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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.

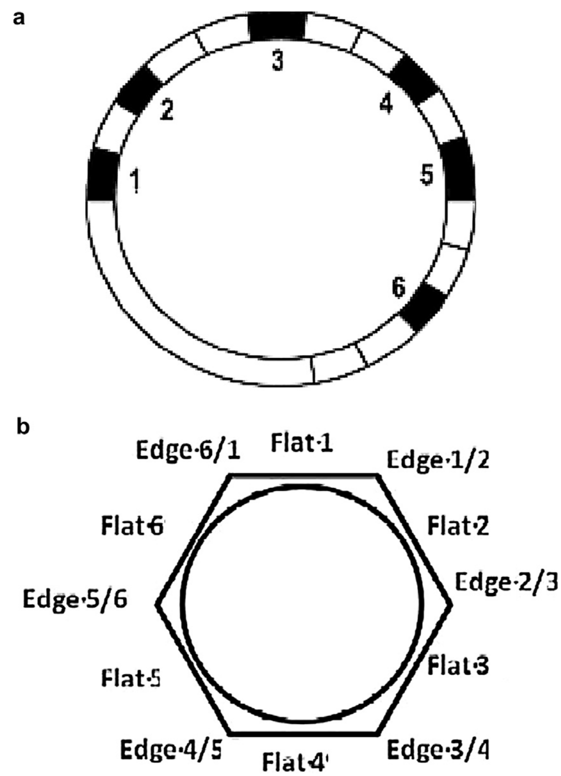

Fig. 1. (a) Cutting scheme for specimens used for measuring the material density of reactor BN-350 temperature compensator. This scheme was used for six separate elevations from −500 to +500 mm from core midplane. (b) Designations of corners and flats for the BOR-60 guide tube.

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