Handling of risks of events with low probability and severe consequences at a nuclear power plant

Criteria and methodology for presentation

Master of Science Thesis in the Nuclear Engineering program

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Division of Nuclear Engineering
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ABSTRACT

Since the accident in the Japanese nuclear power plant Fukushima Dai-ichi the discussion on severe nuclear accidents has increased. Much interest has been directed towards severe nuclear accident prevention and mitigation, which both are needed in order to lower the risk of a nuclear accident and ensure public safety. This report describes a study of civil nuclear related risks of events with very low probability but severe consequences. The study aims to create a concept of a methodology on how to include low probability severe consequence risks in a risk management process; focusing on the economic consequence for the operator and owner.

The studied risk management is a part of E.ON Kärnkraft Sverige AB's (EKS) risk management process. EKS experienced an interest to expand their risk management process to include risks with low probability and severe consequences and in this report a methodology on how this can be done is presented. The methodology has been created from studying the risk management process focusing on the tree reactors at the nuclear power plant Oskarshamn Kraft Grupp (OKG) outside Oskarshamn. In order to understand the included risks as well as the context and concept of the risk management process several areas needed to be studied. The project included studies on severe accident mitigation and prevention, important severe accident sequences, possible economic consequences, legal and insurance framework within the Swedish nuclear industry, and the EKS and OKG risk management process.

The methodology focuses on the severe consequences of the risks and assumes that these may be initiated by a number of accident sequences. The consequences of the sequences are described using three parameters: radioactive release, property damage and business interruption, which are connected to an economic impact on the owner and operator. The analyses of these risks should provide risk assessment material for further steps in the risk management process.

Key words: Nuclear safety, risk management, methodology, economic impact

Hantering av risker med låg sannolikhet och allvarliga konsekvenser på ett kärnkraftverk
– Kriterier och metodik för presentation
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Examensarbete inom masterprogrammet Nuclear Engineering

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SAMMANFATTNING

Efter olyckan i det japanska kärnkraftverk Fukushima Dai-ichi har diskussionen kring allvarliga kärnkraftsolyckor ökat. Mycket intresse har riktats mot förebyggande och lindrande åtgärder vid allvarliga olyckor. Olycksförebyggande och skadebegränsande åtgärder behövs för att minska risken för kärnkraftsolyckor och därigenom öka allmänhetens säkerhet. Denna rapport beskriver en studie av kärnkraftsrelaterade risker med mycket låg sannolikhet men allvarliga konsekvenser med fokus på de ekonomiska konsekvenserna för operatören och ägaren av en kärnkraftsreaktor. Studien syftar till att skapa ett koncept av en metodik för hur risker med låg sannolikhet och allvarliga konsekvenser kan inkluderas i en riskhanteringsprocess.

Den studerade riskhanteringsprocessen är en del av E.ON Kärnkraft Sverige AB:s (EKS) riskhanteringsprocess och där det finns ett intresse att utöka sin riskhanteringsprocess för att till en högre grad innefatta risker med låg sannolikhet och allvarliga konsekvenser. Genom en studie av bland annat EKS riskhanteringsprocess har en metod för detta skapas. Metoden fokuserar på de tre reaktorerna på kärnkraftverket Oskarshamn Kraft Grupp (OKG) utanför Oskarshamn. För att skapa förståelse kring riskerna med låg sannolikhet och allvarliga konsekvens samt riskhanteringsprocessen krävdes att flera studieområden inkluderades i projektet. Projektet omfattade studier av förebyggande åtgärder och konsekvenslindring vid allvarliga kärnkraftsolyckor, sekvenser vid allvarliga kärnkraftsolyckor, ekonomiska följder av allvarliga kärnkraftsolyckor, juridisk och försäkringsmässig struktur inom den svenska kärnkraftsindustrin samt EKS och OKG:s riskhanteringsprocesser.

Metoden fokuserar på dessa riskers eventuella konsekvenser och utgår från ett antal olyckssekvenser kopplade till reaktorhaveri. Konsekvenserna från olyckssekvenser beskrivs med hjälp av tre parametrar: radioaktiva utsläpp, egendomsskador och produktionsbortfall. Parametrarna är kopplade till ekonomiska konsekvenser för ägaren och operatören för kärnkraftverket. Metoden bör resultera i informationsmaterial för riskbedömning i riskhanteringsprocessens efterföljande steg.

Nyckelord: Kärnkraftssäkerhet, risk management, metodik, ekonomisk påverkan

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LIST OF ABBREVIATIONS

APRI	Accident Phenomena of Risk Importance
BWR	Boiling water reactor
DCH	Direct Containment Heating
EKS	E.ON Kärnkraft Sverige AB
ESV	E.ON Sverige AB
HPME	High Pressure Melt Ejection
IAEA	International Atomic Energy Agency
INES	International Nuclear Event Scale
MCCI	Molten Core Concrete Interaction
OKG	Oskarshamn Kraftgrupp
O1	Oskarshamn 1
O2	Oskarshamn 2
O3	Oskarshamn 3
PSA	Probabilistic Safety Assessment
PWR	Pressurized water reactor
RAF	Riskbedömning av fenomen
RCPB	Reactor Coolant Pressure Boundary
ROAAM	Risk Oriented Accident Analysis Methodology
SAR	Safety Analysis Report
SAMÖ/KKÖ	Samverkansövning /Kärnkraftsövning
SSM	Strålsäkerhetsmyndigheten
TPL	Third Party Liability
TMI	Three Mile Island

1. INTRODUCTION

The Swedish and global nuclear industry actors are well aware of the challenges in operating safe nuclear power. Through organisations such as IAEA (International Atomic Energy Agency) safety issues are lifted and investigated aiming to inform on and increase safe operation performance. After the accident in the Japanese nuclear power plant Fukushima Dai-ichi the discussion on severe nuclear accidents has increased. As a result of the accident EU issued assessment on all nuclear reactors in the European Union focusing on nuclear safety. The assessment involved stress tests, which aimed to investigate the robustness and safety in case of extreme natural events, e.g. earthquakes or flooding. The stress tests showed that safety levels of all nuclear reactors were high and, even though almost all needed improvements, no reactors needed to be put out if operation.(1) Event though the stress tests' main focus was natural events the overall interest on severe nuclear accidents prevention and mitigation has increased.

In Sweden the nuclear reactor safety is monitored by the Swedish government in close cooperation with the nuclear power plant operators and owners. In practice the governmental representation is executed through the authority SSM (Swedish Radiation Safety Authority, Strålsäkerhetsmyndigheten). SSM provide regulations and requirements which the power plant operator is obliged to follow. These are monitored by SSM to ensure a high level of nuclear safety and radiation protection.(2) In order start and run a nuclear power plant the operator need to hand in a SAR (Safety analysis report) in which the power plant design and safety is demonstrated.

The operators and owners need to have control over their risks, both technical and other, and this is executed both by deterministic and probabilistic risk analysis but also using a risk management approach. When creating the SAR the nuclear power operators perform analyses on the probability and consequences of different risks of events, among which some have very low probability but severe consequences. Risks with low probability may be regarded as acceptable, if however the risks involve extreme consequences, they may still be a non-neglectable threat both to the public, in terms of radioactive release, and to the operator and owner, in terms of large economic impacts. All types of risks, including risks with low probability and severe consequence, need to identified, analysed, evaluated, and possibly treated.

E.ON Kärnkraft Sverige AB, henceforth EKS, is a part of the German energy company E.ON, which has a business focus on the electricity and gas industry. EKS owns parts in all Swedish nuclear reactors and is the majority owner in nuclear power plant Oskarshamn Kraft Grupp, henceforth OKG, outside Oskarshamn. OKG and EKS work systematic with identifying and handling risks and the companies has a well-established risk management process for identification, analysis, evaluation and treatment of risks. Low probability severe consequence technical risks are identified, analysed and handled in the risk handling process at OKG as well as in the E.ON group. However, it could be interesting to extend the inclusion of these risks in the EKS risk management process in order to increase understanding on how the occurrence of them can economically affect OKG and EKS.

In this project a concept has been created on how the EKS risk management can include low probability severe consequences techno-economic risks. The extension of the risk management further on referred to as the methodology, focuses on the consequences of the risks and assumes that these may be initiated by a number of sequences. The sequences all have consequences with severe impact on the reactor core. In the methodology the consequences from the sequences are described using three parameters: radioactive release, property damage and business interruption. The parameters are connected to cost categories, which may be significant in a nuclear accident scenario. The total economic consequences for each sequence should be described in worst case, realistic case and best case. The analysis of these risks is suggested to be performed every third years and provides risk assessment material for following steps in the risk management process.

1.1 Problem analysis

E.ON Kärnkraft Sverige AB (EKS) has a risk management process for analysis of techno-economic risks, identified at the nuclear reactors in EKS portfolio. Risks with very low or extremely low probability and severe or extreme consequences are identified, analysed and treated in the OKGs risk management process and at the E.ON group level. Even though these risks have a very low probability they need to be analysed since the consequences could lead to an extensive economic impact on EKS and OKG. However, an extended inclusion of these risks in the EKS risk management process could further increase the knowledge of how severe consequence techno-economic risk can economically impact OKG and EKS.

1.2 Purpose

The aim of the project is to expand the EKS risk management process to include techno-economic risk of events with very low or extremely low probability but severe or extreme consequences in nuclear power plants. The result of the project should aim to be used in the development of a method for analysis and presentation of these risks.

The product from the project should provide the following:

- Criteria on which risk of events should be handled in the methodology.
- A concept of a methodology describing how the techno-economic risks can be structured, analysed, and evaluated in terms of economic impact on EKS and OKG. The methodology should to be based on and integrated in EKS existing risk management for techno-economic risks. The methodology should also include recommendations on how these risks of events should be presented to management based on the EKS existing presentation format.
- Suggestions on implementation of the methodology including updating and analysis frequency.
- An investigation and discussion on which risks of events are appropriate to include and how they are related to the economic consequences as well as the legal and insurance framework.

1.3 General aim and methods

The aim of this project is to provide a concept of a methodology for how to further include risks of events with low probability and severe consequences into the risk management process at EKS. The result should contain a methodology concept, criteria for which risks should be included and suggestions on implementation.

In the creation of the methodology four areas needed to be studied: (i) information on severe accidents sequences, (ii) information on risk management and enterprise risk management, (iii) information on insurance and legal systems concerning nuclear accidents, and (iv) information on which costs the owner/operator will face after a nuclear accident.

(i) The information on severe accident sequences where retrieved from literature studies of articles on nuclear reactor accident progression and also study of previously occurred accidents. A study was also carried out using reports from APRI (Accident Phenomena of Risk Importance), which is a Swedish collaboration on nuclear safety, and on the reactor specific SARs (Safety Analysis Report) and PSA Level 2 reports. APRI and SAR were the main sources of information. In the study experts at E.ON and OKG were consulted. In connection to this area a meeting at KTH (Kungliga Tekniska Högskolan) was set up to discuss ROAAM (Risk Oriented Accident Analysis Methodology), which is an analysis methodology for severe accidents, and how it may be related to the study described in this report. (ii) The information on risk management and enterprise risk management consisted both of retrieving knowledge on the areas in general, but also understanding how the concepts are used in the E.ON organization. This meant both external literature studies and studies of internal E.ON and OKG material as well as discussions with risk managers at OKG, EKS and ESV. (iii) Further, the Swedish insurance and legal systems concerning nuclear accidents were studied partly in a literature study but mainly through discussions with experts on ESV and OKG. The discussions were essential, since the legal and insurance systems were difficult to understand and combine with the technical risk of events. (iv) Finally, the information on costs connected to a nuclear accident were mainly studied in a literature and treated from an owner or operator perspective. The literature study included both nuclear accidents, e.g. Fukushima, and articles on the subject.

By using the knowledge from the background study the concept of the methodology could be created along with criteria for usage and a short discussion on usage and update of the methodology. The collected and studied information also provided useful information in understanding the general effects from a nuclear accident on a nuclear power owner or operator.

1.4 Delimitation

The study includes all nuclear reactors at the OKG site close to Oskarshamn. The included nuclear reactors are Oskarshamn 1, Oskarshamn 2, and Oskarshamn 3. All the included reactors are Boiling Water Reactors (BWRs).

The methodology and criteria will be adapted to risk of events with very low probabilities, i.e. of less than or around 10^{-5}/reactor year, and severe consequences with substantial economic effects.

Costs related to the risk of events are studied in the project. The costs, which have been studied, are direct cost on the operator or owner in case of a nuclear accident. Some indirect costs, e.g. business interruption costs on undamaged reactors on site are included. Other indirect costs, e.g. trademark loss costs or costs from political changes are not included. Nor are costs from the society point of view, e.g. costs for Swedish health care load increase, included.

The analysis and discussion of the risks, specified above, have the main focus on the techno-economic risk with a non-neglectable economic impact. The study does not include political, tax-related, or trademark risks. The project only includes risk of events related to failure in the reactor core, e.g. core melt, and does not include risks not related to damage of the reactor core, e.g. large failure of turbine, even if these are connected to large economic impact. The project only includes risks of events related to a single reactor failure and does not include simultaneous failure of several reactor on the same plant. Even though simultaneous failure is of much interest, especially after the Fukushima accident, the area could not be fitted into the limited project duration. The project scope does also not include risks related to transport of radioactive material.

2. E.ON AND OKG

E.ON Sverige AB, henceforth ESV, is the Swedish regional unit of E.ON AG, which is a German energy company focusing on the electricity and gas industries. ESV is divided into several subsidiaries, of which E.ON Kärnkraft Sverige AB, henceforth EKS, is the one handling E.ON's presence in the Swedish nuclear power industry and the Swedish nuclear waste facility, SKB.(3) EKS holds shares in all of the Swedish nuclear power production sites: 54.5 % in OKG AB, 29.56 % in Ringhals AB, and 9.9 % in Forsmark Kraftgrupp AB, as well as 12 % in SKB.(4) EKS is thus the majority owner in OKG AB, which operates the Oskarshamn nuclear power plant.(5) The Oskarshamn nuclear power plant will be the focus in this report. EKS also hold a large share in the Ringhals nuclear power plant, which consists of one BWR and three PWRs (Pressurized Water Reactor) with a total installed capacity of 3733 MW. Further EKS holds a small share in Forsmark Kraftgrupp AB, which operates a nuclear power plant consisting of three BWRs. EKS is minority owner in both Ringhals and Forsmark Kraftgrupp AB, but these plants are not included in this study.(6) As share owner in the nuclear power plants EKS has interest of ensuring continuous and safe power production from all reactor units.

OKG AB is the owner and operator of three reactors at the Simpevarp peninsula outside Oskarshamn in Sweden.(7) The plant consists of three nuclear power generating reactors of the type BWR with a total installed capacity of 2603 MWe.(5) Together the rectors produce 10 % of the electricity used in Sweden. As previously described EKS owns 54.4 % of OKG AB and the remaining 45.5 % is owned by Fortum.(7) Henceforth OKG will be referred to as reactor operator and EKS and Fortum as reactor owners. If the report only refers to owner in singular form this should be interpreted as EKS. The OKG organization is divided in eight departments were three are based on the production units and five are specialized on shared functions. Organized under the specialized department for technology is the unit TR, which stands for "Teknik, Reaktorsäkerhet och Tvärteknik" (Technology, Reactor safety and Interdisciplinary technology). TR performs safety analyses, estimations and documentation. The unit acts as support in safety related issues at the OKG power plant.(8)

3. E.ON Risk Management process

Risk management is as a tool to assess risks within a certain context. A risk is characterized by the severity of its impact (consequence) and likelihood of occurrence (probability). The consequence may be either positive or negative, which means that the risk may either be a threat or an opportunity. (9) ch.6 In this project the risks are linked to technical failures which lead to large economic impacts on a company and the risks are referred to as techno-economic risks.

Several models and definitions exist on what risk management is. However, most agree that a risk management process includes identification, analysis and evaluation of risks.(9) Within E.ON risk management is described as ”The culture, processes and structure that are directed towards the effective management of potential opportunities and threats to E.ON”.(10)

This chapter describes the risk management and enterprise risk management structure within E.ON. The first section provides a general view on E.ON’s enterprise risk management (ERM) and the second section provides a closer look into the risk management process of techno-economic risks connected to EKS.

3.1 E.ON Sverige ABs Enterprise Risk Management

E.ON is a German company and is therefore obliged to follow German legislation, which since 1998 includes the KonTraG (Control and Transparency in Business Act). Section 91 paragraph 2 in the KonTraG specifies that a company’s board of management should take appropriate actions to early discover risks with existence threatening effect.(11) As a result existence threatening risks must be reported to the company management board. Existence threatening risk reporting applies to risks with a monetary loss of more than € 50 Million.(12) For E.ON this means that risks with a worst case impact of € 50 Million or more must be reported to the E.ON Group management.

E.ON Kärnkraft Sverige AB’s risk management process is regulated by E.ON Sveriges ERM process. The ERM process aims to structure and manage the risks that could affect the ability to reach the company objectives. E.ON Sveriges ERM strategy is a continuous work process including policy creation, planning, risk management, measuring, and monitoring and will further be referred to as the risk management circle. The risk controlling strategy, which assures that the risk management work is performed in the outlined way focusing on relevant risks, is central in the ERM process. The risk management process is delegated to business unit level and the group risk manager is responsible for the controlling function.(11)

The E.ON ERM is, as previously described, divided in five steps; policy creation, planning, risk management, measuring and monitoring.(11) The risk management and measuring steps are the most relevant to the EKS risk management process. A graphical presentation of the five steps can be seen in figure 1 and all steps all described below.

The *policy step* is connected to the creation of policy guidelines. The risk policy is revised every year and it describes the internal policy of performance of the risk process and is applicable throughout E.ON Nordic.(11)

The *planning step* includes the creation of a yearly risk plan, which shall be used for improvement of the ERM process. The risk plan shall be based on strategies, policies and stakeholder analysis of the organisation and should focus on interesting areas within risk reporting, operational risks, financial risks, strategy and risk, project risk handling, insurance, information safety and crisis management.(11)

The *risk management step* is connected to the risk management process, which aims to detect and analyse a spectrum of everything from currency risks to technical risks throughout the organisation, including EKS. The risk management processes shall be provided with input on how risks shall be processed and which risks shall be reported to group management. In general the output from the risk management processes shall work as a basis for result reporting and budgeting as well as enterprise risk exposure analysis.(11)

In the *measuring step* of the risk management circle the risk material from the department risk management processes is reported and analysed. The risk report is based on information from the local risk managers, who are responsible for carrying out the risk management processes. The report is reviewed and updated in discussion between the risk manager and the business controller. The reported material is extended with Monte Carlo simulations after which it is reviewed in discussion between the risk manager and the CEO of the business unit. The risks are divided in: KonTraG risks, which are those with low probability but severe economic impact, and cluster risk in Risk and Chances, which are those risks and chances which are expected to have an impact on the company. The final risk report is presented to the Financial Director for Generation Sweden for sign-off before it is submitted to Generation Center and Group Management for further submittal to the different Management Boards.(11) In the process of producing the report the identification and analysis is documented.

