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NRL Report 7095

The Influence of Composition on the Fracture Toughness of Commercial Nuclear Vessel Welds

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June 23, 1970

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Prepared for

II Inter-American Conference on Materials Technology, Mexico City, D.F., Mexico, August 24-27, 1970

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CONTENTS

Abstract ii
Problem Status ii
Authorization ii

INTRODUCTION 1

FABRICATION OF NUCLEAR VESSELS 2

DEFINING IRRADIATION EFFECTS 4

COMPOSITION VARIATIONS AND RADIATION EMBRITTLEMENT 6

Comparison of Radiation-Embrittlement Sensitivity Between Plate and Weld 6
Comparison of Relative Radiation-Embrittlement Sensitivity of Plate and Weld Selected for Two Reactor Vessels 10

REDUCING RADIATION-EMBRITTLEMENT SENSITIVITY THROUGH COMPOSITION CONTROL 10

SUMMARY AND CONCLUSIONS 14

REFERENCES 15

ABSTRACT

The weld joint of a nuclear vessel is considered as potentially the weakest link in its reliability. This is because the weld presents a possible region of physical and metallurgical discontinuity, the welding process offers added chances for the introduction of defects and undesirable components or stresses, and, for nuclear reactor pressure vessels, the radiation environment may accentuate the other negative aspects of the weld through differential radiation damage. Consequently, the fracture toughness of nuclear vessel welds has become the focal point for those concerned with the reliability of nuclear vessels.

Irradiation studies of welds of the ASTM Type A302-B and A533-B steels, most commonly used for commercial water reactor vessels, have demonstrated several instances in which the weld metal exhibited lower fracture toughness or greater elevation of the brittle-to-ductile transition temperature than that observed for the companion base-plate and weld heat-affected-zone material. Examination of the structure and composition has led to the conclusion that composition is critical to the level of radiation-induced embrittlement. The level of copper and phosphorus contents has been shown to be especially critical to the level of embrittlement with welds having high copper (>0.20%) and phosphorus (>0.015%) showing greater embrittlement than those containing lesser amounts. These experimental observations have been verified through laboratory tests in which these constituents and other residual elements have been controlled in weldments simulating those for reactor service.

The study of controlled weld composition has been extended to the welds of the higher strength ASTM Type A543 steel with even more remarkable results than those observed for the lower strength steels of current commercial reactor vessel construction. These results when applied in specifications for future reactor vessels should go far toward alleviating radiation embrittlement of reactor vessels and also provide guidance for projecting the level of fracture toughness of operating vessels at selected points in the lifetime of a vessel.

PROBLEM STATUS

This is an interim report on one phase of the problem; work is continuing.

AUTHORIZATION

NRL Problem M01-14
Projects RR 007-11-41-5409
AEC-AT(49-5)-2110
USA-ERG-11-69

Manuscript submitted March 11, 1970.

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THE INFLUENCE OF COMPOSITION ON THE FRACTURE TOUGHNESS OF COMMERCIAL NUCLEAR VESSEL WELDS

INTRODUCTION

All of the nearly one hundred commercial nuclear power plants constructed, under construction, or planned in the United States have welded pressure vessels. Several of the early plants were fabricated of ASTM Type A212-B carbon-silicon steel (similar to new A515 Grade 70 analysis), whereas more recent vessels were of either A302-B or A302-B steel modified with added nickel (similar to newer A533, Grades A, B, and C). Higher strength A542 and A543 steels are also approved for nuclear reactor vessel construction by the American Society of Mechanical Engineers (ASME), Boiler and Pressure Vessel Code, but have not yet been used for a nuclear vessel.

Most of the nuclear containment vessels have been shop fabricated and shipped to the reactor site for inclusion in the plant. An alternative, shop fabrication of segments with later field assembly, has been applied in the United States for the Monticello boiling water reactor (BWR), and other vessels have been approved for field assembly. Regardless of the technique used, the welding process and the subsequent stress-relief heat treatment and nondestructive examination of the welds are crucially important. In general, the careful procedures applied have resulted in welds of equal or superior toughness to the base-plate steel in the as-constructed state. In service, however, radiation has been shown to change this relationship between plate and weld.

Over the lifetime of a water reactor vessel (usually projected as 40 years), the neutron exposure on the inside of the vessel may reach fluences as great as 5 to 6×10^{19} n/cm^2 >1 MeV. This level will vary greatly, of course, from one plant to another or from one type of reactor to another but may result in significant changes in the fracture toughness of the vessel constituents. The BWR vessel, by the very nature of plant design, may receive as much as an order of magnitude lower neutron exposure than the vessel of a pressurized water reactor (PWR) of the same power level.

Tests for fracture toughness, including the ASTM Drop Weight Test (1) for defining the nil-ductility transition temperature; the ASTM Charpy V-notch Impact Test (2); the Compact Tension Test (3) for defining the plane-strain fracture toughness; and the Dynamic Tear Test (4,5) as developed at the U.S. Naval Research Laboratory (NRL) have all been applied in evaluating irradiated pressure vessel steels and weldments. The mechanics and the interrelationships of these several approaches to the evaluation of the fracture toughness of metals and their broader applications to quality assurance are covered in another paper of this conference (6) and in a broad review of the subject in Ref. 7. For the purposes of this paper, irradiation-effects studies will be referenced primarily to the Charpy V-notch Impact Test and its relationship with the Drop Weight Test.

Neutron-irradiation effects studies have been conducted to show the relative toughness of several steels and their related welds and weld heat-affected zones. The observation of significant variations in radiation embrittlement resulted in studies to assess both the technological and scientific bases for such variations. The technologically based study is described with indications of the strong influence of composition on the degree of embrittlement observed in several commercial and special steel plates and welds.

The study, though relatively limited in scope to date, provides data which demonstrate the potential for controlling the radiation-embrittlement sensitivity of future nuclear reactor pressure vessels.

