Analysis of the Containment Phenomena, Including Thermal-Hydraulic Processes and Fission Products Behaviour after Inadvertent Withdrawal of the Regulating Control Rod Group During Full-Power Operation

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Abstract. The inadvertent withdrawal of the regulating control rod group during full-power operation leads to an increase in the reactor power and thus to an increase in the primary circuit temperature and pressure. The fuel assemblies with the highest power peaking factors reach the state of boiling crisis and may be damaged. The present analysis of the processes in the containment is performed using the COCOSYS computer code. The calculation is part of a complex analysis of the accident that includes calculations with three other computer codes – determination of the isotopic inventory of the core at the end of the fuel campaign, evaluation of the number of damaged fuel assemblies and the mass and energy release into the containment, analyses of the radiological consequences of the accident. The analysis with the COCOSYS code demonstrated that a significant amount of the radioactive products released from the primary circuit are retained in the containment and only a small part of them reaches the environment through the leakages. It was confirmed that the acceptance criteria for the containment pressure and temperature are met.

Keywords: ATWS, COCOSYS, containment phenomena, fission products behaviour.

1 Introduction

The modernization programme of Kozloduy NPP (KNPP) foresees operation at an uprated power level of 104% nominal power. As part of the safety assessment, beyond design basis accidents (BDBA) have to be analyzed. The anticipated transient without scram with an inadvertent withdrawal of the regulating control rod group during full-power operation is found to be one of the limiting BDBA scenarios. This accident leads to an increase in the reactor power and thus to an increase in the primary circuit temperature and pressure. The fuel assemblies with the highest power peaking factors reach the state of boiling crisis and may be damaged.

The variant calculations, performed with the RELAP computer code, show that the following operators' actions are needed in order to prevent unacceptable consequences: initiation of high pressure injection pumps TQ14,24,34D01 not later than 3 min after the signal for reactor scram in order to introduce negative reactivity and opening of the emergency gas evacuation line (YR) 15 min after the signal for the reactor scram in order to decrease the pressure in the primary circuit.

The present analysis of the processes in the containment is performed using the COCOSYS computer code [1]. The calculation is part of a complex analysis of the accident that includes the following calculations:

- determination of the isotopic inventory of the core at the end of the fuel campaign using the ORIGEN computer program;
- determination of the number of the damaged fuel assemblies and the mass and energy release to the containment with the help of the RELAP code;
- the COCOSYS code is used for analysis of the thermal-hydraulic phenomena in the containment and the behaviour of the gaseous and aerosol fission products as well as for determination of the source term (leakage of the radioactive material from the containment into the environment);
- the radiological consequences of the accident are analysed with the COSYMA computer program.

2 Initial Conditions, Boundary Conditions and Assumptions

The initial conditions for the air inside the containment are: temperature equal to 40°C and pressure equal to 0.0998 MPa. It is assumed that the leakage from the hermetic construction corresponds to the design leakage, which is 0.3% of the free volume for 24 hours at the design pressure of 0.5 MPa. According to the tests, the real leakage is not more than 0.223%. The off-site power is available. One spray pump is assumed to be unavailable. This leads to higher pressure in the containment and to a less intensive washout of the aerosols.

The mass and energy release through the pressurizer's safety valves and through the emergency gas evacuation line are boundary conditions for the containment analysis. These boundary conditions are calculated with the RELAP code (Figure 1, Figure 2).

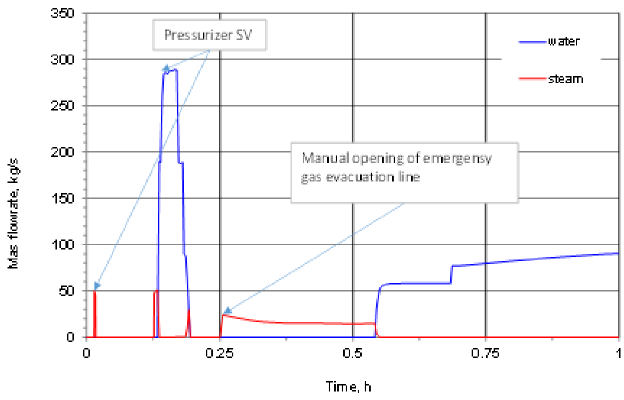

Figure 1. Water and steam mass flow to the containment.

