SM-1A Reactor Pressure Vessel Surveillance: Irradiation of Follow-On Capsules in the SM-1 Reactor

CHARLES Z. SERPAN, JR.

Reactor Materials Branch
Metallurgy Division

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Three capsules containing Charpy V-notch specimens of a duplicate ring-forging of SM-1A reactor pressure-vessel steel were prepared for placement into the SM-1A reactor as part of the continuing vessel surveillance program of that reactor. These capsules plus two more control capsules were irradiated in the SM-1 reactor at 440°F (227°C) to match the SM-1A reactor pressure-vessel transition temperature and fluence conditions prior to the SM-1A annealing. The capsules were then furnace annealed under the SM-1A reactor annealing conditions and were reirradiated in the SM-1 to the fluence and transition-temperature conditions of the SM-1A at the end of Core III. Control points were established after each step.

Significant differences in flux levels at a point in the SM-1 reactor were noted between an earlier flux-monitor irradiation and the subsequent surveillance-capsule irradiations. These differences were found to be directly related to the two different fuel cores in place at those times. Higher fluxes were generated at the core edge during the flux monitor irradiation since the core was old and the center was considerably burned out. Lower fluxes were measured at the same core-edge location during the surveillance-capsule irradiations since a new, smaller diameter core peaked in flux toward the center.

The information developed and documented herein will be required for evaluation of the surveillance capsules after they are removed from irradiation in the SM-1A reactor.

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PROBLEM STATUS

This is an interim report on the phase of the program; work on this and other phases is continuing.

AUTHORIZATION

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SM-1A REACTOR PRESSURE VESSEL SURVEILLANCE: IRRADIATION OF FOLLOW-ON CAPSULES IN THE SM-1 REACTOR

INTRODUCTION

The ferritic-steel pressure vessel of the Army SM-1A Reactor reached a level of embrittlement in mid-1967 such that it was annealed in place to reduce the vessel steel transition temperature (1). Subsequent power operations again began to increase the vessel transition temperature toward the pre-established limit. To provide a means for monitoring the rise in vessel transition temperature and to evaluate the effects of annealing conditions on irradiated steel representing the reactor vessel, a surveillance program has been conducted in the SM-1A (2). This program began with initial operations of the reactor and was increased by two sets of follow-on specimen capsules prior to the annealing operation (3, 4). Post annealing surveillance requirements are now being met with a third set of follow-on capsules. To be realistic, these capsules were irradiated in the SM-1 reactor under environmental conditions of temperature (440° F, 227° C) and neutron spectrum closely approximating those of the SM-1A. The capsules were to duplicate as nearly as possible the condition of the SM-1A vessel at the end of its fuel Core III. It is the continuing availability of surveillance capsules being irradiated under realistic temperature and service conditions that provides sufficient data to assure the safe operating condition of the reactor.

EXPERIMENTAL PROCEDURE

The plan for the third series of follow-on capsules is shown schematically in Fig. 1 and is outlined as follows:

1. Irradiation of five capsules containing Charpy V-notch specimens in the SM-1 Reactor at Ft. Belvoir, Virginia, at 440° F (227° C) to the neutron fluence received by the SM-1A reactor vessel just prior to its annealing (1.8×10^{19} n/cm^2 >0.5 MeV);

2. Annealing of the irradiated capsules in furnaces at NRL for 28 hours at 560° F (293° C) followed by 144 hours at 572° F (300° C);

3. Reirradiation in the SM-1 to the neutron fluence of the SM-1A reactor vessel wall at the end of Core III (2.4×10^{19} n/cm^2 >0.5 MeV);

4. Insertion of two capsules into the SM-1A.

In the event of a second annealing of the SM-1A vessel, the third capsule, J2, would be irradiated again in the SM-1 to match the neutron fluence on the SM-1A vessel, annealed to duplicate the conditions of the second SM-1A vessel annealing, and then inserted to continue the surveillance program.

