RESULTS OF IRRADIATION
OF NICKEL-REFLECTOR TEST SUBASSEMBLIES

by

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ABSTRACT

Because of interest in the use of nickel in EBR-II as a reflector material, two subassemblies containing Nickel-200 were irradiated under conditions typical of those for a reflector subassembly. The primary purpose of the irradiation tests was to determine the corrosion rates at sodium flow rates of approximately 0.7 fps and temperatures between 700 and 920°F. Difficulties were encountered during the in-reactor handling of one of the subassemblies, which had been irradiated for one year. The results of the examination showed that Nickel-200 was compatible with the EBR-II primary-system sodium, but that it had swollen at a higher rate than Type 304 stainless steel in the fast neutron flux. The higher swelling rate for the nickel components nearest the center of the reactor core caused the solid Nickel-200 spindle (which held the Nickel-200 test specimens) to bow approximately 0.18 in. at its midlength. The bow of the Nickel-200 spindle in turn caused the subassembly to bow, resulting in the handling difficulties that were encountered.

I. INTRODUCTION

Several years ago, there was great interest in the use of nickel as a reflector material in EBR-II. Preliminary information had indicated that its use would increase the power density of the subassemblies in the outer rows of the reactor core and thereby increase the effectiveness of EBR-II as an irradiation test facility.

A search of the literature revealed little applicable information concerning the corrosion of nickel in liquid sodium. It was known that there was no direct chemical reaction between nickel and sodium when the oxygen level of the sodium was low, as was the case in EBR-II, and also that the corrosion loss was governed by mass transport of nickel from high-temperature regions to lower-temperature regions. Unfortunately, sodium corrosion by mass transport was not well-characterized, so rates of metal loss could not be calculated from fundamental properties of the system.

Thorley and Tyzack¹ had reported a corrosion rate of 3.9×10^{-3} in./year for nickel and a rate of 6.1×10^{-3} in./year for Inconel 600, a high-nickel alloy, in the same test. Greenberg² had exposed Inconel 600 to EBR-II outlet sodium for 119 full-power days and found no measurable weight change. Thus, it appeared likely that unclad nickel would have a corrosion rate suitably low for use in EBR-II.

A corrosion experiment was introduced into EBR-II to provide the necessary reassurance before a full-scale reflector test was undertaken. The location in the reactor and the hydraulic conditions in the test subassembly were chosen to be as nearly as possible the same as those in the proposed reflector. Ring type samples provided a sensitive measure of corrosion rate.

The experiment was divided into a short-term test (2910 MWd) and a long-term test (12,960 MWd). The subassembly containing the short-term test was removed from the reactor without difficulty, and no problems were encountered during subsequent handling of the subassembly. The specimens from the subassembly were weighed, and the short-term corrosion rate of the nickel was determined. While the subassembly containing the long-term test was being removed from the reactor, however, difficulty was encountered with centering the core holddown on the subassembly position. After several attempts, the holddown was properly positioned and the subassembly was removed from the core with less than 500 lb of force. (A limit switch is set to trip at 500 lb.) While the subassembly was being inserted into the reactor storage basket, the presence of some abnormal condition became apparent. The subassembly could be inserted into the basket with a moderate assisting force, but could not be withdrawn with normal forces. A manually applied force of about 300 lb was required to withdraw it. The normal upper limit of force used to withdraw subassemblies from the storage basket is 200 lb.

Because of the postirradiation handling difficulties encountered with this subassembly, the subassembly and its components were subjected to several examinations in addition to those required for determining the corrosion rate of the nickel specimens. These additional examinations and their results are described in Sec. IV of this report.

II. DESCRIPTION OF SUBASSEMBLIES

Both subassemblies used in the tests were identical Type P-1 experimental-irradiation subassemblies. Each contained a right-cylindrical spindle of solid Nickel-200 approximately 60 in. long and 2.047 ± 0.005 in. in diameter that was fastened (pinned) to the subassembly's inner-blanket-type lower adapter. Thirty Nickel-200 ring specimens having outside diameters of 2.161 ± 0.005 in. were placed on the spindle along its length. Five of the rings were plated with a hard chrome plate (Specification QQ-C-320 Type 2, Class 2) for comparison. The rings were held in place by a cap washer and retaining stud at the top end of the spindle. A standard subassembly hex can was lowered over the rings and welded to the lower adapter to complete the subassembly. Each subassembly contained an orifice that limited the sodium flow through the subassembly to 1.2 gpm during irradiation. Figure 1 shows the bare spindle and the spindle with the rings in place. The subassembly for the long-term test was designated A-837S; that for the short-term test, A-838S.

