Summary of a Study on Fuel Cladding Failure Detection Systems of Japan Experimental Fast Breeder Reactor "JOYO"

by

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I. Introduction

In the experimental fast breeder reactor "JOYO", that is the first sodium-cooled fast reactor in Japan (50 MWt power output and eventually increased 100 MWt), two independent fuel cladding failure detection systems are installed.

One of these, called Delayed Neutron Detection (DND) system, monitors the primary coolant sodium for delayed neutron-emitting fission products. The other, called Cover Gas Detection (CGD) system, monitors the argon cover gas for gaseous fission products.

In the sodium-cooled fast breeder reactors, the detection of fuel failure is very difficult because of high backgrounds due to both fission products from fissile impurity in sodium and gamma activities from Na-24 and A-41. "Fission background", which arises from the fissile impurity, is very important for the fuel cladding failure detection system, because this background is essentially indistinguishable from the fuel failure signal.

"Non-fission background", which is caused by gamma-activities of Na-24 and A-41 and by stray radiations from the core, can be reduced to tolerable level by means of shielding and electronics.

Therefore the fission background gives the minimum counting rate in the system and the lower limit of sensitivity.

Fission background and sensitivity were evaluated and then system design studies were carried out.

Summary of studies are described in the following section.
II. Evaluation of Fission Background and Sensitivity on the DND and the CGD Systems

For the DND and the CGD systems, activity levels of the fission background and fuel failure were calculated and then the sensitivity was evaluated in comparison between both levels.

Surface contamination of fuel pins and natural uranium impurity in sodium are considered as the fission background.

Calculating Models

Simplified models as shown in Figs. 1 and 2 are employed for calculation on the background and the fuel failure signals.

Main assumptions are as follows;

1. Fission products suddenly burst upon the fuel failure.
2. Characteristics of the core are represented by a point.

Equations for the calculations are listed in the last and numerical data are given in Table 1.

Calculation of Background Level

Assuming the surface contamination of 10 dpm/100 cm$^2$ and the natural uranium concentration of 50 ppb in sodium, the total amount of fissile materials is 44 μg/l in sodium (Table 2).

The following results are obtained.

- Background level of DND system — $1.30 \times 10^3$ dps/l of sodium
- Background level of CGD system — $1.53 \times 10^4$ dps/l of argon

Calculation of Failure Signal Level

Assuming that fission products are suddenly released from PuO$_2$-UO$_2$ of 10 mg, the following results are obtained.

- Signal level of DND system — $1.67 \times 10^3$ dps/l of sodium
- Signal level of CGD system — $4.35 \times 10^4$ dps/l of argon
Sensitivity Evaluation

Table 3 and 4 show the results of sensitivity evaluation, in which fuel failure detection limits are specified with double background level.

It is estimated that detection limit of the DND system is burst fuel failure of 7.8 mg and CSD system is 3.5 mg. As a reference, the amount of these failures can be given by the exposure area of 1.5 cm² and 0.67 cm², respectively, if the fission product release is based on recoil.
III. System Design Studies

The system must be designed so as (i) to have appropriate counting rate during normal reactor operation and upon the fuel failure and (ii) to be shielded against the "non-fission background" to tolerable level. Before the construction, some system design studies were carried out.

Evaluation of Signal Counting Rate

(i) The DND system

Fig. 3 shows the ordinary detector - moderator system of DND, where sampled sodium passes through the graphite moderator.

For simplification of the system, a different graphite moderator system, installed beside the primary coolant pipe, has been studied. Its schematic diagram is shown in Fig. 4.

Delayed neutron counting rate in the ordinary and simplified systems were calculated and the results are given in Table 5.

The counting rate in the simplified system seems to be acceptable and the design is being proceeded under this concept.

(ii) The CJD system

In the CJD system, a wire precipitator will be employed. The fission background counting rate is estimated and the result is shown in Table 6.

Shielding Design

(i) The DND system

In this system, the background arises mainly from the gamma activity of Na-24 in the primary coolant pipe. The dose rate is approximately estimated $10^3$ R per hour at the detector - moderator position under the steady state.

According to our estimation, the gamma background must be reduced to 0.1 R per hour in order to avoid the gamma pile-up in neutron detector.

The lead shielding of 20 cm - thick is required around the detector - moderator.
The core neutron shielding may be required but detailed calculation will be made after final reactor shielding design.

(ii) The CGD system

A-41 and Na-24 are sources of gamma background. For the evaluation of their effects in the precipitator, the activity levels of the A-41, Na-24 and the fission background have been calculated. 99% removal efficiency of the sodium vapor trapping was taken in this calculation. The results are listed in Table 7.