To assure adequate knowledge of all the conditions present during the numerous steps of the preparation sequence, additional control capsules were also used. These plus the SM-1A surveillance capsules are shown in Fig. 2 as they were located within the dummy fuel element (DFE) used in corner position 72 of the SM-1 reactor (indicated

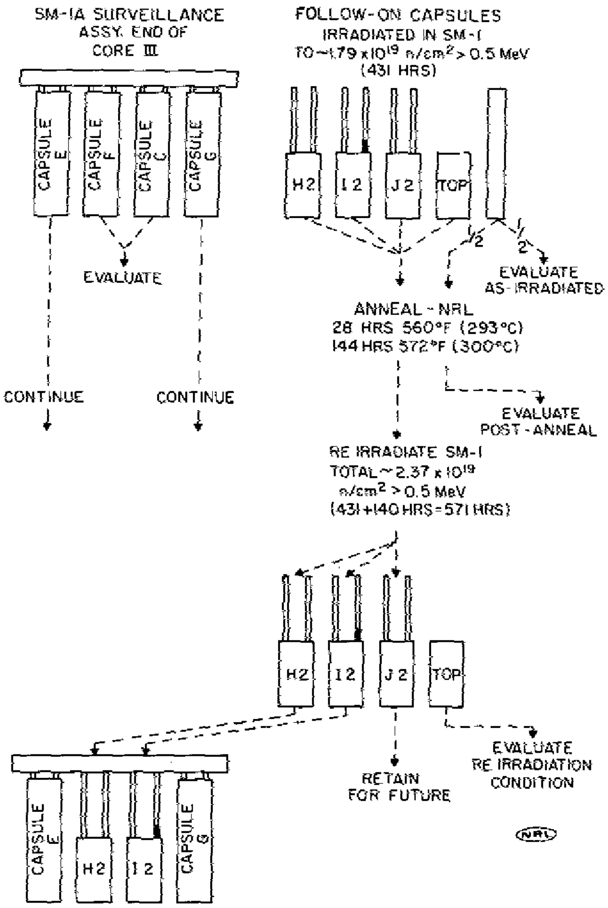

Fig. 1 - Schematic outline of steps involved in the preparation of three capsules for the SM-1A surveillance program

in the figure). Included for reference are the fluence values for $n/cm^2 > 0.5$ MeV measured from iron flux-detector wires located within the central, long capsule plus the small extension from it nearly touching the lower end of the DFE.* The long central capsule was irradiated only during the initial exposure to match the 1.8×10^{19} $n/cm^2 > 0.5$ MeV fluence of the SM-1A; it was then opened so that half the specimens could be tested in the as-irradiated condition while the others were annealed under the above-noted conditions to obtain a measure of the annealing recovery possible. These results are shown in Fig. 3. The four short capsules were not opened and were annealed along with the 12 remaining Charpy-V specimens of the central capsule. After the second irradiation of the four short capsules, the control capsule noted only as "TOP" (the capsule without the long hanger attachments) was opened and the specimens evaluated. These results are shown in Fig. 4.

All Charpy-V specimens were taken from a 2-5/8-in. -thick duplicate ring-forging made from the same heat as the reactor vessel and prepared in close accordance with actual vessel fabrication procedures (1-4). The specimens from the half-thickness of the

*All neutron dosimetry values in this report are presented in terms of n/cm^2, > 0.5 MeV and were derived from a transport theory calculation of the SM-1 reactor neutron spectrum (5) coupled with data based upon iron flux detector wires.

