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Application of the ALARA Principle to Minimize the Collective Dose in NPP Accident Management within the Containment

This research focuses on application of the ALARA principle to minimize the collective doses (both for NPP personnel and the public), relating to admission of personnel to the containment for accident management activities and depending on operation of ventilation systems.

Results from assessment of radiation consequences are applied to a small-break LOCA with failure of LPIS at VVER-1000 reactors. The public doses are evaluated using up-to-date RODOS, MACCS and HotSpot software for assessment of radiation consequences. The personnel doses are evaluated with MicroShield and InterRAS codes. The time function and optimal value of the collective dose are defined.

The developed approach can be applied for minimization of the collective dose for optimization of accident management strategies at NPPs.

Keywords: ALARA principle, radiation consequences, minimization of collective dose, small-break LOCA.

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Застосування принципу ALARA з метою мінімізації колективної дози в процесі управління аварією в контайнменті на АЕС

Дослідження спрямовано на застосування принципу оптимізації для мінімізації дозових навантажень на персонал АЕС та населення, пов'язаних з часом початку проведення відновлювальних робіт персоналом у контайнменті та режимом роботи вентиляційної системи.

Наведено результати оцінки радіаційних наслідків аварії з малою течею та відмовою САОЗ НТ на реакторі типу ВВЕР-1000. Колективні дози опромінення населення розраховувалися з використанням сучасних програмних кодів RODOS, MACCS і HotSpot. Дози опромінення персоналу визначалися за допомогою кодів MicroShield та InterRAS. У рамках застосування принципу ALARA отримано функцію змінення колективної дози з часом та її оптимальне значення.

Даний підхід може бути застосований для мінімізації колективної дози опромінення в оптимізації стратегій управління аваріями на АЕС.

Ключові слова: принцип ALARA, радіаційні наслідки, мінімізація колективної дози, аварія з малою течею теплоносія першого контуру.

In order to improve safety of NPPs, an important step towards implementation of the optimization principle is to achieve minimum radiation exposure to personnel, the public and the environment both in normal operation and in accident conditions. In recent years, scientific and research capabilities in this area have been expanding [1—4]. In particular, research of the processes leading to the formation of radioactive releases during accidents involving spills of liquid radioactive materials in areas with forced ventilation was performed by SSTC NRS in [4]. Radiation exposure caused by such processes is estimated in this study using a variety of atmospheric transport models. They are implemented in the program codes MACCS [5], RODOS [6] and HotSpot [7]. However, these codes are more often used for the safety analysis of nuclear power plants (e.g. predictive assessments [8, 9] or real-time calculations [6]) than for optimization of the accident management strategies or improvement of the emergency plans. Unfortunately, today the main criterion for the optimization of emergency response is the factor of economic justification [10].

The aim of this study is to optimize the radiation accident management strategy according to the criterion of radiation impact on the public and personnel at every stage of the accident.

Radioactive release management. The main parameters that influence the formation of public exposure doses in case of accidents in the containment are:

activity of radionuclides in the air space of the containment;

radioactive steam-gas mixture flow into the environment through containment leakages or by the exhaust ventilation system;

weather conditions accompanying the release.

In case of some accidents, it becomes possible to control the release. For example, it can be isolation of a small leakage from the primary circuit, control of forced ventilation system circulation, or bleed of air fraction into the adjacent containment rooms.

There are many methods of reducing the radioactive release from the containment. For example, the Filtered Containment Venting System (FCVS) can be used [11]. The delay time of radioactive substances within the containment is critical for appropriate countermeasures to protect the public from exposure to a radioactive cloud passing in the early phase of an accident (shelter, evacuation, iodine prophylaxis, relocation) [12]. Even short-term retention of the steam-gas mixture in the containment can significantly reduce the proportion of noble gases and radioactive iodine radioisotopes in the release due to radioactive decay. Even for 3 days of retention, iodine activity reduces by 10 times and noble gas activity reduces by approximately 3 times.