As a result it can be said that

(1) the sodium vapor trap with removal efficiency of 99% is sufficient for this CGD system even if the total amount of Na-24 vapor is adsorbed on the precipitator wire, and

(2) the gamma background of A-41 must be reduced to less than $10^{-3}$ by shielding.
IV. Conclusion and Future Works

As a result of above studies, the following conclusions have been obtained.

(1) In "JOYO", natural uranium impurity in sodium is dominant as the fission background, which restrict the detection limit and also gives the minimum background counting.

(2) Sensitivity of CGD system is higher than that of DND system, although it depends on the fuel failure mechanism and the fission products behaviors in sodium and cover gas.

(3) For designing and fabricating the systems, the following works will be necessary at least.

(i) Delayed Neutron Detection system
    To investigate the counting efficiency of detector - moderator system to obtain the appropriate delayed neutron counting.

(ii) Cover Gas Detection system
    (a) Investigation on counting efficiency and shielding effect of precipitator.
    (b) Development of sodium vapor trap easily maintained and investigation of its vapor trapping efficiency.

Block diagrams of the DND and the CGD systems preliminary designed are shown in Figs. 5, 6 and 7.
Equations

DND system

Background

\[ n(DN) = \sum_i \rho_{BG} \sigma_f \phi Y_i e^{-\sigma_f \Phi^* (1-e^{-\lambda_{it} t})} e^{-\lambda_{it} t} \]

\[ t^* = t_c \times t / t_r \]  
(dps/1 of sodium)

Signal

\[ n(DN) = \sum_i \rho_{BG} \sigma_f \phi Y_i e^{-\sigma_f \Phi^* (1-e^{-\lambda_{it} t})} e^{-\lambda_{it} t} \]

(dps/1 of sodium)

CGD system

Background

\[ n(CG) = \sum_j \rho_{BG} \frac{Y_j}{Y_a} \sigma_f \phi Y_j e^{-\sigma_f \Phi^* \frac{E \lambda_j(2)}{\lambda_j(1)} (1-e^{-\lambda_j(1) t})} \]

\[ \times e^{-\lambda_j(1) t a} (1-e^{-\lambda_j(1) t p}) e^{-\lambda_j(2) t a} \]  
(dps/1 of argon)

Signal

\[ n(CG) = \sum_j \rho_{BG} \sigma_f \phi Y_j e^{-\sigma_f \Phi^* \frac{E \lambda_j(2)}{\lambda_j(1)} (1-e^{-\lambda_j(1) t})} \]

\[ \times e^{-\lambda_j(1) t a} (1-e^{-\lambda_j(1) t p}) e^{-\lambda_j(2) t a} \]  
(dps/1 of argon)
where,

\( n(DN) \) : Emission rate of delayed neutrons in 1 litre of sodium at the detector position

\( n(CC) \) : Emission rate of decay beta rays from daughter nuclide in 1 litre of argon gas at the detector position

\( N_{BG} \) : No. of fissile atoms in 1 litre of sodium

\( N_s \) : No. of fissile atoms released

\( J_f \) : Microscopic fission cross section \( (\text{cm}^2) \)

\( \phi \) : Average neutron flux in core \( (n/\text{cm}^2\cdot\text{sec}) \)

\( i \) : Subscript which expresses the \( i \)-th group of delayed neutrons

\( j \) : Subscript which expresses the \( j \)-th parent (1) or daughter (2) nuclide

\( Y \) : Fission yield

\( \lambda \) : Decay constant \( (\text{sec}^{-1}) \)

\( t \) : Reactor operating time (irradiation time) at full power \( (\text{sec}) \)

\( t_c \) : Transit time of coolant through the core \( (\text{sec}) \)

\( t_d \) : Transit time of delayed neutron precursors from core to detector position \( (\text{sec}) \)

\( t_r \) : One round time of coolant through the primary coolant system \( (\text{sec}) \)

\( t_a \) : Transit time of rare gases from core to precipitator \( (\text{sec}) \)

\( t_p \) : Soak time of the wire in precipitator chamber \( (\text{sec}) \)

\( t_e \) : Transit time from precipitator chamber to detector position \( (\text{sec}) \)

\( E \) : Precipitation efficiency

\( V_c \) : Volume of coolant in reactor core region \( (\text{l}) \)

\( V_p \) : Volume of upper plenum coolant in reactor vessel \( (\text{l}) \)

\( V_a \) : Volume of reactor cover gas plenum \( (\text{l}) \)
Table 1. Numerical Data

