APPROACHES OF RISK MEASURES MINIMIZATION AND APPLICATION TO INSPECTION

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During recent years, both the nuclear industry and nuclear regulatory bodies have recognized that probabilistic risk analysis has evolved to the point that it can be used increasingly as a tool in decision making and risk minimization. In this paper the Integrated Risk-Informed approach and risk measures are considered. They are complementary to the defence-in-depth philosophy and is proposed to be used in safety-related decision making, e.g. for optimizing activities related to NPP operation, in service inspection, testing, and maintenance.
The following topics are discussed in this paper:
- The integration of deterministic and probabilistic approaches in order to define integrated risk measures and approaches for risk-informed decisions when deterministic and probabilistic methods integration are used;
- Decision making and risk management in order to minimize risk, using proper inspection and maintenance procedures, as well as seek other benefits additional to safety improvements and risk reduction.
In addition, this paper presents a case study, which partly integrates reliability and risk assessment applying physical-based and statistical-based methods for Development of Risk-Informed In-service Inspection Program. The methods application and the case study include results, obtained through the author's participation in a number of related research projects.

I. INTRODUCTION

In general, the risk measures minimization and application to inspection is risk informed action and is related to the process of decision making. The general concept of risk informed decision making (RIDM) was described in TECDOC-1436 [1] and further discussion of the integrated risk informed decision making (IRIDM) process was given in INSAG-25 [2], which presented a framework for the decision making process. One of the aims of these publications was to provide a common understanding in the international nuclear community (designers, suppliers, constructors, licensees, operators, technical support organizations, and regulatory bodies) of how to implement a risk informed decision making process. However, both publications did not provide guidance on how the IRIDM process should be established and carried out in practical manner or even specifically for risk measures minimization and application to inspection.

The risk-informed approach with appropriate risk measures/estimates aims to integrate systematically quantitative and qualitative, deterministic and probabilistic safety considerations. There is explicit consideration of both the probability of events, i.e. failures, and their potential consequences, supported by consideration of sound engineering practice and managerial arrangements. Estimates of risk, likelihood and consequence, are based on knowledge or data from experience, or derived from a formal, structured analysis such as a Probabilistic Safety Assessment (PSA).

I.A. Key Elements of the IRIDM Process

The key elements of the IRIDM process are shown in Fig. 1 below, which is based on the descriptions of a framework and the process given in INSAG-25 [2]. The IRIDM process shown in Fig. 1 below includes several Key Elements (KE), each of which has implicit risk aspects. Each KE comprises several Constituent Factors (CF) (not shown on Fig. 1 below), which further define the safety requirements and other conditions, and are used to evaluate the options being considered. In any particular application, not all the KE, nor all their CF, will be relevant to the issue under consideration. The aim of defining this framework is to better focus licensee and regulatory attention on design, operational and security issues commensurate with their importance to public health and safety.

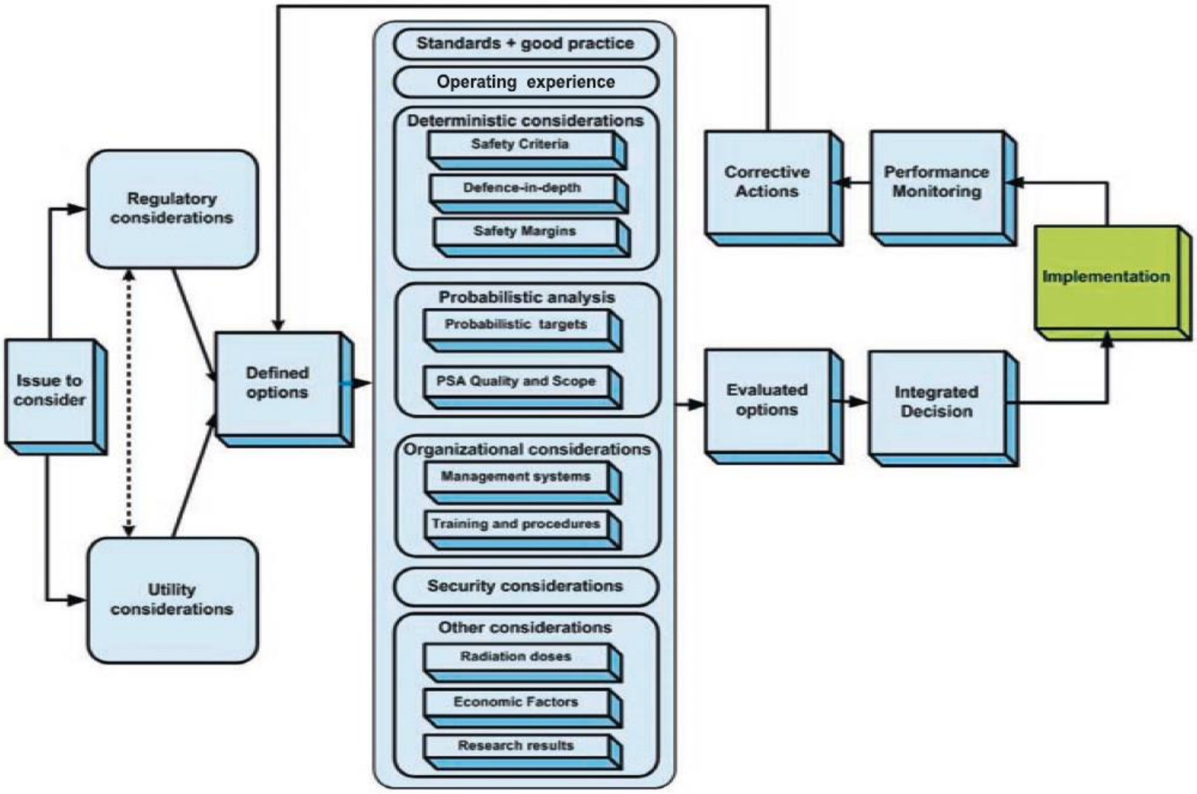

Fig. 1. Key elements of the IRIDM process (based on IAEA INSAG-25 [2]).

I.B. Stages in Performing General IRIDM Process

The general process for the RI Decision Making includes the following main stages:

- Stage I Characterization of the issue and team formation;
- Stage II Preparation for the evaluation of the options;
- Stage III Assessment, integration and documentation;
- Stage IV Selection of the option to implement;
- Stage V Implementation of the selected option;
- Stage VI Performance monitoring.

The stages listed above reflect the logical order of tasks to be performed. Some of the associated activities may be performed in parallel. Hence the order of stages does not represent a sequence in time. Iterations between the different stages may also be necessary. After completion of stage V, the results of implementation of the selected option are monitored.

