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SUBJECT: DETERMINATION OF THE NIL-DUCTILITY-TRANSITION TEMPERATURE FOR
A212B STEEL USED IN THE N. S. SAVANNAH PRESSURE VESSEL

TO: Distribution

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ABSTRACT

The nil-ductility-transition (NDT) temperature, as defined by the Naval Research Laboratory drop-weight test, was determined on the A212B carbon-silicon steel used in the pressure vessel of the N. S. Savannah nuclear reactor. Correlations were made with the Charpy-V-notch impact energy at NDT. Specimens taken at two different thickness locations from material used in the upper closure head of the reactor vessel yielded NDT temperatures of 0 - 20°F which correspond to Charpy-V-notch impact energies of 11 - 19 ft-lb. Testing of as-received material used in the lower closure head indicated that the NDT temperature was 50°F which was equivalent to an average Charpy-V-notch impact energy of 12 ft-lb. After normalizing and stress-relieving this material, in order to more closely approximate the final condition of the reactor vessel, NDT was reduced to less than 10°F.

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I. INTRODUCTION

The material selected for the pressure vessel of the N. S. Savannah nuclear reactor plant is A212B carbon-silicon steel. The boiler plate for this vessel was required to meet the standards set forth in U. S. Coast Guard Specification 51.04, Class A, Grade D.¹ Embodied in this specification is ASTM A-212-54 at Grade B^(ref 2) which defines the chemical and tensile requirements that the steel must meet. These requirements are summarized in Tables I and II, respectively.

In addition, this material was guaranteed by the mill to have a Charpy-V-notch impact strength of 15 ft-lb at 10°F. This practice is consistent with the requirements of Naval Specification MIL-S-210204^(ref 3) which states that carbon steel pressure-containing parts shall have a minimum average impact energy of 15 ft-lb at 10°F based on three Charpy-V-notch specimens, and further that no more than one test value shall be below the minimum average with no test result being more than 5 ft-lb below the minimum average. Since the temperature at which a Charpy-V-notch impact energy of 15 ft-lb is attained has been selected by some investigators as being equivalent to the nil-ductility transition temperature for A212B steel,⁴ it could be inferred that the steel in the Savannah pressure vessel would have an NDT temperature of 10°F or lower.

Some concern has been evinced over the adequacy of experimental evidence supporting this impact-energy criterion in lieu of an actual determination of the NDT temperature. Consequently, the Metallurgy Division of the Oak Ridge National Laboratory was requested by the Maritime Reactors Branch of the AEC to experimentally ascertain the validity of this criterion on material obtained

¹Marine Engineering Regulations and Material Specifications, U. S. Coast Guard, CG-115, pp 6 - 7 (March 1, 1958).

²ASTM Standards, Part 1, "Tentative Specification for High Tensile Strength Carbon-Silicon Steel Plates for Boilers and Other Pressure Vessels," American Society for Testing Materials, pp 501 - 503 (1954).

³Military Specification Steam Generators, Pressurized Water, Nuclear Naval Ship Propulsion, Section 3.5.2.1, MIL-S-21204 (February 12, 1958).

⁴Tentative Structural Design Basis for Reactor Pressure Vessels and Directly Associated Components (Pressurized Water-Cooled Systems), Department of the Navy - Bureau of Ships, pp 25 - 27, December 1, 1958.

TABLE I

CHEMICAL COMPOSITION OF A212B STEEL

ASTM A-212-54 aT*

<u>Element</u>	<u>Wt %</u>
Carbon (max)	0.35
Manganese (max)	0.90
Phosphorus (max)	0.035
Sulfur (max)	0.04
Silicon (ladle analysis)	0.15 - 0.30
Silicon (check analysis)	0.13 - 0.32

TABLE II

MECHANICAL REQUIREMENTS OF A212B STEEL

ASTM A-212-54 aT*

Tensile Strength	70,000 to 85,000 psi
Yield Point (min)	38,000 psi
Elongation, in 8 in. (min)	16%**
Elongation, in 2 in. (min)	19.5%**

* ASTM Standards, Part 1, "Tentative Specification for High Tensile Strength Carbon-Silicon Steel Plates for Boilers and Other Pressure Vessels," American Society for Testing Materials, pp 501 - 503, (1954).

