UDC 621.039:548.3

INVESTIGATION INTO HYDRIDE REORIENTATION IN DUMMY FUEL ROD CLADDING (Zr-1%Nb) UNDER INTERNAL PRESSURE DURING TESTING SIMULATING SNF HANDLING AND ACCIDENTS WITH LIMITING CLADDING HEATING UP TO 410 °C

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This paper presents the results of experimental investigations into hydride reorientation that (HRT) can occur in fuel rod claddings under conditions simulating normal and some accident SNF handling modes with limiting cladding heating up to 410 °C. Dummy fuel rods with Zr-1%Nb cladding with different hydrogen content under internal pressure (cold pressure under cladding of 3, 4, and 5 MPa) were subjected to testing with heating up to 410 °C, holding at this temperature during 8 h and subsequent cooling. It was found that at a hydrogen concentration of 400 ppm, intensive hydride reorientation in the dummy fuel rod claddings during thermal test begins at a tangential stress of ≈ 55…60 MPa at 410 °C. As the hydrogen concentration decreases, the intensity of test impact on hydride reorientation decreases significantly. SNF thermal cycling and holding in DSFSF significantly increases hydride reorientation. In the claddings with a 400 ppm hydrogen concentration subjected to 3 thermal cycles 180↔410 °C, almost complete hydride reorientation occurs. Mechanical testing of samples with different hydrogen content was conducted before and after the hydride reorientation test.

INTRODUCTION

One of the dangerous phenomena in fuel assembly handling is hydride reorientation. When heated in the process of drying, hydrides of tangential orientation, which is favorable in terms of its effect on the plasticity and which is set by the cladding tube manufacturing technology, can dissolve. Long-term dry storage of SFA fuel rods can result in formation of radial hydrides with orientations set by acting stresses. Hydride reorientation can lead to plasticity reduction in SFA zirconium claddings and promote their damage. In view of this dangerous phenomenon, large-scale, systematic and increasingly detailed investigations into the phenomena responsible for SFA zirconium cladding degradation, including hydride reorientation are being conducted in all countries, which have "dry" storage facilities, for which test methods are being developed and facilities are being established.

Currently, the technology for manufacturing cladding tubes determines their propensity towards formation of hydrides of a favorable tangential orientation (in terms of the effect of hydrides on cladding plasticity under operating stresses). Under stress, hydrides perpendicular to the tensile stress and parallel to the compressive stress are formed. Initial orientation of hydrides in zirconium fuel rod claddings changes when they are dissolved during heating, and hydrides of a different orientation set by the stress are formed during subsequent cooling. SNF handling and further long-term storage create the conditions which promote reorientation of hydrides from the favorable (tangential) orientation set by the processing – TO (Technology Orientation) and subsequent formation of hydrides of the unfavorable orientation set by the stress – SO (Stress Orientation) [5–7].

The main array of information on SNF behavior during dry storage relates to typical PWR (14×14 PWR – 17×17 PWR) and BWR (8×8 BWR – 10×10 BWR) fuel assemblies [8]. Considering their potential danger, hydride reorientation and hydrogen embrittlement of zirconium SFA components require systematic, routine and increasingly detailed examination [9].

MATERIALS AND METHODS

The test material was Zr-1%Nb (E110) cladding tubes with an external diameter of 9.13 mm and a wall thickness of 0.68 mm in as received state (finish annealing at 580 °C, 3 h) [8]. The tubes were used for cutting out 2.7 mm wide annular samples for the mechanical tests.

The samples were hydrogenated in the facility for saturation in hydrogen gas atmosphere ("dry" hydrogenation) at atmospheric pressure and at the temperature of 400 °C [10].

Hydride reorientation test is conducted in accordance with the NFC STE methodology on hydrogenated dummy fuel rods [10] under internal pressure of 3, 4, and 5 MPa with Zr-1%Nb alloy claddings with heating to 410 °C (Fig. 1).

Fig. 1. Dummy Fuel Rod Appearance [10]

The temperature mode for the hydride reorientation test was selected based on the requirements for the maximum allowable SNF handling temperature used in different countries [12]. A cycle of tests was previously conducted with limiting heating up to 450 °C, which is the maximum allowable temperature for WWER-1000 SFA handling and loading into the SS ZNPPP DSFSF [13].

In this study, the limiting temperature for SNF handling used in Hungary (410 °C) was taken as the basis, based on the requirements for the maximum allowable handling temperature for WWER-440 SNF [12].

The temperature modes used during the hydride reorientation test are shown in Table 1 and Fig. 2.

