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# Notch Ductility Properties of SM-1A Reactor Pressure Vessel Following the In-Place Annealing Operation

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CONTENTS

## ABSTRACT

The embrittlement condition of the Army SM-1A reactor pressure vessel, as modified by the recently completed in-place anneal, was assessed and an analysis was made of the reembrittlement behavior of the vessel steel with subsequent radiation service. Experimental results from the reactor surveillance program developed through one complete irradiation and annealing cycle are presented, together with a summary of experimental information on the annealing response of the vessel steel (A350-LF1, Mod.) from accelerated irradiation programs. These data indicate a 0°F maximum pressure vessel wall Charpy-V 30 ft-lb transition temperature after the in-place anneal versus a -80°F preservice transition temperature (based on the notch-ductility properties of a duplicate ring forging). The maximum Charpy-V 30 ft-lb transition temperature of the pressure vessel before the annealing operation was estimated at 190°F.

A projection of postanneal pressure vessel lifetime in terms of neutron fluence >0.5 Mev was derived from spectra calculations and the experimentally predicted reirradiation response of the pressure vessel steel. The maximum permissible vessel wall fluence is estimated at $5.5 \times 10^{19}$ $n/cm^2 > 0.5$ Mev. This is comparable to 124.7 Megawatt years of reactor operation.

## PROBLEM STATUS

A final report on one phase of the problem; work on other phases continues.

## AUTHORIZATION

NRL Problem M01-14
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# NOTCH DUCTILITY PROPERTIES OF SM-1A REACTOR PRESSURE VESSEL FOLLOWING THE IN-PLACE ANNEALING OPERATION

## INTRODUCTION

This report presents the most recent experimental information developed on the postirradiation annealing response of the Army SM-1A reactor pressure vessel steel (A350-LF1 (Modified)). The data come from two sources: the accelerated irradiation test program using the Union Carbide Research Reactor (UCRR) and the Oak Ridge Low Intensity Test Reactor (LITR), and the surveillance test program conducted at the SM-1A reactor. Two materials representative of the central vessel forging were employed in both programs. These included a 3-5/8-in.-thick fabrication test plate and a 2-5/8-in.-thick duplicate ring forging, both from the same steel heat as the vessel and prepared in close accordance with actual vessel fabrication procedures. Data obtained from both materials are used throughout, since their response to neutron irradiation was equivalent. The final pressure vessel lifetime analysis, however, is referenced to the Charpy-V 30 ft-lb transition temperature of the duplicate ring forging, since the properties of this forging are considered to be more representative of the preservice condition of the SM-1A pressure vessel.

The assessment of the embrittlement condition of the SM-1A pressure vessel, as modified by the recently completed in-place anneal, is the primary purpose of this report. It is aided by experimental results from the surveillance program developed through one complete irradiation and annealing cycle. The analysis includes projections of the reembrittlement behavior of the vessel steel to be expected with subsequent radiation exposure under normal SM-1A operations.

## ANNEALING RESPONSE OF THE SM-1A PRESSURE VESSEL STEEL

### Accelerated Irradiation and Annealing Studies

In the interest of a complete reference document, all test data which are directly applicable to the evaluation of properties recovery achieved by the in-place annealing of the SM-1A pressure vessel are compiled below. The summary includes previously reported data (1, 2) and those data points derived from the latest series of accelerated-irradiation, test reactor experiments. The effect of neutron irradiation on the nil-ductility transition (NDT) temperature of the SM-1A pressure vessel steel has been determined from Charpy-V properties of the test material. Drop-weight tests initially performed on this material resulted in NDT temperatures of -70°F and -40°F, respectively, for the duplicate ring forging and the fabrication test plate. These temperatures corresponded well with the Charpy-V 30 ft-lb transition temperatures for the two materials (-80°F and -40°F).

This correspondence between the drop-weight NDT temperature and the Charpy-V 30 ft-lb transition temperature has also been observed after irradiation, thus validating the use of the change in Charpy-V 30 ft-lb transition temperature, $\Delta T$, as a measure of the change in the NDT temperature, $\Delta NDT$, of the SM-1A vessel steel.

For simplicity, all fluence values in this section are in terms of $n/cm^2 > 1$ Mev and assume a fission spectrum neutron energy distribution at the respective irradiation locations. Previous research at NRL (3) has shown this method of reporting neutron fluences to be conservative when comparing SM-1A pressure vessel wall exposures to accelerated irradiation exposures in the LITR core. Spectral conditions are considered, however, in arriving at the most realistic postanneal lifetime estimate.

## Irradiation Response of the SM-1A Pressure Vessel Steel Without Intermediate Annealing

The Charpy-V transition temperature behavior of the SM-1A pressure vessel steel is summarized in Table 1 and shown graphically in Fig. 1. The data have been developed from both the 3-5/8-in.-thick fabrication test plate and the 2-5/8-in.-thick duplicate ring forging. As can be seen in Fig. 1, the irradiation responses of both materials are very similar. All but two of the data points shown in Fig. 1 represent accelerated irradiation exposures conducted in the LITR (respective core positions are separately identified in the figure). The two data points for the lowest fluence conditions were obtained from SM-1A pressure vessel surveillance samples and appear to be in satisfactory agreement with the accelerated irradiation data trend line. All but one of the accelerated irradiations were conducted at a controlled temperature at 430°F to simulate the SM-1A pressure vessel operating conditions. The trend line for transition temperature increase versus neutron fluence is reproduced in subsequent figures as a basic embrittlement curve for this heat of A350-LF1 (Modified) steel.

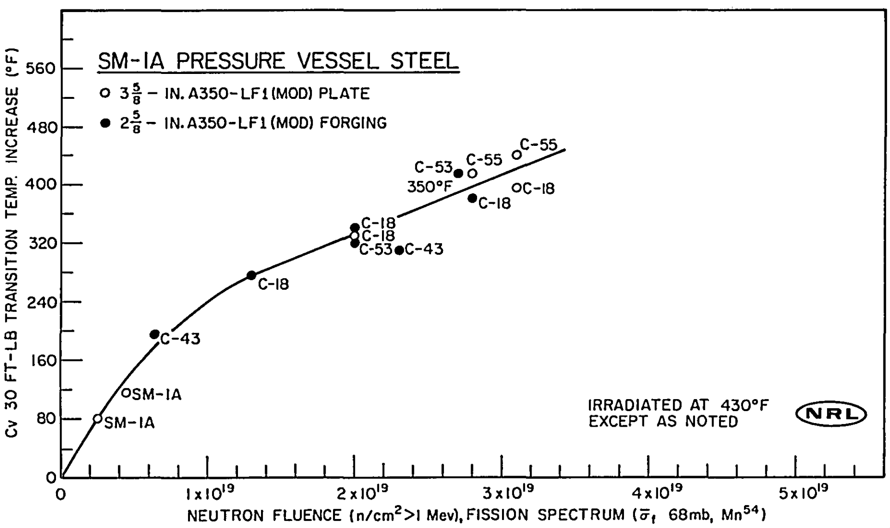


Fig. 1 - Charpy-V transition temperature behavior of the SM-1A pressure vessel steel irradiated at 430°F. This embrittlement curve will be repeated in subsequent figures.

## Low-Temperature Irradiation and Cyclic Annealing Experiments

In the initial stages of planning the SM-1A pressure vessel annealing, two temperature approaches (700°F versus 585°F) were actively considered. To demonstrate the merits of each annealing approach, cyclic irradiation and annealing experiments were conducted in which the two annealing-temperature applications were simulated. Because low-temperature annealing specifications were not firmly defined when these experiments were planned, 585°F was estimated to be a reasonable value for the low-temperature

Table 1
Charpy-V Transition-Temperature Behavior of the SM-1A Pressure Vessel Steel, A350-LF1 (Modified), After Irradiation at 430°F

| Material Source | Irradiation Facility | Fluence* ($n/cm^2 > 1$ Mev) | Charpy-V 30 ft-lb Transition Temperature (°F) | | | Full Shear Energy Absorption (ft-lb) | |
|---|---|---|---|---|---|---|---|
| | | | Initial | Irra-diated | ΔT | Initial | Irra-diated |
| SM-1A test plate | SM-1A P.V. (surveillance) | $2.6\times10^{18}$ | -45 | 35 | 80 | - | - |
| SM-1A test plate | SM-1A P.V. (surveillance) | $4.8\times10^{18}$ | -45 | 70 | 115 | 120 | 115 |
| SM-1A duplicate forging | LITR, C-43 | $6.4\times10^{18}$ | -80 | 115 | 195 | 130 | 90 |
| SM-1A duplicate forging | LITR, C-18 | $1.3\times10^{19}$ | -80 | 195 | 275 | 130 | 95 |
| SM-1A duplicate forging | LITR, C-53 | $2.0\times10^{19}$ | -80 | 240 | 320 | 130 | 90 |
| SM-1A test plate | LITR, C-18 | $2.0\times10^{19}$ | -45 | 285 | 330 | 120 | 70 |
| SM-1A duplicate forging | LITR, C-18 | $2.0\times10^{19}$ | -80 | 260 | 340 | 130 | 70 |
| SM-1A duplicate forging | LITR, C-53† | $2.7\times10^{19}$ | -80 | 335 | 415 | 130 | 75 |
| SM-1A test plate | LITR, C-55 | $2.8\times10^{19}$ | -45 | 370 | 415 | 120 | 60 |
| SM-1A duplicate forging | LITR, C-18 | $2.8\times10^{19}$ | -80 | 300 | 380 | - | - |
| SM-1A test plate | LITR, C-18 | $3.1\times10^{19}$ | -45 | 350 | 395 | - | - |
| SM-1A test plate | LITR, C-55 | $3.1\times10^{19}$ | -45 | 395 | 440 | 120 | 55 |
| SM-1A duplicate forging | LITR, C-43 | $2.3\times10^{19}$ | -80 | 230 | 310 | 130 | 70 |

*$\bar{\sigma}$ 68 mb, $Mn^{54}$, fission.
†Irradiated at 350°F.

anneal series. Subsequently obtained data, however, revealed no significant difference in recovery between the actually employed 572°F pressure vessel annealing temperature and the 585°F value selected for the annealing experiment series.

Capsules containing Charpy-V specimens of the SM-1A pressure vessel material (duplicate ring forging) were irradiated in the Union Carbide Research Reactor to a neutron fluence simulating that at the pressure vessel wall and were annealed out-of-reactor under the selected heat treatment conditions. This sequence was repeated for three complete cycles for each of the two annealing temperatures, to determine the re-irradiation embrittlement rates and the properties behavior during subsequent annealing applications. Enough specimens were used to permit the determination of the Charpy-V 30 ft-lb transition temperature increase, ΔT, after each irradiation cycle, as well as the extent of recovery, ΔR, following each annealing cycle. The irradiation temperature for this series of evaluations was less than 240 °F.