** Adjusted for 6-in.-thick plate.

from the N. S. Savannah pressure vessel. This report describes the results of measurements made to determine the NDT temperature and the corresponding Charpy-V-notch impact energy for that material. A corollary purpose of the study was to provide base-line data from which changes in the properties of the pressure-vessel steel during irradiation can be deduced.

II. REVIEW OF PREVIOUS WORK

A. General Background

For a steel structure to fail in a brittle manner, three conditions must exist simultaneously:

1. A crack starter, such as a welding-arc strike or a re-entrant angle, must be present.
2. Localized stresses in the vicinity of crack starter must exceed the yield stress.
3. The temperature of the material must be at or below the nil-ductility transition (NDT) temperature.

Good design and fabrication practices, of course, emphasize procedures which will minimize the first and second conditions. However, since it is virtually impossible to totally eliminate these conditions, the surest method for preventing brittle fracture is to operate the structure above the NDT temperature when reasonable stress levels exist.

The NDT temperature is defined as that temperature below which steel structures may potentially initiate brittle fractures in the presence of sharp notches or flaws. This temperature is generally determined by the drop-weight test devised by investigators,^{5,6} at the Naval Research Laboratory. These authors comment on NDT as follows, "... the ability of a steel to yield even slightly in the presence of a cleavage crack and thereby preclude the

⁵P. P. Puzak, E. W. Eschbacher, and W. S. Pellini, Welding J. 31(12), 561-s - 581-s (December 1952).

⁶P. P. Puzak, M. E. Schuster, and W. S. Pellini, Welding J. 33(9), 433-s (September 1954).

initiation of brittle fracture is determined by the metallurgy of a small volume of material at the root of the crack flaw. At temperatures above the NDT of a given steel such yielding is deemed possible. However, at or below the NDT, the steel is unable to tolerate even localized yielding at the root of a sharp crack flaw without potentially being able to initiate brittle fractures."⁷

The validity of the NDT criterion has been established by correlation with service failures. Puzak et al.,⁸ have recently reported on a study in which the NDT temperatures of steels involved in seventeen service failures were measured. Included in the evaluation were ship plates, propellers, pressure vessels, turbine spindles, and forged shapes. It was found in every case examined that the actual failure temperature was below the NDT temperature as measured in the drop-weight test. The ability of the drop-weight test to predict service failures was thus reasonably well substantiated. This survey further indicated that the NDT criterion was applicable to castings and forgings, as well as rolled plates.

The NDT temperature can, of course, be correlated with a Charpy-V-notch impact energy for a particular material at the same temperature. It is tempting to seek an invariant impact-energy criterion for NDT which will be applicable to all types of steel. Unfortunately, however, selection of an invariant energy level can only be made with reference to a particular class of steels and then only after an extensive correlation analysis has been made. Such correlations are presently available on only a few steels, primarily those used in World War II ships. In the rimmed and semi-killed mild steels used in these structures, NDT was found to be associated with a Charpy-V-notch energy of 10 ft-lb or less. In fully-killed, mild steels, on the other hand, Charpy-V-notch energies as high as 24 ft-lb were obtained

⁷P. P. Puzak and A. J. Babecki, Normalization Procedures for NRL Drop Weight Test, NRL-5220 (November 3, 1958). Naval Research Laboratory.

⁸P. P. Puzak et al., "Correlations of Brittle-Fracture Service Failures With Laboratory Notch-Ductility Tests," Welding J. 37(9) 391-s - 407-s (September 1958).

at NDT. (ref 9) The fallacy of attempting to apply an energy criterion applicable to one class of steels to another class of steels is obvious.

