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Core Release Model Evaluation in the ISAAC Code for PHWR

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Abstract

The ISAAC fission product release calculation is based on detailed FPRAT models developed by Jaycor. For volatile fission product release calculations, either the Cubicciotti steam oxidation correlation or the NUREG-0772 correlation is used. In this study, evaluation is carried out for these volatile fission product release models. As a result, in the case of early release, the IDCOR model with an in-vessel Te release option shows the most conservative results and for the late release case, the NUREG-0772 model shows the most conservative results. Considering both early and late release, the IDCOR model with an in-vessel Te bound option is evaluated to show mitigated conservative results. In addition, a sensitivity study on detailed core nodalization is performed. In the study, 380 horizontal fuel channels in the Wolsong plant are nodalized into 12 (6 channels per loop, 3×3 Core Pass) representative channels and detailed by 16/20/24 channels. For reference accidents, LOAH and large LOCA are selected as representing high and low pressure sequences, respectively. According to the results, the original 12 channel approach with 3x3 core passes is evaluated to be sufficient as an optimal scheme.

Key Words : core release, fission product, PHWR, ISAAC, IDCOR, NUREG-0772, core nodalization

1. Introduction

An ISAAC computer code [1], which was developed for a Level-2 PSA in 1995, was developed mainly with the fundamental models for CANDU-specific severe accident progression and also the accident-analyzing experiences are limited for Level-2 PSA purposes. Hence the volatile fission product release model and the core nodalization model, which are known to affect core release behavior of fission products directly or indirectly, are evaluated to both analyze calculation boundaries and choose optimal scheme in core release. As a research strategy, sensitivity studies of the model parameters and sensitivity coefficients are performed.

The ISAAC volatile fission product release calculation in a core is based on either the steam oxidation model of Cubicciotti (= IDCOR model) [2] or the NUREG-0772 empirical correlations [3]. In this study, the results from the two models are analyzed first by testing the effects of core blockage in case of the IDCOR model. The release of volatile fission product from the core is limited by the release rate from the fuel matrix, except in some cases for tellurium (Te) which may be bound with the cladding. Chemical bonding of tellurium to the cladding has been found to occur in some experiments in which the zirconium (Zr) was less than 70-90% oxidized [4]. Under these conditions, the tellurium would not behave as a volatile fission product. ISAAC contains a model which, when selected by the user, allows the tellurium to remain in the core region, supplying decay heat during core heat up, and to be transported with Zr and the molten fuel during core relocation. The tellurium is then released from the melt as Zr is oxidized during the CCI phase of the accident. This option is specified in ISAAC by setting the model parameter FTEREL to zero to prevent Te release in the core. For the NUREG-0772 option, the release rate calculated is further limited by dividing it by 40 if the fraction of zircaloy in the cladding that is oxidized is less than the user-specified model parameter FTENUR (default value is 90%). So, the effects of sensitivity coefficients like "FTEREL" in the IDCOR model and "FTENUR" in the NUREG-0772 model are analyzed.

While the ISAAC computer code has a fixed primary system nodalization, the fuel channel configuration inside the calandria is flexible and the user is supposed to define the number of fuel channels in the broken and unbroken loop in both the closed loops (loop 1 and loop 2), respectively. Though the code can simulate the maximum 37 representative fuel channels in loop 1 and loop 2, a total of 6 channels (3 channels in the broken loop and 3 channels in the unbroken loop) is originally defined in loop 1 and the same configuration is assumed for loop 2, for the reference calculation. Figure 1 shows the 3 by 3 channel configuration in loop 1 (6 channels per loop, 3×3 Core Pass). Once the user sets up the core configuration, the structure of the variable heat sinks for the inlet and outlet feeders is defined automatically in the code. In general, core nodalization schemes have an effect on fuel thermal-hydraulic behavior which affects the accident progression and fission product behavior in turn. So, the effect of detailed core nodalization with 16 (8 channels per loop, 4×4), 20 (10 channels per loop, 5×5), and 24 (12 channels per loop, 6×6) representative channels on fission product behavior are analyzed, considering that the code allows the user to group 380 fuel channels into up to 74 core channels based on their elevations, power levels, core passes and loops.

