THE EFFECT OF NEUTRON RADIATION ON THE DEFORMATION BEHAVIOR OF SPENT FUEL STORAGE CHANNELS

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ABSTRACT

Boron containing stainless steels are utilized by the nuclear power industry for storage, transportation, and control of neutron radiating materials. The suitability of this type of stainless steel for these applications is attributed to the increased neutron absorption capability provided by the boron addition, specifically because of the B^{10} isotope. Boron may be present in the steel as natural boron which contains about 18.4 wt% B^{10} (balance B^{11} isotope), natural boron with an enrichment of the B^{10} isotope or all B^{10}. Applications include spent-fuel storage racks and channels, transportation casks, reactor control rods, burnable poison, and neutron shielding.

The effect of radiation on the deformation of nuclear spent fuel storage channels manufactured from NeutroSorb PLUS® borated stainless steel with 1.4 wt% boron continues to be studied, and this paper reports on the current status of the work.

Long and short channel samples 229 mm (9.0") and 114 mm (4.5") long with 157 mm x 157 mm (6.187" x 6.187") cross- section and a wall thickness of 2 mm (0.080"), were subjected to neutron fluence levels of $5x10^{15}$ and $1X10^{17}$ n/cm^2. The channels were mechanically deformed before and after irradiation. The tests were performed by subjecting the short samples to a compressive load that was applied perpendicular to the long axis of the channel section until the channel section was flattened. The compressive load was applied to the short samples in three different ways. Some samples were tested by positioning the welded surfaces in the vertical plane, other samples were tested by positioning the welded surfaces in the horizontal plane, while some were tested by applying the load along the diagonal of the channel (corner-to-corner). The compressive load for the long samples was applied parallel to the long axis of the channels near the corner of the sample.

Unirradiated samples were compressed until the opposing sides met. No fracture of the walls, corners, or welds occurred. After irradiation, the channels also withstood significant amounts of plastic deformation without cracking. After irradiated channels received extreme amounts of deformation, i.e. the width of the channel was reduced from 157 mm (6.187") to less than 127 mm (5"),a few samples experienced cracking of the welds. These cracks were typically less than 25 mm in length, and were arrested by running out of the weld, thereby not causing total failure of the weld. This severe amount of plastic deformation of a spent fuel channel could not take place in a spent fuel pool without inflicting severe damage on the fuel bundle itself.

The results showed that the radiation induced a small, but measurable increase in the load required to deform the channels. Work is continuing to determine why the increase in load occurred and to determine if the yield strength of the steel increased.

INTRODUCTION

Neutron irradiation of steel produces changes in the physical properties of the material. For example, such properties as strength, ductility, and fracture resistance can all be affected by irradiation with neutrons. (1) The intent of this work is to evaluate the effect of radiation on the mechanical properties of a commercial borated stainless steel alloy, NeutroSorb PLUS®, manufactured by Carpenter Technology Corporation. Baseline mechanical properties for the borated stainless steels as a function of boron level are reported by Martin. (2,3) Prototype spent fuel channels of a standard design normally produced from 304-L stainless steel were manufactured using 2.03 mm (0.080") thick x 330.2 mm (13") wide NeutroSorb PLUS® strip conforming to the requirements of ASTM Specification A887-89, Type 304 B5, Grade A. The hot band was produced by rolling 4100 kg (10,000#) Hot Isostatically Pressed powder metal slabs into 4.82 mm (0.190") thick x 762 mm (30") wide sheet coil. This coil was slit to an appropriate width and processed to final thickness via a series of cold rolling and annealing cycles. Twenty-three 3556 mm (140") long pieces of sheet were roller leveled and cut from one coil and shipped to the fabricator, U.S. Tool and Die.

The composition and mechanical properties of the finished material are as follows:

Composition - Heat No. C1836 in weight %.

C 0.034, Mn 1.93, Cr 18.22, Ni 13.03 Co 0.06 B 1.38

Mechanical Properties

Yield Strength	55 ksi

Ultimate Tensile Strength	103 ksi
Elongation in 2" (50.8 mm)	27%
Hardness	92 HRB

U.S. Tool and Die fabricated 10 channels 157 mm (6.187") square x 2 mm (0.080") wall by bending equal legged "U" sections with a 3.81 mm (0.15") radius bend. Two "U" sections were positioned on a seam welder, so that the leg ends were touching, and joined using autogenous gas tungsten arc welding. Dimples were coined periodically along the length of the "U" sections that would later be used to spot weld adjacent channel sections together. A photograph of the manufactured channels is shown in Fig. 1.