Results from the individual experiment series are summarized in Table 2 and are presented graphically in Figs. 2 through 5. As shown in Fig. 2, the recovery following each 585 °F annealing period exceeded 90%. The final annealing cycle produced a net recovery of 88% of the total ΔT above the initial preirradiation value, or an overall ΔT of only 35 °F. The observed recovery is significantly higher than would be expected from previous experimental data on the SM-1A steel, where equivalent annealing treatments would suggest a recovery of about 75% (4). The earlier experiments, however, were conducted on material irradiated at 430 °F. This higher irradiation temperature, while not having a significant effect on the rate of ΔT during irradiation, will be seen to have a marked effect on the degree of recovery ΔR during subsequent annealing. The effect of irradiation temperature is considered further in a separate experiment described later.

Table 2
Results From Cyclic Low-Temperature (<240 °F)
Irradiation and Annealing Experiments

| Cycle Number | Fluence ($n/cm^2 > 1$ Mev)* | Charpy-V 30 ft-lb Transition Temperature (°F) | | | | | | % Recovery |
|---|---|---|---|---|---|---|---|---|
| | | Initial | As-Irradiated | ΔT | As-Annealed | ΔR | Residual ΔT | |
| 585 °F/168-hr Annealing Treatments | | | | | | | | |
| 1 | $1.45 \times 10^{19}$ | -80 | 215 | 295 | -55 | 270 | 25 | 92 |
| 2 | $\approx 0.7 \times 10^{19}$ | -55 | 195 | 250 | -45 | 240 | 10 | 96 |
| 3 | $\approx 0.8 \times 10^{19}$ | -45 | 205 | 250 | -45 | 250 | 0 | 100 |
| Cumulative | $2.85 \times 10^{19}$ | -80 | 205 | 285 | -45 | 250 | 35 | 88 |
| 700 °F/48-hr Annealing Treatments | | | | | | | | |
| 1 | $1.45 \times 10^{19}$ | -80 | 235 | 315 | -80 | 235 | 0 | 100 |
| 2 | $1.45 \times 10^{19}$ | -80 | 235 | 315 | -80 | 235 | 0 | 100 |
| 3 | $1.45 \times 10^{19}$ | -80 | 235 | 315 | -80 | 235 | 0 | 100 |
| Cumulative | $4.35 \times 10^{19}$ | -80 | 235 | 315 | -80 | 235 | 0 | 100 |

*$\bar{\sigma}$ 68 mb., $Mn^{54}$, fission.

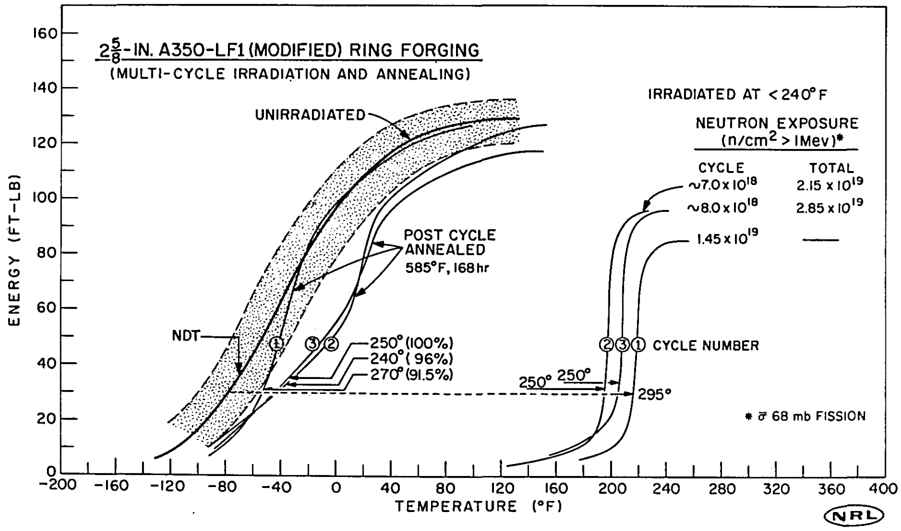


Fig. 2 - Transition temperature behavior of the SM-1A pressure vessel steel with cyclic, low-temperature (< 240°F) irradiation and intermediate 585°F, 168-hr annealing

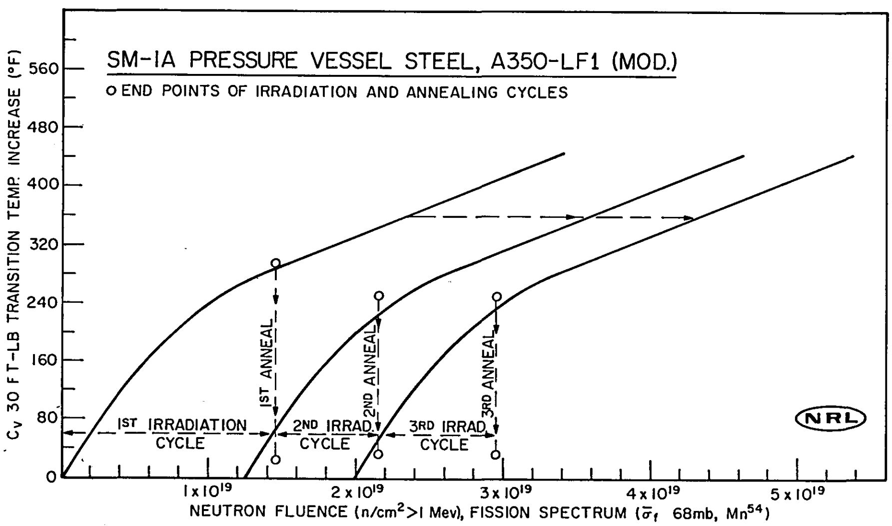


Fig. 3 - Transition temperature behavior of the SM-1A pressure vessel steel with cyclic, low-temperature (< 240°F) irradiation and intermediate 585°F, 168-hr annealing with reference to the SM-1A steel embrittlement curve (shown in Fig. 1)

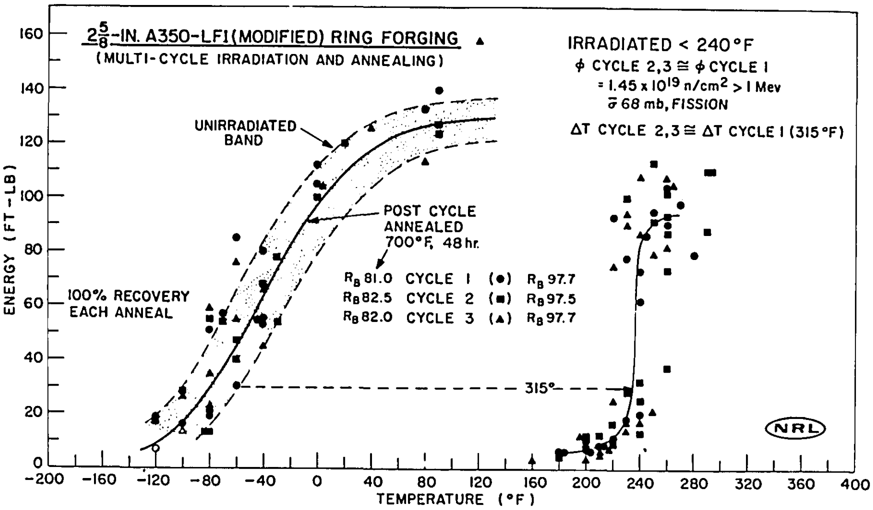


Fig. 4 - Transition temperature behavior of the SM-1A pressure vessel steel with cyclic, low-temperature (< 240°F) irradiation and intermediate 700°F, 48-hr annealing

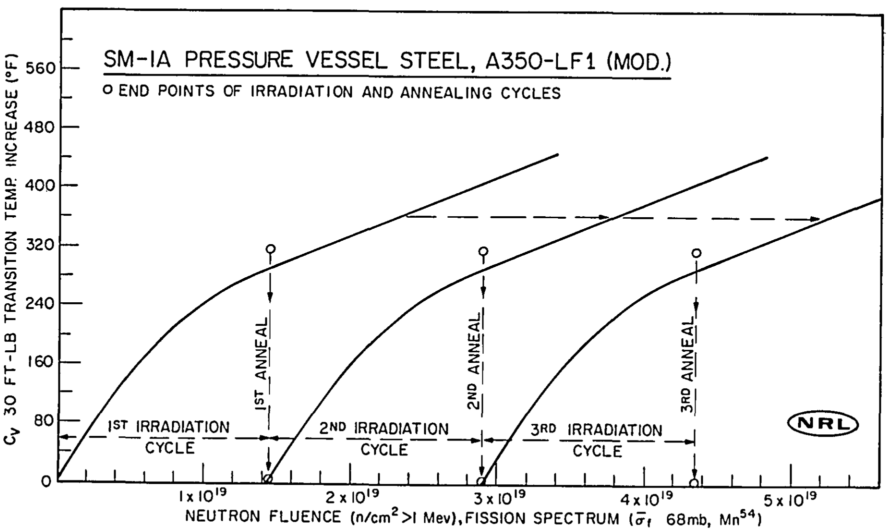


Fig. 5 - Transition temperature behavior of the SM-1A pressure vessel steel with cyclic, low-temperature (< 240°F) irradiation and intermediate 700°F, 48-hr annealing with reference to the SM-1A steel embrittlement curve

One additional point concerning the data presented in Fig. 2 merits discussion. Noting that irradiation cycles 2 and 3 received approximately 50% less exposure than cycle 1, it would appear that embrittlement for cycles 2 and 3 progressed at a higher rate, since ΔT was 250°F for cycles 2 and 3 as compared to 295°F for cycle 1. This, however, is not the case. Figure 3 shows the 585°F annealing data plotted with reference to the basic SM-1A pressure vessel steel embrittlement curve (Fig. 1). This curve shows a relatively rapid initial rate of embrittlement. After a neutron fluence of approximately $8 \times 10^{18}$ n/cm$^2$, however, the slope of the curve flattens as the steel becomes less sensitive to continued exposure. Since the second and third cycles of the 585°F annealing experiment were limited to fluences of less than $8 \times 10^{18}$ n/cm$^2$, the end points of the irradiation cycles appear on the steep slope of the curve. When the basic embrittlement curve is transposed to include the end points of each irradiation-annealing cycle, as illustrated in Fig. 3, the embrittlement rate is seen to be very similar during all three irradiation cycles.

Results from the 700°F annealing series are presented in Figs. 4 and 5. Complete notch ductility recovery was obtained with each annealing treatment. Significantly, during the second and third irradiation-annealing cycles, the steel behaved as though it had no prior exposure history. It should be noted that, in this experiment, the second- and third-cycle neutron exposures were increased to match the first-cycle exposure; the data thus verify that the embrittlement rate was *not* accelerated during reirradiation.