FABRICATION OF NUCLEAR VESSELS

Water reactor vessels are usually shop fabricated for later integration into the total system at the reactor site. The first step in fabrication is the forming of heavy steel plate, as shown in Fig. 1 (8). Occasionally, cold or warm forming is used, especially for thinner plates. Hot forming is accomplished in the 1700 to 2000°F (925-1100°C) range. After hot forming, the plate sections are heat treated, usually by water quenching and tempering, to develop the optimum balance of strength and toughness. Cylindrical shell segments are then joined either by submerged-arc welding after heat treatment or by electroslag welding prior to heat treatment. The latter is used only to a limited extent, but, where it is used, it is necessary to heat treat the full weldment to refine the coarse, columnar grain structure and to restore notch toughness. (Figure 2 illustrates the electroslag weld and its refinement by heat treatment (8).) Nozzles and other penetrations are then provided and the heads joined to complete the vessel. The upper head is usually designed to be bolted to a forged flange which is welded to the shell. The lower head is usually welded to the intermediate cylindrical vessel portion, and then stress-relieving heat treatment is employed to remove mechanical strains as well as to soften

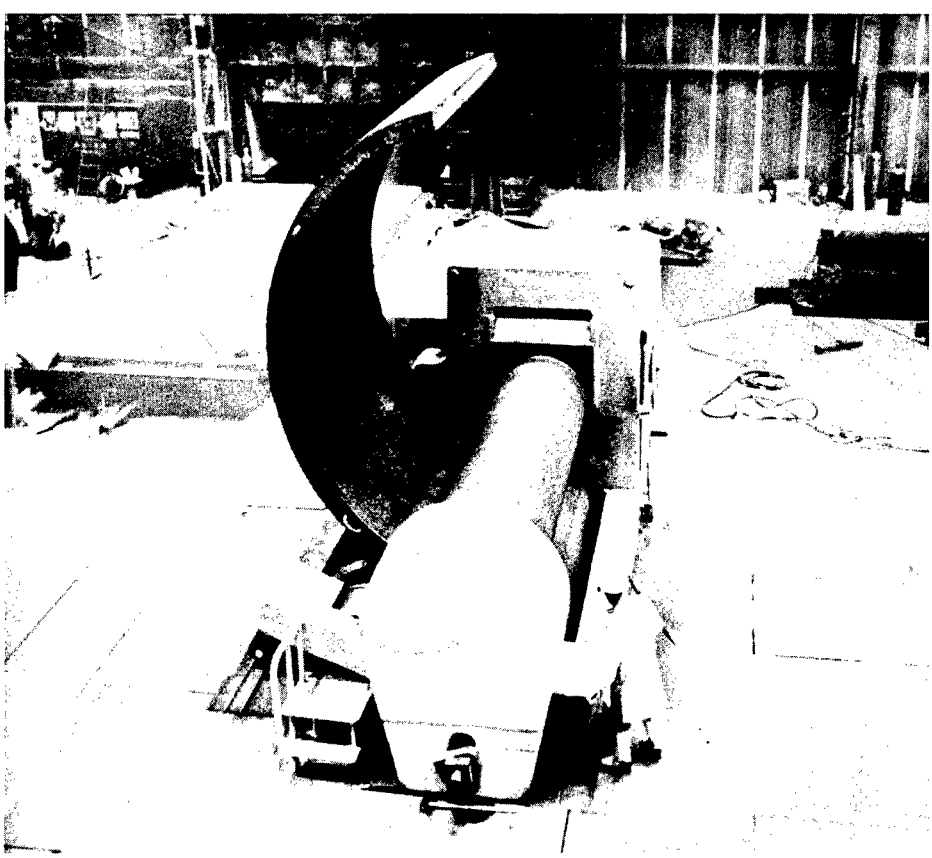

Fig. 1 - Nuclear reactor shell plate being formed on horizontal plate-bending rolls. (Courtesy of Babcock and Wilcox Co.)

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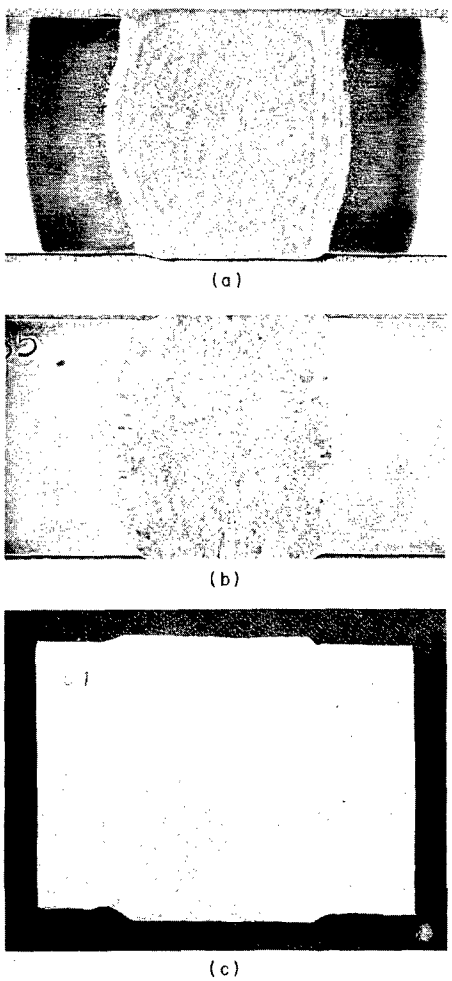

Fig. 2 - Electroslag well nugget in A543 steel (etchant: nitric, acetic, alcohol). (a) As-welded condition. Note concentric coarse-grained solidification pattern in weld and dark heat-affected zones. (b) After-heat-treatment condition (1650°F, 899°C water quenched, 1260°F, 682°C water quenched). Note that heat-affected zones have been eliminated by this heat treatment. (c) After cycling and heat treatment. Note grain refinement in weld and elimination of the heat-affected zones.

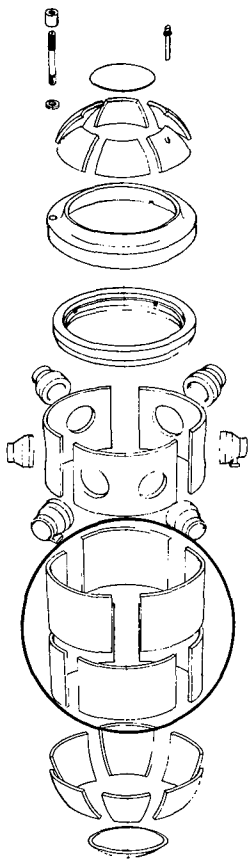

Fig. 3 - Expanded view of PWR vessel showing individual plate before welding. Cylindrical shell receives highest neutron exposure. (Courtesy of Combustion Engineering Corp.)

the weld metal and to reduce cracking susceptibility of welds and weld heat-affected zones (9). Figure 3 provides a schematic expanded view of a typical PWR vessel before welding showing the four major regions: the top closure head, the nozzle-flange course, the cylinder (core) course, and the lower head. A typical completed vessel minus the top head is shown in Fig. 4. It is clear that welding is extremely important to the construction of a nuclear vessel. Various published reports provide more details of the submerged arc and electroslag welding procedures for nuclear vessels (9-12).