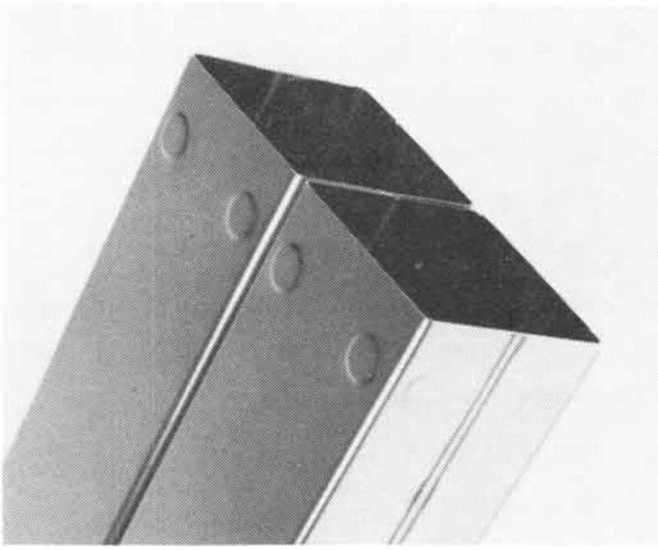


Fig. 1. Fabricated spent fuel storage channels-produced from NeutroSorb Plus strip containing 1.4 wt.% boron. Photo shows two 157 mm. by 157 mm square channels spot welded together.

Recent events associated with the embrittlement of some neutron absorbing materials have suggested a critical need to evaluate the behavior of borated materials exposed to moderate-to-high neutron fluences. Under such exposure, neutrons interact with the boron to create alpha particles (the nuclei of helium atoms). The alpha particles eventually lead to the formation of gas filled voids which, in turn, could theoretically alter the strength, ductility and fracture toughness of the steel.

NeutroSorb PLUS stainless steel products have been used to provide thermal neutron attenuation in spent-fuel shipping containers, and spent fuel pool racks, while only receiving partial credit for its structural properties. This material is a modified Type 304 Stainless Steel with boron levels from 0.25% up to 2.25%. In the cited applications, they are exposed to moderate neutron fluxes which, over the typical 20 to 40 year life, can result in neutron fluences on the order of 10^{13} n/cm^2. In non-boron containing steels, a neutron fluence of this magnitude is not sufficient to produce a measurable decrease in ductility or losses in fracture toughness. Results obtained by Soliman et. al (4) on the effects of neutrons on borated stainless steel showed no significant change in the mechanical properties of these materials due to irradiation at fluences of $1x10^{13}$ n/cm^2, $5x10^{15}$ n/cm^2, and $1x10^{17}$ n/cm^2.

One concern of the nuclear utilities, in using borated stainless steel for spent-fuel storage racks, is in-service failure, postulated to occur during seismic loading or as a result of a fuel assembly drop during fuel transfer to the spent-fuel pool. This study was undertaken in an attempt to develop data that would allow designers to understand how borated stainless steel spent fuel channels would behave under loads that would produce significant amounts of plastic deformation. An ideal rack material would, of course, withstand plastic deformation without the onset of cracks. If the effect of neutrons on these materials could also be quantified and found to be acceptable, then this information should allow designers to consider the use of borated stainless steel in more applications. In order to achieve this goal, borated stainless steel channel samples were irradiated to neutron fluence levels of $5x10^{15}$ and $1x10^{17}$ n/cm^2 and mechanically tested after irradiation. Non-irradiated channel samples were also mechanically tested to obtain a comprehensive picture of the radiation effects on these materials. The samples were tested according to the test matrix shown in Table I found under Results and Discussion.

EXPERIMENTAL TECHNIQUE

A total of 16 borated stainless steel channel samples with a 157 mm x 157 mm (6.187" x 6.187") cross-section (4 long samples each 228.6 mm (9") long and 12 short samples each 114.3 mm (4.5") long were cut from long sections of the fabricated spent fuel channel. These samples were divided into 3 batches; non-irradiated, low fluence, and high fluence. The samples were irradiated at the Pennsylvania State University Breazeale Radiation Science and Engineering Center which has a TRIGA pool-type reactor with maximum power level of 1 MWt. The low fluence samples were irradiated to $5x10^{15}$ n/cm^2, while the high fluence samples were irradiated to $1x10^{17}$ n/cm^2. A special fixture was designed to hold the samples alongside the core face during irradiation.