B. Data on A212B

A tabular summary of the available information on NDT for A212B is included in Table III and, where reported, correlations are made to Charpy-V-notch impact energies at same temperature. From these data, a wide divergence in NDT temperatures can be observed. In addition, the NDT temperature can be correlated to Charpy-V-notch impact energies from 8 to 48 ft-lb. This extensive variation between steels of the same nominal composition emphasizes the need for specific determinations of NDT on each heat of steel. Unfortunately, the heat treatment is not known for all the steels on which data are presented, and it may well be that the NDT for A212B produced according to present fine-grained practice will exhibit much less variation from heat to heat than that indicated in Table III.

III. MATERIAL

The pressure vessel for the N. S. Savannah reactor is being fabricated by the Babcock and Wilcox Company which is the prime contractor to the Maritime Reactors Branch for the reactor core and steam-generating equipment of the pressurized-water power plant. A total of five hot-rolled slabs of A212B from two melts was purchased for use in the pressure vessel. Pertinent mill-test data on this material are summarized in Tables IV and V. This steel was aluminum-killed to produce a fine-grained structure and maximum toughness.

In fabrication of the major portion of the pressure vessel, the two 6-11/16-in.-thick slabs of A212B steel from Melt 19017 were formed into cylindrical shells and joined together by a girth weld to create a large cylinder approximately 15 ft long and 9-1/4 ft in dia. A forged flange of Al05 steel was welded to the upper end of the cylinder and a hemispherical closure head formed from 6-1/2-in.-thick A212B steel was welded to the lower end of the cylinder. A similar hemispherical shape was fabricated for the upper closure head and a second Al05 steel flange was welded to this to complete the upper head assembly. Final closure of the vessel is to be effected by

⁹P. P. Puzak and W. S. Pellini, "Evaluation of the Significance of Charpy Tests for Quenched and Tempered Steels," Welding J. 35(6) 275-s (June 1956).

TABLE III

MEASURED VALUES OF NDT FOR A212B STEEL

Steel	Specimen Size (In.)	NDT Temperature (°F)	Charpy-V-Notch Impact Energy at NDT (ft-lb)	Reference
51	4-1/2 x 4-1/2 x .72	0	--	(a)
51	1 x 3-1/2 x 14	-20	--	(a)
52	4-1/2 x 4-1/2 x .72	0	--	(a)
52	1 x 3-1/2 x 14	-20	--	(a)
79	4-1/2 x 4-1/2 x .72	0	14-33	(a) (d)
79	1 x 3-1/2 x 14	-10	19-28	(a) (d)
79	1-1/2 x 3-1/2 x 14	0	--	(a)
A212 shell	1 x 3-1/2 x 14	+70	11	(b)
A212B pressure vessel	1 x 3-1/2 x 14	+80	8	(b)
A212B (as-received)	1 x 3-1/2 x 14	-100	--	(c)
A212B (normalized)	1 x 3-1/2 x 14	-80	--	(c)
79	4-1/2 x 4-1/2 x .72	+10	23-38	(d)
XY	4-1/2 x 4-1/2 x .72	0	12-48	(d)

^aP. P. Puzak and A. J. Babecki, Normalization Procedures for NRL Drop Weight Test, NRL-5220 (November 3, 1958), Naval Research Laboratory.

^bP. P. Puzak et al., "Correlations of Brittle-Fracture Service Failures with Laboratory Notch-Ductility Tests," Welding J. 37(9), 391-s - 407-s (September 1958).

^cHomogeneous Reactor Quar. Prog. Rep. for Period Ending July 31, 1957, ORNL-2379, p 130 (September 27, 1957).

^dPrivate communication from F. Lambert, Union Carbide Nuclear Company.