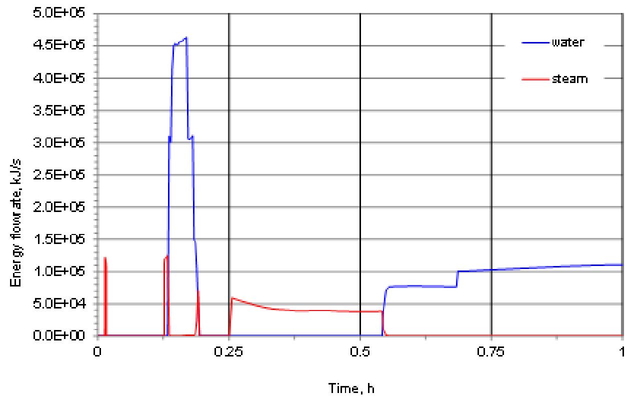

Figure 2. Water and steam energy flow to the containment.

Boundary conditions and assumptions related to the release and dispersion of the fission products are: 1. Isotopic content in the core; 2. Activity of the primary circuit coolant; 3. Number of the failed fuel assemblies; 4. Fraction of the fission products released from the failed fuel; 5. Retention of fission products in the primary circuit; 6. Decay heat; and 7. Chemical reactions of reagents, added into the spray water.

1. The isotopic content in the core at the end of the fuel cycle for the given burn-up was calculated with ORIGEN in the nuclear physics division of KNPP. Four different aerosol components (CsI, Cs, Rb and water) and 21 isotopes of 5 elements are used (Table 1).

Table 1. Considered isotopes

Number	Element	Isotope	Number	Element	Isotope
1	**Cs**	Cs134	12	**Kr**	Kr85
2		CS135	13		Kr85m
3		Cs136	14		Kr87
4		Cs137	15		Kr88
5		Cs138	16	**Rb**	Rb88
6	**I**	I129	17		Rb89
7		I131	18	**Xe**	Xe133
8		I132	19		Xe135
9		I133	20		Xe135m
10		I134	21		Xe138
11		I135			

Table 2. Fraction of the fission products

	Release from the damaged fuel, % of the fuel inventory	**Release to the containment, % of the released amount**	
		Atmosphere	**Water**
I131	8	8	/
Kr85	10	10	/
Other noble gases	5	5	/
Other halogens: $I_2 \rightarrow 4.85\%$, $CH_3I \rightarrow 0.15\%$, $CsI \rightarrow 95\%$	5	5	/
Alkali metals Cs, Rb	12	12	/

2. The activity of the primary circuit coolant is not taken into account. According to the operational data from the plant, the activity of the primary coolant is about 10E+12 Bq, while the activity inventory in the core is about 10E+20 Bq.

3. The calculations with the RELAP code demonstrated that 42 fuel assemblies failed (due to DNBR < 1). The fuel failure starts 449 seconds after the accident and leads to a release of fission products from the damaged fuel cladding. The duration of the release is 187 seconds. The activity released from the core is increasing in linear trend over this time.

4. The assumption about the fraction of the fission products released from the failed fuel is according to Regulatory guide 1.183 (Table 2) [2].

5. The retention of fission products in the primary circuit is neglected.

6. The decay heat is taken into account. It is calculated with ORIGEN by KNPP.

7. The pH of the water in the containment sump is conservatively assumed to be 5.5, although hydrazine is added to the spray water. The presence of K^+ in the spray water is not taken into account. In the WWER type reactors, $K_2Cr_2O_7$ is added to the spray water. The result from the reaction: $K^+ + I_2 \rightarrow KI$, is a soluble compound and is retained in the water.

