Nuclear Engineering and Technology 51 (2019) 125–137

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Contribution of production and loss terms of fission products on in-containment activity under severe accident condition for VVER-1000

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ARTICLE INFO

Article history:
Received 25 December 2017
Received in revised form
28 August 2018
Accepted 4 September 2018
Available online 7 September 2018

Keywords:
IRBURN
VVER-1000 reactors
Source term calculation
Containment engineering safety features

ABSTRACT

The purpose of this paper is to study the source term behavior after severe accidents by using a semi-kinetic model for simulation and calculation of in-containment activity. The reactor containment specification and the safety features of the containment under different accident conditions play a great role in evaluating the in-containment activity.

Assuming in-vessel and instantaneous release of radioactivity into the containment, the behavior of in-containment isotopic activity is studied for noble gasses (Kr and Xe) and the more volatile elements of iodine, cesium, and aerosols such as Te, Rb and Sr as illustrative examples of source term release under LOCA conditions. The results of the activity removal mechanisms indicates that the impact of volumetric leakage rate for noble gasses is important during the accident, while the influence of deposition on the containment surfaces for cesium, mainly iodine isotopes and aerosol has the largest contribution in removal of activity during evolution of the accident.

1. Introduction

As a result of nuclear power plant (NPP) operation, large amount of fission products (FPs) are produced. Radionuclides may escape to the environment and affect the source term during an accident.

The containment is the last barrier for the fission products to keep inside the containment. The engineering safety features (ESFs) in the containment such as charcoal and high efficiency particulate air (HEPA) filters which are implemented in the containment could reduce the public risk.

Quantification of time dependent radioactivity released inside the containment during a severe accident in a nuclear power plant, is important to study the source term behavior. In addition to the levels of radioactivity released during an accident, production and removal rates are important too.

The escape of fission products from containment to environment primarily depends upon the ventilation exhaust rates, leakage rate, deposition, re suspension, recirculation, filtration efficiencies, droplet collection efficiency, and spray system operation [24]. The FPs as source term include the noble gases (Kr, Xe), Cs and I isotopes as well as aerosol (such as Sr, Ru, and Te) [8].

Based on [24] technical data and NPP containment features, some researchers developed a kinetic model for simulating the ESFs of research as well as power reactors [1] [13]; [18]; [11].

[1] developed a model for the Pakistan Atomic Research Reactor-1 (PARR-1) containment. Later, a single containment model for PWR 1000 MWe was developed according to the Three Mile Island reactor by Ref. [13]. They studied source terms in different accidents for PWR reactors such as a large break loss of coolant accident (LOCA), station blackout (SBO), small break loss of coolant accident (SBLOCA) and Feedwater accidents [14]; [15] [18]. used a kinetic model for estimation of the source terms in accidents including LOCA, reactivity initiation accident (RIA) and fuel handling accident (FHA).

[10] developed a code system named IRBURN for quantification of the in-containment activity and presented a kinetic model for simulation and calculation of in-containment activity in VVER-1000 reactors after severe accidents.

In the previous works, we extended the IRBURN code system [3,9] capability by adding new modules for determination and calculation of the in-containment source terms for VVER-1000 reactor under accident situation [10,11] and [12]. The new IRBURN code uses a new MATLAB based program for burn-up calculation that incorporates the neutron importance calculation module [11] and [12] using the MCNIC method [4] and [5] and generation of importance-spectrum weighted neutronic cross

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https://doi.org/10.1016/j.net.2018.09.003

sections for burnup calculations [11]. Using time dependent bilinear weighted neutronic cross sections for simulation of the in-containment source term in VVER-1000 power reactors under severe accidents, improves the accuracy and precision of source term evaluation analysis [10].

In previous work [10], we extended the IRBURN capabilities for estimation of the in-containment source term in VVER-1000 power reactors and quantified it in a severe accident. In this work, the effect of containment engineering safety features during severe accidents is studied by using the IRBURN code. A LOCA scenario in a VVER-1000 reactor was considered as an example. The time dependent behaviors of in-containment source term are studied in four confined groups of fission products including noble gasses, cesium, iodine and aerosol. Time varition of the production and the loss terms in volumetric and surface activities for above categories are studied by considering two groups including long and short lived isotopes. For this purpose, Kr-90 and Ru-105 are selected. Moreover, the differences for the time dependent behaviors of in-containment volumetric activities are explained.

2. Plant description (VVER-1000)

Bushehr Nuclear Power Plant (BNPP) VVER-1000 reactor is a pressurized light water reactor which is including 163 hexagonal fuel assemblies in six different types. Each Fuel assembly has 311 fuel rods, one central tube, one instrumental tube, and 18 guiding channels.

A fuel rod consists of a tube with an outside diameter of 9.1×10^{-3} m and end-pieces of zirconium alloy filled with the pellets of sintered UO_2 with a length of 3.842 m. The fuel pellet is made of UO_2 whose the average fuel density is 10.55 g/cm^3. The effective irradiation time of fuel assembly operation between refueling is about 7000 h. Moreover, light water is used as reactor coolant and moderator as well. The schematic of VVER-1000 reactor is shown in Fig. 1. The VVER-1000 reactor core and fuel assembly specifications are given in Table 1)FSAR[1] 2007).

The BNPP containment consists of inner steel and outer reinforced concrete containment. Inner steel containment limits the hermetic volume and it presents a sphere with a diameter of 56 m, supported by reinforced concrete bed. The inner containment is intended for restricting radioactive substances release due to accidents and for isolating those systems and components which are necessary to perform their intended functions in order to mitigate the consequences of the accident. The free volume and surface of the BNPP containment are about 71660 m^3 and 53250 m^2, respectively. The normal containment exhaust is 240000 m^3/h. The recirculation flow rate is 4.44 m^3/s. High efficiency particulate air filters in conjunction with activated charcoal filters are employed within the containment filtered ventilation system [6]. The diagram of the BNPP containment building is shown in Fig. 2. The outer reinforced concrete containment presents a cylinder with an external diameter of 62.8 m.

3. Time dependent in-containment activity

The ESFs in the containment are all features like charcoal and high efficiency particulate air filters with containment coolers and blowers which have been implemented for safety purposes. As is mentioned before, the release of fission products from containment to environment depends upon the containment characteristics such as leakage rate, re suspension, recirculation, filtration efficiencies, exhaust rates, and spray system operation. For this reason, the time dependent in-containment activity is calculated by using a balance between surface and volumetric activities. The general form of time dependent in-containment activity (q_v) is described as

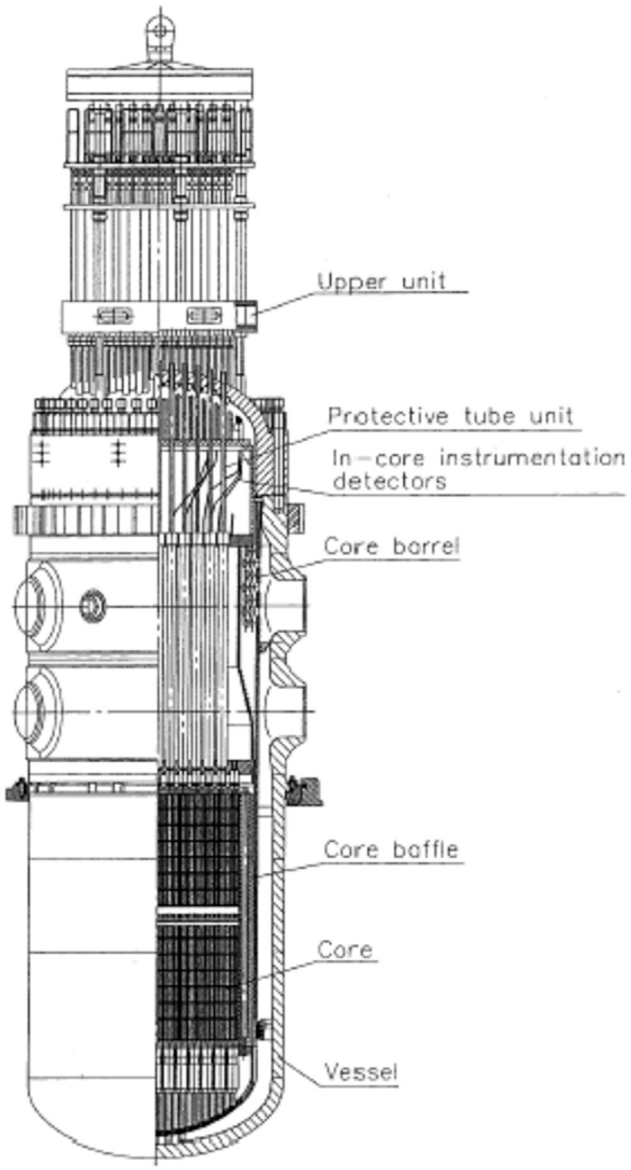

Fig. 1. The schematic of VVER-1000 reactor [6].