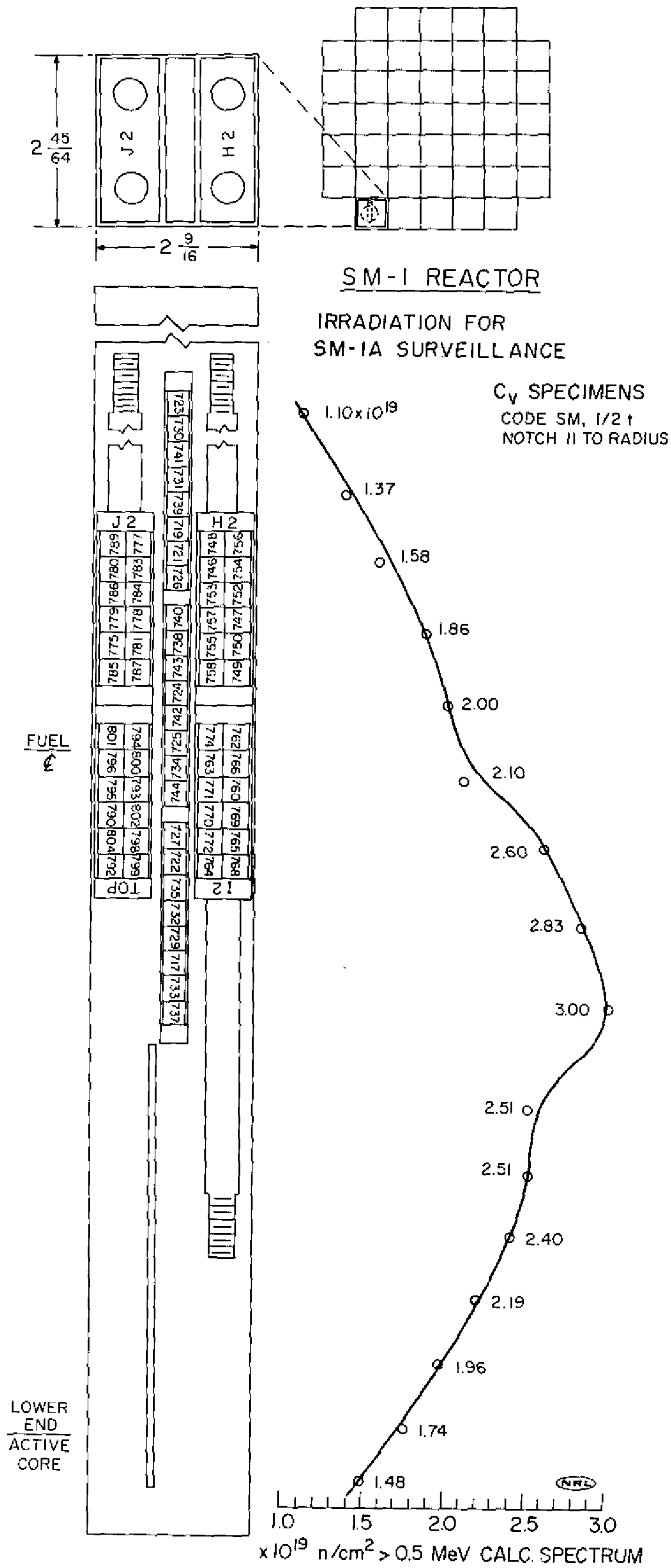

Fig. 2 - Schematic drawing of the SM-1A surveillance and control capsules showing capsule identification, specimen identification, and location and orientation of the capsules in the dummy fuel element and in the SM-1 reactor. Fluence levels for irradiation of the long central control capsule are indicated.

