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Development of a framework of safety goals for nuclear installations and its application in Germany

Keywords

safety goals, safety assessment, safety verification, multi-units

Abstract

The International Atomic Energy Agency has started a few years ago a project to enhance the existing framework for safety goals for nuclear installations and currently is finalizing a publication aimed to provide guidance for a more holistic approach to establishing and utilizing safety goals for nuclear installations. The intention was to develop a more consistent and holistic framework for safety goals that would be composed of a hierarchical structure of qualitative concepts (e.g. defense in depth, various safety requirements) and quantitative risk metrics. The safety goals should be technology neutral at the higher level and should cover both normal operation and accident conditions as well as the risk to workers, public, and the environment. In the paper the development of a hierarchical framework for safety goals is described including a methodology to derive lower-(more technical) safety goals from the higher goals. Moreover a process for assessing the degree of compliance with the safety goals and their consistent use is provided. As an example the developed framework is applied to the German regulatory framework for nuclear installations but focused on nuclear power plants.

1. Introduction

Quantified risk and hazard analysis techniques are emerging as powerful tools for the safety management of different types of hazardous plants as the process industry and the nuclear industry where these approaches are already applied since many years. Although the concept in general remains similar, differences exist in methodological practices and particularly in the range of applications, focus and emphasis in implementing these tools for the different industries [3]. The quantified risk and hazard analysis in the process industry and in the nuclear industry vary apparently. In particular the use of probabilistic safety assessment for other than compliance with formal criteria dominates in the nuclear industry. Role and interpretation of such quantitative safety goals vary from country to country [2]. Therefore, even in the nuclear field it is not possible to provide a uniform solution and a set of safety goals suitable for all countries; however a certain degree of harmonization can obviously be achieved by applying a structured framework.

The activities for the development of a framework of safety goals for nuclear installations have been started before the Fukushima accident happened but this accident contributed to the discussions how to assess the safety level of a multi-unit site with nuclear power plants or a site with different types of nuclear installations.

The main objectives of introducing a safety goals framework are to provide a clear, logical, hierarchical structure in order to:

- Develop a coherent, consistent set of safety goals that link technology neutral high level goals with more detailed technical ones at lower levels;
- Help designers, vendors, operators and regulators to achieve consistent levels of safety across different facilities and technologies including site – wide considerations;
- Provide the general public with assurance that sufficient, uniform, high levels of protection are being achieved.

Safety goals may be observed, measured or calculated and can be both qualitative and quantitative. Safety goals help in answering the questions “how safe is safe enough?” and “has the required level of safety been achieved in practice?”

The term 'goals' is often used in a way that is synonymous with the terms 'criteria', 'objectives' or 'targets'.

In most cases, overarching safety goals are defined by governments backed up by more detailed goals determined by national regulatory authorities, and all installations are expected to achieve them. In some countries this is an absolute requirement. In others, compliance is goal setting and is required as far as reasonably practicable.

Safety goals can be expressed in several ways and may relate to individual facilities and activities or to whole sites. They can range from a high level principle (e.g. dose exposure based on a fraction of the chance of cancer incidence) through to extremely detailed requirements (e.g., the maximum fuel clad temperature), with intervening layers of goals (e.g., levels of radiological release into the environment). This eventually leads to the development of a large number of detailed technical and operational safety goals, which can appear to be unrelated to one another. The lack of clarity of how the set of safety goals relate to one another and contribute to the overarching aim can mean that it is not obvious that all aspects of safety are covered and on the other hand that all the safety goals are necessary.

2. IAEA's Hierarchical Framework for Safety Goals

In defining a set of safety goals, it is necessary to understand:

- how the safety goals reflect the operational state of the facility and its lifecycle stage,
- how the safety goals are related,
- how the more technical safety goals reflect the higher levels,
- how the more technical level safety goals demonstrate that the higher levels are actually met.