All of the above methods allow reduction in radiation doses to some extent.

Evaluation of collective doses. On example of a small-break loss-of-coolant accident (SB LOCA) with failure of the low-pressure injection system (LPIS) at VVER-1000 reactors, consider the dynamics of dose values over time.

After an accident with leak of the primary coolant and failure of the system to maintain primary coolant inventory at low pressure, operational personnel need to take actions to restore the failed equipment. These actions include the restoration of equipment whose failure led to the LPIS failure (recovery of at least one channel for primary makeup). Obviously, the timely recovery of failed equipment restores the system. As a result, severe damage to the reactor core is prevented.

If exact time for emergency personnel actions is known, uncertainty remains regarding the entry of staff into the access-control area. Early entry into the containment premises is associated with significant doses for mitigation of the accident

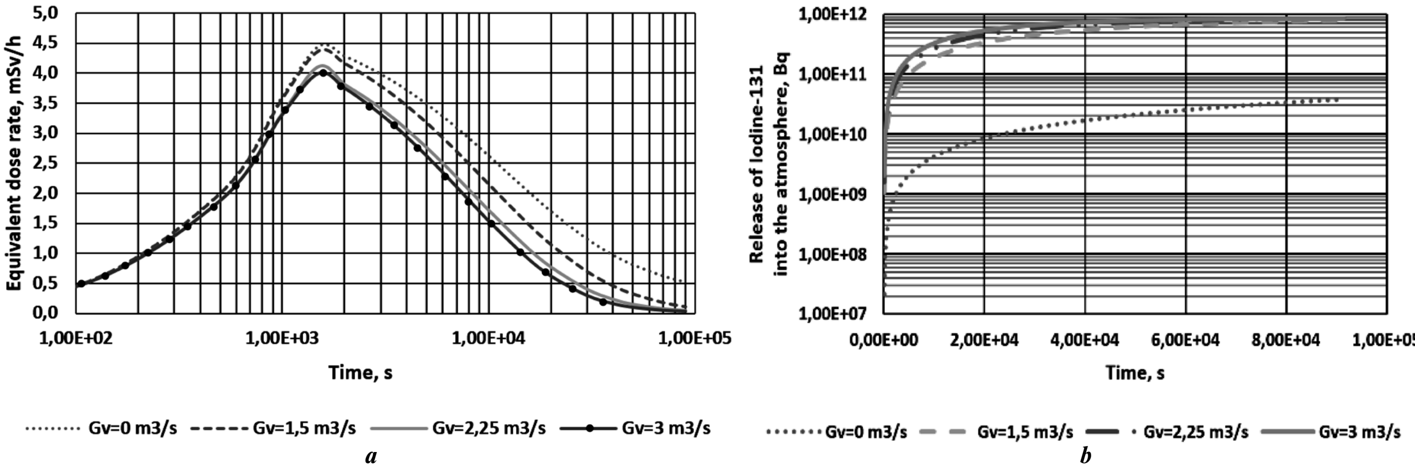


Fig. 1. Equivalent dose rate within the containment (*a*) and I-131 release into the atmosphere (*b*) for different ventilation flow rates

(Fig. 1a) and high levels of equivalent dose rate (EDR). Late entry of personnel leads to a massive release of the steam-gas mixture into the environment (Fig. 1b).

Assessment of the collective effective dose for personnel and the public includes the use of various special tools of exposure dose assessment. Examples of such tools are shown in Table 1. The values of doses for personnel and the public were obtained with these tools (Figs. 2 and 3).