TABLE IV

CHEMICAL COMPOSITION OF A212B STEEL FOR N. S. SAVANNAH PRESSURE VESSEL

Melt No.	Slab No.	Carbon Wt %	Manganese Wt %	Sulfur Wt %	Silicon Wt %	Phosphorus Wt %
19017	1	0.26	0.72	0.033	0.20	0.014
19017	3	0.26	0.72	0.033	0.20	0.014
20477	3	0.28	0.79	0.028	0.23	0.014
20477	4	0.28	0.79	0.028	0.23	0.014
20477	2	0.28	0.79	0.028	0.23	0.014

TABLE V

MECHANICAL PROPERTIES* OF A212B STEEL FOR N. S. SAVANNAH PRESSURE VESSEL

Melt No.	Slab No.	Yield Point (psi)	Tensile Strength (psi)	Elongation in 2 in. (%)	Reduction in Area (%)	Charpy-V-Notch Impact Energy at 10°F (ft-lb)
19017	1	46,400	75,000	32	61.7	29-31-38
		45,900	74,200	33	59.8	
19017	3	47,700	76,400	33	59.8	35-28-33
		43,700	74,900	35	60.8	
20477	3	48,000	78,000	34	58.5	35-30-30
		49,200	76,900	32	59.8	
20477	4	47,000	77,000	33	57.0	20-20-23
		47,500	79,500	33	56.0	
20477	2	47,500	77,300	32	59.6	38-38-38
		46,900	75,500	34	60.2	

*Test specimens normalized at 1625 ± 1675°F and water cooled, then stress relieved at 1125 - 1175°F.

bolting the forged flanges together. The lower and upper closure heads were fabricated from Melt 20477, Slab Nos. 3 and 4, respectively. Slab No. 2 from Melt 20477 was used to fabricate a spare hemispherical head.

Portions of Slab Nos. 3 and 4, Melt 20477, were sent to ORNL from the Babcock and Wilcox Company for evaluation of NDT. No material was available from the other melt which was used in the cylindrical shell. The steel sample from Slab No. 3, Melt 20477, was in the as-received (hot-rolled) condition and consequently not representative of the lower closure head in its final heat-treated condition. The material from Slab No. 4 received by ORNL more closely approximated in thermal history the upper closure head, however. This latter slab was clad on one surface with 0.109 in. of type 304 stainless steel after a 300°F preheat. The clad slab was then formed into a hemispherical head at 2200°F. After forming, the material was normalized at 1650°F and spray quenched, followed by a stress-relief anneal of 7 hr at 1125°F. At this point, a ring of material approximately 20 in. in width was removed from the perimeter of the hemisphere to properly size the head prior to attachment of the upper flange by welding. Material from this ring was used in the NDT evaluation. Subsequent to the receipt of this scrap for testing at ORNL, the upper head has received seven stress-relieving operations at 1100 - 1150°F with the total time at temperature being 32-1/2 hr.¹⁰

IV. EXPERIMENTAL PROCEDURE

Material for the drop-weight and Charpy-V-notch impact tests was sawed from both the inner, or clad, surface and at a plane midway between the inner surface and the center of Slab No. 4, Melt 20477. Material was sawed from only the surface of Slab No. 3. Standard Charpy-V-notch impact specimens were machined from material taken at each location. Full-size and subsize drop-weight specimens also were sawed from each material sample.

¹⁰ Private communication from J. D. Fultz, Oak Ridge National Laboratory.

The full-size specimens were 3-1/2 in. wide x 14 in. long x 1 in. thick while the subsize specimens were 2 in. wide x 5 in. long x 5/8 in. thick. Most of the drop-weight specimens were of the subsize variety to economize on material. Puzak and Babecki¹¹ have demonstrated in a study of 26 different steels that an agreement of $\pm 10^{\circ}\text{F}$ for NDT was obtained between the reference standard or full-size specimen and subsize specimens of the dimensions cited.

To prepare the drop-weight specimen for testing, a weld bead of a brittle, hard, facing material (Murex Hardex "N"), approximately 2-1/2 in. long, was laid along a longitudinal center line on one surface of the sawed rectangle using a 3/16-in.-dia coated electrode. This weld bead was notched at mid-length to within 0.070 - 0.085 in. of the base metal using an abrasive cut-off wheel. Figure 1 (Y-29512) shows typical specimens of both sizes ready for testing.