Table 1
The VVER-1000 specifications [6].

Parameters	Value
Thermal core power (MW)	3000
Average enrichment (wt %U-235)	1.6, 2.4, 3.3, 3.62
Core equivalent diameter (m)	3.16
Pitch between the assemblies (m)	0.236
Height of the heated part (m)	3.53
Fuel	Pellets UO_2
Pellet density (kg/m^3)	$(10.4–10.7) \times 10^3$
Outside diameter of cladding (m)	9.1×10^{-3}
Inside diameter of cladding (m)	7.73×10^{-3}
Outside diameter of pellet (m)	7.57×10^{-3}
Diameter of pellet central hole (m)	1.5×10^{-3}
Pellet height (m)	$(9.0–12.0) \times 10^{-3}$
Fuel rod length (m)	3.842
Height of fuel stack in the cold state (m)	3.53
Maximum linear heat rate of the fuel rod (W/cm)	448

[1] Final Safety Analysis Report.

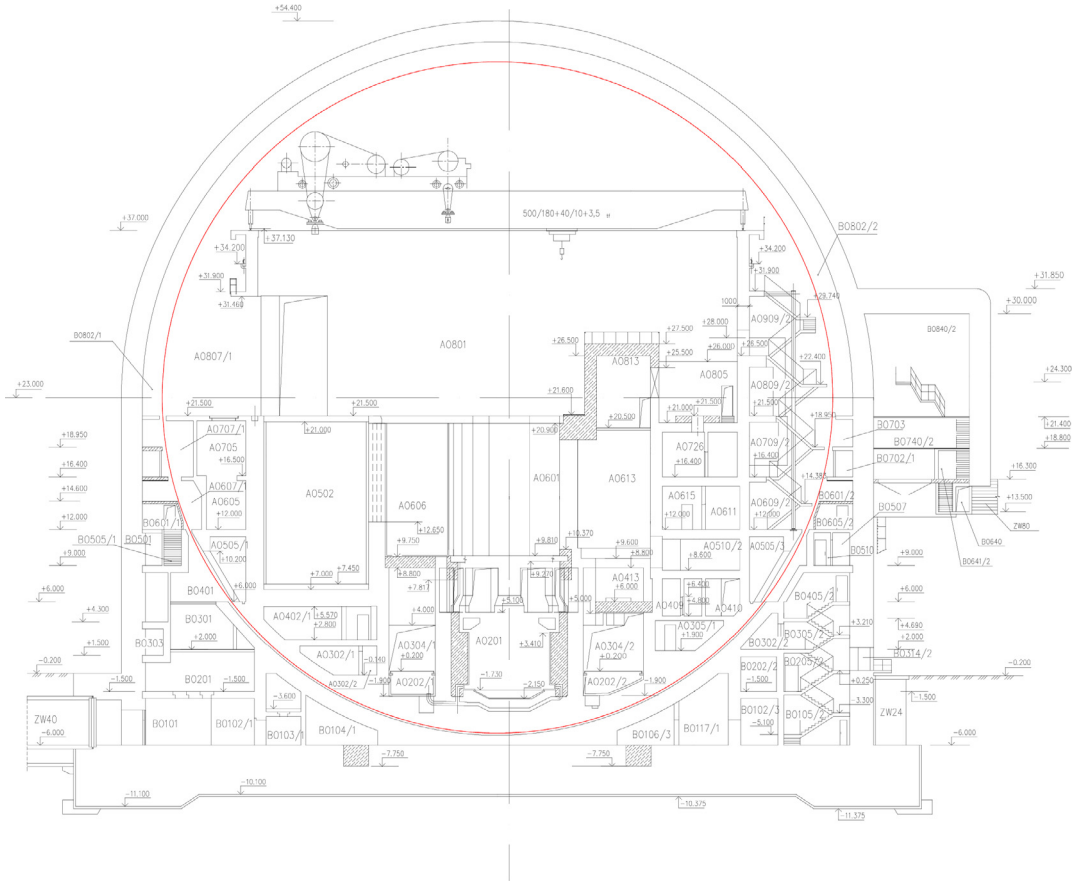

Fig. 2. The BNPP VVER-1000 containment building [6].

follows [8,24–26]:

$$\frac{dq_v(t)}{dt} = \underbrace{S(t) + r\frac{A}{V}q_a(t)}_{\text{Production}} - \underbrace{\lambda q_v(t) - u_t\frac{A}{V}q_v(t) - R_{rc}\frac{\eta_{rc}}{V}q_v(t) - \frac{HE_iF}{V}q_v(t) - \frac{3hE_aF}{2dV}q_v(t) - \frac{L_r}{V}q_v(t)}_{\text{Loss}} \quad (1)$$

According to Eq. (1), the net volumetric activity rate is equal to volumetric rate of productions (production terms) minus volumetric rate of losses (loss terms). The production term is the time dependent source for isotope ($S(t)$) plus the re-suspension rate of activity from free surface ($r\frac{A}{V}q_a(t)$). The loss terms are composed of decay of isotope ($\lambda q_v(t)$), deposition on the containment surfaces ($u_t\frac{A}{V}q_v(t)$), removal with recirculation filtration ($R_{rc}\frac{\eta_{rc}}{V}q_v(t)$), removal of isotopes by containment spray system for iodine $\left(\frac{HE_iF}{V}q_v(t)\right)$ and for solid fission products ($\frac{3hE_aF}{2dV}q_v(t)$), and volumetric leakage of isotopes from the containment ($\frac{L_r}{V}q_v(t)$).

The balance equation for activity from containment free surface is defined as follows:

$$\frac{dq_a(t)}{dt} = u_t q_v(t) - rq_a(t) \quad (2)$$

The first and second terms on the right side of Eq. (2) are the deposition of isotope on containment free surface ($u_t q_v(t)$) as the production term and re-suspension from the containment surfaces ($rq_a(t)$) as the loss term, respectively.

In these equations, q_v(t) is volumetric activity (Bq/m^3), $S(t)$ is time dependent source of volumetric activity (Bq/m^3.s), r is re-suspension rate (s^{-1}); A is containment free surface (m^2), V is containment free volume (m^3), q_a(t) is the activity on surface of containment (Bq/m^2), λ is decay constant (s^{-1}), u_t is deposition velocity (m/s), R_{rc} is recirculation rate (m^3/s); η_{rc} is filter efficiency, H is partition coefficient, E_i is droplet collection efficiency for elemental iodine, F is spray flow rate(m^3/s), h is containment height (m), E_a is droplet collection efficiency for aerosols, d is droplet diameter (m), and L_r is exhaust rate (m^3/s).

The time dependent source $S(t)$ is suggested by Ref. [2]; in which the source is exponentially decreasing after the accident.

$$S(t) = (1 - f_x)A_c f_f f_w f_c m e^{-w_x t} \Big/ V \quad (3)$$

Where m is the normalization constant, A_c is the total activity in the core at the initiation time of the accident, f_f is the release fraction from fuel to coolant, f_w is the release fraction from the

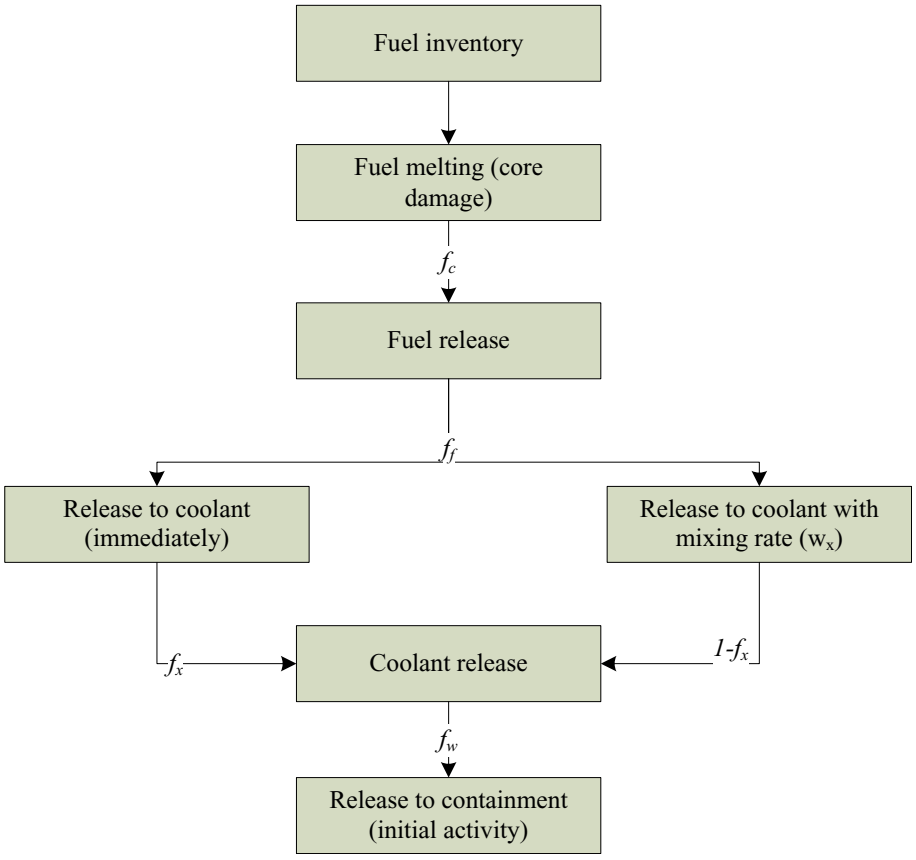

Fig. 3. Flow diagram of fission product release in containment.

coolant to air, and *fc* is the fraction of core damaged during the accident. f_x is the fraction of activity that becomes available immediately after the accident and the rest of activity gradually enters into the containment from coolant as function of time (Fig. 3).

