Journal of Nuclear Materials 502 (2018) 177–190

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Canadian experience in irradiation and testing of MOX fuel

S. Yatabe*, M. Floyd, F. Dimayuga

Canadian Nuclear Laboratories, Chalk River, Ontario K0J 1J0, Canada

HIGHLIGHTS

- MOX performance in experimental irradiations at CNL was very similar to that of UO_2.
- Fission gas release in MOX fuel shows a strong dependence on maximum powers achieved.
- Fission gas release in MOX fuel shows a weaker (secondary) dependence on burnup.
- Fission gas release increases in MOX when the power exceeds 55 kW/m, regardless of burnup.
- Sheath strains in MOX occur at the low end of the range of UO_2 sheath strains.
- Fission-gas release, grain growth and oxide thickness on sheath appear to be related to the homogeneity of the MOX fuel.

ARTICLE INFO

Article history:
Received 28 September 2017
Received in revised form
18 January 2018
Accepted 8 February 2018
Available online 12 February 2018

Keywords:
Plutonium
Mixed oxide
Fuel performance
Fuel homogeneity
Irradiation

ABSTRACT

Experimental irradiation and performance testing of Mixed OXide (MOX) fuel at the Canadian Nuclear Laboratories (CNL) has taken place for more than 40 years. These experiments investigated MOX fuel behaviour and compared it with UO_2 behaviour to develop and verify fuel performance models.

This article compares the performance of MOX of various concentrations and homogeneities, under different irradiation conditions. These results can be applied to future fuel designs.

MOX fuel irradiated by CNL was found to be comparable in performance to similarly designed and operated UO_2 fuel. MOX differs in behaviour from UO_2 fuel in several ways. Fission-gas release, grain growth and the thickness of zirconium oxide on the inner sheath appear to be related to MOX fuel homogeneity. Columnar grains formed at the pellet centre begin to develop at lower powers in MOX than in UO_2 fuel.

1. Introduction

Mixed OXide (MOX) fuel is nuclear fuel that includes more than one oxide of fissile material. MOX usually consists of plutonium (Pu) blended with Natural Uranium (NU), reprocessed uranium, or Depleted Uranium (DU) oxides. It is an alternative to the Low-Enriched Uranium (LEU) fuel used in Light Water Reactors (LWRs). MOX is manufactured from plutonium recovered from used reactor fuel (through reprocessing) or from surplus weapons-grade plutonium and has been manufactured on an industrial scale for approximately 40 years [1].

In-reactor MOX fuel behaviour is similar to that of UO_2 (in terms of crystallographic, physical and neutronic properties). Thus, MOX has been used to replace UO_2 in thermal reactors originally designed to burn UO_2 [2].

MOX has been deployed commercially on a large scale since the 1980s [3]. Approximately 10% of all reactors worldwide use MOX fuel, including approximately 40 LWRs [4].

Experimental MOX fuel irradiations have been conducted by Belgium, Canada, the Commission of the European Communities (now European Commission), France, Germany, Japan, Organization for Economic Cooperation and Development (OECD) (Halden, Norway), United Kingdom, and the U.S.A. [5]. The purpose of these experiments (some of which are still underway) is to compare MOX and UO_2 behaviour, develop MOX fuel performance models, and validate design codes. Fabrication procedures, fuel rod geometries, and operating conditions have also been investigated [5].

This report summarizes MOX irradiation testing in Canada. Canadian Nuclear Laboratories (CNL, formerly Atomic Energy of Canada Limited (AECL)) has over 40 years of experience in the manufacture, irradiation testing, and post-irradiation examination (PIE) of MOX Pressurized Heavy Water Reactor (PHWR) fuel.

* Corresponding author.
E-mail addresses: Susan.Yatabe@cnl.ca (S. Yatabe), Mark.Floyd@cnl.ca (M. Floyd), Ike.Dimayuga@cnl.ca (F. Dimayuga).

https://doi.org/10.1016/j.jnucmat.2018.02.015
0022-3115/

Abbreviations

AECL	Atomic Energy of Canada Limited
CivPu	Civilian Plutonium
CNL	Canadian Nuclear Laboratories
DU	Depleted Uranium
FGR	Fission-Gas Release
GG	Grain Growth
HE	Heavy Elements
HFA	High Fission Area
ID	Inside Diameter
INTER	Intermediate
LEU	Low-Enriched Uranium
LWR	Light Water Reactor
MIMAS	MIcronized MASter Mix
MOX	Mixed OXide
NPD	Nuclear Power Demonstration
NRU	National Research Universal
NU	Natural Uranium
OD	Outside Diameter
OE	Outer Element
OECD	Organization for Economic Cooperation and Development
PHWR	Pressurized Heavy Water Reactor
PIE	Post-Irradiation Examination
SCC	Stress-Corrosion Cracking
SEU	Slightly Enriched Uranium
WPu	Weapons-grade Plutonium

Conventional MOX (U, Pu)O_2 fuel bundles have been irradiated in both the Nuclear Power Demonstration (NPD) and National Research Universal (NRU) reactors. Key parameters used in the evaluation of PHWR fuel performance include fission-gas release (from the fuel pellets to the internal free void) and diametral sheath strain [6–8].

