Radiation Resistant Weld Metal for Fabricating A533-B Nuclear Reactor Vessels

BY J. R. HAWTHORNE

A Mn-Mo-Ni submerged arc welding filler metal shows high radiation embrittlement resistance with selected limitations on copper, phosphorus and other impurities. Capabilities for 550 F (288 C) nuclear service to 10^{20} n/cm^2 fluences are revealed

ABSTRACT. A Mn-Mo-Ni filler metal has been successfully tailored for improved radiation embrittlement resistance. The upgraded filler metal has special application to the submerged arc welding of A533-B nuclear reactor pressure vessels.

High resistance to radiation embrittlement was demonstrated by a 6 in. thick test weld and was achieved through selective restrictions on the content of certain impurity elements, primarily copper (0.10% maximum as-deposited) and phosphorus (0.010% maximum as-deposited). To help achieve a low copper content, a non-copper clad filler metal was used. The copper and phosphorus contents of the test weld deposit were 0.05% and 0.010% respectively. Preirradiation tensile properties satisfied A533-B Class 2 specification requirements. The Charpy-V 30 ft-lb transition was -50F (-46C) and approximated well the drop weight nil-ductility transition (NDT), -60F (-51C).

Essentially no embrittlement of the weld metal was observed following an exposure of 2.7×10^{19} n/cm^2 >1 MeV at 550 F (288C). This exposure condition is comparable to that estimated for many operating reactor vessels at end-of-life. Results for a factor of ten higher fluence (2.5×10^{20} n/cm^2) clearly denoted a superior 550 F (288C) radiation resistance. The Charpy-V 30 ft-lb transition remained below 200F (93C) and the Charpy-V shelf level remained above 80 ft-lb. Projections of high fluence weld properties by Ratio Analysis Diagram (RAD) procedures indicated a nonsusceptibility of 12 in. thick deposits of this quality to plane strain fracture.

Weld heat-affected zone performance was also explored for the case of controlled composition (radiation resistant) plate. Resistance of the heat-affected zone to embrittlement by 2.7×10^{19} n/cm^2 was found equal to that of the controlled composition weld deposit and superior to that of the base metal.

Observations clearly signify the need for restricting the impurity content of welds and plates for critical nuclear service applications.

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Introduction

Nuclear reactor pressure vessels are currently being constructed of ASTM Type A533-B Class 1 steel. Large vessels typically involve several thick plates joined by the submerged arc welding process. Plates (representing different melts) and welds of commercial production in general have shown significant sensitivity to radiation-induced embrittlement under reactor operating conditions (550F, 288C).[1,2] Marked variability in radiation sensitivity, however, has been noted and traced to individual impurities content differences.

Laboratory investigations[3] revealed that certain elements are more harmful than others. More important, they revealed that radiation resistance could be improved appreciably selective restrictions on the level of specific element impurities. These findings were confirmed on the commercial scale recently by a 30 ton demonstration melt of A533-B steel.[4] Plate (6 in.) from this specially controlled melt exhibited superior radiation resistance compared to unimproved commercial materials. In order to realize the full potential of radiation resistant plate in welded structures, a filler metal with at least comparable radiation embrittlement resistance would be required. This paper describes the development of such a filler metal for A533-B steel.

The potential for developing filler metal compositions with high radiation resistance was shown earlier with an experimental 2¼ Cr-1Mo-.40Si-.10C filler metal series for A543 and A542 steel.[5,6] In this weld series as in the demonstration test for A533-B plate, close control over

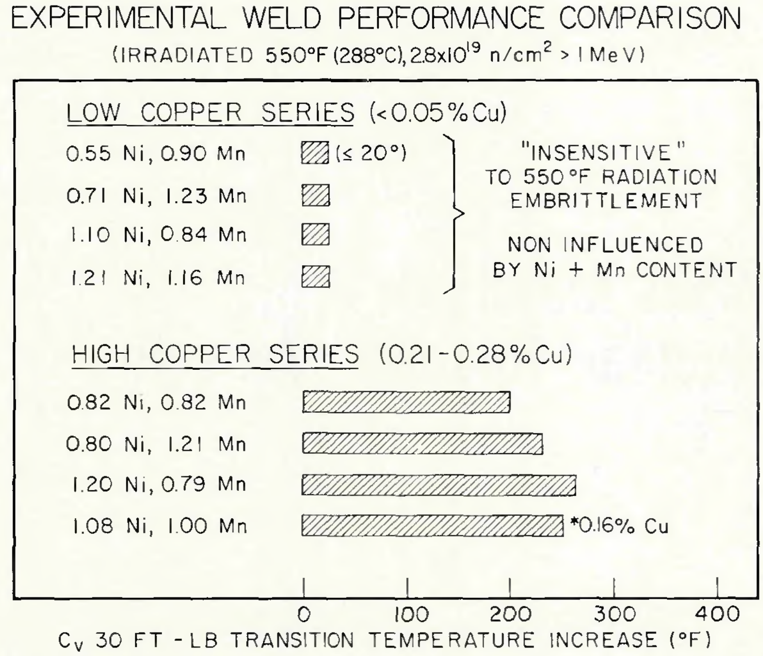

Fig. 1—Summary of observed radiation embrittlement resistance of the weld series. Primary division of behavior along the line of the low vs. high copper content is quite evident[5]