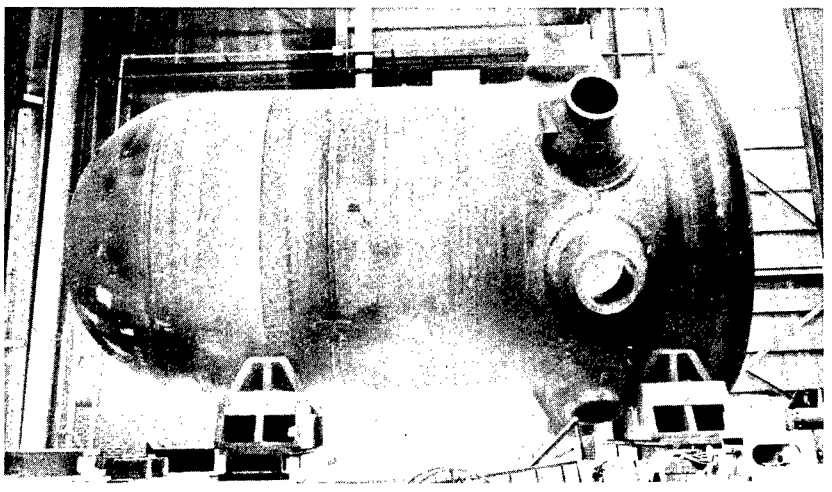

Fig. 4 - Typical large United States PWR vessel minus top head.
(Courtesy of Combustion Engineering Corp.)

In reference to Fig. 3, the circled region permits visualization of the core region overlapping the two plate sections of the central cylindrical portion, thereby indicating the region wherein irradiation exposure of welds is of interest. In most reactors, the longitudinal welds joining the six plates of the two-layer cylindrical shell region as well as the circumferential weld joining the two cylindrical shells all receive the higher neutron exposures inherent to the core region. Thus the strength, ductility, and fracture toughness of these welds and heat-affected zones must be as good as those of the adjacent plate. Further, the properties after irradiation also should be as good or better than those of the base plate. Recognition of the fact that the weld metal, in some cases, was more sensitive to radiation embrittlement has led to an increasing emphasis on comparative irradiation studies and stronger efforts to develop weld metals of low sensitivity to radiation.

DEFINING IRRADIATION EFFECTS

Neutron radiation, through mechanisms not yet well understood, reduces the ductility of ferritic steels while increasing the strength and hardness. The decreased ductility and fracture toughness of pressure-vessel steels is a function of many factors, but especially of the specific steel and the specific nuclear and physical environment. (For a more detailed review see Ref. 13.) Thus, it is not possible without describing the steel and defining the environment to project the degree of vessel embrittlement. To overcome this problem of individuality of response among vessel steels, a plan for the continuing surveillance of reactor-vessel steel embrittlement has been adopted and applied in most commercial power reactors. The program involves the placement of Charpy V-notch

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specimens at peak neutron exposure locations inside the reactor-vessel wall. Such specimens, along with neutron dosimeters, are removed periodically and evaluated to assess the current, and to project the future, condition of the irradiated vessel. Such in-reactor programs are not sufficient in themselves, however, since the understanding of the fracture of thick sections must be related through separate experimental programs in order to establish the fullest meaning from surveillance data. (See Refs. 6 and 7 for more details of fracture-safety evaluation through the use of laboratory specimens.) Furthermore, experimental programs to assess irradiation embrittlement offer much background for the more limited surveillance program. These experimental studies have involved simulation of the reactor environment but on an accelerated basis, so that vessel lifetime fluences could be reached in weeks or months.

Such studies have focused on the problem of ductility or fracture toughness in the presence of a notch. The basic tool, the Charpy V-notch test (ASTM Type A), has been utilized primarily because of its convenient size and wide acceptability for specification of steels. It has several disadvantages relative to the larger notch-ductility test, the Dynamic Tear (DT) test, but serves well the purpose of comparing various irradiated steels. It even provides meaningful absolute data when correlated to the drop-weight nil-ductility transition (NDT) temperature test (14), which provides a single reference temperature (rather than a curve) having meaning for fracture safety analysis. The nature of the irradiation data obtained is described in Fig. 5. The typical Charpy V-notch data curves and related NDT values indicated on the curve are shown for the irradiation of A302-B (a reference heat) steel at a typical reactor temperature (550°F, 288°C) to a neutron fluence, ~3×10^{19} n/cm^2 >1 MeV, which represents a typical lifetime fluence for a pressurized water reactor. Both the increase in transition temperature or NDT (see Ref. 14 for basis for correlation) and the reduction in the energy-absorption capacity of the irradiated steel are important.

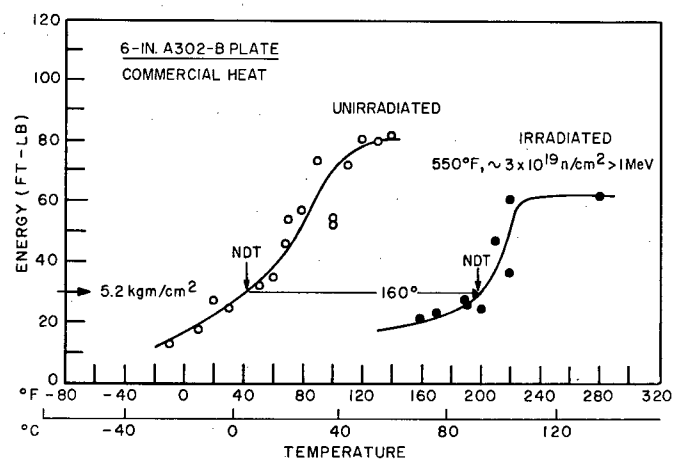

Fig. 5 - Typical Charpy V-notch and NDT data for irradiated A302-B steel

As irradiation data were accumulated, trends of NDT or transition temperature increase vs neutron fluence, as in Fig. 6 were established. Such early data, based primarily upon irradiations at low temperature, demonstrated relatively high uniformity of embrittlement. Later, however, as data for more recently produced steels, e.g., A533 and A543, irradiated at higher temperatures became available, bigger variations became apparent. From these observations of variable sensitivity to irradiation embrittlement, studies developed to determine the metallurgical causes for such variability.