In summary, the aspects to be considered while defining the safety goals framework include the following:

- Overall individual and societal risk goals,
- Environmental protection,
- Quantitative/qualitative safety goals,
- Sources of radioactive hazard,
- Application to existing and older facilities,
- Plant states,
- Lifetime stages,
- Operational aspects,
- Adequate models and data,
- Treatment of uncertainties,
- Treatment of natural external events,
- Multi-unit or multi-facility sites.

One requirement on the safety goals hierarchy is that it shall be applicable to all nuclear installations during their entire lifetime, that it shall cover both operational states and accident conditions, and that it shall consider all sources of radioactivity on the site.

The highest level safety goal would be expected to remain unchanged over all life cycle phases, while lower level safety goals may be different for different life cycle phases, and may also change during the life time of an installation. Both operational states (normal operation and anticipated operational occurrences) and accident conditions need to be considered.

Safety goals are typically qualitative or quantitative. Semi-quantitative safety goals are basically a separate type, but have been included among the quantitative safety goals. Quantitative safety goals may be either deterministic or probabilistic. PSA is one (but not the only) basis for probabilistic analyses. Quantitative deterministic safety goals are often defined as success criteria for a particular deterministic assessment.

The resulting spectrum of safety goals is illustrated in *Figure 1*.

Figure 1. Basic types of safety goals

Where there are nearby facilities or sites under the control of different licensees which share systems or have the potential for interactions, it is a decision for the country on how to apply the "site" level safety goals. Whatever safety goals are developed, the framework should be established on the basis that protection of the public and the environment is the fundamental objective and details regarding ownership of sites should not be allowed to diminish this objective.

An example of a hierarchical framework for safety goals for nuclear installations developed by the IAEA and included in the draft TECDOC [8] is provided in *Figure 2*. The picture illustrates how the levels of safety goals relate to different aspects of safety (society/site/facility) and to technology (technology independent/specific), and the potential overlaps.