## Controlled-Temperature Cyclic Irradiation-Annealing Experiment

Following the selection by the Army of the low-temperature annealing approach for SM-1A pressure vessel embrittlement relief, a two-cycle irradiation and annealing experiment was designed and performed for close simulation of actual vessel service and annealing conditions. The consecutive aims of this experiment were to subject Charpy-V samples of the SM-1A duplicate forging material to: (a) a neutron fluence equivalent to that of the pressure vessel beltline (peak flux) at 430°F, a temperature representative of vessel service, (b) a 168-hr, 585°F annealing treatment in the reactor, (c) reirradiation to a second-cycle fluence corresponding to the predicted maximum permissible vessel exposure, and (d) a second 585°F/168-hr annealing treatment out of the reactor. To perform this experiment, special half-length assemblies for tandem irradiation were designed to allow the removal of one specimen assembly containing control (reference) specimens, while the second assembly remained in the reactor for a second irradiation period. Three such half-capsule assemblies were required to perform the two-cycle experiment. Data were developed on ΔT following each irradiation period and on ΔR following each interval annealing treatment. Figure 6 shows the overall experiment plan and the sequence of cyclic operations. The results of this experiment are summarized in Table 3 and are presented graphically in Figs. 7 and 8.

Some operational difficulties were encountered in conducting the experiment, although, considering the experiment complexity, the overall performance was very satisfactory. One problem, temperature control, caused a section of capsule 1 to be irradiated at a lower temperature than was desired (350°F versus 430°F). Correlations among the available specimens in this capsule, however, did provide valid values for the first-cycle transition temperature annealing recovery.

Analysis of activation dosimeters distributed through each capsule revealed a definite axial flux gradient across the capsules. This gradient is attributed to the vertical separation of the half-capsules (required for lead access) which resulted in the displacement of each half-capsule away from the "flat flux region" of the irradiation facility used. Due to this flux gradient, the Charpy specimens were separated according to their respective exposures in the test. The two distinct exposure levels resulted in two sets of data, as shown in Table 3, and in the corresponding figures. The first-cycle ΔT values for

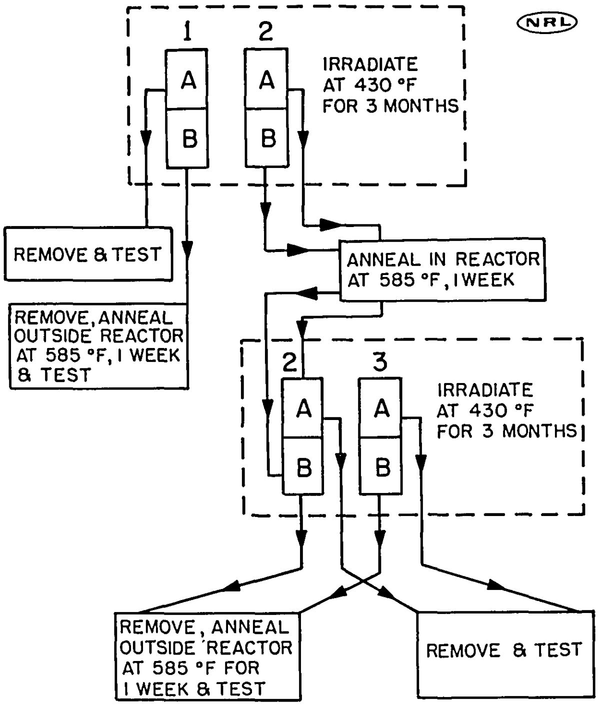


Fig. 6 - Experiment plan and the sequence of operations for controlled-temperature, two-cycle irradiation and annealing experiment. Three half-capsule irradiation assemblies were used.

capsule 2 (Table 3) were obtained by interpolating capsule 1 (first-cycle reference) data for the respective fluence levels.

A critical evaluation of the data in Table 3 suggests that (a) the first SM-1A pressure vessel annealing cycle can be expected to yield embrittlement recovery exceeding 70%, (b) the transition temperature shift of the SM-1A steel is not accelerated when reirradiation follows an annealing treatment, (c) the benefits of annealing under these conditions appear to be greater with a more frequent (i.e., after less fluence) annealing schedule following the first annealing cycle (76% recovery for cycle 2 at the lower fluence zone versus 65% recovery for the higher fluence zone), (d) a significant full-shear energy level is retained by the highly irradiated but intermittently annealed SM-1A steel forging, and (e) the 168-hr, 585°F annealing treatment probably cannot be used to limit ΔT indefinitely, since a residual increasing transition temperature appears to be present following each annealing cycle. This increase

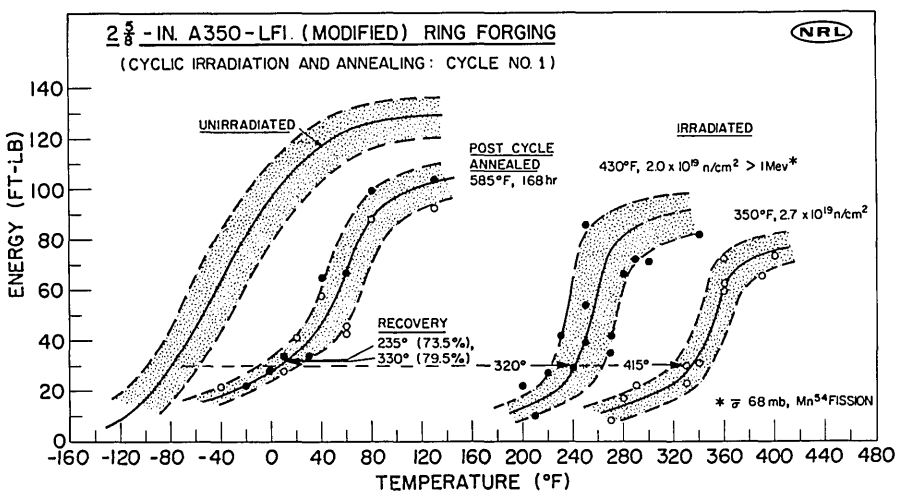


Fig. 7 - Cyclic 430°F irradiation and 585°F, 168-hr annealing of the SM-1A pressure vessel steel showing the Charpy-V notch ductility behavior with the first irradiation and annealing cycle (Irradiation Assembly 1). The two distinct specimen fluence levels resulted from an axial flux gradient within the irradiation assembly.

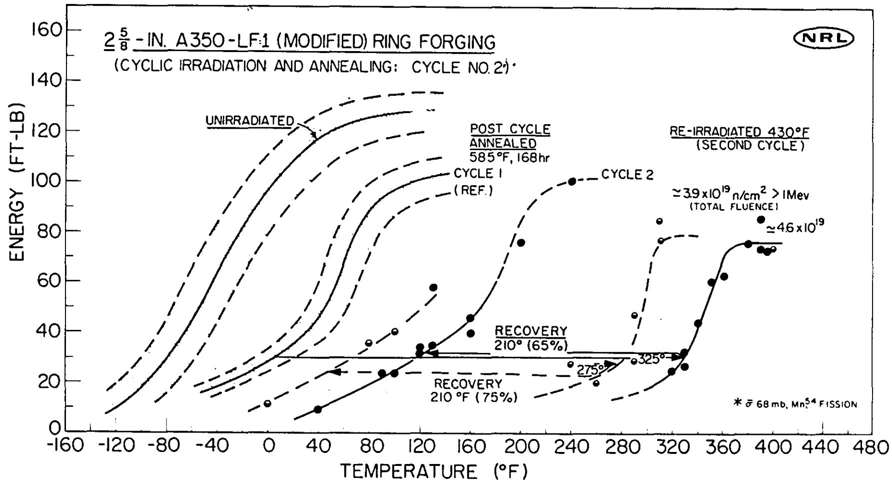


Fig. 8 - Cyclic 430°F irradiation and 585°F, 168-hr annealing of the SM-1A pressure vessel steel showing the Charpy-V notch ductility behavior following the second irradiation and annealing cycle (Irradiation Assembly 2). The postcycle annealing data for the first cycle are also indicated for reference. The two distinct fluence levels resulted from an axial flux gradient within the irradiation assembly.

Table 3
Results From Cyclic Controlled Temperature (430°F) Irradiation and Annealing Experiment Using 585°F/168-hr Annealing Treatments

| Cycle Number | Fluence ($n/cm^2 > 1$ Mev)* | Charpy-V 30 ft-lb Transition Temperature (°F) | | | | | | % Recovery |
|---|---|---|---|---|---|---|---|---|
| | | Initial | As-Irradiated | ΔT | As-Annealed | ΔR | Residual ΔT | |
| **Low-Flux Zone of Irradiation Capsule** | | | | | | | | |
| 1 | $2.12\times10^{19}$ | -80 | 255 | 335 | 5 | 250 | 85 | 75 |
| 2 | $1.78\times10^{19}$ | 5 | 280 | 275 | 70 | 210 | 65 | 76 |
| Cumulative | $3.90\times10^{19}$ | -80 | 280 | 360 | 70 | 210 | 150 | 58 |
| **High-Flux Zone of Irradiation Capsule** | | | | | | | | |
| 1 | $2.50\times10^{19}$ | -80 | 310 | 390 | 5 | 305 | 85 | 78 |
| 2 | $2.10\times10^{19}$ | 5 | 330 | 325 | 120 | 210 | 115 | 65 |
| Cumulative | $4.60\times10^{19}$ | -80 | 330 | 410 | 120 | 210 | 200 | 51 |

*$\bar{\sigma}$ 68 mb, $Mn^{54}$, fission.

may be greatly reduced by selecting the optimum reannealing frequency (optimum fluence between anneals).

## Temperature Sensitivity of the Annealing Response

It was anticipated that minor departures from the selected annealing temperature might be required in performing the actual annealing operation. Thus, an experiment was conducted to evaluate the effect of such departures on the overall recovery. Six groups of Charpy-V specimens were irradiated at 430°F to a neutron fluence of $1.3 \times 10^{19}$ n/cm$^2$ > 1 Mev. Five of the six groups of irradiated specimens were subjected to individual 168-hr postirradiation annealing treatments of 550, 560, 570, 580, and 590°F, respectively, while the sixth group of specimens (control) served to establish ΔT during the initial irradiation. The results of this experiment are shown in Fig. 9.

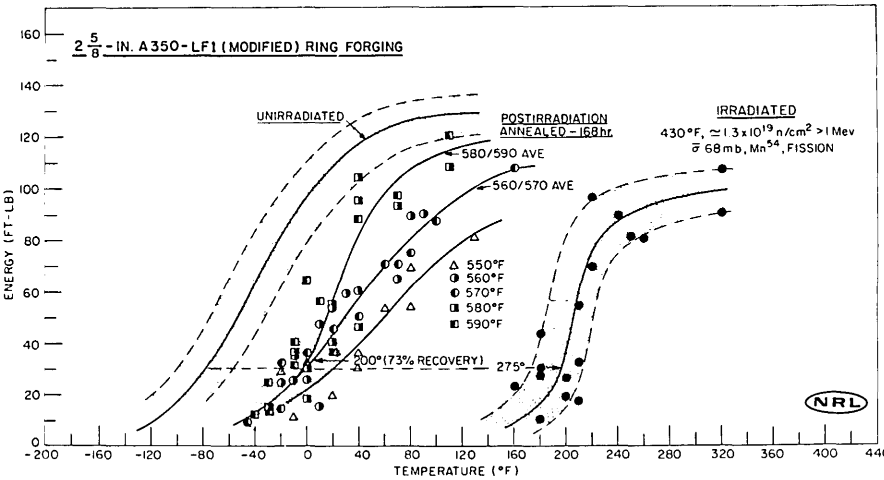


Fig. 9 - Response of the SM-1A pressure vessel steel to the 168-hr postirradiation heat treatments over the temperature range 550°F to 590°F

The recovery, as measured by the change in the Charpy-V 30 ft-lb transition temperature, was essentially the same for all specimen groups (73%) with the exception of the 550°F group, which had a 64% recovery. The data also reveal that the higher annealing temperatures (580°F and 590°F) were somewhat more effective in the overall embrittlement relief, as suggested by data points above the 45-ft-lb energy level.