CNL facilities can fabricate up to 12 kg of MOX per day. CNL can produce fuels with a wide range of (U, Pu)O_2 microstructures. Homogeneous fuels approaching solid solution have been produced for experiments at CNL, as well as heterogeneous fuels consisting of pure PuO_2 particles within a UO_2 matrix.

Early CNL MOX experiments demonstrated that MOX performance was similar to that of UO_2. Experimental work progressed to include testing of various overall concentrations of Pu and different levels of Pu homogeneity in the MOX fuel.

The CNL MOX fuel program, through the irradiation of fuel bundles in NPD and NRU, has encompassed fuel fabrication development, hot-cell PIE, reactor physics and fuel management.

(Th, Pu)O_2 bundles have also been irradiated in the NRU reactor. These (Th, Pu)O_2 irradiations are described in Refs. [6–11].

2. Description of CNL MOX experiments

This section describes the experimental irradiation campaigns conducted at CNL from 1973 to the present.

CNL has irradiated 25 MOX fuel bundles as part of five major experimental campaigns, described in this paper. Elements from these bundles varied in terms of fuel matrix, overall Pu content and microstructure. Investigations progressed from early studies of the irradiation of experimental MOX fuel elements to the irradiation of full-scale PHWR-design fuel bundles incorporating MOX fuel pellets. Linear powers of up to 66 kW/m and burnups approaching 49 MWd/kgHE have been attained. In this paper, the term “wt. % plutonium in total heavy elements” will be referred to as “wt. %”. Plutonium concentration has ranged from 0.5 to 5.3 wt. % Pu in total HE (Heavy Elements).

Table 1 summarizes the characteristics of the fuels used in each experiment and includes power history information (and in the case of bundles **AKL**, **AMD** and **AMC**, each grouping of elements based on fuel composition). The MOX bundles irradiated at CNL were organized into concentric rings of elements, labelled in the table as OUTER, INNER or INTER (for intermediate) rings. Appendix A provides an illustration of the arrangement of elements and rings in experimental bundles, as well as an explanation of the power distribution associated with the experimental fuel string as mounted in the NRU loop test section.

2.1. NPD-40

MOX bundles were irradiated at CNL as part of the NPD-40 experiment, from 1973 to 1987. NPD-40 demonstrated MOX irradiation to high burnup, under typical pressurized heavy water reactor operating conditions [7,12]. They were irradiated in the NPD reactor.

Six 19-element bundles, fabricated with dry-blended MOX fuel of 3.0–3.3 wt. % Pu, experienced a declining power history from beginning-of-life mid-plane outer element (OE) power ratings up to 50 kW/m to OE burnups of 49 MWd/kgHE.

Table 2 lists chemically-determined burnups for each NPD-40 bundle (by element ring) [13]. Fuel Type I contained annular pellets and standard, collapsible Zr-4 sheathing; Fuel Type II had thick-wall, free-standing (able to withstand collapse) Zr-4 sheathing encasing solid, low-density pellets. Free-standing sheathing was used to prevent possible loss of pellet support resulting from fuel densification. Fuel Type II, with a density of 10.2 Mg/m^3, had increased internal voidage (porosity) to accommodate pellet swelling. Fuel Type I had a density of 10.5 Mg/m^3 or greater, typical of sintered, enriched UO_2.

No defects occurred during the NPD irradiation; dimensional changes and fission-gas release (FGR), which ranged from 2 to 3% in the bundles that were not ramped, were minimal. Following the NPD irradiation, three bundles (**KA**, **KE** and **KF**) were power-ramped in NRU at about 17 MWd/kgHE [7,12]. Bundles **KA** and **KE** were power ramped in 1976, and bundle **KF** in 1981. Failures occurred in bundles **KA** and **KE.** The low density pellets and thick-walled, free-standing sheaths of bundle **KE** exhibited a higher failure threshold (~70 kW/m) than **KA** (49 kW/m).

2.2. BDL-419

The BDL-419 experiment demonstrated that MOX fuel can sustain the operating requirements of PHWRs to burnups >17 MWd/kgHE [14]. In general, the BDL-419 bundles exhibited performance comparable to similarly designed and operated natural UO_2 power reactor bundles.

BDL-419 began in 1980 with 15 36-element fuel bundles containing 0.5 wt. % plutonium in NU. These were irradiated in NRU at powers up to 66 kW/m and to OE burnups ranging from 7 to 38 MWd/kgHE. Bundle **ADR**, with a current OE burnup of 38 MWd/kgHE, continues irradiation to a target burnup exceeding 42 MWd/kgHE. Fourteen BDL-419 bundles have completed their irradiation to OE burnups between 7 and 36 MWd/kgHE. PIE has been completed on seven bundles (**ABB**, **ABC**, **ABD**, **ABE**, **ADN, ADP** and **ADM**).