Actual testing was accomplished in a standard drop-weight machine employing a 60-lb weight. With the subsize specimens, the anvil for loading the specimens by a simple impact bending had a 4-in. test span with a stop 0.075 in. below the surface of the specimen to limit deflection. Energies of 240 ft-lb were imparted to the subsize specimens. The drop-weight anvil is shown in Fig. 2 (Y-27070). The reference-standard specimens required an anvil with a 12-in. span and a stop 0.3 in. below the specimen surface. Energies of 600 - 700 ft-lb were used to fracture the full-size specimens. Specimen temperatures were controlled by using either dry ice-acetone or iced brine mixtures.

During testing, the extremely brittle weld bead, which was on the tension side of the specimen, cracked at the pre-cut notch, creating a flaw of maximum acuity. The crack would or would not propagate into the base metal depending on the temperature. When the temperature was such that the crack propagated to at least one edge of the specimen on the tension side, NDT was achieved.

¹¹P. P. Puzak and A. J. Babecki, op cit.

Fig. 1 (Y-30277) Typical Full-Size and Subsize Drop-Weight Specimens.

Fig. 2 (Y-27070) Anvil for Bending Subsize Drop-Weight Specimens.

Charpy-V-notch impact energies at various temperatures were obtained in the conventional manner using a Sonntag Universal Impact Machine.

V. DISCUSSION OF RESULTS

A. Melt 20477, Slab No. 4

A summary of results obtained with both full-size and subsize drop-weight specimens from Melt 20477, Slab No. 4 (the upper closure head) is presented in Table VI. Data on specimens removed from the inner surface as well as midway between the inner surface and center, are included in this table. The NDT temperature as determined from subsize specimens taken at both locations was 0°F, while the NDT temperature determined from the full-size specimens was 10°F at the surface and 20°F at one-quarter thickness. Because of the limited number of full-size test specimens available, it was not possible to test a specimen at 30°F and establish with complete confidence that 20°F was the NDT temperature. The appearance of typical subsize specimens tested near NDT can be seen in Fig. 3 (Y-29512).

The Charpy-V-notch impact energy curves for specimens taken at both the surface and subsurface locations are presented in Fig. 4 (ORNL-LR-DWG 38271). The surface specimens appear to be slightly tougher than the specimens taken at one-quarter thickness. This may have resulted from more rapid cooling of the surface from the spray quench. From these curves, correlations of NDT temperature and average Charpy-V-notch impact energy were made, as shown in Table VII.

The amount of fibrous (shear) fracture was estimated from each fractured impact specimen by two persons. The estimates were averaged and are plotted in Fig. 5 (ORNL-LR-DWG 38272). No significant differences in amount of fibrous fracture as a function of specimen location are apparent. The transition temperature for 50% fibrous fracture was found to be 90°F.

B. Melt No. 20477, Slab No. 3

A summary of results obtained with both full-size and subsize drop-weight specimens from Melt No. 20477, Slab No. 3, (the lower closure head) is included as Table VIII. Data were obtained only on specimens

TABLE VI

NDT EVALUATION OF A212B STEEL
(Melt 20477, Slab No. 4)

Specimen Size (in.)	Specimen Location	Test Temperature (°F)					
		-20	-10	0	+10	+20	+30
5/8 x 2 x 5	1/4 thickness	X	X	X	0	0	0
				X	0		
				0			
1 x 3-1/2 x 14	1/4 thickness			X	X	0	
						X	
5/8 x 2 x 5	Surface	X	X	X	0		
			X	X	0		
				0	0		
				0			
1 x 3-1/2 x 14	Surface			X	X	0	
						0	

X - Break
0 - No Break

TABLE VII

CORRELATION OF CHARPY-V-NOTCH IMPACT ENERGY AND NDT TEMPERATURE FOR A212B STEEL
(Melt 20477, Slab No. 4)

Specimen Type	Specimen Location	NDT Temperature (°F)	Charpy-V-Notch Impact Energy at NDT (ft-lb)
Subsize	Surface	0	15
Full-Size	Surface	10	18
Subsize	1/4 thickness	0	11
Full-Size	1/4 thickness	20	19

-10° F

0° F
NDT

10° F

20° F

Fig. 3 (Y-29512) Fracture Appearance of Subsize NDT Specimens Taken at One-Quarter Thickness.