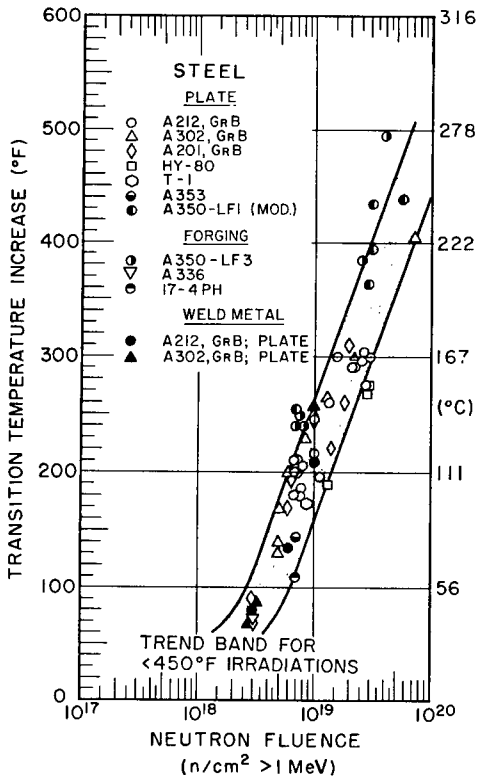

Fig. 6 - Increase in the transition temperature of steels resulting from irradiation at temperatures below 450°F (232°C)

COMPOSITION VARIATIONS AND RADIATION EMBRITTLEMENT

The evaluation by NRL of a large number of irradiated pressure-vessel steels has led to the conclusion that composition is a critical factor in determining the degree of radiation-induced embrittlement. For example, the increase in transition temperature (ΔTT) for two A533-B steels exposed separately in the same test reactor-irradiation facility resulted in quite different effects (Table 1) (15). Though the neutron exposure was less (1.7 vs 2.0×10^{19} n/cm^2 >1 MeV) the 8-1/8-in. A533-B steel showed more than twice the transition increase of the thinner 6-3/8-in. plate of the same nominal composition. A comparative evaluation of the compositions of the two steels (Table 1) reveals no obviously significant variations except in silicon and copper, and these are relatively small. Experience with a large number of such cases of variable embrittlement, however, leads to the conclusion that the variation in copper is significant. Further, experience has also shown that welds which often contain more copper than the parent plate also show greater radiation-embrittlement sensitivity.

Comparison of Radiation-Embrittlement Sensitivity Between Plate and Weld

The relatively large differences in irradiation response observed between heats of pressure-vessel steels are mirrored in comparisons among parent plates and weld metals. Repeatedly, irradiation of weldments of A302-B and A533-B steels has demonstrated greater embrittlement of the weld. Such studies are important, for they define the most susceptible point in the welded nuclear vessel and, at the same time, provide guidance for projecting embrittlement of the vessel during its lifetime and for determining critical constituents or microstructural components acting in the embrittlement process.

An exhaustive comparison of the major components of a 7-1/2-in. A533-B Class 1 submerged arc weldment demonstrates the general observation of greater weld embrittlement. Specimens of the base plate representing material on both sides of the weld (designated plates 1 and 2) were irradiated with specimens of the weld deposit and the weld heat-affected zone (HAZ). Results of irradiated Charpy V-notch tests are shown in Fig. 7 (15). It is clear from a comparison of the curves in the upper and middle section of Fig. 7 (shaded zone is data scatter band) that there is a significant difference in the two plates before irradiation and that this difference is exaggerated somewhat by irradiation. The most significant difference, however, is in the weld-metal data, which show more than twice the radiation-induced temperature increase of the two plates as well as a much greater reduction in the energy absorbed at the upper ("ductile") shelf. The changes observed would probably not be considered severe for a nuclear plant for the relatively low fluence (1.7×10^{19} n/cm^2 >1 MeV) and high temperature (550°F, 288°C). Nevertheless, these changes are large enough to warrant evaluation when higher fluences are projected. Comparisons between plate and HAZ and weld and HAZ show the HAZ to

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Table 1
Composition and Transition Temperature Increases (ΔTT) for Two A533-B Steels

Steel	Composition (wt-%)								
	C	Mn	P	S	Si	Ni	Cr	Mo	Cu
A533-B Cl 1 8-1/8 in.	0.21	1.21	0.010	0.017	0.26	0.47	0.19	0.50	0.19
A533-B Cl 1 6-3/8 in.	0.24	1.27	0.008	0.015	0.19	0.53	0.14	0.48	0.09

	Charpy-V 30-ft-lb Transition Temperature Values		
	Initial	Irradiated	ΔTT
A533-B 8-1/8 in.	+10°F (-12°C)	200°F (93°C)*	190°F (106°C)
A533-B 6-3/8 in.	-50°F (-46°C)	30°F (-1°C)†	80°F (44°C)

*1.7×10^{19} n/cm^2 > 1 MeV.
†2.0×10^{19} n/cm^2 > 1 MeV.

be less sensitive than the weld. Further, because of very good initial fracture-toughness characteristics, the HAZ is superior to the plate after irradiation as well. Extension of the irradiation to higher fluences is necessary before it can be said with assurance that the HAZ is superior to the relatively radiation-insensitive plate material. This observation of superior HAZ resistance to radiation has been general for the A302-B and A533-B steels and is attributed to lower copper content and a desirable microstructure.

Electroslag weldment data provide a similar pattern of a weld more sensitive than the base plate (15). This is vividly described for an irradiated 5-3/4-in. electroslag weldment of A533-B Class 1 steel in Fig. 8 (15). In this case the unirradiated weld is approximately equivalent to the plate after irradiation to 1.6×10^{19} n/cm^2 >1 MeV.

An examination of the composition differences among the steels described in Figs. 7 and 8 reveals the same pattern of higher copper and phosphorus contents in the welds as related to the more radiation-resistant plate material. The copper and phosphorus contents and the related increases in transition temperature are presented in Table 2 (15). It is clear from the tabular comparisons that the incidence of high radiation-embrittlement sensitivity parallels the presence of relatively higher copper and phosphorus, as previously noted. Unfortunately, it is not sufficient to sample a weld at the 1/4- or 3/4-thickness location, analyze for copper and phosphorus, and project the anticipated embrittlement. It has been shown that the copper content (0.09%) and weld-embrittlement sensitivity are low at the weld "root" (weld buildup point) of an 8-in. production weld of A533-B steel, while at the midregion or 1/4-thickness position, copper content is higher (0.14%) and so is embrittlement (16). Exposure to 2.4×10^{19} n/cm^2 >1 MeV at 550°F (288°C) resulted in 90°F (50°C) transition temperature increase for the weld "root" specimens but a 210°F (117°C) increase for the midregion weld specimens. Thus, sampling for chemical analysis, surveillance, or preservice irradiation tests must assure that typical weld metal is taken and not metal which has been remelted so much that the content is diluted to that of the base plate.