Table 1

Temperature modes during hydride reorientation test

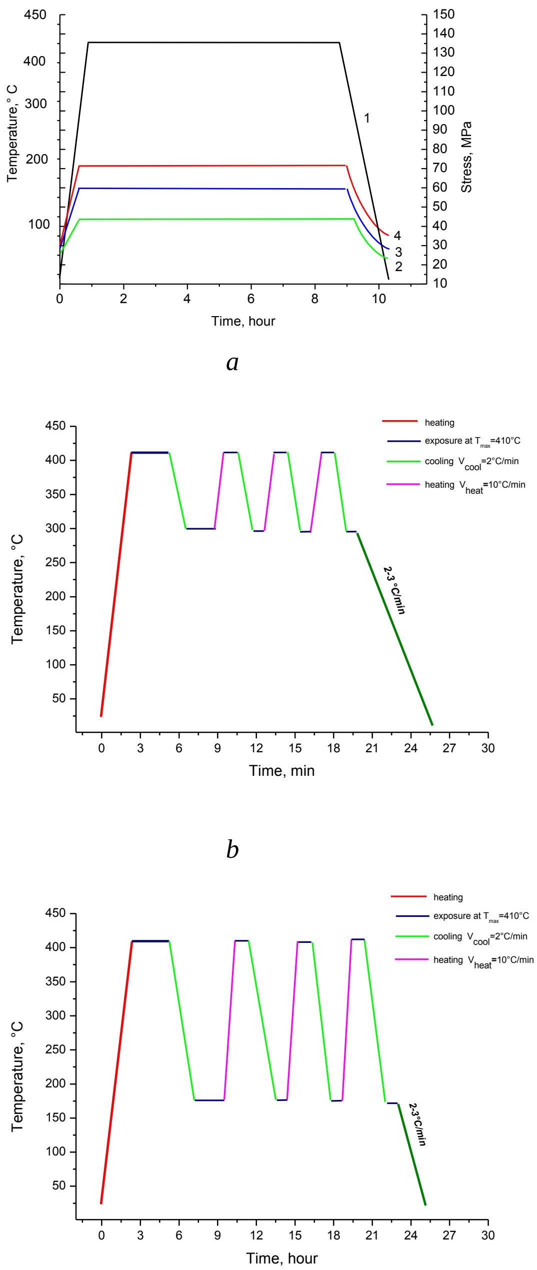
Pressure under cladding (P_{293}), MPa	Mode	Test conditions
3, 4, and 5	Mode 1	Simulation of handling: heating at the rate of ~ 10 °C/min to 410 °C, holding during 8 h and subsequent cooling at the rate of 2…4 ºC/min [12]
3, 4, and 5	Mode 2	Simulation of handling and accidents with 3 thermal cycles: heating at the rate of 10 °C/min, holding for 3 h, cooling at the rate of 2…4 ºC/min to 300 ºC and subsequent 3 thermal cycles 410↔300 °C with holding during 1.4 h at 410 °C and 1 h at 300 °C
3, 4, and 5	Mode 3	Simulation of handling and accidents with 3 thermal cycles: heating at the rate of ~ 10 °C/min, holding for 3 h, cooling at the rate of 2…4 ºC/min to 300 ºC and subsequent 3 thermal cycles 410↔180 °C with holding during 1.4 h at 410 °C and 1 h at 180 °C

The tangential stress in the fuel rod cladding was calculated using the formula:

$$\sigma_\theta = \frac{P_{293} D_{mid}}{2t} \cdot \frac{(T+273)}{293},$$

where P_{293} is internal gas pressure under cladding at room temperature, MPa; D_{mid} – average cladding diameter, mm; T_{test} – test temperature, °C; t – wall thickness, mm.

Characteristics of the dummy fuel rods subjected to the hydride reorientation test, of which the samples for the metallographic studies and short-term mechanical tests were cut out are shown in Tables 2 and 3. The tables also show the tangential stress σ_θ in the dummy fuel rod claddings under pressure at 410 °C (simulated handling conditions with heating up to 410 °C) and the stress at the temperature of the beginning of hydride precipitation for each specific hydrogen concentration [H].



c

Fig. 2. Temperature conditions for dummy fuel rod hydride reorientation test in the mode simulating handling conditions with limiting heating up to 410 °C (mode 1) (a) and accidents with 3 thermal cycles 410↔300 °C (b), and accidents with 3 thermal cycles 410↔180 °C (c)

Table 2

Characteristics of dummy fuel rods for tests simulating handling operations with heating up to 410 °C

Dummy No	[H], ppm	P_{293}, MPa	$\sigma_{\theta,\ \text{TSSP}}$, MPa	$\sigma_{\theta\ \text{at}\ 410\ °\text{C}}$, MPa
1	2	3	4	5
1	104	3	35.2	43.5
19	180	3	39.0	43.5
14	200	3	39.8	43.5

Continuation of Table 2

1	2	3	4	5
26	328	3	44.1	43.5
32	350	3	44.7	43.5
36	400	3	46.1	43.5
29	106	4	47.1	58
20	170	4	51.4	58
21	210	4	53.5	58
27	300	4	57.7	58
31	350	4	59.7	58
35	420	4	62.2	58
39	100	5	58.3	72.4
13	204	5	66.5	72.4
34	250	5	69.4	72.4
30	310	5	72.6	72.4
33	340	5	74.1	72.4
24	410	5	77.3	72.4

Table 3

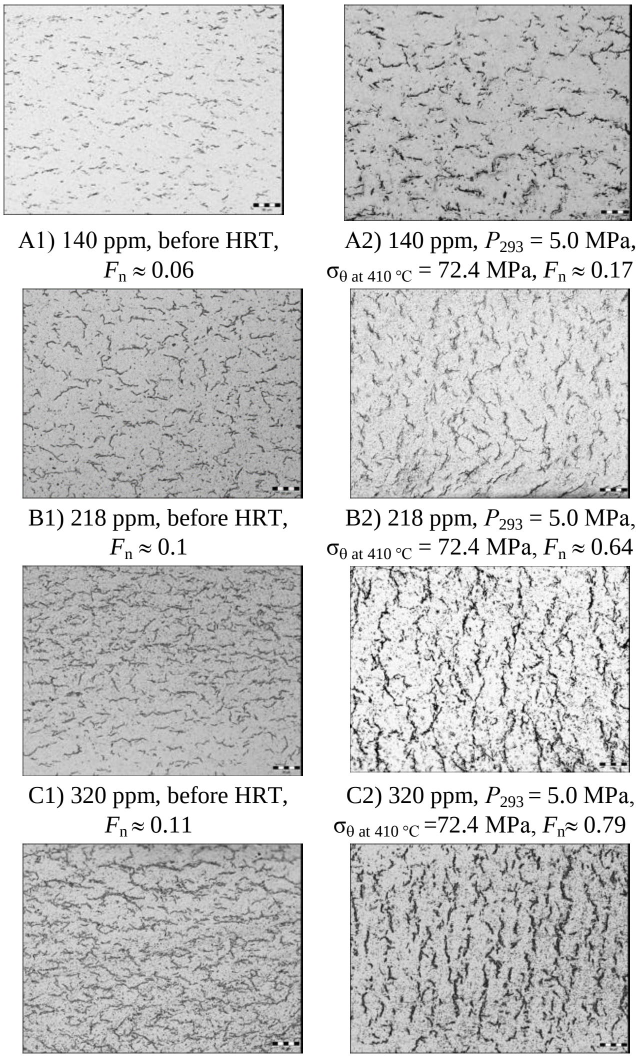
Characteristics of dummy fuel rods for tests simulating handling conditions with heating up to 410 °C and accidents with 3 thermal cycles

