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Swelling of safety rod guide tubes in nonuniform fields of temperature and irradiation

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Abstract

Safety rod guide tubes are important components of fast reactor cores for ensuring safe reactor operation. Their failure or considerable changes of their size may lead to safety rod wedging that is unacceptable. Two guide tubes, one each from BN-350 and BOR-60, were examined post-irradiation to determine the reasons for their deformation and loss of functionality. These tubes were constructed from high-nickel alloy EP-150 and austenitic 18Cr9Ni, respectively.

It is found that various forms of deformation of safety rod guide tubes occur due to non-uniform swelling along the tube height, perimeter and across-wall thickness. The swelling gradients can lead to bowing and ovality, and can be accompanied by significant internal stresses within the tube material. The latter can lead to size reduction of guide tube dimension in some directions due to irradiation creep. High levels of swelling-induced residual stresses, in combination with a swelling-induced embrittlement of the tube material, can lead to the tube failure even in the absence of any external loading.

Keywords: Fast reactor; Swelling; Irradiation creep; Guide tubes; Safety rods; Temperature gradients; Damage dose gradients; Ovality.

Introduction

The void swelling phenomenon was discovered during examination of fuel pin claddings of the DFR reactor [1]. In a relatively short time the basic features of this phenomenon were identified [2, 3]. In particular, swelling was observed within a certain temperature range with a maximum at some temperature. The basic factors determining the level of swelling were found to be first, the irradiation temperature and second, the neutron fluence and its associated damage dose. Other factors such as starting microstructure, dose damage rate and stress were later found to affect swelling and accompanying irradiation creep [4,5].

Almost all structural elements in a fast reactor core operate in spatially non-uniform temperature and radiation fields. Thus, the neutron fluence varies along the core height and radius, while the irradiation temperature also varies along the core height and also over fuel rod or fuel assembly cross–sections. Early examination of BR-5 fast reactor fuel pins showed that an azimuthal non-uniformity of swelling occurred in claddings of peripheral fuel pins due to irradiation temperature variations [6]. The swelling non-uniformity led to bending of peripheral fuel pins and to additional stresses in the claddings [7]. A temperature gradient through the pin cladding wall results in a corresponding gradient of swelling and, as consequence, in the appearance of stresses of different sign at cladding surfaces [8, 9]. Swelling variations in hexagonal ducts of sub-assemblies caused by temperature and dose gradients were found to lead to a distortion of the initial duct geometry that significantly complicated their handling after irradiation [10].

In this paper two examples of the consequences of such gradient-induced distortions are presented. These examples

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Table 1
Chemical specification of EP150 high-nickel alloy, weight % [11]

C	Si	Mn	Cr	Ni	Mo	Nb	Ti	Al	B	Ce	S	P
≤0,10	≤0,8	≤0,7	15,0-17,0	34-38	2,0-2,5	0,9-1,3	0,7-1,1	0,9-1,3	≤0,004	≤0,02	≤0,02	≤0,025

Table 2
Chemical specification of X18M9 steel, weight % [12]

C	Si	Mn	S	P	Cr	Ni	Cu	Ti	Fe
≤0,10	≤0,80	≤2,0	≤0,02	≤0,025	17,0-19,0	8,0-10,0	≤0,30	≤0,1	remainder

are the guide tube of a temperature compensator of the BN-350 reactor and a safety rod tube of the BOR-60 reactor.

Materials investigated

The BN-350 temperature compensator tube is a cylinder with an outer diameter of 84 mm and 4 mm wall thickness. The upper part of the tube has an outside hexagonal shape for spacing the tube from surrounding fuel assemblies. The bottom end of the tube has lugs for bayonet fastening in the pressure header sockets and a throttle device for ensuring the needed coolant flow rate through the safety rod., A one meter long section of the cylindrical tube from the reactor core was brought to the SCC IPPE hot laboratory for investigation. The tube was fabricated from high-nickel alloy EP150 (C-04, Cr-15, Ni-35, Mo-2, Nb, Ti, Al, B), the chemical specification of which is shown in Table 1.

The temperature compensator tube was exposed in the third row of BN-350 reactor core for 370,3 effective full power days. Maximum neutron fluence reached 1.52×10^{23} n/cm^2 (E > 0.1 MeV), corresponding to a calculated dose of 65 dpa. The tube temperature varied from 285 to 420°C along the core height.