This experiment is significant because it shows that minor deviations from the selected annealing temperature would not grossly affect the predicted recovery.

## Results From SM-1A Pressure Vessel Surveillance Capsules and Supplemental Control Capsules

To demonstrate the extent of recovery achieved by the in-place annealing operation, optimum use has been made of the SM-1A pressure vessel radiation damage surveillance program. At the time of annealing, this program consisted of four specimen capsules (A, B, C, and D) in a special hanger assembly above the reactor core. These surveillance capsules were installed at the start of the second core loading. The capsules and the hanger assembly were designed to permit individual capsule removal from the reactor. Because of their location relative to the peak flux plane of the fuel core, the surveillance-assembly exposure conditions were significantly different from those experienced by the pressure vessel wall. First, the maximum fluence at the surveillance location was approximately 50% of the maximum fluence at the pressure vessel wall for an equivalent exposure time. Second, spectral calculations indicated a somewhat "harder" neutron spectrum at the surveillance location than at the pressure vessel wall (3).

Each of the four surveillance capsules contained 22 Charpy-V specimens and two tensile specimens grouped in three vertical layers. Capsule neutron fluences determined from an analysis of activation dosimeters were (a) lower specimen layer: $4.8 \times 10^{18}$ $n/cm^2 > 1$ Mev, (b) center specimen layer: $2.4 \times 10^{18}$ $n/cm^2 > 1$ Mev, and (c) upper specimen layer: $1.2 \times 10^{18}$ $n/cm^2 > 1$ Mev. Since all the capsules were symmetrically oriented with respect to the core, the respective dose rates for the four capsules were equivalent; however, a considerable flux gradient existed in the vertical direction from the core. In comparison with the above values, the fluence for the peak flux zone of the pressure vessel immediately before the annealing operation was estimated at $1.64 \times 10^{19}$ $n/cm^2 > 1$ Mev. This value was based on the analysis of activation dosimeters taken from the pressure vessel wall inside-diameter location in the early stages of the reactor operation and on the plant power history up to the time of the annealing.

Because of the described limitations of the existing surveillance program supplemental capsules containing Charpy-V specimens of the SM-1A duplicate ring forging were irradiated in the LITR and were installed in the SM-1A pressure vessel just before the annealing operation. The combined surveillance-capsule and control-capsule program was designed to provide a maximum of useful data regarding the embrittlement relief, as illustrated in Fig. 10.

Two pairs of capsules, each containing 18 Charpy-V specimens, were irradiated in the LITR at a controlled temperature (430°F). One pair was irradiated to a low fluence, while the second pair received a much higher exposure.

Two of the four original SM-1A surveillance capsules were removed from the reactor before the annealing operation and were replaced with a capsule from each pair of the LITR-irradiated capsules (i.e., a high- and low-fluence unit). The removed capsules were used to determine the preannealing $\Delta T$ conditions of the surveillance assembly specimens. Similarly, the two remaining LITR-irradiated capsules provided $\Delta T$ conditions of the supplemental capsule specimens.

After the annealing operation the two supplemental LITR capsules, and one of the remaining SM-1A surveillance capsules, were removed from the pressure vessel. The specimens from these three capsules were used to determine the extent of embrittlement relief achieved. It should be noted that the central specimen group in each of the original surveillance assembly capsules contained A212-B specimens rather than specimens of the SM-1A steel. The results from these specimens have been included only to demonstrate the differences in the annealing response between the SM-1A steel and the A212-B steel. Specimen identification (with respect to the source of material) by assembly section is given in Table 4. Three replacement capsules (unirradiated) containing Charpy-V specimens of the SM-1A duplicate forging were installed in vacated hanger assembly positions for continued surveillance.

The results from the combined surveillance program are presented in Table 5.

Surveillance-Capsule Results — The results from the surveillance capsules, included in Table 5, are plotted in Figs. 11 through 13. Because of the known vertical flux gradient in the original surveillance capsule assemblies, the three specimen groups in each capsule were treated individually.

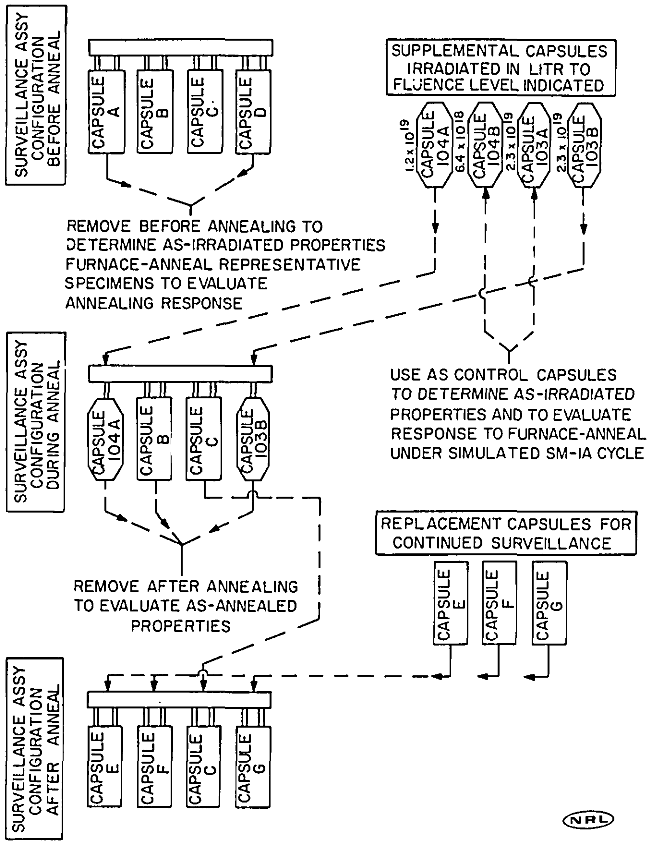


Fig. 10 - The SM-1A surveillance capsule and the supplemental control capsule utilization plan

Table 4
SM-1A Pressure Vessel Surveillance Specimen Material Identification

| Specimen Identification | Lower Specimens | Center Specimens | Upper Specimens |
|---|---|---|---|
| Surveillance Capsule A (Removed before anneal) | SM-1A test plate (8 $C_v$ specimens) | 4-in. A212-B plate (6 $C_v$ specimens) | SM-1A test plate (8 $C_v$ specimens) |
| Surveillance Capsule B (Removed after anneal) | SM-1A test plate (8 $C_v$ specimens) | 4-in. A212-B plate (6 $C_v$ specimens) | SM-1A duplicate ring forging (8 $C_v$ specimens) |
| Surveillance Capsule D (Removed before anneal) | SM-1A test plate (8 $C_v$ specimens) | 4-in. A212-B plate (6 $C_v$ specimens) | SM-1A duplicate ring forging (8 $C_v$ specimens) |

Table 5
Results From the SM-1A Pressure Vessel Surveillance and the Annealing Monitor Specimen Program

| Specimen Identification | Specimen Material Source | Fluence* (n/cm$^2$ > 1 Mev) | Charpy-V 30 ft-lb Transition Temperature (°F) | | | | | | | % Recovery |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Initial | As-Irradiated | ΔT | Annealed in SM-1A† | Furance Annealed† | ΔR | Residual ΔT | |
| Surveillance Capsules A, B, and D (lower specimens) | SM-1A test plate | $4.8 \times 10^{18}$ | -45 | 70 | 115 | 0 | - | 70 | 40 | 61 |
| Surveillance Capsules A and D (lower specimens) | SM-1A test plate | $4.8 \times 10^{18}$ | -45 | 70 | 115 | - | 0 | 70 | 40 | 61 |
| Surveillance Capsules A, B, and D (center specimens) | 4-in. A212-B plate | $2.4 \times 10^{18}$ | 10 | 125 | 115 | 105 | - | 20 | 95 | 17 |
| Surveillance Capsules A and D (center specimens) | 4-in. A212-B plate | $2.4 \times 10^{18}$ | 10 | 125 | 115 | - | 60‡ | 65 | 50 | 57 |
| Surveillance Capsule A (upper specimens) | SM-1A test plate | $1.2 \times 10^{18}$ | -45 | -20 | 25 | - | - | - | - | - |
| Surveillance Capsules B and D (upper specimens) | SM-1A duplicate forging | $1.2 \times 10^{18}$ | -80 | -50 | 30 | -60 | - | 10 | 20 | 33 |
| Supplemental Capsule 104A | SM-1A duplicate forging | $1.2 \times 10^{19}$ | -80 | 180§ | 260§ | -30 | - | 210 | 50 | 81 |
| Supplemental Capsule 104B | SM-1A duplicate forging | $6.4 \times 10^{18}$ | -80 | 115 | 195 | - | -50 | 165 | 30 | 85 |
| Supplemental Capsule 103A | SM-1A duplicate forging | $2.3 \times 10^{19}$ | -80 | 230 | 310 | 20 | - | 210 | 100 | 68 |
| Supplemental Capsule 103B | SM-1A duplicate forging | $2.3 \times 10^{19}$ | -80 | 230 | 310 | - | 20 | 210 | 100 | 68 |

*$\bar{\sigma}$ 68 mb, $Mn^{54}$, fission.
†28 hr at 560°F + 144 hr at 572°F.
‡Furnace annealed 48 hr at 700°F.
§Extrapolated values.