maximum copper and phosphorus content was found necessary for good radiation resistance. Figure 1 shows clearly the detrimental effect of copper on radiation resistance. Charpy-V 30 ft-lb transition temperature increases (ΔT) in this case were found to be approximated well by the expression:

$$\Delta T(°F) = -118 + 14800(\%P) + 990(\%Cu)$$

Translated into composition specification terms, a 0.02% increase in copper content and a 0.002% increase in phosphorus content would provide for a 50F greater transition temperature increase. Information and experience gained from the 2¼Cr-1Mo filler metal development program proved most valuable to the present effort.

Filler Metal Development Specifications and Approach

General filler metal requirements included capability for submerged arc welding thick plates by single arc or tandem arc welding techniques and compatibility for high heat input conditions and high metal deposition rates typical of current vessel fabrication. All mechanical property requirements for A533-B Class 1 weld joints were to be satisfied after a 1150F (621C)—8 hr (minimum) stress relief heat treatment. To preserve existing welding technology and experience regarding A533-B reactor vessel fabrication, filler metal development efforts attempted the modification, i.e., upgrading, of a conventional filler composition (Mn-Mo-Ni) rather than the development of a completely new filler material.

Exact filler metal composition specifications were developed from past experience and collective observations on: laboratory melts of radiation resistant steel (A302-B and Ni-Cr-Mo), the scaleup demonstration test with A533-B steel, the experimental 2¼Cr-1Mo filler metal series, and on various unimproved commercial steels. The limitation of copper and phosphorus impurities received primary attention because of the known highly detrimental effect of these elements on 550F (288C) radiation resistance.

Copper in submerged arc weld deposits may originate from the filler metal and/or from the copper flash coating normally applied to the filler metal to reduce corrosion in storage and to improve current carrying capacity. Phosphorus in the weld deposit may originate from the filler metal and/or from the flux. In each case individual sources of the impurity were reviewed carefully. To help assure a low copper content deposit, a non-copper coated wire was specified. Weld composition specifications developed for the test weld are given in Table 1. Limitations on arsenic, tin, and antimony reflect current uncertainties regarding the influence of these elements on radiation resistance.*

Weldment Fabrication

The experimental weld for irradiation tests was made by Lukens

*The contributions of arsenic, tin, antimony, and other suspect elements to radiation embrittlement sensitivity are currently being assessed.

Table 1—Chemical Composition of Filler Metal as Specified, as Received, as Deposited, and of Base Metal

	Chemical composition, wt-%													
	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	Al	As	Sn	Sb
Filler metal specification[a]	.15–.20	1.80–2.10	LAP–0.010 (max)	LAP–0.010 (max)	0.10 (max)	.55–.75	.10 (max)	.45–.60	LAP–0.10 (max)	.02 (max)	.05 (max)	LAP <.010	LAP <.010	LAP <.005
Filler metal														
Vendor	.17	1.96	.008	.014	.10	.71	.05	.49	.02	—	—	—	—	—
Lukens	.18	1.96	.009	.014	.07	.75	—	.50	.05	.015	—	—	—	—
NRL	.17	1.93	.008	.014	.06	.72	.06	.48	.02	.02	—	<.05	<.01	<.01
Weld Deposit[b]														
Lukens	.14	1.34	.023	.015	.21	.45	.08	.36	.07	.018	—	—	—	—
NRL	.15	1.28	.010	.012	.20	.66	.06	.48	.05	.02	—	<.05	<.01	<.01
Base metal	.17	1.22	.008	.008	.19	.58	.06	.50	.03	.02	.015	<.03	<.02	<.01

a LAP = low as possible
b Carbon Content of weld deposit to be 0.12-0.18

Table 2—Welding Parameters and Conditions

Parameter–Condition	Specified	Actual
Weld process	Submerged arc (tandem electrodes)	As specified (A)
Base metal	A533-B Class 1 (supplied by NRL)	(A)
Filler metal type	Mn-Mo-Ni (non-copper clad)	(A), RACO Heat IP 3607
Flux	Linde 0091	(A), 65 × 200, baked 700F (371C)
Joint design	Double U, 2:1 ratio	(A)
Electrode size	3/16 in. diam. (1/8 in. diam. minimum)	5/32 in. diam.
Electrode connection	Scott connection (ac-ac, 90° phase shift)	(A)
Welding voltage	31-35 v (a.c.)	35 and 25V (lead), 34 and 27 v (trail) (nominal)
Welding current	550/600 amp	600 and 700 amp (lead), 550 and 650 amp (trail)
Travel speed	20-22 ipm	30 and 25 ipm
Heat input	80 kjoules/in. (minimum); 102 kjoules/in. (maximum)	82.4 — 84.1 kjoules/in. (nominal)
Deposition	1/8 in. thickness per pass (nominal) 2-3 beads/layer	(A)
Preheat	250F (121C) (minimum) 300F (148C) (aim)	350F (177C) 135 hr at 300-350 F (149-177 C) before cooling
Interpass	500F (260C) (maximum)	(A)
PWHT	1150F ± 25F (621C ± 14C)-8 hr FC to 600F (316C) at 60F/hr (33C/hr)	1150F ± 25F (621C ± 14C)-8 hr FC to 600F (316C) at 90F/hr (50C/hr)