Dummy No	[H], ppm	P_{293}, MPa	$\sigma_{\theta,\,TSSP}$, MPa	$\sigma_{\theta\text{ at }410\,°C}$, MPa
12	50	3	31.2	43.5
16	300	3	43.2	43.5
7	100	3	34.9	43.5
5	200	3	39.8	43.5
2	200	3	39.8	43.5
4	280	3	42.6	43.5
8	115	3	35.8	43.5
11	65	3	32.5	43.5
15	200	3	39.8	43.5
32	300	4	57.7	58
30	210	4	53.3	58
37	150	4	50.15	58
34	70	4	43.9	58
67	298	4	57.6	58
69	200	4	53.0	58
3	100	5	58.2	72.4
6	50	5	51.96	72.4
10	120	5	60.2	72.4
22	300	5	72.1	72.4
23	200	5	66.3	72.4
9	120	5	60.2	72.4
17	150	5	62.7	72.4
18	100	5	58.2	72.4
25	300	5	72.1	72.4
28	200	5	66.3	72.4

CHANGE OF HYDRIDE ORIENTATION IN DUMMY FUEL RODS DURING TESTS SIMULATING SNF HANDLING WITH LIMITING HEATING UP TO 410 °C

Dummy fuel rods (Zr-1%Nb) under the initial internal pressure P_{293} = 3, 4, and 5 MPa were tested in the mode simulating SNF handling with limiting heating up to 410 °C.

Fig. 3 shows the change in hydride orientation in Zr-1%Nb dummy fuel rod cladding with the initial internal pressure of 5 MPa when tested in the mode simulating SFA handling with a maximum heating to 410 °C.



A1) 140 ppm, before HRT, $F_n \approx 0.06$

A2) 140 ppm, P_{293} = 5.0 MPa, $\sigma_{\theta\text{ at }410\,°C}$ = 72.4 MPa, $F_n \approx 0.17$

B1) 218 ppm, before HRT, $F_n \approx 0.1$

B2) 218 ppm, P_{293} = 5.0 MPa, $\sigma_{\theta\text{ at }410\,°C}$ = 72.4 MPa, $F_n \approx 0.64$

C1) 320 ppm, before HRT, $F_n \approx 0.11$

C2) 320 ppm, P_{293} = 5.0 MPa, $\sigma_{\theta\text{ at }410\,°C}$ =72.4 MPa, $F_n \approx 0.79$

D1) 400 ppm, before HRT, $F_n \approx 0.12$

D2) 400 ppm, P_{293} = 5.0 MPa, $\sigma_{\theta\text{ at }410\,°C}$ = 72.4 MPa, $F_n \approx 0.82$

Fig. 3. Hydride distribution in fuel rod dummy claddings before (on the left) and after their testing in the temperature mode simulating SNF handling with limiting cladding heating up to 410 °C. Initial internal pressure under cladding P_{293} = 5 MPa (mode 1). Cross-section. Reference: 50 µm

The data given in Fig.3 show that for the hydrogen concentrations in Zr-1%Nb claddings of 218 ppm and higher, testing of the dummy fuel rods under the pressure of 5 MPa with heating up to 410 °C results in a significant hydride reorientation. The hydride orientation coefficient for the dummies with the hydrogen content of 400 ppm is 0.82.

Table 2 provides the results of all tests conducted in the mode simulating SFA handling in DSFSF with limiting heating of 410 °C.

Table 4
Hydride orientation coefficients for Zr-1%Nb dummy cladding with initial internal pressure P_{293} = 3, 4, and 5 MPa tested in the mode simulating SFA handling in DSFSF with limiting heating of 410 °C

P_{293} MPa	[H], ppm	$\sigma_{\theta,\ 410\ °C}$ MPa	$\sigma_{\theta,\ TSSP,}$ MPa	F_0, before HRT	F_n, after HRT
3	120	43.45	36.10	0.06	0.09
	190	43.45	39.36	0.08	0.28
	286	43.45	42.81	0.08	0.38
	400	43.45	46.12	0.12	0.68
4	80	58.0	44.85	0.04	0.09
	208	58.0	53.44	0.09	0.56
	280	58.0	56.8212	0.1	0.67
	400	58.0	61.49	0.12	0.78
5	140	72.4	61.89	0.06	0.17
	218	72.4	67.43	0.1	0.64
	320	72.4	73.11	0.11	0.79
	400	72.4	76.87	0.12	0.82

According to the results of hydride reorientation tests of the dummy fuel rod claddings of Zr-1%Nb in the mode simulating SFA handling in the DSFS with limiting heating to 410 °C:

– no significant reorientation of hydrides occurs in the in the dummy fuel rod claddings with a hydrogen content of less than 200 ppm (below the hydride solubility limit in Zr-1%Nb at 410 °C – 206 ppm);

– at a hydrogen concentration above 200 ppm, Zr-1%Nb claddings have a high tendency to hydride reorientation. With a hydrogen content above 200 ppm, the threshold stress before the beginning of intense hydride reorientation does not exceed 58 MPa.

It should be noted that Zr-1%Nb (E110) alloy claddings after four years of operation in WWER reactors (~ 45 (MW·h)/kgU), including fuel rods after operation at Ukrainian NPPs (SUNPP, ZNPP, RNPP, KhNPP) demonstrate insignificant hydrogenation, with a mass fraction of hydrogen of ~ 50…60 ppm and not exceeding 80 ppm. The hydrides in the form of point and plate-like formations up to ~ 80 μm in size have a predominantly tangential orientation, which is favorable in terms of the mechanical properties of the cladding (Fig. 4) [14, 15]. At such a hydrogen concentration, no significant hydride reorientation occurs in the claddings under the conditions that simulate WFA handling operations with heating to 410 °C in DSFSF, and thus, no significant hydrogen embrittlement is expected.