The time dependent source balance equation is described as follows:

$$A_c = f_x A_c + (1 - f_x) A_c m \int_0^T e^{-w_x t} dt \tag{4}$$

The $f_x\ A_c$ is a fraction of activity that is made instantaneously available to the coolant and $(1\text{-}f_x)A_c \exp(\text{-}w_x\ t)$ is the time dependent part of activity that enters during the accident with mixing rate w_x. Integrating over a large time period ($T\sim10/w_x$), m becomes approximately equal to w_x. Also, the f_x value is the fraction of activity enters immediately in the containment at the start of the accident and the rest of it enters the coolant as a time dependent function represented in Eq. (3). At the time of initiation of an accident ($t = 0$), $q_a(0) = 0$, and $q_v(0) = f_f f_w f_c f_x A_c/V$.

4. Calculation of fission product inventory

In the previous work [10], a module for calculating the in-containment fission product activity was developed and implemented into the IRBURN code system. The user can study the source term behavior as a function of time for all fission products in the containment area under various accident situations by the IRBURN code.

The IRBURN in-containment module calculates in-containment accident source term as a function of time for different accident types at LWR reactors, and one can study the effect of containment engineering safety features (ESFs) on isotopic activity during the accident. The flowchart of the IRBURN in-containment module is shown in Fig. 4. The module input (in-containment block) is including accident and isotope lists as well as associated parameters for the accident scenarios which should be determined by the user.

According to Fig. 4, the core inventory is determined by given initial conditions for the reactor system in the core calculation block of the IRBURN code system. The core calculation block uses the importance-spectrum weighted depletion equation to incorporate the neutron importance function in the burnup calculation as follows [11] and [12]:

$$\frac{dN_i(t)}{dt} = \sum_{j=1}^{m} l_{ij}\lambda_j N_j + \phi \sum_{k=1}^{m} f_{ik}\sigma_k^* N_k - (\lambda_i + \phi\sigma_i^*)N_i \tag{5}$$

Where, N_i = atom density of nuclide i, m = number of nuclides, l_{ij} = fraction of radioactive disintegration by other nuclide j which leads to formation of nuclide i, λ_j = radioactive decay constant for nuclide j, ϕ = position and energy-averaged neutron flux, f_{ik} = fraction of neutron absorption by other nuclide k which leads to formation of nuclide i, σ_k^* = importance-spectrum weighted neutron absorption cross-section of nuclide k.

The code incorporates the neutron importance into a burnup model by using MCNIC method [4] and [5]. The IRBURN code uses the neutronic information such as the multiplication factor, flux and spectrum to produce the bilinear weighted cross-section for a given region in each time step. Then, core inventory is calculated

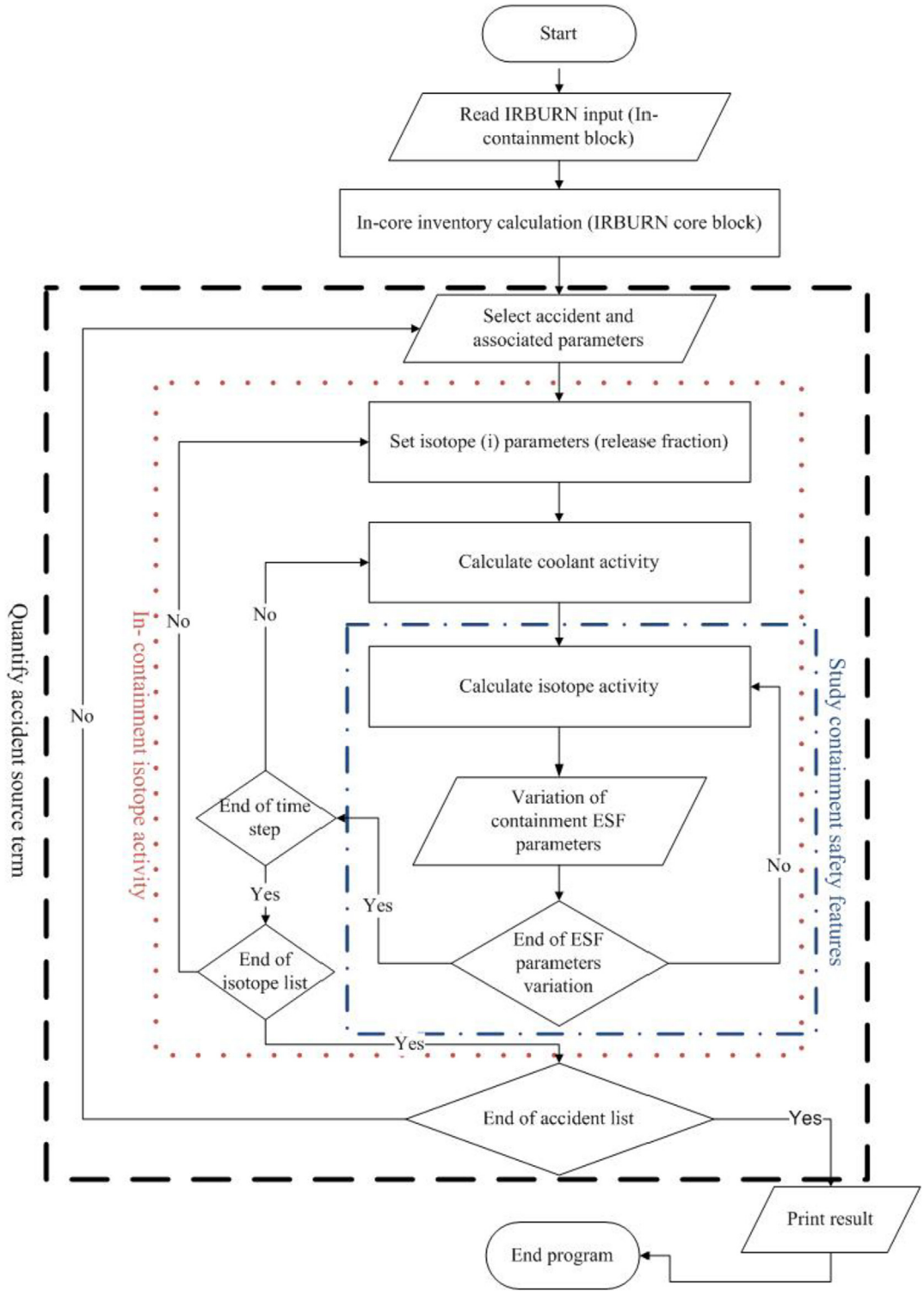

Fig. 4. In– containment calculation via the IRBURN code system.

using the updated library for each time step. Additionally, the program computes isotopic activity as a function of time according to the given data in IRBURN input.

Moreover, the effect of containment ESFs parameters can be studied during an accident. These parameters can be quantified for different accident types and different core inventory calculation schemes.

5. Loss of coolant accident conditions as an illustrative scenario

Several reports have shown that although fractions of activity become airborne at initiation time of the accident, the activity in the containment has a time dependency during an accident [25,26].

NUREG-1150 [17] and NUREG-1465 [25] advice 100% release for

Table 2
Fraction of activity released from the fuel into containment under loss of coolant accident.

Radionuclide type	f_f[a]	f_w[b]	u_t[c](m/s)	r[d](s^{-1})
Noble gases	1	0.95	10^{-6}	10^{-6}
Iodine	0.9	0.3	5.5×10^{-4}	2.3×10^{-6}
Cesium	0.9	0.3	5.5×10^{-4}	2.3×10^{-6}
Tellurium	0.25	0.2	5.5×10^{-4}	2.3×10^{-6}
Barium	0.01	0.2	1.27×10^{-3}	1.5×10^{-5}
Rutherium and Rubedium	0.01	0.1	1.27×10^{-3}	1.5×10^{-5}
Celerium	0.0001	0.1	1.27×10^{-3}	1.5×10^{-5}
Lathanium	0.0001	0.1	1.27×10^{-3}	1.5×10^{-5}
Other fission products	0.0001	0.02	10^{-3}	1.0×10^{-5}

[a] f_f is the release fraction from fuel to coolant.
[b] f_w is the release fraction from the coolant to air.
[c] u_t is deposition velocity.
[d] r is re-suspension rate.