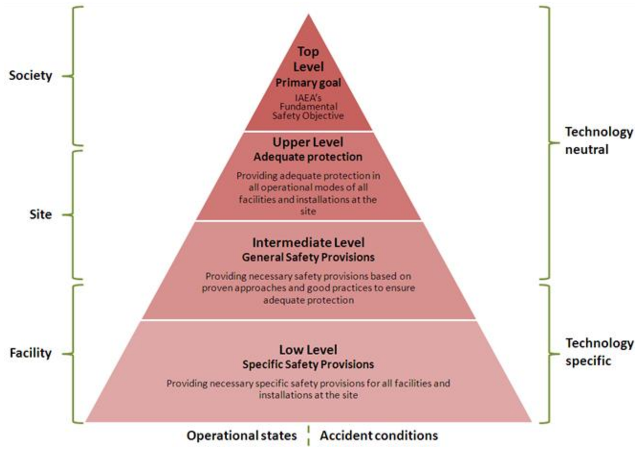

Figure 2. Proposed safety goals framework

Table 1. Levels of safety goals in the example

Level	Overall Objective	Explanations on the Nature of Safety Goals and Examples[1]
Top Level Primary Safety Goal	Protecting people and the environment from harmful effect of ionizing radiation.	Requirements on this level are expressed qualitatively and may presuppose, e.g., the prevention of unreasonable harm to the public and the environment. These safety goals may have a wider scope than nuclear. The safety goals at this level are technology neutral.
Upper Level Adequate Protection	Ensuring adequate protection in all operational modes for all facilities and installations at the site	Upper Level Safety Goals are high level and used as a bridge to support the development of Intermediate and Low Level Safety Goals from the Top Level. In some countries, this is done by relating to levels of risks from other involuntary sources of risk, using quantitative or semi-quantitative expressions of relation between risks from nuclear installations and risks from other involuntary sources of risk, e.g., fatality risks from other sources of energy production. The safety goals at this level are typically technology neutral and have a site-wide scope.
Intermediate Level General Safety Provisions	Providing general safety provisions including technical and organizational measures based on proven approaches and good practices to ensure adequate protection	Intermediate level safety goals typically include principles related to defence-in-depth, safety margins, physical barriers, considerations related to independence and protection of barriers, redundancy and independence, doses for normal operation, amounts of radioactive waste generated, etc. This level also includes the definition of some high-level quantitative safety goals, e.g., over-all large early release frequency (LERF) for the site. The safety goals at this level are still largely technology neutral
Low Level Specific Safety Provisions	Providing specific safety provisions for each facility and installation at the site to ensure adequate protection	A large number of specific deterministic safety goals are in use, e.g., related to maximum fuel cladding temperature in a LWR. This level may also include quantitative probabilistic safety goals, e.g. for frequency of large release, core or fuel damage, barrier strength, or SSC reliability. Technology and facility specific safety goals aimed at assuring the nuclear installation meets the higher level safety goals.

In *Table 1* above, each of the levels of safety goals is briefly characterized.
Safety goals mentioned in *Table 1* shall be seen as examples and do not constitute a complete list of safety goals.

3. Application of the Proposed Safety Goals Framework to the German Regulatory Framework for Nuclear Power Plants

In the past, the safety concept of nuclear power plants as well as licensing and supervising decisions by the competent authorities and their experts in the Federal Republic of Germany were mainly based on deterministic principles. Safety-related decision-making during design and licensing has essentially been based on the verification of compliance with the German regulations pre-describing technical requirements as laid down, e.g., in the German nuclear safety standards.
A probabilistic safety assessment has been essentially performed in the framework of the periodic safety reviews as a supplement to the deterministic safety analysis. Currently, no specific probabilistic quantitative safety goals for nuclear power plants or other nuclear facilities and no site-wide safety goals are determined within the German regulatory framework. However, a recent document requires that modifications of measures, equipment or the operating mode of a nuclear power plant, compared with the unchanged condition of this plant, must not lead to an increase in the average core damage frequency and the average frequency of large and early releases, neither for full power operation nor for low-power and shutdown states, considering all plant-internal initiating events as well as all internal and external hazards, both natural as well as very rare human-made external hazards.

3.1. Current German Safety Requirements for Nuclear Power Plants

The German nuclear regulatory framework has been elaborated over a long time period consisting of the Atomic Energy Act (AtG) [1], ordinances such the Radiation Protection Ordinance (RPO) [4], regulatory guidelines such as Guidelines for Periodic Safety Reviews and a Guide for the Decommissioning, the Safe Enclosure and the Dismantling of Facilities as well as guidelines and recommendations of the German Reactor Safety Commission (RSK).
Detailed technical requirements are laid down in about 100 German nuclear safety standards (KTA safety standards), elaborated by German experts from authorities, technical support organizations, utilities and vendors, issued by the German Nuclear Safety Standards Commission and announced by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety in the Federal Gazette.
Recently, the "Safety requirements for nuclear power plants" [6] have been issued containing fundamental

and general safety-related requirements within the framework of the non-mandatory safety standards and rules that provide more details regarding the required precaution that - pursuant to § 7 para. 2 no. 3 of the AtG - is necessary according to the state of the art in science and technology in order to prevent any damage caused by the construction and operation of a nuclear power plant.

As far as necessary from a safety-related point of view, document [6] shall also be applied to nuclear power plants that pursuant to § 7 (1a) AtG have had their power operating licences revoked or which due to a decision taken by the licensee are in their post-operational phase.

This new regulatory document is now part of the German regulatory framework as shown in *Figure 3*.

