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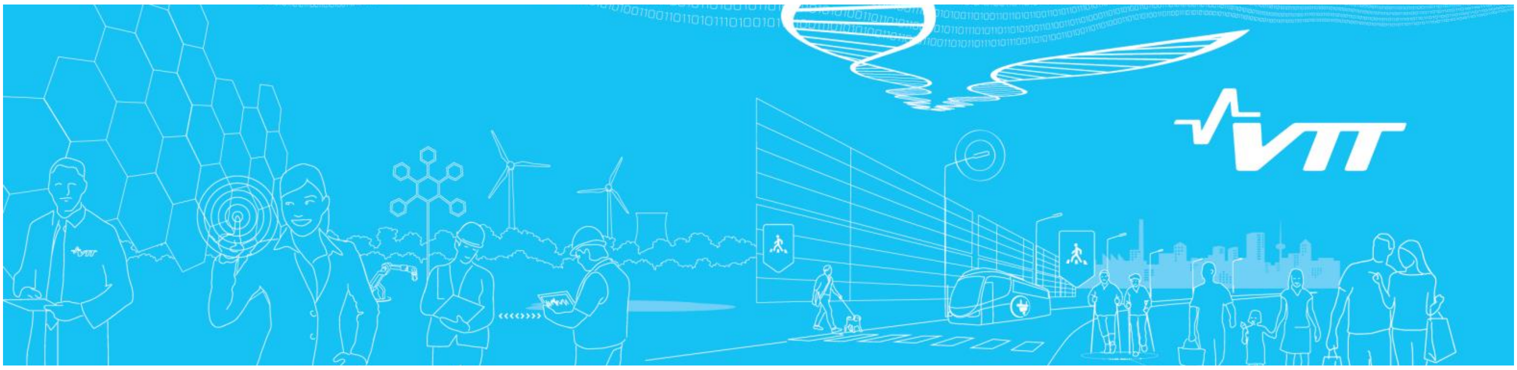

RESEARCH REPORT

VTT-R-04536-15

Connection between PRA and RI-ISI analyses

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Summary

In-service inspections are applied to safety important pipe components in nuclear power plants (NPPs) to ensure their reliability. In Finland, in-service-inspections are planned carefully so that the risk of nuclear accident, employees' exposure to radiation and the cost of inspections are in balance and within acceptable limits. This approach is called risk informed in-service-inspection (RI-ISI).

Probabilistic risk assessment (PRA) is used to calculate the quantitative risk of nuclear accident and analyse the importance of different systems and components. PRA's main purpose is to support risk informed decision making. PRA also supports RI-ISI analyses so that it quantifies the consequences of pipe failures and provides risk importance measures for pipe components.

The purpose of this report is to study how PRA and RI-ISI analyses could support each other better. New development ideas include automatic piping failure consequence calculation in PRA software, extending PRA model to account for piping in more detail and developing PRA's time dependent analysis. It would be possible to develop an integrated software tool for RI-ISI and PRA. It could be beneficial to update PRA and RI-ISI simultaneously, especially if the analyses were more integrated. Uncertainty analysis could also be performed in RI-ISI in the same way as in PRA.

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Contents

1. Introduction

In-service inspections (ISIs) are applied to safety important pipe components in nuclear power plants (NPPs) to ensure their reliability. In Finland, in-service inspections are planned carefully so that the risk of nuclear accident, employees' exposure to radiation and the cost of inspections are in balance and within acceptable limits. This approach is called risk informed in-service inspection (RI-ISI) [1].

Probabilistic risk assessment (PRA) is used to calculate the quantitative risk of nuclear accident and to analyse the importance of different systems and components [2]. PRA's main purpose is to support risk-informed decision making. PRA also supports RI-ISI analyses so that it quantifies the consequences of pipe failures and provides risk importance measures for pipe components. The purpose of this report is to study how PRA and RI-ISI analyses could support each other better.

Figure 1 in the following illustrates the connection between RI-ISI and PRA with a simplified flow chart. The failure modes and effects analysis (FMEA) of piping is basic information needed in both RI-ISI and PRA. RI-ISI analyses obtain consequences of pipe failures, and possibly other risk importance measures from PRA model. Piping failure probability analyses used for RI-ISI might also be utilised in PRA.

