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A COPA Fission Product Release Analysis for a Gen-IV Numerical Calculation Case

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1. Introduction

The fission product (FP) release analysis module FPRC of the COPA code [1,2] is used to calculate the temperature distribution in a coated fuel particle (CFP) of a high temperature reactor (HTR), the FP distribution in a CFP, and the FP release from a CFP. Because it is a major FP source within an HTR fuel element such as a compact or a pebble, the FP release from a CFP must be accurately evaluated.

The COPA code has been verified through the participation in the accident condition (AC) benchmarking of the IAEA CRP-6 [1]. The first part of the accident benchmark problems of the IAEA CRP-6 is a sensitivity study to examine an FP release from a CFP starting with a bare kernel and ending with an irradiated CFP. In the sensitivity study, most results of the COPA code have been in good agreement with other countries' code results. For an irradiated CFP, some differences have been resulted from different assumptions for input data or boundary conditions, and different time step lengths [1].

Another AC benchmarking task on the FP releases from a CFP has been performed in the frame of Gen-IV [3,4], as a follow-on of the CRP-6 AC benchmark. This study summarizes the calculation of the FP releases from a CFP using the COPA FPRC module for a Gen-IV numerical calculation case (NCC) problem [4]. The COPA calculation results have been compared to the calculation results of the PARFUME code [5].

2. Numerical Calculation Case

Ref. [3] describes the details of the NCC such as the irradiation characteristics to check for potential numerical effects, the irradiation temperatures which consist of ten successive linear ramps from 600 to 1000 ℃ during an irradiation length of 100 EFPD each, the fuel properties, the CFP properties, the boundary conditions, and the heating test plan, as shown in Tables I to IV.

Table I: NCC fuel modeling parameters

Category	Parameter	Mean Value
Fuel properties	U-235 enrichment (wt%)	10
	Oxygen/uranium (atomic ratio)	2
	Carbon/uranium (atomic ratio)	0
	Uranium contamination fraction	0
Particle properties	Kernel diameter (μm)	350
	Buffer thickness (μm)	100
	IPyC thickness (μm)	40
	SiC thickness (μm)	35
	OPyC thickness (μm)	40
	Kernel density (g/cm^3)	10.8
	Kernel theoretical density (g/cm^3)	10.96
	Buffer density (g/cm^3)	0.95
	Buffer theoretical density (g/cm^3)	2.25
	IPyC density (g/cm^3)	1.9
	SiC density (g/cm^3)	3.20
	OPyC density (g/cm^3)	1.9
	IPyC anisotropy (BAF)	1.03
	OPyC anisotropy (BAF)	1.03
	Particle asphericity (SiC level)	1.0
Boundary conditions	Ambient pressure (MPa)	0.1

Table II: NCC irradiation characteristics

Burnup (%FIMA)	Fast Fluence (10^{25} n/m^2; E > 0.18 MeV)	Irradiation Length (EFPD)
10[a]	2[a,b]	1000

[a]Burnup and fast fluence assumed to follow linear evolution throughout irradiation.
[b]Fast Fluence (E > 0.18 MeV) = 0.91 × Fast Fluence (E > 0.1 MeV)

Table III: NCC irradiation temperatures

Cycle Number	Cycle EFPD	Surface temperature (°C)
1	100	Ramp 600 → 1000
2	100	Ramp 600 → 1000
3	100	Ramp 600 → 1000
4	100	Ramp 600 → 1000
5	100	Ramp 600 → 1000
6	100	Ramp 600 → 1000
7	100	Ramp 600 → 1000
8	100	Ramp 600 → 1000
9	100	Ramp 600 → 1000
10	100	Ramp 600 → 1000

Table IV: NCC safety test heating plan

Time (hh:mm)	Temperature (°C)
00:00	1000
00:01	1600
200:01	1600

3. Calculation and comparison

The fractional releases of the radioactive isotope ^{137}Cs, ^{110m}Ag, ^{90}Sr and ^{85}Kr were calculated. For an irradiation, the fractional release of a radioactive isotope is defined as the ratio of the accumulated amount of atoms which are released but not decayed yet to the amount of atoms which are generated but not yet decayed. For a heating test, it is defined as the ratio of

the accumulated amount of atoms which are released but not decayed yet to the amount of atoms which are generated until the end of irradiation but not yet decayed.

Table V shows the calculated fractional release data for Ag, Cs, Sr, and Kr after irradiation and the subsequent heating phase. Figs. 1 and 2 show the calculated fractional releases over time in the irradiation and safety phases, respectively. Silver results come in good agreement after irradiation, between 1.6×10^{-5} for COPA and 6.7×10^{-5} for PARFUME, and come in very good agreement after the heating phase with the fractional releases between 46% for COPA and 50% for PARFUME.