Steel Company under a Naval Research Laboratory contract. Welding parameters and conditions, both specified and actual, are given in Table 2. Sections of the 6 in. thick radiation resistant plate from the 30 ton demonstration melt served as base material. Subsequently, weld deposit performance vs. weld heat-affected zone performance could be assessed directly for the case of radiation resistant parent plate. The irradiation performance of the base metal is documented in the literature.[4]

Chemical compositions of the filler metal, the as-deposited weld metal, and the plate are shown in Table 1. All filler metal composition requirements except for sulfur content were satisfied. The somewhat high sulfur content (0.014%) later proved acceptable as discussed below.

The use of a non-copper clad filler metal was not observed to pose special problems to welding operations. Alternate means are available for protecting filler metal from corrosion during storage. Thus, it can be assumed that non-copper clad filler metal can be used with equal success in commercial welding of large nuclear components.

Specimen Preparation and Irradiation

Specimen types included 0.252 in. gage diameter tensile, standard Charpy-V, 5/8 in. thick drop weight (DW), and 5/8 in. thick dynamic tear (DT) specimens. All were oriented with their long axis perpendicular to the welding direction. The notch of weld metal Charpy-V and DT specimens was perpendicular to the weldment surface; the notch of heat-affected zone Charpy-V specimens was parallel to the weldment surface and centered on the fusion line as determined by etching. The heat-affected zone specimens were taken from the one-quarter thickness location only.

Table 3 summarizes irradiation experiments performed. Promising results from the initial (exploratory) irradiation led to the two advanced irradiations listed. Fluence values ($n/cm^2 > 1$ MeV) are given for an assumed fission spectrum distribution and for a calculated spectrum distribution of neutrons in the respective irradiation facilities. Fluences were established using iron neutron detector wires in each experiment. A fission averaged cross section of 68 millibarns (mb) was taken for the $^{54}Fe(n,p)^{54}Mn$ reaction.

Table 3—Irradiation Experiment Summary

Experiment	Specimen type	Exposure temperature °F	Exposure temperature °C	Fluence (n/cm^2 > 1 MeV)	Reactor
1 (Exploratory)	Charpy-V	550	288	2.7×10^{19} (FS)[a] 2.3×10^{19} (CS)[b]	UCRR
2	Charpy-V, Tensile	550	288	2.5×10^{20} (FS) 2.4×10^{20} (CS)	ATR
3	Charpy-V	500	260	2.3×10^{19} (FS) 2.0×10^{19} (CS)	UCRR

a FS—fission spectrum assumption.
b CS—calculated spectrum.

Preirradiation Assessments

Preirradiation strength and notch toughness properties of the weld deposit are summarized in Table 4. Results overall are indicative of good through-thickness uniformity. Significantly, the deposit satisfies Class 2 strength requirements. The drop weight nil-ductility transition (NDT) temperature, -60F (-51C), compares well with the low NDT performance of commercial A533-B Class 1 weld deposits. The Charpy-V energy level at the NDT temperature was 25 ft-lb. Therefore, the Charpy-V 30 ft-lb. index often used as a convenient arbitrary index of NDT for pre-postirradiation comparisons of performance appeared quite appropriate in this case.

Relative drop weight NDT, Charpy-V, and dynamic tear behavior for the preirradiation condition is shown in Fig. 2. As expected, the NDT falls at the toe of the DT curve. The DT shelf level for the midthickness location appears somewhat lower than that for the quarter thickness location. However, due to the narrowness of the weld deposit at the midthickness position, this may be a reflection of base metal properties. The DT shelf level of the plate at this location was approximately 1020 ft-lb.

As noted in Table 4, preirradiation properties of the weld deposit were equal to or superior to those of the base metal. The Charpy-V and DT shelf energy values for both the deposit and plate are comparably high. This is not considered typical, however, for many commercial A533-B welds. In view of the high shelf energy level, it was determined that the 0.014% sulfur content of the filler metal, though out of specification (0.010% maximum), was not cause for weldment rejection.

Irradiation Assessments

Postirradiation Charpy-V results for the weld deposit are shown in Fig. 3; postirradiation tensile data are summarized in Table 5. Data for thermal control specimens included in Fig. 3 and Table 5 show a good stability of weld properties under extended thermal conditioning in the absence of irradiation.

For the exploratory 550F (288C) — 800 hr irradiation experiment, the Charpy-V data points are seen to fall within the data scatterband for the preirradiation condition. The Charpy-V notch ductility of the deposit clearly was not changed by this exposure. Noting that fluences of 2 to 4 x 10^{19} n/cm^2 >1 MeV are a reasonable maximum lifetime estimate for many nuclear vessels now operating, the data suggest that the upgrading of the Mn-Mo-Ni filler metal was most successful.