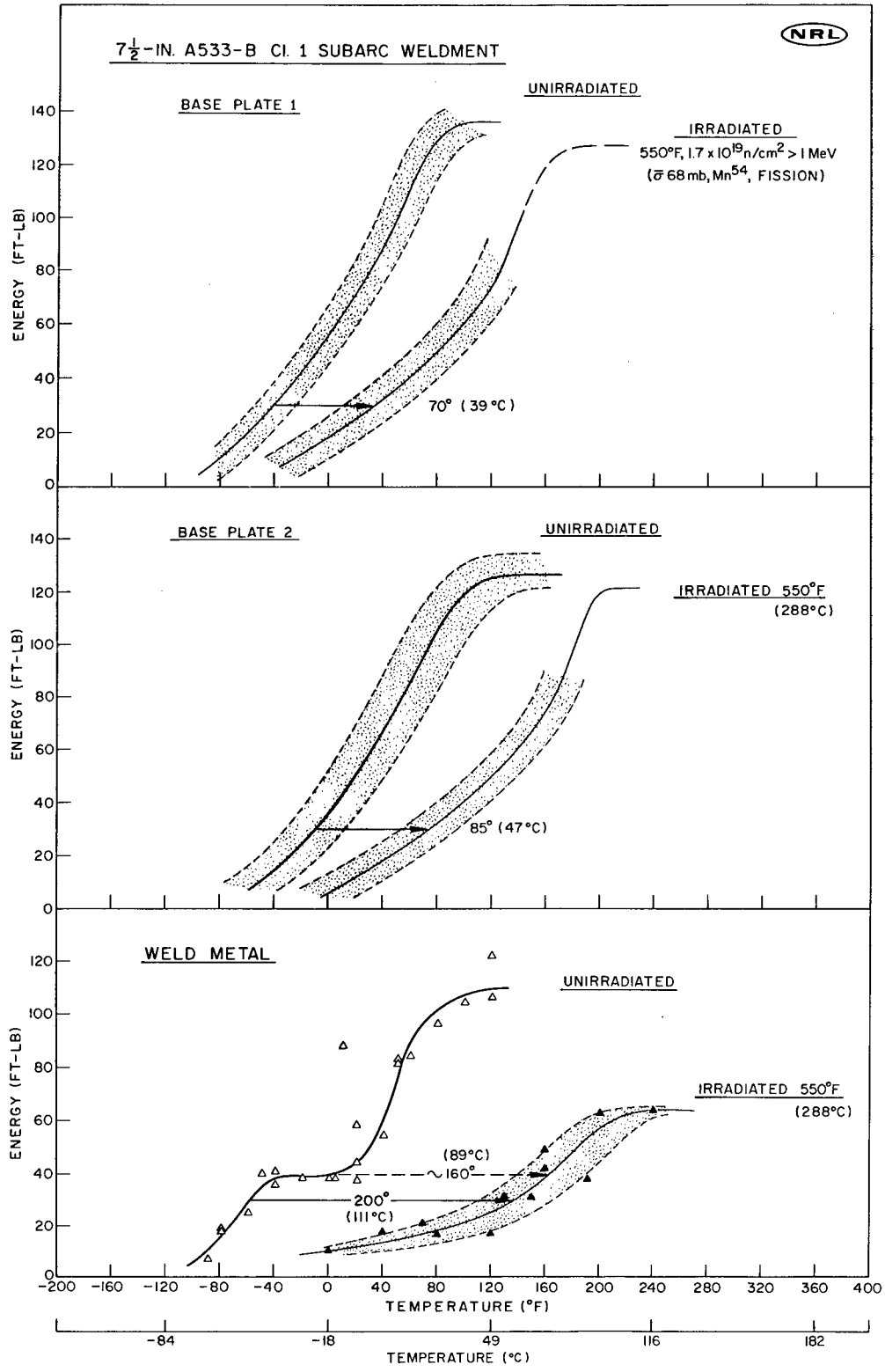

Fig. 7 - Notch-ductility characteristics of a 7-1/2-in. A533-B Class 1 production weldment before and after 550°F (288°C) neutron irradiation showing the relative performance of the base plate vs the submerged arc weld deposit

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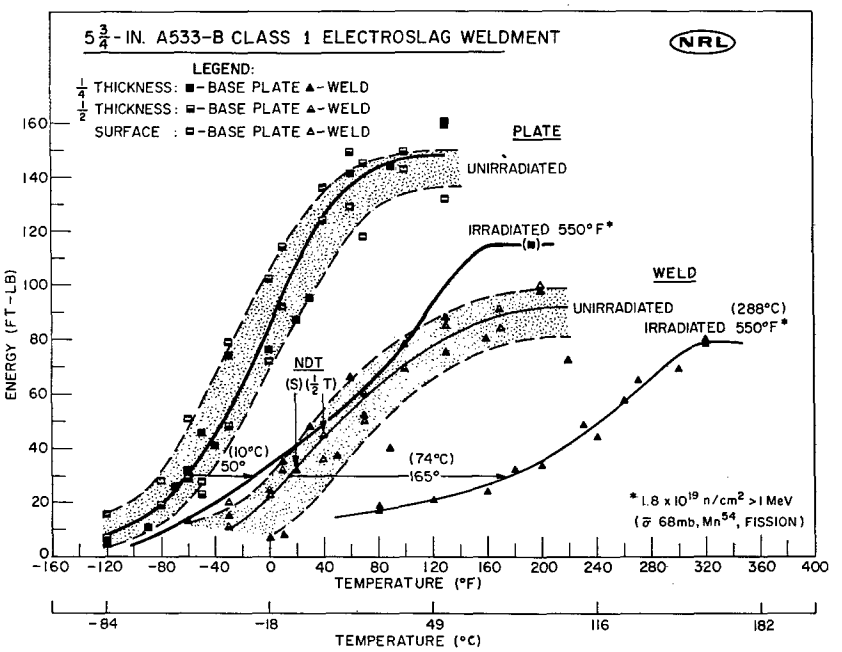

Fig. 8 - Experimental results developed for the 5-3/4-in. A533-B Class 1 electroslag weldment. The notch ductility properties of the parent plate are markedly superior to those of the weld metal, both before and after 550°F (288°C) irradiation. Shaded areas represent preirradiation data for base plate (left) and weld metal (right).

Table 2
Comparison of Radiation-Embrittlement Sensitivity of A533-B Plate and Weld Metal*

Material Identification	Chemical Composition (wt-%)			Charpy-V 30 ft-lb Transition Temperature Increase†
		Cu	P	ΔTT (Observed) (°C)
Weldment				
A533-B Class 1 (Submerged Arc) 7-1/2 in.	Plate 1	0.12	0.008	70
	Plate 2	0.11	0.011	85
	Weld	0.22	0.015	200/160‡
A533-B Class 1 (Electroslag) 5-3/4 in.	Plates 1 and 2	0.12	0.008	50
	Weld	0.19	0.008	165

*Irradiated at 550°F, 288°C to ~1.7×10^{19} n/cm^2 >1 MeV.
†Quarter-thickness layer.
‡40 ft-lb index.