The reference plant for calculation is the 600 MW_e PHWR nuclear power plant with a large dry containment at Wolsong in Korea. For the reference sequence, a large LOCA is analyzed for the bounding calculation which is a transient sequence initiated by a guillotine break in the reactor outlet header with an area of $0.259m^2$ in one loop. It was assumed that the emergency core cooling system injection, moderator cooling

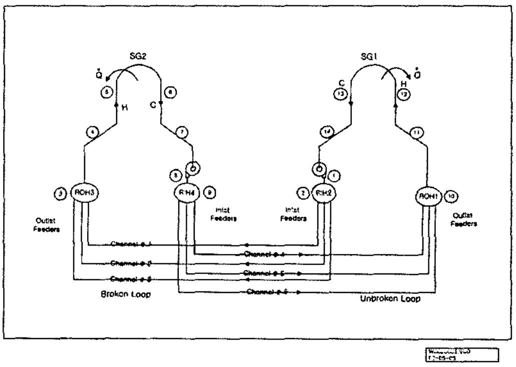

Fig. 1. ISAAC 3×3 Core Pass Configuration

function, shield cooling function for the calandria vault and end shields, containment spray system, and containment local air coolers were not available. The feedwater is initially provided but no main or auxiliary feedwater is available after reactor shutdown which is assumed to occur at 0.87 seconds following the FSAR results [5]. The MSSVs are initially closed but, after the LOCA signal is received at 3.3 seconds (when primary pressure reaches 5.56 MPa), the pressurizer is isolated at 23 seconds and the MSSVs are manually opened at 33 seconds from crash cooldown operation. Major accident sequence timings and the trend of important variables for the thermal hydraulics can be referred from the Wolsong level 2 PSA final reports [6]. In contrast to large LOCA as a representative low pressure sequence, a LOAH as a representative high pressure sequence [7] in which all active heat sinks are not available is additionally analyzed for core nodalization effect analysis.

2. ISAAC Models

The ISAAC fission product release calculation is based on the detailed FPRAT models developed by Jaycor [2] and either the steam oxidation model of Cubicciotti or the NUREG-0772 correlations may be selected by the user to calculate the release rate of the volatile fission products from the fuel. The volatile fission products tracked in this study are CsI and Te which are the key and representative fission products. Major assumptions in calculating the volatile fission product release are:

1. No Fission product occurs until cladding failure. Two criteria are used for cladding failure: either cladding burst due to ballooning, or a user-input failure temperature is reached.
2. Neither aerosol formation nor deposition of aerosols or vapors occurs within the core. Release of the volatile materials is governed by the release correlations only and there are no mass transfer limitations.
3. Tellurium may be bound in the cladding as a telluride and not released upon selection of the user-input parameter.

The steam oxidation model of Cubicciotti (= IDCOR model) assumes that the release of fission gas and volatile fission products follows the kinetics of fuel oxidation when UO_2 is heated in steam. Under this assumption an approximate solution for diffusion in cylindrical pellets can be used directly to predict the release of volatile fission products as a function of time and temperature. The equation is

$$F=1-1[1-4(\tau_h/\pi)^{1/2}]\,[1-4(\tau_\theta/\pi)^{1/2}+\tau_\theta] \qquad (1)$$

Where F = fractional release of the volatile fission product,
τ_h = $D_c t/h^2$, τ_θ = $D_c t/r^2$,
t = time (s),
h = height (h) or r = radius of a fuel pellet (m), and
D_c = chemical diffusion constant representing penetration of oxidant into UO_2 (m^2/s) and the following expression for D_c for UO_2 in steam is used, $D_c(m^2/s) = 9.9\times10^{-3}e^{(-28600/T)}$ with T in Kelvin.

The NUREG-0772 model is an empirical model which is applied to volatile fission products and to a wide range of temperatures. The authors of NUREG-0772 surveyed the available fission product release data and drew crudely fitted curves from the collection of release data which created a family of fission product release rates versus temperature curves. For calculational purposes, the various curves were then approximated with an equation having the form

$$k(T) = Ae^{BT} \qquad (2)$$

Fission Products	1000℃< T <2200℃		T > 2200℃	
	A	B	A	B
Xe, I, Cs	1.65×10^{-7}	0.00667	1.89×10^{-5}	0.00451
Te	2.96×10^{-8}	0.00667	1.17×10^{-5}	0.00404

where k(T), the fractional release rate coefficient, is a function of temperature only, T is the temperature in ℃, and the constants A and B are given for different fission product elements whose values are listed above.

3. In-Containment Source Term Analysis

Table 1 shows the accumulated in-containment fractions of CsI and Te volatile fission products just after calandria tank failure time and at end of calculation (=72 hours) according to the model parameters and sensitivity coefficients, and figures 2 and 3 show the time trends of CsI and Te, respectively. CsI is the representative volatile fission product and Te is a sensitive volatile fission product to the Zr oxidation rate. The key timings in the table are selected as they are the most probable timings for containment failure. In-containment fraction includes the released fraction into every place inside the containment like atmosphere, heat sink walls, and pool, except for corium. The volatile fission products start to release after fuel cladding failure and this early release continues until the fuel bundle drops into the moderator from the fuel channel rupture. Another release (which can be called as a late release) occurs from CCI in the calandria vault after calandria tank failure.