The postirradiation operations and examinations performed on both subassemblies were: (1) removal of residual sodium from the subassembly; (2) removal of the hex can from the rings and spindle; (3) removal of the rings from the spindle; and (4) weighing of the rings. Additional examinations performed on the subassembly containing the long-term test in an effort to determine the cause of the handling difficulties were: (1) measurement of subassembly straightness and flat-to-flat dimensions; (2) measurement of thimble straightness; (3) measurement of the diameter of the nickel rings; (4) visual examination of the rings, (5) determination of density of samples cut from the rings, and (6) radiochemical determination of the integrated neutron exposures of samples cut from one ring (No. 10) located at the reactor midplane.

Fig. 1. Photos Taken during Assembling of Nickel-test Subassembly
Show Bare Nickel Spindle (left) and Spindle with Nickel-200
Rings in Place (right)

III. POSTIRRADIATION HANDLING, EXAMINATION, AND RESULTS

A. Handling and Examination

The irradiated subassemblies were transferred from the reactor to the FEF (Fuels and Examination Facility) using the standard procedures for experimental-irradiation subassemblies. However, to prevent jamming of the subassembly in the IBC (interbuilding coffin), an oversize insert tube was used in the IBC for transferring the subassembly containing the long-term test. The standard sodium-removal procedure for experimental-irradiation subassemblies was used to remove the residual sodium from both test subassemblies. Appendix A briefly describes the procedures for transferring the subassembly and removing the sodium. The small orifices in the subassemblies created a high pressure drop through the subassembly, so the actual flow rates of the gas and water through the subassemblies during sodium removal were lower than normal. To save time, each subassembly was rinsed with 50 gal instead of the usual 125 gal of water.

The standard procedure for removing the hex can from an irradiated subassembly is to make a circumferential cut in the can just above the spot welds that attach the can to its lower adapter. Then, the hex can is withdrawn upward to expose the contents of the subassembly. However, because of the close tolerance between the nickel rings and the hex can, the hex cans were slit axially at one corner for the entire length of the can to prevent scratching of the nickel rings as the can was removed. Figure 2 shows the condition of the long-term test after the hex can was removed.

The rings used in the short-term test were removed from the nickel spindle by removing the cap washer from the top of the spindle and sliding the rings up over the top end of the spindle. In a few cases, the rings were bonded to the spindle by a layer of sodium or sodium-water reaction product between the ring and the spindle. These rings were easily loosened, however, by squirting a small amount of water on the surface of the spindle just above the ring. The rings corresponding to the region above the core centerline in the long-term test were also stuck and were removed in this manner. However, one ring, No. 49 (located near the region corresponding to the bottom of the core), could not be forced past the region corresponding to the midplane of the core, and all rings below this ring had to be removed

SUBASSEMBLY A-837S
WITH THE HEX CAN
REMOVED AFTER
IRRADIATION

Fig. 2. Long-term Nickel Test during Disassembly after Irradiation.
(Composite of two exposures)

by cutting the spindle near its bottom end. All those lower rings were then removed by sliding them over the bottom (cut) end of the spindle. The rings were cleaned with water and clean cloths in the air cell.

The ring specimens from the short-term test were transferred to the Junior Caves, cleaned with a detergent solution in an ultrasonic cleaner, rinsed in deionized water, and dried in air. The specimens were weighed using a Torbal analytical balance, which has an accuracy of ± 0.003 g. Twelve of the rings from the long-term test were cleaned and weighed by the same procedures used with the rings from the short-term test. Two typical specimens from the long-term test were photographed at a magnification of 2 diameters.