Cesium release is negligible after irradiation, with the fractional releases from 9.8×10^{-14} for COPA to 1.8×10^{-12} for PARFUME. The discrepancies of up to two orders of magnitude between the codes may be dominated by numerical calculation effects rather than by differences in the physical model. After the heating phase, the codes are in fairly good agreement with the fractional releases between 4.2×10^{-4} for COPA and 6.7×10^{-4} for PARFUME.

Strontium shows a pretty large discrepancy after irradiation with the fractional release of the low PARFUME result of 4.3×10^{-11} compared to the COPA result of 2.2×10^{-6}. After the heating phase, the fractional releases are in very good agreement with the fractional releases between 3.1×10^{-2} for PARFUME and 3.3×10^{-2} for COPA.

Krypton release is negligible both after irradiation and the heating phase. The low numerical values and large discrepancies between the codes fall into the realm of calculation accuracy.

Physical models of COPA and PARFUME have been summarized in Ref. [4]. There is no big difference in the models. The discrepancy in the fractional releases of the irradiation phase is highly likely to be resulted from different assumptions for input data or boundary conditions, and different time step lengths, as in the CRP-6 AC benchmark.

4. Summary

For the Gen-IV NCC benchmark problem, the fractional releases of ^{137}Cs, ^{110m}Ag, ^{90}Sr and ^{85}Kr from a CFP have been calculated using the COPA code and compared to the PARFUME code results. After irradiation, silver fractional releases are in very good agreement, but there are large discrepancies between the fractional releases of cesium, strontium, and krypton. After heating, between the fractional releases of silver, cesium, and strontium are in fairly good agreement, but a little bit large discrepancy have occurred for krypton. It has been concluded through the comparison of the two codes' physical models that the discrepancies resulted from a numerical calculation accuracy, not from differences in the physical model.

ACKNOWLEDGEMENTS

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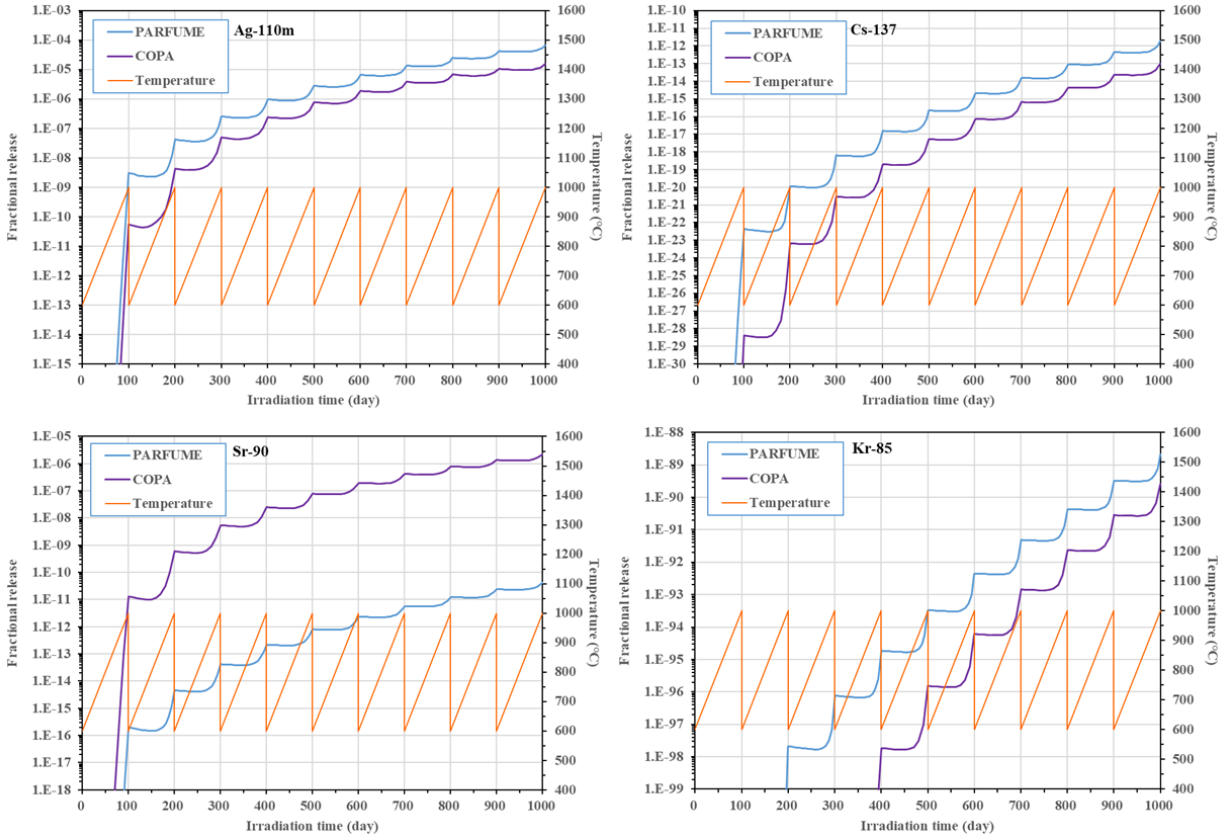

Fig. 1. Calculated Ag, Cs, Sr, and Kr fractional releases during NCC irradiation.