The IRIDM process as carried out in the organization should also be periodically reviewed and improved if deemed necessary. The IRIDM process can be adjusted specifically to risk measures minimization and application to inspection.

II. ISSUES OF INTEGRATED RISK-INFORMED DECISION MAKING

As considered in various papers and projects, like in the ongoing project ASAMPSA_E (see [3] and acknowledgements), there is no common understanding on the correct (or even appropriate) approach to decision making regarding risk in the scientific community as well as with actual end-users. Depending on the subject matter to decide and the role and the interest of the decision maker or stakeholder, different approaches to decision making are advocated or rejected [1, 5, 6, 7, 8, 9]. Moreover, the acceptability of these approaches to the stakeholders or the society obviously depends on the culture of the society in question and the specific values and believes on risk acceptance on a personal and societal level [10]. For the purpose of risk minimization, work on the ethical or legal or theoretical foundations of decision making [11, 12, 13] is clearly out of scope, as it is more a discussion on cultural influences.

It is important to note that the aforementioned issues have partial implications for the further discussions contained in this paper. Decision makers are influenced by factors that transcendent natural science and cannot be resolved in a strictly objective manner in this sense. Consequently, implicit and explicit utility considerations on decision alternatives will necessarily have a strong subjective component. Furthermore, the relevance of information, e.g. from PSA, the acceptability of certain kinds of risks, and finally the adequacy of risk measures to support decisions will depend on the decision maker. In the end, the decision maker has to decide which aspects of risk and thus which risk measures are relevant for each alternative. Therefore, the discussions in this paper have to be understood as options for decision makers. The presented approaches have been identified as suitable for a wide range of typical situations and they might help to select the best decision alternative. The approaches should not be interpreted as a fixed set of rules which can be applied to every situation. Similarly, they might lead to results which decision makers do not agree with. Thus, even if decision makers and PSA analysts follow the approaches in the paper, they should be free to select alternative approaches as they see fit. It is therefore essential that PSA analysts and decision makers agree on the scope of approaches application at an early stage.

II.A. Integration of Deterministic and Probabilistic Approaches

Various recent researches and analyses of complex systems safety methods show that integration of various methods can present more accurate and practical results, which cannot be obtained by single methods used up to now. Two approaches basically different in its nature are based on deterministic analysis and probabilistic analysis. They also can be practically applied for decision making even without any consideration of risk.

Actually, the risk measure is defined in different ways for specific purposes. There is no such one way of defining risk, which is always more adequate than another, since this will depend on the purpose of defining risk. The developed Integrated and Risk-informed (IRI) approach uses risk measures based on qualitative or quantitative information. IRI approach is not a probabilistic approach, which is alternative to the deterministic one, but it is a combination of both. In the integrated risk-informed approach fundamental deterministic safety principles, mainly defence-in-depth and sufficient safety margins, have to be maintained, even if probabilistic evaluation would indicate the safety level, which is already high enough.

The risk measures used in risk-informed approach is related to decision models. It is important to stress that risk information (e.g. from PSA) in IRI approach is not used in order to find the best solution in terms of safety but to select the most efficient solution among a number of alternatives, while achieving the required safety level.

The main elements of integrated risk-informed approach:

- Safety analysis, using deterministic approach and philosophy of defence-in-depth;
- Probabilistic evaluation of risk (insights from PSA);
- Knowledge from operating experience.

One basis of integrated approach, the doctrine of determinism, assumes that any failure has a cause and can be explained and in reality, there are no random failures. It is a matter of knowledge in order to identify, model and explain the cause of any event or effect. Another fundamental concept of deterministic doctrine is that everything could be understood by analysis.

The quantitative analysis in deterministic approach considers the performance of components and compares it with required performance capability under design basis conditions. The analysis process involves the identification of functional failure modes or states of components. In addition, the performance margins between component specific performance capability and the defined design basis performance capability is analysed for each identified functional failure mode or state.

The pure deterministic approach is very effective to achieve a very high safety level. The used or assumed simplicity and predictability also somehow helps in decision making. However, its main disadvantage is that it is not efficient regarding the use of resources (human, financial, others) according to the impact on risk. The decisions produced by deterministic design principles usually have a very high range of conservatism. This is natural, because the same criteria are applicable for high-risk systems and low risk systems. In addition, it is possible to recognise that some practical situations are too complex to clearly identify what is conservative and what is not. An action that is good from one side may be bad from another side (e.g. possible safety-security conflict for decision making). In spite that probabilistic approach can be conservative as well, the more advanced ranking of problems and resources, used for decision-making, is based on measure, received using integrated risk-informed approach. Also, the more advanced ranking process can be based on probabilistic sampling and probabilistic sensitivity analysis.

II.A.1. Definition of Integrated Risk Measure

The definition of risk measure depends on the approach to risk. The choice of a qualitative or quantitative approach is based on the level of available detailed information and the level of rigor and confidence required (e.g. for regulatory acceptance). In determining the integrated risk-informed measure, associated with operation and inspection of a given plant structures, systems and components, in general, four aspects are considered, namely:

1. The failure mode or state;
2. The likelihood of detectable failure;

3. The likelihood of reliable detection of failure;
4. The consequences of failure.

The integration of deterministic and probabilistic approaches is proposed to be made using different methods. The nature of simpler qualitative approach is that it can only act as an indicator of risk, which can be used for simple screening, and does not constitute a risk assessment. Without strict definition, the risk is proposed to be expressed as the combination of the qualitatively assessed actual frequency of failure and the consequences of failure. In developed scheme, the actual frequency of failure is quantitatively expressed as the combination of likelihood of detectable failure (i.e. empirical frequency) and likelihood of unreliable detection of failure (i.e. probability of non-detection).

If qualitative ranking, such as high, medium, and low are used, the rank of this risk kind is limited because there are only nine possible combinations. In this case, a simple bar matrix is proposed to be illustrated in a manageable fashion as schema for risk estimation and results visualization (see the following figure). The values of this matrix are the combination of probabilistic importance evaluation (high, medium, and low) in the actual failure frequency axis and deterministic importance evaluation (high, medium, and low) in the consequence axis.

In general, the risk level increases if there is the increase in the empirical frequency of failure and in the probability of non-detection of failure events as they affect the increase of actual frequency of failure. In quantitative expression case, the normalized parameters' values (e.g. 1, 0.1, 0.01, and etc.) can be used for risk evaluation.