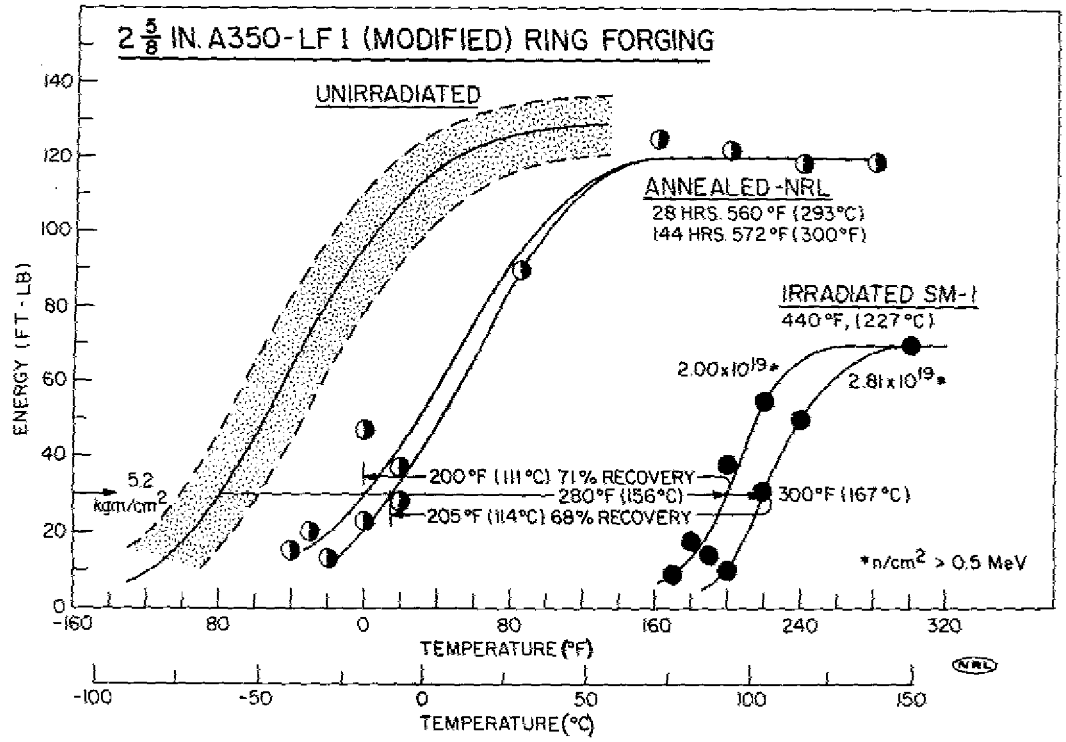

Fig. 3 - Charpy-V notch-ductility results from the long central control capsule of the SM-1A surveillance study. The closed points show the as-irradiated condition for two fluence levels in the capsule. The half-closed points show the result of annealing the irradiated specimens under the SM-1A vessel annealing conditions, as indicated.

ring-forging had their long axis in the forging circumferential direction, and the notches were parallel to the forging radius so that the crack path ran axially in the forging.

The fluence values and test results shown in Figs 2 through 4 are actually from a second series of irradiations. Five capsules were initially built identically to those shown in Figs. 1 and 2 and were irradiated in the SM-1 at full power (10.77 MW) under conditions thought to yield the desired 1.8×10^{19} n/cm^2 >0.5 MeV fluence. The flux values used were those determined in a special flux-monitor irradiation in DFE position 72 at 29.3 percent power and described in Ref. (5). The values were much higher than those measured in the central capsule during the surveillance-capsule irradiation, with the result that the goal exposure of 1.8×10^{19} n/cm^2 >0.5 MeV was not achieved. Accordingly, a second set of capsules was prepared and irradiated under the newly measured flux-value conditions in the DFE. These are the results presented in this report. The reasons for the discrepancy in flux intensity between the flux-monitor irradiation and the subsequent surveillance-capsule irradiations are discussed below.

RESULTS

The Charpy-V notch-ductility results in Fig. 3, obtained from evaluation of the specimens in the long, central capsule, reflect the significant differences in flux (and fluence) values over the length. The values are almost a factor-of-three different from one end to another; it should be evident that the peak flux during this period of reactor operations was significantly below the centerline of the fuel core. Specimens in the central capsule were evaluated by taking every other one to establish the as-irradiated