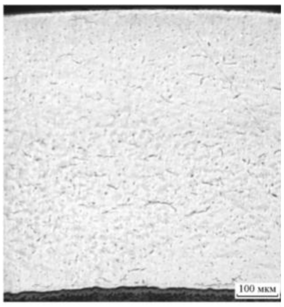


Fig. 4. Hydrides in Zr-1%Nb fuel rod claddings with fuel burn up of ~ 70 (MW·h)/kgU [14]

HYDRIDE ORIENTATION IN DUMMY FUEL ROD CLADDING UNDER INTERNAL PRESSURE DURING TESTING SIMULATING HANDLING CONDITIONS AND ACCIDENTS WITH LIMITING HEATING UP TO 410 °C

Dummy fuel rods under pressure (P_{293} = 3, 4, and 5 MPa) with hydrogenated (50…400 ppm) Zr-1%Nb claddings were subjected to the hydride reorientation test in the modes simulating handling and accidents with 3 thermal cycles 410↔300 and 410↔180 °C.

Before the HRT, hydride orientation coefficient does not exceed 0.08 (Table 4). With a hydrogen concentration increase from 50 to 100 ppm its value increases from 0.04 to 0.7.

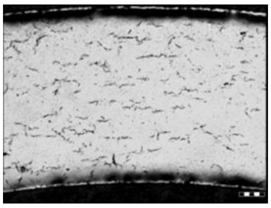
Fig. 5 provides the results of testing dummy fuel rod claddings under the pressure of 3 and 5 MPa after the HRT, which simulated handling conditions and accidents with 3 thermal cycles 410↔300 °C: heating at the rate of ~ 10 °C/min to 410 °C, holding for 3 h → cooling at the rate of 2…3 °C/min to 300 °C, holding for 3 h and 3 subsequent thermal cycles with holding for 1.5 h at 410 °C and for 1 at 300 °C.

The data given in Fig. 6,a and in Table 6 show that for the hydrogen concentration of 100 ppm in dummy fuel rod claddings under the pressure of 3 MPa ($\sigma_{t\ at\ 410\ °C}$ = 43.5 MPa), after the hydrogen reorientation test simulating handling conditions with a limiting heating up to 410 °C and accidents with three 410↔300 °C thermal cycles, the hydrogen orientation coefficient equals 0.24, and it significantly increases with further increasing pressure under the cladding (tangential stress). At a hydrogen concentration of 120 ppm for all stresses during the HRT, the hydride orientation coefficient is above 0.5. At a hydrogen concentration of 300 ppm, significant reorientation of hydrides occurs for all stresses. After the HRT, the hydride orientation coefficient is 0.87.

Fig. 6 demonstrates the results of testing dummy fuel rod claddings under internal pressure of 3 and 5 MPa after the hydride reorientation test simulating handling conditions and accidents with three 410↔180 °C thermal cycles: heating to 410 °C at the rate of ~ 10 °C/min, holding for 3 h → cooling at the rate of 2…4 °C/min to 300 °C, holding for 3 h and 3 subsequent thermal cycles with holding for 1.5 h at 410 °C and for 1 h at 180 °C.

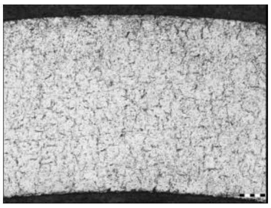
a
Sample No 12,
P_{293} = 3.0 MPa, 50 ppm,
$F_n \approx 0.12$

b
Sample No 6,
P_{293} = 5.0 MPa, 50 ppm,
$F_n \approx 0.23$

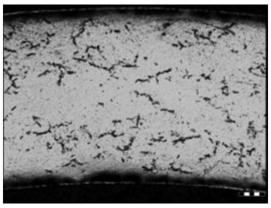


c
Sample No 7,
P_{293} = 3.0 MPa, 100 ppm,
$F_n \approx 0.24$

d
Sample No 3,
P_{293} = 5.0 MPa, 100 ppm,
$F_n \approx 0.42$

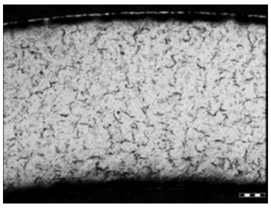


e
Sample No 17,
P_{293} = 3.0 MPa, 120 ppm,
$F_n \approx 0.53$

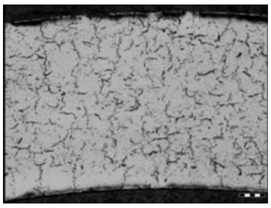


f
Sample No 10,
P_{293} = 5.0 MPa, 120 ppm,
$F_n \approx 0.53$

g
Sample No 5,
P_{293} = 3.0 MPa, 200 ppm,
$F_n \approx 0.7$



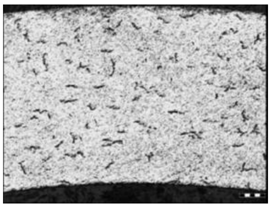
h
Sample No 23,
P_{293} = 5.0 MPa, 200 ppm,
$F_n \approx 0.93$



i
Sample No 16,
P_{293} = 3.0 MPa, 300 ppm,
$F_n \approx 0.87$

j
Sample No 22,
P_{293} = 5.0 MPa, 300 ppm,
$F_n \approx 0.97$

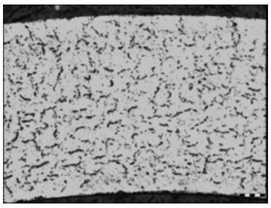
Fig. 5. Results of testing dummy fuel rod claddings under internal pressure of 3 and 5 MPa after HRT which simulated handling conditions with limiting heating of 410 °C and accidents with three 410↔300 °C thermal cycles



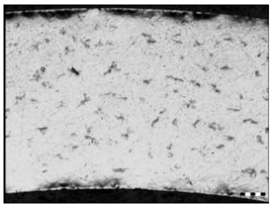
a
Sample No 11,
P_{293} = 3.0 MPa, 65 ppm,
$F_n \approx 0.13$

b
Sample No 8,
P_{293} = 3.0 MPa, 115 ppm,
$F_n \approx 0.44$

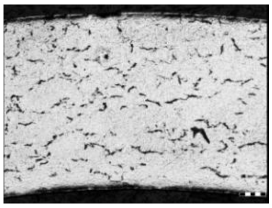
c
Sample No 4,
P_{293} = 3.0 MPa, 200 ppm,
$F_n \approx 0.87$



d
Sample No 2,
P_{293} = 3.0 MPa, 300 ppm,
$F_n \approx 0.89$



e
Sample No 18,
P_{293} = 5.0 MPa, 70 ppm,
$F_n \approx 0.17$



f
Sample No 9,
P_{293} = 5.0 MPa, 120 ppm,
$F_n \approx 0.61$

h
Sample No 28,
P_{293} = 5.0 MPa, 200 ppm,
$F_n \approx 0.72$

i
Sample No 25,
P_{293} = 5,0 MPa, 300 ppm,
$F_n \approx 0.89$

Fig. 6. Results of testing dummy fuel rod claddings under internal pressure of 3 and 5 MPa after HRT which simulated handling conditions and accidents with three 410↔180 °C thermal cycles