In the *monitoring step* a yearly closure, related to the yearly risk plan and results from monitoring and measurements in the risk management circle, is created. The closure should contain descriptions on the activities of the risk manager, an overall assessment of the quality of the process, changes in the external and internal environment, development of "best practice" and identification of areas which are objects of improvement.(11)

The risk management processes at the business units, including EKS, have been developed to fit into the ERM process and to include KonTraG directives. Risks are identified for the current year and three years ahead. Risks are divided in quantifiable and non-quantifiable risks. Quantifiable risks are evaluated separately for each year but with a focus on the remaining of the current year. Risk reporting of quantifiable risks occurs every quarter of the year. For non-quantifiable risks an evaluation is made every third years. A specific threshold gross value is set for reporting of risk from the business units, including E.ON Kärnkraft Sverige, to the management board. Ad hoc risks, including both new risks and increased existing risks, should be reported directly to the E.ON Sverige risk manager if detected and if exceeding a specified threshold value.(11)

Quantifiable risks can be described by a continuous, discrete or combined distribution. In a continuous curve the probability of the risk occurring is 1, but the impact may vary creating a continuous curve. In the curve the worst case (WC), realistic case (RC) and best case (BC) is described. When the risk is described in a discrete way the outcome may be in two or more ways ("it happens or it don't") and the outcomes have different probabilities. The combined curve describes a risk, which is a combination of both a discrete and continuous distribution. In order to complete the analysis risks and opportunities Monte Carlo and sensitivity simulations are performed. When evaluating quantifiable risks a separation is made between gross risk and net risk. Gross value of the risk is the maximum potential loss, assuming the risk occurs and no preventive measures reduce the damage. The gross value can also be described as the worst case subtracted by the losses already considered. The net value of the risk is the potential loss assuming that preventive measures take effect as planned and can be described as the gross value subtracted by the prevention measure effects on the value. Thresholds are set in relation to gross value.(12) Non-quantifiable (or qualitative) risks are evaluated using risk matrix with set levels on probability and consequence.(12)

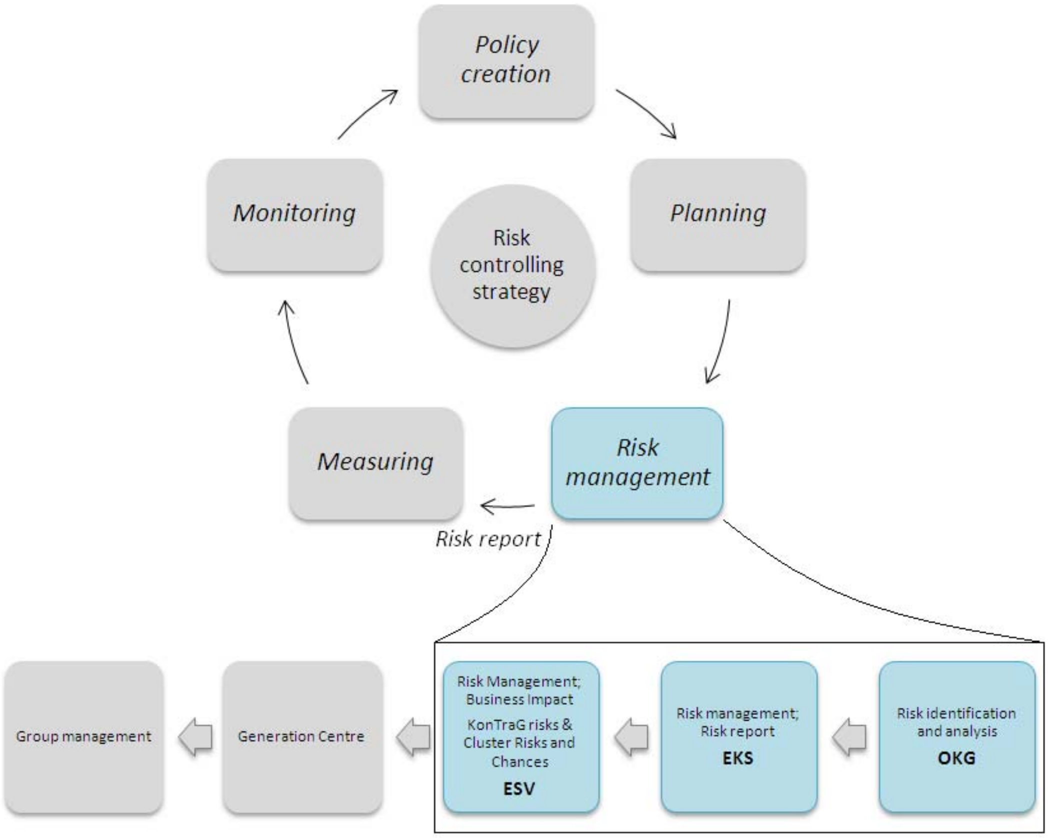

Figure 1. The figure shows a simplified presentation of the ERM process in E.ON organisation and how it is connected to EKS risk management process, which is of interest in this project. The figure has been created on the basis of information from Nils Rosengren (E.ON Sverige AB) and Cecilia Sjövall (E.ON Kärnkraft Sverige AB).

3.2 E.ON Sverige ABs Risk Management process

As previously described risk management includes identification, analysis, and evaluation. Furthermore, risk management also includes treatment of those risks that are considered as unacceptable in terms of probability or consequence. In the identification risks, which may affect the ability to achieve company objectives, are detected and documented.(13) The identified risks are analysed in order to understand the severity (consequence) and likelihood (probability) of the risk.(9) When the risks have been identified and analysed it needs to be decided whether the risks are acceptable or not. If the risk is unacceptable it needs to be either controlled, which includes lowering the probability/consequence or complete avoidance of risk, or treated, which includes retention and transferring of risks. Transferring of risk can be performed by insurance coverage of the economic consequences and retention includes preparation for absorption of economic consequences within the organisation. Both these treatment methods can be found in the E.ON risk handling of low probability severe consequence risks.

This project focuses on the analysis of risks with low probability and severe consequences. In addition it includes identification, evaluation and to some extent treatment of the risks. The risk management identification and analysis of techno-economic risks for the three reactors at OKG are described in this section starting with identification at OKG followed by analysis at EKS and ESV. Graphical presentations of the risk management process and how it relates to the enterprise risk management can be seen in figure 2 and 1, respectively.

3.2.1 Risk Management at OKG AB

The risk management process at OKG basically consists of two functions from a risk management perspective; these are the risk identification and reporting performed by the risk responsible at the departments at OKG, and the collection and analysis of reported risks by the OKG local risk manager.(14)

The risk responsible at the departments have a risk coordinating responsibility within their department and shall assure that risks that have been identified are reported to the OKG risk manager through Aero, which is OKG's risk report software. The risk responsible report risks in Aero continuously as they are identified, handled or changed. When the OKG risk manager sends out a request for a risk briefing the department responsible will review the reported risk for structuring and homogenization of the risk information.(15) This is performed before each quarterly risk report. The risks are described in probability and consequence. The impact consequence is defined as worst case (WC), realistic case (RC) and best case (BC) in lost days of production. The probability is set in unit of choice, which the OKG risk manager translates into percentage.(14)

The OKG risk manager collects the information from Aero and creates a report, which specifies probability and consequence of the risks. The risk manager includes risks with a probability above 5 % in the risk report. When the report is fully approver it is sent on to OKG board and the owners, EKS and Fortum. In addition EKS request information on risks with probabilities between 1 and 5 % and consequences above SEK 25 Million. The risks are analysed for the current year and three years ahead. This is done each quarter of the year at dates corresponding to those of the EKS local risk management process.(15)

3.2.2 Risk Management at E.ON Kärnkraft Sverige AB

The EKS risk manager translates the consequence information in the risk report from OKG into lost production in GWh (EBIT). The risks are presented as WC, RC, and BC and evaluated for the current year and three year ahead, e.g. next quarter 2013, 2014, 2015 and 2016. The EKS local risk manager exclude risk which: i) Have an impact (WC) corresponding to less than the business unit threshold for EKS. ii) Are covered by a budget set aside for unexpected risks, and iii) Can be included in the generic risk group. A risk that has been part of the risk report will be excluded from the new risk report if the impact has been lowered under the threshold value or if the risk has occurred. Sometimes controlled or treated risks may create new risks, which will be included in the risk report.(14)

The risks are transferred into EKS risk documentation and administration program RiskPortfolio by the EKS risk manager. The risk manager also transfers information on the risk, e.g. whether risks are qualitative or quantitative, into the program. Quantitative risks are presented as a discrete, continuous or combined risk curve. Qualitative risks are presented in a risk matrix. The program presents a set of information tables as well as plots showing the probability and consequence.(14)

3.2.3 Risk Management at E.ON Sverige AB

The ESV risk manager will collect information on risks directly from RiskPortfolio. For quantifying purpose the main interest for the ESV risk manager is the probability and consequence (WC, RC and BC) for the quantitative risks and the risk matrix for the qualitative risks. The ESV risk manager is also interested in information on the basis for the evaluation and comments on changes in the risk.(14)

The risk manager collects risks in groups and performs analyses of the risk groups instead of individual risks. Based on the information from RiskPortfolio the ESV risk manager performs Monte Carlo simulations on the business impact. The risk manager sends the risk report on to the Generation Centre in two groups: KonTraG risks and Clusters of Risks and Chances.(16) The risk report provides the input to the Measuring step in the E.ON Sverige ERM process.(11)

It has been difficult to detect what kind of process exists after the Generation Centre and the Group Management and information on this could not be included in the study. For a complete risk management process the identified and analyzed risks should be evaluated on the criteria whether the risks are acceptable or not. This information should constitute the basis for the input in the next risk management loop.

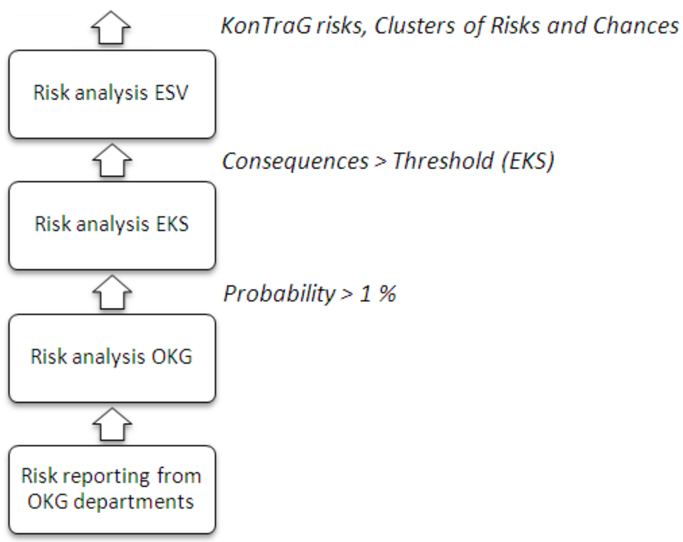

Figure 2. The figure shows EKS risk management process, which is the focus in this study. The figure also show which criteria is used for further reporting of risks in the risk management process.

4. Economic Consequences and Liabilities in a Nuclear Accident Scenario

This chapter contains a presentation of the economic consequences or costs, which have been considered as relevant to include in the methodology. The economic consequences are considered as relevant if they directly affect the operator or owner in case of a nuclear accident; including both external (Third Party Liability) and internal (production, property damage etc.) costs. Economic consequences, which are related to loss or strain on the society as a whole, e.g. strain on health care system, are not included in the study. A graph of all costs discussed in this section can be found in figure 3.

Indirect costs, such as losses due to shut-down of the whole Swedish nuclear fleet due to political decisions have not been included since this lie beyond the project scope. However, indirect costs related to temporary or permanent shutdown of undamaged reactors at the same nuclear plant as the damaged reactor have been included and briefly discussed. It is assumed that the undamaged reactors will experience a long-term stop. Effects of trademark effects or tax-related issues are not included.

4.1 External costs

The cost category *external costs* include effects on the surroundings and third party. This may be health effects or evacuation related issues on the habitants in the areas close to the nuclear plant, but also environmental effects. The external economic consequences are related to the release of radioactive material including the extent of the radiation spread and concentration.

An external cost group, which will not impact the owner or operator but is worth mentioning, is the radiation monitoring cost. The radiation monitoring cost is a burden for society as a whole and after the Fukushima accident it is expected to have a large impact on the total cost. After Fukushima it is expected that the monitoring of health over a 20 year period will cost around US$ 958 Million and include 2 Million persons in the most affected region.(17) The monitoring also includes inspection and preventive measures on foodstuff grown in the affected area.(18) The risk of contamination of food increases with the size of the radioactive release, but even accidents corresponding to a level 4 on the INES scale food control may be needed.(19) Foodstuff has in several post-nuclear accident cases shown to be one of the main sources for internal irradiation of the population.

4.1.1 Cost from Health effect

A release of radioactive material into the surrounding may lead to health effects among personnel at the reactor site and possibly health effects among the public. In this chapter the costs from health effects, which may be generated by a nuclear accident, will be described using three subgroups; *early health effects*, *late health effects* and *fatalities*. The costs from health effects include both effects on personnel working at the power plant and on the public. The description focuses on health issues related to radiation releases but there may also be health issues from mechanical damage, e.g. falling objects. This can be assumed to mainly affect the personnel at the nuclear plant.

The costs generated from health effects can be assumed to come from three sources: the cost of medical treatment, the loss of contribution to the economy, and a monetary compensation. Since the Swedish health care is “free” for the public, and is a cost for the society as a whole rather than for the private person, the cost will not affect the operator or owner. In addition to the cost for medical treatment, the early health effects may create a loss of individuals’ contribution to the economy.(20) This individual loss to the economy is not a cost that will fall on the operator but is an issue for the society. However, a person suffering health effects from a nuclear accident can claim compensation for his or hers health effects from the reactor operator.

Hsieh and Spinrad (21) describe five categories of health effects from a nuclear accident including *early health effects* or early illness as one. The subgroup early illness can be described as illness requiring medical treatment within weeks after the irradiation accident. Often the victims in this subgroup require no further treatment and suffer no lasting negative health effects. If the persons experience prolonged health effects or do not survive they will be included in one of the other subgroups.(21) As previously stated this cost subgroup will be dominated by the claims of compensation from the affected persons.

The *late health effect* costs can, similarly to the early health effects, be divided into the cost of medical treatment, the loss of individual contribution to the economy, and a monetary compensation.(20) The medical treatment and loss of contribution to the economy will not have a significant impact in this study since they are not interesting from an operator perspective. However late health effects may still lead to compensation claims on the operator by the affected persons. As previously described Hsieh and Spinrad divide health effects due from a nuclear accident into five groups. Three of these may be fitted into late heath effect costs. These are: latent cancer, thyroid nodules, and genetic effects.(21)

Latent cancer may be difficult to connect to the nuclear accident since cancer exists in a normal non-irradiated population. However, in some case from the World War II there has been an increase of cancer cases amongst the irradiated population.(21) Some research shows that the probability of delayed or latent cancer can be assumed to increase linearly with the received dose. A radioactive release may result in a high dose for a few persons and a low dose for a large number. It is often in the low dose population that the latent cancer cases increases.(18)

The late health effect cost group also includes thyroid nodules, which is benign or malignant growth on the thyroid.(21) Thyroids cancer is the most common cancer related to radiation exposure. After Chernobyl the increase of thyroid cancer due to large scale radiation exposure has been investigated. This type of cancer, which is rarely seen among children, had a large increase specifically among children and adolescents in the areas around Chernobyl. Some cases occurred the first years after the accident, but the number of detected cases increased rapidly after around 10 years. Between 1990 and 2005 around 5000 children and adolescent were diagnosed with thyroid cancer. However only 20 deaths from thyroid cancer where reported.(22) As the other health effect groups this will for the operator mainly include claims of compensation from the victims.

The impact from the genetic effect costs group is difficult to estimate and Hsieh and Spinrad (21) state that the genetic effect may be a significant effect from an accident and that it may take up to ten generations to “wash out” the genetic illness.(21) However, such long perspectives are not possible to include in this study. This may be an important cost from a society perspective.

Hsieh and Spinrad (21) also describe *fatalities* as one health effect group. The group includes early fatalities, which can be described as deaths that occur within approximately one year after the accident.(21) In Sweden it may be assumed that the majority of residents have a private insurance which provide compensation for the loss. However the affected persons may claim an additional compensation from the operator. Fatalities may also happen at a later time in the post-accident period. The same assumptions can be made for these as for the early fatalities.

4.1.2 Evacuation costs

Even though evacuations are not uncommon in other types of industrial accidents or natural disasters, accidents related to radioactive releases appears to be more sensitive in terms of evacuation due to the high dependence of weather and wind on the impact of contamination spread and concentration.(17) The evacuation may be accompanied or substituted for sheltering of the habitants if the off-site impacts are limited. In the TMI accident sheltering was recommended to the habitants around the power plant in combination with evacuation of pregnant women and children.(23) The sheltering would lead to a cost, however it can be assumed to be lower than for evacuation. The evacuation cost can be divided in the cost for *transportation*, *accommodation* and *loss of income*.

The *transport* costs from an evacuated area will depend on the size of area which should be evacuated as well as the density of the population in the area. Jang et al (20) assume that evacuated people will basically use two kinds of transportations: private cars and emergency organized transports. They also assume that 99 % of the population will chose to travel by car and that every car will in average carry 3.8 persons.(20) Choosing to accept these assumptions, the transportation will not make any significant contribution to the total economic consequences, but on the other hand the emergency response will still need to provide the possibility to move all who cannot be assumed to travel by other means.

The cost for *accommodation* includes both temporary accommodation, during a period of evacuation, and permanent resettlement, in case of a very long-term evacuation e.g. if areas become inhabitable. Jang et al. (20) states that the cost of temporary accommodation due to evacuation depends on: the number of evacuated habitants, cost per night, and duration of the evacuation.(20) It may be assumed that some part of the evacuated people stay in accommodation not related to any cost, i.e. with relatives, friends or in summerhouses. Furthermore it can also be assumed that some spontaneous evacuation will occur. Spontaneous evacuation is unlikely to be covered by insurance and may be hard to claim compensation for. As for long-term or permanent resettlement more extensive measures may be needed. According to IAEA it should be expected that the settlements are at the same standard as those left vacant. This may involve construction of new houses but also creation of infrastructure to support new communities.(18) These costs can be expected to give an impact on the total cost.