The safety rod guide tube from BOR-60 was a hexagonal tube made of 18Cr9Ni steel with a flat-to-flat size of 44 mm and internal cylindrical hole of 42 mm in diameter. The chemical specification of the 18Cr9Ni steel is shown in Table 2.

The safety rod guide tube operated in the BOR-60 reactor up to the maximum fluence of 2.3×10^{23} n/cm^2 (E > 0.1 MeV), corresponding to a calculated dose of 120 dpa. The irradiation temperatures of the tube ranged from 350 to 455°C.

Experimental methods

Post-irradiation diameter measurements of the BN-350 temperature compensator were carried out for two mutually perpendicular directions at distances of 50-100 mm along the core height with an accuracy of ±0.1 mm. Sizes of the reactor BOR-60 safety rod guide tube were measured for various cross sections along the core height at both corner edges and the middle of the flats.

To measure the swelling of the temperature compensator material, specimens of 55mm×10mm×4 mm in size were cut out for five cross-sections along the core height. The cutting scheme and specimen numbering for each section are shown in Figure 1. Swelling was determined for six elevations varying from -500 to +500 mm using the Archimedes technique. Specimens cut out from a non-irradiated part of the compensator far from the core were used as reference samples.

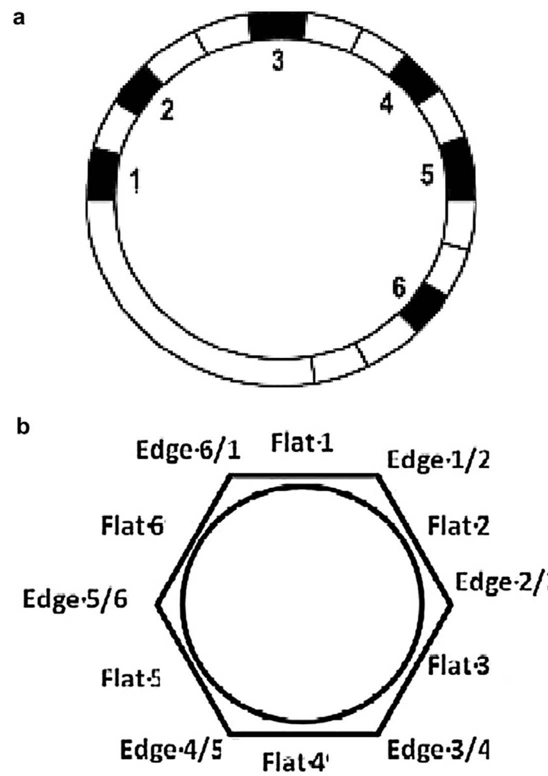

Fig. 1. (a) Cutting scheme for specimens used for measuring the material density of reactor BN-350 temperature compensator. This scheme was used for six separate elevations from −500 to +500 mm from core midplane. (b) Designations of corners and flats for the BOR-60 guide tube.

The density of the BOR-60 safety rod guide tube was measured using specimens of 3-5 g in weight cut from flat middles at nine elevations on flat 2, which was chosen because of its notable dimensional change behavior. The distance between three sets of opposing corner edges was measured at each of three elevations, picking the two corners that bound flat 2, and another opposite corner between flats 4 and 5.

Experimental results

BN-350 temperature compensator tube

A visual inspection of the tube revealed significant bending and diameter increase in the reactor core region. The bending deflection of the tube reached 12 – 15 mm, producing the upward bowing seen in Figure 2.

Measurements of the temperature compensator tube diameter showed that neutron irradiation led to significant irradiation-induced changes in the tube geometry, especially in the region -400 to +200 mm from core midplane where the tube increased in size significantly. While the initial outer

Table 3
Swelling (%) of the BN-350 temperature compensator tube determined by density measurements.

Distance from the core midplane, mm	Position of samples on perimeter (see Fig. 1)					
	1	2	3	4	5	6
500	2,6	2,3	2,5	3,1	3,4	3,6
250	5,5	7,0	5,4	6,8	5,6	6,1
0	10,0	9,9	–	7,5	6,3	6,2
−245	6,3	6,3	8,6	7,3	6,2	5,2
−275	6,0	5,9	7,3	6,3	5,0	4,3
−500	-	1,3	1,4	1,2	0,9	1,0

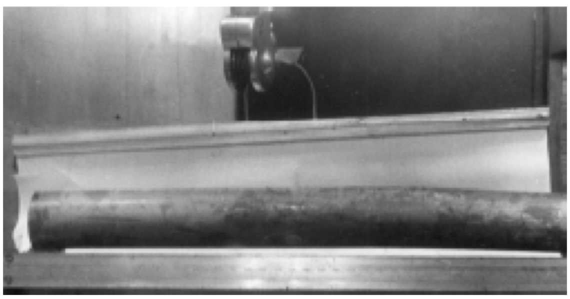

Fig. 2. Visible deformation of the BN-350 temperature compensator tube, showing both bowing and a non-uniform diameter.