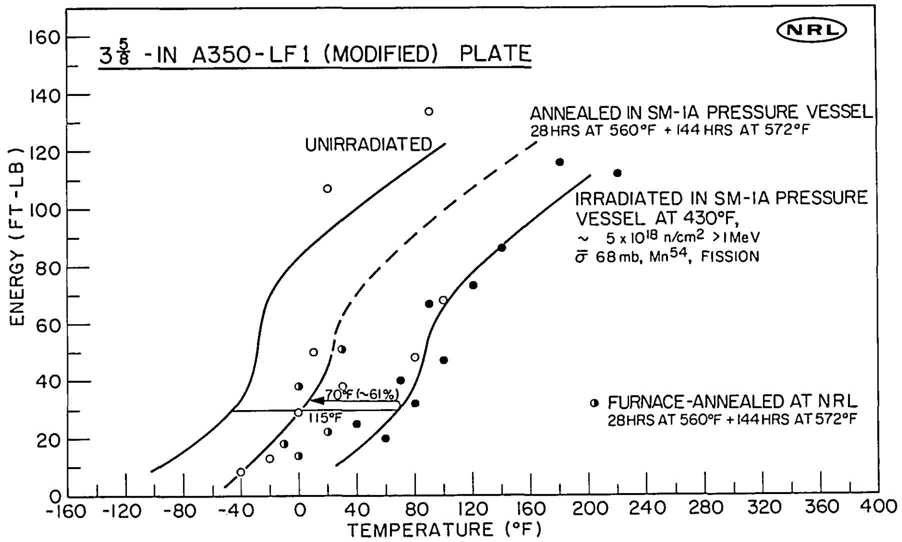


Fig. 11 - Charpy-V transition temperature behavior of the SM-1A pressure vessel test plate specimens (lower layer of surveillance capsules) before and after in-reactor annealing

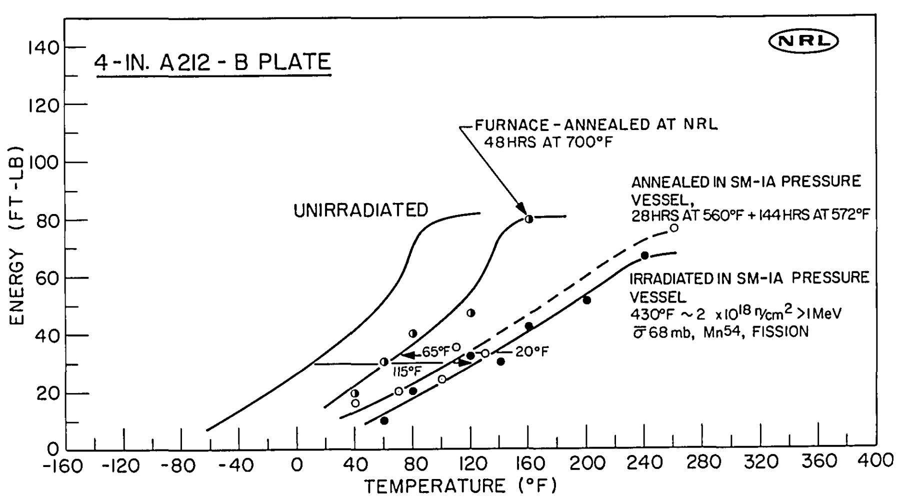


Fig. 12 - Charpy-V transition temperature behavior of the A212-B steel specimens (center layer of surveillance capsules) before and after in-reactor annealing and following a 700°F, 48-hr furnace anneal

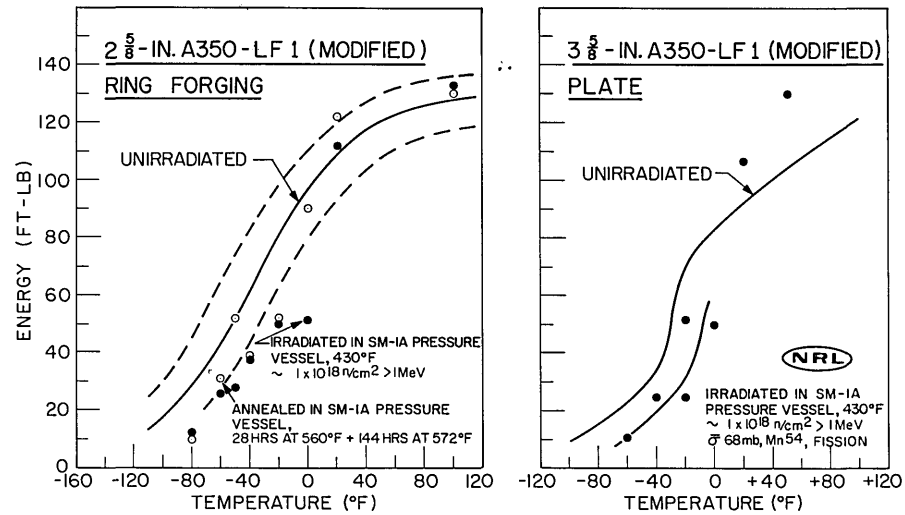


Fig. 13 - Charpy-V transition temperature behavior of the SM-1A pressure vessel test plate and the duplicate ring forging specimens (upper layer of surveillance capsules) before and after in-reactor annealing

Figure 11 shows the properties of the SM-1A test plate specimens located in the *lower* layer of the surveillance capsules before and after annealing in the reactor. A ΔT of 115°F is indicated, followed by a 70°F recovery from the annealing operation. Several of the irradiated specimens (controls) were furnace annealed at NRL using a temperature cycle closely approximating that recorded for the actual pressure vessel annealing operation (28 hr at 560°F plus 144 hr at 572°F). The annealing response of the furnace-annealed specimens duplicated the recovery behavior of the specimens annealed in the reactor, thus indicating that the recorded SM-1A pressure vessel temperature cycle was realized. The percent recovery for the SM-1A surveillance-capsule specimens was somewhat lower than that recorded for the LITR-irradiated supplemental-capsule specimens annealed in the SM-1A (61% versus 68 to 81%; nevertheless, the *residual* ΔT was very similar to that recorded for the low-fluence LITR supplemental-capsule specimens (Table 5). The as-annealed condition transition temperature for all specimens was only 30°F to 50°F higher than the preirradiated condition transition temperature.

The results from the surveillance-assembly center-specimen group (A212-B steel) are presented in Fig. 12 and in Table 5. Slight recovery (approximately 20°F) was produced by the SM-1A annealing sequence. This observation was anticipated from earlier accelerated irradiation-annealing experiments (5) and emphasizes the sensitivity of the annealing response to material type or composition. Several of the as-irradiated A212-B surveillance specimens were also furnace annealed at 700°F for 48 hr and exhibited considerably higher recovery (65°F or 57%).

The results from the surveillance-assembly upper-specimen group (lowest fluence) are in Fig. 13. This group contained specimens from both the SM-1A test plate and the duplicate ring forging. Due to the very low fluence at this specimen location ($\approx 1 \times 10^{18}$ n/cm$^2$) the transition temperature increase was correspondingly small (25°F to 30°F); nevertheless, it is significant that the test plate and the forging materials responded similarly. Some recovery was indicated due to the pressure vessel annealing operation, but, due to the small initial incremental changes, the quantitative estimates are not considered meaningful.

Supplemental-Capsule Results — Figures 14 and 15 illustrate the irradiation and the annealing response of the LITR-irradiated supplemental capsules. These data are included in the complete data summary in Table 5. Figure 14 presents data from the low-fluence capsule. It can be seen that the fluence level for the capsule annealed in the SM-1A was considerably higher than for the capsule furnace-annealed at NRL. Since the as-irradiated specimens were not available to verify the preannealing transition temperature shift of the higher fluence capsule, the transition temperature curve for the as-irradiated condition of these specimens was extrapolated from the lower-fluence-capsule results and the basic embrittlement curve (Fig. 1).

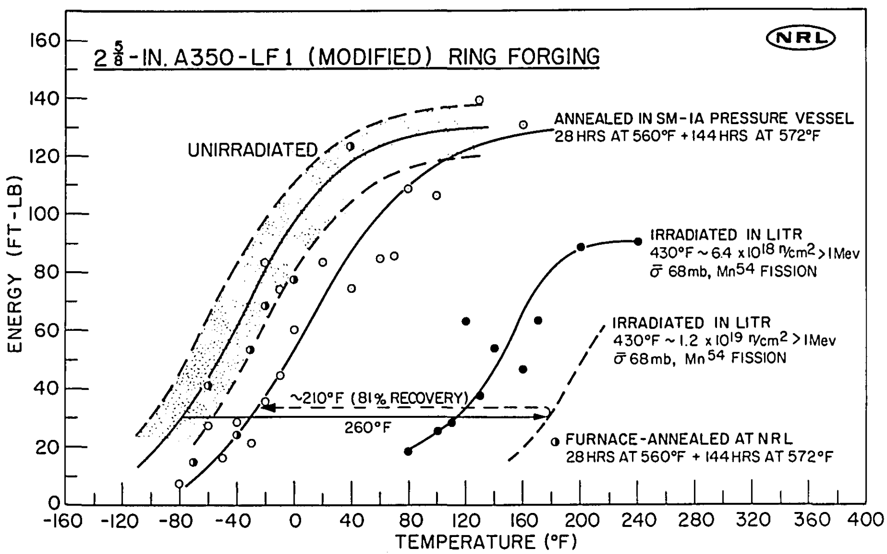


Fig. 14 - Charpy-V transition temperature behavior of the SM-1A duplicate ring forging specimens from the low-fluence supplemental control capsules which were irradiated in the LITR. The annealing responses for both in-reactor anneal and the simulated furnace anneal are shown.

The annealing recovery for both capsules (furnace-annealed and annealed in the SM-1A ranged from 81% to 85% with a residual transition temperature increase of 30°F to 50°F.

Figure 15 shows the irradiation and the annealing behavior of the high-fluence supplemental capsules. In this case both sets of specimens were irradiated to the same fluence ($2.3 \times 10^{19}$ n/cm$^2$), which was somewhat higher than the estimated pressure vessel wall exposure. The corresponding transition temperature shift was 310°F. The recoveries for the furnace-annealed specimens and for the specimens annealed in the SM-1A were identical, amounting to 210°F or about 68%, which corresponds approximately to a 100°F residual transition temperature increase.

Thus, the SM-1A surveillance-capsule and control-capsule plan has demonstrated (a) reasonably good agreement between data from specimens irradiated in the SM-1A and specimens irradiated in the LITR, giving added confidence to the bulk of the annealing response data developed from the accelerated specimen irradiations, (b) an equivalence of the annealing response between specimens annealed within the SM-1A and specimens furnace-annealed at NRL in simulation of the service-anneal conditions — confirming that the indicated temperature cycle was, in fact, achieved, and (c) a dependence of the annealing

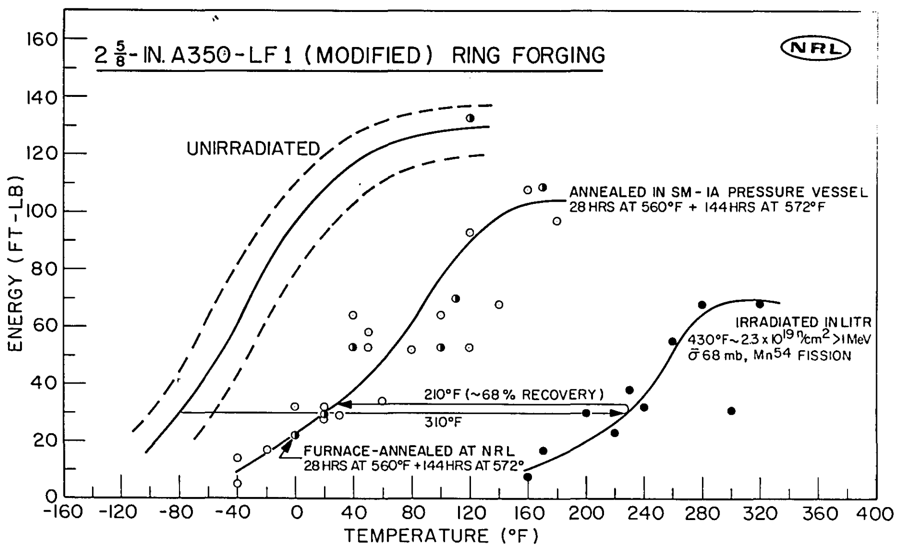


Fig. 15 - Charpy-V transition temperature behavior of the SM-1A duplicate ring forging specimens from the high-fluence supplemental control capsules which were irradiated in the LITR. The annealing responses for both in-reactor anneal and the simulated furnace anneal are shown.

response on irradiation fluence. The SM-1A surveillance capsules and the low-fluence supplemental capsules showed a 30°F to 50°F residual transition temperature increase after the annealing treatment, while a 100°F residual transition temperature increase was recorded for the higher fluence capsules.