The cost from *loss of income* is the sum of the number of people with lost income, the income per day and the duration of the loss, which may exceed the duration of the evacuation.(20) Loss of income can include both loss of possibility to work, and therefore loss of income, but also from loss of source of income, e.g. a farming or fishing industry. In the first case the loss may occur as a result of evacuation from the area in which the workplace is situated. In the latter case the loss will be an effect of evacuation but may also result from an environmental impact on e.g. the farm land and livestock.

4.1.3 Environment Restoration costs

Depending on the level of radioactive release the off-site impact on the environment may be large. Restoration of contaminated areas as well as handling of contaminated materials from an accident is connected both to large economic costs and high risk work for the personnel that are to perform the task.(24) The high risk work could involve a surcharge to the compensation of the workers leading to an even higher cost for the restoration work.

The decontamination and remediation work off-site can be assumed to be connected and interlinked with the on-site clean-up measures. IAEA speak of both short-term and long-term measures for clean-up and handling of waste and contaminated materials. The short term actions include setting up criteria for clean-up etc. as well as mapping of on-site and off-site contamination and create methods and strategies for decontamination and remediation of affected areas. Decontamination and remediation includes collection of large volumes of liquid and solid contaminated materials. Long-term aspect focuses on creating a sustainable situation in terms of waste storage, land use and environment recovery.(25)

4.2 Property damage costs

A nuclear accident will have a large impact on the reactor machinery and components including the reactor core, reactor vessel, containment and other components in the surrounding systems. The cost of the property damage will in most risks, included in this study, be rather a loss than an expense since the impact on the reactor in most cases will be of such extent that the reactor will be damaged beyond repair and permanently shut down. Even if the reactor vessel is intact and only a part of the core has been damaged the cost of cleaning-up and repair in order to restart the reactor will reach unjustifiable high costs. However if the risk involves a bypass release, including a relevantly intact reactor core, the reactor may be able to start again and the damage cost will mainly consist of the expenses for exchanging the damaged fuel elements to new ones.

The economic impact from property damage also includes the cost of cleaning up the reactor area. The environment needs to be restored to the same condition as before the accident which will include an on-site safe environment close to and possibly even on the plant area. The clean-up costs will depend on the level of damage and contamination. To some extent the clean-up of the on-site reactor area can be assumed to be included in the overall decontamination and remediation of the total affected area.

Furthermore the post-measures of an accident will involve handling of radiologic waste, which needs to be moved and prepared for long-term storage. In an accident with severe consequences the radiologic waste may include other parts than the reactor core due to radiologic contamination. The cost of handling and storage of radiologic waste from a nuclear accident can be expected to largely exceed the cost of final storage for a safe shut-down and demolition of a nuclear reactor.

Both the cleaning up of the reactor area and the handling of the radioactive waste are connected to high risks and large costs. Similarly to the off-site environmental restoration costs the high risks work may lead to substantial surcharges in the clean-up and waste-handling work.

4.3 BUSINESS INTERRUPTION COSTS

The business interruption cost is related to the loss of electricity production, which can be assumed to occur in connection to unplanned stops of the reactor. In order to understand why a business interruption generates a cost the commercial chain of electricity within E.ON needs to be understood. OKG produces electricity and EKS buys a share of electricity corresponding to its ownership of OKG (54.4 %) of this electricity to production cost. EKS sell the electricity to E.ON Global Commodities that has a balancing responsibility towards the electrical grid. E.ON Global Commodities sells the electricity partly to E.ON Sveriges commercial sales company and party to electricity spot market, such as Nordpool. Since this study focuses on the effects on EKS, it is further assumed that EKS buy from OKG electricity for production cost and sell it onwards generating a profit for EKS.(26)

EKS will sell electricity at maximum three years in advance, which means that today electricity is sold that will be produced within three years. In case the delivered amount of electricity is smaller or larger than expected, EKS will have to pay or get paid for the difference, respectively. This correction will be done using electricity spot prices. This means that in case the electricity cannot be delivered, EKS will need to repay all sold electricity. If the business interruption is unexpected it can be assumed that the first period will need to be compensated at the levels of the electricity spot prices. If a long stop is suspected a payback level based on the electricity spot or forward price can be agreed upon with the buyer.(26) In this study it is assumed that a long-term stop will lead to payback costs corresponding to three years of electricity production.

4.4 INDIRECT COSTS ON THE NUCLEAR PLANT

This study focuses on the direct costs from a nuclear accident. However some of the indirect cost may be interesting to include. The indirect costs are not related to the on-site or off-site effect of the damaged reactor as such.(27) The indirect effects can be a spin-off effect from a political change in view on nuclear energy, additional safety evaluations at similar reactors, or increase of safety measures. After the TMI accident indirect costs could be seen in forms of a worldwide load factor decrease on PWRs.(28) Another example is the stress tests which are performed on nuclear reactors in EU after the Fukushima accident.

In this project it is assumed that if a severe accident occurs at a Swedish reactor the other reactors on the same site will stop their electricity production. This will create a loss of income by business interruption for the site owners. The reactors may restart when the damaged reactor is under control and the authority provides clearance for production. However this can be expected to take several years. Another possibility is that the authorities do not provide clearance for continuing to run the other reactors on the site. However this is assumed only to be possible due to political decisions and since political risks are not included in the project the undamaged reactors are assumed to restart.

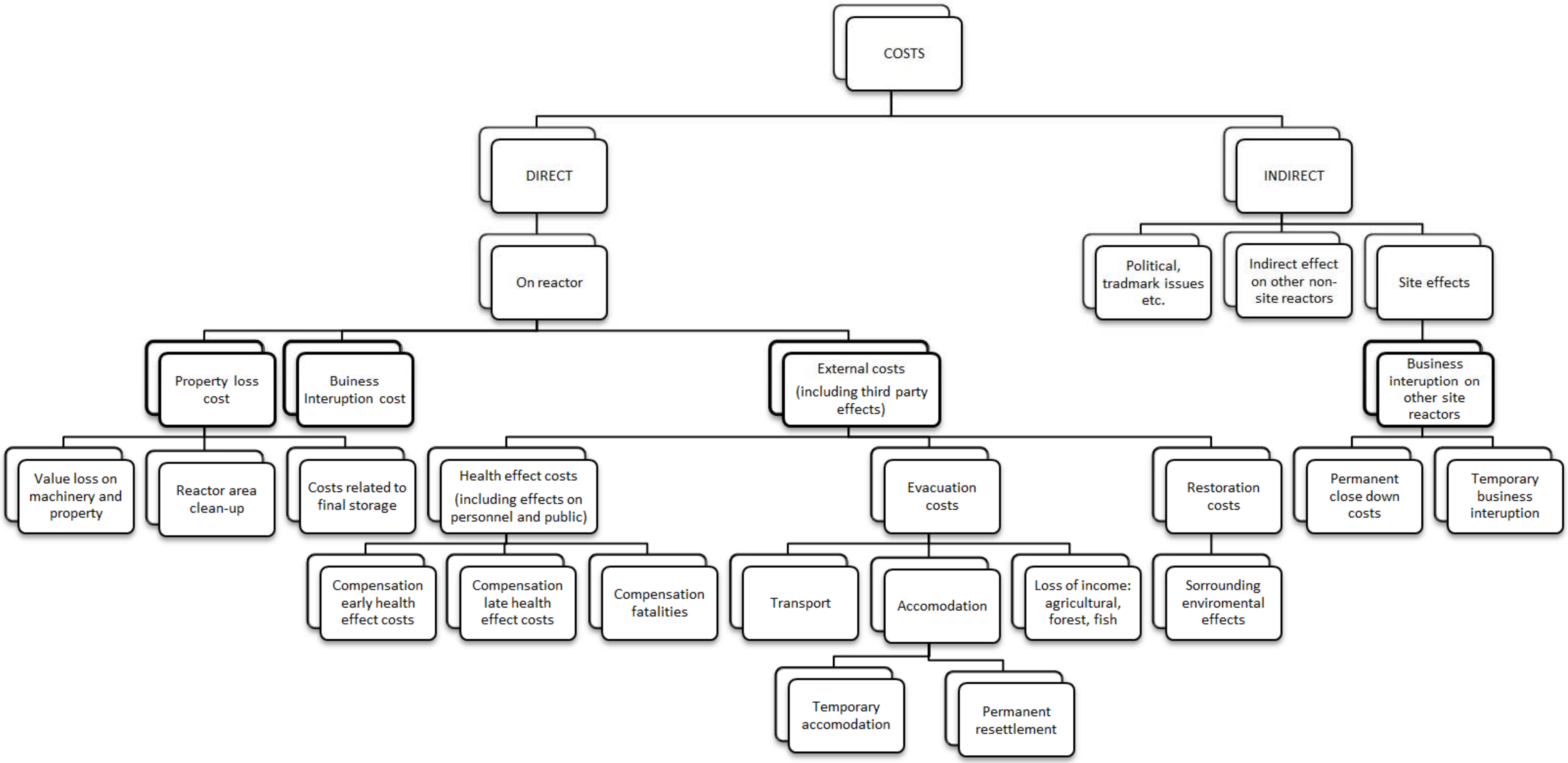

Figure 3. The figure shows the costs, which have been discussed in sections 4.1 to 4.4. The middle row boxes (sharp black edges) are the main cost categories and the lower row boxes are cost groups and subgroups, which are considered as important from an owner and operator perspective. All indirect costs, except “Site effects”, are excluded from the study.

4.5 EXAMPLES OF ECONOMIC IMPACT IN PREVIOUS OCCURRED NUCLEAR ACCIDENTS AND ACCIDENT SIMULATIONS

In order to understand what kind of economic consequences can be expected to arise after a nuclear accident four historical nuclear accidents were studied. These were: Windscale, Three Mile Island, Chernobyl, and Fukushima. The general descriptions on all accidents can be found in Appendix A. In addition the results from the SAMÖ/KKÖ simulation were studied and a description of these costs can be found in this section. A general description of the SAMÖ/KKÖ simulation can be found in Appendix A.

The cost categories are mainly from a company perspective since this is the focus of the project. However some costs, more related to society, can also be found in the descriptions. These have been included to provide a more complete picture on the total economic impact from a nuclear accident.

4.5.1 WINDSCALE, UK, 1957

The Windscale accident led to substantial damage to the reactor core but limited release of radioactive material. Since the reactor was used for plutonium production the accident lead to product production loss rather than power production loss.(29) According to Sovacool (30) the Windscale accident led to a property loss (including property damage, emergency response, environmental remediation, evacuation, lost product, fines and court claims) of approximately US$ 78 million (adjusted to 2006 level of US$) and 33 fatalities.(30) However the figure does not include the cost of sealing up the reactor or the still ongoing cleaning up of the site area. These can be assumed to have a large impact on the total cost. The Windscale reactors started operation in 1950-1951 and the loss of a fairly new reactor can be assumed to have an impact on the total cost (31).

4.5.2 THREE MILE ISLAND (TMI-2), USA, 1979

The Three Mile Island accident led to severe damages on the core and primary system of the PWR reactor, but only to limited radioactive release. According to Evans (32) the TMI accident led to three groups of direct costs for the owner and operators. These costs came from: (i) clean-up of contaminated areas, (ii) writing-off the new reactor and (iii) replacement of power generating capacity. (i) It took 14 years to clean-up contaminated areas and remove the damaged core from the reactor, resulting in a cost of US$ 1000 Million. The clean-up cost includes costs from safe shutdown of the reactor and Evans estimated this cost to US$ 1034 million (adjusted to 1981 level of US$). (ii) Three Mile Island-2 reactor had only been operated fully for a duration equivalent to three months. Evans (32) estimates that the writing-off costs for the new TMI-2 reactor were US$ 1000-3000 million (adjusted to 1981 level of US$). (iii) Since the owners of the power plant needed to continue deliverance of electricity to the grid they needed to buy replacement generation. Since the second undamaged reactor TMI-1 was stopped and remained non-operating for three years after the TMI-2 accident the replacement generation became a non-neglectable cost in the total economic impact.(32)

According to Sovacool (30) the TMI-2 accident led to a property loss (including property damage, emergency response, environmental remediation, evacuation, lost product, fines and court claims) of approximately US$ 2.4 billion (adjusted to 2006 level of US$), but no fatalities.(30) Lars Högberg (33) appreciates the total cost for TMI accident to approximately US$ 5000-10000 Million.(33)

4.5.3 CHERNOBYL, SOVIET UNION (NOW IN UKRAINE), 1986

The Chernobyl accident led to a substantial damage on the reactor, including the reactor building, and a large release of radioactive material. Lars Högberg (33) states that over the first 25 years after the Chernobyl accident the cost has been appreciated to US$ 250 000-500 000 Million. This is mostly due to large costs related to clean-up, recovery work as well as a safe storage of the damaged core.(33) Sovacool (30) means that the Chernobyl accident led to a property loss (including property damage, emergency response, environmental remediation, evacuation, lost product, fines and court claims) of approximately US$ 6.7 billion (adjusted to 2006 level of US$) and 4056 fatalities.(30) The Belarus government presented an expected value of US$ 235 billion to clean-up and rehabilitate the area round Chernobyl over a 30 year period.(34) The divergence in the figures says something about the difficulty in estimating the total cost of this accident and nuclear accidents in general.

Munro presents data from the UN (2002) in which it is stated that apart from direct damage costs from the accident costs related to consequence mitigation in the exclusion area, social protection and health care, research and monitoring of the environment and health, disposal of nuclear waste and improvement of settlements as well as resettlement of people should be considered. Other costs were related to opportunity loss of agricultural and forest industry in the affected area. Further, the accident generated large costs due to the shutdown of the whole Chernobyl site and the cancellation of the Belarus nuclear program.(29)

Chernobyl affected the whole of Europe and the accident led to large costs for many countries. The impact in Sweden was related to mitigation measures to agriculture, horticulture, reindeer breeding, fish and game hunting (moose) and summed up to a total cost of SEK 367 Million.(29)

4.5.4 Fukushima Dai-ichi, Japan, 2011

The Fukushima accident led to severe damage to several reactors and large releases of radioactive material. The cost of clean-up of the evacuated areas close to Fukushima can still not be specified with any precise number. But very rough estimations show that the clean-up may cost US$ 14 billion over 30 years. Including compensation to victims and resettlement of evacuated people the cost may reach as high as US$ 250 billion.(17) Some additional costs are presented in table 1. The costs continue to increase when including an estimated cost of monitoring health effects on around 2 million people for 30 years after the Fukushima accident. The cost estimation is set to US$ 958 million for the Fukushima Medical University.(17)

Lars Högberg (33) estimates the total cost over a 50-year period to US$ 100 000-500 000 Million. In the process TEPCO, the owner of the Fukushima plant, has been completely nationalized by the Japanese government.(33)

Table 1. The table shows some additional cost groups from the Fukushima accident. The estimated costs are in the period October 2011-January 2012.(35)

Replacement generation	US$ 680 Million
Bring crisis at power plant to control	US$ 1.37 Billion
Mental distress caused by accident	US$ 1.15 Billion
Companies who become inoperable due to evacuation etc.	US$ 1.32 Billion
People who could not work	US$ 1.84 Billion
Compensation of losses of agricultural and marine goods sales	US$ 870 Million
Cleaning up residential areas	US$ 2.9 Billions

4.5.5 SAMÖ/KKÖ

In 2-3 February 2011 a simulation was performed in order to study the overall society response in case of a nuclear accident at OKG. The focus of the simulation was to combine collaboration simulation, Samverkansövning (SAMÖ), and nuclear simulation, Kärnkraftsövning (KKÖ), into one simulation, SAMÖ/KKÖ.(36) The SAMÖ/KKÖ simulation was based on imaginary severe nuclear accident on OKG, including severe core damages and radioactive release. The simulated accident was judged to a level 5 accident on the INES scale. SAMÖ/KKÖ provided several interesting results for the effects on society evaluated 7 weeks after the accident simulation. Some of the results are very interesting from an operator cost perspective. Three main areas of interest have been selected for further description in this section: *evacuation*, *environmental impact*, and *claims of compensation*.

It was assumed that around 12 000 habitants were *evacuated*. It is not specified whether the evacuation became a temporary accommodation or permanent resettlement after these 7 weeks. It is however assumed that the habitants could return to their homes in order to collect things etc, but not to resettle within the first 7 weeks after the accident.

The most affected area around the nuclear plant was assumed to receive high doses with substantial *environmental impact*. The accident was assumed to result in severe consequences on the farm land and agricultural industry in the area, but also to impact the forestry and fishing in the contaminated areas. The SAMÖ/KKÖ results state that the contaminated areas would be subject to monitoring and that some particularly affected areas would risk to become restricted for up to 50 years after the accident due to severe radioactive fallout.

The SAMÖ/KKÖ results include a short description of the assumed level of *claims of compensation*. These were beforehand prospected not to reach the maximum level in the Third Party Liability Law of SEK 3.3 Billion and that the Nordic nuclear insurance pool (NNI) would therefore not experience problems coping with the claim levels. However, four weeks after the simulated accident it was seen that the total claims of compensation could have reached over SEK 6 Billion.(37)

4.5.6 Comparison financial impact on studied accidents

In this section the costs of the four studied nuclear accidents are further investigated focusing on the composition of the costs between cost groups. The nuclear accident cost composition is compared between the accidents, which each correspond to different levels of damage and radioactive release.

Costs from the four nuclear accidents have been collected in table 2. The information is the same as that described in the sections above with some additions and alterations. In the cost presentation and discussion it should be noted that because of the lack of information the numbers are approximate and should be regarded as a hint on the cost composition and level rather than an exact numbers. Since three reactors at Fukushima developed to nuclear accidents related to the reactor core all costs have been divided by three assuming that three reactors accidents led to most of the external effects.

The cost groups in table 2 cover most costs expected after a nuclear accident. Some costs may exist in more than one cost group, e.g. compensation to victims, and are therefore included more than once. Due to lack of information on how the cost groups have been calculated all costs have been included in the format, in which there were found in the literature. Therefore it may be more interesting to study the relative total economic impact, which calculated by comparing the total economic impact to that of TMI (see table 2). The TMI accident has been chosen as the reference case, since this is often regarded as a "successful" case in terms of off-site impact.

Since the available information varies between the accidents, assumptions have been made on several of the costs groups. The assumptions are described in table 2. The assumptions have been made in order to present a more realistic economic impact than if unknown costs would have been neglected completely. However, some costs are assumed as neglectable in relation to the total economic impact or as not being comparable with the other accident costs, e.g. cost due to replacement generation of electricity (TMI, Fukushima) is not considered comparable to the loss of plutonium production (Windscale, Chernobyl).