In order to obtain a homogeneous neutron flux over all the sample sides, each side was irradiated for equal time. To obtain an accurate fluence, gold foil dosimetry was used. Samples irradiated to a high fluence level were held in the reactor pool for 16 weeks while the low fluence irradiated samples were held for 8 weeks in the reactor pool to allow for the decay of the short-lived nuclear activation products.

The long samples were mechanically tested by placing the channels between two flat plates. Some of the short samples were mechanically tested in compression by placing the channel between two flat plates and loading the specimen on two parallel sides of the sample in a "side-to-side test" as shown in Figs. 2a and 2b.

Other short channels were tested in compression by placing the channels between special fixtures designed to load the channel along two opposing corners in a "corner-to-corner test" shown in Fig. 2c. In order to evaluate the weld quality, dye penetrant tests were carried out to detect defects on each sample prior to irradiation. After the dye penetrant test, the samples were tested according to the test matrix given in Table I. Video and Still cameras were used to record deformation of the samples as the mechanical testing progressed.

RESULTS AND DISCUSSION

Spent fuel channel samples were mechanically tested by flattening in several different orientations to measure the peak load required for deformation, and the amount of plastic deformation which could take place before fracture of the borated stainless steel occurred.

Figure 3 shows a sequence of photos that demonstrate the large deformations that took place in the side-to-side flattening test. The samples were actually flattened until the opposing sides met. Once the applied load was removed, some

TABLE I
Peak Load Required to Flatten Channel Section

SAMPLE ORIENTATION	SAMPLE SURFACE	WELD POSITION	NEUTRON FLUENCE	PEAK LOAD kg(lbs)
side-to-side	smooth	side	unirradiated	1193(2625)
side-to-side	smooth	top	unirradiated	1181(2600)
side-to-side	dimpled	side	unirradiated	1204(2650)
side-to-side	dimpled	side	$5x10^{15}$ N/cm^2	1250(2750)
side-to-side	dimpled	side	$1x10^{17}$ N/cm^2	1318(2900)
corner-to-corner	smooth	N/A	unirradiated	204 (450)
corner-to-corner	dimpled	N/A	unirradiated	204 (450)
corner-to-corner	smooth	N/A	$5x10^{15}$ N/cm^2	204 (450)
corner-to-corner	dimpled	N/A	$1x10^{17}$ N/cm^2	215 (475)
axial on corner	dimpled	N/A	unirradiated	5912 (13007)
axial on corner	dimpled	N/A	$5x10^{15}$ N/cm^2	6424 (14132)
axial on corner	dimpled	N/A	$1x10^{17}$ N/cm^2	7015 (15433)

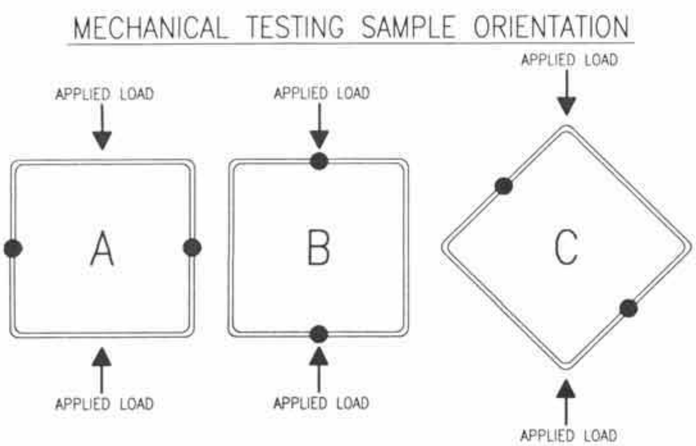


Fig. 2. Mechanical testing sample orientation showing three test orientations: a) side-to-side test with welds on the sides (weld is indicated by black dots); b) side-to-side test with welds on the top and bottom; c) corner-to-corner test. The axial test orientation with the load applied along the longitudinal axis of the channel is not shown.

springback occurred. The flattening test sequence for a corner-to-corner test is shown in Fig. 4. Note the special grooved fixtures that were used to prevent slippage of the sample during test. Again the channel section was flattened until the opposing sides met. Examples of the load-displacement curves for both unirradiated and irradiated side-to-side tests are given in Figs. 5 and 6 respectively. Results obtained from the load-displacement curves for all samples tested are presented in Table I.