Reactor power
Fuel materials (Core) 18 w/o PuO₂–UO₂
Average neutron flux \(2 \times 10^{15} \text{n/cm}^2\text{.sec}\)
Burn up \(2 \times 10^4 \text{MWd/T}
Natural uranium impurity in sodium 50 ppb
Surface contamination of fuel pins 10 dpm/100 cm²
Transit time of coolant through the core 0.16 sec
Transit time of delayed neutrons from core to detector position 25 sec
Transit time of rare gases from core to precipitator 75 sec
Precipitation efficiency 80 %

Table 2. Amount of Fissile Materials in Sodium

<table>
<thead>
<tr>
<th>Species</th>
<th>Surface contamination (µg/l)</th>
<th>Impurity (µg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu-239</td>
<td>(6.23 \times 10^{-9})</td>
<td>---</td>
</tr>
<tr>
<td>Pu-240</td>
<td>(2.22 \times 10^{-9})</td>
<td>---</td>
</tr>
<tr>
<td>Pu-241</td>
<td>(0.44 \times 10^{-9})</td>
<td>---</td>
</tr>
<tr>
<td>U-235</td>
<td>0.005</td>
<td>0.3</td>
</tr>
<tr>
<td>U-238</td>
<td>1.438</td>
<td>42.7</td>
</tr>
<tr>
<td>Total</td>
<td>44 (µg/l)</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Sensitivity of DND System

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of fissile</td>
<td>10 mg (PuO₂-UO₂)</td>
<td>44 μg/l of sodium (Natural Uranium)</td>
</tr>
<tr>
<td>materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission rate of</td>
<td>1.67 x 10³ dps/l of</td>
<td>1.30 x 10³ dps/l of sodium</td>
</tr>
<tr>
<td>delayed neutrons</td>
<td>sodium</td>
<td></td>
</tr>
<tr>
<td>Double background</td>
<td></td>
<td>7.8 mg (PuO₂ - UO₂)</td>
</tr>
<tr>
<td>level</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Sensitivity of GGD System

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of fissile</td>
<td>10 mg (PuO₂-UO₂)</td>
<td>44 μg/l of sodium (Natural Uranium)</td>
</tr>
<tr>
<td>materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission rate of</td>
<td>4.35 x 10⁴ dps/l of</td>
<td>1.53 x 10⁴ dps/l of argon</td>
</tr>
<tr>
<td>decay beta rays</td>
<td>argon</td>
<td></td>
</tr>
<tr>
<td>Double background</td>
<td></td>
<td>3.5 mg (PuO₂ - UO₂)</td>
</tr>
<tr>
<td>level</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Background Counting Rate in the Ordinary and the Simplified DND Systems

<table>
<thead>
<tr>
<th></th>
<th>Ordinary sys.</th>
<th>Simplified sys.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of sodium for detection</td>
<td>1 (1)</td>
<td>200 (1)</td>
</tr>
<tr>
<td>Detection efficiency of detector-moderator system</td>
<td>10⁻²</td>
<td>&gt; 10⁻⁴</td>
</tr>
<tr>
<td>Count rate</td>
<td>13 (cps)</td>
<td>&gt; 26 (cps)</td>
</tr>
</tbody>
</table>
Table 6. Background Counting Rate in the OGD System

<table>
<thead>
<tr>
<th>Decay rate of daughter isotope (dps/l)</th>
<th>$1.5 \times 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>The fission product detection efficiency</td>
<td>$4 \times 10^{-1}$</td>
</tr>
<tr>
<td>Volume of the precipitation chamber (l)</td>
<td>1</td>
</tr>
<tr>
<td>Count rate (cps)</td>
<td>$6.0 \times 10^3$</td>
</tr>
</tbody>
</table>

Table 7. Activity Levels in Precipitator

<table>
<thead>
<tr>
<th>Activity level of Na-24 vapor after removal of 99%</th>
<th>(dps/l)</th>
<th>$1.4 \times 10^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity level of A-41</td>
<td></td>
<td>$3.5 \times 10^6$</td>
</tr>
<tr>
<td>Activity level of fission background</td>
<td></td>
<td>$1.5 \times 10^4$</td>
</tr>
</tbody>
</table>
Fig. 1. Calculating Model of DND System
Fig. 2. Calculating Model of CGD System
Fig. 3 Schematic Diagram of Ordinary System

Fig. 4 Schematic Diagram of Simplified System
FIG. 5 System Block Diagram of the DND System
FIG. 6 Systematic Gas Flow Diagram of the CGD System
FIG. 7  Block Diagram of Counting System of the CGD