## STATUS OF THE SM-1A PRESSURE VESSEL LIFETIME AFTER THE ANNEALING OPERATION

The SM-1A pressure vessel lifetime, without the benefit of annealing, has been defined previously in terms of the megawatt-years (MW-yr) of operation before the pressure vessel wall ductile-brittle transition temperature reaches a preselected maximum (3). The Army has established 300°F as the maximum pressure vessel Charpy-V 30-ft-lb transition temperature which can be tolerated by the plant under current operating procedures.

The pressure vessel transition-temperature increase at the time of annealing is based on a previously reported dose rate estimate ($4.05 \times 10^{17}$ n/cm$^2$ > 1 Mev per MW-yr) and on the plant power history prior to the annealing operation. The calculations made in this section are again based on a fission-spectrum assumption for the SM-1A pressure vessel wall positions and the surveillance positions, and for the accelerated irradiations in the LITR. The influence of neutron spectra is considered in the following section.

The SM-1A operating history indicates a 40.4-MW-yr burnup at the time of shutdown for the annealing operation. When the $4.05 \times 10^{17}$-n/cm$^2$-MW-yr conversion factor is used, a peak pressure vessel wall fluence of $1.64 \times 10^{19}$ n/cm$^2$ > 1 Mev is determined. Applying this fluence to the SM-1A steel damage curve (Fig. 16), it can be seen that the corresponding transition temperature increase, $\Delta T$, is 300°F. The preannealing vessel wall Charpy-V 30 ft-lb transition temperature is then 260°F if it is based on the SM-1A

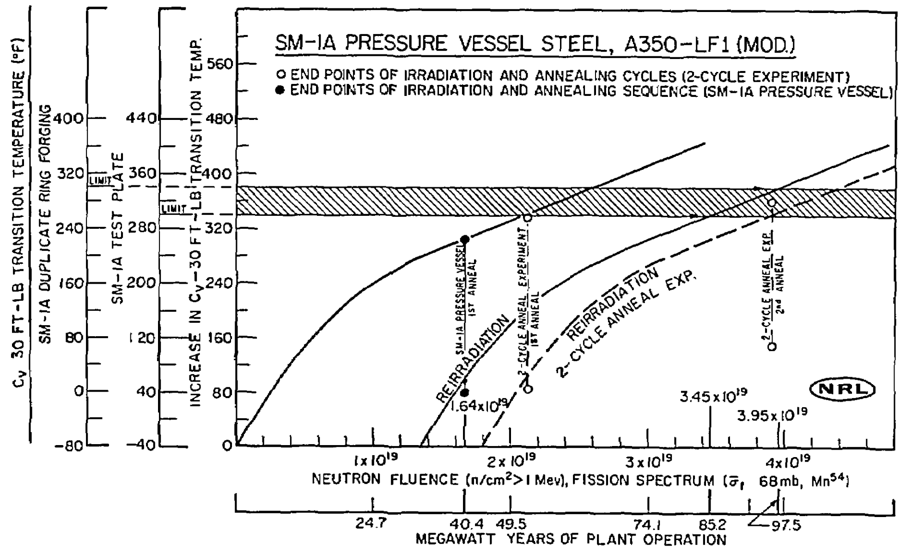


Fig. 16 - Projected reirradiation behavior of the SM-1A pressure vessel following the in-place annealing operation. Fluence values are based on the fission spectrum assumption and a 1-Mev damage threshold.

fabrication test-plate properties, or 220°F if it is based on the duplicate ring (i.e., reference) forging properties. While both values are given in this data compilation, it is suggested that the SM-1A duplicate ring forging is more representative of the actual pressure vessel and, therefore, should be considered as providing the most realistic estimate of the pressure vessel status.

The as-annealed transition temperature increase (or the residual transition temperature increase) for the vessel is estimated at 80°F. The basis for this estimate is derived from the results of the annealing-temperature sensitivity experiment, described in detail in the previous section. In that experiment Charpy-V specimens from the SM-1A duplicate ring forging were irradiated at 430°F to a fluence approximating the SM-1A pressure vessel wall condition ($1.3 \times 10^{19}$ n/cm$^2$ versus $1.64 \times 10^{19}$ n/cm$^2$) and were annealed at temperatures bracketing the actual SM-1A pressure vessel annealing temperature. The data demonstrated 73% recovery in transition temperature, or an 80°F residual $\Delta T$.

The selected residual $\Delta T$ value of 80°F is also found to agree well with the results from the first-cycle anneal of the two-cycle controlled-temperature experiment in which the specimens were irradiated to a somewhat higher fluence ($2.12 \times 10^{19}$ n/cm$^2$) and yielded a residual $\Delta T$ of 85°F.

To estimate the reirradiation behavior, the SM-1A steel damage curve is retraced to include the index point given by the transition temperature for the as-annealed condition (Fig. 16). Following along this curve (labeled "reirradiation"), limiting fluences based on the initial transition temperature for the SM-1A test plate and the duplicate ring forging are found to be $3.45 \times 10^{19}$ n/cm$^2$ and $3.95 \times 10^{19}$ n/cm$^2$, respectively. When converted to MW-yr of plant operation, these values become 85.2 and 97.5 MW-yr.

The method of extrapolating the reirradiation path is substantiated by the results of the two-cycle controlled-temperature irradiation and annealing experiment described in the previous section. These results are also included in Fig. 16 for comparison and thus show that, when the proposed damage path is retraced, the embrittlement projections and the experimentally determined data agree closely.

## NEUTRON DOSIMETRY AND CALCULATED SPECTRUM LIFETIME ANALYSIS

The neutron fluence data presented in Figs. 1 through 16 are based on a fission spectrum distribution of neutrons (Fig. 17) and the assumption that neutrons of energies greater than 1 Mev are responsible for the radiation damage. It has been clearly demonstrated, however, that (a) the neutron spectrum at the SM-1A pressure vessel wall (Fig. 18) is significantly different from a typical core facility spectrum in the LITR (Fig. 19) where some of the accelerated irradiation experiments were conducted (3), and that (b) these spectra are significantly different from a fission spectrum. The differences are such that a significant increase in the lifetime of the SM-1A was realized when the neutron fluence which created a given amount of damage in the LITR was translated into that neutron fluence shown to be appropriate for causing the same damage at the SM-1A pressure vessel wall (3).

This translation was based on the latest data for the activation cross section for the $Fe^{54}(n,p)Mn^{54}$ neutron dosimetry reaction. Specifically, the 82.6-mb cross section deduced by Helm (6) for the fission-spectrum-averaged iron cross section was used rather than the more commonly used 68-mb cross section. This higher activation cross section reflects the trend evidenced by the most recent analyses of the iron cross section, notably those of Helm (6) and of Barrall and McElroy (7). This cross section was, in turn, redetermined for neutrons having energies greater than the lower energy limit of 0.5 Mev rather than for 1 Mev within the calculated spectra of the reactor facilities concerned. The primary reason for extending the lower energy limit for accountable neutrons to 0.5 Mev is based on the work of Dahl and Yoshikawa at Battelle-Northwest (8). In their studies,

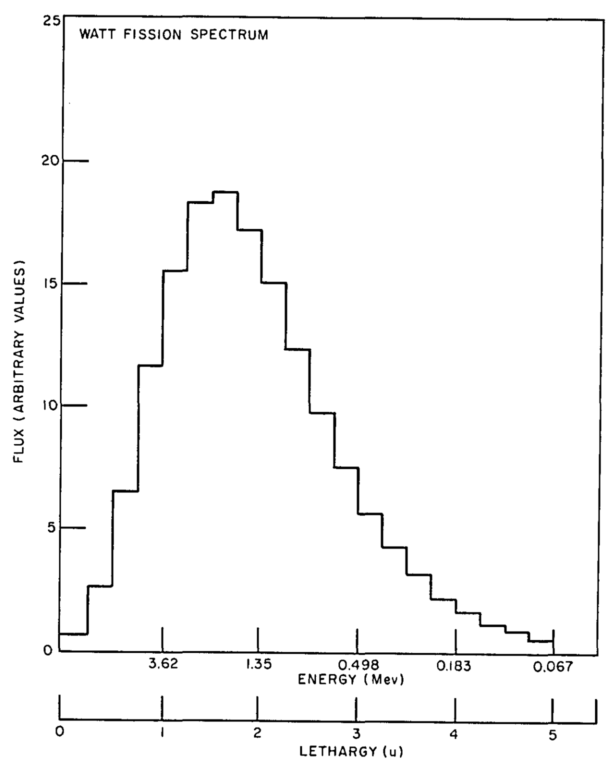


Fig. 17 - Watt fission spectrum plotted by arbitrary flux values in terms of $\phi(u)$ versus 0.25 lethargy (u) units

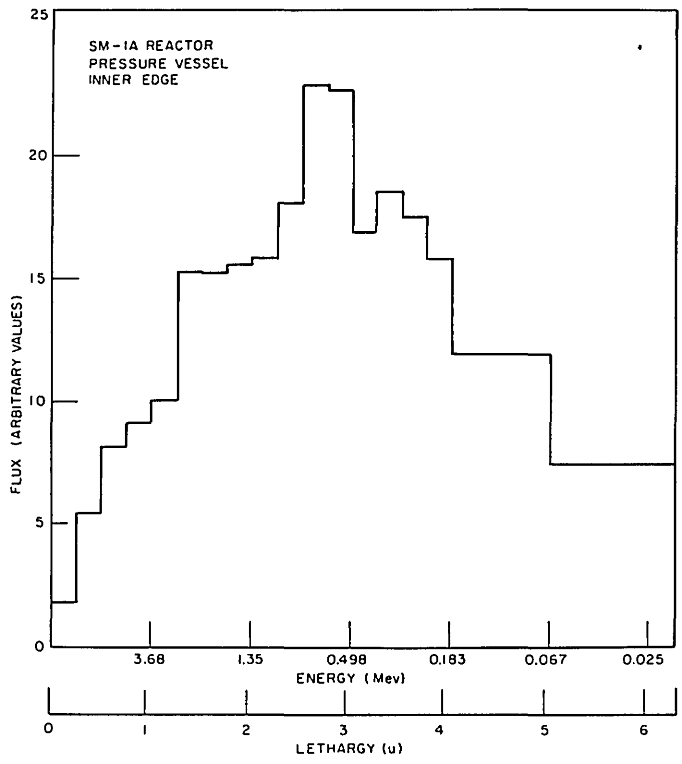


Fig. 18 - Neutron spectrum at the neutron-flux monitor position of the SM-1A reactor centered 1/4-in. closer to the core than the stainless steel vessel cladding

ratios were established relating atomic displacements occurring over the entire energy spectrum for the widest variety of reactor environment types to neutron fluxes having energies greater than 0.183 Mev, 0.5 Mev, and 1 Mev. It was clearly established that the smallest variation in the ratios occurred for the 0.5-Mev lower energy limit condition.

