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Research Article

About definition and practical application of probabilistic safety indicators related to large accidental release*

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Abstract

The probability of a large early release is one of the safety indicators that reflects the risk of fatalities during an accident at a nuclear power plant. Despite the fact that this indicator is very important, it is not defined in the federal rules and regulations of the Russian Federation. The article analyzes the worldwide experience related to determining criteria for large early release taking into account the statistical data of the specific country under consideration. Based on the analysis, the definition of a large early accidental release and the criteria for its achievement are formulated taking into account measures to protect the population living within the protective action planning zone (PAPZ), and an approach for their definition is proposed. A conclusion has been made about the sustainable nature of the goals identified using the NRC approach. A critical analysis of the safety indicators established worldwide allowed for the conclusion that it is necessary to improve the methodology for assessing the safety goals taking into account the specifics of NPP design, regional characteristics, phases of accident progression and other factors. The paper outlines the proposed approaches to determining high-level safety goals based on probabilistic targets – quantitative values for probabilistic health objectives (PHO) designated as PHO1 and PHO2 for the Russian Federation. A definition of a "large early release" is formulated and criteria for its achievement are proposed taking into account measures to protect the population living within the PAPZ. Thus, when assessing the degree, to which these goals are achieved in practice, it is proposed to take into account not only the likelihood of a large release during an accident at a nuclear power plant, but also measures aimed at protecting the population, in particular, evacuation. In this case, early deaths occur only when the population is not evacuated before the critical health dose loads from the release are reached.

Keywords

health objectives, probabilistic safety goals, accidental release, measures to protect the population

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History and approaches to defining probabilistic safety goals

Health objectives of the US Nuclear Regulatory Commission

In Russian regulatory practice, there is no mentioning public health objectives (PHOs) with regard to anthropogenic risks, so it is reasonable to refer the best foreign practices, primarily those of the United States. In 1986, the US Nuclear Regulatory Commission (NRC) approved qualitative and quantitative PHOs.

Two qualitative PHOs (both for people residing in the area around the nuclear power plant and for general population) are as follows (Safety Goals for the Operations of Nuclear Power Plants; Policy Statement; Correction and Republication 1986):

- "Individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear no significant additional risk to life and health".
- "Societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risks".

The NRC also approved the following two quantitative PHOs, which serve to find out if qualitative objectives have been met (Safety Goals for the Operations of Nuclear Power Plants; Policy Statement; Correction and Republication 1986):

- "The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of one percent (0.1%) of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed".
- "The risk to the population in the area near a nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent (0.1%) of the sum of cancer fatality risks resulting from all other causes".

The first quantitative objective involves the risk of a prompt fatality from all types of NPP accidents (that is, the risk of deaths occurring shortly, usually within weeks or months, after the exposure to high doses of radiation). The second one involves the overall risk of death from cancer regardless of the cause. Both objectives are not directed at particular population groups, that is, all age, social and other groups are considered.

The quantitative PHOs have been formulated as follows (Safety Goals for the Operations of Nuclear Power Plants; Policy Statement; Correction and Republication 1986):

- quantitative PHO1 for prompt fatalities – 5.0E-07 1/year based on the risk of death from a man-made accident in the USA;
- quantitative PHO2 for mortality from cancer – 2.0E-06 1/year based on the cancer mortality statistics.

The mentioned PHOs have been determined using the following formula

$$PHO1 = 0.001 * L / N \quad (1)$$

where L is the number of deaths in the country from all causes other than related to chronic diseases; N is the country's population; and 0.001 is the coefficient that allows for 0.1% of the sum of prompt fatality risks;

$$PHO2 = 0.001 * C / N \quad (2)$$

where C is the number of deaths from cancer in the country; N is the country's population; and 0.001 is the coefficient that allows for 0.1% of the sum of cancer fatality risks.

Both quantitative PHOs are statistical by their nature, that is, are determined from the actual statistics of deaths in the USA.

The quantitative PHOs proposed by the NRC are fairly stable. Thus, in 2004, the NRC (Education of Risk Professionals Module 1. Introduction to PRA and basics of PRA, 2009) (the U.S. population of 293,500,000) estimated the changes in the quantitative PHOs as compared with the publication of quantitative PHOs in 1986.