Comparison of Relative Radiation-Embrittlement Sensitivity of Plate and Weld Selected for Two Reactor Vessels

The observation of significant differences in response to neutron irradiation from random selections of typical pressure-vessel plate and weld metal is important, but the validation of this observation from selected samples of actual reactor vessel steels is even more important. To this objective, NRL studies have encompassed steels of selected commercial reactors including samples from the Big Rock Point (BRPR), the Yankee Rowe PWR (YPWR), and the LaCrosse BWR (LACBWR). The first two involved irradiation in the vessel surveillance programs, including exposure in the nuclear plant at locations of accelerated (greater than vessel-wall flux level) positions. The data for the LACBWR were developed by exposing specimens of the representative plates and welds in a test reactor. Data obtained for the BRPR and LACBWR are presented for illustration.

Big Rock Point Reactor — The vessel surveillance program showing the several specimen locations is shown in Fig. 9 (13). A brief review of this program and its results are presented in Ref. 13; more details can be found in Ref. 17. The data for both the vessel wall and accelerated surveillance positions are summarized in Fig. 10 (13). The shaded trend is for low-temperature irradiations as shown in Fig. 6 and is presented for reference. Clearly, the weld is much more sensitive to irradiation than the plate and HAZ. Comparing the compositions of the plate and weld identifies copper as the only significant variant, the plate containing 0.10% and the weld 0.27% copper. The phosphorus content was 0.016% and 0.014%, respectively, for the plate and for the weld. Thus, the observation of sensitivity paralleling copper content is verified from samples of actual BRPR vessel weldments.

LaCrosse Boiling Water Reactor — In a preservice test of the relative radiation-embrittlement sensitivity of two plates and one weldment (plate plus weld metal), representative specimens were irradiated in a test reactor to simulate anticipated service environment (18). Notch-ductility data for irradiation to 2.1×10^{19} are presented in Table 3 (18) along with copper and phosphorus contents. The weld with higher copper and phosphorus levels than the related plates sustained greater embrittlement. Nevertheless, all four materials were relatively more resistant to radiation embrittlement than a similar reference A302-B steel produced several years prior to the LACBWR steels. Thus, while the radiation sensitivity of A302-B and A533 steels appears to be related primarily to copper and phosphorus contents, improved processing with inherent lower residual-element contents also seems to be improving the radiation resistance of reactor vessel steel. The welds, however, according to data available to date, still are significantly more sensitive to embrittlement, and weld composition control seems imperative in order to avoid producing reactor vessels in which the weld quality dictates service limits.

REDUCING RADIATION-EMBRITTLEMENT SENSITIVITY THROUGH COMPOSITION CONTROL

Laboratory demonstrations of near insensitivity to radiation embrittlement in special small heats (~300 lb) of the A302-B steel composition have been repeated with consistent success (19). This effort was then extended to test the capability of commercial steelmaking practice to repeat on a 30-ton heat what had been accomplished in laboratory-scale heats. The test was a notable success, with a low copper (0.03%)-low phosphorus (0.009%) heat of A533 steel showing only 25% of the increase in transition temperature as the reference commercial heat of A302-B steel. (A full description of this study will be published later.) More limited efforts to produce welds of low sensitivity have also met with success.

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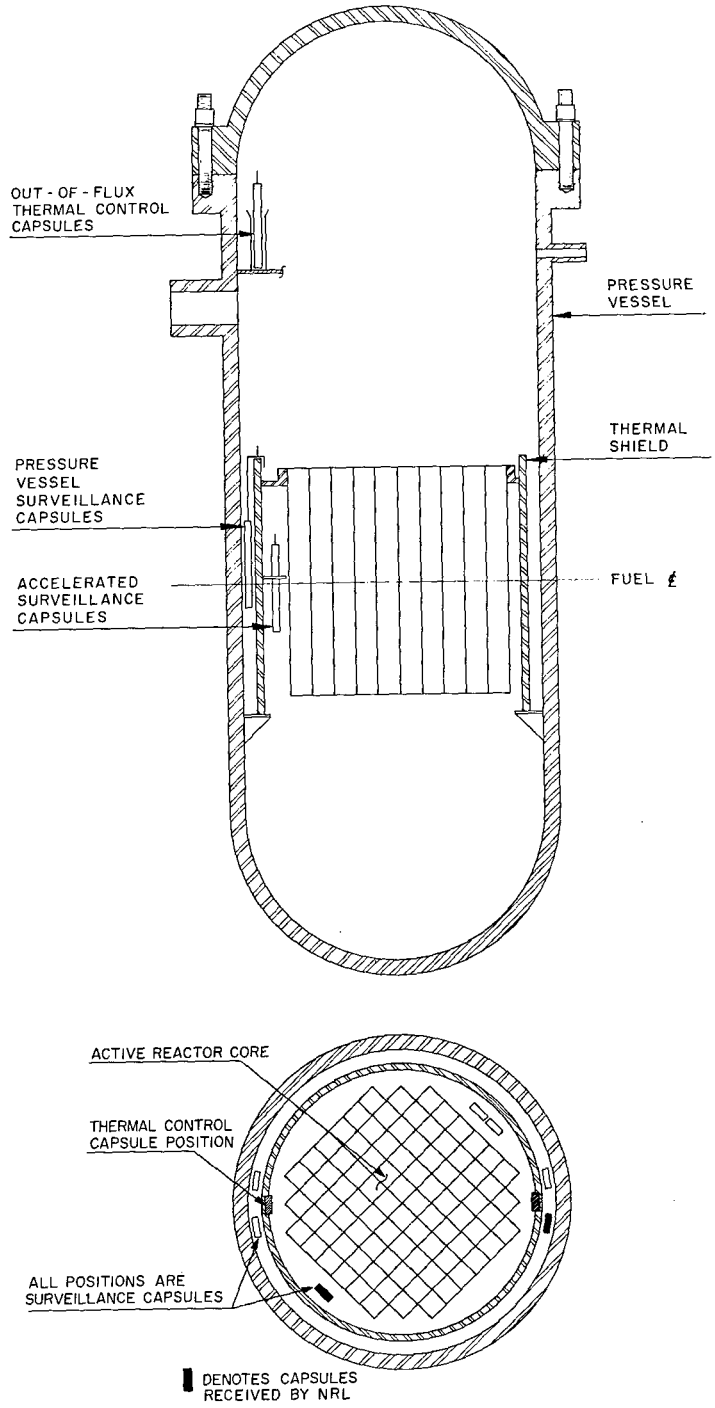