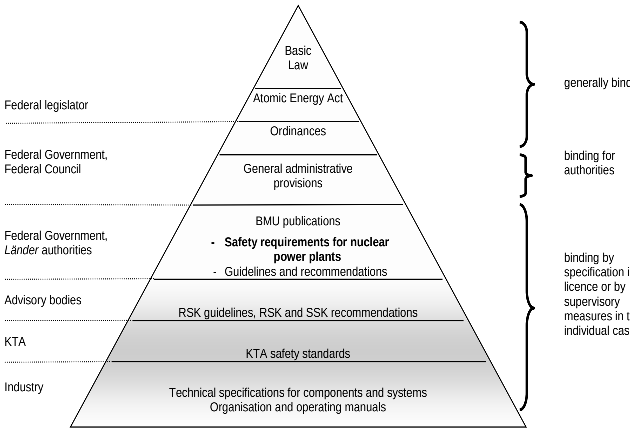

Figure 3. German regulatory framework

3.2. Safety Goals in German regulations

Because the regulatory framework in Germany is very prescriptive compared to other countries like the United Kingdom, specific safety goals are also provided in each level of the German regulatory framework. Moreover, technical and radiological safety goals are formulated for all level of defence in depth for all operational states, accident conditions and beyond design basis conditions.

In [1] it is stated in the first paragraph that the aim of the act is to protect life, health and real assets against the hazards of nuclear energy and the harmful effects of ionising radiation and to provide compensation for damage and injuries caused by nuclear energy or ionising radiation. Moreover, it is stated that the purpose of this act is to prevent danger to the internal or external security of the Federal Republic of Germany from the application or release of nuclear energy or ionising radiation. § 7d of [1] requires that the holder of a licence to operate an installation for the fission of nuclear fuel for commercial electricity production shall provide the realisation of safety measures according to the ongoing state-of-the-art of science and technology which are developed, suitable and adequate for providing more than only an insignificant contribution to further precaution against risks for the public.

The purpose of [6] is to regulate principles and requirements of preventive and protective measures which apply to the use and effects of man-made and naturally occurring radioactive substances and ionizing radiation in order to protect human being and the environment from the harmful effects of ionizing radiation.

The fundamental safety objective in [6] is the protection of human being and the environment against the harmful effects of ionising radiation. Guidelines for the assessment of the design of nuclear power plants are provided in [6] and the correspondent spectra of incidents have originally been defined in the Radiation Protection Ordinance [4].

Those events, which are relevant concerning their radiological impacts and against which precautions must be taken in terms of engineered safeguards or countermeasures are defined in [6] for nuclear power plants. For these events it must be demonstrated by means of computational analyses that the requirements specified in [6] are met. Especially, it has to be demonstrated that the safety-related acceptance targets and acceptance criteria applicable to the different levels of defence in depth are achieved and maintained for these events.

For defined events whose occurrence can be prevented by special measures and equipment – in the following referred to as precautionary measures – it shall be demonstrated that the requirements for the effectiveness and reliability of these precautionary measures are fulfilled.

For these events computational analysis is only required if it cannot be demonstrated that the specified precautionary measures have been met. The verifications of fulfilment of the acceptance criteria shall consider the assignment of load levels of the reactor coolant pressure boundary, the systems outside the primary circuit and the containment, presented in [6] to the events included in the event lists.

The confinement of the radioactive materials present in the nuclear power plant shall be ensured. In order to achieve this safety goal, a safety concept shall be implemented in which measures and equipment are allocated to different levels of defence in depth (DiD) [6]:

- Level of DiD 1: normal operation (specified normal operation)
- Level of DiD 2: anticipated operational occurrences (specified normal operation, incident)

- Level of DiD 3: accidents
- Level of DiD 4a: very rare events
- Level of DiD 4b: events involving the multiple failure of safety equipment
- Level of DiD 4c: accidents involving severe fuel assembly damages.

Recently, the German Reactor Safety Commission described its understanding of safety philosophy including orientation values for the four levels of defence in depth [7].

Furthermore, additional measures and equipment to identify and limit the consequences of plant conditions that are not allocated to the abovementioned levels of defence 1 – 4a due to their low probability of occurrence shall be provided to an adequate extent as a precaution.