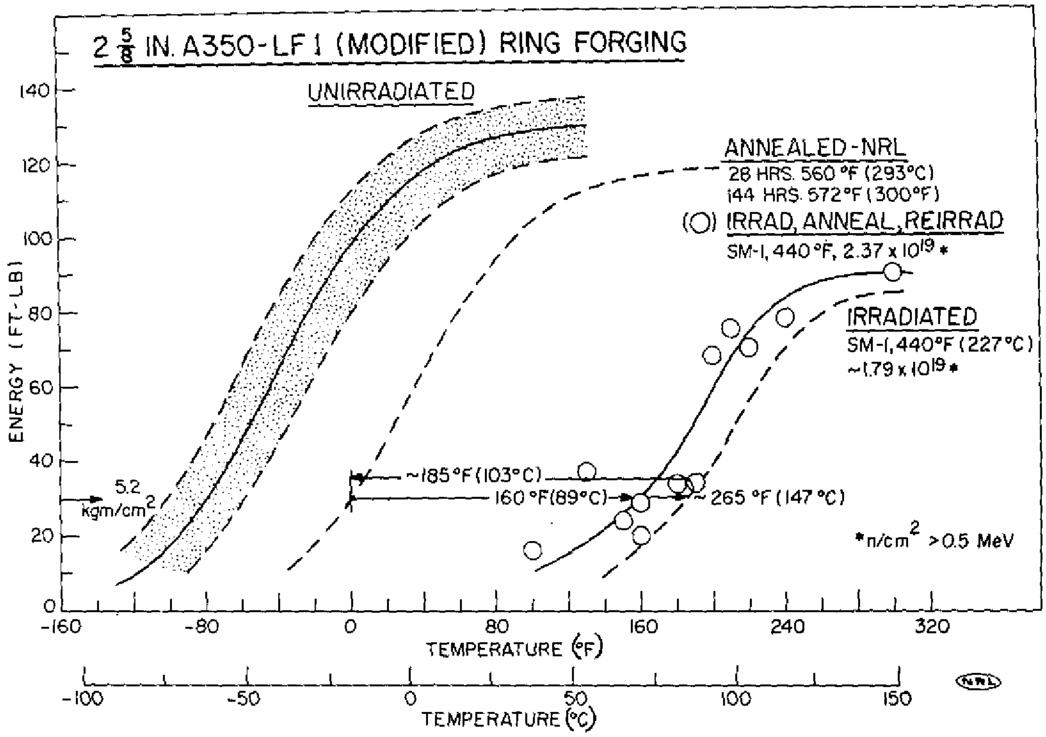

Fig. 4 - Charpy-V notch-ductility results from the control capsule labeled TOP. The open data points represent the final condition for irradiation, annealing, and reirradiation in the SM-1A surveillance study. The as-irradiated and as-annealed conditions indicated are only estimates. Reirradiation of the capsule was conducted with the long central capsule removed; thus, the fast neutron fluence could have been proportionately higher during this irradiation period.

condition (closed circles) with the remaining specimens being annealed to establish the postirradiation-annealed condition (half-closed circles). Two curves are shown for both the as-irradiated and postirradiation-annealed conditions, since the fluence gradients dictated clear separation between the data. The amount of increase in 30-ft-lb transition temperature of the Charpy-V specimens compared very well with the previously established trend for this steel (4). The amount of recovery of initial transition characteristics, 71% and 68% of the Charpy-V 30 ft-lb transition temperature, also compared well with the 73% recovery exhibited by this steel in the actual SM-1A reactor vessel annealing operation (4).

Results for the specimens in the short capsule (labeled TOP) following reirradiation to an accumulated fluence of 2.37×10^{19} n/cm^2 >0.5 MeV are depicted in Fig. 4. Here, the only absolute data are those for the final condition (the open-circle points about the solid line), and it is thus necessary to interpolate to establish the progress of the irradiation sequences based on the results of the central capsule.

DISCUSSION

Notch Ductility Data

The operations data for the entire irradiation exposure of the surveillance capsules, Table 1, show that exposure occurred over a period of 571 hours 20 minutes, with the

Table 1
Reactor Operations Data for SM-1 Irradiation
of SM-1A Surveillance Capsules
(Full Power = 10.77 MW(t))

Reactor Startup Time	Reactor Shutdown Time	Hours at Power	Energy (MWh)
Initial Irradiation*			
2300: 5/9/70	2200: 5/27/70	431:20	4500
Reirradiation			
1600: 6/21/70	1200: 6/27/70	140	1500

*Includes operation at 50% power from 1400 to 1800 on 5/12/70 and from 1430 to 1830 on 5/14/70; downtime, 40 minutes on 5/24/70.

initial irradiation consuming 431 hours 20 minutes and the postannealing reirradiation consuming the remaining 140 hours. Taking the flux for irradiation of the TOP capsule from Fig. 5 as 1.15×10^{13} n/cm^2 sec >0.5 MeV gives fluences (shown in Fig. 4) of 1.79×10^{19} n/cm^2 >0.5 MeV for the as-irradiated condition (dashed line) and 2.37×10^{19} n/cm^2 >0.5 MeV for the final condition (solid line). Recovery of 70 percent was assumed from data presented in Fig. 3.