The information in the table has been used to create graphs, which are displayed in figure 4. The graphs are intended to show the difference and similarities in composition of the cost groups between the accidents. In figure 4 it can be seen that the compensations to victims and resettlement of evacuated people are large cost groups in both the Chernobyl and Fukushima accident. However in the Chernobyl case the clean-up cost makes up almost three quarters of the total economic impact. In the Windscale and TMI cases the compensation costs are much smaller, which is due to the limited radioactive release and impact on environment and population. In the TMI case the writing-off a new reactor has a large impact on the total cost. At Windscale the cost of bringing the crisis into control has a fairly large impact. However this can be due to a combination of the comparably low total cost of the accident and the assumption that this cost is the same as in TMI. The Windscale case is dominated by the cost of clean-up, which has been assumed to be at the same levels as in the TMI case.

In conclusion is can be seen that nuclear accidents, which led to large radioactive releases (Windscale, Chernobyl, and Fukushima), will have an economic impact which is dominated by compensation and clean-up related cost groups. Whereas the economic impact from the TMI accident, which led a limited radioactive release, is dominated by other cost groups.

Table 2. The table shows the economic impact on the owner or operator in the studied nuclear accident. Please note that all costs have been adapted for a single reactor failure and that unknown costs have been included using a number of assumptions, which are described below the table (see footnotes a-j).

Economic impact of reference case accidents (US$ Million)				
Reference case accidents (INES Level)	Windscale (5)	Three Mile Island (5)	Chernobyl (7)	Fukushima (7)
Property damage, emergency response, environmental remediation, evacuation, lost product, and fines and court claims	87[a]	2688[a]	7504[a]	2501[j]
Clean-up costs	2285[b]	2285[a]	235000	4667[j]
Writing-off new reactor costs	0[c]	6630[a]	0[c]	0[d]
Compensation to victims and resettlement of evacuated people	0[e]	0[e]	83333[f]	83333[j]
Replacement generation	0[e]	38[h]	0[g]	227[j]
Bring crisis at power plant to control	228[i]	228[i]	457[i]	457[j]
Total economic impact	**2601**	**11869**	**326294**	**91185**
Percentage of TMIs economic impact	**22**	**100**	**2732**	**768**

a) Costs have been recalculated to cost-level of 2012 in order to be comparable between accidents. This has been done using the cost index.

b) The clean-up cost of Windscale is assumed to be at the same level as TMI since the effects of the accidents were similar. Further the cost of the capsulation of the Windscale reactor is unknown, but assumed to be included in the clean-up cost.

c) The reactor was used for plutonium production and cannot be handled as a power producing reactor. For this reason the costs has been assumed to be neglectable in comparison to the total cost.

d) The Fukushima reactors can be assumed to have no cost due to loss of new reactor, since the reactors had operated for almost their complete lifespan.

e) Assume that no resettlement was needed at Windscale and TMI, and that the compensation to victims has been included in another cost category this cost group has been set to zero for these accidents.

f) The evacuation and compensation category for Chernobyl is assumed to be of the same level as Fukushima, since both accidents were judged as INES level 7 accidents.

g) Since the facilities where not producing electrical power but plutonium this cost group has been neglected in the Windscale and Chernobyl accidents.

h) The replacement generation at TMI is assumed to correspond to one sixth of that at Fukushima. This is because total thermal power at Fukushima (four damaged operating reactors) where six times larger than at TMI (one damaged reactor).

i) For Windscale and TMI the cost of bringing the crisis under control can be assumed to be smaller than at Fukushima since the accidents led to a more limited radioactive release and property damage. In this study it is assumed that this cost is half of that at Fukushima. However in Chernobyl the costs could be assumed to be in the same range.

j) All costs in the Fukushima case have been divided by three in order to compare the costs for one reactor experiencing a nuclear accident. It is assumed that of the 4 affected reactors at Fukushima 3 were object to nuclear reactor failure and gave the largest impact on the economic impact.

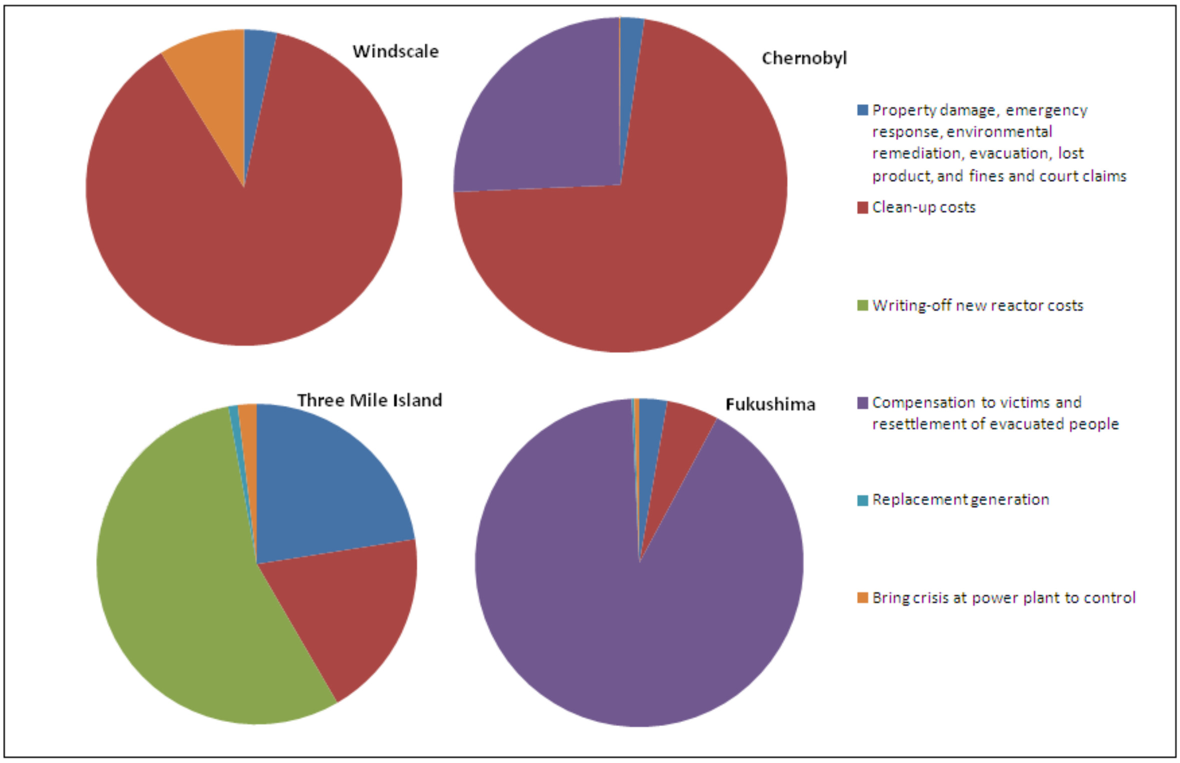

Figure 4. The graphs show the economic impact composition between the different cost groups, described in table 2, for the four studied nuclear accidents.

4.6 LEGAL FRAMEWORK

The Swedish law regulating the TPL at a radiologic accident is called Atomansvarighetslagen. The law was issued in 1968. The law aims to assure that victims will be compensated for third party damages in case of a nuclear accident. The law is based on the Paris convention from 1960. The Paris convention was created by a number of European civil nuclear states in order to elaborate and internationally homogenize legislation concerning the TPL and insurance.(39) An important principle is that the liability is channelled to the operator, i.e. "strict" liability, which means that the nuclear reactor operator is liable regardless of who caused the accident. Apart from the strict liability the Paris convention enforces limited liability and that the operator must have insurance coverage or other economic safety which can cover his liability in relation to third parties.(40)

The law applies for both accidents at the power plant: in the reactor area, but also for accidents that may occur in transport of the nuclear fuel. This project only includes accidents on a nuclear power plant and does not include transporting accidents. The law specifies a radiologic damage as both damage as a result of the radiological characters of a nuclear fuel or radioactive product including poisonous, explosive and in other ways dangerous properties of the substances, and radiological damage from other substances in a nuclear facility.(1§) If a person has experienced radiologic damage and a non-radiologic damage, which cannot be separated from the radiologic damage, the law will apply to the total damage. 16§ (41)

If a radiological damage is detected it shall be reported at least three years after detection and at the latest reported 10 years after the accident. (21§) In 11§ it is specified that the operator is not liable for the accident in case of initiation by war, riot or similar events, or sever natural disasters of exceptional form. According to 34§ the Swedish state is also relieved from responsibility in these cases.(41)

The maximum liability amount has been set to 300 special drawing rights, which is an international currency used by the International Monetary Fund and the corresponding value in Swedish crowns will be determined at the time of the accident.(17§) The operator should ensure that the maximum liability value is insured. The TPL insurance shall be approved by the Swedish government.(22§) The total maximum liability including both operator and the Swedish state corresponds to a value of 425 special drawing rights.(31§) The law also applies for liability if the radiologic accident affects Denmark, Finland, Norway, and other member state of the Paris convention and the maximum liability values for the operator and Swedish state combined is 6 billion SEK. (31a§)The operator will however not be liable to higher levels than 300 special drawing rights.(41)

In 2004 the Paris convention was revised in order to ensure that nuclear accident victims in the member states would be provided with fair compensation. The revised convention increased the economic liability level and expanded the limits of which damages shall be included in TPL. As an example the revised convention prolongs the time limit on the validity of claims to 30 years instead of the previous limit of ten years. The maximum liability level was raised to a minimum of € 700 Million for which the operator shall show economic security. Member countries may choose to have higher national TPL levels.(42)

In Sweden the new law on TPL, "Lagen om ansvar och ersättning vid radiologiska olyckor", was drafted in order to adapt to the revised Paris convention. However the convention has not been accepted by all member states and the Swedish law will not come into effect before the convention has been approved, unless the Swedish government decides otherwise.(43) When the law comes into effect, Atomansvarighetslagen will become invalid.(44)

In many ways the suggested new law is similar to the existing but differs in some aspects. The new not yet implemented law specifies a radiologic damage as (see full text in Swedish below): (1) Personal injury or property damage, (2) Economic loss due to personal injury or property damage, (3) Loss of income from activities which are directly damaged from the degradation of the environment, and (4) Cost related to restoration of the environment or compensation for lost environment profits. (7§)(44)

According to §51 in the new law the damage from a radiologic accident must be reported at latest three years from detection of damage in order to receive compensation. A non-health related damages must be reported at latest ten years after the radiologic accident. In case of a health-related damage it must be reported at latest 30 years after the radiological accident. The law will not apply to a radiologic accident, which is a direct effect of war, riot or similar events.(11§) However, no exception is specified for the liability in case of an accident as a result from severe natural disasters.(44)

In § 27 of the new law it is prescribed that the operator has unlimited liability. In §30 it is specified that the operator should have insurance coverage or other economic security up to a level of € 1200 Million, which is € 500 Million higher than the by the Paris Convention described minimum. If the liability charges reach levels, which cannot be compensated by the operator, the state will, with contributions from other member states of the Paris convention, have a liability value up to a maximum of € 300 million.(43§) Monetary value transformation to Swedish crowns will be performed using the currency exchange rate valid at the time of the radiologic accident. 50§(44)

"Med radiologisk skada avses i denna lag en skada som har orsakats av eller uppkommit till följd av en radiologisk olycka och är

1. en personskada eller sakskada,

2. en ekonomisk förlust som är en direkt följd av en personskada eller sak- skada,

3. en inkomstförlust som inte omfattas av 1 eller 2 men till följd av en betydande försämring av miljön har orsakats av en skada på ett ekonomiskt intresse som är direkt knutet till miljön, och

4. en kostnad för att återställa miljön eller kompensera för förlorade miljö- värden, om det är en miljöskada som inte är obetydlig och den eller de åtgärder som kostnaden avser har godkänts som rimliga av den myndighet som regeringen bestämmer."

Figure 5. The figure shows a part of the possible future Swedish law (based on the reviewed Paris Convention) on third party liability in case of a nuclear accident (Lagen om ansvar och ersättning vid radiologiska olyckor). The text describes what in the law defines radiologic damage.(44)

4.7 INSURANCE SYSTEM

The owner and operator of the plant shall have insurance coverage for nuclear accidents. The purpose with the insurance coverage is to protect the plant owner, operator and third parties from costs related to a nuclear accident. Insurance is one form of treatment of such risks that are found unacceptable in the risk management process. This nuclear insurance coverage exists in combination with the conventional insurance coverage which is common for most large scale industries.

The insurance system in Sweden consists of three insurances: property insurance, business interruption insurance and TPL insurance. The operator, here OKG, will be insured by the property insurance and the TPL insurance. The majority owner, which is E.ON at OKG, has taken the responsibility to handle these insurances on behalf of OKG. However all owners pay an ownership corresponding part of the insurance premium cost, which means that E.ON pays a part of the insurance premium for each of the Swedish nuclear power plant (Ringhals, Oskarshamn, Forsmark, and Barsebäck). The property insurance covers damage on the plant and radioactive material during transport within the premises.(73)

The TPL insurance shall cover impacts on third parties. The insurance claim is limited to 10 years after the time of accident, but this may change in implementation of the revised Paris convention. The TPL insurance does not cover damage related to Force Majeure in case of earth quake, war, riot or similar situations etc and the same applies for the property insurances.(45) The terms of the TPL insurance shall comply with the law from 1968 (Atomansvarighetslagen). The insurance will cover private property, health effects and economic effects from these. However the insurance will not cover costs from singlehanded economic loss, which for example means that loss of income from inaccessibility of work place due to evacuation is not included in the insurance. The TPL insurance has a maximal value of 300 Million Special Drawing Rights, approximately SEK 3.3 Billion.(45)

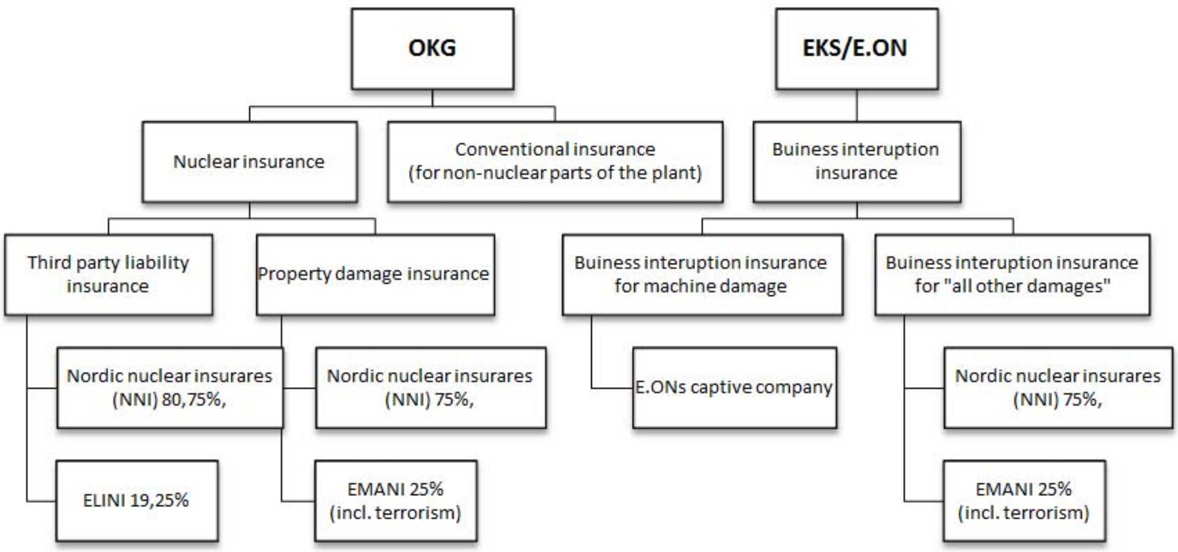

Figure 6. The figure shows the insurance structure for the reactors at OKG. The Conventional insurance has been included in the figure, but this study focuses on the nuclear related insurances and Business interruption insurances. The Third Party Liability insurance and Property damage insurance are structured under OKG and the Business Interruption insurance under EKS.

The insurance coverage from the property and TPL insurance of a Swedish nuclear power plant is based on an insurance pool system, which is a system where insurance companies collaborate in order to cope with the high monetary levels connected to the insurance. The power plant owner cannot insure the nuclear reactors to unlimited values. The insurance companies contribute with their excess resources to the pool and these may vary between the different companies.(45) The Nordic Nuclear Insurer (NNI) is a pool including both the Swedish and Finnish insurers. The purpose of the pools is to cover the insurance need for owners, operators, and suppliers for nuclear facilities or other activities connected to the nuclear industry. In 2012 in total 18 insurance companies from Sweden and Finland where a part of NNI.(46) NNI itself is reinsured in international nuclear insurance pools.(45) Apart from the NNI pool, the TPL insurance is covered by ELINI, which was created by nuclear operators in a so called mutual insurance company. The total TPL insurance structure is divided 80.75 % in NNI and 19.25 % in ELINI. The same system exists for the property insurance where a European mutual insurance company called EMANI takes a share of the coverage. The EMANI insurance coverage includes damages caused by acts of terrorism. The total property insurance structure is divided 75 % in the NNI and 25 % in EMANI.(43)

The revised Paris convention is a part of an international process of increasing the insurance level of nuclear industry. The Paris convention enforces the reactor owner to have insurance coverage for € 700 Million. The Sweden government is most likely to choose an additional coverage of € 500 Million.(45) However the owner may choose how these last € 500 Million are covered and in OKGs case the extra € 500 Million may become ensured by E.ON AG as a corporate bond. The state shall guarantee to cover costs between € 1200 and € 1500 Million in case the victims cannot be compensated by the operator. What happens if the TPL cost would reach higher than € 1500 Million is not included in this study since it is a political issue, which have generally been excluded from the study. In the Paris convention the claim can be made up to 30 years after the accident and the environment must be restored to the same condition as before the accident.(45) The revision of the Paris convention might affect the other insurance lines when it comes to available capacity for sums insured.