Table 1. Effective dose components

Group	Irradiation ways	Calculation tools
Personnel	External exposure from cylinder (radioactive steam-gas mixture within the containment)	MicroShield [13]
	External exposure from disk (liquid radioactive material)	
	Due to inhalation	InterRAS [12]
Public	External exposure from cloud	RODOS/ MACCS/ HotSpot
	Due to inhalation	
	Due to external exposure from ground surface	

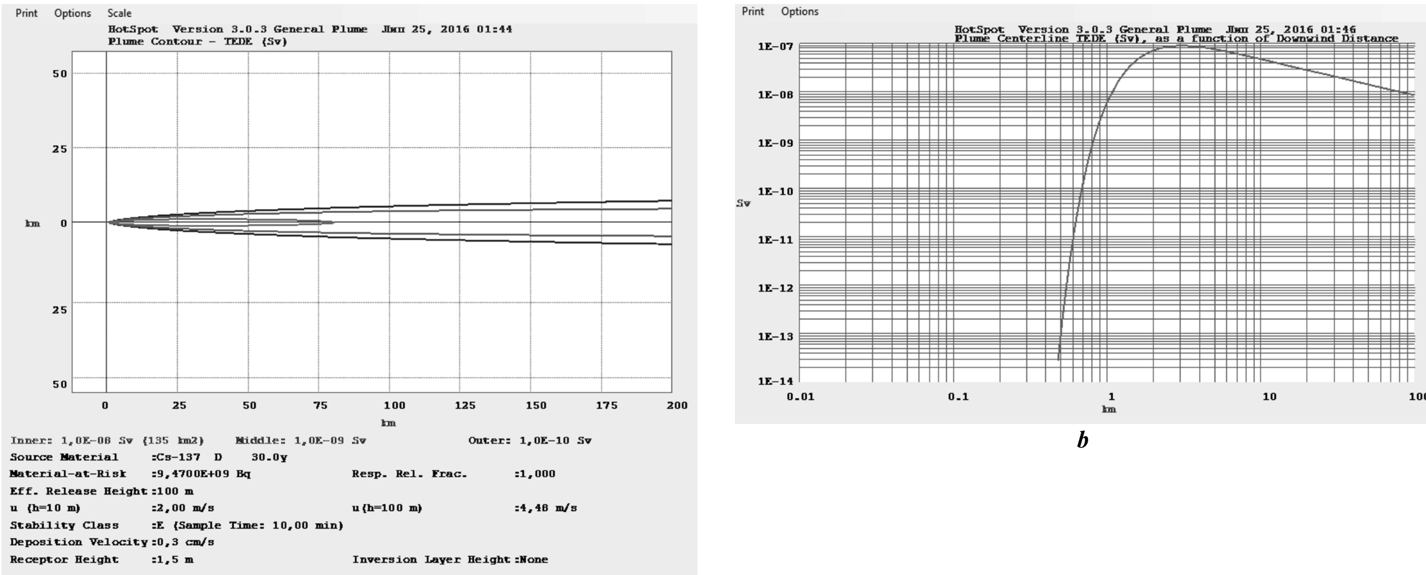
EDR dynamics was found within the containment (Fig. 1a) towards defining collective doses. The collective doses to the public are calculated with several codes. The obtained data were compared against the parameter effective dose rate. The calculation results showed sufficient convergence and did not exceed the 20 % relative error.

The most conservative results were show by the US codes MACCS and HotSpot (Fig. 2) including a simplified model of atmospheric transport in comparison with the RODOS code (Fig. 3). The calculations showed that MACCS code was suitable for probabilistic assessments of radiation consequences, while RODOS was intended for predictive calculations of doses in emergencies.

Unlike the American codes, RODOS can specify a continuous source of release, gives the possibility to calculate the dose rate with a time step from 10 min, and allows using the current weather and population density databases. Therefore, the RODOS code is the most suitable option for the evaluation of the collective dose to the public.