The final increase in transition temperature following postannealing reirradiation in Fig. 4, 160°F (89°C), is somewhat higher than would be expected for the sequence of irradiation and annealing steps based on data in Ref. 4. The annealing recovery was between 68% and 71% whereas the actual SM-1A annealing recovery (4) was 73%. This could tend to make the final transition temperature slightly higher. Finally, reirradiation of the TOP capsule containing these specimens was conducted in the DFE with the central capsule removed and a layer of water in its place. Because this volume was between the TOP capsule and the main fuel core, the fast flux could have been somewhat higher through water rather than through steel during reirradiation, thus promoting the somewhat higher transition temperature increase. This type of potentially variable radiation response can be expected for capsule J2, since it also was shielded by the central capsule during the initial irradiation. Capsules H2 and I2 that were placed into the SM-1A, however, were not shielded by any other capsules and therefore should display an irradiation response behavior as depicted in Fig. 3 for the irradiated and annealed conditions.

Neutron Flux Data

As noted above the neutron flux levels measured for the surveillance exposure irradiation were significantly different from those measured in the flux-detector irradiation (5); both sets of values are shown in Fig. 5 for comparison. It is pointed out that all the fluxes in Fig. 5 are based on the full-power operation of the SM-1 reactor, which is 10.77 MW(t). The fluxes reported in Ref. 5 are based upon a power level of only 10 MW(t) and were adjusted to 10.77 MW(t) for inclusion in Fig. 5. In Fig. 5 the DFE is depicted completely full of water during flux-monitor irradiation except for the 1/4-in.-diameter tube holding the flux detector wires. For the surveillance-capsule irradiation the DFE was almost entirely filled with steel and had only very small water layers.

