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Storage of defective fuel pins in SFR core

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Abstract

An open fuel pin failure is a breach in the fuel pin cladding that allows direct contact between the primary coolant and the nuclear fuel. In this paper we focus on the sodium-fuel interactions in a Sodium cooled Fast neutrons Reactor (SFR), reviewing the main aspects of the fuel pin failure evolution with an emphasis on the Reaction between the Oxide fuel and the Sodium (ROS). This reaction leads to the formation of an uranoplutonate phase with approximately half the density of the initial oxide. In turn this can cause significant fuel swelling and the potential further degradation of the fuel pin. The maximal fuel swelling due to the formation of the uranoplutonate can be estimated for non-irradiated fuel based on the physico-chemical properties of the pellets, as further described in this paper.

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Keywords: uranoplutonate, sodium fast reacors; fuel pin failure; sodium-fuel reaction, fuel swelling

1. Introduction

Of the several types of reactors considered for development as part of the generation IV, the Sodium Fast Reactors (SFR) have raised the most interest and over 400 reactor-years of experience was gained globally in operating them [1]. The renewed interest of the CEA in the fast-neutron reactor R&D have led to the present-day design studies for the construction of the sodium-cooled fast neutrons reactor ASTRID, with several improvements via-à-vis previous CEA-operated SFRs[2].

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Since the safe operation of the reactor is the highest priority concern for the CEA, this study is focused on the sodium-fuel interactions and the subsequent fuel pin failure evolution, in order to evaluate the available data relative to the requirements imposed by the ASTRID operational conditions.

A fuel pin failure represents a breach in the pin cladding which is the first confinement barrier of the nuclear fuel inside the reactor core. It can lead to the contact between the coolant and the compounds inside the fuel pin including the nuclear fuel, and to a chemical reaction that alters the fuel behavior and could potentially lead to fuel dissemination in the primary coolant. The phenomenology of the fuel pin failure evolution as a result of the Reaction between the Oxide fuel and Sodium (ROS), both under irradiation in reactor conditions as well as in internal storage will be addressed in the first part of this paper, followed by a brief discussion on some of the thermodynamic data available on the sodium-fuel systems. The kinetic aspects of the reaction are also addressed in this paper and since the data currently available on the sodium –fuel reaction rate is limited, the need for further research is underlined. In this regard a series of experiments could be performed in order to investigate the reaction rate variation with different parameters. Since the pellet swelling can give an indication of the advancement of the reaction, we describe a simplified method for estimating of the maximum radial fuel swelling due to the ROS for non-irradiated fuel, based on the initial fuel pellet characteristics such as its diameter, density, Pu/M and the reaction temperature. In kinetic studies this can provide an estimation of the progress of the reaction relative to the equilibrium but it could also be used to estimate the maximum fuel swelling and diametric deformation of the fuel pin in Beginning Of Life (BOL) fuel pin failures.

2. General phenomenology of a fuel pin failure

Once the sodium infiltrates the fissile column the Reaction between the Oxide fuel and Sodium (ROS) is initiated forming the Fuel-Sodium Reaction Product (FSRP) of which the main component is the trisodium uranoplutonate, more or less pure depending mainly on the fuel burnup. This compound has physical properties very different from the initial mixed-oxide. In particular the density and thermal conductivity are listed in Table 1.

Table 1. Main physical properties comparison of the $(U,Pu)O_2$ and Na_3MO_4

Compound	$(U,Pu)O_2$ [3]	*Na_3MO_4 [4]
Theoretical density (g/cm^3)	10.99 – 11.08 (10 - 30 at% Pu)	5.59 – 5.68 (depending on T)
Thermal conductivity (W×m^{-1}×K^{-1})	1.7 – 5.4 depending on temperature, composition, burnup, O/M	0.9 – 1.0 (depending on T)
Morphology	Compact sintered grains	Laminar layers with a high porosity

*M=U+Pu ;physical properties of the $Na_3(U,Pu)O_4$ with less than 30 % molar Pu are considered similar to those of Na_3UO_4

Sodium uranoplutonate has roughly half the density of the original mixed-oxide leading to a lower thermal conductivity and considerable swelling of the fuel. This can favor the further degradation of the fissile column and the propagation of the fuel pin failure. While under irradiation in the reactor core the high temperature of the fuel surface and the high radial thermal gradient of the fuel that causes a radial oxygen migration, favor the ROS. Thus the defective assembly is placed in a low-power position referred to as Internal Storage where the reaction is significantly slowed by the low fuel temperature and by the absence of a thermal gradient that can supply the oxygen.

Although the ROS and its effects on the safety of the reactor operation have been the focus of multiple studies, many thermodynamic and kinetic aspects of the reaction are still unknown.

2.1. Fuel pin failure evolution under irradiation in core conditions

Stratin *et al*[5] observed the fuel pin failure evolution and propagation as a result of the ROS under irradiation in the reactor core in experimental “Run Beyond Cladding Breach” irradiations. They have shown the deleterious effects of the ROS coupled with significant fluctuations in the reactor power. However the ROS alone is unlikely to