The owners will in most cases have business interruption insurance, but since this is not mandatory some owners may choose not to. The business interruption insurance covers the owners' loss from stop in electricity production. If the power production is lost the owner has to buy external power in order to deliver the power volume which has been sold in advance to the international trading company.(73) The business interruption insurance is based on the loss of the production corresponding to the owner share. In the property and production loss insurances Force Majeure can be referred to in case of war, riot or similar situations.(45) The business interruption insurance is divided in two parts. The first is for business interruption in connection to damage on machinery, meaning that the accident should come from "inside", e.g. failure of turbine blade. This insurance is covered by an E.ON captive insurance company. This business interruption insurance has a deduction level corresponding to 60 days of production loss. The insurance has a maximum indemnity period of three years after the accident. The second business interruption insurance is for production loss due to "all other events". The insurance include machinery breakdown damage in the "hot zone". This insurance is covered by NNI and EMANI and the business interruption insurance has a deduction level corresponding to 120 days of production loss. The insurance has a maximum indemnity period of two years after the accident. In order to receive insurance support from a production loss the stop needs to be correlated to a property or machinery breakdown damage.(45)

5. NUCLEAR SAFETY

This project focuses on risks of events with low probability and severe consequences. If one of these risks of events would occur the result could be a nuclear accident. Using the nuclear safety terminology accidents can be described as either design basis accidents or beyond design basis accidents. Design basis accidents are within the criteria which the system is designed to handle. Design basis accidents do not include severe overheating of the core. The beyond design basis accidents are generally more severe than the design basis accidents and may involve core degradation and radioactive release.(47) This project focuses on the risk of events that could lead to beyond design basis type of accidents. A beyond design basis accident, which leads to significant core degradation, is defined as a severe accident.(48) Lars Högberg (33) states in his article on severe accidents that it exist two essential objectives for safety work: (1) prevention of events developing into core damages, whatever the initial cause may be, and even though the probability may be very low accidents may still occur, and (2) prevention of large scale releases of radioactive nuclides.(33) Even though this study does not claim to investigate details of the existing safety work it is still important to study the principles of safety measures in a nuclear power plant in order to understand the context of low probability severe consequence risks.

In this section nuclear accident prevention and mitigation is described as well as the concept of defence-in-depth and multilayer protection. This section also includes a short description on the safety analysis preformed at OKG with focus on the SAR as well as deterministic and probabilistic analysis.

5.1 NUCLEAR ACCIDENT PREVENTION AND MITIGATION

In order to ensure that an initiating event do not lead to a nuclear accident several different safety systems exist in a nuclear reactor. Hindering accident propagation and limiting the impact on the public involve both accident prevention and mitigation. The definitions on prevention and mitigation within nuclear safety may vary and are not strictly separated. Generally prevention means hindering something to occur while mitigation rather means lessening the severity of the consequences from something already occurring.(49)(50) Assuming that the “something” in this case is a core damage in form of melting, the prevention would be the systems which prevent melting of the core to start while the mitigation would be to lower the consequences from the melting of the core. However in the IAEA definitions of prevention and mitigation the meanings somewhat overlap.(48)

The IAEA Safety Glossary defines that, in the context of nuclear damage, prevention measures should prevent or minimize the effects after a nuclear incident, which can in turn is described as an event with possible non-neglectable impact on the safety.(48) The principle of accident prevention is to install preventive measures, which should stop the initiating events from becoming accidents and thus ensure safety. Preventive measures relevant in both the design and operation phase for a nuclear reactor. The preventive measures also includes a safety inspired attitude among the staff encouraging discussion and critical thinking in order to early detect abnormalities and risks.(51)

According to the IAEA Safety Glossary mitigation can be described by an intervention to reduce or even avoid doses to reach the public.(48) Accident mitigation should lower the impact of an event and involve both on-site and off-site actions. INSAG-12 specifies three different accident mitigation areas. The first area is accident management, which includes preplanning of response and operation practice in order to restore control over the reactor if the condition would exceed design criteria. The accident management should aim at reaching safe reactor shut down as well as keeping the integrity of the confinements intact. The second area is engineered safety features, which includes multi barrier protection that should keep radioactive material contained. The off-site countermeasures are relevant in those cases that involve a threat to the surrounding environment and the public. Countermeasures may include evacuation and sheltering but also restriction on consumption of goods from contaminated farmland.(51)

Even if the definitions of prevention and mitigation are not altogether separated, and mitigation can be defined as a part of the prevention in terms of reducing effects from an initiating event, the basic difference between the measures is that of radioactive release and off-site impact. In this report it is assumed that prevention measures are systems that should prevent core damage to occur and mitigation measures are systems that should avoid or reduce radioactive release from a damaged on the core. This study only involves risk of events including a damaged core and only mitigation measures will be relevant.

5.1.1 DEFENCE-IN-DEPTH

INSAG-12 specifies three fundamental principles for safety: management responsibility (including safety culture), strategy of defence-in-depth, and general technical principles.(51) All areas are needed to ensure safety and in this study the main focus is on the safety measures connected to defence-in-depth. The concept of defence-in-depth includes both accident prevention and mitigation. Defence-in-depth involve a multilayer safety system which consists of several barriers, which protect the public and the environment. If an initial event leads to a failure of the inner barrier the next barrier will be threatened and so forth. Some types of events, e.g. earth quakes and fires, may jeopardise several barriers simultaneously.(51)

The multilayer system consists of physical safety barriers which protect the surrounding by encasing the dangerous material.(51) Multi barriers are two or more natural or engineered barriers which work as protection against radioactive releases. Severe accidents may occur if several barriers lose their integrity and this may lead to large radioactive release.(47) IAEA states that defence-in-depth and multi barrier principles should be included in the design in order to lower the probability of radioactive release.(52)

The Swedish Radiation Safety Authority, Strålsäkerhetsmyndigheten (SSM), specifies and enforces four radiological safety barriers at the Swedish nuclear reactors. These are the fuel matrix itself, which can endure high temperatures. The second barrier is the fuel cladding, which is made of Zircaloy and protects the fuel. The third barrier is the reactor vessel including piping system, which is described as the RCPB (Reactor Coolant Pressure Boundary). The vessel consists of a 15-20 cm thick steel capsule. The fourth barrier is the reactor containment, which is a capsule of steel reinforced concrete and gas tight sheet material. If the containment integrity is threatened by high pressures, gas can be released through a filtration system, which scrubs the gas from radioactive substances. In this way the gas can be released to the environment without containing high concentrations of radioactive substances and in doing so lowering the containment pressure to controllable levels.(53) These barriers are used at the three reactors at OKG power plant.(54)

5.2 THE SAR AND SAFETY ANALYSIS AT OKG

In Sweden the safety framework of nuclear power plant activity is monitored by the Swedish government in cooperation with the nuclear power plant owner. In practice the governmental representation is executed through the authority SSM (Strålsäkerhetsmyndigheten), which provides regulations and requirements that the power plant owner is obliged to follow. The regulations and requirements are monitored by SSM to ensure a high level of nuclear safety and radiation protection at the Swedish nuclear power plants.(2) In order for nuclear power plant to run the nuclear power plant owner need to hand in a SAR (Safety analysis report) in which the power plant design and safety is demonstrated.

The SAR is an extensive report including both descriptions of the reactor design and safety measures. The SAR shall show that the plant design is within regulations and that it provides a high level of prevention and mitigation of accidents. As a part of the SAR the output of the safety analysis performed at the power plant should be presented. In order to investigate safety at the reactors deterministic and probabilistic analyses are performed. The deterministic safety analysis aims to identify which initiating events may lead to variation in the reactor behaviour. This may be done in test matrixes with variation of parameters and simulation of the result.(55) At OKG the deterministic analysis of severe accident is performed in the Modular Accident Analysis Program (MAAP), which simulates the response of the reactor when provided with a number of function failures or events.(56)

Complementary analysis to the deterministic can be performed in probabilistic safety assessment (PSA), which can be used both for an identification of sequences that can lead to accidents and an assessment of the probability of a sequence occurring.(55) The PSA analysis is divided into three levels. In PSA Level 1 the probability of core damage is investigated. In PSA Level 2 the probability of a radioactive release to the environment is investigated. In the top level, PSA Level 3, the consequences for the surroundings in case of a radioactive release are investigated. The Swedish requirements are currently that PSA level 1 and 2 shall be performed. The results from the deterministic and probabilistic analyses are included in the SAR.(57)

OKG also takes part in several collaborations in order to gain more knowledge on nuclear safety. One of these is the Accident Phenomena of Risk Importance (APRI) reports. APRI is a collaboration between Swedish nuclear companies, universities, and authority and a new report is published by SSM approximately each third year.(58) The APRI reports have been an important reference in this study.

6. Systematisation of Nuclear accident sequences

If allowed to propagate through the reactor safety systems and barriers, an initiating event may lead to severe consequences. In the systematisation of possible accident consequences a number of sequences were chosen to describe different ways in which the radiologic barriers could be breached. Each sequence may be the result of several different initiating events and should describe the final stages in a risk evolution before the end status of the accident is reached. The end status of the reactor should be evaluated in terms of radiologic release, property damage and business interruption. The level of these parameters is very much connected to which barrier has lost its integrity. The sequence approach provided a structure for the low probability severe consequence risks and a connection to the end status description of the reactor. This project focuses on connecting the end status of a nuclear reactor to the economic impact on the reactor owner and operator. How this is done is described in chapter 7.

The list below consists of a number of sequences, which have been systemized by which radiological barriers the sequence primarily threatens. The included barriers are the fuel matrix, the fuel cladding, the RCPB, and the reactor containment. The list also contains bypass release sequences. All sequences, which have been considered as non-neglectable in terms of threat to the barrier integrity, are shown in table 4 and described in this chapter. The basis of the choice of sequences and source of information on sequence characteristics are the APRI reports, OKGs Safety Analysis Report (SAR) from 2012 (O1), 2008 (O2) and 2012 (O3), and reports from PSA Level 2 analyses of the three reactors at OKG. A future reference could also be the output from the project at KTH aiming to develop a risk oriented framework for safety analysis of severe accidents in Nordic BWRs. The project is based on a Risk Oriented Accident Analysis Methodology (ROAAM), which is based on the defence-in-depth approach focusing on reducing the uncertainty in safety analysis of severe accidents. ROAAM has an integrative approach including both risk assessment and risk management, which makes it very interesting in connection to this study. The progress of ROAAM will be described in coming APRI reports.(59)

In this section an attempt has been made to isolate non-neglectable sequences. In reality the sequences are interlinked and the occurrence of one sequence may increase the probability of another sequence. More information concerning research and theory on the sequences can be found in the APRI reports, which are published by SSM and available on their webpage.

It should be noted that some sequences are not considered as non-neglectable in all three references. The section has been made on the assumption that the sequence should be considered as non-neglectable in at least one of the references. For some phenomena large uncertainties exist in the knowledge on probability and possible consequences, and in those cases the sequences have been included even though the references may not explicitly describe the phenomenon as non-neglectable. Exception can also be found in bypass release were literature and studied accident have been used as references.

Table 3. The table shows the sequences, which have been considered as non-neglectable in terms of barrier integrity threat. The sequences have been divided by which barriers are assumed to have lost their integrity and which barrier is threatened to lose its integrity next if the sequence occurs.

Barrier categories	Consequence sequences
Barrier breached integrity: Fuel matrix, Fuel cladding	Re-criticality by re-flooding
	Formation of crucible
	Metallic crust formation at lower head due to in-vessel melt pour (APRI)
	In-vessel Retention
Barrier breached integrity: Fuel matrix, Fuel cladding, RCPB	In-vessel steam explosion
	In-vessel hydrogen detonation
	In-vessel hydrogen deflagration
	Global creep rupture of vessel
	Balloon rupture
	Local creep rupture
Barrier breached integrity: Fuel matrix, Fuel cladding, RCPB, Containment	Molten Corium Concrete Interaction (MCCI)
	Core melt coolability and melt through of base material in dry or water filled
	Hydrogen gas detonation
	Hydrogen gas deflagration
	Direct Containment Heating (DCH)
	Ex-vessel steam explosion
Barrier beached integrity: Bypass	Diffuse releases (incl. filtered release)
	Containment bypass release
	Reactor Vessel and Containment bypass release
	Leakage of contaminated water from containment

6.1 Lost integrity of Fuel capsule barrier and Fuel matrix barrier

If the temperatures reach high levels or if mechanical effects threaten to rupture the geometry, the fuel matrix and fuel cladding may be at risk. In this section the focus is on sequences involving integrity loss of the fuel cladding and matrix due to overheating and melting of the core material. The section also includes two different types of molten core configurations.

6.1.1 Re-criticality by re-flooding

If the reactor loses the make-up water injection and the level of the reactor water decrease, the temperature of the reactor fuel and control rods will increase. The control rods will melt at approximately 1225°C, but the fuel will keep its geometry up to at approximately 1825°C. Since the control rods will melt at a lower temperature than the fuel rods there will be a short time period when the control rods have started to melt but the reactor geometry remains intact. This time period may, depending on the rate of the temperature increase, last for a few minutes up to 40 minutes. If the make-up water injection with non-borated water is recovered the core will re-fill with water and a re-criticality may be introduced. This will only be applicable for a short period since there is a low likelihood of criticality when the core has lost its geometry and water is present. The conditional probability for containment rupture due to re-criticality is set to 1.1E-2 in the SAR for reactors O2 and O3.(60) The SAR for O1 does not specify this phenomena as among those regarded as non-neglectable.(57) The effect may lead either to a short peak of criticality or a more prolonged residual effects, whereas the more prolonged effects are suggested to be a larger threat to the vessel and the containment integrity.(61) The prolonged effect may lead to a pressure increase that could harm the reactor vessel and increase the probability of high pressure related vessel rupture sequences. The pressure increase may however take several hours before reaching levels that may harm the containment.(60)

The phenomena is, according to the “Riskbedömning av fenomen” (RAF), not a risk dominated phenomena since the condition (described above) will only prevail for a short time and that it is likely that the boric system could be started in a reasonable time to decrease the criticality. Re-criticality is not a risk dominated phenomena in either PWR or BRW reactor types.(62) Since the phenomenon is described as important in the PSA level 2 analyses and SAR it is however included in the methodology sequences.

6.1.2 MOLTEN CORE MIGRATION MODES AND IN-VESSEL RETENTION

Assuming the core has started to melt and migrate, but the reactors have been successfully pressure relieved, two different melt behaviours are possible. Either a metallic crucible is created with a melted pool on top or a metallic crust will be created directly in the lower head of the reactor vessel. In the case that a crucible is created with a melted pool on top, the crucible may fail and the core material is spread on the lower head. This was the case at the TMI accident. In this case the vessel penetrations at the vessel floor are at risk and the probability of melt-through of the reactor vessel increases. If the molten core pours directly into the lower head a metallic crust can be created. In this case the vessel penetrations are at lower risk, but additional molten core and core debris may accumulate at the top of the metallic crust and the reactor vessel will experience an increased probability of creep rupture.(63)

If the lower head of the reactor vessel is filled with water the molten core may fragment and create a particulate bed when it pours into the lower head. The integrity of the reactor vessel may be ensured with efficient reactor vessel cooling of the bed. Otherwise the core material may re-melt into a pool. The possibility to cool the molten core pool depends on the access of water as well at the depth of the molten core pool. The SAR for O2 (60) states that research show that if the pool depth is less than 10 cm the pool can be cooled and maintained in the reactor vessel. For depth larger than 10 cm the research diverges and possible melt-through cannot be neglected.(60)

In-vessel retention (IVR) means that the reactor vessel does not lose its integrity even though the core has lost its geometry and a partial core melt has occurred.(64) Studies on IVR, based on the TMI-accident, show that if the core melt pour into a deep water volume at the lower head of the vessel the molten core may fragment. In such a case the vessel, as well as vessel penetrations, may keep their integrity and the reactor vessel will remain intact.(61) In the KTH studies on in-vessel coolability it was found that IVR was possible if both the external cooling and the Control Rod Guide Tubes (CRGT) cooling are present and functioning.(58) IVR is a desirable state since the loss of containment integrity is less likely and the cleaning-up will be simplified compared to if the molten core pours into the containment.(64)

The loss of geometry due to melting of the fuel matrix and cladding will increase the probability of vessel rupture. However with appropriate measures the molten core may stay in the reactor vessel. The phenomena are described as mainly threatening the fuel matrix and cladding and the IVR phenomenon is interesting to discuss for all three reactors.

6.2 LOST INTEGRITY OF REACTOR COOLANT PRESSURE BOUNDARY

The reactor coolant pressure boundary (RCPB) is the collective notation of the reactor vessel with surrounding systems. Sequences that may threaten the integrity of the RCPB are collected under this head. The sequences are considered as non-neglectable risks and important when discussing nuclear reactor safety. These are melt-through of reactor vessel, RCPB integrity loss by reactor vessel rupture (including global creep rupture, local creep rupture and balloon rupture), and in-vessel steam explosion. It should be noted that for some of the sequences are not considered as non-neglectable in all main references (APRI, SAR and PSA Level 2 report) but in only one or two of them.

Some sequences, which are described in section 6.3, are also relevant when discussing reactor vessel integrity. These are Direct Containment Heating (DCH) and hydrogen gas deflagration and detonation. Hydrogen gas deflagration and detonation are only possible when there is an access of oxygen and since the reactor vessel is filled with water and steam the sequence can be considered unlikely. Oxygen may be present in the containment at up or down progression when the reactor is in start-up and shut-down conditions. In both the reactor vessel and the containment a rupture may lead to leakage of oxygen inwards or hydrogen gas outwards and hydrogen deflagration and detonation may occur.(64) The phenomenon is considered as more relevant in the containment failure sequences and is further discussed in that section. In the case of DCH the phenomena/sequence includes high pressure melt-through of the reactor vessel and ejection of the molten core material into the containment.(64) High pressure melt ejection (HPME) will be discussed in connection to DCH, since the overall sequence is more relevant when discussing reactor containment integrity failure.

6.2.1 Melt-through of Reactor Vessel

When a more extensive part of the core has molten there is a risk that it will pour into the lower head of the reactor vessel. If the lower head is filled with water the molten core will fragment and create a particulate bed at the reactor vessel lower head. However the fragmented bed can re-melt and create a molten core pool at the lower head. As described in the SAR of O2 Chapter 6.18 (60) a crust may be formed between the pool and the vessel wall. If sufficient cooled it may be possible to hinder further melt propagation and hold the molten core in the reactor vessel.(60) In APRI-4 it is stated that the risk of vessel melt-through may be reduced if the lower head of the vessel is water-filled.(65) More information on in-vessel retention can be found in section 6.1.2.

If the cooling is not successful, there is a risk that the core melt will melt through the reactor vessel. It is most likely that the molten core will propagate through the reactor vessel via the control rod penetrations or via the split between the molten core crust and the reactor vessel.(64) This is also stated in APRI 1, where melt-through via the vessel penetrations is considered as the most probable melt-through scenario. However, newer research shows that the phenomenon may not be of the previously believed importance.(66) In the case of melt-through of the vessel penetration the hole may enlarge as more molten core flow through it creating a gradual increase of the molten core flow. This is seen as positive since it decreases the probability of steam explosion in the reactor containment, since the water is heated up by the initial small stream of molten core.(64)

The reactor vessel may also experience melt-through due to creep in the reactor vessel material. This is further described in section 6.2.2.

