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Effect of Fuel Structure Materials on Radiation Source Term in Reactor Core Meltdown

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1. Introduction

The fission product (Radiation Source) releases from the reactor core into the containment is obligatorily evaluated to guarantee the safety of Nuclear Power Plant (NPP) under the hypothetical accident involving a core meltdown. The initial core inventory is used as a starting point of all radiological consequences and effects on the subsequent results of accident assessment. Hence, a proper evaluation for the inventory can be regarded as one of the most important part over the entire procedure of accident analysis.

The inventory of fission products is typically evaluated on the basis of the uranium material (e.g., UO2 and USi2) loaded in nuclear fuel assembly, except for the structure materials such as the end fittings, grids, and some kinds of springs. However, the structure materials are continually activated by the neutrons generated from the nuclear fission, and some nuclides of them (e.g., ^{14}C and ^{60}Co) can significantly influence on accident assessment. During the severe core accident, the structure components can be also melted with the melting points of temperature relatively lower than uranium material. Therefore, it is necessary to analyze the kind and activity of the radionuclides produced in fuel structure materials although this consideration is not included in the regulatory guides.

In this study, the nuclear assembly (CE16×16) loaded in Ulchin unit 5 and 6 was considered for activation calculation of the fuel structure material. A series of the calculation were performed by using ORIGEN-S module in SCALE 6.1 package code system [1]. The total activity in each part of structure materials was specifically analyzed from these calculations.

2. Materials and Methods

The nuclear fuel assembly loaded in the core of Ulchin unit 6 is composed of a 16×16 array of 236 fuel rods and 5 guide tubes welded to spacer grids, which is closed at the top and bottom by end fittings. Especially, the structure materials such as the end fittings, grids, and some kinds of springs are made with various alloys of Stainless Steel, Inconel, and Zircaloy. During the period loaded in the core, these materials are continually activated by fission neutrons, and daughter nuclides (radionuclides) should be considered to derive the conservative results for radiological consequences and accident assessment.

In this study, the ORIGEN-S module in SCALE 6.1 package code system is used for activation calculations of these materials, and the details of those are presented in **Table 1**. The hardware structure of CE 16×16 can be classified into upper plenum, end fitting, cladding, and grid, and upper end fitting and cladding accounts for nearly 90% of total weight. The Scaling factor is also applied to reflect the change of neutron flux outside the active fuel region. The average neutron flux is obtained from the axial neutron flux distribution for the BOC and EOC of Ulchin unit 6. The elemental composition in each part of nuclear fuel assembly is specifically shown in **Table 2**.

3. Results and Discussions

The activation calculations of fuel structure materials were performed and the total activities of each component were obtained as shown in **Table 3**. The Zircaloy-4 material which is the greater part of metal structure covers almost all the rest of the total activity. Most of activity results from the lower end fitting and the upper plenum, except for the cladding material. The upper grid on the other hand releases activities relatively lower than others. The activation of the structures is directly related to the neutron flux in each part as well as the elemental composition of the materials.

Table 1 Classification and Main Properties of Fuel Assembly Structure

Region		Materials	Weight [kg]	Scaling Factor	Average Neutron Flux	Neutron Flux in Each Region
Cladding		Zircaloy-4	126	1.00	4.0E+13	4.0E+13
End Fitting	Upper	Stainless Steel 304	11	0.05		2.0E+13
	Lower		6	0.20		8.0E+13
	Spring	Inconel X750	5	0.05		2.0E+13
Upper Plenum		Stainless Steel 302	4	0.20		8.0E+13
Grid	Upper	Zircaloy-4	1	0.20		8.0E+13
	Lower	Inconel 625	1	0.20		8.0E+13

Table 2 Elemental Composition of Fuel Assembly Structural Materials [grams]

Element	Cladding	Upper End Fitting	Lower End Fitting	End Fitting Spring	Upper Plenum	Upper Grid	Lower Grid
H	1.638E+00	-	-	-	-	1.300E-02	-
B	4.158E-02	-	-	-	-	3.300E-04	-
C	1.512E+01	8.800E+00	4.800E+00	1.995E+00	6.000E+00	1.200E-01	1.000E+00
N	1.008E+01	1.430E+01	7.800E+00	6.500E+00	5.200E+00	8.000E-02	-
O	1.197E+02	-	-	-	-	9.500E-01	-
Al	3.024E+00	-	-	3.991E+01	-	2.400E-02	4.000E-01
Si	-	1.100E+02	6.000E+01	1.497E+01	4.000E+01	-	-
P	-	4.950E+00	2.700E+00	-	1.800E+00	-	-
S	4.410E+00	3.300E+00	1.800E+00	3.500E-01	1.200E+00	3.500E-02	-
Ti	2.520E+00	-	-	1.247E+02	-	2.000E-02	4.000E-01
V	2.520E+00	-	-	-	-	2.000E-02	-
Cr	1.575E+02	2.090E+03	1.140E+03	7.483E+02	7.200E+02	1.250E+00	2.100E+02
Mn	2.520E+00	2.200E+02	1.200E+02	3.492E+01	8.000E+01	2.000E-02	-
Fe	2.835E+02	7.573E+03	4.131E+03	3.392E+02	2.791E+03	2.250E+00	5.000E+01
Co	1.260E+00	8.800E+00	4.800E+00	3.243E+01	3.200E+00	1.000E-02	1.000E+01
Ni	2.520E+00	9.812E+02	5.352E+02	3.609E+03	3.568E+02	2.000E-02	6.200E+02
Cu	2.520E+00	-	-	2.495E+00	-	2.000E-02	-
Zr	1.234E+05	-	-	-	-	9.791E+02	-
Nb	-	-	-	4.490E+01	-	-	3.500E+01
Mo	-	-	-	-	-	-	9.000E+01
Cd	3.150E-02	-	-	-	-	2.500E-04	-
Sn	2.016E+03	-	-	-	-	1.600E+01	-
Hf	9.828E+00	-	-	-	-	7.800E-02	-
W	2.520E+00	-	-	-	-	2.000E-02	-
U	2.520E-02	-	-	-	-	2.000E-04	-

