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Analysis of Chromium Oxide Doped Pellet for LWRs Using FRAPCON Code

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1. Introduction

In the last two decades, studies have primarily focused on adding metallic dopants, such as Al_2O_3, Cr_2O_3, and Nb_2O_5. The addition of dopants increases the self-diffusion and creep of the UO_2. This study presents the advantages of Cr_2O_3-doped UO_2, including better retention of fission products, large grain sizes, and improved creep rate [1]. The slight changes in thermal conductivity because of the addition of a dopant have minimal influence on the fuel performance and melting temperature. The low neutron cross-section of Cr_2O_3 allows for a response function like that of UO_2. During the last two decades, Westinghouse has investigated ADOPT (Advanced Doped Pellet Technology) UO_2 fuel doped with oxides, such as Cr_2O_3 and Al_2O_3 [2]. Accident tolerant fuel (ATF) plans will be soon realized using a Cr coating, i.e., a thin layer of oxide deposited on the zircaloy cladding. Another solution is to use ferritic alloys or Silicon Carbide (SiC) to replace the zirconium alloys [3-5].

ADOPT concept can use a more tolerant cladding, such as SiC and Iron-Chromium Aluminum (FeCrAl) alloys. Currently, EnCore® Fuel project is composed of PROtect program to cover all the safety requirements. Framatome and Westinghouse suggested a well-adjusted formulation, i.e., UO_2 + 500 ppm Cr_2O_3 + 200 ppm Al_2O_3, capable of increasing the grain size from 10 µm to 50–60 µm and enhancing the theoretical densities from 96% to 97.3%. The preferred dopants are reductive oxides exhibiting lower neutron penalties, such as Cr_2O_3, Nb_2O_5, TiO_2, Al_2O_3, MgO, and silicates. Table I shows a few dopant oxides used with UO_2.

Table I: Physical properties of the dopant oxides

Chemical elements	Cr	Al	Mg	Nb	Si	Ti	V
Capture cross-section (Barns)	3.1	0.23	0.064	1.15	0.16	6.1	5.6
Dopant oxides	Cr_2O_3	Al_2O_3	MgO	Nb_2O_5	Si_2O_3	Ti_2O_3	V_2O5

In open literature found reduced results about ADOPT fuels. The IFA-677.1 experiment evaluated the performance of six rods subjected to a high initial rating for Halden Boiling Water Reactor conditions [6]. These tests used two rods containing UO_2 fuel doped with Cr_2O_3 and Al_2O_3, the ADOPT fuel supplied by Westinghouse. It based this study on the fuel licensing code FRAPCON-4.0 adapted to support ADOPT fuel. IFA-677 tests exhibited improved fuel oxidation resistance owing to the addition of Cr [7]. A significant safety advantage is postponing the pellet-cladding interaction (PCI) and desirable creep Cr_2O_3, and cracking behaviors compared to standard UO_2. The United States Nuclear Regulatory Commission (US NRC) has endorsed the FRAPCON system as a licensing code [7]. The FRAPCON system is a computational tool designed to analyze the thermal and mechanical behaviors of a fuel rod under regular operation under steady-state conditions. Presently, audit codes adopted by the USNRC allow the simulation of UO_2, (U, Pu)O_2, UO_2-Gd_2O_3, and zirconium-based alloys.

In addition, the FRAPTRAN code permits transient analysis. The last version, FAST, which unified FRAPCON and FRAPTRAN codes, also permit simulate FeCrAl alloys as cladding [8-9].