The subsequent high fluence experiment (No. 2 of Table 3) served to establish the full potential of the filler metal for severe 550F (288C) nuclear service. The duration of this experiment was less than that of the above exploratory experiment because of the order-of-magnitude greater flux (n/cm^2-sec) in the Ad-

Table 4—Preirradiation Properties of Weld Deposit and Base Metal

Property[a]	Weld deposit	Base metal[b]
Yield strength, ksi	87.3 89.0 (surface)	66.8 68.9 (surface)
Tensile strength, ksi	100.8 101.2 (surface)	86.3 88.0 (surface)
Elongation, % in 1 in.	23.5	28.8
Reduction of area, %	68.4	70.7
Drop Weight NDT, °F	-60 (-51C)	-20 (-29C)
Charpy-V 30 ft-lb transition, °F	-50 (-46C)[c]	-60 (-51C)[d] -15 (-26C) (1/2T)
Charpy-V shelf energy, ft-lb	118[c]	145[d] 120 (1/2T)
DT 50% energy transition, °F	25 (-4C)[e]	25 (-4c)[e]
DT shelf energy, ft-lb	1590 1330 (1/2T)	1130 1020 (1/2T)

a Quarter thickness location unless specified.
b Non-welded plate condition[5] unless specified (longitudinal orientation).
c Through thickness locations.
d Welded plate condition.
e Quarter and half thickness locations.

Table 5—Tensile Properties of Weld Deposit After High Fluence 550F (288C) Irradiation

Condition	Test temperature, °F	Test temperature, °C	Yield strength, ksi	Tensile strength, ksi	Elongation, % in 1 in.	Reduction in area, %
Unirradiated	75	24	87.3	100.8	23.5	68.4
	550	288	74.8	92.0	19.9	63.8
Thermal control	75	24	84.8	96.2	21.9	67.4
(800 hr)	550	288	71.6	90.5	21.1	71.4
Irradiated	250	121	104.5	109.4	16.5	63.3
(2.5 × 10^{20} n/cm^2)	400	204	95.7	107.9	17.6	61.1
> 1 MeV	550	288	93.5	105.7	19.4	63.8

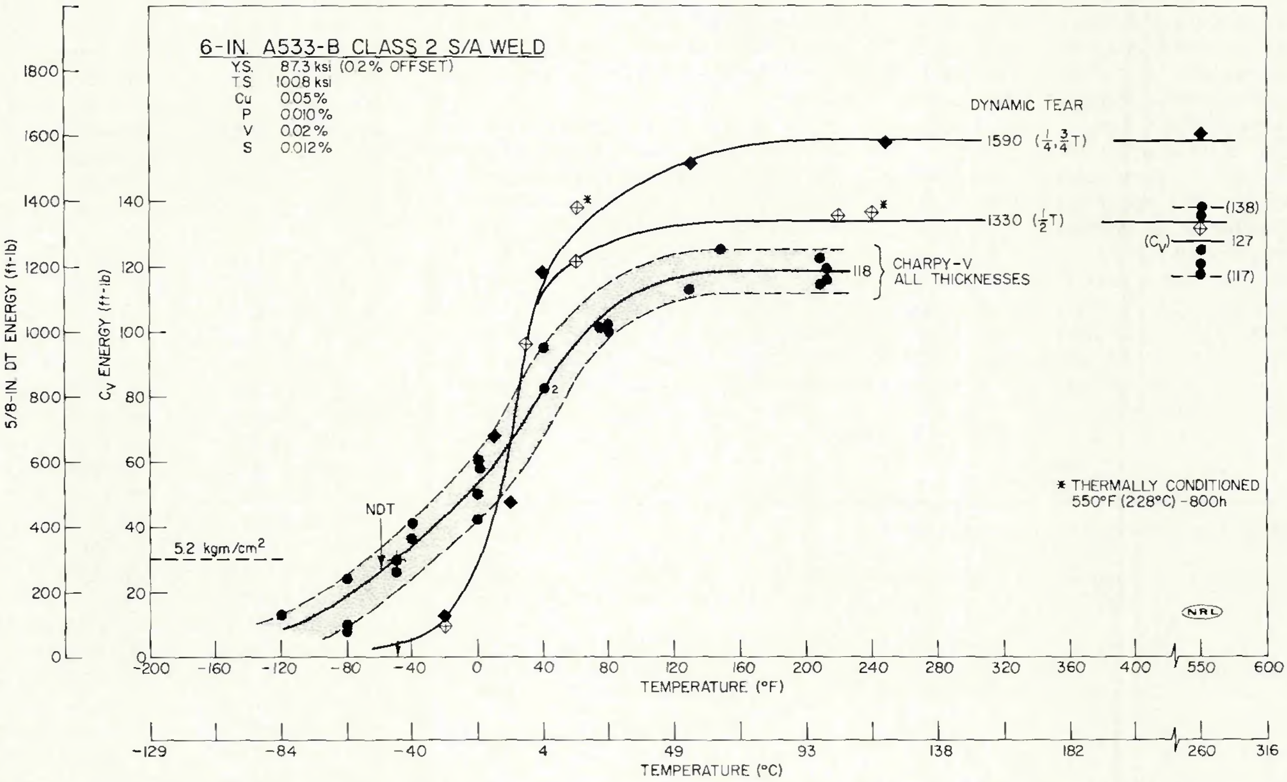

Fig. 2—Preirradiation notch ductility of the weld deposit determined by drop weight, dynamic tear (DT), and Charpy-V test methods. Results are indicative of good through-thickness uniformity