The conditional probability of reactor vessel melt-through, assuming core melt and successful measures such as cooling of the melt, has been set to 1E-2 in the SAR for the O2 unit.(60) In the O1 and the O3 units vessel melt-through, assuming the same conditions, has not been included among those sequences that may lead to a threat of reactor containment integrity.(57)(67)

6.2.2 Reactor Vessel Creep Modes

In the case of a severe core melt the molten core and debris will affect the reactor vessel durability. Apart from melt-through of the reactor vessel penetrations, a rupture of the reactor vessel may occur by melt-through as a result from a *local creep* or a *balloon rupture* but also by a *global creep rupture*.

If the molten core pours down into the lower head of the reactor vessel and creates a molten core pool, heat will be transferred to the reactor vessel wall. Due to an internal circulation in the molten core pool the metal section of the molten material will move upwards seen from the very bottom of the reactor vessel. This area in the reactor vessel, including the reactor wall, will experience extensive heating, which may lead to creeping in the reactor vessel wall material.(64)

A *global creep rupture* may be a result of such heating of reactor vessel wall and can result in a large rupture of the vessel.(62) In a global rupture large parts of the reactor vessel will fissure round the circumference of the reactor vessel. In the PSA Level 2 reports it is stated that this sequence is less probable than a reactor vessel failure by melt-through of a vessel penetration.(64) The RAF investigation points out that since much is unknown about this phenomenon, it cannot be ruled out for either PWR or BWR type reactors, and for this reason the phenomenon has been included in among the interesting sequences.(62)

The reactor vessel may also fail due to other creep related modes. The heat-up of the reactor wall may include a creep mode which leads to the creation of a hole rather than a full collapse of the lower head. Depending on parameters such as level of heat transfer and amount of molten core material, the rector may rupture at the bottom of the lower head or at the separation between the oxidized and metallic parts of the core melt. In the first case the phenomenon can be called a *balloon creep rupture*, but also “fish mouth”, and the latter case a *local creep rupture*.(58) In the case that a “fish mouth” is created, a larger flow of molten core into the containment can be expected.(64) APRI-7 (58) refers to a KTH-study, which shows that a balloon rupture may occur when the molten poll depth is between 0.7 and 1.1 m and that a local creep rupture may occur when the depth is between 1.5 to 1.9 m. The study states that if the CRGT cooling is accompanied by external cooling, in-vessel retention may be possible.(58) p.77 These phenomena have not been considered in SAR for the units O1, O2, and O3, but have been included since indications exist that the phenomena may become of importance in future research.

6.2.3 IN-VESSEL STEAM EXPLOSION

Steam explosions may occur both in the reactor vessel, when the molten core pours down into a water-filled lower head, and in the reactor containment, when the molten core pours down into a water-filled dry-well or a wet-well. In this section the steam explosion inside the reactor vessel will be discussed. Steam explosion in the containment is discussed in section 6.3.2.(64)

When the molten core comes in contact with the water it is fragmented and a large volume of steam is created. During this fragmentation the heat exchange will be limited by an isolating layer around the fragmented particles. If this layer is disrupted the heat exchange between the water and the fragments become very intense and induces a rapid local pressure increase, which can spread to surrounding fragments leading to an avalanche effect.(64) The occurrence and impact of the in-vessel steam explosion depends on the surrounding pressure, the temperature of the water and the molten core, and the composition of the core. The water temperature in the reactor vessel can be assumed to be at steam saturation temperature. This will lower the effect on the steam explosion probability, which is increased by a large difference between water and molten core temperature. Water in the containment is on the other hand often sub-cooled, which increases the risk of ex-vessel steam explosion. The level of over-heating in the molten core also affects the probability of a steam explosion. If the over-heating is low, the fragmented particles will quickly solidify and the probability of a steam explosion will decrease. If however the over-heating is very high, the fragmented particles will lead to the creation of large volumes of steam and possibly hydrogen gas. This will also lower the probability of steam explosion.(64)

In APRI 4 it is stated that an in-vessel explosion, which has been the object for much studies during the 20th century, poses a low risk to the containment integrity. APRI 4 refers to several experiments where steam explosion has not occurred if not a pressure wave was externally introduced.(65) However, since the phenomena are only briefly discussed in PSA Level 2 and not discussed for the risk for reactor vessel barrier breach, the in-vessel explosion scenario cannot be considered as neglectable and has been included among the sequences.

6.3 LOST INTEGRITY OF REACTOR CONTAINMENT BARRIER

If the RCPB barrier has lost its integrity, the containment barrier has an increased probability of losing its integrity. This section contains sequences, which may threaten the integrity of the containment. These are hydrogen gas deflagration or detonation, ex-vessel steam explosion, core melt coolability in containment and melt-through of the containment floor, direct containment heating, and MCCI. Some of the phenomena may lead to large damages, not only to the containment, but also to the reactor building, e.g. by hydrogen detonation.

The Swedish strategy for mitigation of a core melt scenario focuses on the enhancement of the containment barriers as well as the pressure relief and filtration of released gases. As a part of the mitigation, the melted core, which has penetrated the reactor vessel, will pour into the deep water filled containment.(58) The flooding of the cavity is a reduction measure for MCCI (Molten Core Concrete Interaction). The minimization of MCCI is a fundament in severe accident management.(58) For this reason the units O1 and O2 have a wet well which is filled with water at all times. Unit O3 has a dry well which will fill up with water if there is an increased risk of vessel melt-through and containment effect.

6.3.1 HYDROGEN GAS DEFLAGRATION/DETONATION

If the reactor fuel has reached sufficient temperatures, interaction between water and cladding material (Zirconium) is possible; leading to production of hydrogen gas. Studies show that the amount of hydrogen can be used as an indication of the degree of core damage in a temperature increase. However the production of hydrogen gas in presence of oxygen may lead to hydrogen gas deflagration or detonation (61). When discussing in-vessel sequences, the hydrogen will be a product of oxygen-core interaction. In ex-vessel sequences however, the hydrogen gas can be expected to come either from oxygen-core interaction and/or core-concrete interaction.(65)

Assuming that a hydrogen-oxygen gas mix is present together with sufficiently low amounts of steam, a hydrogen gas explosion may occur in two ways: by deflagration or by detonation. In the hydrogen deflagration alternative the expansion of the fire is slower than the speed of sound. The deflagration will thus lead to a slow pressure increase in the containment. If the fire expands with a speed larger than the speed of sound hydrogen detonation will occur. In a detonation scenario the containment will experience a rapid pressure increase, which can damage the containment structure and increase the risk of leakage.(64)

In a BWR the core will risk hydrogen gas detonation or deflagration only when the vessel is air-filled or when air has leaked into the containment. During operation the vessel is filled with nitrogen and the probability of a hydrogen explosion is low.(62) In a BWR the risk of a hydrogen explosion increases at start-up and shut-down conditions, e.g. when the containment needs to be accessed, since the containment will then be air-filled.(62) According to the APRI-3 it is difficult to prove that the containment would remain intact if a large volume of hydrogen gas would develop and detonate during air-filled containment conditions.(62) A hydrogen gas explosion is not included among those considered as threatening to the containment integrity in the SAR for the units O1, O2, and O3.(57)(60)(67) However, since much is still uncertain as regards to the probability of a hydrogen gas explosion, both in-vessel and ex-vessel hydrogen gas explosion sequences have been included in the study.

6.3.2 EX-VESSEL STEAM EXPLOSION

Assuming that the core has melted and migrated through the reactor vessel, leading to a pour of molten core into a water-filled containment, there is a risk of an ex-vessel steam explosion. The steam explosion can occur since the molten core, which is a mix of molten metal and other materials, has a high temperature compared to the surrounding water. The mixing may lead to a pressure wave which could damage the containment structure, increasing the risk of leakage in the containment.(64)

The ex-vessel steam explosion sequence has a similar scenario as the in-vessel steam explosion. Apart from the parameters, which affect the probability of in-vessel steam explosion, APRI-4 describes additional parameters, which may affect the impact on the containment. These are: the vessel melt-through scenario, the fragmentations and penetration parameters into the containment water pool, the coolability of the particles, and the oxidized core melt explosivity.(65) An ex-vessel steam explosion can lead to a pressure peak, which may affect the containment integrity.(64)

Research results show divergence on whether steam explosions could threaten the reactor containment integrity or not. The RAF projects show that steam explosion is only non-neglectable for ex-vessel scenario in the BWR reactor type.(62) In APRI-7 studies on in-vessel and ex-vessel steam explosions shows that the reactor vessel could keep its integrity in the case of an in-vessel explosion, which would thus not threaten the containment integrity. However it could not be concluded that the containment would keep its integrity if an ex-vessel steam explosion would occur.(58) In APRI-4 the risk of containment damage at weak spots in the containment is highlighted. The same is true for scenarios involving multiple steam explosions, serial or parallel, at different locations in the containment. These are important areas to study in order to extend the knowledge on steam explosion risk level.(65) Ex-vessel steam explosions are of much interest in the Swedish BWR reactors since they are designed to let the core melt drain into water as it enters the containment.(63)

The conditional probability for ex-vessel steam explosions in unit O3, assuming core melt, vessel melt-through and low vessel pressure, has been set to 1E-3 in the SAR. However, when assuming high vessel pressure, the conditional probability has been set to 3E-3.(67) The conditional probability for the units O1 and O2, assuming vessel melt-through at low vessel pressure, has been set to 1E-4 in the SAR.(60)

6.3.3 Direct Containment Heating

If the core has melted and the material leaves the reactor vessel at high vessel pressure by a vessel penetration melt-through the melt will enter the reactor containment at a high velocity along with hydrogen gas and vaporized water. This phenomenon is called High Pressure Melt Ejection (HPME). The molten core and gas injection into the containment may lead to oxidation of metal particles. The oxidation increasing the amount of hydrogen in the gas at the same time as the molten core particles heat up the containment atmosphere. The mixture also increases the risk of hydrogen deflagration and detonation. This phenomenon is called Direct Containment Heating (DCH) and it may threaten the containment integrity.(64)

DCH may be a threat to the containment integrity if both reactor vessel pressure and the containment pressure reach threshold pressures for structure durability. DCH has been considered as a non-neglectable threat to the containment in the SAR from 2012 for both O2 and O3. For O1 DCH has been considered as not posing a threat to the containment integrity. The conditional probability assuming core melt, vessel melt-through at high pressure and containment failure with non-functional PS-function has been set to 1E-2 in the SAR for both O2 and O3.(60)

6.3.4 Core melt coolability in the containment and melt-through of the containment basemat

The containments in all reactors at OKG, O1, O2 and O3, are BWR-containments of pressure-suppression (PS) type. This means that the containments are divided into two separate compartments, which have been separated from each other by an intermediate floor. In the upper compartment the reactor pressure vessel and its piping are located; this is called a dry-well. In the lower compartment a large condensation pool is located; this is called a wet-well. The intermediate floor has a large number of blow-down pipes, which ends well below the surface of the condensation pool. If a pipe break occurs in the piping connected to the reactor vessel, the released steam will cause a rapid pressure increase in the dry-well. The steam will flow through the blow-down pipes into the condensation pool in the wet-well and in this way the pressure build-up in the dry-well is suppressed and kept at a level below the design pressure level of the containment, which is about 5 bars. Compared to a PWR-containment, which does neither have suppression pool nor is divided in dry- and wet-well, the overall volume of a BWR PS-containment is about 1/10 of the PWR containment, which is a so called large dry containment.

When the molten core propagates into the containment it may encounter either a dry or wet surrounding. As described above the reactors at OKG are constructed so that the molten core should land in a wet surrounding. The O1 and O2 units have wet-wells, which are permanently filled with water, situated under the reactor vessel. Unit O3, however, has a lower dry-well, which is surrounded by contained water and will be filled with water when necessary. If the containment is filled with water the stream of core melt will be fragmented and assembly as a gravel layer. However, if the containment is dry the melted core will spread over the containment as a homogeneous layer and cooling abilities will depend on e.g. the depth of the layer. The ability to cool the molten core will affect how much it can spread in the containment.(62) This may be the case in O3 if pumping of water in to the containment malfunctions.

Since the reactors at OKG have been designed to be filled with water in an accident scenario the case where the molten core will fall into water will be further described. When the molten core migrates into the reactor containment it will become partly or fully fragmented. In core melt sequences involving large molten core volumes and a high melting velocity from the broken vessel the molten core risk to become only partial fragmented.(66)

The porosity and particle size of the fragmented layer will affect the coolability. If cooling in the fragmented core fails the bed can re-melt and form a pool at the containment bottom.(62) The width of the containment floor will affect the spread and layer thickness. In addition, the shape of the fragmented pile will also affect the coolability. If the pile has a pyramid shape the cooling will be more efficient than if the layer is flat.(64)

The material may re-melt at the bottom of the containment and as the material interacts with concrete, gases may be created that can lead to high pressure in the containment increasing the risk of a failure in the containment structures.(62) The interaction between the molten core and the concrete is further described in section 6.3.5. In APRI 6 the results from KTHs DEFOR test is followed by a statement that the fragmented bed, assuming a high porosity and sub-cooled water would have some coolability margin for re-melt of material. However the report also stated that there may be internal sections of the fragmented bed which have low or no accessible cooling.(68)

The containment has a number of penetrations at the borders of the containment floor. If the containment is dry the core melt will accumulate at the bottom. As a result the penetrations protections will be molten through, leaving the penetrations open. The conditional probability for penetration protection melt-through in unit O3, assuming dry containment, has been set to 1. Penetration protection melt-through may occur in a water-filled containment as well, if the fragmented particles re-melt. For a water-filled containment the conditional probability for unit O3 for melting of the containment penetration covers on at least one penetration is set to 1E-3 in the SAR.(67) For unit O2 the phenomenon has been regarded as interesting to study further, but no conditional probability could been found.(60) For unit O1, however, the phenomenon has not been regarded as a threat to the containment integrity in the SAR.(57)

6.3.5 MCCI

MCCI stands for Molten Core Concrete Interaction and is a group of phenomena describing the interaction between the molten core and the concrete in the containment.(58) Interactions should be avoided in order to keep the containment intact. For this reason the containment can be filled with large volumes of water, which fragment the molten core into particles.(58) Even if the containment is filled with water the core debris may re-melt and interactions with the containment may occur.(61) If the containment does not contain water or if the core debris re-melt at the containment bottom the molten core will start to interact with the concrete. At low temperatures the water in the concrete will separate and steam will be produced. At higher temperatures the molten core will start to erode into the concrete and with an increasing temperature the core erosion rate will increase. In the interaction with the concrete, carbon monoxide and hydrogen gas may be created and these gases can provide transport for particles in the core debris to move up into the containment. In addition, hydrogen gas may be produced when the molten core debris reach the steel reinforcement.(64) This phenomenon has been included since it is not stated as non-neglectable in the references.

If the molten core has been fragmented and can be efficiently cooled, severe interaction between core melt and concrete is unlikely. If however the containment is dry, the probability will be higher. Another risk is that the pedestal may be dry at melt-through and if enough core melt propagates to the pedestal floor there may be an increased risk of core melt-concrete interaction.(64) The risk applies to the unit O1 and O2, but both reactors have down-comer arrangements, which should ensure that the core-melt will drain into the suppression pool in the wet-well. The risk does not apply to unit O3, since the reactor does not have a pedestal arrangement and could not be affected by this phenomenon.(8)

6.4 RELEASE THROUGH BYPASS OF BARRIERS

Bypass sequences are releases of radioactive substances without rupture of safety barriers such as reactor vessel and containment. Either the bypass includes a bypass of the reactor vessel and the containment, or a bypass only of the containment in case of failure of reactor vessel. Bypass scenarios may lead to large releases, which include large parts of the core inventory. However the extent of the release will depend on whether the bypass is directly from the reactor vessel or from failure in containment isolation. (69) In APRI-5 bypass leakage is discussed; stating that a leakage of radioactive material may be generated by a non-leak tight vessel and/or containment. The report states that leakage often occurs in a system connected to the containment and the reason is often that isolation of the system has not been successful.(61)

Assuming that the core has experienced some level of melting and production of airborne radioactivity, a failed isolation of the reactor vessel may lead to a bypass of the containment and a direct release of radioactive material. This kind of release will have a large impact since it is unfiltered.(70) In PSA Level 2 four release groups are defined as most relevant: a diffuse leakage, a filtered release from the scrubber, a breached containment or a failure in the closing of the containment isolation valves, and a bypass release from a failure in the isolation of systems connected directly to the reactor vessel. Diffuse leakage is always present when the reactor experience core damage and reactor vessel failure since the containment cannot be assumed to be completely leak-tight. Diffuse leakage can however be assumed to be within the acceptable levels of releases.(71)

Furthermore the Fukushima Dai-chi accident provided an example of an additional bypass release source. In the cooling of the damaged reactors at Fukushima, large quantities of water, both sea and fresh water, were poured into the reactor areas of the affected reactors. Some of the water was boiled off by the over-heated molten cores but some also found its way to the environment.(72) This kind of bypass release is little discussed but may prove to be of importance in the post-studies of the Fukushima accident.

7. Developed Criteria, Methodology and Implementation

In this chapter the developed concept of criteria and methodology as well as suggested implementation are presented. The concept of the criteria has been developed in connection to the structure in the methodology and consists of a maximum probability and a minimum consequence. The concept of the methodology can be described as a number of steps in which the input is systematised and translated into economic impact. This study focuses on providing a concept of a methodology and further development is needed in order to provide a full methodology for analysis including estimations of monetary economic impact.

The description of the methodology includes a short discussion on what risks of events, which in the study are described as consequence sequences or sequences, are appropriate to analyse and how they are related to the methodology. The methodology also contains an analysis of the size and distribution of the economic consequences as well as the legal and insurance framework. More information on these subjects can be found in corresponding theory sections and in the concluding remarks. Suggestions are provided for the documentation and creation of presentation material, which should be sent on to ESV and the management board. Suggestions on implementation and frequency of analysis can also be found in this section. The implementation also provides information on which functions within the organization are affected by risk management methodology.

7.1 Criteria

The risks of events that are to be used in the methodology are risks with very low probability and severe consequences. The methodology should include risk of events with probabilities around or less than 10^{-5} per reactor years. The probability criterion has been chosen from the total probability of core damage in PSA Level 2 analysis, which is around 10^{-5} per reactor year for the units O1, O2, and O3. (57)(60)(67) The risks included in the methodology should have possible consequences corresponding to a minimum level of barrier integrity breach in the fuel matrix and the fuel cladding. In terms of consequence categories this corresponds to a worst case minimum level of D1R1 (the R and D categories are further described in section 7.2.3) and a business interruption of at least three years. D1R1 can more explicitly be described as: (D1) Damage on reactor core and (R1) Small/Acceptable release. Even though D1R1 and three years of business interruption describe the lowest possible level of consequences it may still result in a substantial economic impact for the owner and operator.