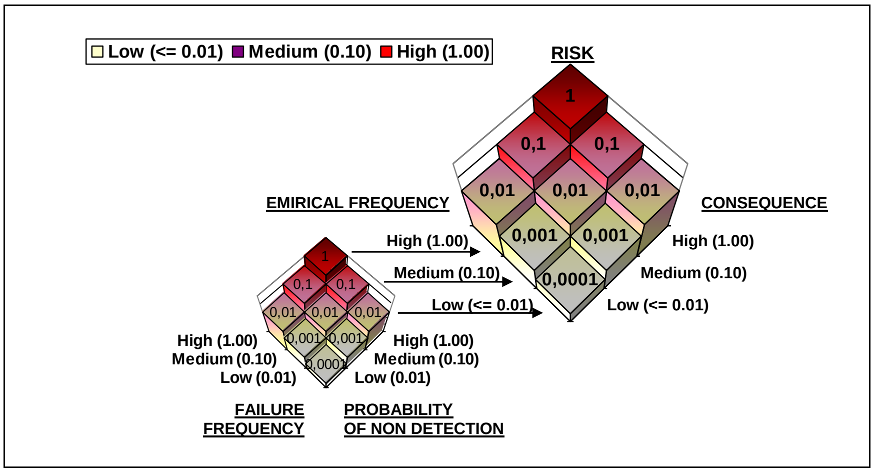

Fig. 2. Simplified schema for qualitative risk estimation and results visualization.

In order to reflect the impact of inspection and probability of non-detection, the more precise and formal mathematical quantitative definition of risk for one component can be expressed as follows:

$$R_c = \sum_i \sum_d \sum_s [f_i \cdot p_i \cdot P(d \mid i)] \cdot P(s \mid d) \cdot C(c \mid s) \cdot \tag{1}$$

Here, R_c is the risk of consequence expressed by measure c, f_i is the frequency of the detectable initiating event i (i.e. failure frequency), p_i is the probability of non-detection of initiating event i, $P(d|i)$ is the conditional probability that the initiating event i will lead to plant damage state d; $P(s|d)$ is the conditional probability that plant damage state d will lead to the source term (radioactive release) s, and $C(c|s)$ is the conditional consequence measure, c, given the occurrence of source term s. The proposed risk measure is more complex than the typical one as the failure frequency is evaluated, using the separation of information, related to the probability of empirical failure and the probability of detection of failure.

The results of typical probabilistic risk assessment study in nuclear industry can also be treated as risk measures. The selection of appropriate quantities, resulting from PRA as risk measures, and target quantities for optimisation is a very important step (see [4] to get a view on existing risk measures). The results of optimisation depend on this selection. Risk measures can be defined for each component in terms of annual core damage frequency (CDF) and, if available, in terms of annual frequency of large early release (LERF). However, in order these measures to be consistent with R_C measure, the reliability of the estimates of initial events frequency should be investigated additionally.

Operational Experience Application

Plant specific operating experience should be used in determining both the initiating event frequencies and initiating event consequences. A continuous plant specific data collection and processing system should be set up and maintained as it is considered important for the achievement of reliable data. For that purpose, there is a demand to have the operating experience feedback programmes which yield plant specific data for the use in the PSA. Generic data is used only when plant specific data does not exist or it is so scarce that reasonable and reliable estimates cannot be provided. The estimation of reliability parameters (e.g. failure frequency) are supported by a Bayesian updating of generic data if necessary.

Ideally, the considered parameters of risk model should be based on detail operational data of considered system. However, due to small quantity or unavailability of system-specific data the risk assessment often has to rely on various sources and types of information:

- The general engineering (expert) knowledge;
- The failure data in other similar but not identical systems;
- The failure experience with the specific-system being studied.

In such cases expert judgment, generic information, or surrogate data are used directly or in combination with (limited) system-specific data. In general, various information types can be proposed to be considered and integrated.

If PSA results are to be used for risk-informed applications, the data requirements should be far stricter than in a typical use of PSA results. The measure, based on IRI approach, includes the data reliability measure, which is related to degradation level detection efficiency (i.e. failure inspection reliability) and represents the generic data reliability insights and insights regarding uncertainty of failure events occurrences and classification. Typically, the data and detection reliability (probability of non-detection) insights are not included in the PSA scope and appropriate deterministic analysis of consequence. Some investigations, concerning data reliability.

II.A.2. Risk-Informed Assessment and Results Visualization

The risk associated with different systems, components and structures has become subject to re-evaluation when the results of additional information became available. Detailed, systematic, plant specific analyses with an operational experience are thought to give realistic and relevant estimates of used risk measures. Such risk estimates could be considered as useful also for the risk-informed applications, e.g. modification of the inspection and testing strategy. In this section, the general model of risk-informed assessment as well as formulas for risk measure calculation and visualization is presented.

The first task for risk informed (RI) approach application is the determination of the high-risk components or locations. The procedure for risk ranking and decision-making is proposed to be based on division of overall system risk into so called components risks measures. For practical applications these measures can be calculated as the product of degradation frequency estimate P and estimate C of consequence probability to degrade the overall safety. If there are some degradation states k (e.g. crack with small leak, crack with large leak) up to maximum degradation state D - failure (e.g. pipe rupture) then the total conditional risk due to the component i degradation influence on the main system is proposed to be expressed as such sum:

$$R_i = \sum_{k=1}^{D} n_i \cdot P_{i,k} \cdot C_{i,k} . \tag{2}$$

Each summand reflects the conditional risks due to the component i degradation state k influence on the main system and they are assumed to be mutually exclusive. In fact, the risk R_i reflects the risk of the single ($n_i=1$) component i or the risk of similar components group i with n_i components influence to overall risk to degrade the safety of system. As an example, in Nuclear Industry the influence to overall risk can be expressed as Conditional Core Damage Frequency (CCDF), where the overall system risk reflects the total Core Damage Frequency (CDF). The conditional risk due to some subsystem S specific degradation states influence on overall system safety is proposed to be expressed as follows:

$$R_S = \sum_{i=1}^{N} R_i = \sum_{i=1}^{N} \sum_{k=1}^{D} n_i \cdot P_{i,k} \cdot C_{i,k} . \tag{3}$$

In practice, the conditional probability to degrade the safety of system (consequence $C_{i,k}$) can be assessed as safety barrier used for CCDF calculation in PSA. As an example, the CCDF for different postulated Loss of Coolant Accident (LOCA) events can be used as such safety barrier. These safety barriers in most cases can be taken from PSA model. The calculation of frequencies (probabilities estimates expressed per time unit), related to the degradation states occurrence, usually needs a separate model which includes the information and assumptions concerning failure detection procedure and its reliability.