Table 3
In-containment source term equation parameters.

Parameter	Symbol	Value
Containment free volume (m^3)	V	71660
Containment free surface area (m^2)	A	53250
Containment leakage rate (m^3/s)	L_r	16.66
Recirculation rate (m^3/s)	R_{rc}	4.44
Core damage fraction	f_c	50%
Recirculation filter efficiency	E	0.1
Exhaust filter efficiency	η_{rc}	0.9–0.99
Fraction of Ac released immediately	f_x	20%
Mixing rate (s^{-1})	w_x	0.01
Spray flow rate (m^3/s)	F	0.0–1

noble gases from coolant. In NUREG-1150, the coolant retention of 70–90% for iodine, 75–95% for cesium and 90–97% for other fission products have been suggested. However, according to the experiments, the coolant retention for iodine and cesium is in the range of 70%–90% and 60%–90%, respectively [22] [16]; [20]; [7].

Additionally, according to the report of TOKYO Electric Power Company [23], the core meltdown percentages for Fukushima Daiichi unit one, unit two and unit three under loss of power along with the unavailability of emergency core cooling system (ECCS) were about 55%, 35%, and 30%, respectively.

In this illustrative scenario, we assumed the LOCA with unavailability of the ECCS hydro accumulators while keeping the integrity of the containment under design pressure.

As the removal rate of the molecular iodine from the containment is less than that of aerosols, conservatively it was assumed that during the coolant leak, 99% of the iodine remains in the containment atmosphere in the form of molecular iodine. According to the VVER-1000 safety report, it was assumed that 1% of the iodine is released into the containment as organic iodine compositions and all cesium is released as the aerosol. The fuel release fractions for various isotopes have been selected according to Table 2. (Mehbbob et al., 2015 [1]; [8,21,25] [19]; FSAR, 2007).

Moreover, inner surfaces of the containment are considered as rough concrete surfaces. The in-containment source term equation parameters during accident are defined in Table 3. According to the FSAR, the exhaust filter efficiency is varied for idoine (0.99) and aerosol (0.9).

6. Result and discussion

6.1. VVER-1000 core inventory

The amount of the calculated nuclide activities for the first operational cycle in the VVER-1000 determined by using the

Table 4
The calculated activities for VVER-1000 core at the end of cycle (Bq).

Nuclide	Half Life (s)	Decay constant	This work	FSAR	Nuclide	Half Life (s)	Decay constant	This work	FSAR
Kr-83 m	6.60E+03	1.05E-04	4.14E+17	N/A	I-134	3.15E+03	2.20E-04	6.65E+18	7.25E+18
Kr-85	3.38E+08	2.05E-09	1.15E+16	N/A	I-135	2.38E+04	2.91E-05	5.59E+18	5.88E+18
Kr-85 m	1.61E+04	4.30E-05	9.16E+17	8.33E+17	Xe-131 m	1.03E+06	6.74E-07	3.13E+16	N/A
Kr-87	4.59E+03	1.51E-04	1.80E+18	2.35E+18	Xe-133	4.53E+05	1.53E-06	6.01E+18	6.96E+18
Kr-88	1.02E+04	6.78E-05	2.54E+18	3.15E+18	Xe-133 m	1.89E+05	3.66E-06	1.84E+17	N/A
Kr-89	1.90E+02	3.64E-03	3.16E+18	4.11E+18	Xe-135	3.27E+04	2.12E-05	1.36E+18	8.73E+17
Kr-90	3.22E+01	2.15E-02	3.13E+18	4.18E+18	Xe-135 m	9.17E+02	7.56E-04	1.13E+18	N/A
Rb-86	1.61E+06	4.30E-07	1.81E+15	N/A	Xe-137	2.30E+02	3.02E-03	5.25E+18	N/A
Sr-89	4.36E+06	1.59E-07	3.53E+18	4.33E+18	Xe-138	8.50E+02	8.15E-04	5.16E+18	N/A
Sr-90	9.19E+08	7.54E-10	8.84E+16	2.66E+17	Cs-134	6.48E+07	1.07E-08	6.27E+16	1.45E+18
Sr-91	3.41E+04	2.03E-05	4.20E+18	4.40E+18	Cs-134 m	1.04E+04	6.64E-05	4.33E+16	N/A
Sr-92	9.75E+03	7.11E-05	4.43E+18	5.44E+18	Cs-135	7.26E+13	9.55E-15	3.41E+11	N/A
Y-90	2.30E+05	3.01E-06	9.16E+16	N/A	Cs-135 m	3.18E+03	2.18E-04	7.49E+15	N/A
Y-91	5.06E+06	1.37E-07	4.38E+18	N/A	Cs-136	1.13E+06	6.12E-07	5.59E+16	N/A
Zr-95	5.55E+06	1.25E-07	5.26E+18	6.07E+18	Cs-137	9.47E+08	7.32E-10	1.06E+17	2.90E+17
Zr-97	6.08E+04	1.14E-05	5.06E+18	5.55E+18	Cs-138	1.93E+03	3.59E-04	5.65E+18	N/A
Mo-99	2.37E+05	2.92E-06	5.36E+18	2.42E+17	Cs-138 m	1.74E+02	3.98E-03	2.47E+17	N/A
Tc-99 m	2.17E+04	3.20E-05	4.69E+18	N/A	Cs-139	5.64E+02	1.23E-03	5.38E+18	N/A
Ru-103	3.40E+06	2.04E-07	3.81E+18	2.76E+18	Cs-140	6.36E+01	1.09E-02	4.82E+18	N/A
Ru-105	1.60E+04	4.34E-05	2.76E+21	N/A	Ba-140	1.11E+06	6.27E-07	5.29E+18	5.92E+18
Ru-106	3.18E+07	2.18E-08	4.93E+17	2.86E+17	La-140	1.45E+05	4.79E-06	5.34E+18	5.96E+18
Rh-105	1.27E+05	5.45E-06	2.00E+18	N/A	Ce-141	2.81E+06	2.47E-07	5.12E+18	5.37E+18
Sb-127	3.33E+05	2.08E-06	2.67E+17	N/A	Ce-143	1.19E+05	5.84E-06	4.82E+18	N/A
Sb-129	1.55E+04	4.46E-05	8.49E+17	N/A	Ce-144	2.46E+07	2.82E-08	2.41E+18	4.40E+18
Te-127	3.36E+04	2.06E-05	2.59E+17	N/A	Pr-143	1.17E+06	5.91E-07	4.78E+18	N/A
Te-127 m	9.42E+06	7.36E-08	2.90E+16	N/A	Nd-147	9.56E+05	7.25E-07	1.97E+18	N/A
Te-129	4.18E+03	1.66E-04	8.37E+17	N/A	Np-239	2.03E+05	3.41E-06	5.25E+19	N/A
Te-129 m	2.90E+06	2.39E-07	1.24E+17	N/A	Pu-238	2.77E+09	2.50E-10	3.76E+14	N/A
Te-131	1.50E+03	4.62E-04	2.53E+18	2.46E+18	Pu-239	7.59E+11	9.13E-13	6.97E+14	N/A
Te-131 m	1.08E+05	6.42E-06	3.95E+17	N/A	Pu-240	2.06E+11	3.36E-12	3.83E+14	N/A
Te-132	2.82E+05	2.46E-06	4.07E+18	3.85E+18	Pu-241	4.53E+08	1.53E-09	8.81E+16	N/A
I-131	6.95E+05	9.98E-07	2.83E+18	2.82E+18	Am-241	1.36E+10	5.08E-11	2.87E+13	N/A
I-132	8.28E+03	8.37E-05	4.14E+18	3.85E+18	Cm-242	1.41E+07	4.92E-08	3.55E+15	N/A
I-133	7.49E+04	9.26E-06	6.00E+18	6.96E+18	Cm-244	5.73E+08	1.21E-09	4.64E+13	N/A

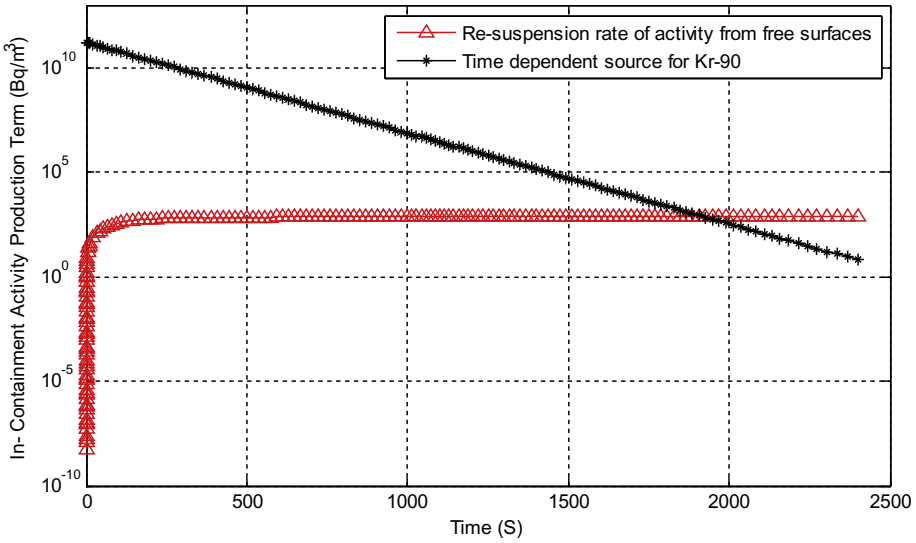

Fig. 5. In– containment activity production terms as a function of time for Kr-90 (short lived isotope).