In 2004, according to the data from the US Center for Disease Control and Prevention:

- 112,000 persons died from all causes other than related to chronic diseases;
- 597,000 cancer deaths were recorded.

According to formulas (1) and (2) and data from the US Center for Disease Control and Prevention, the PHOs have the following values:

- 3.8E-7 1/year (~4.0E-07 1/year) for PHO1 (mean individual risk of rapid fatalities);
- 1.9E-6 1/year (~ 2.0E-06 1/year) for PHO2 (mean individual risk of cancer mortality).

Thus, it has been shown that the quantitative PHOs defined in 1986 are slightly less stringent against the situation in 2004.

Applying the NRC-proposed approach to Russia's conditions (as evidenced by the 2021 data, Russian population is 146 million (Population of the Russian Federation by sex and age as of January 1, 2021 (Statistical Bulletin), 2021) and the number of sudden deaths associated with injuries and other external anthropogenic effects is about 128 000 and the number of cancer deaths is about 283,000 (Number of deaths by cause of death in 2021, 2022), leads then to the following estimates:

- quantitative PHO1 is equal to 8.77E-07 (~ 9E-07) 1/year;
- quantitative PHO2 is equal to 1.94E-06 (~ 2E-06) 1/year.

Therefore, the NRC's quantitative PHO1 (5E-7 1/year) for prompt fatalities is more stringent than that one which could be defined for Russian Federation based on the NRC methodology, but the quantitative PHO2 for cancer mortality is fully applicable.

The situation in Turkey is similar to that one in Russia (Ölüm ve Ölüm Nedeni İstatistikleri-2019, 2020). So, for example, the cancer death risk in Turkey is some 200 per one hundred thousand people per year. Accordingly, the average individual risk of cancer mortality expressed as the PHO2 value is 2.0E-06 1/year.

Probabilistic safety goals (PSGs)

NRC PSGs

In a practical sense, the quantitative PHOs have been replaced by the PSGs outlined in the Decision Guide included in NRC Regulatory Guide 1.174 (An Approach For Using Probabilistic Risk Assessment In Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis, Regulatory Guide 1.174, Revision 3 2018) (issued in 1998, revised in 2018).

The following values have been defined for PSGs:

- 1.0E-04 1/reactor-year for the nuclear reactor core damage frequency;
- 1.0E-05 1/reactor-year for the frequency of large early accidental releases.

The NRC justified that a probabilistic goal for a large early release frequency of 1.0E-05 1/reactor-year is a suitable surrogate for the quantitative PHO1 of 5.0E-07 1/year for prompt fatalities, and the target for the core damage frequency equal to 1.0E-04 1/reactor-year is a suitable surrogate for the quantitative PHO2 for cancer mortality (2.0E-06 1/year) (Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing, 2018).

It is important to note that the NRC defined goals rather than criteria. However, the NRC believed that defining goals for a large late accidental release frequency is excessive. The NRC did not consider it necessary as well to undertake a Level 3 probabilistic safety analysis (PSA), the objective of which is to estimate the frequency of different public dose loads and the frequency of fatalities for the population in the NPP area, for verifying compliance with the goals specified.

IAEA and EUR approaches to consideration of large early accidental releases

In accordance with the IAEA's approach formulated in INSAG-12, 1999, the new NPP design should be aimed at keeping the frequency value of large accidental releases, which require countermeasures to be taken to protect the public, at the lowest possible level. In this case, large-scale measures are considered as prompt countermeasures for protecting the population outside the NPP site, such as evacuation of the population residing in the area adjacent to the NPP. The dose load levels, which require evacuation, are expected to vary between 0.1 and 0.5 Sv, this being in accordance with the recommendations of the International Commission on Radiation Protection. The core damage frequency and large release frequency target values are shown in Figs 1, 2 (based on information in INSAG-12, 1999 and, Probabilistic Safety Goals for Nuclear Power Plants. Phases 2-4/Final Report 2011). To comprehend Fig. 1, one should take into account that INSAG-12 introduced the term "practical elimination" for large early releases, but did not provide a numerical definition for the frequency of such releases (i.e., did not define the frequency value, at achieving of which, large early releases can be classified as "practically eliminated" events).