vanced Test Reactor (ATR) facility. The results depict a transition temperature increase of 235F (131C) for the fluence of 2.5 x 10^{20} n/cm^2 and a Charpy-V shelf reduction of only 36 ft-lb. It is highly questionable if unimproved A533-B weld metals could withstand this high level of exposure. For example, a 12 in. thick submerged arc weld deposit prepared under closely monitored conditions for the AEC Heavy Section Steel Technology (HSST) Program exhibited a Charpy-V 30 ft-lb. transition temperature increase of 270F (150C) for a fluence only one tenth that of this experiment.[2]

The 500F (260C) experiment (No. 3 of Table 3) was conducted as a partial test of the temperature dependence of the weld metal radiation resistance. Accordingly, attempts were made to duplicate the fluence conditions and exposure period of the 550F (228C) exploratory experiment. Comparison of the results of the two experiments (Fig. 4) show radiation embrittlement resistance to decrease with decreasing exposure temperature. However, the extent of embrittlement for the 500F (260C) experiment is relatively small for the fluence (2.3 x 10^{19} n/cm^2). The decrease in Charpy-V shelf energy ($\sim$20 ft-lb) in this case is not of major consequence because of the relatively high preirradiation level. Combined results of the 500F (260C) and 550F (288C) moderate fluence experiments thus suggest good weld deposit performance for a range of service temperatures.

Figure 5 illustrates the Charpy-V performance of the weld heat-affected zone before and after 550F (288C) irradiation (upper graph) and compares heat-affected zone performance to pre-postirradiation performance of the weld deposit and base metal (lower graph). Note that the heat-affected zone specimens for this determination were exposed in the 550F (288C) exploratory experiment. Postirradiation properties given for the parent plate are estimates based on previous results[4] for the non-welded condition. The data suggest that the heat-affected zone, like the weld deposit, was not embrittled by the exploratory irradiation exposure. Similar irradiation of the plate, however, produces some degree of embrittlement. Accordingly, the plate presents the least resistance to radiation in this case.

Figure 4 indicates that, for the pre- and post-irradiation conditions, the heat-affected zone has the lowest Charpy-V 30 ft-lb transition. However, this index of transition behavior must be recognized as an arbitrary measure of relative steel quality whereas the NDT is quantitative in its description of steel performance. With the assumption that the NDT performance of the heat-affected zone is comparable to that of the plate, the weld deposit would be judged to have the lowest NDT of the three weld components for pre-post-irradiation conditions. Reasons for the difference in Charpy-V energy indices for the plate and weld deposit NDT have not been established.

Tensile property determinations for the 550F (288C) high fluence condition describe a significant elevation in weld deposit strength accompanied by a slight loss in ductility (Table 4). The strength elevation nonetheless is less than that expected for unimproved A533-B or A302-B materials. The evaluation of postirradiation yield strength and Charpy-V shelf energy by RAD procedures[7] permits a projection of nonsusceptibility to plane strain fracture for weldment thickness up to at least 12 in.

Figure 5 indicates a correlation discerned between Charpy-V lateral expansion (mils) and Charpy-V fracture energy (ft-lb) for the weld deposit. As noted, the correlation ratio for the preirradiation condition is less than one. Irradiation tends to reduce the correlation ratio. As a result, a given lateral expansion represents a higher fracture energy for the postirradiation condition than for the preirradiation condition. The change in correlation ratio for the high fluence exposure, however, is seen to be quite small. Thus, this index cannot be used nearly as effectively as other indices for monitoring radiation effects. Supporting evidence has been obtained with irradiated A533-B plate. A variance in preirradiation correlation ratio has also been noted