As shown by the data in Fig. 6,a at a hydrogen concentration of 65 ppm in the dummy fuel rod claddings under the pressure of 3 MPa ($\sigma_{t\ at\ 410\ °C}$ = = 43.5 MPa), after the hydrogen reorientation test, which simulated handling conditions and accidents with three 410↔180 °C thermal cycles, the hydrogen orientation coefficient changes insignificantly and equals 0.13 after the HRT.

At a hydrogen concentration of 100 ppm and higher at all stresses after the HRT which simulated handling conditions with limiting heating up to 410 °C and accidents with three 410↔180 °C thermal cycles, the hydrogen orientation coefficient increases significantly above 0.4 (see Fig. 6,b). With a hydrogen concentration increase to 300 ppm during the HRT, the hydrogen orientation coefficient increases up to 0.97 (see Fig. 6,c). As is clear from the data obtained, at a hydrogen concentration above 100 ppm after all hydrogen reorientation tests, which simulated handling conditions and accidents with three 410↔180 °C thermal cycles, significant hydride reorientation is observed.

Tables 5 and 6 summarize the results of hydride reorientation tests in the modes simulating handling conditions and accidents with three 410↔300 and 410↔180 °C thermal cycles, respectively.

Table 5

Hydride reorientation coefficients in Zr-1%Nb dummy claddings under initial internal pressure P_{293} = 3, 4, and 5 MPa, tested in the modes simulating SFA handling in DSFS and accidents with three 410↔300 °C thermal cycles

P_{293}, MPa	[H], ppm	$\sigma_{\theta,\ 410\ °C}$, MPa	$\sigma_{\theta,\ TSSP}$, MPa	F_0, before HRT	F_n, after HRT
3	50	43.5	31.17675	0.04	0.12
	100	43.5	34.95	0.04	0.24
	120	43.5	36.10	–	0.53
	200	43.5	39.77	0.06	0.7
	300	43.5	43.25	0.07	0.87
4	50	58	41.57	0.04	0.14
	150	58	50.15	0.05	0.34
	200	58	53.02	0.06	0.7
	300	58	57.67	0.07	0.87
5	50	72.4	51.96	0.04	0.23
	100	72.4	58.255	0.04	0.42
	120	72.4	60.17	–	0.53
	200	72.4	66.28	0.06	0.93
	300	72.4	72.09	0.08	0.97

Table 6

Hydride reorientation coefficients in Zr-1% Nb dummy claddings with initial internal pressure P_{293} = 3, 4, and 5 MPa, tested in the modes simulating SFA handling in DSFS and accidents with three 410↔180 °C thermal cycles

P_{293}, MPa	[H], ppm	$\sigma_{\theta,\ 410\ °C}$, MPa	$\sigma_{\theta,\ TSSP}$, MPa	F_0, before HRT	F_n, after HRT
3	65	43.5	32.51	0.04	0.13
	115	43.5	35.82	0.04	0.44
	200	43.5	39.77	0.06	0.87
	300	43.5	43.251	0.07	0.89
4	50	58	41.5689	0.04	0.16
	150	58	50.1	0.05	0.42
	200	58	53.02	0.06	0.74
	300	58	57.66	0.07	0.89
5	70	72.4	54.84	0.04	0.17
	120	72.4	60.17	0.04	0.61
	200	72.4	66.28	–	0.72
	300	72.4	72.09	0.06	0.89

Figs. 7 and 8 show the dependences of the hydride orientation coefficient on the hydrogen concentration and stress at 410 °C in the dummy claddings after the HRT with three thermal cycles 410↔300 and 410↔180 °C.

As seen from Figs. 7 and 8, in both cases, the threshold stress, at which hydride reorientation begins, decreases with increasing hydrogen concentration. In the dummy fuel rod claddings with a hydrogen concentration of 300 ppm, the threshold stress is very low ($\sigma_{t,\ 410\ °C} \approx$ 40…45 MPa). HRT with a tangential stress $\sigma_{t,\ 410\ °C}$ = 72.4 MPa results in a significant hydride reorientation in the claddings with a hydrogen concentration of 200…300 ppm.

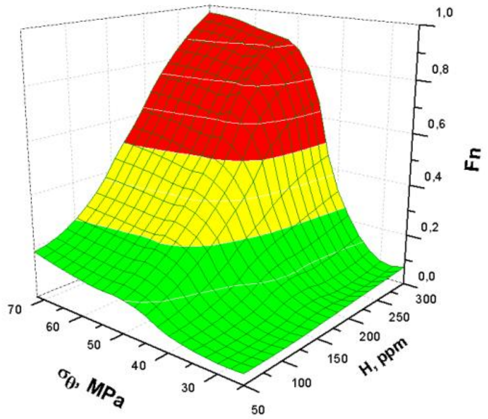


Fig. 7. Dependence of hydride orientation coefficient in internally pressurized dummy fuel rod claddings during testing in the mode simulating handling with limiting heating to 410 °C and accidents with three 410↔300 °C thermal cycles on hydrogen concentration and tangential stress at 410 °C

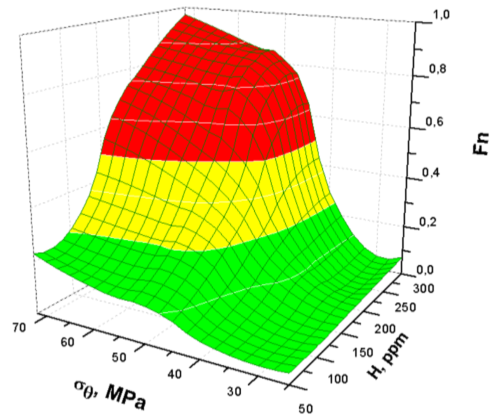


Fig. 8. Dependence of hydride orientation coefficient in internally pressurized dummy fuel rod claddings during testing in the mode simulating handling operations with limiting heating to 410 °C and accident with three 410↔180 °C thermal cycles on hydrogen concentration and tangential stress at 410 °C

As seen from Figs. 7 and 8, in both cases, the threshold stress at which hydride reorientation begins decreases with a hydrogen concentration increase. In the dummy fuel rod claddings with a hydrogen concentration of 300 ppm, the threshold stress is very low ($\sigma_{t,\ 410\ °C} \approx$ 40…45 MPa). HRT with a tangential stress of $\sigma_{t,\ 410\ °C}$ = 72.4 MPa results in a significant hydride reorientation in the claddings with a hydrogen concentration of 200…300 ppm.