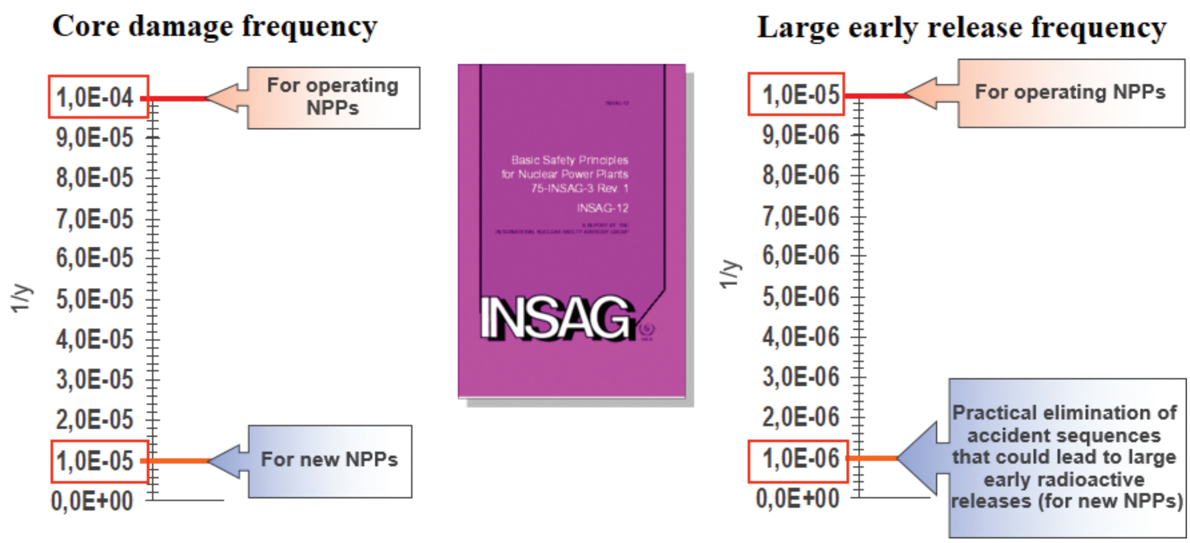

Figure 1. Safety goals according to INSAG-12 (frequency of core damage and frequency of large early release).

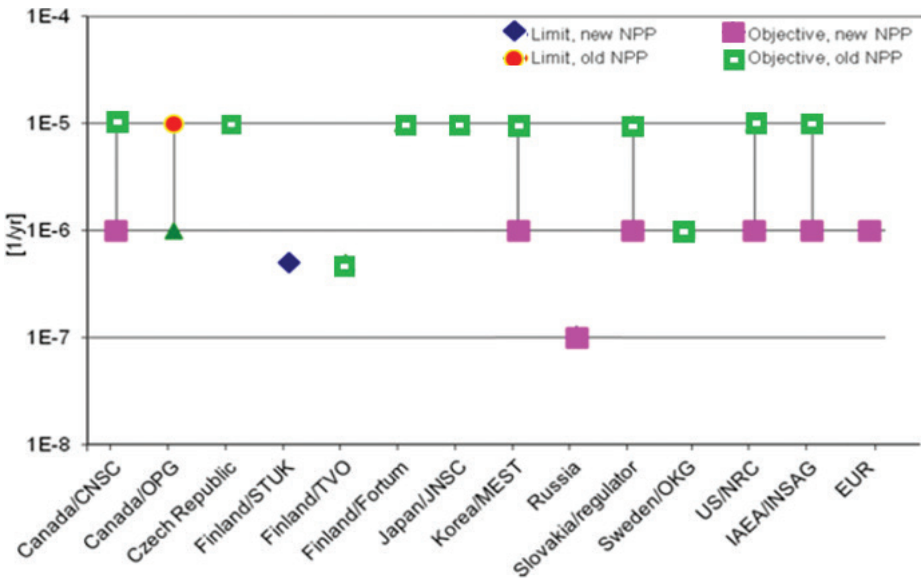

Figure 2. Safety goals defined for different countries (large release frequency).

Section 2.1 of the EUR Requirements of European Operating Organizations (European Utility Requirements for LWR Nuclear Power Plants (EUR), 2016) states that the design of an NPP unit should be such that the accident scenarios leading to an early or large accidental release is practically eliminated. It is shown for the term "early release" in the Definitions section in European Utility Requirements for LWR Nuclear Power Plants (EUR), 2016 that public protection measures are necessary for such release but the probability of their effectiveness is small due to time constraints.