B. Results and Discussion

The pre- and postirradiation weights of the rings from the short-term test are given in Table I, and those of the rings from the long-term test are given in Table II. (Measurement of 12 irradiated rings in the latter test were considered sufficient to obtain the desired data.) The rings above the top of the core region were all irradiated at nearly the same temperature (approximately 920°F) during their residence in the reactor. Figure 3 shows the estimated axial temperature profile during the long-term irradiation; the profile was essentially the same during the short-term test. This profile is based on the temperatures of the adjacent subassemblies; the nickel tests acted as a heat sink during reactor operation because they had low heat generation and low coolant flow. The rings from the top of the subassemblies generally exhibited the greatest weight loss, which indicates that corrosion rate is a function of temperature. However, as can be seen in Tables I and II, there was considerable scatter in the data. The results do show that the corrosion rate was very low. The maximum rate of weight loss of any of the specimens in the long-term test was $0.094 \text{ mg/cm}^2\text{-year}$, which corresponds to a uniform corrosion rate of $1.04 \times 10^{-4} \text{ cm/year}$. The conditions under which this corrosion rate occurred were a temperature of approximately 920°F and a sodium velocity of approximately 0.7 fps. The average weight loss per unit area of the rings irradiated at a temperature of 920°F was approximately 0.072 mg/cm^2 . The average weight loss per unit area of the rings located in the core region was approximately 0.045 mg/cm^2 .

TABLE I. Weight Change of Nickel Rings from
Short-term Test (Subassembly A-838S)

Ring No.	Preirradiation Weight, g	Postirradiation Weight, g	Weight Loss, mg	Weight Loss per Unit Area, mg/cm ²
61 (top)	91.8679	91.8625	5.4	0.061
57	94.5974	94.5917	5.7	0.065
63	91.7012	91.6969	4.3	0.049
21	93.7200	93.7145	5.5	0.062
7 ^a	96.6047	96.6030	1.7	0.019
26	93.1880	93.1841	3.9	0.044
47	92.2191	92.2152	3.9	0.044
43	89.2327	89.2275	5.2	0.059
31	91.7384	91.7339	4.5	0.051
2 ^a	96.6652	96.6646	0.6	0.007
41 ^b	-	93.9656	-	-
35	91.0156	91.0132	2.4	0.027
34 _b	94.9159	94.9115	4.4	0.050
59 ^b	-	95.6641	-	-
40 ^b	-	94.4282	-	-
8 ^a	93.6465	93.6444	2.1	0.024
42	94.6739	94.6713	2.6	0.030
62	92.1540	92.1528	1.2	0.014
36	93.3691	93.3668	2.3	0.026
60	95.2340	95.2308	3.2	0.036
66	91.9137	91.9112	2.5	0.028
4 ^a	95.5713	95.5666	4.7	0.053
46	94.9663	94.9632	3.1	0.035
55	94.4992	94.4933	5.9	0.067
64	91.8081	91.8071	1.0	0.011
25	95.3320	95.3284	3.6	0.041
20	94.0688	94.0665	2.3	0.026
9 ^a	95.1227	95.1209	1.8	0.020
45	92.5307	92.5289	1.8	0.021
67 ^b (bottom)	-	91.9405	-	-

^aChrome-plated.

^bThese were not weighed after irradiation, because they were damaged in handling.

TABLE II. Weight Change of Nickel Rings from Long-term Test (Subassembly A-837S)

Ring No.	Preirradiation Weight, g	Postirradiation Weight, g	Weight Change, mg	Corrected Weight Change, ^a mg	Weight Loss per Unit Area, mg/cm ²
23 (top)	94.5191	94.5129	-6.2	-8.2	0.094
48	95.0253	95.0197	-5.6	-7.6	0.087
68	93.6778	93.6748	-3.0	-5.0	0.057
65	94.1577	94.1528	-4.9	-6.9	0.079
3 ^b	94.4870	94.4880	+1.0	-1.0	0.011
56	93.2827	93.2809	-1.8	-3.8	0.043
69	93.5387	93.5361	-2.6	-4.6	0.052
28	94.3158	94.3133	-2.5	-4.5	0.051
37	95.7573	95.7554	-1.9	-3.9	0.044
10 ^b	93.8896	93.8913	-1.7	-3.7	0.003
27	96.5258	96.5249	-0.9	-2.9	0.033
44 ^c	90.1838	90.1844	+0.6	-1.4	--
Blank ^d	92.9206	92.9225	+1.9	-0.1	--
1 ^d	92.1684	92.1705	+2.1	+0.1	--

^aThere appeared to be a bias of -0.002 g in the control rings, so this -0.002 g was added to the observed weight change to obtain the corrected weight change.

^bChrome-plated.

^cThis ring appeared to be covered with a residue that was not removed during ultrasonic cleaning.

^dThese two rings were stored out of the reactor for use as control samples.

Fig. 3. Axial Temperature Profile for Long-term Test

In this region, the temperature varied from 790 to 910°F. The two chrome-plated rings that were weighed lost only 0.0011 mg/cm² (irradiation temperature of 920°F) and 0.003 mg/cm² (irradiation temperature of 804°F).