Metallographic examinations demonstrated that:

– at a hydrogen concentration of 100 ppm, hydride reorientation test conducted in any of the modes used, has insignificant effect on hydride orientation in Zr-1%Nb claddings;

– at a hydrogen concentration of 150 ppm and higher, Zr-1%Nb claddings have a very high propensity for hydride reorientation.

EFFECT OF HYDROGEN AND HYDRIDE REORIENTATION ON THE MECHANICAL PROPERTIES OF Zr-1%Nb CLADDINGS DURING TESTING SIMULATING HANDLING OPERATIONS AND ACCIDENTS WITH LIMITING HEATING UP TO 410 °C

A series of tests and studies to investigate the effect of hydrogen and hydride reorientation on the mechanical properties of Zr-1%Nb claddings was carried out on annular samples with an outer diameter of 9.13 mm, a wall thickness of 0.68 mm and a width of 2.7 mm:

– cut out from non-hydrogenated fuel rod claddings in as received state;

– cut out from hydrogenated segments of cladding tubes with a hydrogen content of 170…400 ppm;

– cut out from dummy claddings after the hydride reorientation test simulating handling operations in the spent fuel pool and DSFS as well as handling and accidents with a limiting heating up to 410 °C (three 410↔300 and 410↔180 °C thermal cycles). The test temperatures are 20, 180, and 350 °C. The strain rate is $5.7 \cdot 10^{-3}$ 1/s.

Fig. 9 shows the dependence of the strength limit, yield stress and relative elongation of the samples cut out from the cladding tubes and hydrogenated tube segments at the mechanical test temperatures of 20 and 350 °C.

At a temperature of 20 °C, non-hydrogenated cladding tubes have: σ_B = 40.75 kg_F/mm^2, $\sigma_{0.2}$ = 37.5 kg_F/mm^2, and δ = 39.6%.

With a hydrogen concentration increase to 170…400 ppm:

– the strength limit increases to 45.15…48.3 kg_F/mm^2;

– the yield stress increases to 42.2…45.3 kg_F/mm^2;

– the relative elongation decreases but does not go below 27%.

At a temperature of 350 °C, non-hydrogenated cladding tubes have: σ_B = 17.75 kg_F/mm^2, $\sigma_{0.2}$ = 16.00 kg_F/mm^2, and δ = 38%.

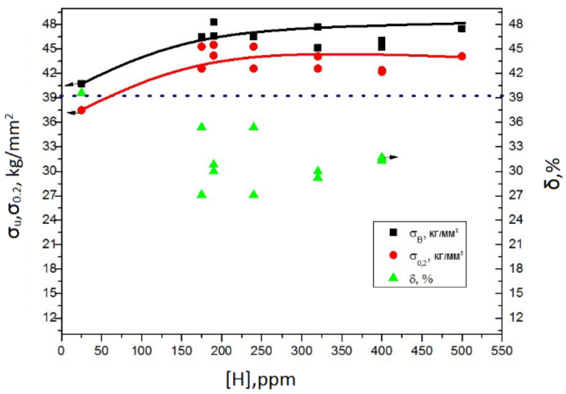
With a hydrogen concentration increase to 170…400 ppm:

– the strength limit increases to 19.1…21.3 kg_F/mm^2;

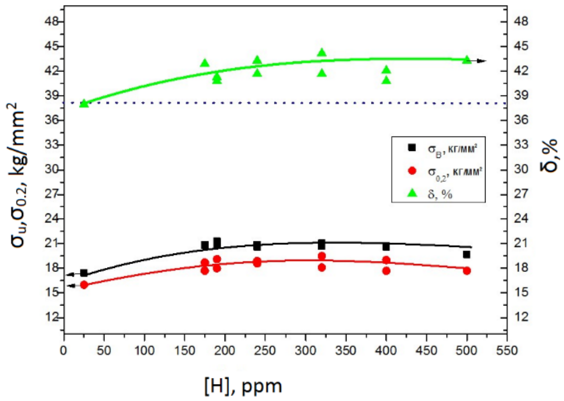
– the yield stress increases to 16.8…19.5 kg_F/mm^2;

– the relative elongation increases to 40.8…44.2%.

Thus, hydrogen (170…400 ppm) promotes strengthening of Zr-1%Nb alloy at both 20 and 350 °C; and at the same time reduces its plasticity at 20 and increases it at 350 °C.



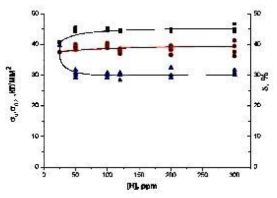
a



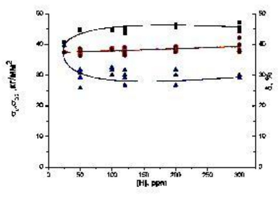
b

Fig. 9. Strength limit, yield stress and relative elongation of Zr-1%Nb (E110) cladding tubes versus hydrogen concentration. Mechanical test temperature: 20 (a) and 350 °C (b)

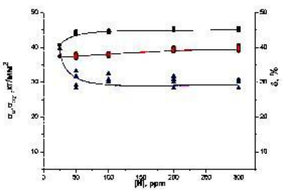
The results of the mechanical test on the samples cut from the hydrogenated Zr-1%Nb dummy claddings subjected to the hydride reorientation test with three thermal cycles at 20, 180, and 350 °C are given in Figs. 10, 11, and 12, respectively. The dummy pressure at room temperature and the temperature mode during the three thermal cycles are shown in the Figs.