The report is structured as follows. Chapters 2 and 3 present briefly the basics of RI-ISI and PRA. The connection between RI-ISI and PRA is discussed in Chapter 4. Chapter 5 presents a simple case example. Development ideas to improve the connection between RI-ISI and PRA are presented in Chapter 6, and Chapter 7 concludes the study.

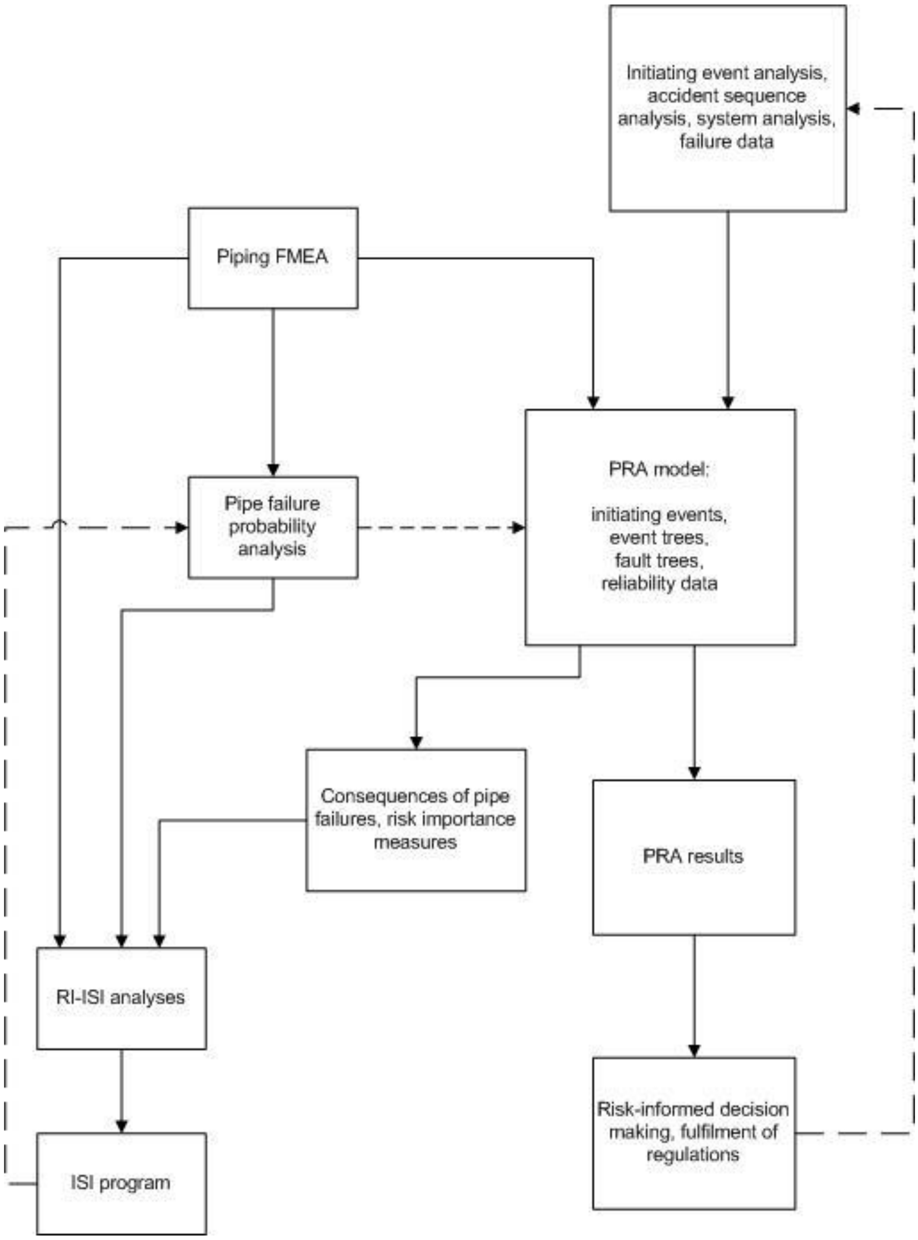

Figure 1. Simplified flow chart of RI-ISI and PRA and their connections.

2. Risk informed in-service inspections

RI-ISI aims to optimize piping component inspections so that the safety of the NPP is as high as possible and the cost of the inspections is as low as possible. The idea is that most inspections are targeted to systems with highest importance with regard to risk. When inspection program is changed, RI-ISI analyses are used to show that the core damage frequency does not increase, and that the cost or employees' exposure to radiation is reduced. [1]

The probability of the failure and the consequence of the failure are the main measures used when deciding whether a piping component should be inspected and how often. The failure probabilities can be estimated based on degradation mechanisms, operating experience and structural analyses. For structural analysis, probabilistic fracture mechanics (PFM) analysis can be used [3], and several computer codes exist, including probabilistic VTTBESIT [4, 5].