The surface condition of the rings was not changed significantly by the EBR-II environment (see Fig. 4). The good condition of the surface of the rings indicates the high corrosion resistance of Nickel-200 under the low flows and moderate temperatures of this test.

IV. DESCRIPTION AND RESULTS OF ADDITIONAL EXAMINATIONS PERFORMED ON LONG-TERM TEST TO DETERMINE CAUSE OF HANDLING PROBLEMS

A. Measurement of Subassembly Straightness

The straightness of the subassembly (A-837S) containing the long-term test was checked in the FEF with a device that consists of a vertical beam with stops at the top and the bottom and six dial indicators spaced about 12 in. apart along the length of the subassembly. The measurements were made by holding the subassembly against the stops and reading the dial indicators. This procedure was repeated for all six flats. The maximum variation in the dial-indicator readings for the six flats at a given axial location is a value (TIR, for total indicator runout) that is twice the deviation of the subassembly at that location from a straight line drawn between the top and bottom stops on the beam. The results of the TIR measurements were:

	<u>Distance from Top of Hex Can, in.</u>				
	<u>6</u>	<u>20</u>	<u>32</u>	<u>46</u>	<u>62</u>
TIR, in.	0.058	0.164	0.229	0.176	0.049

These TIR measurements indicated that at its midlength the subassembly was bowed toward the axial center of the reactor.

B. Measurement of Spindle Straightness

Qualitative determinations of the straightness of the spindle were obtained by four methods: (1) measuring TIR in the subassembly straightness

Cr-PLATED: IRRADIATED

UNPLATED: IRRADIATED

Cr-PLATED: UNIRRADIATED

UNPLATED: UNIRRADIATED

Fig. 4. Surfaces of Chrome-plated and Bare Nickel-200 Rings,
Comparing Typical Surface Condition of Irradiated
(long-term) Rings and Unirradiated Rings

tester; (2) rotating the spindle in the VAD (vertical assembler-dismantler) and photographing it at 90° intervals; (3) photographing the spindle against a gridded background; and (4) laying the spindle on a relatively flat surface and observing the gap between the spindle and the reference surface.

The results of the TIR measurements were:

	<u>Distance from Top of Spindle, in.</u>				
	<u>3</u>	<u>17</u>	<u>29</u>	<u>43</u>	<u>50</u>
TIR, in.	-0.244	0.211	0.300	0.132	-0.102

The measurements obtained for the spindle are less accurate than those obtained for the hex can of the subassembly, because aligning the dial indicators on the round surfaces of the cylinder was more difficult than aligning them on the flats of the hex can. The measurements indicated, however, that the spindle at its midlength was also bowed toward the center of the reactor.

The photos in Fig. 5 show the distance of travel of the top of the spindle as it was rotated in the VAD. The total deviation at the top of the spindle was about 3/4 in. during this rotation, which indicates that the top of the spindle deviates from straightness by about 3/8 in. These measurements also indicate that the spindle was bowed about 3/16 in. at its midlength. Figure 6 shows photographs of the spindle against the gridded background. The deviation from straightness is slightly greater than 1/8 in. at the midlength of the spindle. A maximum gap of between 1/8 and 1/4 in. was observed at the midlength of the spindle by rolling it across a relatively flat table.

C. Diameter Measurements on the Nickel-200 Rings

Diameter measurements were made on the rings with a remotely operable Bausch and Lomb DR-25 optical gauge. Measurements were made at the top, midlength, and bottom of each ring at two azimuthal orientations (0° and 90°). No diameter measurements were made on the rings before their irradiation, except to ensure their conformance to fabrication specifications. Table III gives the results of the measurements. These results indicate that the rings positioned near the core region during irradiation did,

M-5783

0° ORIENTATION

M-5782

ROTATED 90° CLOCKWISE

M-5781

ROTATED 180° CLOCKWISE

M-5784

ROTATED 270° CLOCKWISE

Fig. 5. Photos Showing Top of Subassembly A-837S (after Hex Can Had Been Removed) As It Was Rotated in the VAD. Note position of top of subassembly with respect to tape to right of subassembly in each photo

Fig. 6. Photographs of Nickel-200 Spindle from Subassembly A-837S in Front of Gridded Background. Spindle appears to be fairly straight in photo on left, but is bowed approximately 3/16 in. in photo on right

indeed, swell, but no quantitative information could be inferred from these measurements.