Visualization of Risk-informed Measures

The risk-informed measures can be estimated for each state of degradation in similar component (or location) of considered subsystem. In order to simplify the risk interpretation, according to the dominating risk part, like in approaches of other authors [14, 15] only two generalized values C_{Plot} and P_{Plot} (as one point coordinates) for each component are defined (as example, see the following figure).
In case of two degradation states (e.g. leak and rupture):

$$R_i = n_i \cdot P_{i,1} \cdot C_{i,1} + n_i \cdot P_{i,2} \cdot C_{i,2} = P_{i,Plot} \cdot C_{i,Plot}; \tag{4}$$

$$C_{i,Plot} = \begin{cases} C_{i,1} \text{ if } P_{i,1} \cdot C_{i,1} > P_{i,2} \cdot C_{i,2} \\ C_{i,2} \text{ if } P_{i,1} \cdot C_{i,1} \le P_{i,2} \cdot C_{i,2} \end{cases}; \; P_{i,Plot} = \frac{R_i}{C_{i,Plot}}. \tag{5}$$

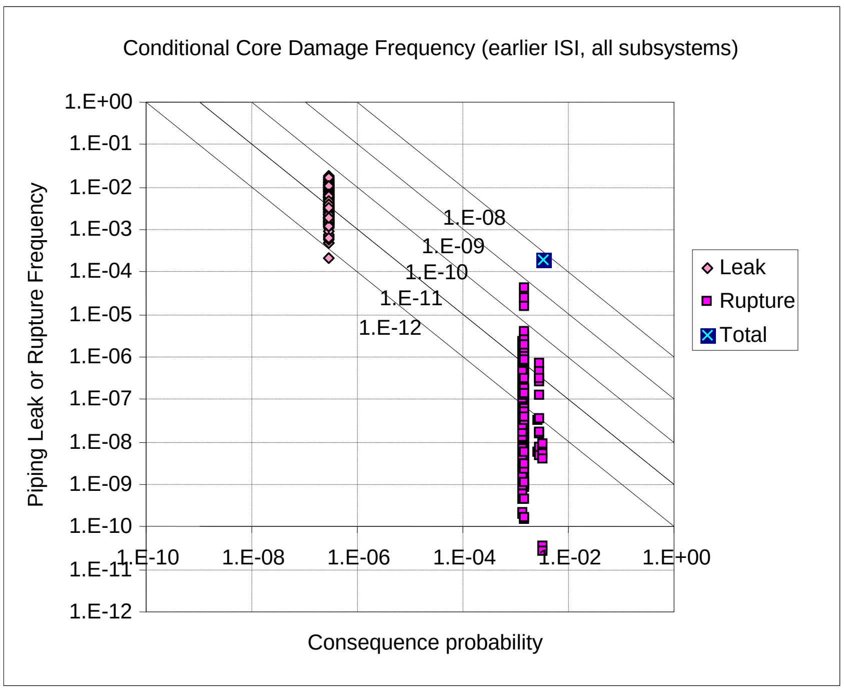

Fig. 3. Conditional Core Damage Frequency per Weld for Various Piping.

In case of D degradation states:

$$C_{i,Plot} = \underset{C_{i,k}}{\arg} \; \underset{k\in(1,D)}{\max} (P_{i,k} \cdot C_{i,k}); \; P_{i,Plot} = \frac{R_i}{C_{i,Plot}}. \tag{6}$$

The total risk R* coordinates C* and P* are proposed to be expressed as follows:

$$C^* = \underset{C_{i,Plot}}{\arg} \; \underset{i\in(1,N)}{\max} C_{i,Plot} \text{ and } P^* = \frac{R^*}{C^*}. \tag{7}$$

The presented general model for risk-informed assessment and result visualization is proposed to be used in order to model failure detection (e.g. inspection) and risk reduction process. The presented modelling method is very useful for risk ranking and decision making purpose [17]. In future it would be interesting to discuss how the results of practical decisions based on such decompositions differ (if at all) from decisions based on various sensitivity and importance measures.

II.B. Decision Making and Risk Management to Minimize Risk

The content of this section is mainly directed towards the investigations of decision-making framework and how general decision-making and inspection process can be applied for risk reduction. In this section, some aspects, that may be considered when discussing a strategy for risk informed in-service inspection and testing, are presented as well.

General Procedure of Decision-Making

The main steps of proposed decision-making procedure (see the following figure) are:

- The analysis of issue and the available data sources;
- The quantitative modelling of considered details;
- The simulation and ranking of alternatives;
- The quantitative selection from alternatives;
- The analysis of decision and final case.

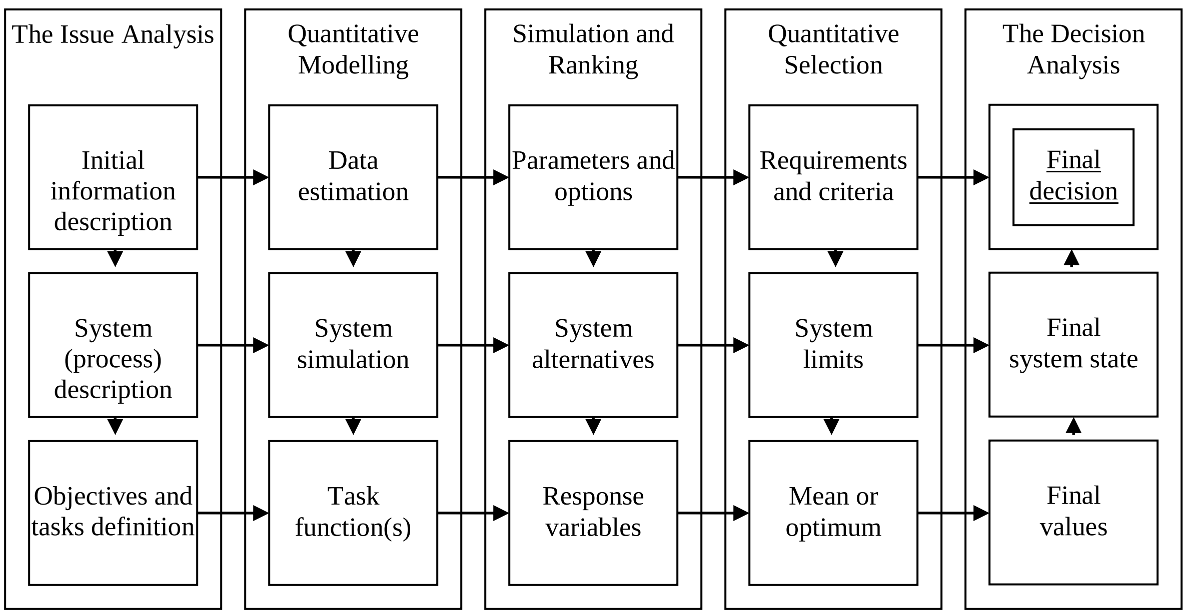

Fig. 4. Decision making procedure.