IRBURN code is presented in Table 4. In comparison with available results in FSAR, the discrepancies can be related to the difference between cross section libraries (mainly absorption cross-sections), burnup chain, fission yields and the variation of the boron concentration during the operational cycle and consequently the variation of neutron importance as well as the neutron spectrum which will affect on averaged cross sections and fuel material inventory time dependency.

6.2. Containment engineering safety features parameters

The production terms are based on two important parts including precursors and re-suspension rate of activity from free surfaces. The loss rates are due to the terms including decay of fission product, leakage from containment, deposition on the surfaces of containment, recirculation filtration, and removal by spray system.

In the previous work [10], the time dependent semi kinetic model was verified by comparison the in-containment activity for various isotopes with [24] technical data, and other similar works [1] and [15].

In this section, we demonstrate the contribution of ESFs in the volumetric in-containment source term. All parameters for the calculation are shown in Tables 2 and 3

6.2.1. Influence of production terms

According to Eq. (1), the production term includes time dependent source and re-suspension rate of activity from containment free surfaces. All parameters for the calculation of production terms are extraced from Tables 2 and 3 In this category, two different behaviors are observed. These behaviors are shown in Figs. 5 and 6.

According to Figs. 5 and 6, the re-suspension rate of activity from free surfaces is increasing promptly at the initiation of the accident, and then increases slowly with time. The values of u_t and r for Kr-90 and Ru-105 are considered 10^{-6}, 1.27×10^{-3} and 10^{-6}, 1.5×10^{-5}, respectively. In contrast, the time dependent source is slightly decreased during time after initiating of the accident for

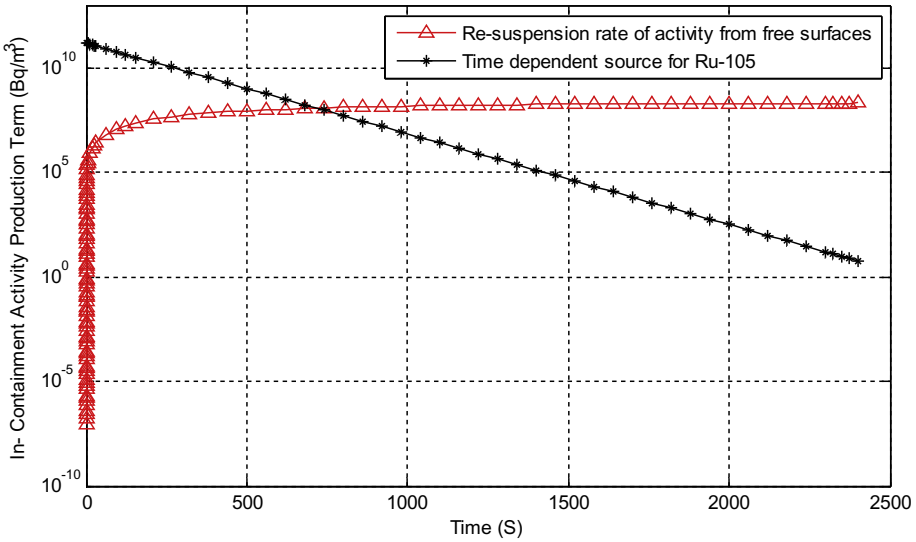

Fig. 6. In– containment activity production terms as a function of time for Ru-105 (long lived isotope).

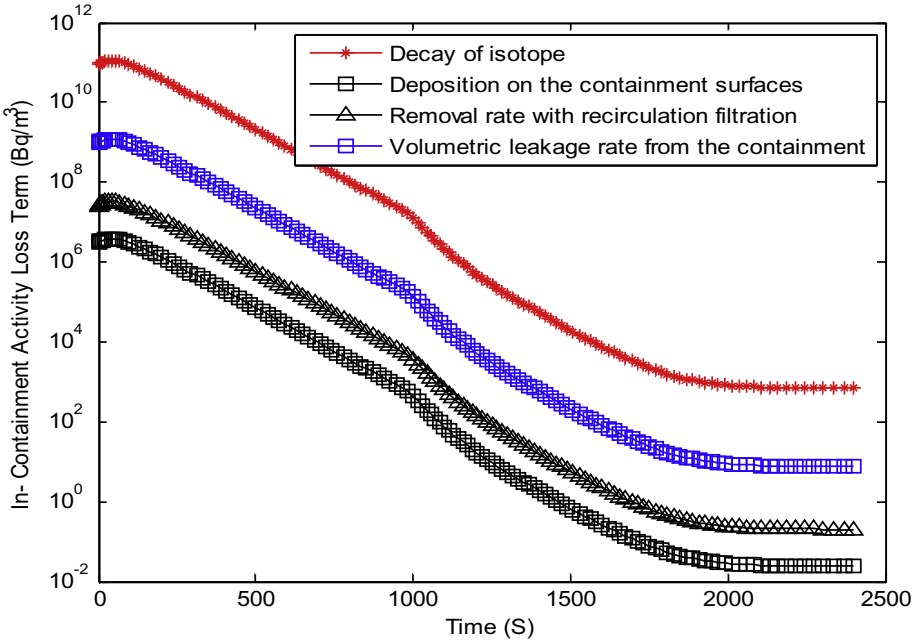

Fig. 7. In– containment activity loss terms as a function of time for Kr-90.

isotopes with short lived (Fig. 5) rather than long lived isotopes (Fig. 6). Although, the decreasing manners for those two isotopes are similar but the decreasing rates are different. The difference may attribute due to the differences of the total activity in the core at the initiation time of the accident, the release fraction from fuel to coolant (f_f) and the release fraction from the coolant to air (f_w).

At the beginning of the accident for Kr-90 ($T_{1/2} = 32$ s), the re-suspension rate of activity from free surfaces is less than the time dependent source rate. But the contribution of the re-suspension rate from free surfaces is increasing promptly after the accident. After 2000 s the re-suspension rate overcomes the time dependent source. But, for Ru-105 ($T_{1/2} = 1.6 \times 10^4$s) re-suspension rate overcomes the time dependent source after 700 s.

The results show that re-suspension rate of activity from free surfaces due to long lived isotopes has higher contribution in comparison with the re-suspension rate of activity due to short lived isotopes. After a long time during the accident, this factor has the highest contribution in the production term.

6.2.2. *Influence of loss terms*

For loss terms including decay of isotopes, deposition on the containment surfaces, removal rate with recirculation filtration, removal of isotopes by containment spray system for iodine and solid fission products and volumetric leakage rate, the following

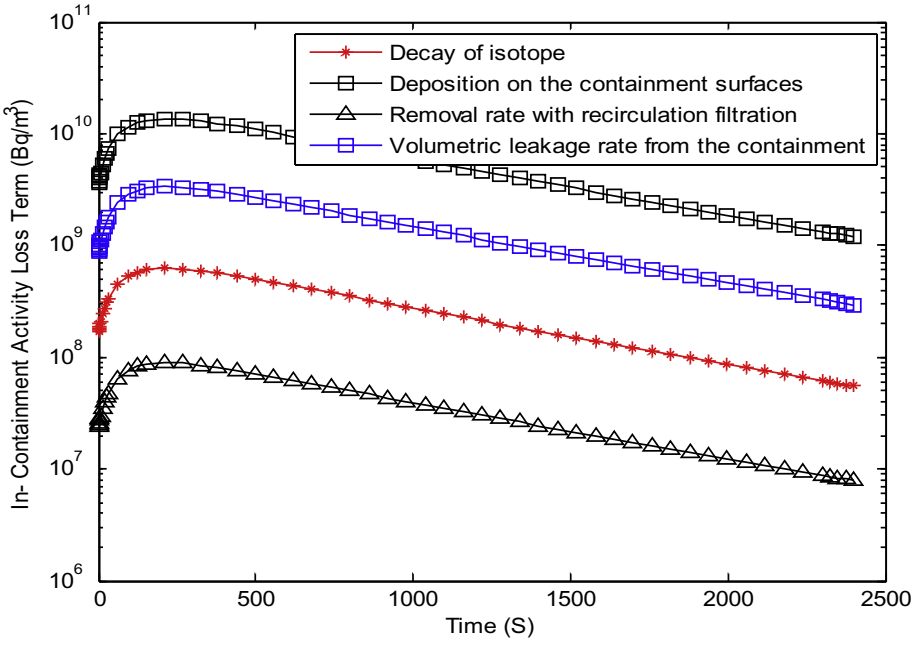

Fig. 8. In– containment activity loss terms as a function of time for Ru-105.

manners are observed in different isotope categories. These behaviors are categorized in noble gas, iodine, cesium, and aerosol. All required parameters for the calculation of loss terms are extraced from Tables 2 and 3 Moreover, the assumption for considered scenario is presented in Section 5.