According to the comparison analysis of the model options for CsI release, early release is about 5 times larger in the IDCOR model ("ID" in figures) but late release occurs more rapidly and reaches about a 1.5 times larger accumulated fraction at 72 hours in the NUREG-0772 model ("07" in figures), as shown in figure 2. Major release occurs around the temperature of fuel melting and the release rate in the IDCOR model

Table 1. Accumulated In-containment Fractions of CsI and Te

Accumulated in-containment fractions[%] in large LOCA			IDCOR				NUREG-0772	
			Blockage		No Blockage		Blockage=N/A	
			CsI	TeO_2	CsI	TeO_2	CsI	TeO_2
FTENUR=90%	In-Vessel Te bounded	At CT failure	20.7	0.0	22.4	0.0	5.0	0.0
		At 72 hours	30.9	22.8	32.7	23.3	44.5	30.9
	In-Vessel Te released	At CT failure	22.3	22.3	22.3	22.3	Same with Te bounded case	
		At 72 hours	32.1	27.8	32.2	27.8		
FTENUR=70%	FTEREL =N/A	At CT failure	N/A				4.9	0.0
		At 72 hours					44.5	30.9
FTENUR=1%	FTEREL =N/A	At CT failure					4.8	0.7
		At 72 hours					44.2	30.6

looks more sensitive around the melting temperature. In the NUREG-0772 model, fission product release starts after the fuel reaches the temperature of 1000℃ and increases exponentially to the melting temperature and shows a 1-2% accumulated rate around 1700℃-1800℃. For Te release, considerable amounts (about 20%) are released early in the in-vessel Te released case (FTEREL=1, "R" in figures) in the IDCOR model but no early release occurred in either option for the NUREG-0772 model and the in-vessel Te bounded case (FTEREL=0, "B" in figures) in the IDCOR model. The accumulated fraction at 72 hours is larger in the order of the NUREG-0772 model, the in-vessel Te released case in the IDCOR model, and the in-vessel Te bounded case in the IDCOR model, as shown in figure 3. For the analysis of core blockage ("C"(=candling) or "NC"(=no candling) in figures) due to corium candling in the IDCOR model, no difference is shown from the CANDU horizontal core characteristics.

Next, the spatial distribution of the CsI volatile fission product is analyzed. CsI mass fractions inside the fuel channel (at corium), outside the fuel channel (at corium), inside the broken loop, inside the intact loop, inside the calandria tank (at corium), and inside the containment (at atmosphere, heat sink walls, pool, and corium) are shown in figures 4, 5, 6, 7, 8, and 9, respectively. According to this, almost all of the fuel inside the fuel channels transport into the calandria tank in 10 hours due to fuel melting and fuel channel rupture. About 25%-80% of the CsI (which is option dependent) also transports into the calandria tank with fuel transport while 10%-25% and 7%-30% of the released CsI remains inside the broken and intact loops, respectively. All the CsI which exists in the corium after transport into the calandria tank, transports into the containment (i.e., into the calandria vault as a compartment of the containment) with none remaining inside the calandria tank. Before calandria tank failure, about 4%-20% of the CsI (which is option dependent) already exists inside the containment which is released through the break from the beginning and increases rapidly from the CCI after calandria tank failure as noticed in figure 2.