The **Figure 1** shows the activity of main nuclides which contribute greatly to the total activity of each structure component. The upper/lower end fitting and the upper plenum are commonly affected from the nuclides of ^{56}Mn, ^{51}Cr, ^{55}Fe, ^{58}Co, ^{54}Mn, and ^{60}Co. This result means that these are produced from their parent nuclides, generating a large amount of activity during their decay procedure. In particular, it is very important that some of them have very small quantities but enough to induce high activity. The activated structures are needed to be considered for the accident source term because the initial inventory in the accident is used for the radiological consequences assessment regardless of the half-lives of the nuclides.

Table 3 Total Activity of Each Fuel Assembly Structure

Region		Activity [Bq]
Cladding		5.88E+15
End Fitting	Upper	7.97E+13
	Lower	1.73E+14
	Spring	4.17E+13
Upper Plenum		1.14E+14
Grid	Upper	9.36E+12
	Lower	3.77E+13
Total		6.34E+15

4. Conclusions

The fission product inventory is generally evaluated based on the uranium materials of fuel only, even though the structure components of the assembly are continually activated by the neutrons generated from the nuclear fission. In this study, the activation calculation of the fuel structure materials was performed for the initial source term assessment in the accident of reactor core meltdown. As a result, the lower end fitting and the upper plenum greatly contribute to the total activity except for the cladding material. The nuclides of ^{56}Mn, ^{51}Cr, ^{55}Fe, ^{58}Co, ^{54}Mn, and ^{60}Co are analyzed to mainly effect on the activity. This result can be used for the preliminary data of the accident source term considering the fuel structure material of assembly.

Acknowledgements

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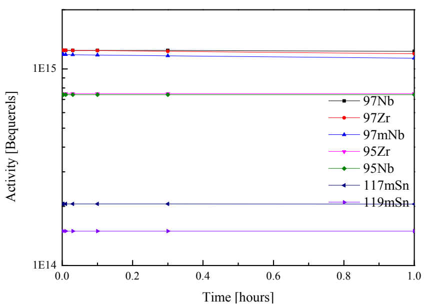
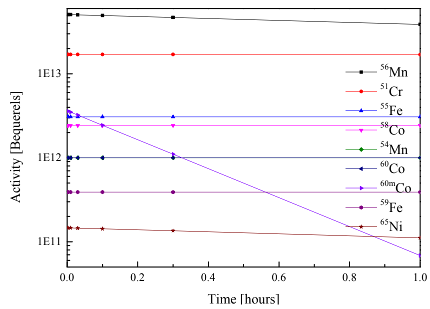
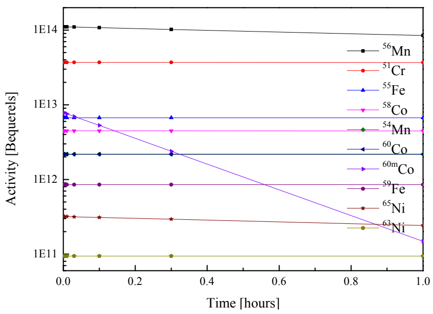


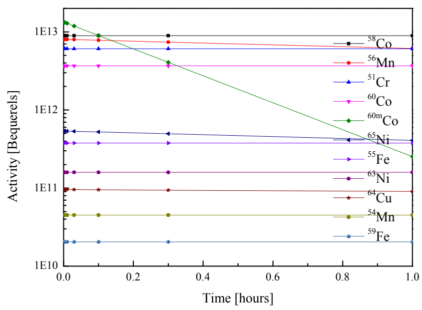
(a) Cladding



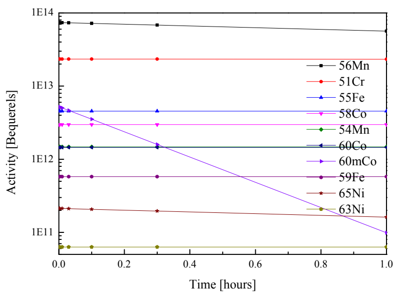
(b) Upper End Fitting



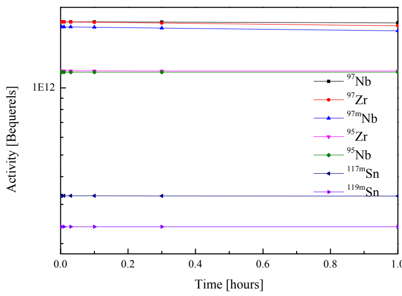
(c) Lower End Fitting



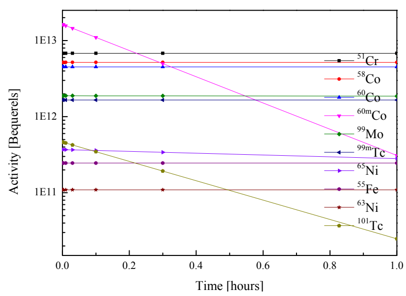
(d) End Fitting Spring



(e) Upper Plenum



(f) Upper Grid



(g) Lower Grid

Fig. 1 Activity Change of Major Nuclides for Each Fuel Structure Part