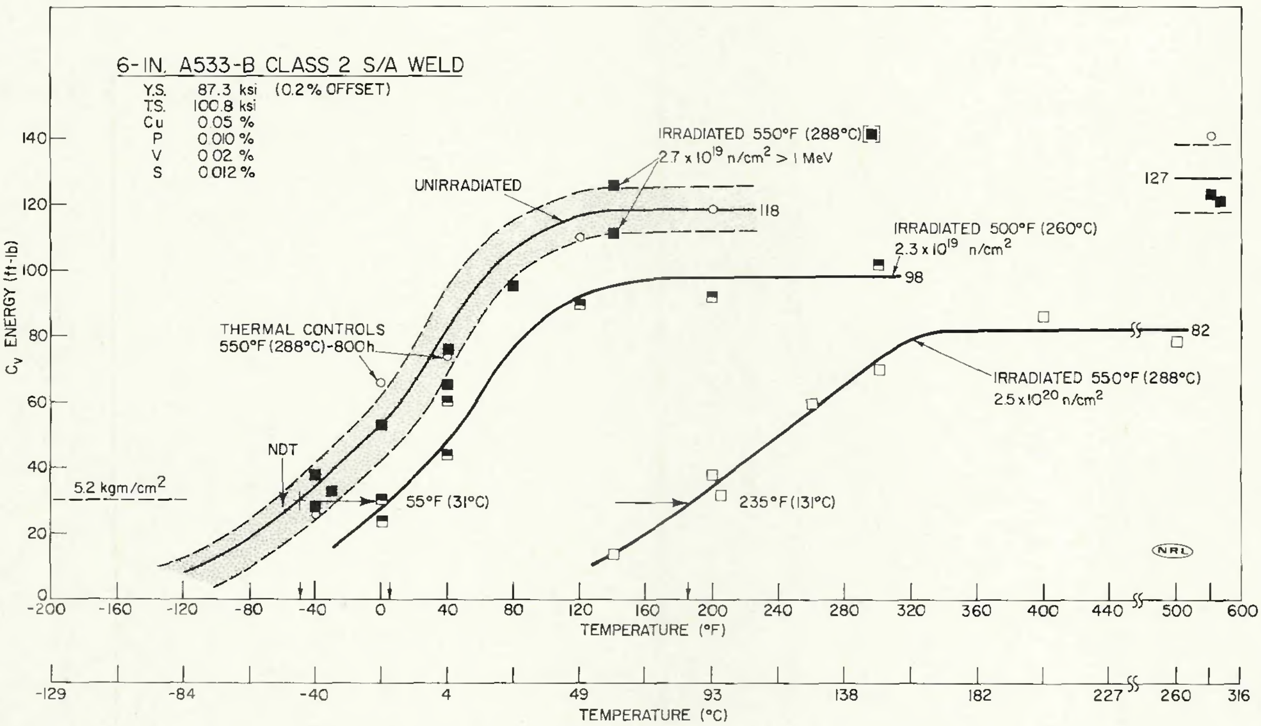

Fig. 3—Charpy-V performance of the weld deposit after elevated temperature exposure to moderate and high fluences. High radiation embrittlement resistance is clearly indicated

among plate, forging, and weld metals. Thus, lateral expansion may not be as universal an index of notch toughness as has been suggested recently.

Discussion

This study clearly establishes the benefits of a low impurities content to the radiation embrittlement resistance of Mn-Mo-Ni weld deposits. In Fig. 6 results for the demonstration weld are compared to the range of performance for unimproved commercial weld deposits and A533-B plates. The performance of plate from the 30 ton demonstration melt is also shown in this frame of reference. The potential of the improved filler metal for fluence applications well beyond those for unimproved filler metals is quite obvious. Accordingly, it is recommended that weld deposit impurities content, especially copper and phosphorus content, be restricted for critical nuclear service applications by filler metal specifications and flux selection.

The detrimental effect of copper on steel radiation resistance was traced recently to the enhancement of the yield strength elevation by irradiation.[6,8] In explanation of this enhancement, transmission electron microscopy has shown that the presence of copper (0.3%) in iron greatly increases the number of defects produced by neutron irradiation via heterogeneous nucleation.[8] A greater defect density would readily account for the greater postirradiation strength elevation of copper-containing plate and weld metals. Less is known about the phosphorus contribution; however, it has been suggested[6] that the mechanism has a form somewhat similar to that of temper embrittlement. Regardless of