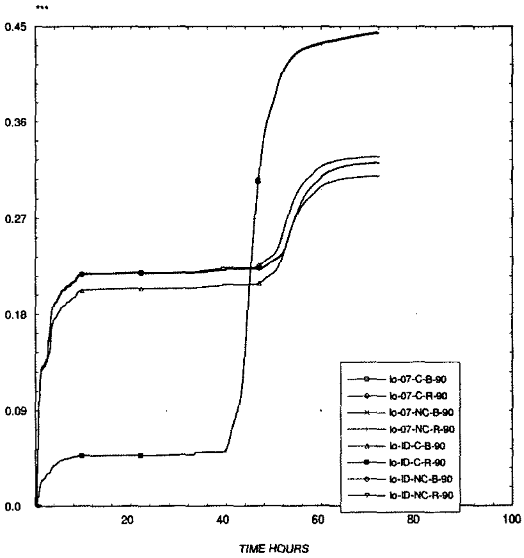

Fig. 2. In-containment Fractions of CsI

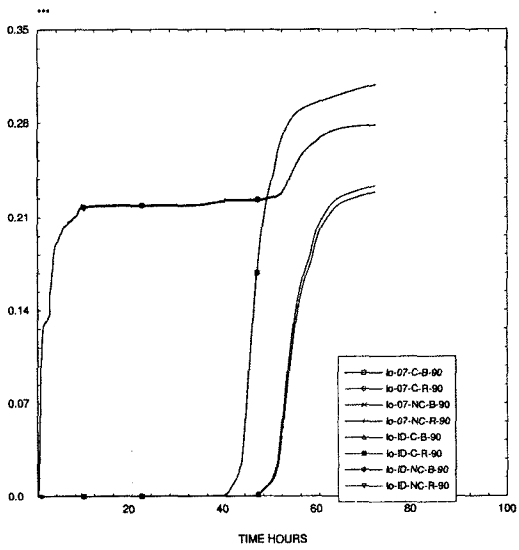

Fig. 3. In-containment Fractions of Te

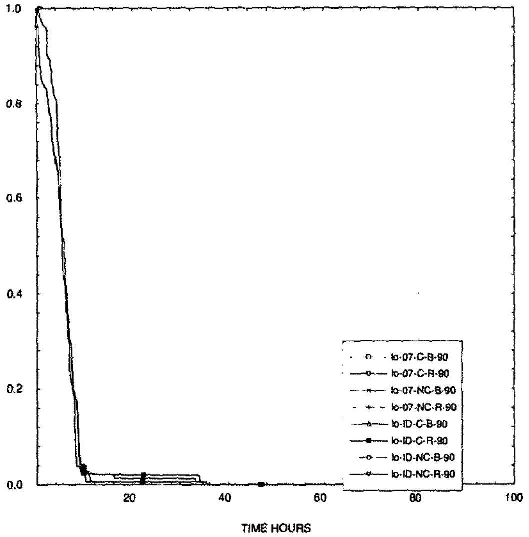

Fig. 4. CsI Fractions Inside the Fuel Channel

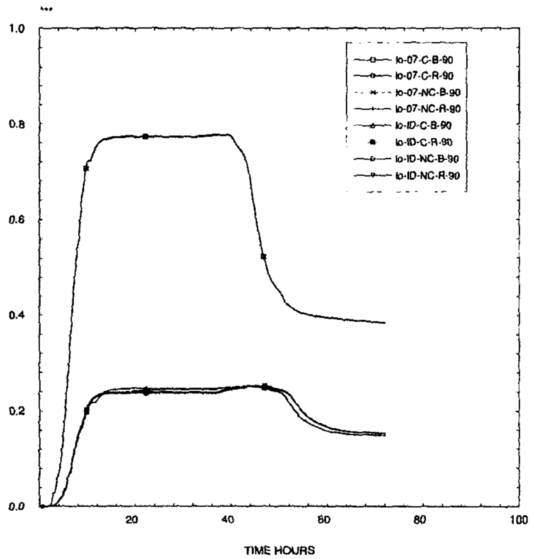

Fig. 5. CsI Fractions Outside the Fuel Channel

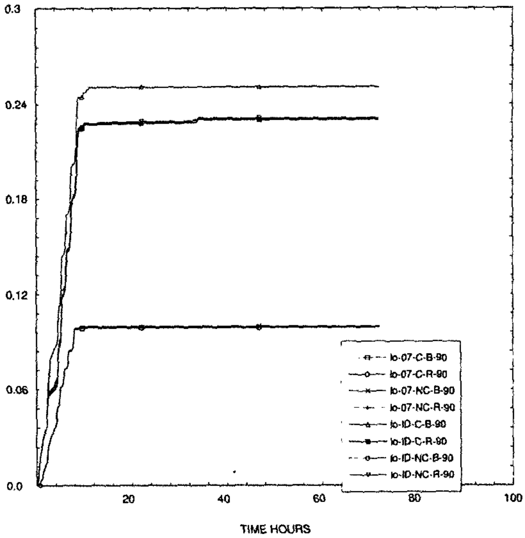

Fig. 6. CsI Fractions Inside the Broken Loop

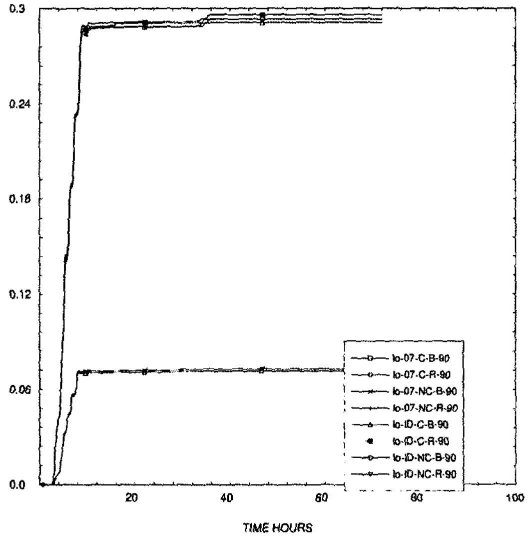

Fig. 7. CsI Fractions Inside the Intact Loop

As an illustration, spatial distribution of CsI (in mass fraction) is compared in figures 10 and 11 for the representative cases of NUREG-0772 model (07-C-R-90) and IDCOR model (ID-C-R-90), respectively. After CCI in the calandria vault, CsI inside the corium (about 