Therefore, measures and equipment of the internal accident management shall be provided and planned in supplement on levels of defence 4b and 4c of the defence in depth concept. Therefore, a safety goal on the intermediate level, e. g, is to maintain effective defence in depth.

A further safety goal is to provide effective features to support the external accident management in order to assess the consequences of accidents for accidents involving severe fuel assembly damages with potential or actually occurred releases of nuclear materials into the environment and to mitigate as far as possible their effects on human being and the environment.

All equipment that is necessary for shutting the reactor down safely, for maintaining it in shutdown condition, for removing the residual heat or for preventing a release of radioactive materials shall be designed and maintained in such a condition that they fulfil their safety-related functions even in the case of internal and external hazards as well as very rare man-made external hazards.

Radiological safety goals are set for the different levels of defence in depth:

- On levels of DiD 1 and 2
  - radiation exposure of the personnel shall be kept as low as achievable for all activities, even below the limits of the Radiation Protection Ordinance, taking into account all circumstances of each individual case,
  - any discharge of radioactive materials with air or water shall be controlled via the specially provided discharge paths; the discharges shall be monitored as well as documented and specified according to their kind and activity, and
  - any radiation exposure or contamination of people and the environment by direct radiation from the plant as well as by the discharge of radioactive materials shall be kept as low as achievable, even below the limits of the Radiation Protection Ordinance, taking into account all circumstances of each individual case.
- On level of DiD 3
  - the maximum radiation exposure limits for the personnel in connection with the planning of activities for the control of events, the mitigation of their effects or the removal of their consequences shall not exceed the relevant limits of the Radiation Protection Ordinance,
  - the maximum design limits for the plant for protecting the population against any release-induced radiation exposure shall not exceed the relevant accident planning levels of the Radiation Protection Ordinance,
  - any release shall only happen via specially provided release paths; the release shall be monitored and shall be documented and specified according to its kind and activity; and
  - the on-site and off-side radiological consequences shall be kept as low as possible, taking into account all circumstances of each individual case.
- On level of DiD 4
  - the planning of activities to control events of level of defence 4a as well as for the planning of activities in connection with internal accident management measures shall be based the relevant requirements of the Radiation Protection Ordinance regarding the anticipated radiation exposure of the personnel,
  - the monitoring of releases of radioactive materials from the plant according to their kind and activity shall be ensured and
  - the on-site and off-side radiological consequences shall be kept as low as possible,

Taking into account the measures and equipment for the internal accident management provided on levels of DiD 4b and 4c:

- any releases of radioactive materials into the environment of the plant, caused by the early failure or bypass of the containment and requiring measures of the external accident management for the implementation of which there is not sufficient time available (early release), or
- any releases of radioactive materials into the environment of the plant requiring wide-area and long-lasting measures of the external accident management (large release)

shall be excluded, or their radiological consequences shall be limited to such an extent that measures of the external accident management will only be required to a limited spatial and temporal extent. The occurrence of an event or event sequence or a state can be considered as excluded if it is physically impossible to occur or if it can be considered with a high degree of confidence to be extremely unlikely to arise.

Moreover, intervention reference levels are set in [5] for

- Sheltering: 10 mSv from external exposure in seven days and effective dose commitment resulting from radionuclides inhaled during this period.
- Evacuation: 100 mSv from external exposure in seven days and effective dose commitment due to the radionuclides inhaled during this period.
- Temporary resettlement: 30 mSv external exposure in one month,
- Long-term resettlement: 100 mSv external exposure in one year due to deposited radionuclides.

The goal to maintain the integrated management system and to maintain and enhance safety culture is addressed in [6].

Typical deterministic examples for deterministic low level safety goals which have to be fulfilled are:

- No critical boiling at cladding tube or maintenance of an appropriate temperature-time criterion of the cladding tube,
- Cladding tube temperature < 1200 °C or
- Amount of shutdown reactivity.