Impact Energy Transition Curves for A-212 B Steel [Heat 20477, Slab 4] .

Fig. 4

TABLE VIII

NDT EVALUATION OF A212B STEEL
(Melt 20477, Slab No. 3)

Specimen Size (in.)	Specimen Location	Heat Treatment	Test Temperature (°F)					
			10	20	30	40	50	60
5/8 x 2 x 5	Surface	As-Received	X	X	X	X	X	0
						0	0	
1 x 3-1/2 x 14	Surface	As-Received					X	0
							X	0
5/8 x 2 x 5	Surface	Normalized* and Stress Relieved	0	0	0		0	

X - Break

0 - No Break

* One hour at 1650°F with air cool followed by 1 hr at 1150°F with air cool.

Fracture Appearance Transition Curve for A212B Steel [Heat 20477, Slab 4].

Fig. 5

removed from the surface. Since this material was in the as-received condition and therefore not representative of the actual thermal history of the lower closure head, four of the subsize specimens were tested in a heat-treated condition in order to more closely approximate the final component. Heat treatment consisted of normalization of the 5/8-in.-thick test specimens at 1650°F for 1 hr followed by air cooling, then annealing at 1150°F for 1 hr again followed by air cooling. Data on these specimens are also presented in Table VIII.

The NDT temperature for both sizes of specimens in the as-received condition was $\pm 50^\circ\text{F}$. It can be estimated from the Charpy-V-notch impact-energy temperature curve of Fig. 6 (ORNL-LR-DWG 40225) that an average impact energy of 12 ft-lb is obtained at NDT for as-received specimens. Normalization and annealing significantly lowered the NDT temperature to below 10°F . A definite determination of NDT for the heat-treated samples was not obtained since only four specimens were available. However, it can be estimated from the curve for the heat-treated specimens in Fig. 6 that NDT would be equivalent to a Charpy-V-notch impact energy of about 20 ft-lb.

The estimated fibrous fracture transition curves for this material in both the as-received and heat-treated conditions are shown in Fig. 7 (ORNL-LR-DWG 40226). A decrease of about 50°F in the transition temperature for 50% fibrous fracture may be noted. The marked improvement in impact properties in the normalized and stress-relieved specimens appears to be associated with microstructural modifications. Figures 8 (Y-30133) and 9 (Y-30134) illustrate the microstructures of the as-received and the heat-treated material, respectively. Marked refinement of the ferrite grain size and size of the pearlite colonies can be seen in the latter illustration.

C. General Discussion

The tests described above indicate that the maximum observed NDT temperature for normalized and stress-relieved A212B steel was $+20^\circ\text{F}$. Thus, above this temperature, brittle fractures should not be initiated

Fig. 6. Impact Energy Transition Curve for A212 B Steel [Heat 20477, Slab 3]

Fig. 7. Fracture Appearance Transition Curve for A212 B Steel [Heat 20477, Slab 3]

Fig. 8 (Y-30133) Microstructure of As-Received A212B Steel Used in the Lower Closure Head of the N. S. Savannah Pressure Vessel. Note coarse grain size. Etchant: 2% Nital.

Fig. 9 (Y-30134) Microstructure After Normalization and Stress-Relief of A212B Steel Used in the Lower Closure Head of N. S. Savannah Pressure Vessel. Note extensive grain refinement with heat treatment.

even if localized stresses reach the yield point. Puzak and Pellini¹² have pointed out that, if a structure is operated at a somewhat higher temperature defined as the "fracture transition for elastic loading" (FTE), brittle fractures will not propagate through elastically loaded regions. The FTE temperature has been found to be equal to the NDT temperature plus 30 to 50°F. Thus, it may be estimated that, if the N. S. Savannah pressure vessel is operated at a temperature of at least 70°F, brittle fractures will neither initiate nor propagate. This conclusion must be tempered by the realization that the NDT was not measured on material used in the flanges or in the shell but only in the closure heads of the vessel.