Discussion regarding the NRC's probabilistic safety goals

Despite the fact that the approach to defining safety goals developed by the NRC for the U.S. NPPs has been adopted by most countries in the world, there are a number of aspects that require, as a minimum, to be discussed and considered when formulating safety goals for a particular country.

Initially, the NRC did not define the term "large early accidental release". In the context of regulation 1.174 (An Approach For Using Probabilistic Risk Assessment In Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis, Regulatory Guide 1.174, Revision 3 2018), the frequency of a large early accidental release is used as a surrogate for quantitative PHOs on early mortality and can be defined as "The frequency of accidents resulting in significant, unmitigated releases from containment during the time period before effective evacuation of the nearby population can be done such that the potential for early health effects exists".

The first harmonized quantitative approach to defining the term "large early accidental release" was developed by the NRC in SECY-93-138, 1993:

- the term "large" applies to releases that result in an amount of iodine in the release that exceeds approximately 2 to 5% of the original isotope content in spent reactor fuel;
- the term "early" applies to releases within 4 to 10 hours after the accident starts.

In fact, the term "early" is related to evacuation of the population, that is, where an accidental release occurs before the end of evacuation, it shall be defined as "early".

However, NUREG/CR-6595 (Revision 1), 2004 states that even late accidental releases (that is, those occurring beyond 10 hours after the start of the accident) are expected to lead to early fatalities, specifically where the accident conditions make it impossible to evacuate the population (e.g., tsunami or earthquake). This may be why NUREG-0800, 2014 recommends that new reactors should be checked for compliance with the large accidental release goals regardless of the time of the release (only for passive reactors, i.e., reactors in which the main safety functions are performed by passive systems, e.g., the AP-1000 reactor). The choice of the criterion for insignificance of the additional risk from the NPP as 0.1% of the total risk (of early fatalities or cancer deaths) has never been justified by the NRC but it is exactly the criterion the goals directly depend on. Nevertheless, the selected value is considered to be acceptable since the probabilistic safety goals obtained on its basis have been accepted both by the IAEA Safety Standards Series No. SSG-3, SSG-4 2010, and by most IAEA Member States (NEA/CSNI/R(2009)16, 2009).

The PSGs (core damage frequency and large early accidental release frequency) obtained on the basis of quantitative PHOs mean, in essence, that the conditional probability of early fatalities, provided there is a large early accidental release, is estimated to be 5.0E-2, and the conditional probability of death from cancer, provided nuclear fuel is damaged in the core, is estimated to be 2.0E-02. Without going into the details of such estimates presented in Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing, 2018, the following should be noted.

The conditional probability of a cancer death is estimated from analyses undertaken for one NPP in the USA. The estimation took into account the possibility for evacuating 90% of the population within four to eight hours in the NPP area (25 miles). The conditional probability of early fatalities was estimated based on the averaged data for NPPs in the USA, where more than 100 NPPs of various designs with different containment designs were in operation in 1986. Both estimates may not be applicable to countries with small numbers of NPPs where modern units are built or operated, with extra measures taken to confine the melted core inside the reactor vessel, in the core catcher, or in the containment, and with additional measures for managing beyond design basis accidents. For modern NPPs, the release of fission products beyond the containment in severe accidents in quantities potentially leading to early death or cancer (assuming fuel is damaged in the core) is much less likely than for units in operation in the United States in 1986. For such countries, estimates can be both excessively conservative and excessively optimistic depending on the specific unit design, the conditions in the NPP area (primarily meteorological, agricultural, and demographic), and the level of technology used (specifically, to be able to arrange for the timely evacuation of large number of people).

The NRC has not specified what should be included in the scope of the PSA, the results of which are required to be compared with the NRC's goal benchmarks, namely, whether it includes other sources of radioactivity (e.g., nuclear fuel in the spent fuel pool), the unit states taken into account (power operation, shutdown, refueling, etc.), and the initiating events taken into account (only internal initiating events or initiating events caused by internal and external hazards as well). At the present time, a full-scale PSA (Safety Standards Series No. SSG-3, SSG-4, 2010) is required for all types of radioactivity sources and for all operational states of the NPP unit. Accordingly, the NRC-defined targets have to be evaluated using a full-scope PSA (the frequency of nuclear fuel damage has to be evaluated instead of the nuclear reactor core damage frequency), which also affects the estimated conditional probabilities.