Fig. 9 - Schematic of Big Rock Point nuclear reactor showing relative locations of surveillance capsule positions

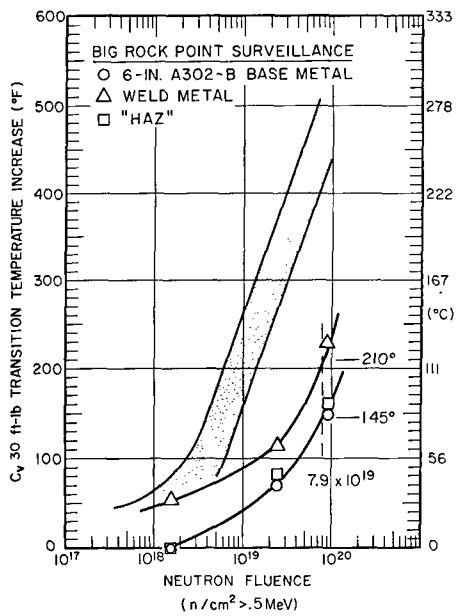

Fig. 10 - Increases in transition temperature for the Big Rock Point reactor surveillance steels including plate, weld, and weld heat-affected zone. Data are plotted for computed spectrum and in reference to the NRL trend band for steels irradiated at <450°F (232°C).

Table 3
Notch Ductility of LaCrosse Reactor Vessel Plate and Welds*

Thickness Location	Orientation in Plate	Charpy-V, 30-ft-lb Transition Temperature (°F (°C))		
		Unirradiated	Irradiated	ΔT
Heat NP-1056 (Plate -0.11% Cu, 0.007% P; Weld -0.18% Cu, 0.016% P)				
1/4 - 3/4	Longitudinal	35 (2)	120 (49)	85 (47)
Weld	†	10 (-12)	120 (49)	110 (61)
HAZ	Fusion line	-65 (-54)	0 (-18)	65 (36)
Heat NP-1057 (0.11% Cu, 0.006% P)				
1/4 - 3/4	Longitudinal	-35 (37)	~-25 (-32)	<20 (11)
Heat NP-1058 (0.16% Cu, 0.008% P)				
1/4 - 3/4	Longitudinal	-25 (-32)	40 (4)	65 (36)

*Irradiated at 550°F, 288°C, to 2.1×10^{19} n/cm² > 1 MeV ($\bar{\sigma}$ 68 mb, ^{54}Mn, fission spectrum).
†Notch parallel to plate thickness, specimen perpendicular to weld length.

In Fig. 8, the commercial electroslag weld of A533-B steel showed significantly greater sensitivity than the related plate. This weld was deposited using a copper-coated electrode which showed a copper content of 0.19% vs 0.12% for the plate. On a subsequent weld the copper plating, which is intended to provide corrosion protection and to aid electrical current flow, was omitted with a resulting lower copper (0.09%) content and a related lower radiation-embrittlement sensitivity. Whereas the weld made with

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copper-plated wire showed a shift in transition of 165°F (92°C) for a neutron exposure of 1.6×10^{19} n/cm^2, the unclad weld wire produced a weld which showed a shift of only 100°F (56°C) for a 50% greater fluence (2.5×10^{19} n/cm^2). The 100°F (56°C) shift compares with a shift of only 60°F (33°C) for the parent plate, which contained the same levels of copper and phosphorus. This adds to evidence that the cast weld structure is relatively more sensitive to radiation embrittlement than the wrought plate structure. This observation only reemphasizes the importance of minimizing constituents which are apparently conducive to accentuated irradiation embrittlement.

Another example of improved weld sensitivity involves efforts to evaluate a higher strength steel composition which has strong potential for service in the next generation of commercial reactor pressure vessels. This steel, A543, is a quenched and tempered Ni-Cr-Mo steel having a yield strength of 85,000 psi or greater.

Initial irradiation studies of the A543 steel produced surprisingly little embrittlement in commercial plate but very large embrittlement of the weld. This wide variation is clearly shown in the upper portion of Fig. 11. Again wide variations in copper content, 0.06% (plate) and 0.48% (weld), were found. However, a series of special low-copper welds was produced. Each of these was relatively insensitive to radiation. Irradiation data for the best of these weld compositions, 1936, are shown in the lower portion of Fig. 11. Success such as this has led to a study in which commercial scale welds for A533 and A543 steels are being produced to special composition specifications for comparison with typical commercial welds of the same nominal type. Irradiation experiments will

