EVALUATION OF FISSION PRODUCT RELEASE FOLLOWING SINGLE CHANNEL ACCIDENTS FOR REFURBISHED WOLSONG-1

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Abstract

Fission product inventories and their releases during postulated single-channel accidents in the CANDU reactor, such as a feeder break, pressure tube rupture, channel flow blockage and end fitting failure, were evaluated for the refurbished Wolsong 1 nuclear power plant using the latest CANDU safety analysis codes, which are called IST (Industrial Standard Toolsets). The basic methodology applied in the current fuel safety analysis was compared with the methodology used in the case of Wolsong 2/3/4 safety analysis, and the results from both cases were also compared. According to the analysis results, fission product inventories and releases following the single-channel accidents for a refurbished Wolsong 1 plant were slightly small compared to those of Wolsong 2/3/4 plants.

1. Introduction

Wolsong-1 NPP (Nuclear Power Plant), as the first commercially operated CANDU-6 reactor in Korea, has been in service since 1983. The plant has had an excellent operating achievement, having had an average capacity factor of 86 percent. The original operating license was granted for a period of 30 years, and is valid until 2012. However, the long period of operation of Wolsong-1 NPP would create some problems due to the aging of the reactor component. Analyses of the reactor core data gathered from Wolsong-1 NPP indicate that the pressure tubes and feeder tubes are nearing the point in time where they may exceed their fitness for service criteria [1]. Therefore, consideration has been given to replacing all fuel channel assemblies, calandria tube assemblies, and the feeder tubing system. In addition, from the PSR (Periodic Safety Review) assessment by the regulatory institute, a refurbishment of Wolsong-1 NPP was requested to enhance the operation and safety margin.

Currently, Wolsong-1 NPP has been conducting a refurbishment project from late 2009. The major activities are the replacement of all 380 fuel channels and calandria tube assemblies, as well as the connecting feeder pipes and other related activities such as replacing the control computers, and the addition of trip parameter for moderator high-temperature of SDS #1 (shut down system). To support the licensing for the refurbishment project of Wolsong-1 NPP, a full-scope safety analysis is being carried out by a joint team of Korea Atomic Energy Research Institute and engineering companies. The purpose of the safety analysis is to confirm that the margin of safety in the final safety analysis report (FSAR) of Wolsong-1 NPP will not be reduced as a result of any changes from the original design.

This paper focuses on an evaluation of the fission product inventory and release for postulated single-channel accidents such as a feeder break, pressure tube rupture, channel flow blockage, and end fitting failure accident considering the refurbishment of Wolsong-1 NPP. The considered single channel accidents result in the failure of fuel sheath as well as fuel channel, so the produced fission gas within the fuel during the normal operation could be released into the moderator or containment building directly when the accidents occurr. Thus, released fission gases are provided as a source term of the radiation dose. Results from the fuel safety analysis for the refurbished Wolsong-1 NPP were compared to those results from Wolsong 2, 3 and 4 FSAR, and it was confirmed that the refurbishment of Wolsong-1 NPP did not result in a reduction of safety margins in terms of the fission gas release.

2. Evaluation methodology for fission product release

The objective of the fuel safety analysis is to estimate the quantity and timing of a fission product release from the fuel in the affected channel following the postulated single channel accidents. Fission product release calculations consist of three parts: (i) calculation of fission product inventory and its distribution within each fuel element during normal operation before an accident, (ii) estimation of the fractional release of the different chemical species based on the fuel temperatures following the accident, (iii) and determination of the release of different isotopes by multiplying the fractional release with the inventories.

2.1 Calculation of initial fission product inventory

The initial fission product inventories and distributions at the time of the accident were calculated using ELESTRES-IST code [2] for the limiting channel by applying the same methodology to all single-channel accidents. The limiting channel was assumed to have a channel power of 7.3 MW and two central bundles at 935 kW. Here, 7.3 MW and 935 kW were the LCO (Limiting Condition for Operation) power values for a fuel channel and fuel bundle, respectively. Power-burnup data for each ring of each bundle in the limiting channel at the time of the accident were determined based on the bundle power and burnup as shown in Table 1 and over-power envelop as shown in Figure 1. The axial bundle power distribution of the limiting channel was determined based on a relatively high power channel, O6 channel, and the burnups of each bundle were determined by the maximum bundle average burnup for each bundle location of 380 channels. Detailed procedures to obtain the element's power-burnup history and key input variables of ELESTRES-IST code are described in reference 3.

