₂O₃ and CaO in each flux. This approach ignores possible interactions between the components of the flux, the protection afforded by the slag to the weld metal, and the complexities of slag/weld metal reactions. For example, the slag formed by flux L5 was extremely fluid, and the less effective protection it provides in comparison to flux L1 would account for the higher oxygen levels found with L5 compared with L1, although flux L5 contained only CaO and CaF₂. Despite these limitations, the oxygen potential concept provides a

rough ranking of the different fluxes—Table 5. However, it is also clear that the high oxygen levels measured at the weld metal droplet stage and the importance of slag/metal reactions must be considered if any comprehensive understanding of the factors that control the final weld metal oxygen levels is to be obtained.

Summary

The results of the present study have shown that air entrapped within the porous flux particles represents the most important source of nitrogen contamination in SAW. Air also contributed to oxygen pickup, particularly at the electrode tip, but flux decomposition and/or flux entrapment within the arc column must be considered as major sources of oxygen contamination at the droplet and weld pool stages. This is confirmed by the observation that there was no significant change in the nitrogen content between the electrode and droplet stages, but there was a marked increase in oxygen as droplets traversed the arc column for all the fluxes investigated. The differences in behavior between nitrogen and oxygen pickup are further illustrated by the influence of welding current at a fixed heat input. An increase in welding current led to an increase in oxygen but a small decrease in nitrogen levels in the weld metal. This was attributed on the one hand to factors, such as flux decomposition, which become more prevalent as the arc temperature increases at higher currents, and on the other hand to a greater opportunity for nitrogen desorption during the slightly longer time available for solidification.

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WRC Bulletin 301 January 1985

A Parametric Three-Dimensional Finite Element Study of 45 Degree Lateral Connections By P. P. Raju

This bulletin contains a summary of three-dimensional finite element studies carried out on four lateral configurations subjected independently to internal pressure, external in-plane moment on the nozzle, and external in-plane moment on the run pipe. Stress indices for various critical regions are summarized.

Publication of this report was sponsored by the Task Group on Laterals that reported to the Subcommittee on Reinforced Openings and External Loadings and the Subcommittee on Piping Pumps and Valves of the Pressure Vessel Research Committee of the Welding Research Council.

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WRC Bulletin 305 June 1985

This bulletin contains three summary reports prepared by the Japan Pressure Vessel Research Council (JPVRC) Subcommittee on Hydrogen Embrittlement:

1) "Hydrogen Attack Limit of 21/4 Cr-1 Mo Steel," by Task Group I;

2) "Embrittlement of Pressure Vessel Steels in High Temperature, High Pressure Hydrogen Environment," by Task Group II; and

3) "Hydrogen Embrittlement of Bond Structure Between Stainless Steel Overlay and Base Metal," by Task Group III.

The three Task Group reports were translated and summarized for publication by JPVRC and have been reviewed and edited by the U.S. PVRC Subcommittee on Hydrogen Effects for publication in this bulletin.

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WRC Bulletin 308 September 1985

Verification and Application of an Inelastic Analysis Method for LMFBR Piping Systems By H. D. Hibbitt and E. K. Leung

The primary purpose of this report is to show when elbow end effects are important, and how they influence the predictions of stress and strain components in the inelastic range. The secondary purpose is to demonstrate an economical inelastic analysis method which can be used routinely to design piping systems operating at elevated temperature.

The publication of this report was sponsored by the Subcommittee on Elevated Temperature Design of the Pressure Vessel Research Committee of the Welding Research Council. The price of WRC Bulletin 308 is \$14.00 per copy, plus \$5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Ste. 1301, 345 E. 47th St., New York, NY 10017.