TABLE III. Average Diameters of Nickel-200 Rings
from Subassembly A-837S

Ring No.	Postirradiation Average OD, in.	Minimum Diameter Change, ^a in.	Maximum Diameter Change, ^b in.
23 (top)	2.167	+0.001	+0.011
45	2.167	+0.001	+0.011
68	2.165	-0.001	+0.009
65	2.166	0.000	+0.010
3 ^c	2.167	+0.001	+0.011
56	2.165	-0.001	+0.009
32	2.165	-0.001	+0.009
54	2.165	-0.001	+0.009
53	2.167	+0.001	+0.011
6 ^c	2.169	+0.003	+0.013
38	2.165	-0.001	+0.009
50	2.170	+0.004	+0.014
69	2.167	+0.001	+0.011
28	2.171	+0.005	+0.015
37	2.172	+0.006	+0.016
10 ^c	2.171	+0.005	+0.015
27	2.174	+0.008	+0.018
44	2.167	+0.001	+0.011
24	2.169	+0.003	+0.013
39	2.168	+0.002	+0.012
11 ^c	2.171	+0.005	+0.015
58	2.166	0.000	+0.010
30	2.168	+0.002	+0.012
33	2.167	+0.001	+0.011
22	2.168	+0.002	+0.012
29	2.163	-0.003	+0.007
5 ^c	2.169	+0.003	+0.013
51 (bottom)	2.166	0.000	+0.010

^aDiameter change if the maximum specified OD (2.166 in.) is used as the preirradiation diameter.

^bDiameter change if the minimum specified OD (2.156 in.) is used as the preirradiation diameter.

^cChrome-plated.

D. Density Determinations on Samples from the Nickel-200 Rings

The six rings positioned on the spindle in the region corresponding to the core region of the subassembly were cut into six equal sections, as shown in Fig. 7, for density determinations. Using six sections made it possible to obtain the density changes that occurred across the subassembly as well as axially along its length. The density of each of the sections was determined by the immersion (Archimedes) technique. The immersion medium was carbon tetrachloride held at a constant temperature of 25.2°C. Precision of the density determinations on these samples was $\pm 0.005 \text{ g/cm}^3$. Measurements had been made previously on several of the rings before they were irradiated. These measurements indicated that the chrome-plated rings had an average density of 8.847 g/cm^3 and the nonplated rings an average density of 8.881 g/cm^3 .

Table IV gives the results of the density measurements for each section of each ring.

TABLE IV. Densities (g/cm^3) of Samples of Nickel-200 Rings
from Core Region of Subassembly A-837S

Ring No.	Sample No.					
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>
69	8.856	8.854	8.870	8.872	8.867	8.847
28	8.812	8.838	8.863	8.862	8.846	8.815
37	8.784	8.813	8.841	8.849	8.836	8.799
10 ^a	8.742	8.779	8.805	8.800	8.774	8.742
27	8.769	8.808	8.842	8.847	8.814	8.772
44	8.772	8.791	8.841	8.856	8.846	8.804

^aChrome-plated.

Fig. 7. Sampling Diagram for Density Specimens from a Typical Nickel-200 Ring from Subassembly A-837S

These values were used for the plots of Figs. 8, 9, and 10. The plots were made to ascertain the minimum and maximum densities of each ring. Plotting of the density values makes it possible to obtain better values for maximum and minimum density (and hence, better values for swelling) than using the measured values themselves. The samples used in the density determinations were cut using the number on the rings as an index point. However, since no attempt was made during the loading of the subassembly to align these numbers, the azimuthal orientation of the rings on the spindle during irradiation was not necessarily the same for all the rings.

Table V lists the maximum and minimum densities and the maximum and minimum volume and length changes for the rings. Volume changes are assumed equal to the density changes and to be isotropic so that the length changes are equal to 1/3 the volume changes. Figure 11 plots the maximum and minimum volume changes.

TABLE V. Maximum and Minimum Measured Densities and Maximum and Minimum Volume and Length Changes of Nickel-200 Rings from Core Region of Subassembly A-837S

Ring No.	Max Density, g/cm ³	Min Density, g/cm ³	Preirrad. Density, g/cm ³	Min $\Delta V/V$, %	Max $\Delta V/V$, %	Min $\Delta L/L$, %	Max $\Delta L/L$, %
69	8.872	8.846	8.881	0.101	0.394	0.033	0.131
28	8.867	8.807	8.881	0.158	0.833	0.053	0.278
37	8.849	8.782	8.881	0.360	1.115	0.120	0.372
10 ^a	8.808	8.733	8.847	0.441	1.289	0.147	0.440
27	8.851	8.762	8.881	0.338	1.340	0.113	0.447
44	8.856	8.772	8.881	0.282	1.227	0.094	0.409

^aChrome-plated.