6.2.2.1. Noble gasses (Krypton & Xenon). Release of noble gasses cannot be mitigated easily because of their less reactivity nature and they have considerable contribution to the whole body dose. They escape from the containment without filtration. By studying noble gas categories including Kr and Xe isotopes, the following behavior in loss terms is observed:

6.2.2.1.1. Kr isotopes. For Kr-83 m, Kr-85 m, Kr-87, Kr-88, their largest contribution to the removal of activity is due to the volumetric leakage rate and then, the decay of isotopes, removal rate with recirculation filtration and deposition on the containment surfaces, respectively.

But, the removal of activity for Kr-85 is in a different way. The

Table 5
The peak activity order of removal mechanisms for isotopic list (Bq/m^3).

Isotope list	Removal mechanisms			
	Decay of isotope	Deposition on the containment surfaces	Removal with recirculation filtration	Volumetric leakage of isotopes from the containment
Kr-83 m	2.56E+08	1.81E+06	1.51E+07	5.66E+08
Kr-85	1.43E+02	5.17E+04	4.31E+05	1.62E+07
Kr-85 m	2.35E+08	4.07E+06	3.39E+07	1.27E+09
Kr-87	1.58E+09	7.78E+06	6.48E+07	2.43E+09
Kr-88	1.02E+09	1.12E+07	9.34E+07	3.50E+09
Kr-89	4.21E+10	8.60E+06	7.17E+07	2.69E+09
Kr-90	1.14E+11	3.93E+06	3.28E+07	1.23E+09
Rb-86	4.09E+00	8.98E+03	5.89E+01	2.21E+03
Sr-89	6.10E+00	2.85E+04	2.38E+02	8.92E+03
Sr-90	7.24E-04	7.13E+02	5.95E+00	2.23E+02
Sr-91	9.23E+02	3.38E+04	2.82E+02	1.06E+04
Sr-92	3.38E+03	3.53E+04	2.94E+02	1.10E+04
Y-90	2.99E+00	7.39E+02	6.16E+00	2.31E+02
Y-91	6.51E+00	3.53E+04	2.94E+02	1.11E+04
Zr-95	7.14E+00	4.25E+04	3.54E+02	1.33E+04
Zr-97	6.25E+02	4.07E+04	3.40E+02	1.27E+04
Mo-99	1.70E+02	4.33E+04	3.61E+02	1.35E+04
Tc-99 m	1.62E+03	3.75E+04	3.13E+02	1.17E+04
Ru-103	4.09E+03	1.89E+07	1.24E+05	4.66E+06
Ru-105	6.25E+08	1.36E+10	8.93E+07	3.35E+09
Ru-106	5.65E+01	2.44E+06	1.60E+04	6.02E+05
Rh-105	1.18E+02	1.61E+04	1.35E+02	5.05E+03
Sb-127	5.95E+01	2.14E+03	1.79E+01	6.71E+02
Sb-129	6.79E-01	6.85E+03	5.71E+01	2.14E+03
Te-127	1.53E+06	3.04E+07	4.62E+05	1.73E+07
Te-127 m	6.16E+02	3.42E+06	5.19E+04	1.95E+06
Te-129	3.89E+07	9.57E+07	1.45E+06	5.45E+07
Te-129 m	8.57E+03	1.47E+07	2.22E+05	8.34E+06
Te-131	3.11E+08	2.75E+08	4.17E+06	1.56E+08
Te-131 m	7.32E+05	4.66E+07	7.06E+05	2.65E+07
Te-132	2.89E+06	4.79E+08	7.27E+06	2.73E+08
I-131	4.41E+06	1.81E+09	2.74E+07	1.03E+09
I-132	5.29E+08	2.59E+09	3.92E+07	1.47E+09
I-133	8.65E+07	3.82E+09	5.79E+07	2.17E+09
I-134	2.19E+09	4.06E+09	6.16E+07	2.31E+09
I-135	2.52E+08	3.54E+09	5.36E+07	2.01E+09
Xe-131 m	1.28E+05	1.41E+05	1.17E+06	4.40E+07
Xe-133	5.56E+07	2.70E+07	2.25E+08	8.44E+09
Xe-133 m	4.07E+06	8.26E+05	6.89E+06	2.59E+08
Xe-135	1.73E+08	6.08E+06	5.07E+07	1.90E+09
Xe-135 m	4.40E+09	4.32E+06	3.60E+07	1.35E+09
Xe-137	6.16E+10	1.51E+07	1.26E+08	4.74E+09
Xe-138	2.14E+10	1.96E+07	1.63E+08	6.12E+09
Cs-134	1.05E+03	4.00E+07	6.06E+05	2.27E+07
Cs-134 m	4.43E+06	2.72E+07	4.13E+05	1.55E+07
Cs-135	5.08E-09	2.17E+02	3.30E+00	1.24E+02
Cs-135 m	2.44E+06	4.57E+06	6.93E+04	2.60E+06
Cs-136	5.33E+04	3.56E+07	5.40E+05	2.03E+07
Cs-137	1.21E+02	6.76E+07	1.03E+06	3.85E+07
Cs-138	2.96E+09	3.37E+09	5.11E+07	1.92E+09
Cs-138 m	9.64E+08	9.90E+07	1.50E+06	5.63E+07
Cs-139	8.51E+09	2.83E+09	4.29E+07	1.61E+09
Cs-140	3.49E+10	1.31E+09	1.99E+07	7.45E+08
Ba-140	3.49E+04	5.25E+07	3.44E+05	1.29E+07
La-140	1.34E+03	2.64E+05	1.73E+03	6.50E+04
Ce-141	6.64E+01	2.54E+05	1.66E+03	6.25E+04
Ce-143	1.48E+03	2.39E+05	1.57E+03	5.88E+04
Ce-144	3.56E+00	1.19E+05	7.81E+02	2.93E+04
Pr-143	3.06E+01	3.85E+04	3.21E+02	1.20E+04
Nd-147	1.55E+01	1.59E+04	1.33E+02	4.97E+03

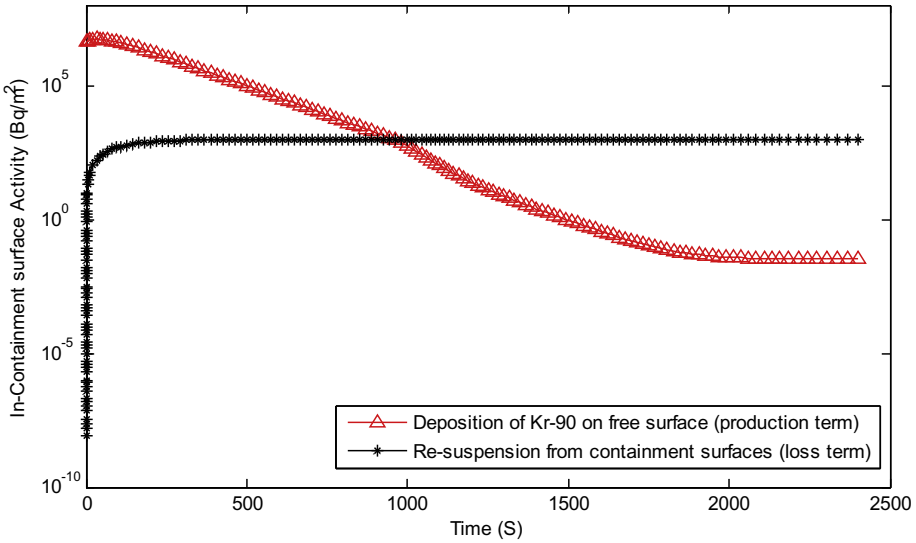

Fig. 9. In-containment surface activity (Bq/m^2) for Kr-90 as function of time.

volumetric leakage rate is the most important part. The removal rate with recirculation filtration, deposition on the containment surfaces and the decay of isotopes are the second, third and fourth part of the activity removal in this case.

