# 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 are obligatorily evaluated to guarantee the safety of a Nuclear Power Plant (NPP) under a 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 the accident assessment. Hence, a proper evaluation for the inventory can be regarded as one of the most important parts over the entire procedure of an accident analysis.

The inventory of fission products is typically evaluated on the basis of the uranium material (e.g., $UO_2$ and $USi_2$) loaded in nuclear fuel assembly, except for the structure materials such as the end fittings, grids, and some types 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 an accident assessment. During a severe core accident, the structure components can also be 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 units 5 and 6 was considered for the activation calculation of the fuel structure material. A series of calculations were performed using the ORIGEN-S module in the SCALE 6.1 package code system [1]. The total activity in each part of structure materials was specifically analyzed from these calculations.

## 2. METHODS AND MATERIALS

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 the spacer grids, which is closed at the top and bottom by end fittings. In particular, 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 the SCALE 6.1 package code system is used for activation calculations of these materials, and the details of these are presented in Table 1. The hardware structure of CE 16×16 can be classified into upper plenum, end fitting, cladding, and grid, where the upper end fitting and cladding account for nearly 90% of the total weight. The scaling factor is also applied to reflect the change in 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 the nuclear fuel assembly is specifically shown in Table 2.

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 | - |

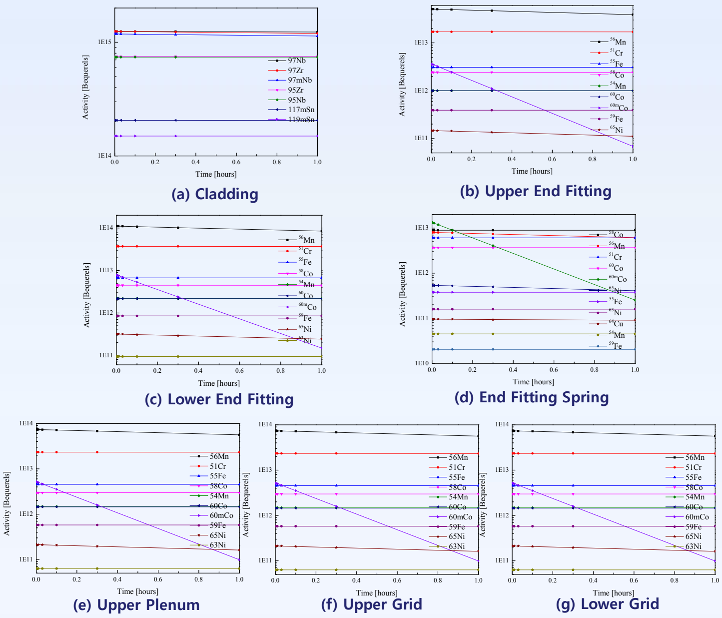
## 3. RESULTS AND DISCUSSIONS

Activation calculations of the 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 of the remaining total activity. Most of the 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 the 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 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 |

The Figure 1 shows the activity of the 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 that are sufficient 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.



(a) Cladding (b) Upper End Fitting (c) Lower End Fitting (d) End Fitting Spring (e) Upper Plenum (f) Upper Grid (g) Lower Grid

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

## 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 the 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 the activity. This result can be used for the preliminary data of the accident source term considering the fuel structure material of the assembly.