2. Materials and Methods

The material properties of the doped fuel, based on Cr_2O_3 and Al_2O_3 additions, are like those of the undoped fuel because of low dopant solubility. Westinghouse and Framatome claimed they dismissed the changes in the thermal properties for low concentrations of dopants. Therefore, in this study, we considered the same models adopted for the standard UO_2. UO_2 has a low thermal conductivity of 8.68 W/m-K at 298 K. It dissolved the metallic oxides in the UO_2 matrix to reduce the fission gas release (FGR) rate.
Material library MATLIB describes all thermal physical properties of the fuel, coded in FORTRAN language. The thermal conductivity of the fuel, FTHCON subcode, the specific heat of fuel FCP, and the thermal expansion FTHEXP may suffer a slight revision to adapt to Cr_2O_3 additions. A critical point of UO_2 doped with Cr_2O_3 refers to the different grain sizes of UO_2, and the Al-doped UO_2 pellets slowly increased with increasing sintering temperature and time. Thus, the higher creep rate exhibited by the ADOPT shows a more viscoelastic behavior. Then, the free space in the pellets keeps fission products, reducing the internal pressure of the rod at the end of its life cycle. The IFA-677.1 manufactured by Westinghouse contained a single cluster of six rods with an active fuel length of about 400 mm and initial enrichment of about 4.95%. The discharge rod average burnup for 500 days achieving 26.3 MWd/kgU. Zircaloy was the cladding material used, and the active stack length for rod 1 was 398.6 mm and 403.5 mm for rod 5. Table II shows two compositions of Cr_2O_3-doped UO_2 fuel analyzed.

Table II: Composition of Cr_2O_3-doped UO_2 fuel used in IFA 677.1

Experiment IFA 677.1	Fuel rod 1	Fuel rod 5
Fuel Cr_2O_3 content (ppm)	900	500
Fuel Al_2O_3 content (ppm)	200	200
Average grain size (µm)	56	45
Fission gas release(%)	19%	19%

As a result, the fission gases xenon and krypton in nuclear fuel impact the fuel performance. These fission gases precipitate into bubbles resulting in fuel swelling, speeding up the PCMI. Thus, the fission gas release model suffers significant changes in terms of diffusion gas coefficients. Doped fuel has a prominent grain size, changing the mechanical responses, creep rate, and decreases the FGR under the same models as UO_2. Equation 1 describes the diffusion coefficients of Cr_2O_3-doped fuel.

$$D^{doped} = \exp\left(-\frac{\Delta H_1}{KB}\left[\frac{1}{T}-\frac{1}{T_1}\right]\right)D_1^{undoped} + \exp\left(-\frac{\Delta H_2}{KB}\left[\frac{1}{T}-\frac{1}{T_1}\right]\right)D_2^{undoped} + D_3^{undoped} \quad (1)$$

where K_B is Boltzmann's constant (ev/K), T is fuel average temperature (K), T_1 is 1773 K, ΔH_1 = 0.3198 (ev), ΔH_2 =-0.3345 (ev). Massih model defines all undoped diffusion coefficients that increase with temperature increasing.
FRAPCON code employs fission gas release based on the traditional Forsberg-Massih model. FGR model defines two coefficients first, intra-granular gas diffusion, which calculates fission gas transport within the fuel grains. In the second stage, calculate the grain-boundary gas involving both fission gas swelling and release. FGR causes pressure build-up and thermal conductivity degradation. Figure 1 shows the diffusion coefficient as a function of the temperature of doped fuel. In this modeling over 1773 K, the diffusion coefficients of doped fuels are higher than UO_2 fuel.