Table 1 Bundle power and burnup distribution in the limiting channel used in fission product release calculation (channel inlet = position 1)

Bundle Position	Bundle Power (kW)	Bundle Average Burnup (MW·h/kgU)
1	111.8	42.6
2	406.1	100.0
3	619.7	136.1
4	761.4	157.1
5	874	170.7
6	935	183.7
7	935	183.8
8	875.6	170.7

9	744.9	193.1
10	577.5	225.3
11	363.8	225.3
12	95.3	193.1

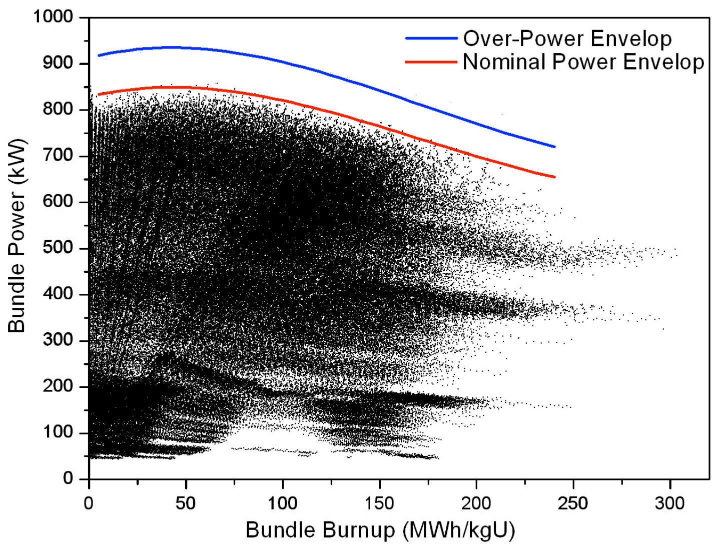

Figure 2 Nominal and overpower envelops for refurbished Wolsong-1 NPP

For the case of a flow blockage and an inlet feeder break among the single channel accidents, the power at the time of the accident of the 48 simulated elements in the limiting channel was boosted by 5% to account for the increase in channel power due to channel coolant voiding. The 5% power increase of all elements was assumed to last for 15 minutes for a conservative estimation of the fission product inventory.

2.2 Transient fission product releases for each single channel accident

Methodologies and assumptions for transient fission product release for each single-channel accident depend on the postulated accident in the limiting channel. Table 2 summarizes the assumptions used in the evaluation of the transient fission product release for each single-channel accident.

Table 2 Assumptions and methodology for transient release calculation for each single-channel accident

Accident	Assumptions at the time of the accident	Transient Release Calculation
Feeder Break	▪Consideration of coolant voiding effect: 5% power boost and maintaining for 15 minutes ▪ Failure of all fuel elements ▪ Release of gap inventory only	▪ Evaluation of transient release from grain boundary and in-grain inventories due to fuel temperature increase ▪ Applying Gehl model ▪ Until the channel failure time plus 2 sec for conservative evaluation

Pressure Tube Rupture	▪ Failure of all fuel elements ▪ Release of gap and grain boundary inventories	▪ No additional fission product release
Channel Flow Blockage	▪ Consideration of coolant voiding effect: 5% power boost and maintaining for 15 minutes ▪ Failure of all fuel elements ▪ Release of all fission product inventories	▪ No additional fission product release
End Fitting Failure	▪ Failure of all fuel elements ▪ Release of gap inventory only	▪ Evaluation of transient release from grain boundary and in-grain inventories due to fuel oxidation and diffusion ▪ Applying REDOU code ▪ Until the channel failure time

2.2.1 Inlet feeder break

A stagnation feeder break was focused on in this paper [4]. A stagnation break is defined as a break that results in a near-zero channel flow due to a force balance between the upstream side and downstream end. This break is characterized by rapid fuel and pressure tube heat up, fuel damage, and the failure of the fuel channel. Radionuclide can be released directly into the containment through a broken feeder pipe and to the moderator through the failed channel.