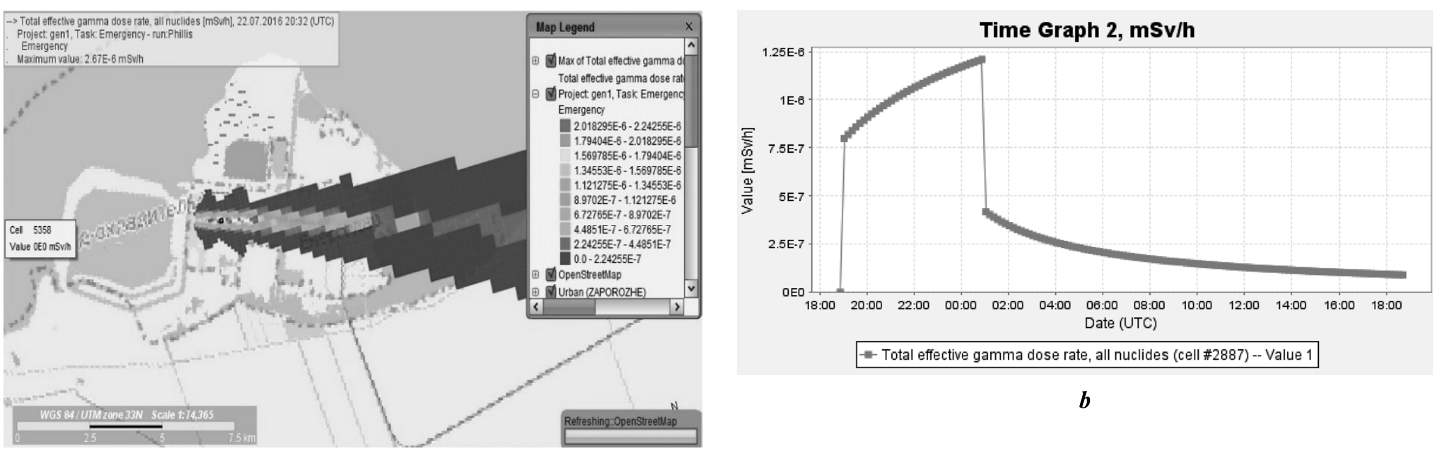
Table 2. Activity data for MicroShield code (maximal values of activity within the containment)

Group	Radionuclide	Activity, Bq	
		Steam-gas mixture	Released coolant
Long-lived radionuclides	Sr-90	5,63E+05	9,25E+06
	Ru-103	9,98E+05	1,64E+07
	Ru-106	5,27E+04	8,65E+05
	Cs-134	6,44E+09	1,06E+11
	Cs-137	9,59E+09	1,57E+11
	Ce-141	7,05E+06	1,16E+08
	Ce-144	4,34E+05	7,12E+06
Iodine	I-131	8,92E+11	1,78E+11
	I-132	2,23E+12	4,46E+11
	I-133	2,46E+12	4,92E+11
	I-134	1,52E+12	3,04E+11
	I-135	2,07E+12	4,14E+11
Noble gases	Kr-85	1,18E+11	0,00E+00
	Kr-85m	2,21E+12	0,00E+00
	Kr-87	1,99E+12	0,00E+00
	Kr-88	5,79E+12	0,00E+00
	Xe-133	1,86E+13	0,00E+00
	Xe-135	5,52E+12	0,00E+00
	Xe-135m	8,40E+11	0,00E+00



a *b*

Fig. 2. Effective dose evaluation using HotSpot code (data for I-131): contour (*a*), centerline (*b*)



a *b*

Fig. 3. Effective dose evaluation using RODOS code: field of effective dose rate (*a*), effective dose dynamic at a distance (4 km) from release source (*b*)

Application of the ALARA principle. For SB LOCA, ALARA optimization [14] of the collective dose is made on the assumption that the individual doses do not exceed the level of deterministic effects, i.e. conditions for the linear no-threshold model “dose-effect” are met [15].