Suggested U. S. Navy practice¹³ is consistent with the premises outlined above. This practice requires that during both hydrostatic testing and operation, the maximum applied load, including internal pressure, shall be restricted to 20% of the design value at temperatures less than 60°F above NDT.

It is interesting to correlate the FTE temperature as determined in the drop-weight test ($FTE = NDT + 50^\circ$) with the 50% fibrous fracture transition temperature as determined from the Charpy impact specimens, since both transition temperatures relate to crack propagation. This has been done in Table IX. It can be seen that reasonable agreement is generally obtained with the maximum deviation between the two types of transition temperatures being 40 Fahrenheit degrees.

Another factor, which must be taken into account when predicting an operating temperature above which brittle fractures cannot occur, is damage to the pressure vessel from fast-neutron bombardment. It is well established¹⁴ that irradiation of carbon steels by fast neutrons will produce significant increases in the transition temperature. Consequently, the minimum

¹²P. P. Puzak and W. S. Pellini, "Evaluation of the Significance of Charpy Tests for Quenched and Tempered Steels," Welding J. 35(6) 275-s (June 1956).

¹³Tentative Structural Design Basis for Reactor Pressure Vessels and Directly Associated Components (Pressurized Water-Cooled Systems), Department of the Navy - Bureau of Ships, pp 25 - 27, December 1, 1958.

¹⁴R. C. Berggren and J. C. Wilson, Recent Data on the Effects of Neutron Irradiation on Structural Metals and Alloys, ORNL CF-56-11-1 (January 30, 1958).

TABLE IX

CORRELATION OF TRANSITION TEMPERATURES FOR CRACK PROPAGATION

Slab No.	Specimen Size	Specimen Location	Specimen Heat Treatment	FTE (NDT + 50)	50% Fibrous Fracture Transition
				°F	°F
3	Full-Size	Surface	As-Received	100	109
3	Subsize	Surface	As-Received	100	109
3	Subsize	Surface	N and S. R. *	< 60	60
4	Full-Size	Surface	N and S. R. *	60	90
4	Subsize	Surface	N and S. R. *	50	90
4	Full-Size	1/4 Thickness	N and S. R. *	70	90
4	Subsize	1/4 Thickness	N and S. R. *	50	90

* Normalized at 1650°F and stress relieved at 1150°F.

temperature at which the vessel operates must be increased as the neutron dosage increases. The exact amount of the increase in transition temperature with irradiation is difficult to predict. However, some recent data presented by Wilson¹⁵ on subsize Izod impact specimens of A212B indicate that an increase in the transition temperature of 45 Fahrenheit degrees occurred after a fast neutron dose of 5×10^{18} n/cm² at 175°F and an increase in the transition temperature of 100 - 200 Fahrenheit degrees occurred after a dose of 5×10^{19} n/cm² at the same temperature. These doses bracket the expected dose for the Savannah pressure vessel during twenty years of operation.

VI. CONCLUSIONS AND RECOMMENDATIONS

1. On the basis of an evaluation of two slabs from one heat of A212B steel used in the upper and lower closure heads for the N. S. Savannah pressure vessel, the maximum NDT temperature for normalized and stress-relieved material was found to be 20°F.

2. Significant improvements in the notch-toughness were realized by normalizing and stress relieving the slab of steel which had not been previously heat treated. The NDT temperature was lowered by at least 40 Fahrenheit degrees and the fracture appearance transition temperature was reduced by 50 Fahrenheit degrees.

3. Correlations of Charpy impact energies with NDT temperatures indicated that a value of 20 ft-lb was more realistic than the suggested 15 ft-lb level.

4. In the initial stages of operation, it is recommended that the N. S. Savannah pressure vessel be operated above 70°F when pressurized and that this minimum operating temperature be increased as the fast-neutron dosage of the vessel increases. The increase in minimum operating temperature can best be determined by placing Charpy impact specimens in the vessel and testing these after various exposures.

¹⁵J. C. Wilson, "Effects of Irradiation on the Structural Materials in Nuclear Power Reactors," Geneva Paper A/Conf. 15/p/1978 (June 1958).

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