Based on consequences and failure probabilities, piping components are ranked or categorised. A risk matrix is often used to categorise the piping components. Table 1 presents a simple example of a risk matrix for RI-ISI. The piping components are divided into five inspection categories: A, B, C, D and E. The piping components in category A are inspected the most, and the piping components in E the least.

Table 1. A risk matrix.

		Consequence		
		low	medium	high
Probability of failure	high	C	B	A
	medium	D	C	B
	low	E	D	C

3. Probabilistic risk assessment

PRA [2] is used at NPPs to support decision making and fulfil regulatory requirements. PRA analyses accident sequences leading to core damage (level 1 PRA) and radioactive releases (level 2 PRA), and calculates the core damage frequency and frequencies of source terms (radioactive release categories). Most important initiating events, systems and components with regard to the risk can be identified using PRA. That information can be utilised in identifying systems' weaknesses, allocating resources to maintenance activities, prioritising components for testing and optimizing test intervals.

The state-of-the-art methods in PRA are event trees and fault trees. An event tree represents how an accident can evolve from an initiating event via failures of safety systems to a consequence, e.g. core damage. A fault tree represents which events can cause the analysed system to fail. Fault trees are linked to branching points in event trees. From fault trees, minimal cut sets are solved. Minimal cut sets are minimal combinations of events that can cause the top event, e.g. system failure. Probabilistic assessment is performed based on minimal cut sets and reliability data of components.

4. RI-ISI and PRA

For RI-ISI analyses, the failure probabilities of piping components and the consequences of piping failures need to be estimated [1]. Typical consequence measures are the conditional core damage probability/frequency (CCDP/CCDF) and the conditional large early release probability/frequency (CLERP/CLERF). CCDP/CCDF is usually more convenient from the computational point of view and it can always be calculated from the PRA model of the NPP.

A failure of a piping component can, for example, cause disturbance in the plant's usage or failure of a system. All piping components are not separated in PRA. Typically, one initiating event or basic event is used to represent the failures of piping components and other events with similar consequences. Failures of safety system pipes not causing initiating events do usually not appear in PRA at all [6]. Their consequences are often analysed using other "surrogate" basic events, e.g. pump and valve failures, which are included in the PRA model. The consequences of initiating events and basic events in PRA may represent the consequences of piping failures only roughly, and therefore, more accurate consequence analyses may be needed in RI-ISI analyses.

An important result in PRA are risk importance measure values of components and systems. Importance analysis is also a significant part of RI-ISI, but the importances of piping components cannot be directly calculated in PRA, because different piping components do not have separate basic events. Instead, the importance analysis of RI-ISI is performed separately. Fussell-Vesely, risk increase factor, risk decrease factor and Birnbaum importance are commonly used importance measures [7]. Reference [8] suggests that the differential importance measure should be used for RI-ISI.

5. Simple example case

A simple model with two loss of coolant accident (LOCA) scenarios is used to illustrate the connection between PRA and RI-ISI. The PRA model contains two initiating events, large LOCA and small LOCA, and corresponding event trees. The event trees are presented in Figures 2 and 3.

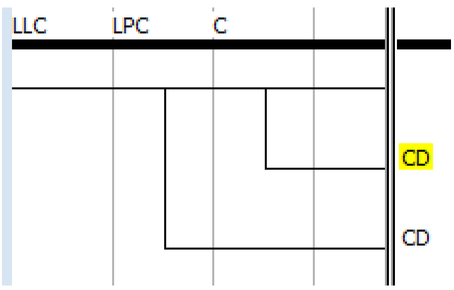

Figure 2. Event tree for large LOCA.