For other isotopes including Kr-89 and Kr-90, the contribution to the removal of activity from the largest to the lowest is due to the decay of isotopes, volumetric leakage rate, removal rate with recirculation filtration and deposition on the containment surfaces, respectively. This behavior is shown in Fig. 7. The peak value of the loss terms is observed at time 32s after initiation of the accident. The maximum values for largest to lowest loss term are about 1.14×10^{11}, 1.23×10^{9}, 3.27×10^{7}, and 3.93×10^{6}, respectively. According to the results, the decay of isotopes for Kr-90 is a dominant factor in the loss term mechanism because of the Kr-90 decay constant has higher value in Eq. (1).

6.2.2.1.2. Xe isotopes. The largest to the lowest contributions in the removal of activity, for Xe-131 m is volumetric leakage rate, removal rate with recirculation filtration, deposition on the containment surfaces and the decay of isotopes, respectively. The order of contributions for Xe-133 and Xe-133 m is volumetric leakage rate, removal rate with recirculation filtration, the decay of isotopes and deposition on the containment surfaces, respectively. The order of contributions for Xe-135 is volumetric leakage rate, the decay of isotopes, removal rate with recirculation filtration and deposition on the containment surfaces, respectively. The order of contributions for Xe-135 m, Xe-137, and Xe-138 are the decay of isotopes, volumetric leakage rate, removal rate with recirculation filtration and deposition on the containment surfaces, respectively.

6.2.2.2. Cesium. Cesium is another important isotope in the accident analyses for a commercial nuclear power plant. It is released in various forms including gaseous and aerosol forms. The cesium is biologically dangerous and can have a major contribution to the effective dose [13].

The contributions to the removal of activity from the largest to the lowest for Cs isotopes are as follows:

For Cs-134, Cs-135, Cs-136, and Cs-137: deposition on the containment surfaces, volumetric leakage rate, removal rate with recirculation filtration and the decay of isotopes.

For Cs-134 m, and Cs-135 m: deposition on the containment surfaces, volumetric leakage rate, the decay of isotopes and removal rate with recirculation filtration.

For Cs-138: deposition on the containment surfaces, the decay of isotopes, volumetric leakage rate and removal rate with recirculation filtration.

For Cs-138 m, Cs-139, and Cs-140: the decay of isotopes, deposition on the containment surfaces, volumetric leakage rate and removal rate with recirculation filtration.

6.2.2.3. Iodine. The iodine isotopes have radiological risk and can affect the health by causing the lung cancer [13]. The iodine is released in various forms which depend on the accident condition.

The activity loss terms for I-131 are the deposition on the containment surfaces, volumetric leakage rate, removal rate with recirculation filtration and the decay of isotopes, respectively.

The other important iodine isotopes including I-132, I-133, I-134, and I-135 are removed due to deposition on the containment surfaces, volumetric leakage rate, the decay of isotopes and removal rate with recirculation filtration during the accident time.

6.2.2.4. Aerosol. As a result of an accident, some isotopes release in the form of particles and aerosols including Sr, Ru and Te isotopes due to agglomeration and nucleation process. The removal activity of the most important aerosol is due to the following mechanisms:

6.2.2.4.1. Sr isotopes. Sr-89 and Sr-90 activities decrease by deposition on the containment surfaces, volumetric leakage rate, removal rate with recirculation filtration and the decay of isotopes.

Sr-91 and Sr-92 activities are removed by deposition on the containment surfaces, volumetric leakage rate, the decay of isotopes and removal rate with recirculation filtration.

6.2.2.4.2. Ru isotopes. In Ru-103 and Ru-106, the contribution to the removal of activity from the largest to the lowest are deposition on the containment surfaces, volumetric leakage rate, removal rate with recirculation filtration and the decay of isotopes, respectively.

In the case of Ru-105, deposition on the containment surfaces, volumetric leakage rate, the decay of isotopes and removal rate with recirculation filtration have the largest to the lowest contributions to the removal of Ru-105 activity, respectively, as is depicted in Fig. 8. The results show that the deposition on the

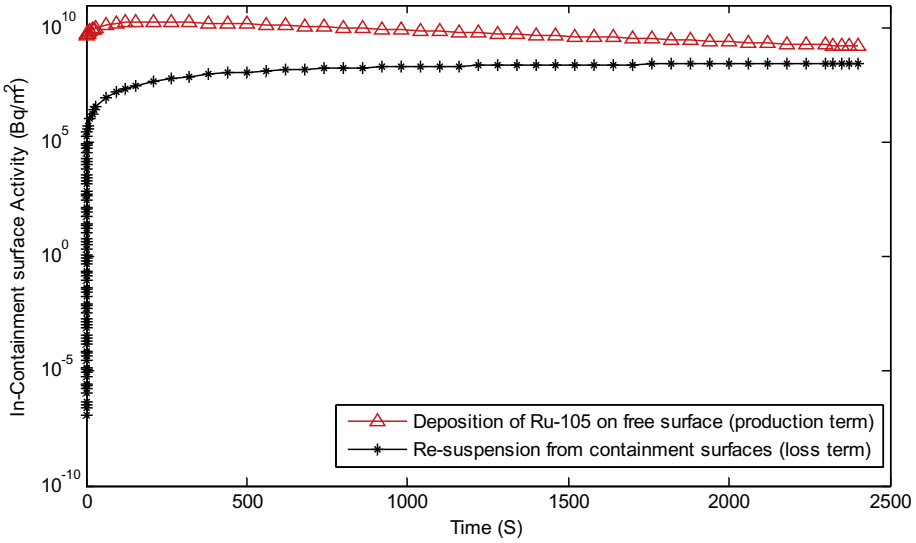

Fig. 10. In-containment surface activity (Bq/m^2) for Ru-105 as function of time.

containment surfaces for Ru-105 is the most important of the removal mechanisms because of the large surface area and the high deposition velocity of Ru-105.

6.2.2.4.3. Te isotopes. The largest to the lowest contribution in the removal of activity for Te-127, Te-129 and Te-131 m is deposition on the containment surfaces, volumetric leakage rate, the decay of isotopes and removal rate with recirculation filtration, respectively. The order of contributions for Te-127 m, Te-129 m and Te-132 are deposition on the containment surfaces, volumetric leakage rate, removal rate with recirculation filtration and the decay of isotopes, respectively. For Te-131, the decay of isotopes, deposition on the containment surfaces, volumetric leakage rate and removal rate with recirculation filtration have the largest to the lowest contribution in the removal of activity.

In summary, the peak activity orders of removal mechanisms for FPs are shown in Table 5. According to the results, the decay of isotope has commonly lower importance than other removal mechanisms. The deposition on the containment surfaces has higher importance than removal with recirculation filtration and volumetric leakage of isotopes from the containment in mostly isotopes. The volumetric leakage of isotopes from the containment is higher than the removal with recirculation filtration in all isotopes.

6.3. Activity from containment free surface

In this section, the production and loss term mechanisms dut to activity from containment free surface is studied by the IRBURN code. The calculation is performed based on given parameters in section 5, Tables 2 and 3

According to Figs. 9 and 10, evaluations for Kr-90 and Ru-105 show that the surface time dependent source is increasing during the accident. Furthermore, the deposition of isotope on free surface is increasing during time after initiating of the accident for isotopes, and then it decreased exponentially after reaching a maximum value. The loss term including the re-suspension from containment

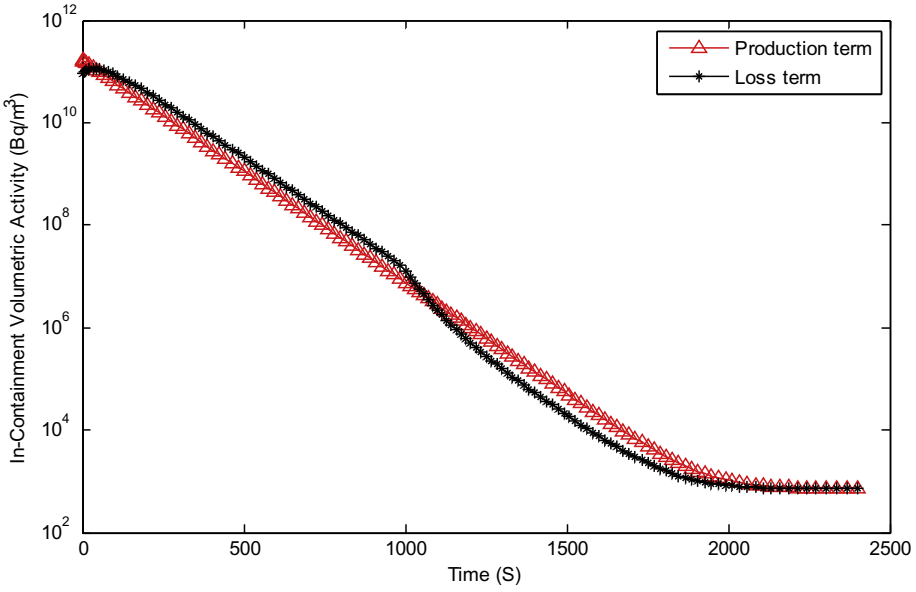

Fig. 11. In-containment volumetric activity (Bq/m^2) of Kr-90 as a function of time.