Since no further data have yet emerged to suggest any alteration required for either the lower energy limit (0.5 Mev) or the fission-averaged iron activation cross section (82.6 mb), they will be used in the present analysis of the SM-1A pressure vessel lifetime.

The irradiation embrittlement data developed for both the duplicate ring forging and the test plate of A350-LF1 (Modified) steel (Table 1) have been replotted in Fig. 20 as open data points representing a neutron fluence greater than 1 Mev in terms of a fission spectrum. Included in this figure are the same embrittlement data replotted as closed points in terms of calculated spectra and for fluences greater than 0.5 Mev; the fluences have also been adjusted for the relative damage predicted for the pressure vessel wall of the SM-1A, as discussed in Ref. 3. The line through the open, fission spectrum data is the same line shown in Fig. 1. The line through the closed points now becomes the reference line for embrittlement versus calculated spectrum fluence and will be carried forward. Inspection of the two lines reveals that the calculated spectrum line may fit the data points somewhat better than the fission spectrum line, particularly at the higher fluences. In both cases the average behavior line ignores the data point at 310°F, which may be considered slightly conservative.

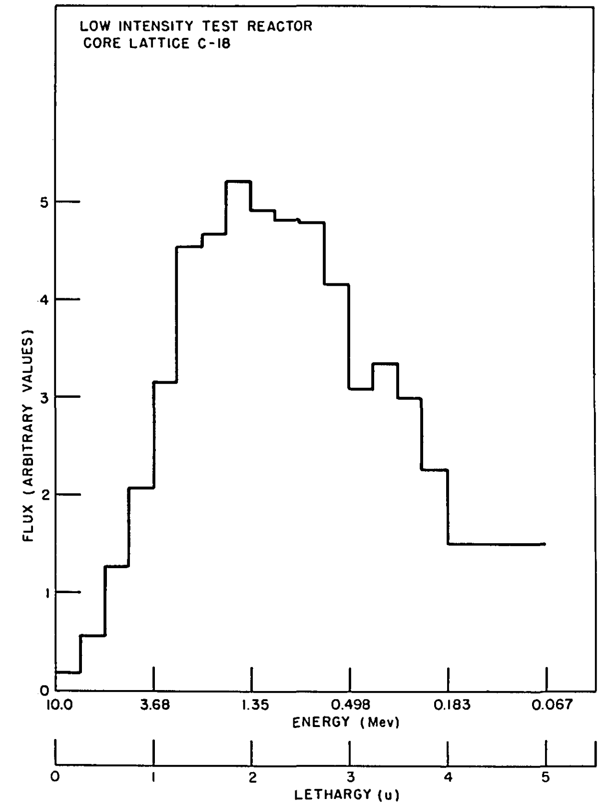


Fig. 19 - Neutron spectrum in the C-18 core lattice position of the LITR

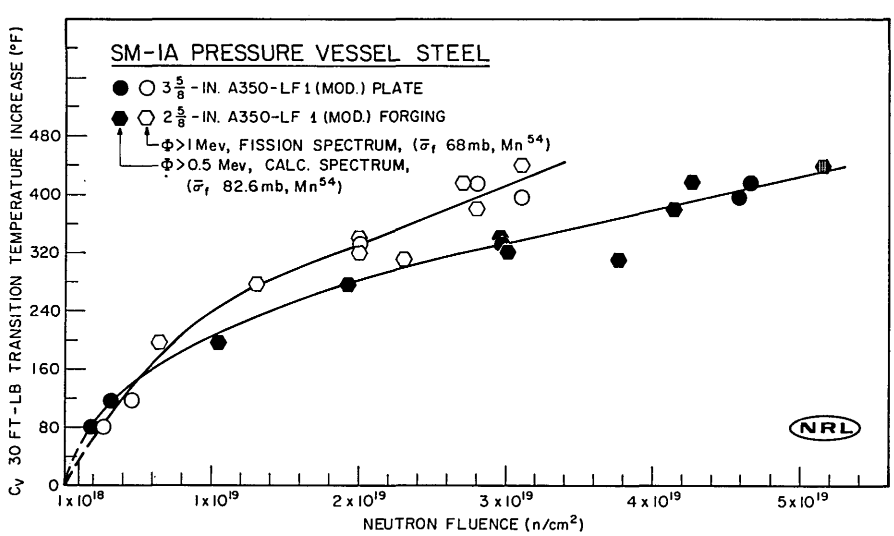


Fig. 20 - The SM-1A pressure vessel steel embrittlement curve. Comparison between assumed >1 Mev, fission spectrum, and >0.5 Mev, calculated spectrum fluences

The data presented in Fig. 20 are summarized in Table 6. In columns 4 through 9 the data development is similar to the progression shown previously (3). For clarity, however, the development of pertinent values for the first line in Table 6 will be shown. Column 5 gives the iron activation cross section for particular locations in the LITR and the SM-1A in terms of $n/cm^2 > 0.5$ Mev, using a fission-averaged cross section of 82.6 mb as a base.

Column 6 shows the values for the neutron fluence of each embrittlement point in terms of $n/cm^2 > 0.5$ Mev for the calculated spectrum of the actual irradiation location of the data point, i.e., a core lattice position in the LITR or the above-core surveillance location in the SM-1A, as in the case for lines 1 and 2. In determining this fluence, it should be remembered that the *product of the flux times the cross section for one criterion must equal the product of the flux times the cross section for any other criterion.* This can be expressed as:

$$\Phi_f\ (>1\ \text{Mev}) \times \bar{\sigma}_f\ (>1\ \text{Mev}) = \Phi_{cs}\ (>0.5\ \text{Mev}) \times \bar{\sigma}_{cs}\ (>0.5\ \text{Mev}), \qquad (1)$$

where $\Phi_f$ (>1 Mev) is the fluence of neutrons having energies greater than 1 Mev in a fission spectrum, $\bar{\sigma}_f$ (>1 Mev) is the cross section for neutrons having energies greater than 1 Mev in a fission spectrum, $\Phi_{cs}$ (>0.5 Mev) is the fluence of neutrons having energies greater than 0.5 Mev in a calculated spectrum, and $\bar{\sigma}_{cs}$ (>0.5 Mev) is the cross section for neutrons having energies greater than 0.5 Mev in a calculated spectrum.

In evaluating Eq. (1) for $\Phi_{cs}$ (>0.5 Mev), notice that the value for $\Phi_f$ (>1 Mev) is given in column 3 of Table 6 and the value for $\bar{\sigma}_{cs}$ (>0.5 Mev) is given in column 5. The value for $\bar{\sigma}_f$ (>1 Mev), 98.12 mb, is derived from the fission-averaged cross section (activation cross section averaged over the *entire fission spectrum*) of 68 mb. Observe now that the fluences shown in column 3 are those having energies greater than *1 Mev only*, *not* over the *entire spectrum*. Therefore, the 68-mb value for the *entire* spectrum is divided by 0.693, the fraction of neutrons in a fission spectrum having energies greater than 1 Mev, thus yielding the cross section for neutrons in a fission spectrum having energies greater than 1 Mev:

$$\frac{68\ \text{mb}}{0.693} = 98.12\ \text{mb} = \bar{\sigma}_f\ (>1\ \text{Mev}). \qquad (2)$$

The evaluation of $\Phi_{cs}$ (>0.5 Mev) is as follows: After substitution of the appropriate values, Eq. (1) becomes

$$0.26 \times 10^{19}\ n/cm^2 \times 98.12\ \text{mb} = \Phi_{cs}\ (>0.5\ \text{Mev}) \times 143.5\ \text{mb}; \qquad (3)$$

or

$$\Phi_{cs}\ (>0.5\ \text{Mev}) = 0.18 \times 10^{19}\ n/cm^2.$$

Column 7 gives the damage indices $K_i$ for the specific reactor locations. Column 8 shows the factors which result from relating the experimental location damage indices ($K_i$ values) to the damage index at the SM-1A pressure vessel wall ($K_j$ = 197.2). The factors $K_i$ and $K_j$, which have been discussed in detail (3), need only be put into ratio with one another and multiplied by the calculated spectrum fluence (Column 6) to yield the fluence of neutrons at the pressure vessel wall of the SM-1A. This is the fluence which is projected to be required to effect the amount of embrittlement shown in Column 2 of Table 6. The values in Column 9 are the fluences (calculated spectra, >0.5 Mev) for the closed data points in Fig. 20.