Considering risk reduction procedure, it can also be treated as general inspection and testing procedure with specific parameters and objective to minimize total risk. The following separate actions of general inspection (including testing) procedure are proposed: Objects selection, Targets specification, Tools qualification, Physical process, Results evaluation, and Experience feedback. Governed by scope, objectives and strategy of inspection and testing, the proposed general inspection procedure can be regarded as a closed loop (see the following figure).

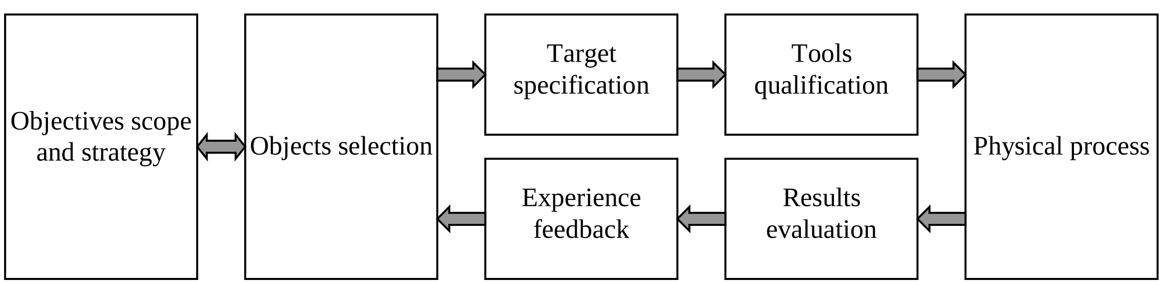

Fig. 5. Elements of a general inspection procedure.

In order to perform a selection of objects (structures, systems and components) for the risk-informed ISI/IST programme and to optimise the testing and inspection frequencies, a more detailed procedure needs to be implemented for such applications. So, the scope of general inspection procedure was considered in order to investigate the possibilities of using the plant specific PSA analyses, minimise the risk and effectively allocate resources for in-service inspection and in-service testing. Therefore, according to the general decision-making and inspection procedure, the general inspection and risk reduction research procedure is proposed and presented in the following figure.

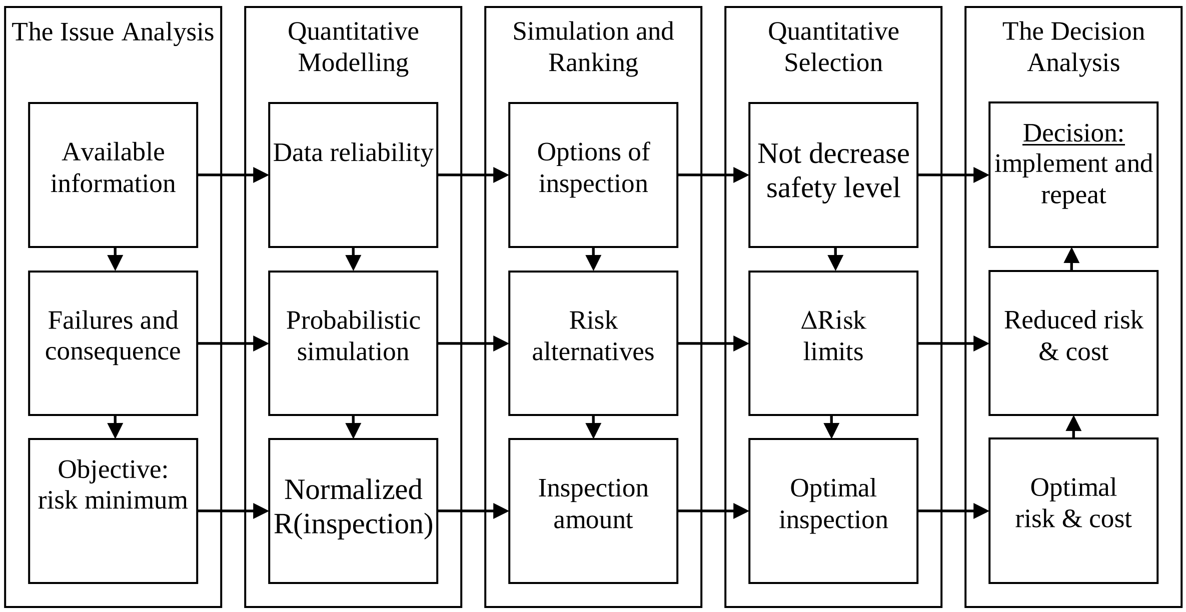

Fig. 6. Inspection and risk reduction research procedure.

When making decisions under uncertainty it is reasonable to use all parameters and related available information, old and/or new, objective or subjective. This is especially true when the consequences of the decisions can have a significant impact, financial or otherwise. If directly applicable data for a specific parameter is sufficiently plentiful, it may be practical to derive an uncertainty distribution from the data using classical statistical approaches.

However, in many cases, a useful assessment of uncertainty cannot be obtained solely from existing performance data, which may be in doubt e.g. if obtained under different operating conditions. In these cases, it is necessary to do the best that one can, integrating such information into a state-of-knowledge probability distribution for the parameter in question. An important basis for information integration in such cases is Bayes' theorem.

In developing the approach of risk-informed decision-making, which takes into account the uncertainties, various decisions have to be made. Firstly, it has to be decided how the numerical results are to be compared with any acceptance guidelines. Furthermore, recognizing that not whole uncertainties are represented in the probability distribution, a decision has to be made on how to handle these issues. The proposed decision is to allow a variety of models and assumption, but require alternates to be considered, e.g. by performing sensitivity analyses to determine whether the decision will change if alternates are used. The decision would then be made by assessing the relative changes of those alternatives' impact on the task function(s).

There is a general agreement that there are substantial uncertainties in any risk measure. Therefore, for most applications, it is left as a general expectation that a decision maker will give less credit to risk values with a larger uncertainty.