7.2 Methodology

A risk of event leading to an accident can be described as an initial event propagating through one or several safety systems and safety barriers resulting in a negative effect. In this methodology the focus is on providing information on the effects in terms of economic impact on EKS and OKG. Hence the methodology starts by assessing what effects may come from initiating events in terms of possible consequences.

The core of the methodology is a number of consequence sequences and their corresponding number of lost radiological barriers. The consequences from the sequences can then be interrupted using consequence categories, which can be correlated to cost groups as well as legal and insurance effects. Including the legal and insurance effects and cost levels an economic impact can be calculated for each sequence. The economic impact should be presented in the levels best case, realistic case and worst case.

The steps in the methodology are described in the following sections and a graphical illustration can be seen in figure 7.

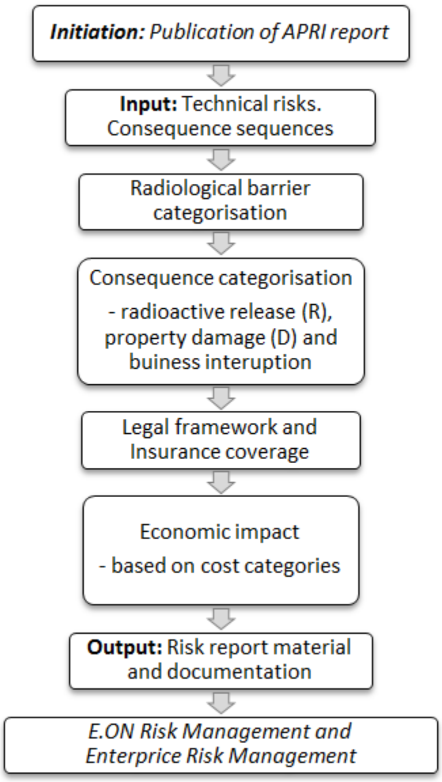

Figure 7. The figure shows a schematic presentation of the basic steps in the methodology. Steps 3 to 6 (from the top) provide the core of the methodology, in which the knowledge on the potential consequences from the sequences are structured and translated into economic impact.

7.2.1 INPUT: CONSEQUENCE SEQUENCES

The input to the methodology consists of information of risk of events called sequences with worst case level consequences corresponding to at least R1, D1 and a business interruption of at least three years as well as a probability of equal to or less than 10^{-5} per reactor year. In this study focus has been on the consequences and how these can be translated into economic impact. It is however important to include probability in the analysis in order to have a complete description of the risk or sequence. If possible, the probability should be described by the probability for core damage and the conditional probability for the sequence. The sequence information should, apart from the probability, describe the consequences in expected levels of release and the property damage in terms of worst case, realistic case and best case. The business interruption will be set to a constant value in all cases, since the minimum duration is three years after which no additional costs add on. The input should also specify the risk owner, a general description of the risk of events and a description of what has changed since the last evaluation.

The consequence sequence information is suggested to be provided by the safety analysis at OKG and describes different ways in which the radiologic barriers can lose their integrity. For example the reactor vessel may rupture either by high pressure ejection, low pressure pour, steam explosion etc., and these different scenarios make up the consequence sequences. The consequences sequences should be included if they cannot be considered as non-neglectable in at least one of the chosen references. The consequence sequences are structured by the barriers, which the sequences risk to breach. In the methodology all included sequences are connected to severe effect on the reactor core geometry and will involve integrity breach as at a minimum for both fuel cladding and fuel matrix. The consequence sequences have been developed from the literature study and in discussion with representatives at EKS and OKG. An example of which sequences are appropriate to include using the current knowledge on reactor threatening events, can be found in section 6.

7.2.2 Barrier categorisation

The main structure of the methodology is built on the level of which radiological barriers are threatened to lose their integrity from occurrence of a specific sequence. Assuming that the failure of barriers for the included sequences will start with a failure of the fuel cladding and matrix; possibly resulting in a failure of the pressure vessel and even the containment. The RCPB and containment may also experience bypass, which is a leakage of radioactive material without physical failure of barriers. In this way a number barrier failure groups, including bypass, describe the levels of severity of sequence consequences. The barrier categorization will serve as main structure and basis for the D- and R-scale. The consequence sequences provided in the input will be structured in the barrier categories based on which barrier the sequence poses a direct threat to and if bypass release is possible. For further information on how different sequences can pose a threat to the radiological barriers see section 6.

7.2.3 Consequence categorisation

The consequence sequences can be connected to a more detailed consequence structure. In the refined structure the possible consequences from each sequence are described using three consequence parameters, which together provide a more complete picture of the consequence distribution and level. The chosen parameters are connected to cost categories as well as legal and insurance areas. The included parameters are level of radioactive release, property damage and business interruption. In this section each parameter is described first separately and then interlinked. At the end of the section the connection between the consequence categories and cost categories is described.

7.2.3.1 Radioactive Release Scale

In order to correlate the radioactive release from a consequence sequence to a level of economic impact a scale of radioactive release was created. The radioactive release scale, further referred to as R scale, has four levels: R1 to R4, which increase in severity of radioactive release. The levels are presented in table 5. As can be seen in the table the levels correspond both to the INES scale levels and to the release levels used in PSA Level 2 and SAR.

The four groups R1-R4 are related to the four high levels in IAEA's INES scale considering the off-site effects aspect. The INES scale has been used since it is well known and internationally recognised. The INES levels 4 to 7 do not include the received dose, but focuses on the released amount of radioactive material in equivalence to the iodine isotope ^{131}I, while in reality a release of core inventory will lead to the release of a spectrum of radioactive isotopes. In the methodology the ^{131}I value of R1 corresponds to the INES level 4, R2 to the INES level 5, R3 to the INES level 6 and R4 to the INES level 7. INES levels 4 to 7 are specified as "an event resulting in an environmental release corresponding to a quantity of radioactivity radiologically equivalent to a release to the atmosphere" (19) in amounts as follows: for level 4 - Equivalent to more than tens of TBq ^{131}I or 250 D2, for level 5 - Equivalent to more than hundreds of TBq ^{131}I or 2500 D2, for level 6 - Equivalent to more than thousands of TBq ^{131}I, and for level 7 - Equivalent to more than several tens of thousands of TBq ^{131}I. Accidents in all considered INES levels, 4 to 7, can be expected to have an off-site impact. According to the INES manual it specified that in a level 4 release, the only probable effect would be local food control. It also specifies that level 5 releases will lead to recommendations on sheltering and evacuation and a level 7 release will lead to wide-spread and long-term effects on the public and the environment. (19)

The categories are also related to the release categories in the PSA level 2 and the SAR reports. The first category R1 corresponds to the release level acceptable releases, which is a release corresponding to less than 0.1 % of the core inventory in an 1800 MW reactor. The level is assumed to correlate to a release outside the RCPB but not outside the containment. Pressure relief through the scrubber will lead to a level R1 release. Even though the containment is intact diffuse release risk to occur since the containment cannot be assumed to be completely leak-tight. The second category R2 corresponds to a non-acceptable radioactive release, which are all radioactive releases corresponding to more than 0.1 %

of the core inventory in an 1800 MW reactor. The release is described as a limited release and it may require evacuation and sanitation of on-site and off-site areas. The third category R3 includes both large releases and large early releases. Large releases are radioactive releases above 10 % of the core inventory. Large early releases are releases above 10 % and the release occurs 6-10 hours after the accident. Extreme radioactive releases could be an effect of an early release where the reactor building is not present to delay the release. The time is important partly because of changes in the release composition and partly because emergency response measures may not be in place to react until after 10 hours. R4 does not have a direct correspondence in the SAR and PSA level 2 release categories, but can be assumed to be larger than 10 % of the core inventory and involve a large environmental impact on the surroundings.

The INES and SAR scales do not specify which type of radioactive release the categories include. However it should be noted that the releases may involve both radioactive releases to the atmosphere and radioactive releases in forms of leakage of contaminated water. If the containment has been breached by MCCI it can be assumed that some leakage of contaminated water will occur.

Table 4. The table shows how the levels in the Radioactive release (R) category corresponds to both the INES-scale and radioactive release levels used in the SAR.

Level of radioactive release
R1-level corresponds to: • Release outside RCPB and small releases to the environment equivalent to more than tens of TBq ^{131}I or 250 D2 • Acceptable releases (<0.1% of the core inventory of a 1800 MW reactor)
R2-level correspond to: • Limited release to the environment equivalent to more than hundreds of TBq ^{131}I or 2500 D2 • Non-acceptable releases (>0.1% of the core inventory of a 1800 MW reactor)
R3-level corresponds to: • Release to the environment equivalent to more than thousands of TBq ^{131}I • Large releases – Large early releases (>10% of the core inventory of the reactor and if early 6-10hours after accident)
R4-level corresponds to: • Severe release to the environment equivalent to more than tens of thousands of TBq ^{131}I

7.2.3.2 PROPERTY DAMAGE SCALE

The property damage scale, further on referred to as the D scale, includes four levels of property damage. The levels describe to which extent the reactor core, RCPB, and containment have been damaged. Some levels include damage on surrounding systems, which is a collective description for supportive systems, which penetrate or physically support the RCPB or the containment. Damage on supportive systems may also come from bypass release, where safety barriers are intact but a release has occurred from bypass.

The scale is based on an accident scenario were the damage on the reactor and surrounding systems increases as the consequences from a sequence become more severe. The scale is not applicable for all types of consequences since some accidents sequences may damage other systems in the reactor area without having significant effect on the reactor core etc. However, since this project focuses on consequence sequences involving a severe impact on the reactor core system, the scale has been adapted to those kinds of scenarios. The first level, D1, corresponds to damage on the reactor core. On this level the fuel matrix and the control rods have been damaged. However the core melt have not started to reassemble at lower head of the reactor or started to penetrate the vessel material. The second level, D2, corresponds to severe damage in core and significant effects on RCPB. On this level the core has been severely damaged, e.g. a significant parts of the core has melted and reassembled at the lower head. This level may include bypass over both the RCPB and the containment. The third level, D3, corresponds to severe damage on the core, the RCPB and the surrounding systems, and limited damage on the containment. On this level the core and the RCPB have been severely damaged, e.g. a core melt through of the reactor vessel has led to a melt pour into the reactor containment. Severe damage on the RCPB of this type will have effects on the reactor containment. This level includes a limited damage to the containment but does not include containment rupture. The level may also include bypass release of radioactive material through e.g. pressure relief venting. The fourth level, D4, corresponds to severe damage on the core, the RCPB and the containment as well as surrounding systems. On this level the reactor containment has suffered severe damages, e.g. MCCI, and surroundings systems have been affected due to pressure release and high tension on the construction. A severe damage on the reactor containment may result in a contamination spread in- and outside the reactor building and area.

The monetary value of the reactor will be lost when the fuel and the control rods experience substantial damage. This is the case for all sequences included in the methodology and in that aspect the economic impact between levels D1-D4 will not differ. The other two aspects, which are based clean-up of contaminated on-site areas and treatment of waste, will however depend on the level of the property damage and barrier integrity breach.

Table 5. The table shows the levels in the Property damage (D) category used in the methodology. The levels are adapted for core damaging sequences.

Level of property damage
D1-level corresponds to: Damage on reactor core
D2-level corresponds to: Severe damage on the core and significant effects on the RCPB
D3-level corresponds to: Severe damage on the core, the RCPB and the surrounding systems, limited damage on the containment
D4-level corresponds to: Severe damage on the core, the RCPB and the containment as well as the surrounding systems

7.2.3.3 Business Interruption Level

The business interruption parameter consists of a constant value, which is the same for all sequences. Two reasons exist to why the business interruption cost has been fixed: (i) amount of presold electricity, and (ii) the criteria of the methodology.

(i) When the production is stopped in a reactor, due either to damage on the reactor or due to damage on another reactor on the same site, a business interruption occur. Since the electricity has been presold three years in advance the owner, in this case EKS, needs to pay back the buyer, in this case E.ON Global Commodities, for the electricity which will not be delivered. This process is described more in detail in section 4.3. In short this means that the reactor owner will have a cost of maximum three years' worth of electricity production. After three years it can be assumed that no additional business interruption costs will occur. (ii) The criteria state that the methodology will be adapted for risk of events with a minimum consequence corresponding to D1R1 and a three years business interruption. In conclusion it can be assumed that consequences for all sequences will have the same contribution from the business interruption.

7.2.3.4 Interrelations between the R- and D-scales

The D- and R-scales are interconnected since the level in one scale is connected to certain levels in the other scale. This can be seen in the property damage category where D1 and D2 can be assumed to be connected to either a diffuse release or a limited release (R1 or R2), since the RCPB is still intact. In the case of a bypass sequence an unacceptable release may occur, which means that D2 also can correspond to R3. D3 can on the other hand lead to acceptable, unacceptable, and even large releases or early large releases (R1, R2, or R3). D3 could not lead to R4 release, since the containment is intact, however a scenario, involving a malfunctioning scrubber, could lead to a R3 release. D4 however would at least lead to a R3 or R4 release, depending on how much of the core has migrated into the containment and on the extent of the containment rupture. In table 7 the described connections can be found. As previously stated, all sequences will experience the same level of business interruption.

Table 6. The table shows how the levels in the Radioactive release (R) category correspond to specific levels in the Property damage (D) category.

Level of property damage	Level of radioactive release
D1	R1, R2
D2	R1, R2, R3
D3	R1, R2, R3
D4	R3, R4

7.2.3.5 Relationship between consequence categories and cost categories

As previously described, the economic impact from a nuclear accident can be described using a number of cost categories: external costs, property damage costs and business interruption costs, which in turn each include a number of cost groups and subgroups (see sections 4.1 to 4.4). The cost categories can be correlated to the consequence categories (R, D and business interruption) and provide a more economically connected structure of the consequence from a certain sequence. The R-scale, which depends on the radioactive release, is connected to the external cost category, which includes costs related to effects on the public. The D-scale, which depends on the level of property damage, is related to the cost of property damage, including the value loss, the clean-up of the reactor area, and the disposal of the contaminated waste. The business interruption parameter is related to the business interruption cost, including both the business interruption on the damaged reactor and the undamaged reactors at the same site.

In table 8 the effects on the cost groups and sub-groups are described for each level in the R-scale, which describes the level of radioactive release. In table 9 the same thing is shown, but this time for the property damage costs for each level of the D-scale. The business interruption related costs category has not been included in the table, since it consists of a constant value. The business interruption will however include both the cost of business interruption on the damaged reactor and business interruption on the undamaged reactors that are located on the same site as the damaged reactor.

The cost descriptions (table 8 and 9) have been developed by combining the literature study on nuclear accident costs and the economic impact from the studied nuclear accident and also in discussion with representatives at EKS. The tables provide a general picture of what effects can be expected from the property and radioactive release levels and the corresponding costs. In this way the two categorisation systems can be combined and provide a basis for further analysis. In order to provide a monetary value of the impact from a sequence the cost groups and sub-groups needs to be further developed and given a set monetary value for each level of the R-or D-scale. This, however, include extensive work, which was not possible in this study.

Table 7. The table shows how the cost groups and cost subgroups can be described for each level in the Radioactive release (R) category.

Cost Group	Sub-groups	R1: Acceptable releases and Tens of TBq ^{131}I	R2: Unacceptable releases and Hundreds of TBq ^{131}I	R3: Large releases and Early large releases and Thousands of TBq ^{131}I	R4: Several tens of thousands of TBq ^{131}I
Evacuation	Transport	No evacuation needed [a]	Evacuation to first level [a]	Evacuation to second level [a]	Evacuation to third level [a]
	Accommodation	No accommodation needed	Sheltering and temporary accommodation needed.	Sheltering, temporary accommodation and permanent resettlement needed	Sheltering, temporary accommodation and permanent resettlement needed; to larger extent than in R3.
	Loss of income	Loss of income due to short-term restriction on farmland, fishing and forestry industry.	Loss of income due to temporary unavailability, of e.g. farmland, and possible loss of product production, e.g. milk production, for a period.	A loss of income due to temporary unavailability of e.g. farmland, and long-term loss of economic use of land e.g. farmland and forest. Longer periods and larger extent than in R2.	A loss of income due to temporary unavailability of e.g. farmland, and long-term loss of economic use of land e.g. farmland and forest. Longer periods and larger extent than in R3.
Health effect costs	Compensation for fatalities	Fatalities possible among rector personnel.	Fatalities possible among rector personnel.	Fatalities possible including among personnel and public.	Fatalities possible including among personnel and public.
	Compensation for early health effects	Possible early health effects among personnel. No expected early health effects among public.	Possible early health effects among personnel. No expected early health effects among public.	Early health effects possible among personnel and public.	Probable early health effects among personnel and possible public.
	Compensation for late health effects	Possible early health effects among personnel. No expected early health effects among public.	Possible early health effects among personnel. No expected early health effects among public.	Late health effects possible among personnel and public.	Late health effects probable among personnel and public.
Restoration cost	Restoration of surrounding environment	No restoration needed	Possibly some restoration needed	Restoration of surrounding environment needed; extent depending on affected area and disposition of nuclides	Substantial restoration of surrounding environment needed; extent depending on affected area and disposition of nuclides

a) In the table the evacuation cost category depend on three levels of evacuation. This assumption has been made based on literature study of the Fukushima accident, in which three evacuation zones where set up in order to protect the public. In the table it is assume that the evacuation always involves three levels, but that in R1 to R3 all levels are not needed and evacuation will only occur to the first (R2) and second (R3) level.

Table 8. The table shows how the cost groups and cost subgroups can be described for each level in the Property damage (P) category.

Cost Group	Property damage category: D1	D2	D3	D4
	Damage on reactor core	Severe damage on the core and significant effects on the RCPB	Severe damage on the core, the RCPB and the surrounding systems, limited damage on the containment	Severe damage on the core, the RCPB and the containment as well as the surrounding systems
Value loss on machinery and property	Partial value loss of reactor	Complete value loss of reactor	Complete value loss of reactor	Complete value loss of reactor
Reactor area clean-up	On-site in reactor building clean up. Limited to inside environment.	On-site in reactor building clean up. Limited to inside environment.	Extensive clean-up on-site. Limited to inside environment.	Extensive clean-up on-site needed. Both inside and outside environment on the plant area.
Costs related from final storage of radioactive waste	Partial core and vessel object to final storage.	Full core and vessel object to final storage.	Full core object to final storage; partly in-vessel, partly ex-vessel. Contamination to reactor containment and vessel.	Full core in-vessel and ex-vessel object to final storage. Contamination to all in-building systems.