In the case of a radiation accident within the containment, minimization of the collective dose is reduced to determine the time of entry into the containment:

$$f(t) = \left[n \int_{t}^{t+T} D_w(t)dt + \int_S \int_0^t m(x,y) D_p(t) dt dS \right] \to \min,$$

$D_w(t)$ — individual effective dose rate to body (personnel), Sv/sec; $D_p(t)$ — individual effective dose rate to body (public), Sv/sec; n — number of personnel, man; $m(x, y)$ — population density, man/m^2; S — square of contaminated territory, m^2; T — time of mitigation (period of operations the restoration of the failed equipment and decrease of the leakage rate), sec; t — time of entry, sec.

Fig. 4 shows the curves of the collective doses to personnel and the public for SB LOCA with LPIS failure at VVER-1000 that were obtained for the early phase of an accident (1st day). These values depend on the time of emergency personnel entry into the access-control area. Curve 1 shows the collective dose to be received by personnel (3 persons) for 30 min of operations on the restoration of the failed equipment and decrease of the leakage rate. Curve 2 describes the collective dose to the public due to release to the environment. Curve 3 is the total collective dose to the public and personnel.

Emergency entry of 3 persons into the containment to mitigate an emergency release on the 6th hour of an accident will allow the lowest possible value of collective dose in the early phase of the accident to be achieved — 6 man·mSv.

The results show that the optimum function of the collective dose is not observed in all cases. In condition of stable

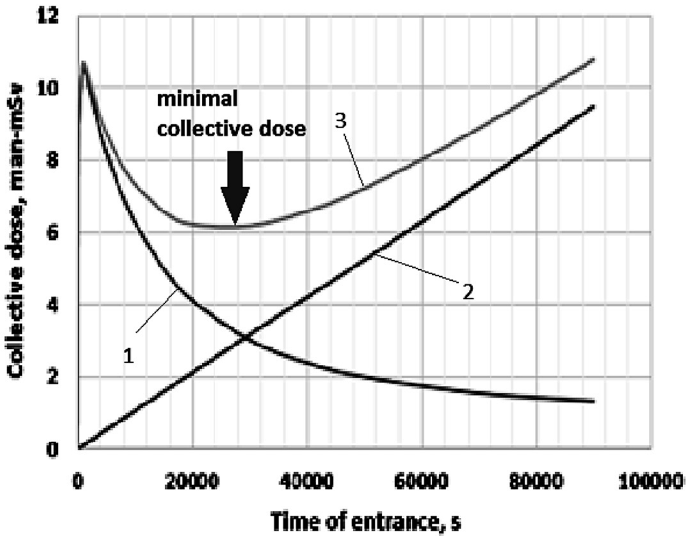


Fig. 4. Collective doses to personnel and public (hermetic containment)

atmosphere and light wind, nearby settlements with a high population density may be exposed to the collective dose by orders of magnitude greater than the predicted collective dose for personnel. In this situation, the failure function of collective dose will be disproportionately low in comparison with the absolute values of doses. Minimization of radiation exposure does not bring an expected effect.

The optimization principle with the collective dose criterion can be applied for the following conditions:

compliance with the permissible leakage for the containment (0,3 % of the containment volume per day for VVER-1000 [11]) with disabled ventilation;

controlled release through ventilation systems using treatment filters;

timely implementation of urgent countermeasures to protect the public;

unstable atmosphere conditions (stability categories from A to C according to Pasquill classification [1]) and strong winds (more than 4 m/sec);

low population density in areas surrounding the nuclear power plant.

Conclusions

In this research, the approach on application of the ALARA principle to minimize the collective dose in NPP accident management within the containment was developed. On example of SB LOCA, it has been shown that such accidents can be managed using the criteria of the total collective dose to personnel and the public. A series of the calculations using different computer tools for public dose evaluation (RODOS, MACCS, HotSpot) were done, the obtained results are well correlated. The limitation of the developed approach was identified.

The proposed ALARA principle of collective dose optimization can be introduced into the emergency operating procedures, accident management guidelines and emergency plans.

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