III. RISK-INFORMED IN-SERVICE INSPECTION

Traditionally, the inspection and maintenance strategy is deterministically based on the intuitive or quasi-quantitative assessment of safety. The PSA is proposed to be used to support new inspection program and reduce the risk, taking into account the relative risk significance of the components or locations. Once the new ISI program has been defined, the PSA can help to demonstrate that the effect on the overall risk due to program changes can be acceptable.

The main objectives of ISI program, based on the IRI approach, is related to the estimation of the likelihood of severe damage (e.g. core damage) and consequences (e.g. large release of radio nuclides) and application of this information in order to select most risky components and locations for ISI and maintenance. In addition, in such program the following problems presented in the following figure should be solved.

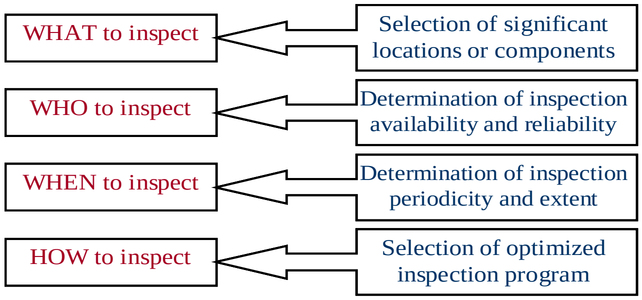

Fig. 7. ISI problems and solutions supported by IRI approach.

Using the integrated risk-informed approach, it is possible to estimate and compare the existing ISI program with set of new possible programs and according to the safety and acceptability requirements and optimization criteria, to suggest the ISI program improvements.

The steps for risk-informed inspection program development were summarised in the following list of tasks:

- Analyze the system and components degradation and failure mechanism;
- Estimate data reliability and the probabilities of degradation and failure P;
- Assess the conditional probabilities of the worst consequence C;
- Using probabilities P and C formulate risk measure R;
- Perform the calculated risk ranking for each part of system;
- Considering the parts with highest risks define a new inspection program;
- Estimate the total risk changes (e.g. risk in the new case - risk in the previous case);
- Estimate costs and positive effects due to the new inspection program;
- According to the results, make recommendations concerning further inspection.

Moreover, the ISI, based on RI approach, should be considered as a living program. Therefore, as part of its implementation process, performance monitoring, periodic update and corrective action program need to be established. Data reliability, probabilistic analysis of degradation and failure occurrence as well as risk measures formulation and estimation.

In general, ISI programs are intended to address all dynamic systems that are subjected to degradation. The incorporation of risk insights in the programs can help inspections to focus on the more important locations. The ISI, based on IRI approach, broadly consists of ranking the elements for inspection according to their risk significance and developing the inspections strategy (frequency, method, size limits, etc.) corresponding to their risk significance. It provides a framework for allocating inspection resources in coast effective manner and helps to focus the inspection activities where they are most needed.

III.A. Risk Categorization and Ranking

Having risk measures or risk reduction estimates for each component or any group in various cases the final assessment phase includes the ranking at different level and selection of alternative RI-ISI programme.

When the risk for all components is determined, a procedure for risk ranking is proposed to be applied in order to define the components with a high risk. The objective of the risk ranking process is to form the components groups with different risk category and focus the inspection activities on the risk significant components in order to decrease the failure frequency or possible undesirable consequences of this failure.

The relative risk categories are proposed to be used for this purpose. They are directly dependent on failure category and consequence category. The failure category is an engineering estimate of likelihood of failure. The consequence category is based on the margin in system capacities to mitigate the component failure and the margin in safety important systems to reach a critical level. The severity of consequence can be used to classify the component failures in different categories of safety significance.

The risk measures of failure allow to focus the inspection on the most critical parts or considered subsystems. If it is important to manage risk significance, the relative risk categories and risk ranking to these categories (or levels) can be used in order to guide the inspection program without separate ranking (according to the categories of failure frequency and consequence). For example, the five relative risk levels are presented in the following table.

Table 1. Risk levels defined according to CCDF

Relatively Very High Risk	$1*10^{-08} \leq$ CCDF
Relatively High Risk	$1*10^{-09} \leq$ CCDF $< 1*10^{-08}$
Relatively Medium Risk	$1*10^{-10} \leq$ CCDF $< 1*10^{-09}$
Relatively Low Risk	$1*10^{-11} \leq$ CCDF $< 1*10^{-10}$
Relatively Very Low Risk	CCDF $< 1*10^{-11}$

These relative risk levels can be defined according to the CCDF values of different welds (see the following figure). The relative risk levels are proposed to specify that the riskiest system part would be included at a very high-risk level. The application of such risk levels is proposed to be related to risk ranking of each subsystem. For example, a different amount of percentage of components from different risk level and subsystem can be selected for inspections. It was noted that selection, according to each subsystem is more conservative, as in this case, the more components should be selected due to the integer number of components in each subsystem.

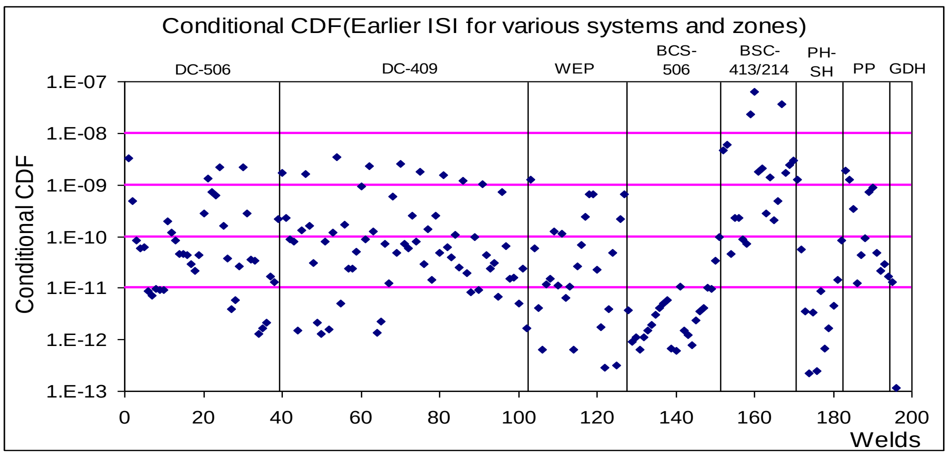

Fig. 8. CCDF values profile for different pipe subsystems.

The risk levels amount and the risk interval, assigned to each level, is the subject of global optimization. Typically, the interval of each risk level is the same size. The equal intervals are more effective for management with relative risk. The number of intervals is directly proportional to the possibilities of inspection management and it is inversely proportional to the complexity and the amount of different combinations.