In order to simplify the transient fission product release calculation, it was assumed that all fuel sheaths in the channel failed, and the entire gap inventory was released instantaneously at the beginning of the accident. The result of the assumption is that the fractional release of the fission product at time zero is overestimated. The calculation of the transient fission product release from the fuel grains and grain boundary was performed by applying Gehl's release model [5]. Gehl's model correlates the percentage of fission gas release (Z_c) with the fuel centerline temperature ($T_{c/l}$) in K and the time-averaged centerline heating rate ($dT_{c/l}/dt$) in K/s as follows:

$$Z_c = 7.58 \times 10^{-19} T_{c/l}^{5.7} \left(\frac{dT_{c/l}}{dt} \right)^{-0.346}$$

Additional releases were superimposed on the transient release predicted using Gehl's model, to account for Zircaloy/UO_2 interaction and UO_2 oxidation. These releases were temperature dependent and calculated as a percentage release of fission products located within the grains of fuel and the grain boundary. The additional release fractions were added to the releases predicted by Gehl's model. Fuel rewet following the channel failure or injection of emergency core coolant could result in fuel pellet cracking and powdering due to induced thermal stresses. Therefore, the remaining fission gas stored on the grain boundaries was assumed to be released at the time of the channel failure.

2.2.2 Pressure tube rupture

Past reactor operating experience has shown that a pressure tube will leak long before the critical crack size is reached. Hence, the tube will exhibit a leak before break behavior occurs. However, the analysis of the pressure tube rupture assumes the most limiting case of a spontaneous rupture of the pressure tube such that the calandria tube surrounding the ruptured pressure tube is assumed to fail instantaneously and all the fuel in the channel are ejected into the moderator. Therefore, all fuel sheaths in the ruptured channel are assumed to fail at the time of the accident, instantly releasing their gap inventory of fission products. If the fuel pellets are ejected from the sheath and break up into smaller fragments, then a portion of the grain boundary inventory may also be released. For a conservative estimation of a fission product release, all gap and grain boundary inventories in the channel were assumed to be released at the time of the accident, and no additional release was assumed following the accident. In-grain inventory release during the transient after pressure tube rupture was not expected since the fuel temperatures remained relatively low.

2.2.3 Channel flow blockage

A flow blockage causes a sudden reduction of flow through the blocked channel. Depending on the severity of the blockage, the reduced flow through the channel can result in severe heat up of the fuel, hence possibly leading to pressure tube and calandria tube failure. Following channel failure, some or all the fuel bundles as well as the molten material, if any, may be ejected into the moderator. Fuel bundles, which are ejected into the moderator, may sustain mechanical damage due to impact with other bundles and structures and the fuel pellets may be broken up into smaller fragments.

It is assumed that all fuel sheaths in the affected channel fail at the time of the accident, instantly releasing their gap inventory of fission products. If the fuel pellets are ejected from the sheath and break up into smaller fragments, then a portion of the grain boundary inventory may also be released. Fuel elements that remain lodged in the channel between the channel rupture location and the blocked side may continue to heat up after channel rupture. Since this cannot be ruled out for any fuel bundles, it is assumed that the grain boundary inventory and the in-grain inventory of the fuel elements are also released at time zero. As a result, all fission product inventories (gap + grain boundary + in-grain inventories) were assumed to be released promptly at the time of the accident. Therefore, there was no additional transient release during the transient period. The inventories include the effect of 5% power increase at the time of the accident due to coolant voiding.

2.2.4 End fitting failure

Failure of a fuel channel end fitting at the rolled junction with the pressure tube could lead to the ejection of fuel from the channel into a fuelling machine vault. Ejected fuel bundles are likely to be damaged by impact, so that a prompt release of fission products into the containment would be expected.

In order to simplify the analysis, all fuel element sheaths in the affected channel are assumed to fail immediately at the time of the accident. Therefore, no detailed analysis of fuel sheath behavior following the accident is required. Furthermore, the fuel element sheaths are assumed to be sufficiently damaged such that the fuel pellets are ejected and break into spherical fragments. These assumptions are conservative and result in an over estimation of fission product release from fuel during the accident.