The peak loads required to deform the three unirradiated side-to-side tests were nearly the same, varying only from 1181 kg (2600 lbs) to 1204 kg (2650 lbs). However after irradiation to $5x10^{15}$ n/cm^2, the peak load increased to 1250 kg (2750 lbs). After irradiation to a fluence of $1x10^{17}$ n/cm^2, the peak load increased further to 1318 kg (2900 lbs), an indication that some increase in the yield strength of the borated stainless steel is beginning to take place as a result of α generation due to neutron collisions with the boron atoms. Further work may be needed to confirm the theory that the yield strength is increased by α generation within the borated stainless steel. Visual observations and analysis of the load vs displacement curves indicated that none of the unirradiated side-to-side samples cracked either in the base metal or welds. The irradiated samples did exhibit a few small cracks in the welds which did not cause complete weld failure, but propagated into the base metal and arrested. These cracks may have occurred because of some strengthening of the base metal which resulted in higher stresses on the welds, or small weld defects could have been present which initiated small cracks during the flattening tests. In either case, a borated stainless steel spent fuel rack of this design would undergo significant amounts of plastic deformation before any failure of the welded channel section would occur. In fact, this severe amount of plastic deformation of a spent fuel channel could not take place in a spent fuel pool without inflicting severe damage on the fuel bundle itself.

In the corner-to-corner tests, observed results were very similar to those of the side-to-side tests. However, since the peak loads were much lower, 204 kg (450 lbs), any increase in peak load due to the neutron irradiation would be very difficult to measure due to the limited sensitivity of the load cell, even though the loads do appear to increase slightly as shown in Table I. Unlike the side-to-side test, no failure of the welds was observed in the corner-to-corner flattening tests. Also the data indicates that samples with dimples provided the same response as samples without dimples. Therefore the dimples are not expected to pose any problems in such a spent fuel rack design.

Axial testing of the 228 mm (9") long samples was attempted to evaluate the failure of the channel sections in a buckling mode. However, as demonstrated by this research, the welded channel sections possessed high strength, ductility, and resistance to brittle fracture. As a result, the axial loading test (when the load was applied uniformly to the full end section of the channel) did not produce plastic deformation, or any failure, of the unirradiated 228 mm (9") channel at 10,000 kg (22,000 lb), the peak capacity of the hot cell Instron machine. Therefore, the loading configuration was changed to ensure that some plastic deformation or fracture of the channel could be observed. The loading fixture was modified