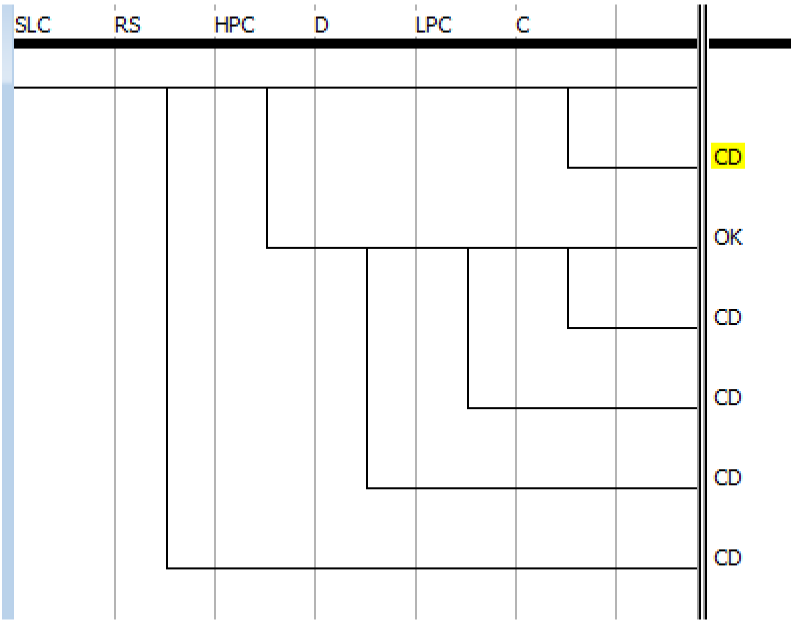

Figure 3. Event tree for small LOCA.

The event trees could correspond to a pressurized water reactor NPP, but they are very simplified and do not represent any actual NPP. In the case of large LOCA (LLC), core damage (CD) occurs if low pressure cooling (LPC) or recirculation cooling (C) does not work. In the case of small LOCA (SLC), core damage (CD) occurs if reactor scram (RS) does not work. If reactor scram works, core damage can be avoided if high pressure cooling (HPC) and recirculation cooling (C) work, or if depressurisation system (D), low pressure cooling (LPC) or recirculation cooling work. Failure probabilities for the safety systems are presented in Table 2.

Table 2. Failure probabilities of safety systems.

System	Probability of failure
Low pressure cooling system	1E-4
Recirculation cooling system	1E-4
Reactor scram system	1E-7
High pressure cooling system	1E-4
Depressurisation system	1E-2

Failure of piping component S with small diameter in the primary system is assumed to cause small LOCA. The conditional core damage probability is:

$$1 - (1 - 10^{-7}) \cdot (1 - 10^{-4}) \cdot (1 - 10^{-4}) - (1 - 10^{-7}) \cdot 10^{-4} \cdot (1 - 10^{-2}) \cdot (1 - 10^{-4}) \cdot (1 - 10^{-4})$$

$$= 1.01 \cdot 10^{-4}.$$

Failure of piping component L with large diameter in the primary system is assumed to cause small LOCA with probability of 0.5 and large LOCA with probability of 0.5. The conditional core damage probability is:

$$0.5 \cdot 1.01 \cdot 10^{-4} + 0.5 \cdot (1 - (1 - 10^{-4}) \cdot (1 - 10^{-4})) = 1.51 \cdot 10^{-4}.$$

The average yearly failure probability of piping component S is 1E-5, and the average yearly failure probability of piping component L is 2E-6. In the classification approach used in [9], both components would have high consequence of failure, and the failure probability of S would be medium, while the failure probability of L would be low. Component S should be inspected every 3 years and L should be inspected every 5 years.

6. Development ideas

6.1 Extending PRA model

The integration of PRA and RI-ISI analyses would improve if the PRA model contained the pipe failures that are included in RI-ISI. However, a straightforward extension could complicate the PRA model and calculations too much. PRA models include initiating events, such as LOCA, which can be caused by several different pipe failures. Only a single frequency (possibly with uncertainty distribution) is needed for an initiating event in PRA analyses. PRA calculations would not benefit from dividing initiating events to smaller parts. In addition, pipe failures that can cause safety systems to fail are often excluded from PRA because their contribution is very small.

From a RI-ISI point of view, it could be practical to have the same failure events in the PRA model. That way, the consequence measures could directly be obtained from the PRA model without separate considerations.

In PRA documentation, the used initiating event frequencies need to be justified. Having the frequencies of contributing pipe failures counted separately could improve the justification. This would also increase the traceability in PRA.

It would be possible to develop initiating event (and basic event) modules in PRA software. A module could be used as a single entity in calculations, or the user could decide to open the module and separate the sub-events belonging to the module. In this manner, pipe failures analysed in RI-ISI could be included in the PRA model without complicating the normal PRA calculations.