It is necessary to note that expressions concerning risk levels are used only in a relative sense. In the risk-informed methodologies, it is recognized that there are many variables in calculations and the determination of absolute risk numbers is often not cost effective. Risk-informed inspections are more focused on a systematic determination of relative risks. In this way, facilities, units, systems, equipment, or components can be ranked in relation to relative risk. The relative risk measure serves in order to focus the risk management efforts on the highest ranked risks without looking at the more uncertain absolute values of risk.

III.B. Evaluation Criteria and Requirements for RI Decisions

In order to make a systematic evaluation of selection schemes it is necessary to establish some evaluation criteria. One extreme position is to fix one or more risk values, for instance for new designs in nuclear industry the core damage frequency (CDF) shall be less than 10^{-5} per reactor year, and the large early release of radioactive substances frequency (LERF) shall be less than 10^{-6} per reactor year. Then any distribution of inspections and tests over systems and components is acceptable as long as these targets are reached. Another position is to state that a certain level of inspection effort in terms of amount and cost is adequate, and the effort shall be distributed between components and regions so the best safety benefit will be reached.

The benefit of new inspection program based on the IRI approach should be quantified in measurable values. Such measures changes in nuclear industry can be expressed using total system CDF or the large early release of radioactive substances frequency. The change of conditional CDF (or correspondingly LERF) can be defined as follows:

$$\Delta CDF = CDF(new\ program) - CDF\ (current\ program). \tag{8}$$

The possible new ISI program based on IRI approach is proposed to be based on different locations of inspection, intervals between inspection, and inspection techniques. The additional inspections activities on high-risk locations in separate subsystems causes conditional ΔCDF ≤ 0 and, at the same time, total ΔCDF ≤ 0 and ΔLERF ≤ 0. In addition, if very low risk locations from the ISI-program will be removed, then the total inspection activities and unnecessary radiation exposure to plant personnel can be reduced with possibly only a small increase in ΔCDF and ΔLERF. For different combination of inspection activities, it is possible to evaluate ΔCCDF. In this way, the benefit of the new ISI program can be quantified in relation to the current ISI program.

For example, the update of Lithuanian Nuclear Regulation requires: “In order to avoid the necessity of evacuating the population to distances beyond the limits laid down in the standards for nuclear plant sitting, an effort should be made to ensure that the probability of the worst possible emergency release of radioactive materials specified in the standards does not exceed 10^{-7} per reactor year.” In addition, there is stated, that the target CDF per reactor year is less than 10^{-5}. However, in Lithuania as well as in majority of IAEA member countries, there are still no formal requirements for ΔCCDF, which is evaluated for ISI and supported by PSA.

The NRC has adopted probabilistic safety criteria for assessing changes to plant design or operational practices. In regulatory guides the NRC have been established that these criteria can be used to justify changes to a plant’s licensing basis, taking into consideration the impact on plant risk, to assess when changes in plant risk might be acceptable. Based on mentioned practice, the following acceptable guidance for changes in risk measures is proposed:

- If ΔCDF ≤ 0 or ΔLERF ≤ 0, then the change is acceptable.
- If ΔCDF > 0, then change should be 10 times smaller than the absolute CDF value
  (similar criteria can be used for LERF).

The second statement discussed above differs from NRC guidelines, in order to have more conservative acceptance criterion, which is based not on the absolute measure of risk. In spite of the chosen PSA procedure, there will always be a certain degree of uncertainty in the absolute CDF values. The alternative criterion, based on relative risk values, is proposed to be expressed as follows:

$$\Delta CDF/CDF < 1/10. \tag{9}$$

This means that the increase of CDF in a relative sense should be small or negative. In practice, a combination of absolute and relative acceptance criteria is very suitable for ranking. A criterion, based on an absolute measure of the CDF, can still be desirable as a general objective to reach a sufficiently small total CDF for the plant. In general, the used IRI approach is a systematic evaluation approach, which made possible to satisfy defined deterministic safety requirements and probabilistic risk-informed criteria as for effective decision-making purpose these requirements had been integrated into the general system.

The new ISI program, based on IRI approach, can be regarded as a very good inspection program where conditional CDF for inspected system, total CDF together with number of future inspections, and radiation exposure are reduced compared to the currently planned inspection program. The optimization of the inspection program is also based on the IRI approach and is discussed in more detail below.

III.C. New Inspection Program Optimization

The expectations on the benefit of the integrated risk-informed approach may be dependent on end-user standpoint. Operators may primarily think of the reduction of cost, whereas regulators may think of an improvement of safety and both of them may be interested in a more effective use of their limited resources.

When changing from the traditional inspection scheme to the risk-informed scheme, the inspection effort is redistributed among the systems and components. If the total inspection effort and extent is kept constant, the benefit will primarily be on the safety side. If the change is made in a risk-neutral manner i.e. risk measured by PSA, the benefit will predominantly be an economic one. It is important to keep the appropriate balance and in this regard, the regulatory aspects to assess this balance should be clearly set up.

The IRI approach (like presented in regulatory guide 1.178 [16]) involves a systematic and quantitative risk consideration for components, subsystems, and systems. Risk assessment is used to address the severity of consequences and the likelihood of degradation. The combination of the different these two parameters allow the determination of the risk significance of the different components (e.g. pipe welds) to be considered for the inspection programs.

In addition to others RI-ISI approaches the specific formalisation and relation between risk and inspection activities is proposed to help determine the adequate and optimum inspection program. The following target function for risk and inspection activities optimization can be proposed:

$$F_{IR}(I) = \sqrt{I_N^2(Activities\ parameters) + R_N^2(Risk\ parameters)}; \tag{10}$$

where I_N and R_N is normalized measures of inspection activities and risk (correspondingly to normalized ISI amount and normalized CCDF). The notation I represents the set of parameters specific to inspection program.

Then the task of optimization, developing new ISI program, is proposed to be defined by a minimization of this target function F_{IR} and satisfying the requirements and criteria presented above. The optimal ISI program is proposed to be defined as follows:

$$I^* = \arg \min_{\substack{p_r \in (0,\dots,T), \\ e_r \in (0\%,\dots,100\%), \\ r \in (1,2,\dots,L)}} (F_{IR}(I(p_r, e_r))); \tag{11}$$

where $I(p_r, e_r)$ is interpreted as ISI program with the following parameters: p_r – period between inspections for risk level r and e_r – extent of each inspection for risk level r. The highest risk level index r = 1. The amount of risk levels is denoted as L. In general, the minimization should be performed according to all possible p_r and e_r in each risk level r.