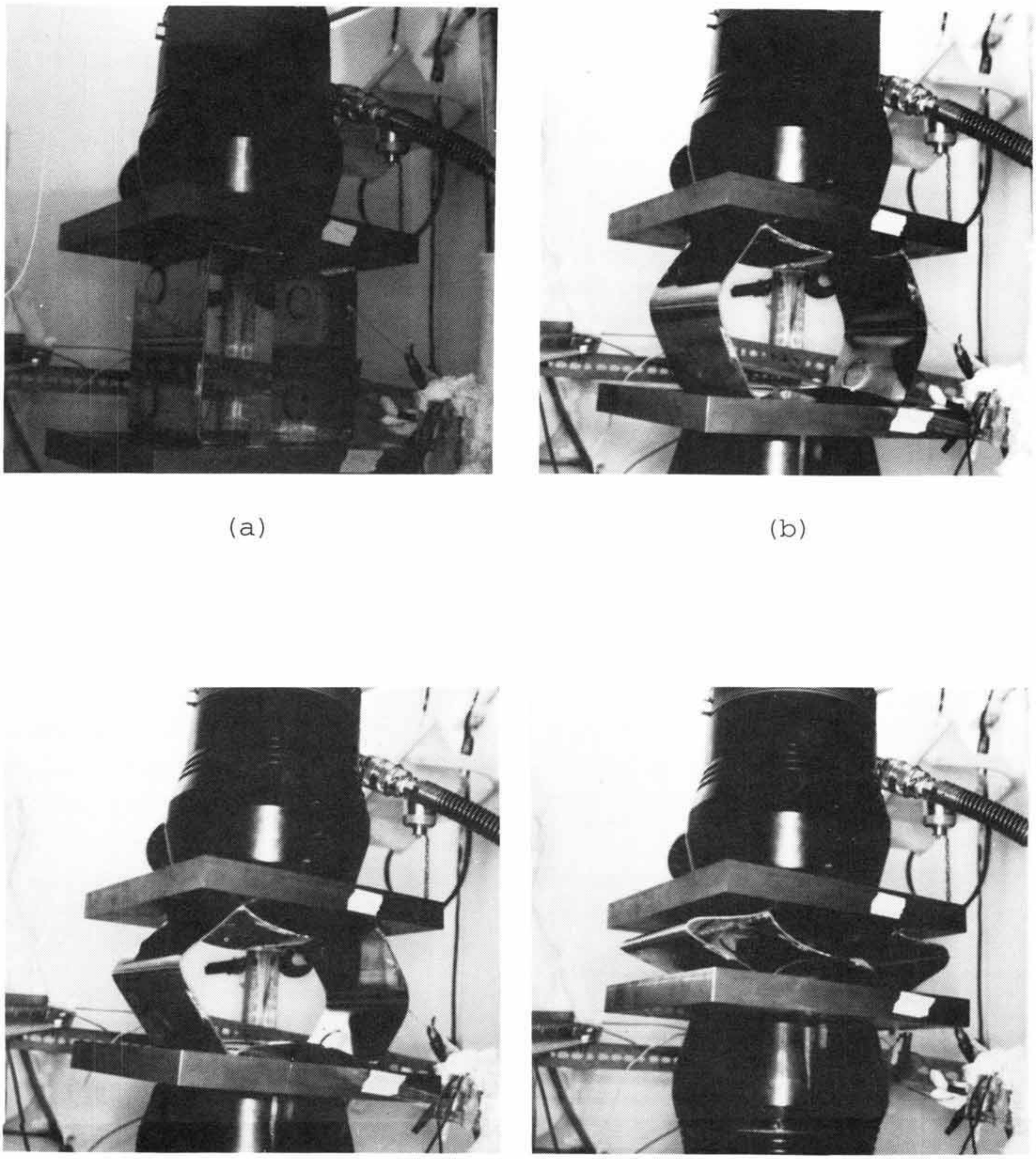
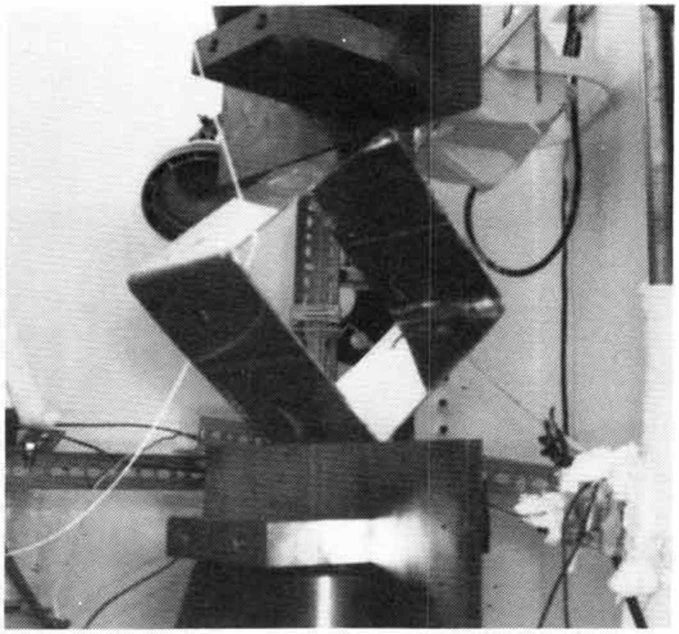
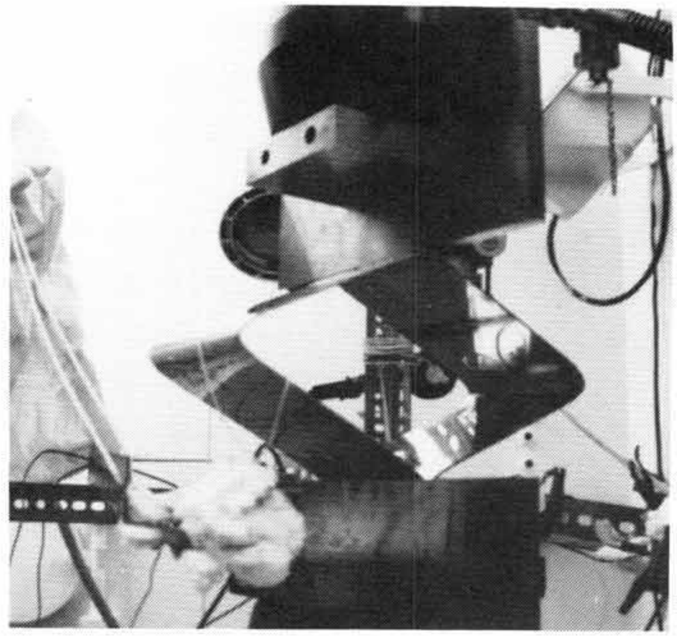


