

INTEGRAL TESTING OF ATF FUEL UNDER HIGH TEMPERATURE ACCIDENT CONDITIONS IN THE CODEX FACILITY

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INTRODUCTION: The main objective of accident-tolerant fuel (ATF) development is to withstand high-temperature accident conditions in nuclear reactors. An important part of ATF fuel qualification involves experimental testing of fuel components in both in-pile and out-of-pile test facilities. The CODEX experimental program included two tests with ATF fuel materials: the CODEX-ATF test, conducted in a steam atmosphere, and the CODEX-ATF-AIT test, which simulated an air ingress scenario.

1. THE CODEX FACILITY

The CODEX facility had hexagonal bundles with 7 electrically heated fuel rods in both experiments. The test section was similar to the previous CODEX experiments [1][2][3]. The height of test section was 1000 mm, but the length of the rods was only 650 mm (CODEX-ATF) and 910 mm (CODEX-ATF-AIT), so the upper part of the shroud was used for thermocouples, without fuel rods. The fuel rods were filled with zirconia pellets and heated by tungsten wires. The rods were individually pressurised. In the CODEX-ATF test the seven-rod bundle consisted of three uncoated and four Cr coated optZIRLOTM cladding tubes and uncoated spacer grids and shroud were used. In case of CODEX-ATF-AIT tests all rods, spacer grids and the shroud were coated by chromium. The Zr shroud was surrounded by several thermal insulation layers, electrical heaters and a steel tube (Fig. 1). The Cr coating of components was carried out at the Czech Technical University in Prague. The main parameters of the test section are summarised in Table 1.

FIG. 1. Horizontal cross section of the test section with thermal insulations

TABLE 1. MAIN CHARACTERISTICS OF CODEX TEST SECTIONS WITH ATF FUEL
CODEX-ATF CODEX-ATF-AIT

Number of fuel rods	7	7
Cladding of fuel rods No. 2., 4. and 6.	optZIRLOTM Cr coated	optZIRLOTM
Cladding of fuel rods No. 1., 3., 5. and 7.	Cr coated	optZIRLOTM
Length of fuel rods	650 mm	910 mm
External diameter of fuel rods	9.1 mm	9.1 mm
Pellet material inside of the rods	ZrO ₂	ZrO ₂
Pellet material in the bottom of the rods	Al ₂ O ₃	Al ₂ O ₃
Spacer grid material	Zr1%Nb Cr coated	Zr1%Nb
Number of spacer grids	2	3
Shroud material	Zr2.5%Nb Cr coated	Zr2.5%Nb
Shroud thickness	2 mm	2 mm
Length of shroud	1000 mm	1000 mm

The online gas composition measurement at the test section outlet was conducted using a quadrupole mass spectrometer. Gas sampling at the outlet was achieved by inserting a sampling tube into the off-gas pipe. The measurement system recorded system and rod internal pressures, flow rates, outlet gas composition, values of input and output power, coolant inlet and outlet temperatures and rod temperatures. Several high temperature thermocouples were built into the surface of fuel rods, shroud and insulation layers at different elevations.

2. THE CODEX-ATF EXPERIMENT

The CODEX-ATF simulated a high temperature nuclear power plant severe accident terminated by water quench. The test focused on the observation of fuel failure and degradation mechanisms.

In the preparatory phase the facility was heated up to 600 °C in 0.2 g/s steam and 0.2 g/s argon flow rates using both external heaters and fuel rod heaters. The heat-up phase continued with the same flow rates and with 1000 W heating power on the rods and 800 W power of external heaters. The cladding burst took place at ≈900 °C on most of the rods. The temperature increase was very smooth. During the quench phase, room temperature water was injected to the bottom of the test section, when the cladding temperature in the top of the bundle was above 1600 °C. In the upper part of the fuel rods 1400 °C was reached (Fig. 2.).