The number of such combinations can be very huge. In order to decrease the number of unnecessary combinations, the additional heuristic conditions can be used, e.g. the proposed following conditions:

$$p_r \le p_{r+1};\ e_r \ge e_{r+1};\ \ p_r \ne 0;\ p_r \ne T;\ e_r \ne 0. \tag{12}$$

These conditions, where $r \in (1,2,...,L-1)$, mean that for higher risk level r the period between inspection is shorter and the extent of inspections is larger than for lower risk level r+1 and also there is excluded some unacceptable cases (e.g. no inspection for each risk level). Also, in order to decrease the combinations only a few values of defined extent can be used, for example see following figure, where $e_r \in (100\%, 75\%, 50\%, 25\%)$.

If there are tools for risk and inspection estimation, then the finding of the optimized inspection program is proposed to be done by expert or using special developed software. The expert judgment is usually based on the rules that are more heuristic and less demonstrable. The automatic optimization typically uses such conditions that are more formal and require less recourses, so there are more possibilities to find optimal solutions and to confirm that with given model it is the best. Still it is important to remember that there are various limitations with the use of models (some of which have deeply embedded and not always transparent task functions or expert judgments).

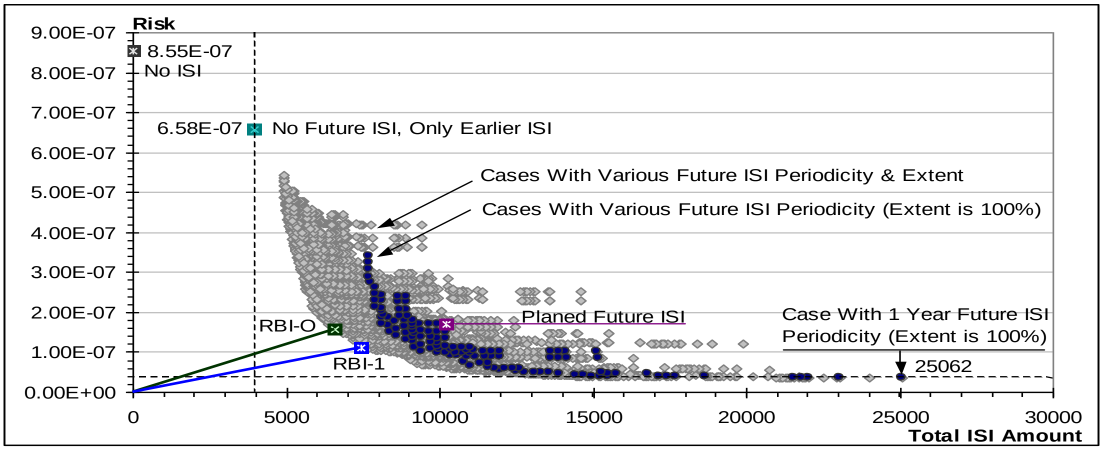

Fig. 9. The optimization of inspection program.

The reduction of risk can even be investigated as separate task for which various current projects, like project NUGENIA+ part REDUCE (Justification of Risk Reduction through In-Service Inspection) are initiated. As another example, the above figure shows features and benefits of the possible ISI programs, which were investigated in a pilot study IRBIS and its update performed for Ignalina NPP [17]. The program RBI-1, defined by expert, is attractive because both the risk of conditional core damage and the number of total inspections (and radiation exposure) are reduced. In this figure there are also presented the ISI programs based on various inspection parameters. The selections of parameters by expert do not necessarily result in absolute optimum program. This is only example of parameter combination that can serve for finding an approximate minimum value. According to the experiments performed with computer and target function for optimal ISI program, it is possible to find the most optimal program from the calculated variations (see RBI-O program in the above given figure).

IV. CONCLUSIONS

During recent years, both the nuclear industry and nuclear regulatory bodies have recognized that probabilistic risk analysis has evolved to the point that it can be used increasingly as a tool in decision making and risk minimization.

As summarized in ASAMPSA_E project [3], from the IRIDM and PSA point of view, it is adequate to mention that PSA methods are flexible enough to provide the decision maker with almost all technical values which he might ask for risk minimization. This covers information about the plant (e.g. frequency of various plant damage states), environmental data (e.g. frequency of different source terms) and health effects (e.g. frequency of radiation exposure to the public). It is nevertheless prudent that decision makers are aware of the strengths and weaknesses of PSA and seek support of PSA experts, especially to discuss whether the PSA status is consistent with its application to support decision-making.

Typical in-service inspection can be routinely carried out by the utilities in order to detect and characterise possible material degradation in a timely way. It is clear that by performing ISI, utilities are acting effectively in order to reduce the *likelihood of failure* of these components. Furthermore, it is clear that the selection of systems and components with consideration for their *consequences of failure* has a direct bearing on the effectiveness of ISI programmes, in terms of their contribution to overall plant safety.

The application of ISI is entirely consistent mainly with the deterministically based philosophy of defence in depth. However, ISI programmes carried out to current requirements essentially reflect qualitative engineering judgements. This means that without the benefit of quantitatively based risk-informed insights, a disproportionate effort may be expended on the inspection of certain items that do not contribute significantly to the overall plant risk. Equally, there is a possibility that certain risk significant items may not be covered in the inspection programme. The benefit of the risk-informed approach to ISI is that it increases existing engineering judgement and experience in a way that helps to refocus ISI according to the assessed contribution.

The uses of risk information in the optimization of the ISI program help to focus better and allocate limited resources. In addition, one of the outcomes of the optimization process may be a reduction in overall operational and maintenance costs while maintaining a high level of safety.

The benefit with respect to safety will also depend on the appropriate balance between the given weight to risk assessment and defence-in-depth, respectively, when selecting the items for the inspection. A risk-informed selection can suggest that 90% or more of the safety important components should be excluded from the inspection, because they are classified so as to have a low failure probability and medium or low consequences of failure. On the other hand, the deterministic safety principle *defence-in-depth* requires the integrity of the locations, which are safety important to the plant.

Apart from these questions of balances, at any rate, the risk-informed approach provides possibilities to improve the effectiveness of ISI. These are:

- The risk connected with the failure of components can be better assessed, and thus parts of components that deserve special attention can be better identified.
- The examinations can be targeted to the relevant damage mechanisms, and the maintenance of systems can be directed accordingly.
- Faster feedback from experience and integration of research findings is enabled to timely modify the inspection and maintenance programmes.
- The risk-informed approach enables a more unified concept of routine inspection, testing and ageing monitoring.

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