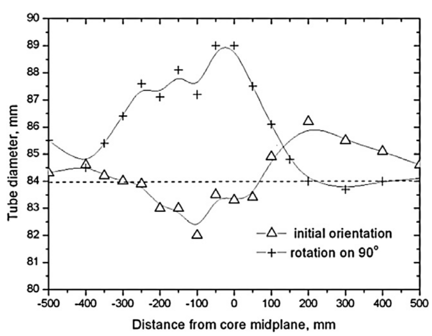

Fig. 3. Diameter measurements for the BN-350 temperature compensator tube in two mutually perpendicular directions, showing development of significant ovality as a result of swelling variation across the tube.

tube diameter was 84 mm, the diameter of the irradiated tube reached levels as high as 89 mm in the core midplane along one tube traverse, as shown in Figure 3. Along the perpendicular traverse the tube diameter decreased at distances of −250 mm to 50 mm from the core midplane, with the diameter reducing to 82 mm at a distance of 100 mm below core midplane. As a consequence, significant ovality occurred in the tube diameter, with a reversal in ovality direction above +150 mm.

Archimedes measurements of swelling are shown in Figure 4 and Table 3. The swelling of EP150 varies substantially both along the height and perimeter of the tube. Maximum swelling (~10 %) was observed at the core midplane (350°C, 65 dpa) for sections 1 and 2, while sections 5 and 6 on the opposite side were ~6,3%. In upper and lower cross-sections of the tube, the maximum swelling was only 3,6 and 1,4 %, respectively. Significant swelling variations were observed along the tube perimeter. In all investigated cross-sections except for the lowest one, a significant swelling gradient was observed around the tube perimeter.

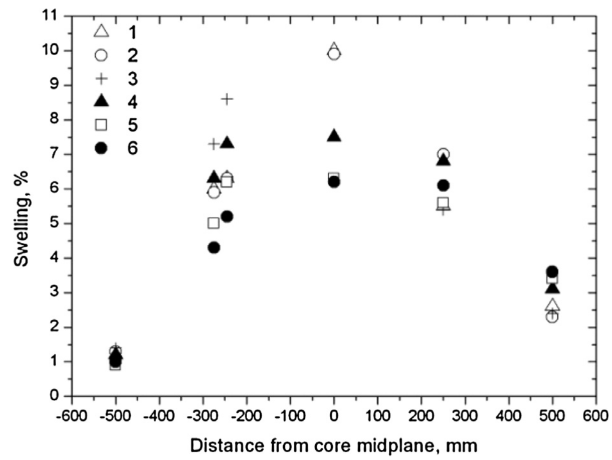

Fig. 4. Swelling variations in the temperature compensator tube along its height and perimeter according to density measurements. Specimen numbering is in accordance with the scheme shown in Fig. 1b.

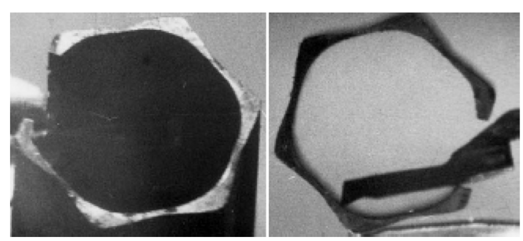

Fig. 5. Various cross-sections of the safety rod guide tube after irradiation in BOR-60. The tube failed during initial cutting (left figure) at -275 mm where the swelling was on the order of ~4-7% around the perimeter. The tube slice shown in the right Fig. did not fail during cutting. The irradiation temperature at this height was 455°C, the neutron fluence was 1.97×10^{23} n/cm^2. Note that the originally flat faces are concave with respect to the adjacent corners.

BOR-60 safety rod guide tube

A visual inspection of the BOR-60 safety rod guide tube showed that the hexagonal tube suffered noticeable deformation. In particular, it is clearly seen that an inward bending of the hexagonal tube faces has occurred, as seen in Figure 5. The visual inspection results are confirmed by measurements of the flat-to-flat and corner-to-corner distances shown in Figure 6.