The REDOU code [6] was used to simulate the temperature transient of the fuel fragments as well as the fission product releases due to oxidation. The fuel temperatures at the time of the accident were the volume-average fuel temperatures prior to the ejection provided from the ELESTRES-IST simulation results for the limiting channel. Fission product releases are greater for higher fuel temperatures, and thus, fuel temperatures have been over estimated.

At the time of sheath failure (time zero), the gap inventory of all of the fuel elements in the channel was assumed to be released. The remaining fission product inventory was bound within the grains or on the grain boundaries of the fragments of UO_2. If a fuel pellet fractures into many small fragments, the surface area of exposed UO_2 pellet increases. It is assumed that this increase in exposed surface area causes additional release of fission products, which were previously on the grain boundaries. The fraction of the grain boundary inventory released after fuel fragmentation was assumed to be equal to the ratio of exposed surface area to the total grain surface area in the pellet. The total grain surface area was calculated by assuming that the grains are spherical. As a result, the prompt releases consist of all gap inventories and a part of the grain boundary inventory. The fractional release of iodine due to fuel fragment oxidation after the accident was evaluated by using the REDOU code. Calculated transient fractional releases of iodine from each element were then multiplied by the bound inventory in that element to obtain the iodine activity transient. These were then summed up over all of the elements in the limiting channel. The in-grain bound inventories of noble gases such as Kr and Xe were assumed to be instantly released at the time of the accident.

3. Results of fission product release and discussion

Based on the methodology and assumptions described in Sec. 2, fission product inventories and their releases were evaluated for each single channel accident such as a channel flow blockage (CFB), feeder break (FB), end fitting failure (EFF) and pressure tube rupture (PTR) for a constructed limiting channel.

3.1 Results of initial fission product inventory

Fission product inventories at the time of the accident were evaluated using the ELESTRES-IST code. The same analysis conditions under normal operation were used in the calculation except a 5% power boost for feeder break and channel flow blockage accidents. Table 3 summarizes the results for fission product inventories and their distributions of the limiting channel for each-single channel accident. Total inventories for FB and CFB accidents were 149,219 TBq, and for PTR and EFF were 146,159 TBq. Due to the 5% power boost maintained for 15 minutes at the time of the accident, the total inventory of the FB and CFB for 18 isotopes is about 2% greater than that of the PTR and EFF. In particular, the power boost had a significant effect on the gap inventory so that the gap inventory for FB and CFB was about 18% greater than the PTR and EFF cases. Calculated fission product inventory was provided as source terms in evaluating the transient fission gas release following the single-channel accidents.

Table 3 Results of fission product inventories for the limiting channel at the time of accident

Isotope	Total Inventory (TBq)		Gap Inventory (TBq)		Grain Boundary Inventory (TBq)		In-Grain Inventory (TBq)	
	FB CFB	PTR EFF	FB CFB	PTR EFF	FB CFB	PTR EFF	FB CFB	PTR EFF
I-131	6390.6	6390.1	433.2	379.3	959.8	982.7	4997.8	5028.1
I-133	15156.2	15142.2	535.1	433.5	2274.6	2327.0	12346.4	12381.7
I-135	14269.7	14228.9	322.2	252.3	2142.3	2186.9	11805.2	11789.7
I-137	8341.6	7944.3	7.5	5.4	1265.5	1234.7	7068.7	6704.3

Kr-85	23.3	23.3	0.7	0.7	3.2	3.4	19.4	19.2
Kr-87	5672.1	5596.9	24.4	18.2	853.1	860.9	4794.6	4717.8
Kr-89	11325.4	10760.3	10.7	7.6	1718.0	1670.2	9596.8	9082.5
Xe-133	14043.8	14041.8	911.6	749.3	2108.4	2158.7	11023.9	11133.8
Xe-138	14878.6	14259.0	29.0	20.6	2250.1	2200.6	12599.4	12037.8

FB: Feeder Break, CFB: Channel Flow Blockage, PTR: Pressure Tube Rupture, EFF: End Fitting Failure