3 Results Obtained with COCOSYS

The sequence of events in the COCOSYS calculation is shown in Table 3. The release of high-enthalpy coolant through the pressurizer's safety valves causes an increase of the pressure in the containment. Isolation of the containment takes place and the ventilation systems are stopped (460 seconds after the accident).

The maximum pressure of 0.155 MPa is reached 640 seconds after the initiation of the accident (Figure 3). It is reached after all the fission products are released from the damaged fuel cladding. This maximum calculated value is well below the design pressure of 0.5 MPa. After that, the intensive condensation on the surfaces of the walls and

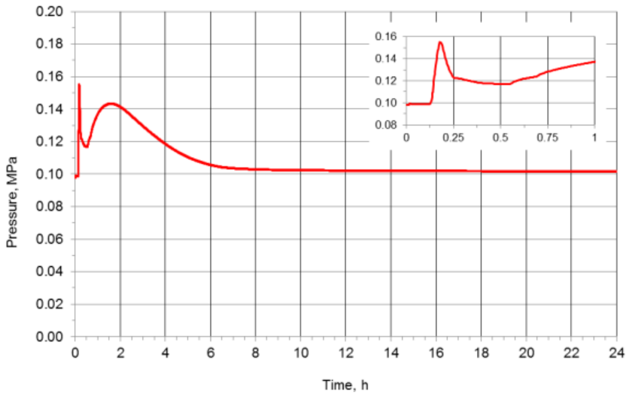

Figure 3. Containment pressure.

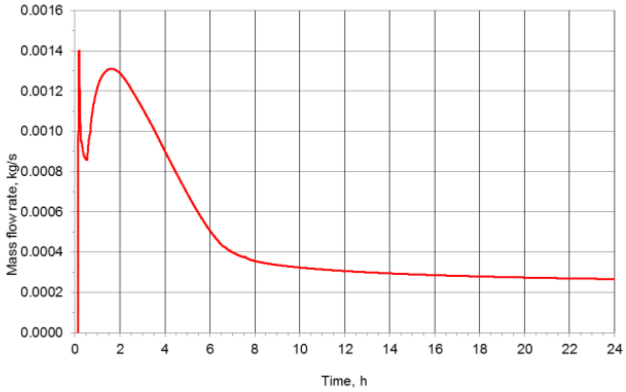

Figure 4. Mass flow rate through the leakages.

equipment leads to a pressure decrease. The highest calculated temperature of the surface wall lining is 70°C (Figure 4) which is more than two times lower than the design temperature of 150°C. The containment spray system is initiated 644 seconds after the accident.

Table 3. Sequence of events

Event	Time, s
Initiating event	0
Failure of fuel rods (postulated)	449
Release of fission products from the failed rods to the containment	449–636
Maximum pressure in the containment	640
Initiation of containment spray system	644
End of calculation	86400

Table 4. Masses of Kr, Xe, Cs, Rb, CsI, I_2, RI released into the containment, in the atmosphere of the containment and into the environment

Element	Mass released into the containment, kg	Mass in the containment atmosphere for 24 hours, kg	Mass released into the environment
Kr	5.11E-02	5.11E-02	3.00E-05 kg
Xe	4.35E-03	4.35E-03	2.56E-06 kg
Cs	3.98E+00	8.49E-08	1.22E-05 kg
Rb	3.32E-05	7.08E-13	1.02E-10 kg
CsI	1.44E-01	3.01E-09	4.50E-07 kg
I_2	7.37E-03	5.51E-08	2.86E-07 mol
RI	2.30E-04	2.02E-04	1.04E-06 mol