The NRC's PSGs do not take into account large late accidental releases both for times slightly longer than the times of a large early accidental release (days) and for the times much longer than the times of a large early accidental release (weeks, months, years), which may have negative effects on the population health in the NPP area in the absence of a program of resettlement from the contaminated areas.

Conclusions from the analysis of the information provided

The above information leads to the following conclusions.

1. Quantitative PHOs defined by the NRC in 1986 are of a quite steady nature over time and international perception and can be applied nowadays in different countries (Russia, Turkey, etc.).
2. The conditional probability of early fatalities in conditions of a large early accidental release and the conditional probability of a death from cancer in conditions of fuel damage can differ greatly among countries even for the same NPP unit design, which is explained by the peculiarities of the NPP site. In this connection, the adequacy of the NRC PSGs (frequency of core damage and frequency of large early accidental release) used in a number of countries is questionable, as they do not take into account the peculiarities of NPP designs, population densities, representative weather conditions, national features, level of technological development and technical resources, emergency response program for the population in residential areas in the vicinity of the NPP area. The above aspects affect directly the conditional probability of early fatalities and the conditional probability of a cancer death. PSGs should have a more transparent and explicitly assessed relationship with PHOs. The achievement of PSGs should be assessed for groups of representative scenarios with qualitative differences in the accident progression, which should take into account in an individual manner the conditions for the possibility of evacuation, meteorological forecasts (wind direction, rainfall, etc.), the expected release time and accumulation of critical dose loads, and the emergency planning program.

Consideration should be given to the need to define PSGs for a large emergency release for the accident development phases both slightly exceeding the times of a large early emergency release (days) and exceeding greatly these times (months). When evaluating the adherence to PSGs, one should take into account not only evacuation and other protective measures but also relocation of the population for a long period of time.

PSGs based on the assessment of the fatality risk for the population, which require performing a Level 3 PSA or dose loads assessment potentially leading to immediate or delayed lethal consequences for the population, seem to be most reasonable.

Proposed approaches to the psg determination and assessment of the npp design compliance with PSGs

Quantitative health objectives proposed

Since the quantitative PHO1 defined by the NRC differs relatively slightly from PHO1 defined according to statistical data for Russia but remains more conservative, and PHO2 has similar values, it seems reasonable and acceptable to use the quantitative PHOs defined by the NRC.

These objectives are proposed to be used as probabilistic targets in the following formulation:

- the aim should be that the risk of a prompt fatality to result from nuclear accidents for the most vulnerable member of the public in the vicinity of the NPP does not exceed a value of 5.0E-07 1/year (quantitative PHO1);
- the aim should be that the risk of fatalities from long-term radiation effects as may result from nuclear accidents for those living in the vicinity of the NPP does not exceed the value of 2.0E-06 1/year (quantitative PHO2).

Proposed PSG1

Taking into account the proposed quantitative PHO1, the following PSG1 formulation can be proposed: the aim is that the probability of a large early accidental release does not exceed a value of 5.0E-07 in one calendar year.

The term "large early accidental release" in this case is defined as follows: a large early accidental release is a release of radioactive products into the environment in amounts potentially leading to a high probability of rapid fatality for the most vulnerable member of the public residing in the NPP area for the time insufficient to arrange for the protective measures of the public in conditions under which the considered release takes place.

Fig. 3 shows representative time points that are important in terms of defining a large early accidental release and estimating the available time for measures to be taken to protect the population in a particular residential area, *j*, for a particular severe accident, *i*. A severe accident is assumed to begin after the safety functions performed by active safety systems are lost since passive systems are normally time-limited and do not eliminate the conditions for a severe accident to take place but postpone the accident onset providing a time margin both for the recovery of active systems and for the arrangement of the population protection measures.

Determination of a large early accidental release implies that estimation of its occurrence in residential area *j* requires taking into account the three key temporal factors shown in Fig. 3 for each accident scenario *i*:

- the time, for which radioactive products enter the environment and cause a dose load potentially leading to a high probability of rapid fatality for the most vulnerable member of the public at any arbitrary point around the NPP ('critical dose loads' hereinafter) (*T0i* + *Tri* + *Tkji*);
- the time from the accident onset to the point when the population protection measures are announced (*Tij*);
- the time required for the population protection measures under accident conditions (*Teij*) to be arranged for to fully stop the effects of radiation on the public.