The recently issued German safety requirements for nuclear power plants [6] extend the use of probabilistic safety assessment to supplement deterministic safety demonstrations to assess the safety significance in case

- of modifications of measures, equipment or the operating mode of the plant, as well as
- of findings that have become known from safety-relevant events or phenomena that have occurred and which can be applied to the nuclear power plants in Germany that are referred to in the scope of application of the "Safety Requirements for Nuclear Power Plants"

for which a significant influence of the results of the PSA can be expected.

Compared with the unchanged condition of the plant, modifications of measures, equipment or the operating mode of the plant must not lead to an increase in the average core damage frequency and the average frequency of large and early releases, neither for power operation nor for low-power and shutdown states, considering all plant-internal events as well as all internal and external hazards as well as very rare human-made external hazards.

Table 2. Safety goals for nuclear installations in Germany with main focus on nuclear power plants

<table>
<tr><td colspan="12"><u>TOP LEVEL</u> - PRIMARY SAFETY GOAL: To protect people and the environment from harmful effects of ionizing radiation</td></tr>
<tr><td colspan="12"><u>UPPER LEVEL</u> SAFETY GOALS: Ensuring adequate protection in all operational modes of the nuclear installations</td></tr>
<tr><td colspan="5">Operational states</td><td colspan="7">Accident conditions</td></tr>
<tr><td colspan="2">O1
To protect workers, the public and the environment</td><td>O2
To provide design features for security</td><td>O3
To avoid or reduce radioactive waste</td><td>O4
To provide design features to facilitate decommis-sioning</td><td colspan="3">A1
Reducing risk to life and health of people from nuclear installations</td><td colspan="2">A2
Any early or large releases of radioactive materials into the environment of the plant shall be excluded, or their radiological consequences limited to such an extent that measures of the external AM will only be required for a limited spatial and temporal extent</td><td>A3
Safety-security interface should be addressed</td><td>A4
Emergency response should be provided</td></tr>
<tr><td colspan="12"><u>INTERMEDIATE LEVEL</u> SAFETY GOALS: Providing necessary safety provisions including technical and organizational measures based on proven approaches and good practices to ensure adequate protection</td></tr>
<tr><td><u>Qualitative</u>
O1-Q1
Maintain integrated management system and safety culture</td><td><u>Deterministic quantitative</u>
O1-D1
To meet radiological criteria for workers by providing adequate radiation protection measures</td><td>…</td><td>… …</td><td>…</td><td><u>Qualitative</u>
A1-Q1
Maintaining effective defence-in-depth</td><td><u>Deterministic quantitative</u>
A1-D1
Maintaining allowed doses for workers in design basis accidents</td><td></td><td><u>Qualitative</u>
<u>A2-Q1</u>
Providing effective SAM design features and SAMG</td><td><u>Deterministic quantitative</u>
<u>A2-P1</u>
Food ban radioactivity levels</td><td></td><td>A3-Q1
Detailed emergency plan</td></tr>
<tr><td></td><td>O1-D2
To meet radiological criteria for discharges to the environment by providing adequate measures for controlling the discharges</td><td></td><td></td><td></td><td>A1-Q2
Maintaining sufficient safety margins</td><td>A1-D2
Maintaining allowed discharges to the environment in design basis accidents s</td><td></td><td></td><td><u>A2-P2</u>
Evacuation radioactivity levels</td><td></td><td></td></tr>
<tr><td></td><td>O1-D3
Not requiring operator actions within 30 minutes after an abnormalg event</td><td></td><td></td><td></td><td>A1-Q3
Providing sufficient redundancy, diversity and physical separation to comply with single failure criterion</td><td>A1-D3
Containment withstanding an aircraft crash according to a specified impact-load-time diagram</td><td></td><td></td><td><u>A2-P3</u>
Habitation radioactivity levels</td><td></td><td></td></tr>
<tr><td colspan="12"><u>LOW LEVEL</u> SAFETY GOALS: Providing necessary specific safety provisions</td></tr>
<tr><td>…</td><td colspan="2">…</td><td>…</td><td>…</td><td colspan="2"><u>Deterministic quantitative</u>
A1-Q1
Max. fuel cladding temperature</td><td rowspan="2"><u>Probabilistic quantitative</u>
A1-P1
Plant modifications should not lead to an increase of the core damage frequency