Table 5. Mass and activity released into the environment

Isotope	Mass, kg	Activity, Bq	Isotope Isotope	Mass, kg	Activity, Bq
Cs134	8.37E-07	4.01E+10	Kr85	3.00E-05	4.35E+14
Cs135	2.50E-06	8.16E+07	Kr85m	2.07E-08	6.30E+12
Cs136	3.98E-09	1.07E+10	Kr87	1.16E-08	1.21E+13
Cs137	8.90E-06	2.86E+10	Kr88	3.03E-08	1.40E+13
Cs138	3.66E-10	5.71E+11	Rb88	4.79E-11	2.13E+11
I129	4.44E-07	2.90E+03	Rb89	5.43E-11	2.79E+11
I131	1.49E-08	6.83E+10	Xe133	2.41E-06	1.67E+13
I132	4.80E-10	1.85E+11	Xe135	1.27E-07	1.20E+13
I133	6.15E-09	2.57E+11	Xe135m	3.02E-09	1.02E+13
I134	2.93E-10	2.89E+11	Xe138	1.17E-08	4.20E+13
I135	1.86E-09	2.43E+11			

The elements with the most significant contribution to the radiological consequences are Xe, Kr, Cs, Rb and I. The masses, released into the containment, the masses in the atmosphere of the containment and the masses released to the environment are given in Table 4. The masses and the activities of the isotopes released outside the containment are given in Table 5.

The noble gases do not sediment and cannot react with other chemical elements. Their release to the environment depends only on their concentration and on the leakage from the containment. The leakage itself is a function of the containment pressure. That is why the major part of the noble gases is released into the environment during the first six hours after the accident. The mass of Kr released into the environment for 24 hours is 3 orders smaller than the mass of Kr released from the fuel (Figure 5).

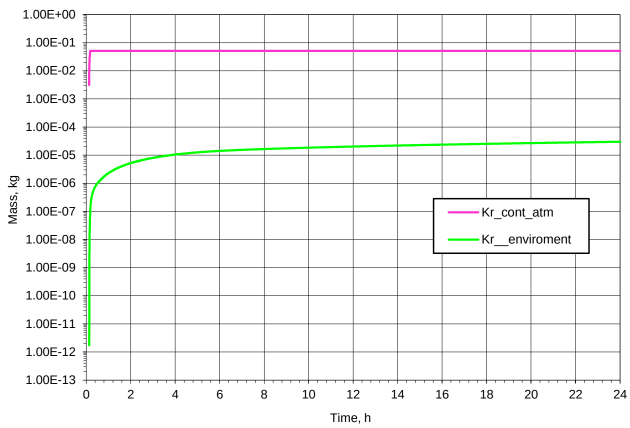

Figure 5. Distribution of Kr in the containment and release into the environment for the period of 24 hours.

The behaviour of the aerosols is more complex. In the course of the accident they partly deposit on the surfaces. Also, due to the condensation of the vapour, they can get to the water phase or to be washed out by the spray water. Finally they are transported to the containment sump. With the sump water, the dissolved aerosols are transported to the primary circuit by the pumps of the emergency core cooling system. Only those aerosols which remain in the atmosphere of the containment could contribute to the radiation release into the environment.

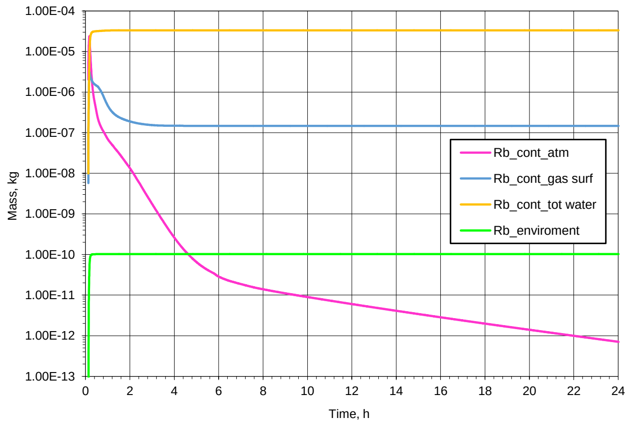

Figure 6. Distribution of Rb in the containment and release into the environment for the period of 24 hours.