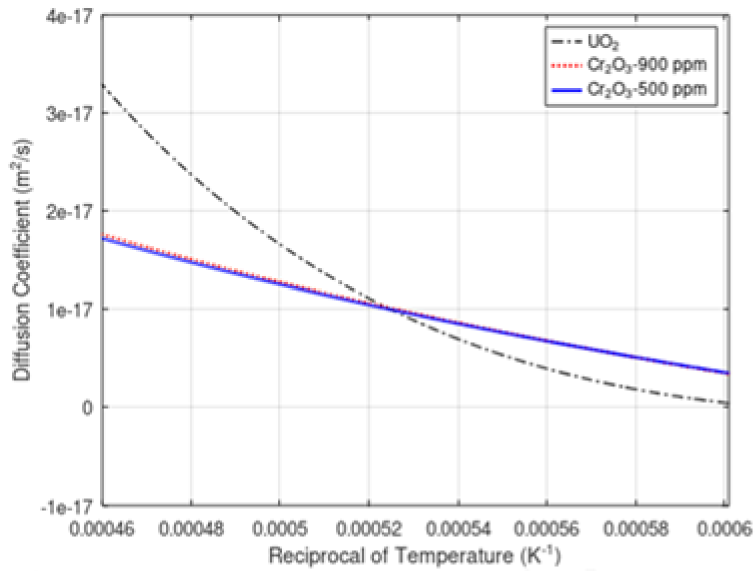

Figure 1: Diffusion coefficients of UO_2 and Cr_2O_3 doped fuel.

3. Results and Discussion

The irradiation cycle applies a linear heating rate ranging from 42 to 46 kW/m, producing the centerline temperature measured between 1500 °C and 1750 °C. The IFA-677 experiment investigated a higher initial reaction rate using doped fuel supplied by Westinghouse and other rods that used standard UO_2, which served as a comparative response. Figure 2 illustrated the FGRs measured and predicted to the doped fuel.

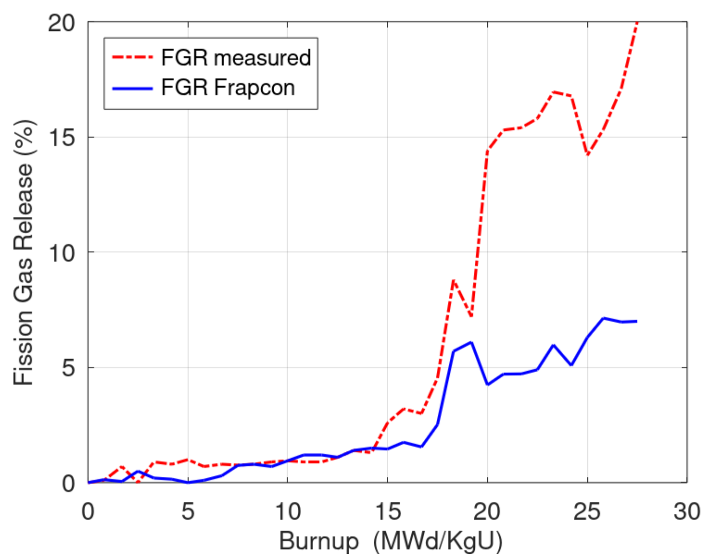

Figure 2: Fission gas release of Cr_2O_3-doped UO_2 fuel

The Cr_2O_3-doped UO_2 exhibited a lower internal rod pressure, and reduced cladding ballooning susceptibility during a hypothetical loss-of-coolant accident. The enlarged grain size minimized the fuel pulverization and degradation levels. IFA-677-rod 5 has predicted FGR of 22.45% and measured values of 16% with a burnup of 26.2 MWd/KgU.

IFA-677 rod 6 undoped fuel showed a predicted FGR of 22.46% and about 19%. Thus, it can conclude the beneficial effects of doped fuel.

4. Conclusions

Most of the material properties of the Cr_2O_3-doped fuel were identical to those of the undoped UO_2. In this study, parameters such as temperature, burn cycle, and concentration of oxide dopants were the relevant factors. Four properties that showed minor changes compared with UO_2 were thermal expansion, thermal conductivity, heat capacity, and fuel enthalpy. The addition of Cr_2O_3 to UO_2 had a slight effect on its thermal properties. The ADOPT pellet fuel exhibited several favorable characteristics: large grain size, increased density (to 10.67 g/cm^3), less FGR, and reduced pellet cladding interactions. During sintering, the ADOPT fuel exhibited a more significant densification and diffusion capacity. The addition of chromium oxide also improved the oxidation resistance in the presence of air and water. A higher creep rate mitigates the pellet cladding contact, improving the mechanical response. The cracking pattern is more homogeneous and relieves the cladding stress. Thus, it concludes that ADOPT fuel is a vital type of ATF option researched by fuel suppliers.

Acknowledgments

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