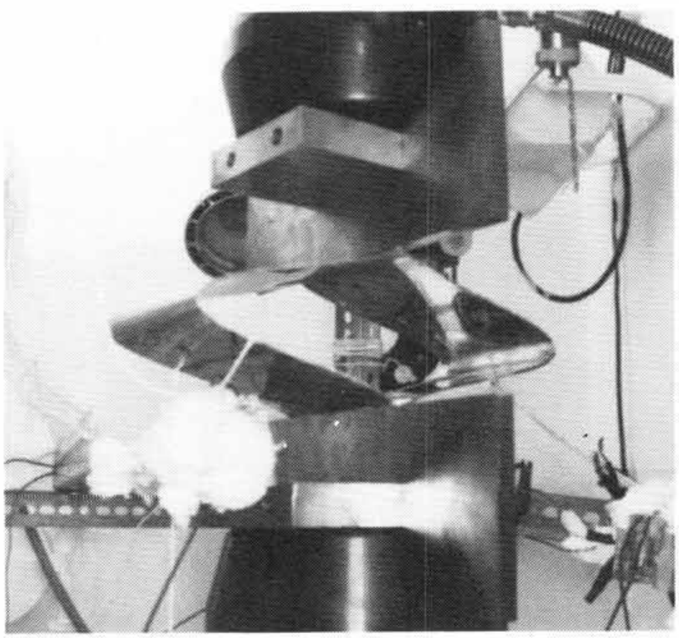
Fig. 3. Flattening test sequence (a-b-c-d) showing deformation of the spent fuel channel at several points during flat plate loading with the welds on the side of the channel.



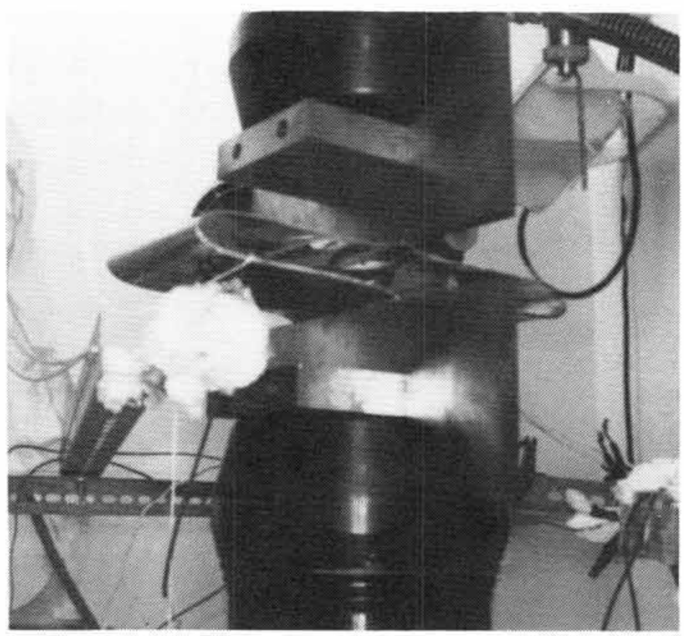
(a)



(b)



(c)



(d)

Fig. 4. Flattening test sequence (a-b-c-d) showing deformation of the spent fuel channel at several points during corner-to-corner loading.

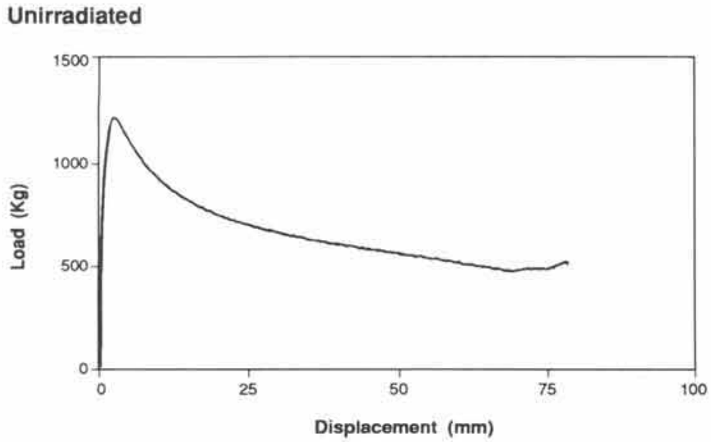


Fig. 5. Load versus displacement curve for a side-to-side flattening test of an unirradiated channel section with dimples and welds on the side.