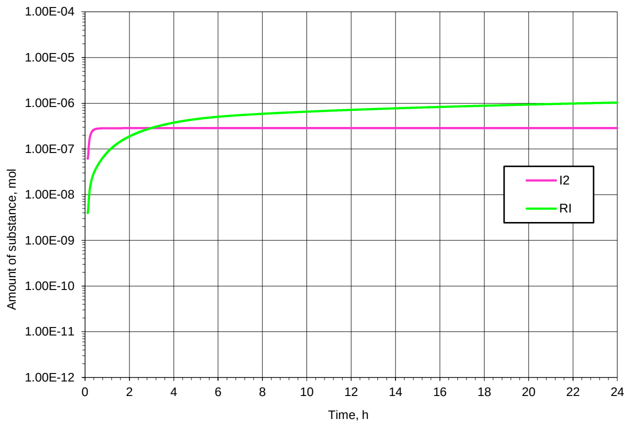

Figure 7. Amount of substance in iodine compounds, released into the environment.

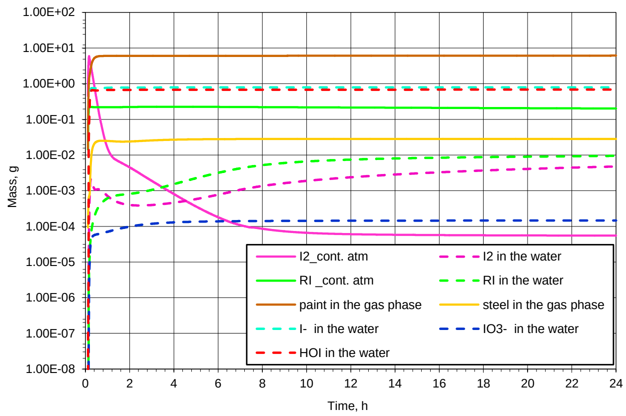

Figure 8. Mass of iodine compounds in the containment atmosphere, on the containment surfaces and in the water.

Table 6. Distribution of Rb isotopes in the containment and released into the environment for the period of 24 hours, kg

Distribution of Rb isotopes	**Mass, kg**
Released from the fuel	3.32E-05
In the atmosphere of the containment	7.08E-13
On the containment walls	1.47E-07
In the sump (or in the primary circuit) and in the water layers of the floors	3.32E-05
Released into the environment	1.02E-10

Rb is effectively deposited on the walls and then washed out by the water coming from the condensation and from the spray. The mass of Rb released into the environment for 24 hours is 5 orders smaller than the mass of Rb released from the fuel (Table 6, Figure 6).

Only the volatile forms of iodine (the molecular I_2 and organic iodides RI) leave the containment (Figure 7) but unlike noble gases, they may deposit mainly on the painted surfaces and in the water. In addition, the different forms of iodine transform due to different chemical reactions (*the whole spectrum of volatile organic iodides is modelled by use of the collective term "RI"*).

The iodine compounds in the gas phase are deposited mainly on the painted surfaces. In the water phase, the soluble iodine compounds are mainly I- and HOI (Figure 8).

4 Conclusion

The analysis with the COCOSYS code demonstrated that a significant amount of the radioactive products released from the primary circuit are retained in the containment and only a small part of them reaches the environment through the leakages.

It was confirmed that the acceptance criteria for the containment pressure and temperature are met.

The source term of radioactive release into the environment, which is a boundary condition for the analysis of the radiological consequences (performed with the COSYMA program), was calculated.

References

[1] Klein-Hessling W., Arndt S., Weber G. (2010) COCOSYS V 2.4 User Manual. GRS.

[2] Regulatory guide 1.183 "Alternative radiological source terms for evaluating design basis accidents at nuclear power reactors", U.S. NRC, July 2000.