3.2 Results of transient fission product release

As summarized in Table 2, transient fission product releases for the pressure tube rupture and channel flow blockage accidents were not considered. For the pressure tube rupture, the gap and grain boundary inventories were assumed to be released promptly at the time of the accident. After the pressure tube rupture, all fuel elements were ejected into the moderator and the fuel temperature was remained relatively low so there was no additional fission product release from the in-grain inventory. For the channel flow blockage, fuel elements which remain lodged in the channel between the channel rupture location and blocked side may continue to heat up after a channel rupture. Therefore, the fission product inventories at the grain boundary and in-grain can be released continuously by the fuel temperature increase. Accordingly, it was assumed that the grain boundary inventory and in-grain inventory of the fuel elements were also released promptly at time zero.

3.2.1 Transient release for the feeder stagnation break

For a conservative estimation, the transient releases were calculated until 13.1 seconds after the break, which included an additional 2seconds for the fuel channel failure time at 11.1 seconds

Transient releases of Iodine isotopes (I-131, I-132, I-133, I-134, I-135, I-137), Krypton isotopes (Kr-83m, Kr-85m, Kr-85, Kr-87, Kr-88, Kr-89) and Xenon isotopes (Xe-133m, Xe-133, Xe-135m, Xe-135, Xe-137, Xe-138) were 26,713 TBq, 10,667 TBq and 18,313 TBq, respectively. The total transient release for all of the Iodine, Krypton and Xenon isotopes is shown in Figure 2. As shown in this figure, the remaining grain boundary inventories were released at the time of a channel failure of 11.1 seconds. The total channel release at 13.1 seconds after the accident is calculated to be 55,693 TBq which is approximately 37.3% of the total inventory at the time of the stagnation feeder break accident.

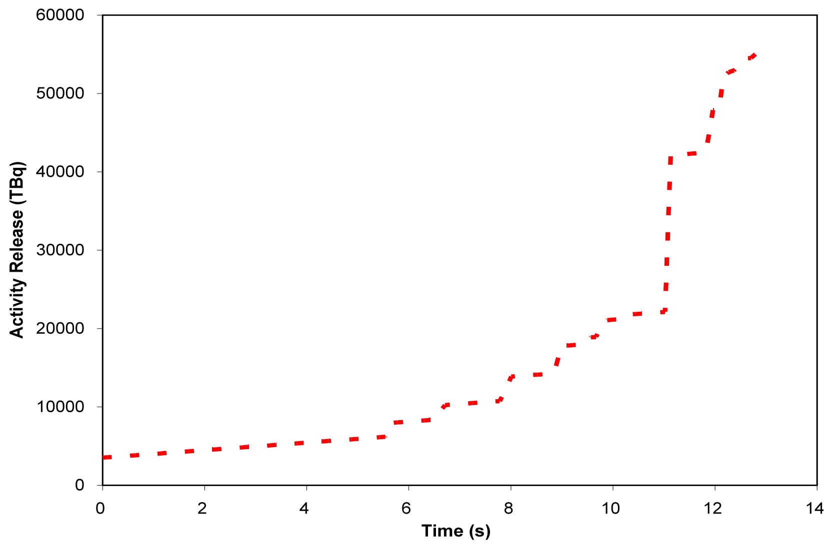

Figure 2 Transient releases for Iodine, Krypton and Xenon following feeder stagnation break

3.2.2 Transient release for the end fitting failure

The transient fission product release was determined by the fuel temperature and extent of oxidation. Using the temperature transient, the extent of oxidation of fuel pellet pieces from the limiting channel was obtained by using the REDOU code. By the end of the simulation time of 600 seconds, all fragments from the channel were completely oxidized and the release rate went to zero, regardless of fragment sizes and initial temperatures. For the limiting channel, a series of iodine release transients were estimated using various assumed initial UO_2 fragment sizes. Critical fragment sizes were determined as those that gave the highest releases. Figure 3 shows the total releases of iodine isotopes from the limiting channel, which are composed of prompt releases from gap and grain boundary inventories released upon fuel fracture and transient releases from the remaining grain boundary and in-grain inventories. The total releases of the iodine isotopes were 5636.4 TBq. As given in Table 4, the entire channel inventories of the noble gases such as I, Kr, and Xe were assumed to be released at the beginning of the transient release and the total transient release of 18 isotopes by the end of the simulation time was 81265.6 TBq.