25%-80%) is rapidly released and half is released at about 50 hours into the accident. Afterwards, CsI inside the corium keeps decreasing while CsI in the containment atmosphere (and pool) keeps increasing, which results in 15%-40% of the CsI remaining inside the corium in the calandria vault at 72hours into the accident. In the same manner, spatial distribution of Te/TeO_2 (in mass) is

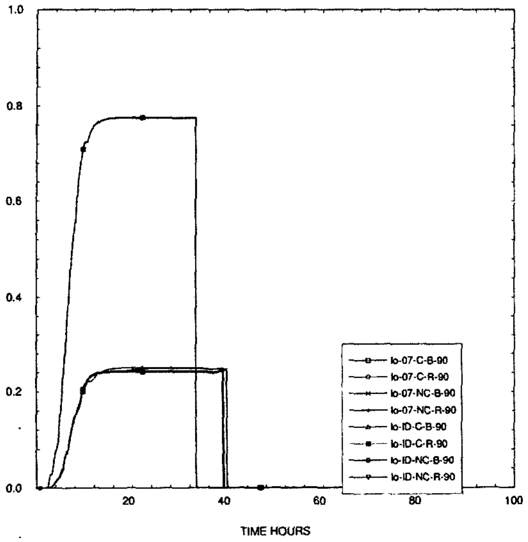

Fig. 8. CsI Fractions Inside the Calandria Tank

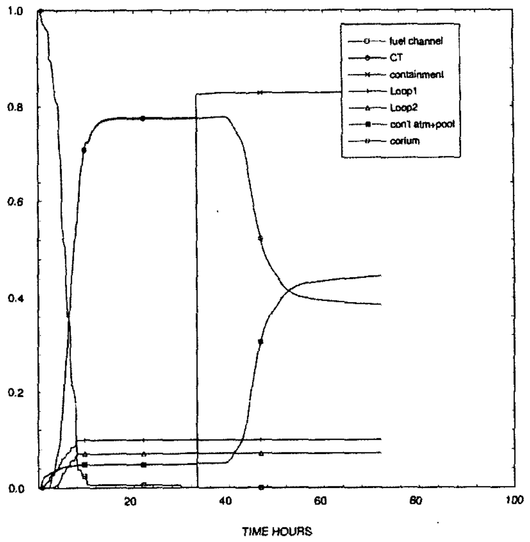

Fig. 10. Spatial Distribution of CsI [%] in NUREG-0772 Case (07-C-R-90)

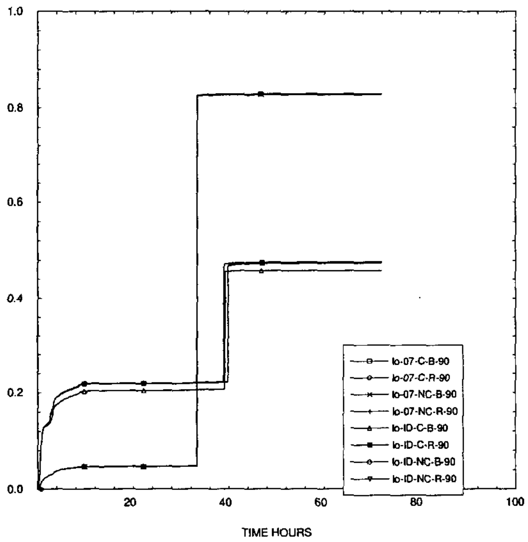

Fig. 9. CsI Fractions Inside the Containment

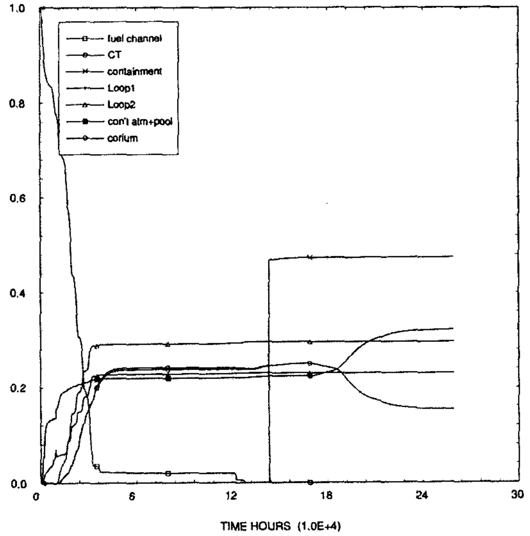

Fig. 11. Spatial Distribution of CsI [%] in IDCOR Case (ID-C-R-90)