Figure 6 shows that there is very little change in any dimension below the core midplane, indicating that no significant swelling or irradiation creep has occurred. Above the core midplane the three flat-to-flat distance measurements show a reduction in width of 1-1.5%, with only one exception at +500 mm. The variation between measurements of

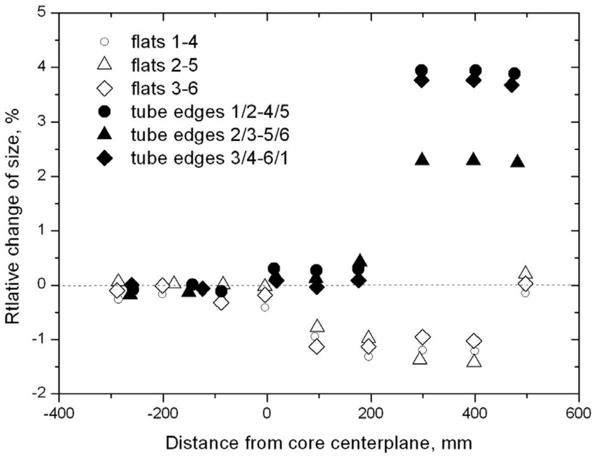

Fig. 6. Change of linear dimension along the length of the BOR-60 safety rod guide tube, measured across opposite corner edges and also across opposite faces

the three sets of faces at each elevation is visible but not very large.

When measuring the distance between corner edges, however, there is an abrupt increase of distance between 200 and 300 mm. For two sets of opposite corners (1-2 and 2-3) the increases are nearly equal at ~3.7 - 4% over the height of 300-500 mm, suggesting that these two across-duct dimensions are similarly oriented with respect to the core center, while the third set (4-5) are less at 2-2-2.4%, resulting from a different orientation spanning a lower dpa range.

In Table 4 the data on swelling from density measurements of the safety rod guide tube material are shown for flat 2 and some of the adjacent corners at higher elevations where swelling is significant. These data show that the maximum swelling of the middle of flat 2 is observed at ~250 mm from the core midplane. With only one exception, the swelling of the corners significantly exceeds that of the face at each elevation.

Discussion

Safety rod guide tubes are important components of the fast reactor core for ensuring safe reactor operation. Their failure or considerable changes of their size may lead to a safety rod wedging that is unacceptable. In this work it was shown that gradients in temperature and neutron dose in reactors BOR-60 and BN-350 can cause significant deformation of the safety rod guide tubes. It should be especially noted that a substantial increase in size in one direction is often accompanied by a reduction of size in other directions. The data obtained are in agreement with the data of Refs. [13, 14], where guide tubes of the compensating rods of the reactor BOR-60 were studied. One of these tubes was unloaded from the reactor because of wedging of a compensating rod. A visual inspection of the upper tube part revealed heavy deformation, with flat middles noticeably concaved with respect to corner edges. Most importantly, when the tube was checked with a gauge equal in diameter to the compensating rod, some reduction of the tube flow area was detected.

In fuel assemblies it is known that increases in corner-to-corner measurements arise only from void swelling, and that changes in flat-to-flat measurements arise from the combined action of swelling and irradiation creep [15]. At first thought, the shrinkage in face-to-face dimension implies that the pressure outside of the tube is greater than the pressure inside of the tube. However, safety rod guide tubes operate in an unrestricted state, e.g., applied external loads are negligible. The sodium pressure in a guide tube is much lower than the sodium pressure in a fuel assembly, and absorber rods move freely within the guide tube without any significant mechanical impact on the tube. Therefore there is not a significant difference in pressure across the tube wall. In this case all deformation will be determined by swelling and not by irradiation creep. Thus the reduction in flat-to-flat dimension must arise from swelling-induced stresses that arise from differential swelling, with the larger swelling of the two adjacent corners inducing a bending moment on the flat between them.

The present investigation and data from Refs [13-15] indicate that swelling varies in a complex way along the length, perimeter and even across the wall thickness of a guide tube. Additionally, a substantial difference in swelling between the corner edges and face middles is observed for hexagonal guide tubes of BOR-60, as is seen in Table 4.