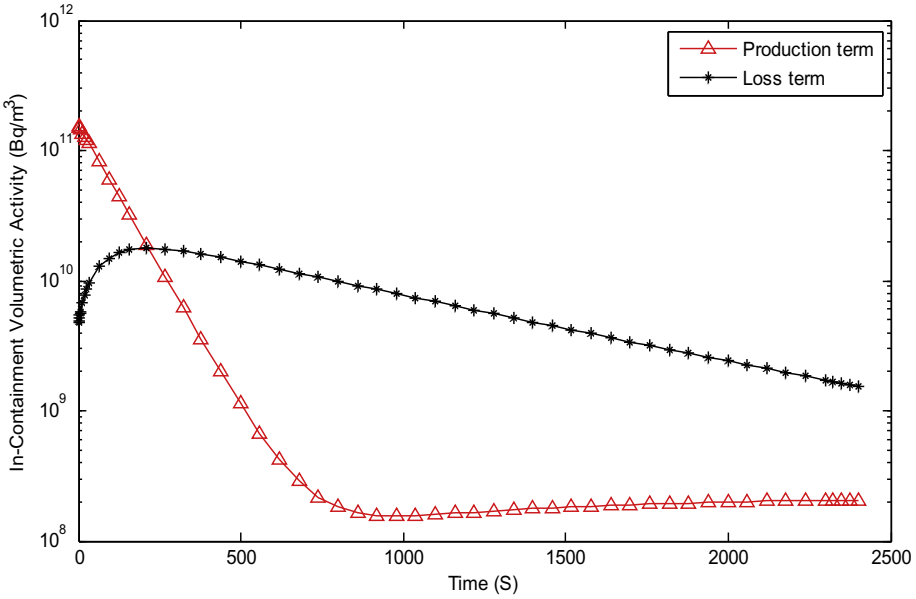

Fig. 12. In-containment volumetric activity (Bq/m^2) of Ru-105 as a function of time.

surfaces is slightly increasing during the accident time after promptly increasing at the initiation of the accident. This manner is similar for Ru-105.

For short lived isotopes, the activity from containment free surfaces is rapidly decreased after a short time from the accident. But, the amount of activity from containment free surfaces for long lived isotopes stays for a longer time after the accident and it gradually decreased during accident time.

As is depicted in Figs. 9 and 10, the peak of surface time dependent activity for Kr-90 as a short-lived isotope is decreased and shifted towards early times after the accident in comparison with the Ru-105 as a long-lived isotope. The peak values of the net surface activity for Kr-90 and Ru-105 are about 5.29×10^6 Bq/m^2 (t = 32s) and 1.83×10^{10} Bq/m^2 (t = 211s), respectively.

6.4. Production/loss term influence in-containment activity

Time dependent behavior of the production and the loss terms mechanisms for Kr-90 and Ru-105 are presented in Figs. 11 and 12, respectively. All requiem parameters for the calculation are presented in Tables 2 and 3 Figs. 11 and 12 show the varition of the production and the loss terms during the accident as well as theirs time dependency. Different time dependent behaviors for the production and the loss terms arise from different half-lives for Kr-90 and Ru-105.

The ratio of production to loss as function of time for Kr-90 and

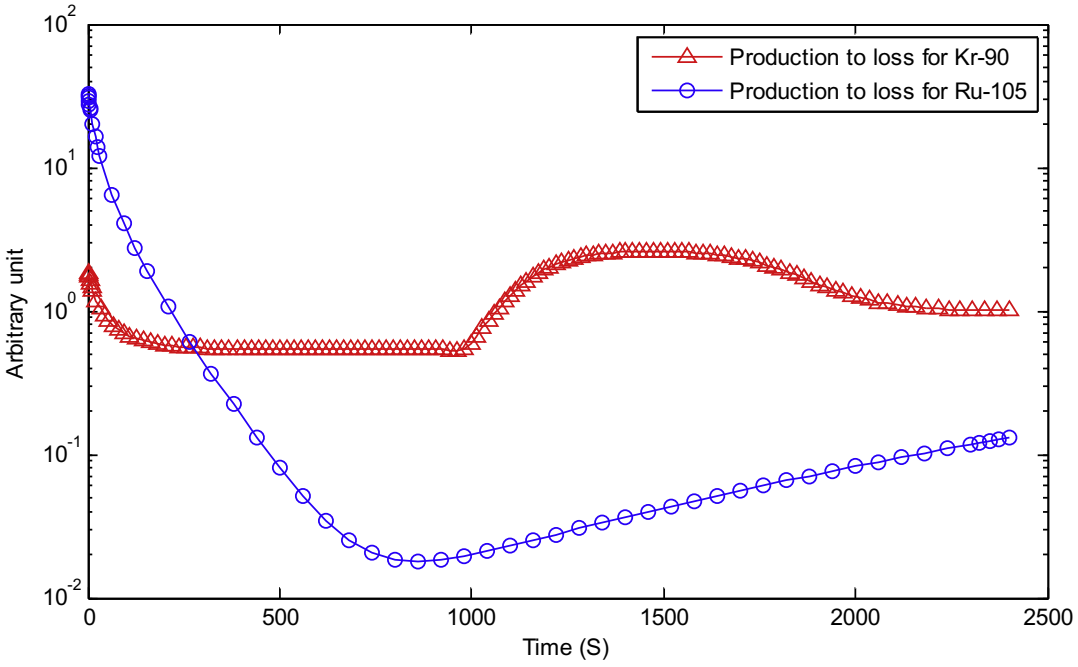

Fig. 13. Comparison between production to loss for Kr-90 and Ru-105 as function of time.

Ru-105 are calculated and compared in Fig. 13. This ratio shows the competitive behavior of the production and the loss terms as well as the overall impact of the removal mechanisms. The results show that the production to the loss term ratio is lower for Kr 90 during the accident until 1057s after the intiation of the accident then the production term becomes higher than loss terms. For Ru-105, this ratio is larger at the beginning of the accident, but it decreases after 1500s. At the beginning of the accident, the Kr and the Ru from the fuel into the containment area are instantaneously released by the factors of 0.95×0.2 and 0.001×0.2, respectively. With the respect to half life, Kr is consumed about 500 times larger than Ru, while Kr-90 production term is about 950 times larger than Ru-105. At the constant loss rate, the production to the loss terms for Ru-105 must be larger than that for Kr-90 at the beginning of the accident.

7. Conclusion

Safety assessment of power reactors especially in accident situation needs the source term evaluations. In this work, a time dependent semi kinetic model has been developed and in-containment activity for various isotopes have been quantified. A program which numerically estimates the in-containment activity has been incorporated in the IRBURN code system to study the fission product's activity inside the containment area of a VVER-1000 reactor. With the developed program, user can study the effect of containment engineering safety features during an accident as well as time dependent behaviors of in-containment volumetric and surface activities.

LOCA scenario in a VVER-1000 reactor was considered as an example, and time dependent behavior of in-containment source term is studied in four groups including noble gasses, cesium, iodine and aerosol. The volumetric and the surface activities mechanisms including production and the loss terms are also studied by considering isotopes in two groups including short lived and long lived. Illustrative samples including Kr-90 and Ru-105 are considered for short lived and long lived isotopes, respectively.

According to the results, the re-suspension rate of activity from free surfaces is increasing promptly at the initiation of the accident, and then increases slowly with time in both groups. The decreasing rate of time dependent source for short lived isotope is greater than long lived isotopes because of the total activity in the core, fuel and water release fractions.

In contrast, the time dependent source is slightly decreased during time after initiating of the accident for isotopes with short lived rather than long lived isotopes.

Additionally, the study of volumetric loss terms mechanisms show that the impact of volumetric leakage rate and the deposition on the containment surfaces for mostly isotopes are the most important loss terms during the LOCA accident scenario. During the accident, a greater amount of most isotopes are maintained in the containment area and deposited on the containment surfaces, while the removal with recirculation filtration has usually lower importance between than removal mechanisms.

The production term of surface activity including the deposition of isotope on free surface is increasing at the initiation of the accident for short and long lived isotopes, and then it decreased exponentially after reaching a maximum value. It observed that the decreasing rates of the surface production terms for short lived isotopes are more than long lived isotopes. The peak value of activity from containment free surfaces for long lived isotopes is reached a longer time after initiation of the accident rather than the short lived isotopes.

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