It is now necessary to translate cyclic irradiation and annealing data described by Fig. 16 in terms of the new calculated-spectrum (>0.5 Mev) trend line for the A350-LF1

Table 6
Development of Calculated Spectrum Fluences for the Experimental Data Applied to the SM-1A Vessel Wall

| (1) Steel | (2) Charpy-V 30 ft-lb Increase (°F) | (3) $\Phi_f > 1$ Mev* ($10^{19}$ n/cm$^2$) | (4) Irradiation Position | (5) $\bar{\sigma}_{cs} > 0.5$ Mev (mb)† | (6) $\Phi_{cs} > 0.5$ Mev $\Phi_f \times \frac{68/0.693}{\bar{\sigma}_{cs}}$ ($10^{19}$ n/cm$^2$) | (7) Damage Index $K_i$ | (8) Relative Damage $\frac{K_i}{K_j \text{ (SM-1A Wall)}}$ ($K_j$ = 197.2) | (9) $\Phi_{cs} > 0.5$ Mev Adjusted to SM-1A Pressure Vessel Wall ($10^{19}$ n/cm$^2$) |
|---|---|---|---|---|---|---|---|---|
| Plate | 80 | 0.26 | SM-1A | 143.5 | 0.18 | 200.4 | 1.016 | 0.18 |
| Plate | 115 | 0.48 | SM-1A | 143.5 | 0.33 | 200.4 | 1.016 | 0.33 |
| Forging | 195 | 0.64 | C-43‡ | 61.1 | 1.02 | 201.0 | 1.019 | 1.04 |
| Forging | 275 | 1.3 | C-18 | 68.2 | 1.87 | 202.8 | 1.028 | 1.92 |
| Forging | 320 | 2.0 | C-53 | 67.6 | 2.90 | 204.4 | 1.037 | 3.01 |
| Plate | 330 | 2.0 | C-18 | 68.2 | 2.88 | 202.8 | 1.028 | 2.96 |
| Forging | 340 | 2.0 | C-18 | 68.2 | 2.88 | 202.8 | 1.028 | 2.96 |
| Forging | 310 | 2.3 | C-43 | 61.1 | 3.69 | 201.0 | 1.019 | 3.76 |
| Forging | 415 | 2.7 | C-53 | 67.6 | 3.92 | 204.4 | 1.037 | 4.06 |
| Forging | 380 | 2.8 | C-18 | 68.2 | 4.03 | 202.8 | 1.028 | 4.14 |
| Plate | 415 | 2.8 | C-55 | 60.8 | 4.52 | 203.2 | 1.030 | 4.66 |
| Plate | 395 | 3.1 | C-18 | 68.2 | 4.46 | 202.8 | 1.028 | 4.58 |
| Plate | 440 | 3.1 | C-55 | 60.8 | 5.00 | 203.2 | 1.030 | 5.15 |

*$\sigma > 1$ Mev = 98.12 mb; $\bar{\sigma}_f$ (cross section averaged over the entire fission spectrum) = 68 mb; $Mn^{54}$.
†Based on a $\bar{\sigma}_f$ of 82.6 mb.
‡C-XX designates the core lattice position in the LITR.

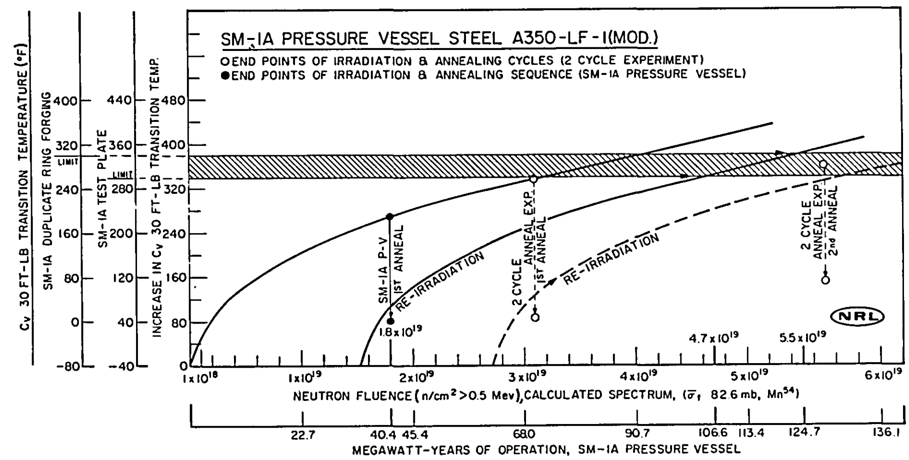


Fig. 21 - Projected reirradiation behavior of the SM-1A pressure vessel following the in-place annealing operation. Neutron fluence values are based on a calculated spectrum distribution greater than 0.5 Mev.

(Modified) steel at the SM-1A pressure vessel wall. This is shown in Fig. 21. The important data relating to this figure are summarized in Table 7. Note that the fluence in terms of 0.5-Mev, calculated spectrum for the time of annealing, is $1.8 \times 10^{19}$ n/cm$^2$. This value has been developed using the MW-yr fluence for the vessel wall of the SM-1A ($4.41 \times 10^{17}$ n/cm$^2$-MW-yr), which was previously developed for the calculated-spectrum 0.5-Mev criterion (3). By comparison, the MW-yr fluence, in terms of the criterion of neutrons of energies greater than 1 Mev in a fission spectrum is $4.05 \times 10^{17}$ n/cm$^2$-MW-yr. Since the SM-1A has operated for 40.4 MW-yr, as noted previously, it is necessary only to multiply the fluence per megawatt-year by the number of megawatt-years. This, then, yields $1.8 \times 10^{19}$ n/cm$^2$ as the criterion for neutrons in a calculated spectrum having energy greater than 0.5 Mev, as opposed to $1.64 \times 10^{19}$ n/cm$^2$ as the criterion for neutrons in a fission spectrum having energy greater than 1 Mev. From Fig. 20 the implication of the value $1.8 \times 10^{19}$ n/cm$^2$ $>$ 0.5 Mev for the fluence at the time of annealing is that the commensurate embrittlement thus *predicted* for the SM-1A vessel wall based on a calculated spectrum analysis is less than that *predicted* by the technique which assumes the fission spectrum. The other values for $\Phi_{cs}$ ($>$0.5 Mev) in Table 7 were derived by the technique of Table 6, column 6, since here it is necessary only to adjust the fluence for a *measured* amount of embrittlement obtained from experimental irradiations. Determinations of the corresponding megawatt-years for the events listed in Table 7 and shown in Fig. 21 are calculated by the simple expressions shown.

By following the trend line in Fig. 21 for the A350-LF1 (Modified) steel behavior, as extrapolated for the vessel wall of the SM-1A, it will be observed that the new lifetime is $4.7 \times 10^{19}$ n/cm$^2$ $>$ 0.5 Mev based on the plate steel and $5.5 \times 10^{19}$ n/cm$^2$ $>$ 0.5 Mev based on the duplicate ring forging. Comparable megawatt-year values for the test plate and the duplicate ring forging are 106 and 124.7, respectively. Without the anneal the lifetime for the SM-1A, in terms of the criterion for neutrons in a calculated spectrum having energy greater than 0.5 Mev, would have been 72.5 MW-yr based on the plate steel and 91.8 MW-yr based on the duplicate ring forging steel.

## SUMMARY

This report presents a complete compilation of the data developed by NRL on the irradiation and annealing behavior of the SM-1A pressure vessel steel (A350-LF1 (Modified)). The data have been obtained from both accelerated irradiation experiments and

Table 7
Summary of the Neutron Fluence and the Megawatt-Year Values for the Various Events in the SM-1A Vessel Wall Lifetime

| Event | Neutron Fluence ($10^{19}$ n/cm$^2$) | | Megawatt-Years of Plant Operation | |
|---|---|---|---|---|
| | $\Phi_f > 1$ Mev Fission Spectrum ($\bar{\sigma}_f$ = 68 mb) | $\Phi_{cs} > 0.5$ Mev* Calculated Spectrum ($\bar{\sigma}_{cs}$ = 82.6 mb) | MW-yr $\frac{f}{\Phi_f}$ $4.05 \times 10^{17}$† | MW-yr $\frac{cs}{\Phi_{cs}}$ $4.41 \times 10^{17}$‡ |
| SM-1A Pressure Vessel | | | | |
| 1st Anneal | 1.64 | 1.8§ | 40.4 | 40.4 |
| 2 Cycle Irradiation and Anneal Experiment | | | | |
| 1st Anneal | 2.12 | 3.09 | — | — |
| 2nd Anneal | 3.90 | 5.69 | — | — |
| Reirradiated to Test Plate Limit | | | | |
| Δ340°F | 3.45 | 4.7 | 85.2 | 106.6 |
| Reirradiated to Duplicate Forging Limit | | | | |
| Δ380°F | 3.95 | 5.5 | 97.5 | 124.7 |

*Determined as described for Table 6, column 6.
†n/cm$^2$-MW-yr fission spectrum (>1 Mev, $\bar{\sigma}_f$ = 68 mb).
‡n/cm$^2$-MW-yr calculated spectrum (>0.5 Mev, $\bar{\sigma}_f$ = 82.6 mb).
§Determined directly: (40.4 MW-yr) ($4.41 \times 10^{17}$ n/cm$^2$ > 0.5 Mev) = $1.8 \times 10^{19}$ n/cm$^2$ >0.5 Mev.

surveillance in the reactor and have been used (a) to define the Charpy-V 30 ft-lb transition temperature increase of the SM-1A pressure vessel steel as a function of neutron exposure under the reactor service conditions, (b) to determine the response of the steel to single and cyclic postirradiation annealing treatments, and (c) to predict the reirradiation behavior of the steel following intermediate annealing.

The data have been analyzed to determine the degree of embrittlement relief obtained by the in-place annealing of the SM-1A and to project the SM-1A lifetime following the annealing operation. Irradiation and annealing responses of the pressure vessel have been indexed to the properties of a duplicate ring forging from the same steel heat. The best estimates of the pressure vessel properties, as modified by the annealing operation, are:

1. The maximum pressure vessel wall Charpy-V 30 ft-lb transition temperature before the in-place anneal was 190°F (a 270°F increase over the preservice condition).

2. The maximum pressure vessel wall Charpy-V 30 ft-lb transition temperature after the in-place anneal was 0°F (an 80°F residual Charpy-V 30 ft-lb transition temperature increase).

3. The pressure vessel lifetime following the in-place anneal will be $5.5\times 10^{19}$ $n/cm^2 > 0.5$ Mev, comparable to 124.7 MW-yr of reactor operation. This total lifetime projection is based on the experimentally predicted reirradiation response of the vessel steel.

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NOTCH DUCTILITY PROPERTIES OF SM-1A REACTOR PRESSURE VESSEL FOLLOWING THE IN-PLACE ANNEALING OPERATION

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A final report on one phase of the problem; work on other phases continues.

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13. ABSTRACT

The embrittlement condition of the Army SM-1A reactor pressure vessel, as modified by the recently completed in-place anneal, was assessed and an analysis was made of the reembrittlement behavior of the vessel steel with subsequent radiation service. Experimental results from the reactor surveillance program developed through one complete irradiation and annealing cycle are presented, together with a summary of experimental information on the annealing response of the vessel steel (A350-LF1, Mod.) from accelerated irradiation programs. These data indicate a 0°F maximum pressure vessel wall Charpy-V 30 ft-lb transition temperature after the in-place anneal versus a -80°F preservice transition temperature (based on the notch-ductility properties of a duplicate ring forging). The maximum Charpy-V 30 ft-lb transition temperature of the pressure vessel before the annealing operation was estimated at 190°F.

A projection of postanneal pressure vessel lifetime in terms of neutron fluence >0.5 Mev was derived from spectra calculations and the experimentally predicted reirradiation response of the pressure vessel steel. The maximum permissible vessel wall fluence is estimated at $5.5 \times 10^{19}$ n/cm$^2$ > 0.5 Mev. This is comparable to 124.7 Megawatt years of reactor operation.

DD FORM 1 NOV 65 1473 (PAGE 1)

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| Embrittlement relief | | | | | | |
| Cyclic irradiation | | | | | | |
| Neutron radiation | | | | | | |
| Neutron fluence | | | | | | |
| Nuclear power reactor | | | | | | |
| Radiation damage | | | | | | |
| Nuclear service | | | | | | |
| SM-1A reactor vessel | | | | | | |
| Heat treatment | | | | | | |

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



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