Differences between swelling of corners and faces can arise from several sources. Non-uniform starting microstructures, where corners are more heavily worked than faces during final production can lead to such behavior, as recently shown by Maksimkin and co-workers [16]. It is thought that the gradient of swelling in the guide tube wall observed in Refs [11 – 13] is caused primarily by the difference of temperatures at the outer and inner guide tube surfaces that can reach as high as 75°C. The swelling gradient over the guide tube perimeter is thought to be due to the temperature non-uniformity that is associated either with non-uniform heating of the guide tube by surrounding subassemblies or with the developing non-coaxial position of the absorber rod inside the tube as it distorts.

The presence of a large swelling gradient gives rise to internal stresses in the guide tube bulk, and then the overall tube deformation will be determined only by the swelling, which in turn depends on swelling-induced stress and resultant irradiation creep strain. Due to irradiation creep the Internal stresses relax to a certain extent, but after the end of irradiation a high level of residual stress remains in guide tubes exhibiting a high swelling gradient. This retention of stress was measured in one control rod tube of BOR-60 using an X-ray diffraction method [14].

Due to high residual stresses and high swelling levels the thermal compensator guide tube of BN-350 failed in the process of cutting with a milling machine (Figure 7). The presence of high swelling levels in austenitic steels is known to induce fragility during room temperature cutting or mechanical testing [4, 5, 17-19], and perhaps the high-nickel tube discussed here may also have swelling-enhanced fragility, having experienced swelling levels as high as 10%. Even before significant swelling occurs, high nickel alloys are known to exhibit other forms of embrittlement during irradiation [20-22].

It is clear that guide tube swelling alone cannot lead to a reduction of initial tube size. Due to the action of swelling

Table 4
Measured density change of the reactor BOR-60 safety rod guide tube material.

Distance from the core midplane, mm	Irradiation temperature, °C	Neutron fluence, n/cm^2 (E > 0.1 MeV)	Density change, %		
			edges 1/2	flat 2	edges 2/3
−480	350	0,1•10^{23}	–	0,2	–
0	350	1,7•10^{23}	–	0,2	–
50	365	1,95•10^{23}	–	−0,5	–
100	380	2,17•10^{23}	–	−0,6	–
150	395	2,31•10^{23}	−4,8	−0,9	−2,9
200	410	2,34•10^{23}	–	−4,8	–
250	425	2,31•10^{23}	−9,3	−5,5	−11,6
300	440	2,17•10^{23}	–	−6,0	–
350	455	1,97•10^{23}	−0,9	−5,8	−8,5

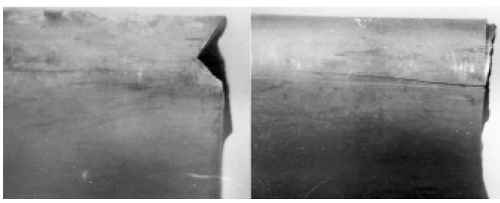

Fig. 7. Fracture of the temperature compensator guide tube at -275mm from the core midplane during cutting in the hot cell.

only, each dimension must increase. Tube dimensions can decrease only due to the local irradiation creep strain overwhelming the local swelling strain. Under certain conditions, substantial internal stresses in the structure arising from differential swelling can lead to negative dimensional changes of this kind.

Conclusions

Based on the study of deformation and swelling in safety rod guide tubes of BN-350 and BOR-60 fast reactors the following conclusions can be made.

1. Irradiation of the temperature compensator in the reactor BN-350 to the maximum dose of 65 dpa leads to a significant bowing (maximal bending deflection of 15 mm) and diameter changes. Around the core midplane the diameter of the cylindrical part of the guide tube increased from its initial value of 84 mm to as much as 89 mm in one traverse direction. In the perpendicular direction the guide tube diameter decreased to a level as low as 82 mm. This produces an ovality in the tube that may impair its continued functionality and lead to wedging of the control rod.
2. The operation of the safety rod guide tube in the BOR-60 reactor up to the maximum dose of 120 dpa led to a significant increase of the hexagonal tube size between opposite flats and the reduction of its flat-to-flat size at the flat middle. Such deformation may interfere with control rod movement.
3. Change of sizes of safety rod guide tubes made of steels EP150 and 18Cr9Ni occurs due to non-uniform swelling of the tube material over the tube height, perimeter and across the wall thickness. Swelling gradients leads to the appearance of substantial internal stresses in the guide tube under the action of which a decrease of initial tube size occurs due to the irradiation creep. A high level of residual stresses in combination with the swelling-induced embrittlement of the tube material can lead to tube failure even in the absence of external loads during irradiation.

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