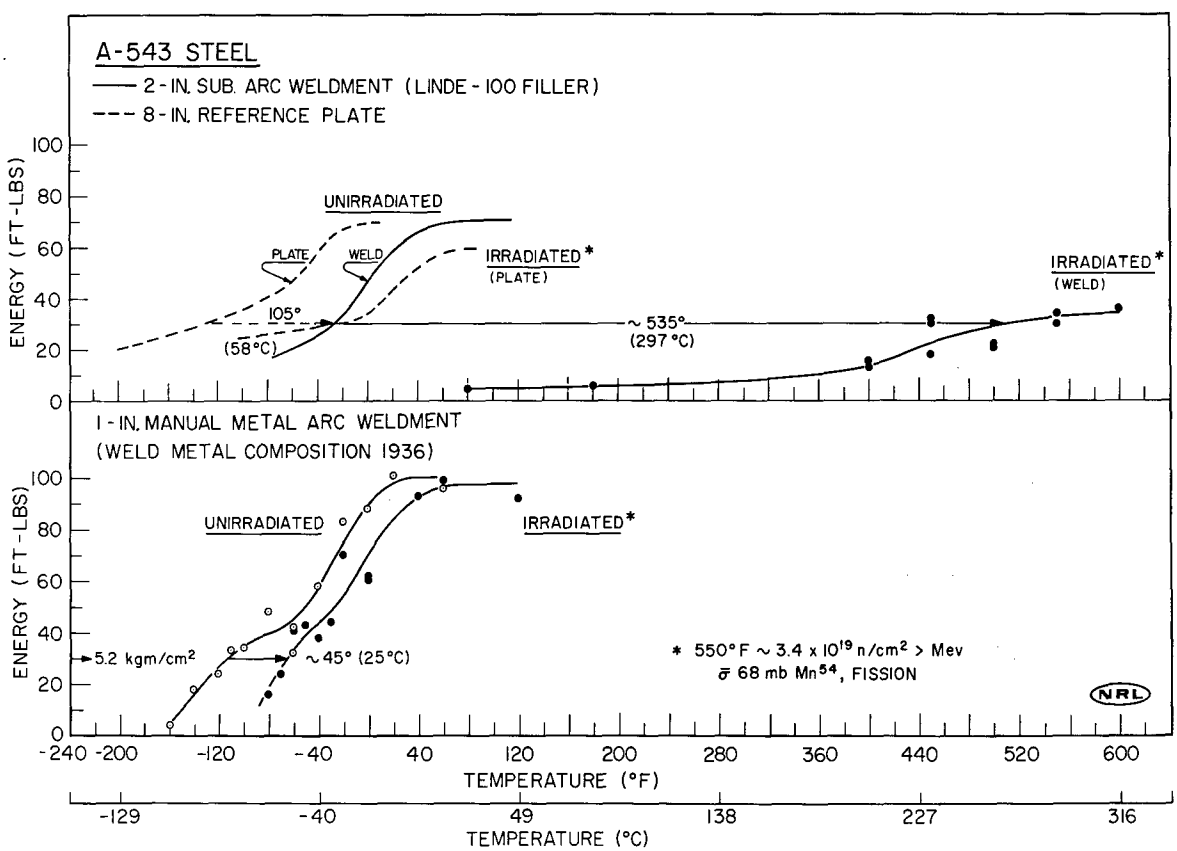

Fig. 11 - Relative resistance of commercial vs experimental A543 weld metal compositions to 550°F (288°C) radiation embrittlement compared to a heavy section A543 reference plate

indicate the degree of success attained on commercial scale welds of controlled composition.

SUMMARY AND CONCLUSIONS

Commercial nuclear power reactors are constructed with welded vessels for primary coolant containment. The quality of these welds during the anticipated life of the reactor is receiving increasing attention because of the unique, and possibly negative, aspects of the weld including the possibility of accelerated embrittlement due to weld sensitivity to neutron radiation.

Notched impact test specimens have been irradiated to evaluate the relative radiation-induced embrittlement sensitivity of weld metal and parent plate from several commercial low-alloy steels typical of those used for reactor vessel construction. Such comparisons have shown the weld metal to be generally more sensitive than the parent plate. Examination of these steels to define possible compositional or microstructural reasons for the variable response have shown that radiation-embrittlement sensitivity is parallel with the copper and phosphorus contents. This observation holds for plate and weld metal from the vessels of the Big Rock Point and LaCrosse boiling water reactors as well as for other commercial weldments of A302-B and A533-B steels studied.

Laboratory and commercial scale studies have shown that minimizing the content of copper and phosphorus as well as that of other residual elements permits the production of steels which are relatively insensitive to radiation embrittlement. The extension of this study of radiation resistance control through composition specification to welds of A533-B and a higher strength pressure vessel steel, Type A543, produced similar successes. Such success if carried to a logical conclusion provides the basis for specifying and producing reactor pressure vessels wherein radiation embrittlement is greatly reduced.

The results of the studies described herein lead to certain conclusions:

1. The most important measure of the service reliability of a reactor pressure vessel is its fracture toughness as determined by simulating a vessel containing a flaw and loaded dynamically to a point near its yield stress.

2. Fracture toughness is reduced in conventional alloy steels for vessel construction by exposure to high-energy neutrons at temperatures representative of nuclear service.

3. Such embrittlement varies significantly among steels and between a plate and the related weld metal.

4. The content of residual elements, especially copper and phosphorus, parallels the degree of radiation embrittlement.

5. Laboratory and commercial scale production of steel plates and weld metals have demonstrated conclusively that control of copper and phosphorus contents, preferably at less than 0.09% copper and 0.010% phosphorus, along with efforts to minimize other residual elements, assures relatively low embrittlement on exposure to nuclear radiation.

Thus, while weld composition and radiation damage studies are continuing to assure the optimum composition for radiation resistance of reactor vessel steels, it is possible, with care, to produce weldments of consistently high resistance to radiation embrittlement, to project anticipated embrittlement due to radiation during vessel life, and to aid the understanding of the fundamental mechanisms of radiation damage. Promising results on the higher strength A543 weldment are being exploited in current studies at the Naval Research Laboratory.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1970-397-177/228

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

THE INFLUENCE OF COMPOSITION ON THE FRACTURE TOUGHNESS OF COMMERCIAL NUCLEAR VESSEL WELDS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

This is an interim report on one phase of the problem; work is continuing.

5. AUTHOR(S) *(First name, middle initial, last name)*

L. E. Steele

6. REPORT DATE June 23, 1970	7a. TOTAL NO. OF PAGES 20	7b. NO. OF REFS 19
8a. CONTRACT OR GRANT NO. NRL Problem M01-14 b. PROJECT NO. RR 007-11-41-5409 c. AEC-AT(49-5)-2110 d. USA-ERG-11-69	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7095 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES Also sponsored by U.S. Atomic Energy Commission, DRDT, Washington, D.C. 20545	12. SPONSORING MILITARY ACTIVITY Department of the Navy (Office of Naval Research), Arlington, Va. 22217; Department of the Army, Nuclear Power Field Office, Ft. Belvoir, Va. 22060

13. ABSTRACT

The weld joint of a nuclear vessel is considered as potentially the weakest link in its reliability. This is because the weld presents a possible region of physical and metallurgical discontinuity, the welding process offers added chances for the introduction of defects and undesirable components or stresses, and, for nuclear reactor pressure vessels, the radiation environment may accentuate the other negative aspects of the weld through differential radiation damage. Consequently, the fracture toughness of nuclear vessel welds has become the focal point for those concerned with the reliability of nuclear vessels.

Irradiation studies of welds of the ASTM Type A302-B and A533-B steels, most commonly used for commercial water reactor vessels, have demonstrated several instances in which the weld metal exhibited lower fracture toughness or greater elevation of the brittle-to-ductile transition temperature than that observed for the companion base-plate and weld heat-affected-zone material. Examination of the structure and composition has led to the conclusion that composition is critical to the level of radiation-induced embrittlement. The level of copper and phosphorus contents has been shown to be especially critical to the level of embrittlement with welds having high copper (>0.20%) and phosphorus (>0.015%) showing greater embrittlement than those containing lesser amounts. These experimental observations have been verified through laboratory tests in which these constituents and other residual elements have been controlled in weldments simulating those for reactor service.

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DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Fracture toughness						
Nuclear vessels						
Embrittlement						
Composition						
Nuclear Radiation						
Submerged arc welds						
Electroslag welds						
Weld heat affected zone						
Neutron fluence						

The study of controlled weld composition has been extended to the welds of the higher strength ASTM Type A543 steel with even more remarkable results than those observed for the lower strength steels of current commercial reactor vessel construction. These results when applied in specifications for future reactor vessels should go far toward alleviating radiation embrittlement of reactor vessels and also provide guidance for projecting the level of fracture toughness of operating vessels at selected points in the lifetime of a vessel.

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

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