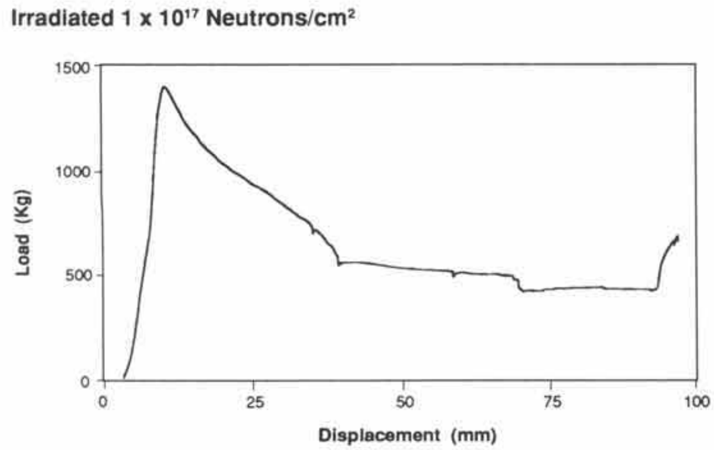


Fig. 6. Load versus displacement curve for a side-to-side flattening test of an irradiated (1×10^{17} neutrons/cm^2) channel section with dimples and welds on the side.

to apply the load only along one corner of the axial channel section as shown in Fig. 7. The corner of the unirradiated sample yielded after a load of 5912 kg (13,007 lb) was applied and several cracks in the base metal were observed. The fracture process behaved in a ductile tearing mode and no cracks were observed near the weld region, nor did any of the cracks propagate far enough to cause complete failure of the channel section. This type of loading simulates the loads which might occur in the event that a dropped fuel element would fall onto the top end of the borated stainless steel channel section. Of course, the test loading used in this research was static, not an impact load.

The irradiated 228 mm (9") long channel samples tested in the axial orientation again exhibited an increase in peak load to 6424 kg (14,132 lbs) at a neutron fluence of 5×10^{15} n/cm^2 and 7015 kg (15,433 lbs) at a neutron fluence of 1×10^{17} n/cm^2. Both the low and high fluence irradiated samples showed significant plastic deformation, accompanied by ductile tearing of the channel walls. When enough deformation occurred to cause weld failure, the welds also exhibited very *slow ductile tearing.*

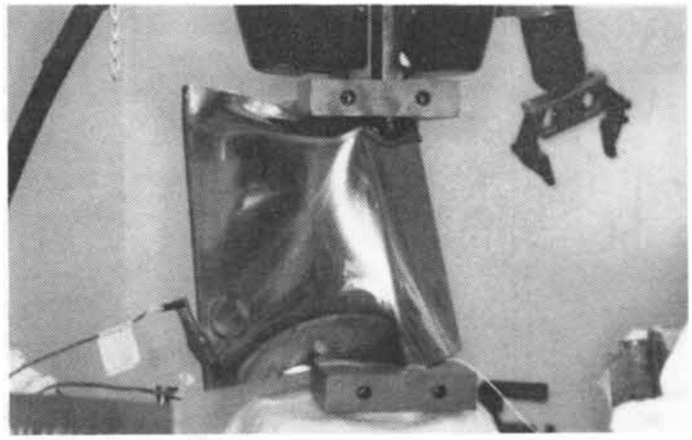


Fig. 7. Flattening test showing severe deformation of the spent fuel channel during axial loading. Note the load is applied only to the corners of the section along the longitudinal axis.

CONCLUSIONS

From the results obtained, there seems to be very little influence of neutron irradiation on the mechanical properties of the NeutroSorb Plus stainless steel fuel channels, except for a possible slight increase in the material's yield strength. This observation is consistent with earlier findings using simple tensile, Charpy and hardness tests.

ACKNOWLEDGEMENTS

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