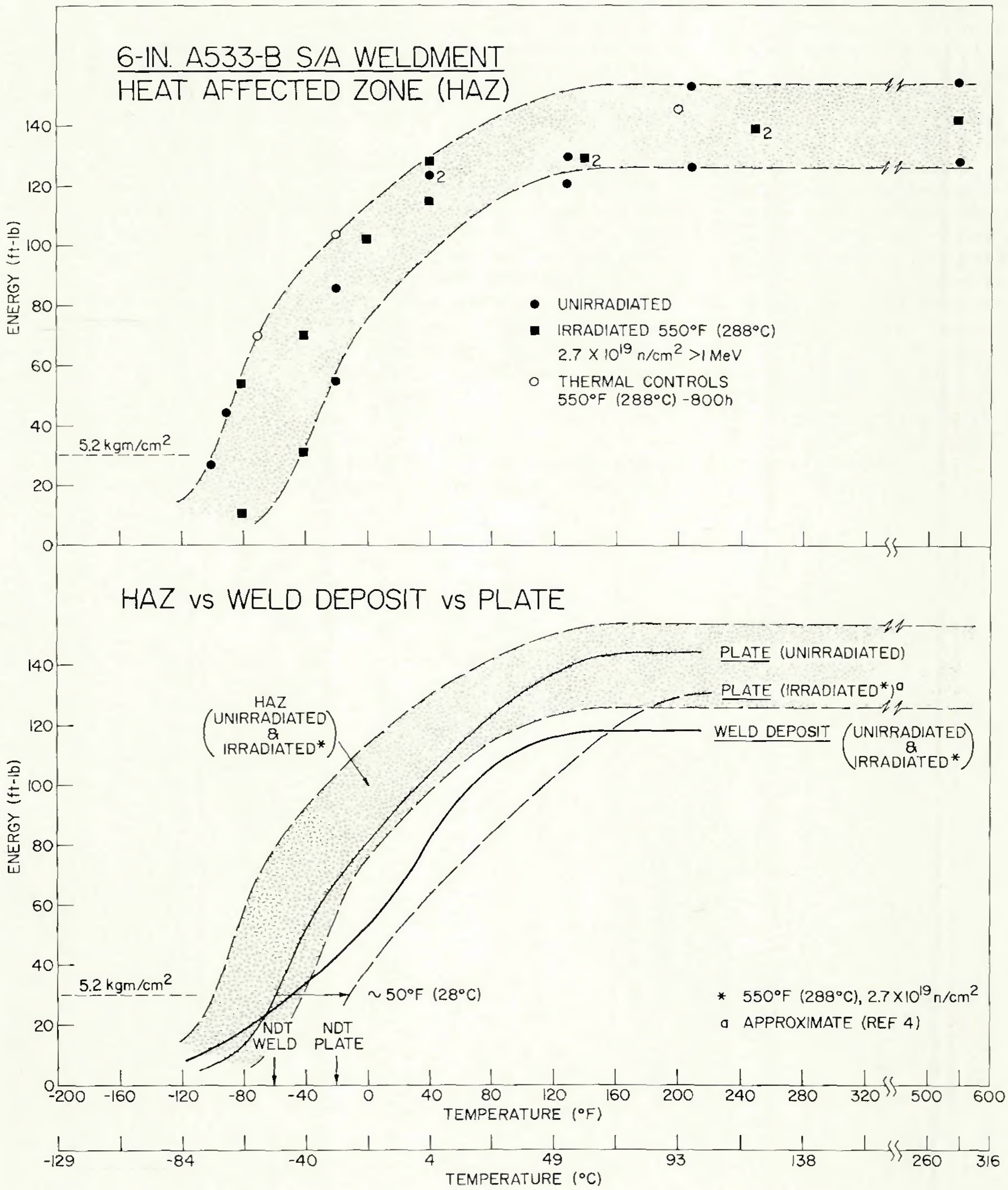

Fig. 4 — Charpy-V performance of the weld heat affected zone. Specimen notch was centered on the fusion line. Upper graph shows nil embrittlement for a moderate fluence exposure. Lower graph depicts the performance of heat-affected zone vs. weld deposit and base metal

this similarity, radiation embrittlement and temper embrittlement for the most part are mutually independent processes.[6]

Significant to the study of mechanisms, some radiation hardening (~3 to 4 R_B) was detected with the 550F (288C) exploratory experiment though no embrittlement was apparent from Charpy-V measurements. Radiation resistant 2¼Cr-1Mo experimental welds[5] also have shown such behavior. A separate and distinct component of radiation damage which has the characteristics of lattice hardening may thus be indicated.

Summary

A Mn-Mo-Ni submerged arc weld filler metal has been successfully tailored for improved radiation embrittlement resistance at reactor vessel service temperatures (~550F, 288C). Radiation resistance was upgraded through special restrictions on the as-deposited content of certain impurity elements.

A 6 in. thick submerged arc test weld with the improved filler metal clearly exhibited A533-B Class 2 strength properties and a drop weight NDT of -60F (-51C). Weld metal embrittlement was not evident for a moderate fluence irradiation of 2.7 x 10^{19} n/cm^2 >1 MeV at 550F (288C); only minor embrittlement resulted from a comparable fluence at 500F (260C). Weld deposit capabilities for fluence service well beyond the demands of current pressurized water reactor systems was revealed by a high fluence assessment. For a fluence of 2.5 x 10^{20} n/cm^2 at 550F (288C), the postirradiation Charpy-V 30 ft-lb transition temperature remained below 200F (93C) and sufficient toughness was retained in the shelf level condition to preclude plane strain fracture in weldment thicknesses up to at least 12 in. Deposits of unimproved filler metals by comparison appear incapable of withstanding such high fluence conditions.

The minimization of certain harmful impurity elements in welded steel plate was found to improve the radiation embrittlement resistance of both the weld heat-affected zone and the unaffected base material. For the particular controlled composition A533-B Class 1 plate utilized in this study, the heat-affected zone was found to have somewhat better preirradiation Charpy-V characteristics and better radiation resistance than the base metal.

It is strongly recommended that the impurities content of weld deposits and plates, especially copper and phosphorus content, be restricted for critical nuclear service applications requiring radiation embrittlement resistance.

Acknowledgments

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Appreciation is also expressed to individual members of the NRL Reactor Materials Branch who contributed to the success of radiation experiment operations.