Fig. 8. Plots of Densities of Samples of Nickel-200
Rings 69 and 28 from Subassembly A-837S

Fig. 9. Plots of Densities of Samples of Nickel-200
Rings 37 and 10 from Subassembly A-837S

Fig. 10. Plots of Densities of Samples of Nickel-200
Rings 27 and 44 from Subassembly A-837S

Fig. 11. Axial Swelling Profile for Rings at Sides of Subassembly A-837S Nearest to and Farthest from Center of Reactor Core

E. Fluence Determinations

Sections from Samples 1 and 4 from ring 10 (chrome-plated) were analyzed for ^{58}Co activity, and the total neutron fluence was calculated. (Analyses and calculations by E. R. Ebersole of ANL-ID.) Table VI gives the results of these analyses and calculations.

TABLE VI. ^{58}Co Activity and Flux and Fluence Values for Two Samples of Ring 10 from Subassembly A-837S

Sample No.	^{58}Co Satd. Activity, dis/sec-g	Spectral-averaged Cross-section, mb	Flux, n/cm ² -sec	Fluence, n/cm ²
1	11.2×10^{10}	16	9.9×10^{14}	2.0×10^{22}
4	4.53×10^{10}	11	4.0×10^{14}	8.1×10^{21}

F. Discussion of Data

The volume changes of the specimens, based on maximum and minimum density changes of the rings, are plotted versus fluence ($E > 0.1$ MeV) in Fig. 12. The fluence values in the figure are based on the maximum fluences determined by Ebersole (Table VI) and are adjusted to the axial flux profile given in the Guide for Irradiation Experiments in EBR-II.³ The data indicate that the rate of swelling of Nickel-200 in this subassembly was temperature dependent. The temperature dependence is shown by the lines drawn through the data representing the samples with "high" and "low" fluence at 750 (ring 44) and 910°F (ring 69). If these lines are considered to represent the swelling rates of these samples, the Nickel-200 swelled twice as fast at 750°F as at 910°F. Because of the uncertainties in the actual operating temperature of the individual samples used for the density measurements, the temperature dependence as obtained from these data is only qualitative. The uncertainties in the operating temperatures are largely due to the uncertainty of the gamma-heating for structural materials in EBR-II.

The data shown in Fig. 11 illustrate the difference in swelling that occurred on the side nearest the center of the core compared to the side away from the core. This difference in the amount of swelling would cause

Fig. 12. Swelling of Nickel-200 in the Long-term Test

the nickel spindle to bow, because the side nearer the core center actually became longer than the side away from the core during irradiation. Appendix B shows how this bowing was calculated. This simple calculation shows that the spindle should have bowed (deviated from the centerline at the mid-length of the spindle) about 0.18 in. This value agrees quite well with qualitative bow measurements made on the spindle. A bow in the spindle of 0.18 in. would also account for a bow in the subassembly of approximately 0.13 in., because there was a diametral clearance of 0.050 in. between the OD of the rings and the ID of the flats of the hex can.

It is obvious that greater swelling would also occur in the stainless steel of the hex can on the side nearest the center of the core than in the material on the side away from the center of the core. Calculations using the WADCO⁴ estimate of the swelling of stainless steel show that a maximum bow of about 0.08 in. could occur due to stainless steel swelling. This bow was calculated by the same technique used for the nickel spindle.

These data and calculations show that the bowing of the long-term test was due to swelling of the nickel spindle. The massive spindle prevented deflection of the subassembly by the normal forces used in the reactor plant to manipulate subassemblies and, therefore, caused the difficulties encountered in handling. Another subassembly - XG04, a Mark-A19 type of experimental-irradiation subassembly - actually exhibited slightly greater bowing than this nickel long-term test without causing handling problems. However, the Mark-A19 subassembly is much less resistant to bowing deflections than the nickel spindle.