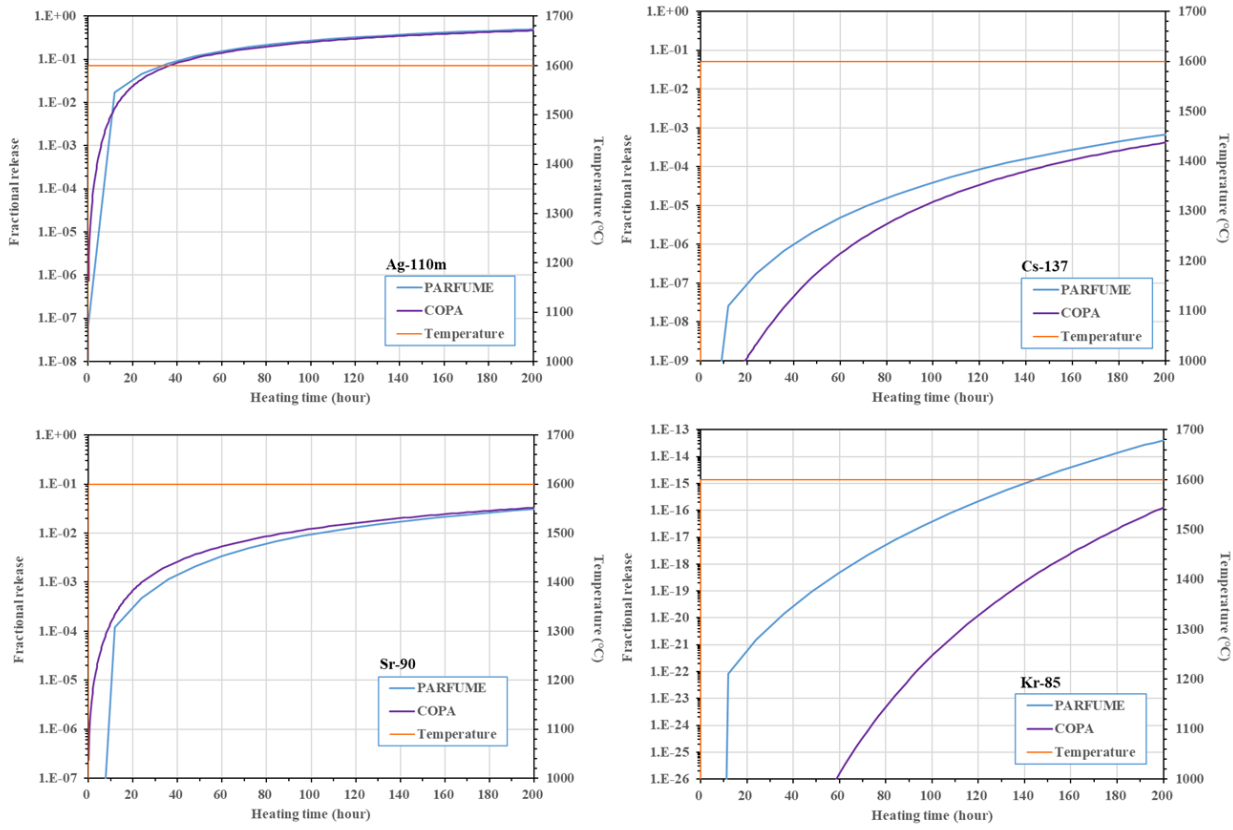

Fig. 2. Calculated Ag, Cs, Sr, and Kr fractional releases during NCC safety testing.

Table V: Calculated Ag, Cs, Sr, and Kr fractional releases for the NCC

	After irradiation				After 200h heating			
	Ag	Cs	Sr	Kr	Ag	Cs	Sr	Kr
PARFUME	6.7×10^{-5}	1.8×10^{-12}	4.3×10^{-11}	2.1×10^{-89}	5.0×10^{-1}	6.7×10^{-4}	3.1×10^{-2}	4.0×10^{-14}
COPA	1.6×10^{-5}	9.8×10^{-14}	2.2×10^{-6}	2.6×10^{-90}	4.6×10^{-1}	4.2×10^{-4}	3.3×10^{-2}	1.3×10^{-16}