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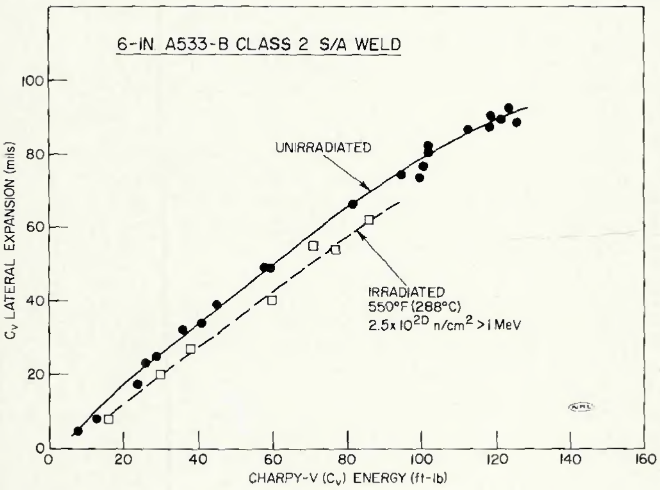

Fig. 5—Correlation of Charpy-V lateral expansion vs. fracture energy for pre-and postirradiation conditions of the weld deposit. The correlation ratio is shown lowered by high fluence. 55F (288C) exposure

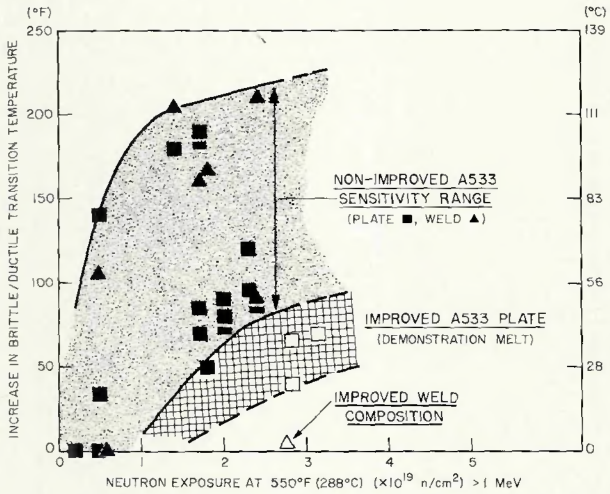

Fig. 6—Increase in Charpy-V 30 ft-lb transition temperature with neutron irradiation at 550F (288C). The performance of the improved composition demonstration weld (open triangle) is excellent compared to the range of performance of unimproved commercial weld deposits and A533-B plates (closed symbols). The performance of improved composition plate from a 30 ton A533-B demonstration melt (open squares) is also shown

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Local Stresses in Spherical and Cylindrical Shells Due to External Loadings

by K. R. Wichman, A. G. Hopper and J. L. Mershon

Several years ago, the Pressure Vessel Research Committee sponsored an analytical and experimental research program aimed at providing methods of determining the stresses in pressure vessel nozzle connections subjected to various forms of external loading. The analytical portion of this work was accomplished by Prof. P. P. Bijlaard of Cornell University. Development of the theoretical solutions involved a number of simplifying assumptions, including the use of shallow shell theory for spherical vessels and flexible loading surfaces for cylindrical vessels. These circumstances limited the potential usefulness of the results to d_i/D_i ratios of perhaps 0.33 in the case of spherical shells and 0.25 in the case of cylindrical shells. Since no data were available for the larger diameter ratios, Prof. Bijlaard later supplied data, at the urging of the design engineers, for the values of $B = 0.375$ and 0.50 (d_i/D_i ratios approaching 0.60) for cylindrical shells. In so doing, Prof. Bijlaard included a specific warning concerning the possible limitations of these data.

Following completion of the theoretical work, experimental work was undertaken in an effort to verify the theory. Whereas this work seemingly provided reasonable verification of the theory, it was limited to relatively small d_i/D_i ratios—0.10 in the case of spherical shells and 0.126 in the case of cylindrical shells. Since virtually no data, either analytical or experimental, were available covering the larger diameter ratios, the Bureau of Ships sponsored a limited investigation of this problem in spheres, aimed at a particular design problem, and the Pressure Vessel Research Committee undertook a somewhat similar investigation in cylinders. Results of this work emphasized the limitations in Bijlaard's data on cylindrical shells, particularly as it applies to thin shells over the "extended range."

Incident to the use of Bijlaard's data for design purposes, it had become apparent that design engineers sometimes have difficulty in interpreting or properly applying this work. As a result of such experience, PVRC felt it desirable that all of Bijlaard's work be summarized in convenient, "cookbook" form to facilitate its use by design engineers. However, before this document could be issued, the above mentioned limitations became apparent presenting an unfortunate dilemma, viz., the data indicate that the data are partially inadequate, but the exact nature and magnitude of the error is not known, nor is any better analytical treatment of the problem available (for cylinders).

Under these circumstances, it was decided that the best course was to proceed with issuing the "cookbook," extending Bijlaard's curves as best as possible on the basis of available test data. This decision was based on the premise that all of the proposed changes would be toward the conservative (or "safe") side and that design engineers would continue to use Bijlaard's extended range data unless some alternative were offered. This paper was therefore presented in the hope that it would facilitate the use of Bijlaard's work by design engineers.

Since the paper was originally issued, a number of minor errors have been discovered and incorporated in revised printings as supplies were exhausted. The third revised printing was issued in April 1972.

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