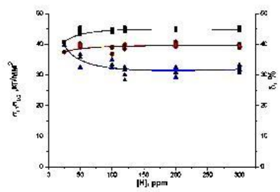
P_{293} = 3 MPa, 410↔180 °C



P_{293} = 5 MPa, 410↔180 °C



P_{293} = 3 MPa, 410↔300 °C



P_{293} = 5 MPa, 410↔300 °C

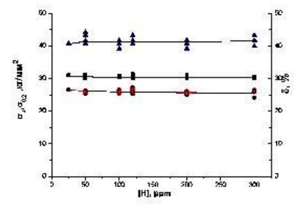
Fig. 10. Strength limit (σ_u□), yield stress ($\sigma_{0,2}$O) and relative elongation (δ% Δ) of Zr-1%Nb dummy claddings versus hydrogen concentration. Mechanical test temperature: 20 °C. Dummy pressure at room temperature and temperature mode during 3 thermal cycles are shown in the Fig.

It follows from the data given in Fig. 10 that regardless of the previous hydride reorientation test mode (see Tables 5 and 6) hydrogen has the following effect on the mechanical properties of Zr-1%Nb dummy claddings at the temperature of 20 °C:

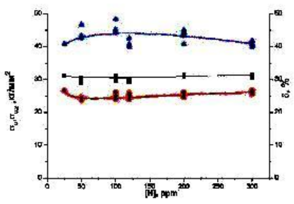
– the strength limit increases from (40.75±0.2) kg_F/mm^2 for non-hydrogenated samples to (45±3) kg_F/mm^2 for samples cut out from dummy claddings with a hydrogen concentration of 100…300 ppm;

– the yield stress increases from (37.5±0.2) kg_F/mm^2 for non-hydrogenated samples to (39…40) kg_F/mm^2 for samples cut out from dummy claddings with a hydrogen concentration of 100…300 ppm;

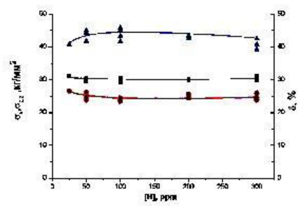
– the relative elongation decreases from (39.6±1)% for non-hydrogenated samples to (32±3)% for samples cut out from dummy claddings with a hydrogen concentration of 100…300 ppm.



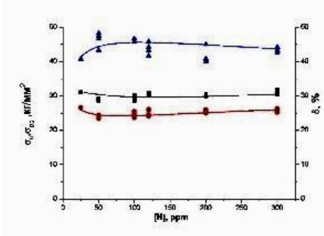
P_{293}=3 MPa, 410↔180 °C



P_{293}=5 MPa, 410↔180 °C



P_{293}=3 MPa, 410↔300 °C



P_{293}=5 MPa, 410↔300 °C

Fig. 11. Strength limit (σ_l,□), yield stress ($\sigma_{0,2}$ O) and relative elongation of dummy claddings (δ% Δ) versus hydrogen concentration. Mechanical test temperature: 180 °C. Dummy pressure at room temperature and temperature mode of 3 thermal cycles are shown in the Fig.

It follows from the data provided in Fig. 11 that regardless of the mode of previous hydride reorientation tests (see Tables 5 and 6) hydrogen has the following effect on the mechanical properties of Zr-1%Nb dummy claddings at the temperature of 180 °C:

– the strength limit practically does not depend on the hydrogen concentration. The strength limit values of samples tested at 180 °C range within (32±2) kg_F/mm^2;

– the yield stress slightly changes in the area of small hydrogen concentrations (50…100 ppm); with further increase in the hydrogen content, the yield stress values either remain virtually unchanged or slightly increase; the yield stress values of the samples tested at 180 °C range within (25±3) kg_F/mm^2;

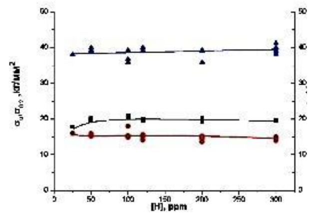
– the dependence of the relative elongation of the samples on the hydrogen concentration reaches its maximum at the hydrogen concentration of 50…100 ppm. The relative elongation values of the samples tested at 180 °C range within (45±4)%.

It follows from the data in Fig. 12 that regardless of the mode of previous hydride reorientation tests (see Tables 5 and 6), hydrogen has the following effect on the mechanical properties of Zr-1%Nb dummy claddings at the temperature of 350 °C:

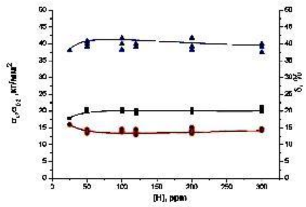
– the strength limit slightly increases with further increase in the hydrogen concentration. The strength limit values of the samples tested at 350 °C range within (20±3) kg_F/mm^2;

– the yield stress decreases insignificantly. The yield stress values of the samples tested at 350 °C range within (16±3) kg_F/mm^2;

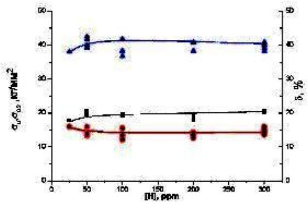
– the relative elongation of the dummy claddings increases from (38.3±0.2) to (42±2)%, while further increase in the hydrogen concentration up to 300 ppm practically does not affect the cladding material plasticity.



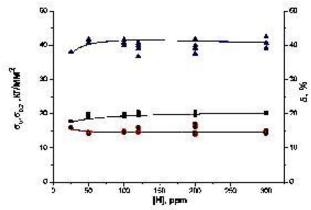
P_{293}=3 MPa, 410↔180 °C



P_{293}=5 MPa, 410↔180 °C



P_{293}=3 MPa, 410↔300 °C



P_{293}=5 MPa, 410↔300 °C

Fig. 12. Strength limit (σ_u□), yield stress ($\sigma_{0,2}$O) and relative elongation of dummy claddings (δ% Δ) versus hydrogen concentration. Mechanical test temperature: 350 °C. Dummy pressure at room temperature and temperature mode of 3 thermal cycles are shown in the Fig.