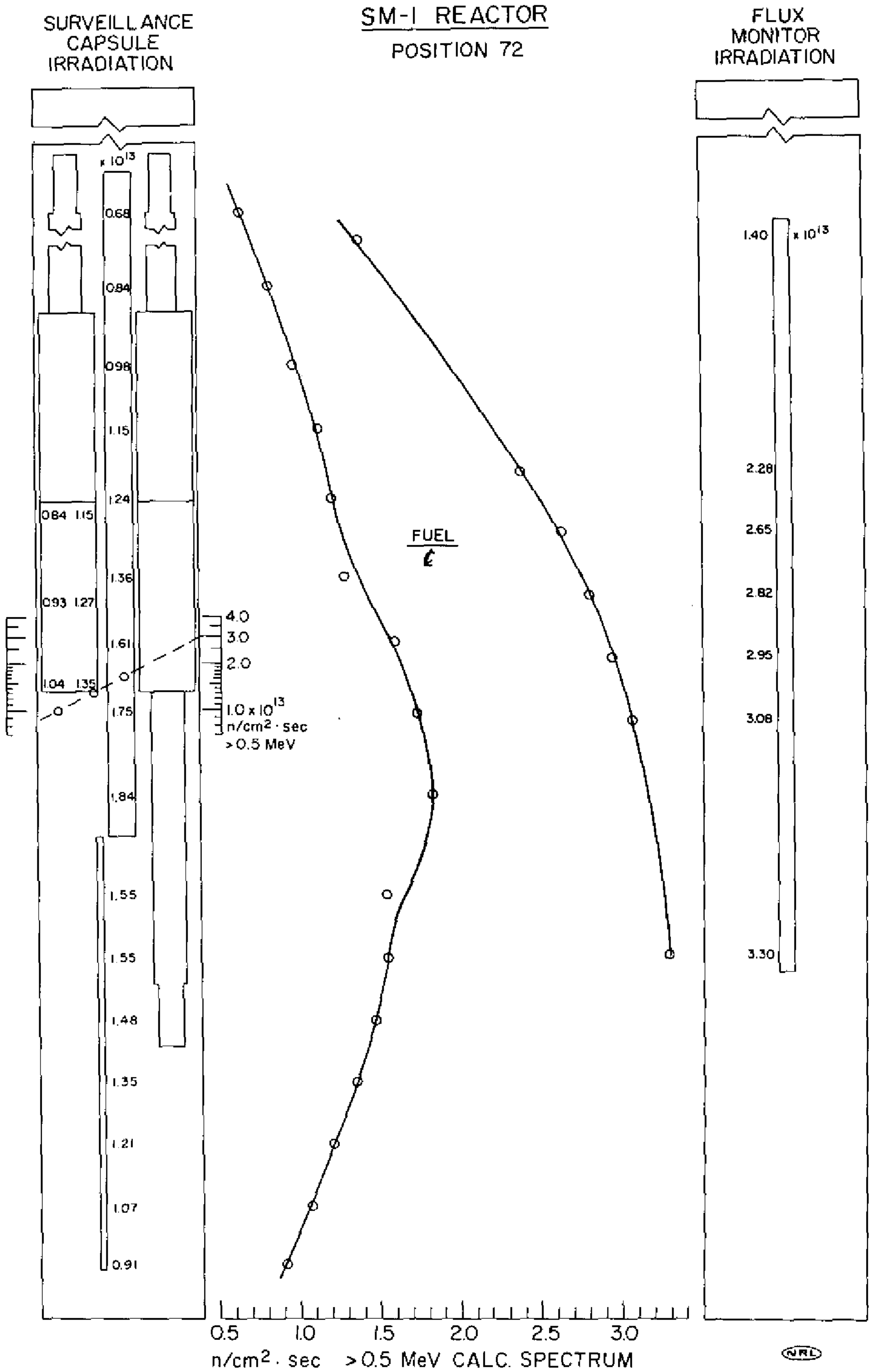

Fig. 5 - Schematic diagram of the dummy fuel element during the flux monitor irradiation and the surveillance-capsule irradiation showing the flux values measured during each exposure. Flux values measured during irradiation of the TOP control capsule are shown, and extrapolation of the flux values across the entire element is indicated on the log scale.

The problem raised by the flux discrepancy is that the high values from the flux-monitor irradiation were used to calculate the operating time period for the surveillance-capsule irradiation. In reality, the flux levels during the surveillance-capsule irradiation were about one-third those expected, so that the resulting fluence was too low. Of the two potential reasons for the discrepancy, (a) unaccounted-for low-power operations during the flux-monitor irradiation, and (b) differences in fuel core loadings, analysis reveals that only the second has validity.

The reason for the flux difference between the flux-monitor irradiation and the surveillance-capsule irradiations was originally thought to result, in part, from long-term low-power operations in the SM-1 during the overall exposure period of the flux monitor. In this 2065-hour irradiation period the reactor operated for about 575 hours at an average power of 29.3%. For the remaining 1490 hours the reactor was almost always critical but the power level was only at about 1%. Thus, there was the suggestion that this long time period at 1% power might generate enough flux to make up the difference. Further analysis revealed, however, that the reactor power level would have to be about 9% during the 1490 hours to make up this increase in flux if the true flux level were 1.8×10^{13} rather than 3.3×10^{13} n/cm^2—sec >0.5 MeV. It was quite clear that this condition did not exist; therefore, the accurate flux level in the DFE during the flux-monitor irradiation was 3.3×10^{13} n/cm^2. sec > 0.5 MeV.