In the example case, initiating event small LOCA could be replaced by a fault tree presented in Figure 4. Components S1, S2 and S3 correspond to the previously analysed component type S, and components L1, L2, L3 and L4 correspond to the component type L. Event SLOC_Oth covers other causes for small LOCA. Basic events L1_SLOC, L2_SLOC, L3_SLOC and L4_SLOC represent the conditional probability that small LOCA occurs if the corresponding component fails, as the failure of L type component might also cause large LOCA instead. In the implementation of an initiating event module like this, building of the fault tree could easily be automated, e.g. using hazard modelling feature of FinPSA software [10].

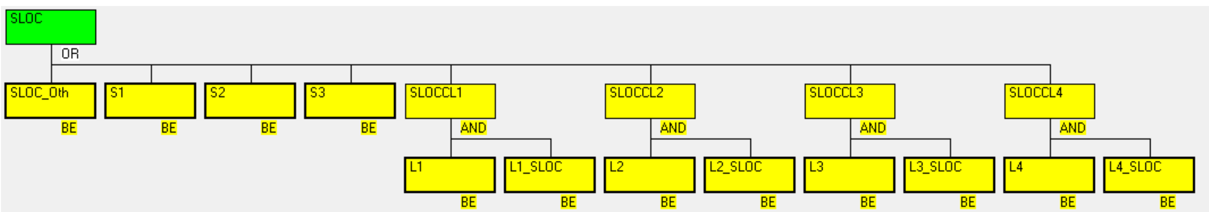

Figure 4. Fault tree for small LOCA.

Initiating events and basic events of PRA do not usually capture the consequences of all piping failures accurately. This is acceptable because conservative results are usually adequate in PRA and uncertainties are high anyway. In RI-ISI analyses, however, more accurate pipe failure consequences are preferred. Having more detailed PRA model with more accurate piping failure modelling and all RI-ISI scope piping components included would be beneficial for RI-ISI. But again, that could complicate the PRA model too much. It would be possible to build different configurations of PRA model so that different versions would be used for different purposes. PRA software include features for such configuration management, e.g. house events, boundary conditions and inactivation of event trees.

6.2 Automatic consequence calculation

CCDP and CCDF are most often used as consequence measures in RI-ISI. In typical PRA software, these measures have to be calculated separately for each component by setting the failure frequency/probability to 1 or derived from other risk importance measures. Many other risk importance measures are already calculated automatically for all basic events. The computation of CCDP and CCDF could be automated similarly. However, this simple approach would work only if there was one initiating event or basic event in the model corresponding to each piping component. This is not always the case, such as in the example of the previous chapter.

A more advanced feature for CCDP and CCDF calculation would be beneficial. In such feature, the user should be able to define piping related events for which to calculate the consequence measures, and it should be possible to assign multiple initiating events or basic events to a single piping component and define conditional probabilities, such as in the example of the previous chapter. Using such feature, CCDPs or CCDFs of piping components could be listed for RI-ISI analyses.

The most convenient way to calculate the CCDP of an initiating event would probably be to calculate the total frequency of the minimal cut sets [11] including the initiating event and divide it by the initiating event frequency. The CCDF of a basic event could be calculated following the same principle. If the CCDP/CCDF needed to be calculated for a group of multiple events, the same computation principle could also be extended.

If CCDPs of initiating events and CCDFs of basic events are calculated, it can be a problem that a CCDP and a CCDF cannot be very well compared to each other. One approach to avoid this problem is to transform the CCDFs into CCDPs in the following way [12]:

$$CCDP = 1 - e^{-CCDF \cdot t},$$

where t is the time the piping failure is in effect. This transformation could be implemented in the PRA software. Determination of parameter t in the reliability data base would be required.

Computation of the conditional large early release probability/frequency (CLERP/CLERF) is in most cases less straightforward than the computation of CCDP/CCDF. Computation of CLERP/CLERF depends on how the level 2 PRA (probabilistic analysis of severe accidents) is implemented and integrated to level 1 PRA (analysis of accidents leading to core damage). Methods used in the level 2 PRA vary a lot, and the integration of the PRA levels 1 and 2 is in most cases not tight. VTT develops FinPSA software [10] that provides dynamic containment event trees for level 2 modelling. It could be studied which would be the best way to calculate CLERP/CLERF in FinPSA.