It should be noted that evacuation of the population is the ideal protective measure but it is impossible to evacuate 100% of the population for time *Teij*. Therefore, the term "evacuation" is replaced by the term "organization of the population protection" which means that a large number of the population (e.g., evacuation of 90% of the population) is moved out of the PAPZ for time *Teij*, and the radiation impact on the remaining population is limited (sheltering, iodine protection) provided that it will be moved to beyond the radiation exposure area for a time larger than *Teij*.

If the dose for the most vulnerable member of the public at any location around the NPP potentially leading to a high probability of a rapid fatality is reached in a time shorter than *Tij* + *Teij*, then a large early accidental release takes place, and if not, no such occurs. Accordingly, the probability that a large early accidental release takes place for the accident being analyzed is equal to the probability that *T0i*+*Tri*+*Tkij*>*Tij*+*Teij* for the most vulnerable member of the public at any point around the NPP.

Thus, the probability of a large early accidental release to take place depends on the following factors.

In terms of estimating *T0i* + *Tri*+*Tkij*, it depends on:

- the rate and amount of fission products entering the environment and the accident progression rate;
- the height and energy of the accidental release;
- the weather conditions that define the propagation and deposition of fission products in the area around the NPP.

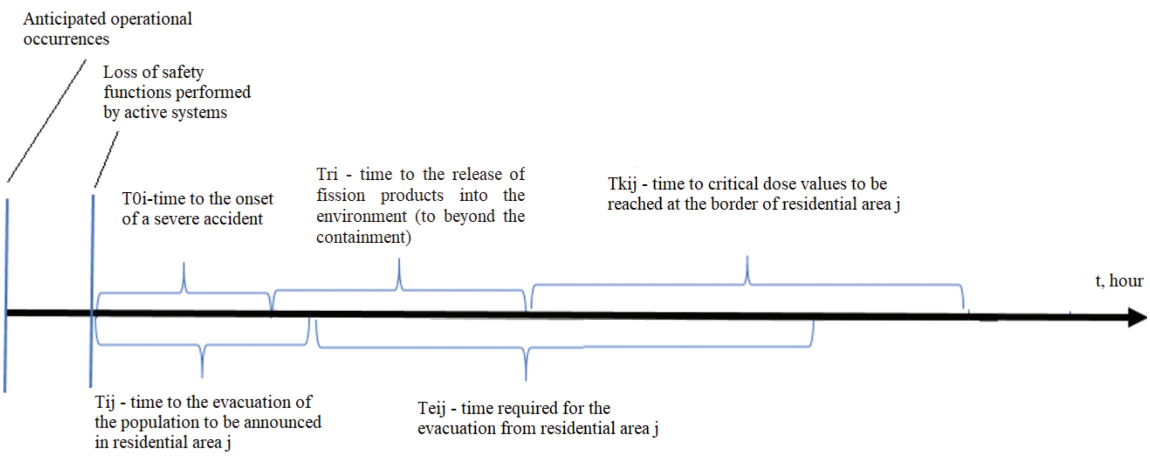

Figure 3. Time intervals important for estimating the available time for measures be organized to protect the public in the event of a severe accident.

In terms of estimating *Tij*, it depends on the conditions in which evacuation is announced.

In terms of estimating *Teij*, it depends on:

- the conditions of evacuation, such as time of the day and whether evacuation routes and shelters are available;
- the readiness of the population for being evacuated;
- the readiness of response systems to implement protective measures, including evacuation of the population, iodine protection, and shelters for the population remaining temporarily in the contaminated area;
- the demographic situation in the NPP area.

The proposed definition of a large early accidental release is not directly connected with the sanitary protection zone (SPZ) or the PAPZ. However, this connection is taken into account in an indirect manner.