The major reason for the difference in flux levels was that the fuel core was completely changed immediately after completion of the flux-monitor irradiation. Thus, subsequent irradiation of the surveillance capsules was conducted under quite different reactor operating conditions. In summary, the differences between Cores II and III, which provided for the irradiation of the flux monitor and the surveillance capsules respectively, were as follows: Core II used 35 elements and Core III used 30 elements—21.50 kg of 93%-enriched $^{235}UO_2$ versus 19.25 kg 93%-enriched $^{235}UO_2$. Nevertheless, elements in Core III each had slightly heavier fuel and boron contents than elements in Core II. In Core III five fewer elements were located in the core corners in positions equivalent to position 72, wherein the flux monitor was located; thus, the equivalent core diameter of Core III was smaller than Core II, so that the flux was concentrated more toward the center of the core. Lastly, the flux monitor was irradiated at the end of Core II life when the fuel was being driven harder than usual to get more burnup. As a result the flux tended to be higher at the edges (such as position 72), where the fuel was not as burned out as in the center. At start-up of Core III the new fuel was not being driven hard, and with the smaller diameter the flux tended to peak nearer the fuel center. Thus, the flux at the core edges was considerably lower during the surveillance-capsule irradiations. Although the composition of both cores was different and hence the neutron spectra would be somewhat different, these variations would not begin to account for the large intensity differences noted between the irradiations in the two cores. Clearly, the cause of the differences in flux levels between the flux-monitor irradiation and the surveillance-capsule irradiation was due to the differences in fuel cores and differences in mode of reactor operations.

It must be noted here that the axial gradient in flux values from the flux-monitor irradiation in Ref. 5 shows the peak to be at the geometrical core centerline. The evidence of the present research shows conclusively that the peak-flux plane is a considerable distance below the geometrical core centerline. Although the raw data from the flux-monitor irradiation did show the peak-flux plane to be quite low in the core, it was not thought to be credible. Instead, it was reasoned that the fixture containing the flux monitors had moved during the irradiation, thus accounting for the difference in axial location of the peak-flux plane. The alignment of flux values relative to the core centerline shown in Fig. 5 of this report is the most accurate information developed in this series of studies.

SUMMARY AND CONCLUSIONS

Three capsules with Charpy V-notch specimens were prepared for insertion in the SM-1A reactor to form a continuing part of the reactor pressure-vessel surveillance program. The capsules, labeled H2, I2, and J2, were irradiated at 440° F (227° C) in the SM-1 reactor along with two other capsules for use as control specimen capsules to the neutron fluence received by the SM-1A reactor vessel wall prior to its annealing. The capsules were then annealed at NRL in furnaces under the conditions that existed during the full-vessel annealing of the SM-1A. Control points were established for the experimental conditions. Three surveillance and one control capsule were reirradiated in the SM-1 to the fluence expected after termination of the third SM-1A core. Capsules H2 and J2 were then removed and shipped to the SM-1A for placement into the reactor during the Core III to Core IV changeover in the summer of 1970. Capsule J2 was retained for future use, and Charpy V-notch specimens in the control capsule were evaluated to establish the final, reirradiation condition of the surveillance capsules.

Significant differences were noted in the flux values measured from the flux-monitor irradiation exposed during Core II and the surveillance-capsule irradiations exposed during Core III. This was found to be related directly to the large differences in the fuel core composition of the two cores and also the mode of reactor operations during the two exposures. The exposure location, however, was the same core edge position in all cases. The higher flux of the flux-monitor irradiation was due to the fuel being driven harder and the flux moving out to the edges of the relatively burned-out core. Lower fluxes in the surveillance-capsule irradiations were due to more power being generated in the center of the new, smaller diameter core.

The observation of significantly different flux levels measured in the same reactor location from exposure during different operating periods has important implications. As was shown in this report, analysis and use of surveillance data obtained under these conditions can create a confused situation and lead to erroneous results. More important however, decisions made relative to the vessel condition from these conflicting data could have serious results. It is crucial therefore that neutron dosimetry be obtained from a representative operational period, details of which are well known.

The information developed and documented herein will be required for the analysis and interpretation of the surveillance capsules upon their return from irradiation in the SM-1A.

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