A1-P2
Plant modifications should not lead to an increase of L(E)RF</td><td><u>Qualitative</u>
A2-Q1-
Providing effective SAM design measures and SAMG</td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="2"></td><td></td><td></td><td colspan="2">A1-Q2-Required number of trains of safety systems</td><td></td><td></td><td></td><td></td></tr>
</table>

Comparison with the unchanged condition refers to the actual core damage frequency evaluated within the (periodic) safety review of the respective plant. If the unchanged condition was not modelled in the safety review, the unchanged condition as well as the planned modification has to be analysed and compared.

As preventive accident management measures according to [6] it is necessary to demonstrate the effectiveness of the accident management measures for cooling of the fuel elements in the fuel pool for the representative event sequences considered if the fuel elements are covered with coolant and measures for maintenance or restoration of the required sub-criticality of the fuel elements in the fuel pool is demonstrated for the representative event sequences if long-term sub-criticality of keff < 0.999.

Table 2 provides the application of the safety goals framework proposed in [8] for the German situation. The top level, upper level and part of the intermediate level safety goals like the radiological limits could in general also be applied to other nuclear installations than nuclear power plants. However, the safety goals, exemplary illustrated in *Table 2*, are focussed on German nuclear power plants because they are explicitly described in the several documents within the German regulatory framework.

It is important to recognise that the application described in *Table 2* was not aimed to be complete. In particular, a large set of low level safety goals exists.

However, it can be illustrated from *Table 2* how the German safety goals can be integrated in the hierarchy of safety goals as proposed in [8].

4. Concluding remarks

The draft TECDOC [8] discusses development and application of a framework of safety goals encompassing high level requirements and detailed technical aspects to form a coherent and consistent approach to nuclear safety. The framework starts from the overarching requirements for safety, which are developed in a hierarchical way. This hierarchical framework is structured in a coherent manner such that the higher level safety goals are related to more detailed lower level safety goals. It can be applied in a holistic manner to a wide range of nuclear installations and multiple-facility sites.

The framework of safety goals described considers approaches in several Member States, international organizations and expert groups.

Safety goals are set to achieve an acceptable level of safety but it is important that a way to demonstrate they are being met exists, hence they must recognise the way in which safety assessment and verification will be carried out.

This is partly the driver for developing a framework of safety goals as the higher level goals are difficult to demonstrate directly. By developing supporting lower level goals which are more technical or operational the process of demonstration can be more easily achieved.

A description of the framework and the general features of safety goals at various levels within the hierarchy have been provided. As an example the application of this concept to the German regulations is described.

Further examples of other countries are presented in [8] to show how to derive the detailed safety goals within the hierarchical framework.

Applications of a framework of safety goals, including its use within an integrated risk informed decision making process, are outlined with the intention of encouraging Member States to consider using such an approach within their safety infrastructure for nuclear installations.

For newcomer countries, which are in the beginning of development of their nuclear power programmes, the approach described in [8] may assist in developing a more holistic, systematic and comprehensive view of the safety goals to be pursued.

For countries with developed nuclear power programmes, it may be useful to apply the approach in [8] for benchmarking the existing framework of safety goals for consistency and comprehensiveness in covering all aspects important to nuclear safety.

Application of the proposed framework of safety goals may provide support in effective communication on the topic of nuclear safety between utility organizations, regulatory authorities and the public.

The publication of the final version of [8] is intended to be issued in 2015.

Acknowledgement

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