compared in figures 12 and 13 for the representative cases of the NUREG-0772 model (07-C-R-90) and IDCOR model (ID-C-R-90), respectively. TeO_2, as an oxidant form of Te, is rapidly released after CCI in the calandria vault in the NUREG-0772 model, while some TeO_2 which is released from the core already exists in both the PHTS and containment in the IDCOR model, and the release rate after CCI in the calandria vault becomes smaller than that of the NUREG-0772 model.

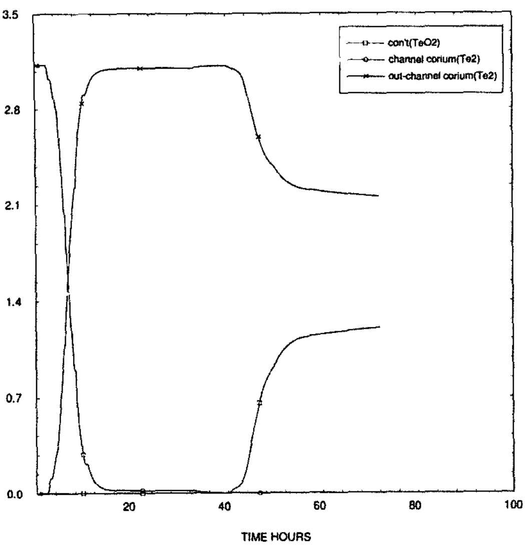

Fig. 12. Spatial Distribution of Te/TeO$_2$ [kg] in NUREG-0772 Case (07-C-R-90)

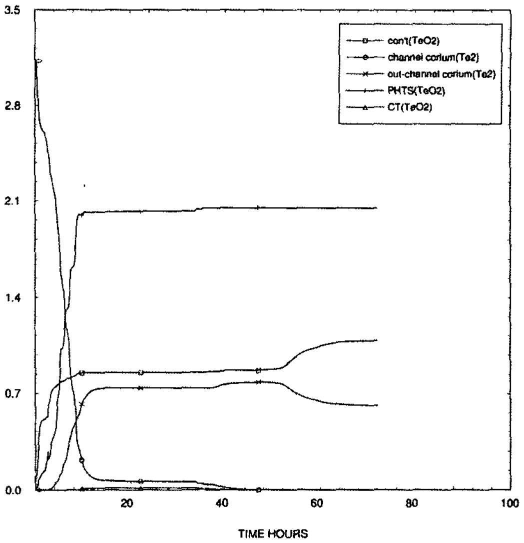

Fig. 13. Spatial Distribution of Te/TeO$_2$ [kg] in IDCOR Case (ID-C-R-90)

4. Core Nodalization Analysis

The change in the number of the representative fuel channels means a change of the number of pressure tubes in a representative fuel channel, which affects the peaking factors and geometry of the channel. So, sensitive analyses are performed after adjusting the inputs for the same core average peaking factors (=1.007) and the same channel height characteristics.

Major failure timings are shown in table 2 for high (LOAH) and low (LOCA) pressure sequences to obtain the changes in accident progression according to core nodalization. The fuel channel rupture (start) time which is affected directly by core nodalization and the calandria tank failure time which is the most probable timing for containment failure are chosen as major failure

Table 2. Major Failure Timings

Accident Sequence	Failure Location	Failure Time [sec (hr)]			
		3x3	4x4	5x5	6x6
LOAH	Loop 1/2 feul channel	22553 (=6.26)	22985 (=6.38)	22642 (6.29)	21700 (=6.03)
	Calandria Tank	148560 (=41.3)	147175 (=40.9)	147672 (=41.0)	146926 (=40.8)
LOCA	Loop 1 fuel channel	9150 (=2.54)	12020 (=3.34)	12014 (=3.34)	9224 (=2.56)
	Loop 2 fuel channel	11166 (=3.10)	11533 (=3.20)	11559 (=3.21)	11293 (=3.14)
	Calandria Tank	143310 (=39.8)	143536 (=39.9)	144048 (=40.0)	143459 (=39.8)