It is necessary to notice the high degree of reproducibility of the results obtained at each of the mechanical test temperatures.

According to the mechanical test results, changing tangential hydride orientation to radial hydride orientation occurring in the Zr-1%Nb claddings during the HRT does not lead to their plasticity reduction.

CONCLUSION

1. Zr-1%Nb cladding tubes were subjected to the HRT in the modes simulating SFA handling operations in DSFS with limiting heating to 410 °C that is accepted in Hungary for WWER-440 reactors and limiting accidents with three 410↔300 °C thermal cycles (mode 1) and 410↔180 °C (mode 2).

2. The test results obtained demonstrate that:

– at a hydrogen concentration of 50…60 ppm in Zr-1%Nb claddings, the hydride orientation coefficient in the dummy claddings after the HRT conducted in the modes used in the study does not exceed $F_n \leq 0.23$;

– at a hydrogen concentration of up to 100 ppm, the HRT conducted in any of the modes used in the study has little effect on the hydride orientation in Zr-1%Nb claddings;

– at a hydrogen concentration of 150 ppm and higher, Zr-1%Nb have a very high propensity for hydride reorientation, $F_n \geq 0.45$;

– at a hydrogen concentration of 200…300 ppm and higher in Zr-1%Nb cladding at $\sigma_{t\ at\ 410\ °C} \geq 43.5$ MPa, almost complete hydride reorientation occurs, $F_n \geq 0.9$.

3. According to the mechanical test results, changing tangential hydride orientation to radial hydride orientation occurring in the Zr-1%Nb claddings during the HRT does not lead to their plasticity reduction.

4. The HRT with a limiting heating up to 410 °C compares in effective enesswith the HRT with a limiting heating up to 450 °C (currently accepted maximum temperature for SFA unloading from the spent fuel pool and placing it in the ZNPP DSFS).

The results of tests and investigations conducted show that SFA handling with limiting heating up to 410 °C and with 410↔300 or 410↔180 °C limiting accidents can lead to significant hydride reorientation, which however will not affect their plasticity during further storage. In view of the potential danger of hydride reorientation and hydrogen embrittlement of zirconium components, systematic, routine and increasingly detailed examination of spent FAs is required.

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Статья поступила в редакцию 21.11.2019 г.

ИССЛЕДОВАНИЕ ПЕРЕОРИЕНТАЦИИ ГИДРИДОВ В ОБОЛОЧКАХ (Zr-1%Nb) МАКЕТОВ ТВЭЛОВ ПОД ВНУТРЕННИМ ДАВЛЕНИЕМ ПРИ ИСПЫТАНИИ, ИМИТИРУЮЩЕМ ПЕРЕГРУЗКИ ОЯТ И АВАРИИ С ПРЕДЕЛЬНЫМ НАГРЕВОМ ОБОЛОЧЕК ДО 410 °С

А.П. Редкина, Т.П. Черняева, В.М. Грицина, В.С. Красноруцкий, И.А. Петельгузов, Е.А. Слабоспицкая

Представлены результаты экспериментальных исследований переориентации гидридов, которая может происходить в оболочках твэлов в условиях, имитирующих штатные и некоторые аварийные режимы обращения с ОЯТ и предельным нагреванием оболочек до 410 °С. Проведены испытания с нагревом макетов твэлов с оболочками из сплава Zr-1%Nb и различным содержанием водорода под внутренним давлением (холодное давление под оболочкой 3, 4 и 5 МПа) до температуры 410 °С, выдержкой при этой температуре 8 ч и последующим охлаждением. Установлено, что при содержании водорода 400 ppm интенсивная переориентация гидридов в оболочках макетов твэлов при термических испытаниях начинается при тангенциальном напряжении ≈ 55…60 МПа и 410 °С. С уменьшением содержания водорода интенсивность воздействия испытаний на переориентацию гидридов значительно снижается. Термоциклирование и выдержка ОЯТ в СХОЯТ приводят к усилению переориентации гидридов. В оболочках с концентрацией водорода 400 ppm, при испытаниях с трехкратным термоциклированием 180↔410 °С происходит практически полная переориентация гидридов. Проведены механические испытания образцов с различным содержанием водорода до и после испытаний.

ДОСЛІДЖЕННЯ ПЕРЕОРІЄНТАЦІЇ ГІДРИДІВ В ОБОЛОНКАХ (Zr-1%Nb) МАКЕТІВ ТВЕЛІВ ПІД ВНУТРІШНІМ ТИСКОМ ПРИ ВИПРОБУВАННІ, ЩО ІМІТУЄ ПЕРЕВАНТАЖЕННЯ ВЯП І АВАРІЇ З ГРАНИЧНИМ НАГРІВАННЯМ ОБОЛОНОК ДО 410 °С

Г.П. Рєдкіна, Т.П. Черняєва, В.М. Грицина, В.С. Красноруцький, І.А. Петельгузов, О.О. Слабоспицька

Представлено результати експериментальних досліджень переорієнтації гідридів, яка може мати місце в оболонках твелів в умовах, що імітують штатні і деякі аварійні режими поводження з ВЯП і граничним нагріванням оболонок до 410 °С. Проведено випробування з нагріванням макетів твелів з оболонками зі сплаву Zr-1%Nb з різним вмістом водню під внутрішнім тиском (холодний тиск під оболонкою 3, 4 і 5 МПа) до температури 410 °С, витримкою при цій температурі 8 год і наступним охолодженням. Встановлено, що при вмісті водню 400 ppm інтенсивна переорієнтація гідридів в оболонках макетів твелів при термічних випробуваннях починається при тангенціальній напрузі ≈ 55…60 МПа при 410 °С. Зі зменшенням вмісту водню інтенсивність впливу випробувань на переорієнтацію гідридів значно знижується. Термоциклування та витримка ВЯП у ССВЯП призводять до значного посилення переорієнтації гідридів. В оболонках з концентрацією водню 400 ppm, при випробуваннях з трикратним термоциклуванням 180↔410 °С відбувається практично повна переорієнтація гідридів. Проведено механічні випробування зразків з різним вмістом водню до і після випробувань.