Table 4 Cumulative fission product release at 600 sec. for end fitting failure

Isotope	Release at 600 seconds (TBq)
I-131	699.1
I-133	1224.6
I-135	1007.6
I-137	443.4
Kr-85	23.3
Kr-87	5596.9
Kr-89	10760.3
Xe-133	14041.8
Xe-138	14259.0

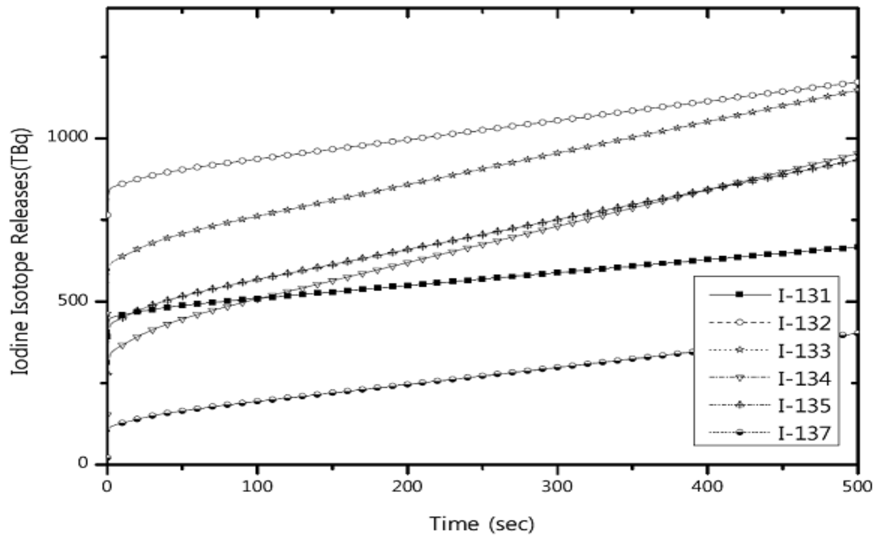

Figure 3 Iodine transient releases following end fitting failure
(prompt release + transient release from grain boundary and in-grain inventories)

3.3 Discussions

The currently used methodology for evaluating the fission product release is almost the same as that of Wolsong 2, 3 and 4 NPPs, except the used safety code version and fuel bundle's power-burnup data, which were newly calculated using the latest reactor physics code [7]. Therefore, it was worth comparing the fuel safety analysis results for both cases. Initial fission product inventories for 18 isotopes of the limiting channel for FB and CFB, and for PTR and EFF, were 149,219 TBq and 146,159 TBq, respectively, for the refurbished Wolsong 1 NPP, and 176,323 TBq for Wolsong 2, 3, and 4. The fission product inventory of the refurbished Wolsong 1 was lower by about 15% than for Wolsong 2, 3 and 4. This difference may come from the different code version of the ELESTRES code and from the minor change of the applied methodology. In the case of Wolsong 2, 3, and 4, the highest fission product inventory was selected during the irradiation period. However, for the case of the refurbished Wolsong 1, the fission product inventory at the time of the accident was calculated. Therefore, it can be said that the result for the refurbished Wolsong 1 was more realistic.

Transient releases for the refurbished Wolsong 1 were lower by about 14.5 % and 16.6 % than for Wolsong 2, 3, and 4, for the feeder break and end fitting failure, respectively.

4. Conclusions

Fission product inventories and their releases during the postulated single channel accidents such as pressure tube rupture, channel flow blockage, end fitting failure and feeder break were evaluated for a refurbished Wolsong 1 nuclear power plant using the latest IST safety analysis codes. According to the analysis results, fission product inventories under normal operating conditions for a refurbished Wolsong 1 plant were lower by about 15% compared to those of Wolsong 2/3/4 plants. Transient fission product releases for feeder break and end fitting failure were also reduced by about 14.5 % and

16.6 %, respectively. From these analysis results for single-channel accidents of the refurbished Wolsong 1, it could be confirmed that the refurbishment of Wolsong 1 NPP did not result in a reduction of safety margins in terms of the fission gas release.

5. References

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