Table 3. Accumulated In-containment Fractions of CsI and Te/TeO$_2$

Accident Sequence	Fission Product	Accumulated In-containment Fractions [%]			
		3×3	4×4	5×5	6×6
LOAH	CsI	39.0	40.5	40.8	39.2
	TeO$_2$	71.1	69.3	69.2	70.4
	Te	20.9	22.6	22.7	21.8
LOCA	CsI	32.2	29.8	29.5	32.0
	TeO$_2$	27.8	25.5	25.1	27.7
	Te	0	0	0	0

timings. In the analysis, the major failure timings are almost the same for both the high pressure sequence whose rupture time in the fuel channel is not different between loops 1 and 2, and for the low pressure sequence whose rupture time in the fuel channel is different between broken loop 1 and intact loop 2. One exception is the fuel channel rupture time of loop 1 in the 4x4 and 5x5 core pass cases in the low pressure sequence which is a little slower than not only all the other cases but also the fuel channel rupture time of loop 2. The cause is unclear at the present.

Next, the average and peak fuel temperatures according to the core passes are compared for the high and low pressure sequences in loop 1 at figures 14/15 and in loop 2 at figures 16/17, respectively. As a result, the temperature behavior according to the core passes is almost the same but the late core melt in broken loop 1 has not occurred in the case of the 5x5 core pass because early core melt occurred in the lowest core node in loop 1 as shown in figures 18 and 19. The late core melt has mainly occurred in parts (less than 7-8%) of the fuel channels having the lowest peaking factor just before calandria tank failure which is judged to have little influence on the total