FIG. 2. Cladding temperatures in the CODEX-ATF test FIG. 3. Cladding temperatures in the CODEX-ATF-AIT test

The total hydrogen production during the experiment was about 3 g, which indicated significant oxidation of

the Zr components. Intense Zr-Cr eutectic formation took place at these temperatures on the external surface of Cr coated cladding tubes. The post-test examination showed large deformation and failure of both coated and uncoated cladding tubes (Fig. 4).

FIG. 4. Bundle cross section (left), damaged uncoated (centre) and Cr-coated (right) cladding tubes removed from the top of CODEX-ATF bundle

FIG. 5. Oxide and nitride formation on the cladding of CODEX-ATF-AIT bundle

1. THE CODEX-ATF-AIT EXPERIMENT The main objective of the CODEX-ATF-AIT test was to check if accident tolerant fuel (ATF) cladding with Cr coating would have a protective role in case of NPP severe accidents with air ingress. The simulated scenario was a reactor accident with corium melting through the bottom head of the pressure vessel and penetration of air+steam mixture from the reactor cavity into the reactor vessel. The experiment was focused on covering several phenomena of fuel behaviour during accidents (burst, oxidation, nitriding, eutectic formation). Slow cool-down was selected to provide information on the state of the bundle before quench. In the preparatory phase the facility was heated up to 600 °C in steam –argon flow using both external heaters and fuel rod heaters. The pre-oxidation phase continued with the same flow rates and with stepwise increased heating power on the rods. During the heat-up phase the rods were pressurised and cladding burst took place between 750-800 °C on most of the rods. The opening allowed the coolant to enter the rods and start chemical reactions on both sides of the cladding. In the intermediate cool-down phase the temperatures were reduced below 750 °C. In the steam-air phase the temperature increase was very smooth compared to the reference experiment CODEX-AIT-3 [2]. The reason of the slower temperature increase was the protective effect of the Cr coating. The duration of air ingress phase in the reference experiment was 1 hour with 1600 °C maximum cladding temperature, and it was 1.5 hour in the CODEX-ATF-AIT with 1545 °C maximum cladding temperature (Fig. 3.). The temperature profile significantly changed during the air ingress phase similar to the reference experiment: the maximum temperature moved from the upper section of the bundle to lower elevations due to the intense chemical interactions in the less oxidised and/or melted lower part. The maximum shroud temperature was similarly around 1470 °C at 300, 500 and 700 mm elevations.

The outlet gas composition showed that during the air ingress phase steam and oxygen starvation conditions were established. The partial consumption of nitrogen indicated the formation of nitrides as well. The total of 1.4 g hydrogen was produced during the pre-oxidation phase and 3.3 g of hydrogen during the air ingress phase. Slow cool-down of the bundle was performed in argon flow in order to avoid interactions that might take place during water quench. At the lower half of the bundle the main degradation mechanism of rods was the Cr-Zr eutectic melt formation and its fast oxidation/nitriding in the last phase of the experiment. From 600 mm upwards, all the pressurised rods were ballooned and the Cr coating became cracked on their surfaces (Fig.5.).

SUMMARY

Two integral tests with ATF cladding materials were conducted in the CODEX facility under steam and steam-air atmospheres (Table 2). The high-temperature behavior of the cladding materials in both tests demonstrated reduced hydrogen production, a lower heat-up rate, and longer coping times, highlighting the advantages of ATF materials. Cr-Zr eutectic formation was observed in both tests, and its role in cladding failure was identified. The experimental data are available in an electronic database for code development and validation purposes.

TABLE 2. MAIN CHARACTERISTICS OF CODEX TEST SECTIONS WITH ATF FUEL

CODEX-ATF	CODEX-ATF-AIT
Max. temperature	1655 °C 1545 °C
Steam atmosphere	Yes Yes
Steam+air atmosphere	No Yes
Oxidation	Yes Yes
Nitriding	No Yes
Cr-Zr eutectic	Yes Yes
Quench	Yes No

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