6.3 Loss of coolant accident frequency estimation

Piping component failures contribute significantly to LOCA frequencies, and they are taken into account in the estimation of LOCA frequencies. However, the estimates are mainly based on expert judgement [13]. PFM analyses utilised more in RI-ISI are typically considered as supporting information only, even though they produce piping failure frequencies. PFM analyses are not directly used because they are considered too simplified, or at least, they have not been validated enough. In the future, if PFM analyses were improved and validated comprehensively, the contribution of piping to LOCA frequencies could directly be obtained from them. Another future development need is to produce a standard for a commonly applicable PFM analysis procedure.

6.4 Time dependent analysis

PFM analyses can compute time dependent probabilities for pipe failures [3], e.g. to see how ageing and inspections affect the probabilities. On the other hand, ageing of components is not included in PRA calculations. The frequencies and probabilities in PRA are typically just updated annually, and the development of the plant risk in the future is not analysed comprehensively. A possibility to calculate the expected time dependent core damage frequency for the plant's whole lifetime would be beneficial and would increase the trust for long term safety. It could also facilitate license renewals. In addition, it has to be noticed that some components excluded from a PRA model can become significant due to ageing.

Possibilities to model ageing in PRA have been studied [14, 15], but have not been done much in practise except for test cases. The interest has been moderate at best, and modelling of ageing is not a regulatory requirement.

Some time dependent failure probabilities can already be taken into account in PRA calculations. For example, FinPSA software [10] can calculate the time dependent core damage frequency that depends on the test intervals of the components. The main challenge in considering ageing is to determine the time dependent degradation/failure probabilities.

For piping components, time dependent failure frequencies can be calculated using the VTTBESIT code [4, 5]. If PFM estimates were considered accurate enough, time dependent initiating event frequencies could be computed by summing up the frequencies of piping failures and other contributors.

From software development point of view, FinPSA could be developed so that it could handle time dependent failure frequencies/probabilities. It would be straightforward just to specify a set of frequencies at chosen time points. FinPSA could then compute the time dependent core damage frequency curve based on the given time points. FinPSA could be developed to support the output format of VTTBESIT. More tight integration of FinPSA and VTTBESIT could also be possible, and it should be decided if the time dependent initiating event frequencies would be calculated with VTTBESIT, with FinPSA or otherwise.

Furthermore, time dependent PRA results, e.g. time dependent conditional core damage probabilities, should also be taken into account in RI-ISI analyses.

6.5 Uncertainty analysis

Uncertainty analysis is an important part of a comprehensive PRA, but in RI-ISI, uncertainties are not taken into account similarly. Uncertainty distributions for conditional core damage probabilities can be calculated in PRA. It should also be possible to specify uncertainty distributions for the frequencies/probabilities of piping component failures. Then, uncertainty analysis could be performed for RI-ISI computations e.g. using simple Monte Carlo approach. For example, an uncertainty distribution could be calculated for the change in core damage frequency when changing the inspection program. The uncertainty analysis feature of PRA software could possibly be utilised, or the analysis could be performed using a separate tool.

6.6 Common analysis software

Since RI-ISI analyses use information from PRA and the analyses may be even more interconnected in the future, having a common software tool for RI-ISI and PRA would be a beneficial option. For example, VTT's FinPSA and VTTBESIT could form a basis for the development of such a tool. Ideally, the consequence values of piping failures would come automatically from the PRA model to the RI-ISI analysis, and pipe failure probability calculations and the chosen in-service-inspection program would automatically affect the input data of PRA. The integration would enable the direct use of PRA features, such as importance measures and uncertainty analysis, in RI-ISI analyses.

6.7 Updating analyses

PRA and RI-ISI are usually developed and updated separately, even though the PRA results can affect RI-ISI analyses. The analyses could be brought closer so that they could be updated simultaneously and kept consistent in a better way. Integrated software support could have benefits also in this area.

7. Conclusions

This report addresses the connection between RI-ISI and PRA. The current situation and development ideas are presented. One possibility to bring RI-ISI and PRA closer would be to develop a software support for better integration. Even common analysis software is a possibility. It would be beneficial to developed automatic piping failure consequence calculator in PRA software. PRA models could also be extended to account for components analysed in RI-ISI, and uncertainty analysis similar to PRA could be developed for RI-ISI. On the other hand, structural analyses performed for RI-ISI could support time dependent analysis in PRA. RI-ISI and PRA should also be updated simultaneously. All the development possibilities would benefit from integrated software support.

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