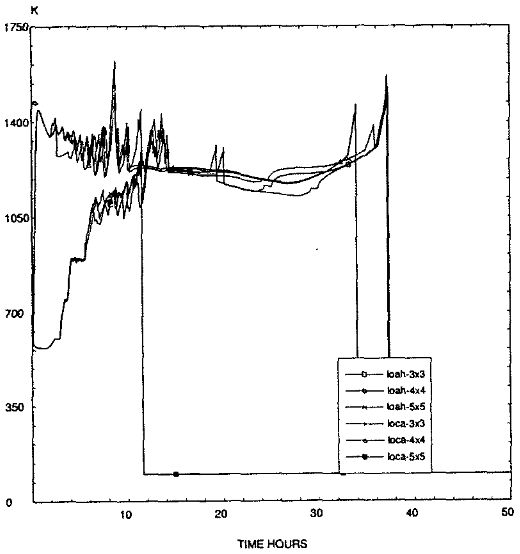

Fig. 14. Average Fuel Temperatures in Loop 1

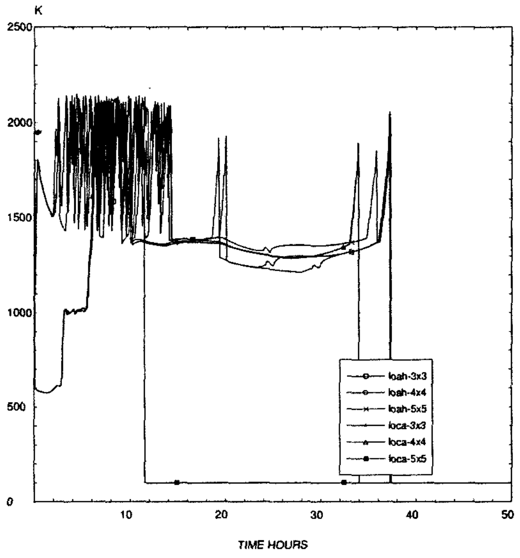

Fig. 15. Peak Fuel Temperatures in Loop 1

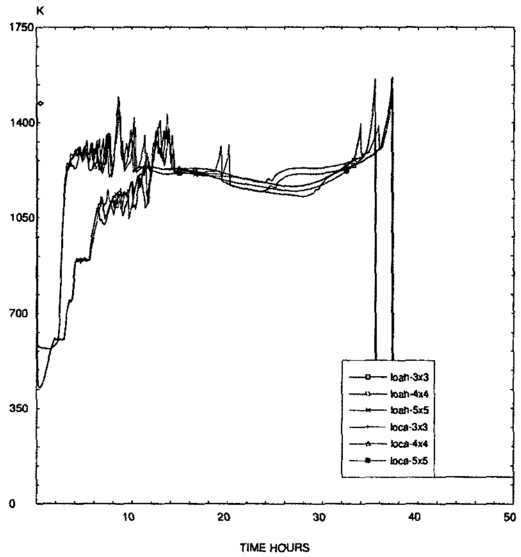

Fig. 16. Average Fuel Temperatures in Loop 2

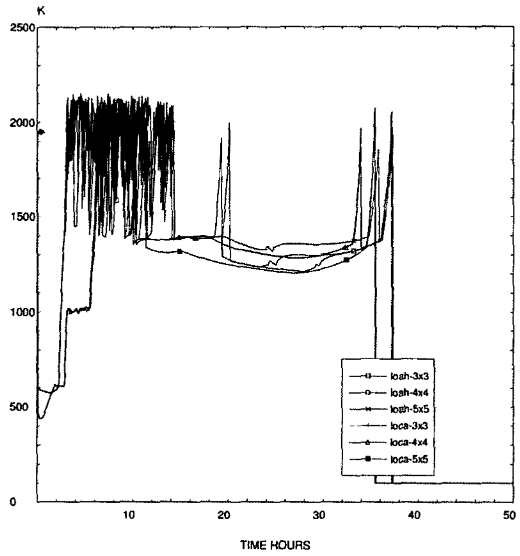

Fig. 17. Peak Fuel Temperatures in Loop 2

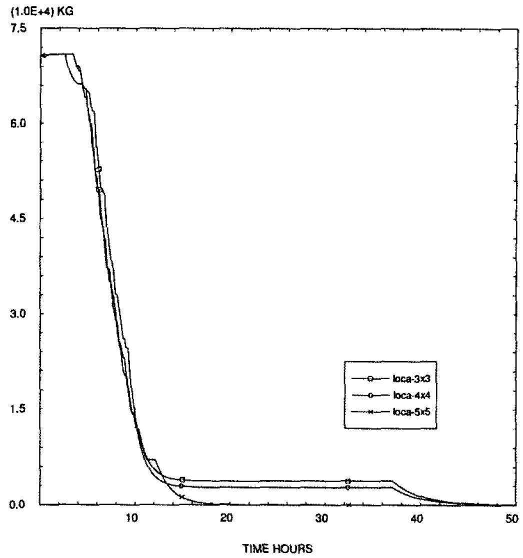

Fig. 18. Corium Mass in Loop 1

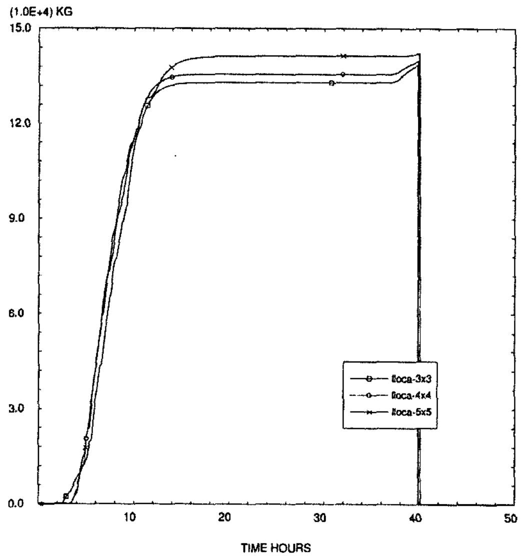

Fig. 19. Corium Mass in Calandria Tank

fuel channel melt behavior.

Table 3 shows the accumulated in-containment fractions of CsI and Te/TeO2 according to the core passes at 72 hours (= end of calculation). As a result, no consistent conservatism is found because the accumulated fractions of TeO_2 is the highest for both high and low pressure sequences in the 3x3 core pass while the accumulated fractions of CsI is the highest for the low pressure sequences but is the lowest for the high pressure sequences in the 3x3 core pass. In general, the trend is similar between 3x3 and 6x6 core passes, and between 4x4 and 5x5 core passes, with the differences less than 10%.

5. Conclusions

ISAAC volatile fission product release model options are evaluated mainly from a viewpoint of release fractions. In the case of early release, the IDCOR model with an in-vessel Te release option shows the most conservative results and for the late release case, the NUREG-0772 model shows the most conservative results. Considering both early and late release, the IDCOR model with an in-vessel Te bound option shows mitigated conservative results. In addition, the detailed core nodalization effect is analyzed via comparing an original 3x3 nodalization (per loop) method with detailed 4x4, 5x5 and 6x6 nodalization methods. According to the results from the core nodalization sensitivity study, an original 3x3 nodalization (per loop) method which groups horizontal fuel channels into 12 representative channels, is evaluated to be sufficient for a optimal scheme because the detailed nodalization methods have no large effect on fuel thermal-hydraulic behavior, total accident progression, and fission product behavior.

Nomenclature

LOAH : loss of active heat sinks
LOCA : loss of coolant accident
CCI : corium-concrete interaction
MSSVs : main steam isolation valves
CT : calandria tank
Con't : containment

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