V. CONCLUSIONS

These tests have shown that Nickel-200 exhibits good corrosion resistance in the EBR-II primary-system sodium at temperatures between 700 and 920°F and flow velocities of about 0.7 fps. The results of the post-irradiation examinations of the long-term test show that Nickel-200 exhibited volume increases of at least three times that of stainless steel at a fluence of 1.7×10^{22} nvt ($E > 0.1$ MeV) and a temperature of 850°F. The results also indicate that subassemblies that are strong and inflexible are likely to cause handling difficulties if they are subject to conditions in the reactor that would cause them to bow.

APPENDIX A

Procedure for Transferring and Removing Sodium from Experimental-irradiation Subassemblies Irradiated in EBR-II

I. Handling and Transfer

- A. By use of the subassembly transfer arm, the subassembly is removed from the reactor storage basket to a position below the transfer port.
- B. The subassembly is grasped by the fuel-unloading machine (FUM) and lifted to the "blowing-and-heating" elevation above the sodium level in the reactor primary tank.
- C. The excess sodium is removed from the FUM gripper and the subassembly by blowing argon gas heated to 615°F down through the subassembly and into the primary-tank cover gas at a rate of approximately 35 cfm for 15 min.
- D. The subassembly is lifted into the FUM and then transferred to the interbuilding coffin (IBC). During these operations, the subassembly is cooled by recirculating argon flowing at a rate of 30 cfm.

II. Sodium Removal

- A. The subassembly in the IBC is moved to the sodium-removal station in the FEF. Cooling is provided by recirculating argon at a rate of 30 cfm in the shielded coffin.
- B. Moisturized argon (argon bubbled through water) is added to the recirculating argon at a rate of 0.4 cfm for 60 min, and the resulting gas mixture is removed from the coffin at this same rate.
- C. The flow of moisturized argon is increased to 7 cfm for 30 min, and the resulting gas mixture is removed at this same rate.

- D. The coffin is purged with dry argon at 30 cfm to remove any accumulated hydrogen formed during the previous steps.
- E. The subassembly is rinsed by flowing pure water up through the subassembly at a rate of 5 gpm until samples of the effluent rinse have a conductivity less than 0.8 micromho and a sodium content less than 0.4 ppm. Usually about 125 gal of water are used during the rinse operation.
- F. The subassembly is dried by blowing dry air through the coffin at 30 cfm for approximately 30 min.

APPENDIX B

Calculation of the Bow of Nickel Spindle from Long-term Test

The bow of the nickel spindle was calculated from the postirradiation lengths of the "hot" and "cold" sides of the spindle. These lengths were determined from the results of the density measurements. The measurements of maximum and minimum density were converted to the length changes of the individual rings. The postirradiation core lengths of the "hot" and "cold" sides were obtained by summing the maximum and minimum length changes of the individual rings respectively. Only the core region (14 in. long) was assumed to have increased in length. The "hot" side was calculated to have a postirradiation length of 14.039 in., and the "cold" side a postirradiation length of 14.013 in. A diameter of 2.047 in. was used for the spindle. The bow was calculated as follows.

The radius of curvature (R) resulting from the length difference is (see Fig. 13)

$$\frac{14.039}{R + 2.047} = \frac{14.013}{R} ;$$

$$0.026 R = 28.685;$$

$$R = 1103.254 \text{ in.}$$

The angle subtended by the arc of the spindle is

$$\theta = S/R,$$

where θ = angle in radians, and

S = length of arc.

Therefore,

$$\theta = \frac{14.013}{1103.254} = 0.0127 \text{ radians,}$$

$$\theta^\circ = \theta(360/2\pi) \approx 0.728^\circ, \text{ and}$$

$$\cos \theta = 0.99992.$$

Fig. 13. Geometrical Model Used for Calculating Bow of Nickel Spindle of Long-term Test

The deviation from a straight line at the top of the spindle is

$$x = r \cos \theta,$$

$$\text{where } r = (R + 2.047) (1 - \cos \theta) = 1105.301 (1 - \cos \theta) = 0.088.$$

Therefore,

$$x = 0.088 (0.99992) = 0.008 \text{ in.}$$

The deviation from a straight line at the top of the spindle is

$$D = d + x,$$

$$\text{where } d = (\text{length of the spindle above the core}) \sin \theta = (22) \sin \theta.$$

Therefore,

$$D = 0.279 + 0.088 = 0.367 \text{ in.}$$

The bow at the midlength of the spindle would be approximately equal to half the deviation at the top, or

$$\text{bow} = 0.184 \text{ in.}$$

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