1. If critical dose loads can be achieved at any point outside the PAPZ in a significantly longer time, then a large early accidental release is achieved with a probability of one, since no rapid measures are provided to protect the population beyond the PAPZ. In this case, "large" means the time equal to a 10-day period, which is used, firstly, as the criterion for evaluating the need for the population protection actions (NRB-99/2009, 2009), and, secondly, 10 days are enough for one to assume with confidence that protective measures are implemented under any emergency conditions.
2. If at any point beyond the SPZ it is not possible to achieve critical dose loads within a sufficiently longer time (10 days), then a large early accidental release is not achieved with a probability of one since no population shall stay within the SPZ.
3. If it is possible to achieve critical dose loads in less than 10 days outside the SPZ but within the PAPZ, then the probability of a large early accidental release for the analyzed accident is equal to the probability that *T0i*+*Tri*+*Tkij*>*Tij*+*Teij* for the most vulnerable member of the public at any point within the limits between the SPZ and the PAPZ.

If critical dose loads outside the SPZ but within the PAPZ can be reached for a time longer than 10 days, then the probability of a large early accidental release for the analyzed accident is assumed to be zero assuming that short-term measures to protect the population against negative radiation effects will be implementedwithin10 days.

Proposed PSG2

No large early accidental release practically guarantees that there are no early fatalities due to a particular accident since this guarantees that at least one of the conditions is fulfilled, namely, that the dose loads on the population around the NPP

- do not reach critical values for the possibility of an early fatality to occur outside the PAPZ;
- reach critical values for the possibility of a prompt fatality to occur within the PAPZ but protective measures have been implemented before the critical value is reached (for a time shorter than *T0i*+*Tri*).

However, no large early accidental release guarantees that the public will not be exposed to radiation that, not leading though to prompt fatalities, have the potential for causing serious adverse health effects. In particular, even where measures to protect the public are taken within the time *T0i*+*Tri*, the public may be nevertheless exposed to radiation leading to prolonged adverse effects.

Conservatively, the following target can be proposed as PSG2:

One should aim at ensuring that the probability of a large accidental release does not exceed 2.0E-06 for one calendar year.

In this case, a large accidental release can be defined as an environmental release of radioactive products in such amounts as to lead potentially to a high probability of fatality for the most vulnerable member of the public residing in the NPP area.

To formulate the criterion of dose loads leading potentially to a prompt fatality, one can use information provided in Ilyin et al. 2010 where it was found that a short-term exposure of 3 to 5 Gy, in the absence of treatment, leads to fatalities of 50% of the people exposed as a result of damage to the bone marrow stem cells. It will be reasonable to use the dose of 4 Gy absorbed within 10 days at any point outside the SPZ as the dose criterion for defining a large early accidental release. Using the dose value of 4 Gy absorbed within a period of 10 days (rather than for one day) compensates for some optimism associated both with the fact that the probability of fatality is high even with lower dose values and with the fact that more than one most vulnerable member of the public residing in the NPP area will be exposed to radiation.

A release, causing the dose loads for the population not leading yet to negative consequences for the population health can be taken as the criterion of a large accidental release. As shown in Ilyin et al. 2010, the probability of a fatality with an absorbed dose of below 1 Gy is excluded even if there is no evacuation or medical aid. Based on this, the value of 1 Gy can be used conservatively as the dose criterion for defining a large late accidental release.

Conclusions

The NRC's probabilistic safety goals established in 1986:

- are referred to as "surrogate" values which, based on limited research (Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing, 2018), have been shown to guarantee the compliance

with PHOs; however, this guarantee does not apply to the conditions that are principally different from those ones in the USA in 1986 since they do not take into account the peculiarities of the NPP designs and sites, population densities, representative weather conditions, national features, state-of-the-art available technical developments and resources, emergency response programs for the population in residential areas in the vicinity of the NPP, etc.;
- are defined in such terms ("early", "large"), which were not initially accompanied by a clear physical content.

Since the probabilistic safety goals depend directly on definitions of a large (early) accidental release, these definitions need to be revised to take into account the conditions specific to the given NPP site:

- the program of protective actions for the public in residential areas near the NPP;
- the time and facilities in possession of the emergency services for evacuation of the population in the context of a particular accident and the weather forecast (wind direction, rainfall, etc.), the estimated time, energy and height of the release of radioactive fission products, etc.

The proposed definitions of a large (early) accidental release and the PSGs based on them will provide:

- a higher level of confidence in protection of the population against the effects of radiation in the event of severe accidents at NPPs;
- the required tool for determining the best possible time to start taking measures to protect the population in the NPP area in the event of anticipated operational occurrences.

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