7.2.4 Legal and insurance effects

The combined consequence categories and cost categories provide a structure for the economic impact. In order to provide a more realistic estimation the legal and insurance effects need to be included. The legal effects include the responsibility structure set by the Swedish TPL law in case on a nuclear accident and radioactive release. To some extent the effects from the TPL law have already been included in the analysis of which costs are interesting from an owner and operator perspective.

Each pair of consequence category and cost category relates to an insurance section and effects from these needs to be included in the analysis. Parts of the external costs are covered by the TPL insurance, which is closely interlinked with the TPL law. However, it should be stated that there is not an exact transfer between the TPL law and insurance. The product damage costs will be partly covered by the Property damage insurance. In both the property and TPL insurance the operator (here OKG) is the insurant. This means that uncovered costs or in Force Majeure situations OKG will experience a large economic impact. The business interruption costs will be covered by a Business interruption insurance, which will cover the costs related to loss of electricity production. More information on the TPL law and insurances can be found in sections 4.6 and 4.7.

In table 10, which due to size have been divided in two, the legal and insurance effects have been described for each cost category, cost group and cost subgroup. The TPL law will only affect the external costs, which depend on the level of radioactive release (R scale). Furthermore, the Property damage insurance will apply to the property damage costs, which depend on the level of property damage (D scale), and the Business interruption insurance to the business interruption costs, which is set by the fixed level of business interruption. The table shows that the business interruption cost group contain two parts; business interruption on the damaged reactor and business interruption on the undamaged reactor at the same site. This is due to the assumption, included in this study, that the damage on one reactor will lead to business interruption on the undamaged reactors located on the same site. The damage connected to the risks that are included in the study, can be described as in the "hot zone" and only the NNI/EMANI insurance will be applicable. The NNI/EMANI business interruption insurance will cover costs up to two years, leaving one year of uninsured repayment costs when assuming three years of business interruption. The insurance is valid for the undamaged reactors if they are contaminated, which could be seen as a property damage. For accidents corresponding to a radioactive release, it can be assumed that the undamaged reactor will experience a business interruption for at least three years due to contamination. If the accident experiences a radioactive release corresponding to a level of R1, the contamination of the undamaged reactors is limited. In this study, it is however assumed that the undamaged reactor will nonetheless experience a business interruption of three years and that this will be covered by the business interruption insurance due to unavailability from contamination or risk of contamination. As a result, all sequences will lead to the same business interruption cost.

Table 9. The table, which continue on the next page, shows how the cost groups and cost subgroups in each cost category are affected by the Swedish TPL law and the three insurance sections. Some cells in the table are left empty indicating that the legal or insurance parameter does not apply for the specific cost group or cost subgroup.

Cost Group		Legal effects from Third party liability law		Insurance effects			
		Atomansvarighetslagen	Lagen om ansvar och ersättning vid radiologiska olyckor (*Future law)*	Third party liability insurance	Third party liability insurance (updated Paris convention)	Property damage insurance	Business Interruption insurance
Evacuation	Transport	The law includes radiologic "damage/injury". Unclear if the definition includes transport. (43)		The evacuation cost is covered in the TPL insurance. (45)	The evacuation cost is covered in the TPL insurance. (45)		
	Accommodation	The law includes radiologic "damage/injury". Unclear if the definition includes accommodation.(43)	The law includes radiologic damage, which includes economic loss as a direct result from property damage (7§), as in the case of contaminated housing facilities.	The cost of temporary stay for the evacuated population will be covered in the TPL insurance. In case of permanent resettlement this could be considered as property damage on the vacant residence and the decrease in value could be claimed as compensation. (45)	The cost of temporary stay for the evacuated population will be covered in the TPL insurance. In case of permanent resettlement this could be considered as property damage on the vacant residence and the decrease in value could be claimed as compensation.(45)		
	Loss of income	The law includes radiologic "damage/injury". Unclear if the definition includes loss of income.(43)	The law includes radiologic damage, which includes economic loss as a direct result from personal injury or property damage and economic loss as a result of significant environmental impact (7§).	Since the law only include loss of income in connection to environmental damage this is also true for the insurance coverage. (45)	Since the law only include loss of income in connection to environmental damage this is also true for the insurance coverage. (45)		
Health effects	Compensation for early health effects	A radiologic damage is covered by the law if it is due to effects (radiologic, chemical or mechanic) from the fuel or from other ionizing radioactive substance in the reactor area. (1§) The law also includes non-radiation damage in connection to radiation damage.(16§)	The law includes radiologic damage, which includes personal injury (7§), e.g. health issues.	Health effects which can be determined to have an origin in the nuclear accident will be covered by the Third Party Insurance. (45)	Health effects which can be determined to have an origin in the nuclear accident will be covered by the Third Party Insurance. (45)		
	Compensation for late health effects	The same is true as for early health effects. In addition the health issue must be reported at latest three years after the issue has been detected. The health issue may be reported at latest 10 years from the accident.(21§)	The same is true as for early health effects. In addition the health issue must be reported at latest three years after the issue has been detected. In must be reported at latest 30 years after the radiological accident. (51§)	Health effects which can be determined to have an origin in the nuclear accident, will be covered by the TPL insurance. However the accident needs to be reported at latest 10 years after the accident. (45)	Health effects which can be determined to have an origin in the nuclear accident, will be covered by the TPL insurance. However the accident needs to be reported at latest 30 years after the accident. (45)		
	Compensation for fatalities	The same is true as for late health effects.	The same is true as for late health effects.	The same is true as for late health effects.	The same is true as for late health effects.		
Restoration cost	Restoration of surrounding environment		The law includes radiologic damage, which includes costs related to restoration of the environment or compensation for lost environment profits.(7§)	The TPL insurance includes decontamination (but not full restoration) of the environment. (45)	In the updated TPL-insurance a demand of complete restoration of the environment may be included. However it is still unclear whether this is possible from insurers' point of view.(45)		

Cost Group		Legal effects from Third party liability law		Insurance effects			
		Atomansvarighetslagen	Lagen om ansvar och ersättning vid radiologiska olyckor (*Future law*)	Third party liability insurance	Third party liability insurance (updated Paris convention)	Property damage insurance	Business Interruption insurance
Business interruption	On damaged reactor						The business interruption insurance covers the owners' loss from stop in electricity production up to 2 years. (73)
	On non-damaged reactors on the same site						If the whole reactor site is contaminated (including the undamaged reactors) the business interruption of the undamaged reactors is also compensational up to 2 years of interruption. (45)
Property Damage costs	Value loss on machinery and property					The property insurance covers damage on the plant. (73)	
	Reactor area clean-up					Decontamination of the reactor area is covered by the property damage insurance. (43)	
	Costs related to final storage					Decontamination of the reactor area is covered by the property damage insurance. (43)	

7.2.5 ECONOMIC IMPACT

By combining the consequence categories with cost categories, legal and insurance effects an approximated economic impact of a specific sequence can be derived. Using the methodology the economic consequences should be described by a worst case, realistic case and best case. The figure below show how the different aspect of the methodology results in an estimation of the economic impact. In figure 8 it can be seen that for each sequence, three cases exist (a worst case, a realistic case, and a best case) and for each of these cases the consequences can be categorised and translated into two economic impacts, one on EKS and one on OKG.

The economic impact on OKG comes from the level of radioactive release and external costs, including effects from TPL law and insurances, and the property damage costs, including effects from the Property damage insurance. The economic impact on EKS will come from the business interruption cost, including the insurance effect from the Business interruption insurances.

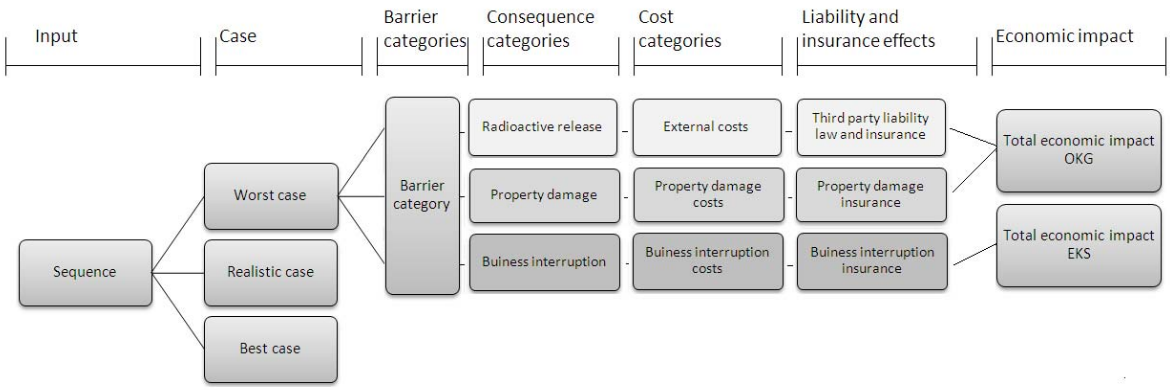

Figure 8. The figure shows a schematic presentation of the systematisation in the methodology.

7.2.6 OUTPUT: DOCUMENTATION AND PRESENTATION MATERIAL

The output of the analysis, described by the methodology, consists of two parts: documentation within EKS and presentation material, which is sent on to ESV and Generation Centre. The presentation material should be included in a risk report, which specifies the properties of the risk of events. The documentation should collect information on the analysed risks in a structured way. Since the analysis can be expected to be performed with some time in between it is important to include information from previous analyses.

Both in the documentation and the presentation material the risk of events should be specified using both probability and consequences. Since the probabilities will be very low and the consequences very severe the focus will be on presenting the consequences in a clear way. The aim of the methodology is to provide quantitative information, which could be used for quantitative analysis. It is desirable that the result of the risk of event could be presented as a continuous, a discrete or a combined graph. The probability should be included in order to provide complete information on the risk and should be presented as the core damage probability with a conditional probability for the specific consequence sequence. Conditional probability may not be available and in those cases the total core damage probability may be sufficient. The consequence should be specified in EBIT using the set of levels of release, property damage and business interruption categories RDP. The groups should include effects from the legal framework and the insurances. The consequences should be described as worst case (WC), realistic case (RC), and best case (BC).

As a complement to the information on the consequence and probability, the risk documentation and report should specify the risk name and owner as well as a description of the risk, the base for evaluation and what has changed since the last analysis.

7.3 Implementation in Risk Management process

The methodology is intended to be used as a support to the implementation of a method to include risk management in the analysis of low probability and severe consequence risks. The analysis of these risks should be connected to EKS risk management process, which is a part of E.ONs enterprise risk management. The output of the analysis should be in similar format as the risk report and provide useful information to Generation Centre and Group Management. However the implementation and frequency of the analysis will not follow the risk reporting, which is performed each quarter. In this section the analysis frequency and general implementation will be described.

7.3.1 Update and analysis frequency

The information, regarding which accident sequences are important to investigate and their probability and consequences, is rarely updated and it can be assumed that the time perspective of change in these risks is slow. However each third year the information on severe accident is updated by the SSM publication of APRI, which is a collaboration between Swedish nuclear companies, universities and authorities. According to SSM the purpose of APRI is to show that the Swedish strategy for protecting the public at a severe accident sequence is sufficient. The collaboration has existed since the 1980's and 7 report has so far been published.(58) Since the APRI report will provide useful information on accident sequences, the update of the methodology should be initiated by the release of a new APRI report. Since the update will change the input to the methodology, an analysis of the risks should be performed in connection to the update. It may also be assumed that no analysis needs to be performed between the updates. This means that the update and analysis will be performed approximately every third year.

7.3.2 Implementation

As previously described, the aim of the methodology is to extend the inclusion of with low probability and severe consequences risks in EKS risk management process, which in turn is connected to E.ON's enterprise risk management circle. A possible implementation is described in figure 8. As the figure shows the process is connected to three fields: Accident analysis, Risk management and Legal and insurance effects, which includes functions at OKG, EKS, and ESV.

The analysis will be initiated by the release of a new APRI report from SSM. The report will provide new information on accident sequences through the research presented in the collaboration. The information from the report should be combined with knowledge at the OKG's department for reactor safety (Reaktorsäkerhet och Tvärteknik, TR), that uses deterministic and probabilistic methods for severe accident analysis. In order to use the information from TR in the EKS risk management process, it needs to be fitted into an appropriate format of the same type as the sequence list in chapter 6. The sequences need to be assessed in terms of radioactive release, property damage and business interruption for a worst case, a realistic case and a best case. It is suggested that the information from TR is delivered to EKS through the risk manager at OKG in order to use existing communication routes between EKS and OKG. The information can then be used in the risk management at EKS to interpret the sequence consequences in terms of consequence categories, R, D, and business interruption, as well as cost categories, including legal and insurance effects. The legal and insurance expertise exist both at ESV and OKG, and when the analysis has been initiated an inquiry needs to done on whether and how these aspects have changed since the last analysis. Including all above described aspects the total economic consequence for each sequence should be described in a risk report, which should be sent on to and included in E.ON's enterprise risk management. The analysis should also be well documented at EKS in order to give useful background in the next analysis. The analysis should include much collaboration between the ESV, EKS, and OKG risk managers as well as risk analytics at TR in order to provide a reliable risk report.

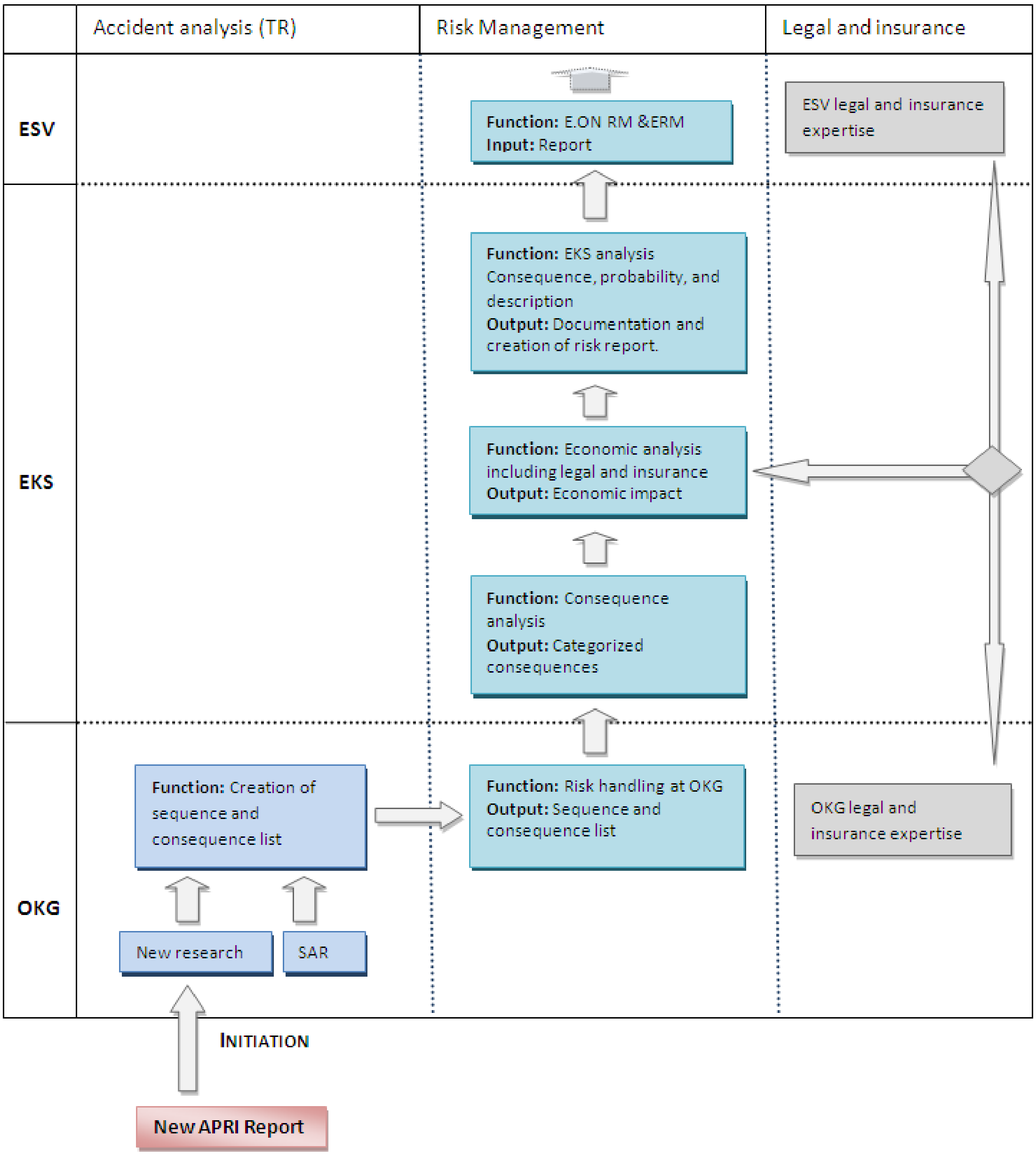

Figure 9. The figure shows a schematic illustration of the suggestions for implementation of the methodology in the organisation. In this implementation suggestion the methodology involves ESV, EKS and OKG and includes three departments, among which the EKS risk management process is central.

8. Conclusion

In conclusion of the study this chapter include some remarks on the developed concept of criteria, methodology and implementation. The chapter also contains a section describing the authors' suggestion on future development and studies.

8.1 Concluding remarks

In this section some concluding remarks on the study are presented and discussed. The remarks focus on connecting the results and conclusions with the problem description and purpose of the study.

8.1.1 Developed Criteria, Methodology and Implementation

A concept of a criteria and methodology for analysis of low probability severe consequence techno-economic risks have been created in this study and described along with suggestions on implementation. The concept describes the general idée of how the EKS risk management process can be extended to include these risks and the study includes possible answers to which risks should be included in the methodology, how the analysis can be performed, and how the methodology can be introduced into the organisation.

The study also shows that the key of the methodology is the transfer of the existing knowledge on low probability severe consequence risks into a structured format and, in doing so, increase the knowledge about these risks. By structuring the knowledge on the risks as well as presenting them in a risk management adapted way, the information on techno-economic risks could become more homogeneous which in turn would make them more comparable and easier to comprehend. Further this could help decision-makers to take more well-informed decisions based on reliable and well-structured information. In this sense it is important to include analysis of low probability severe consequence risks in the risk management process.

Criteria, on which risks should be assessed in the analysis, have been created in the study. The criteria include a maximum probability and a minimum consequence description. However, since no monetary values were included in this study the consequence limit was based on the consequence categories. The criteria could be seen as less important than expected since the consequence sequences are suggested to be provided by the safety analysis department at OKG, which would use research combined with deterministic and probabilistic analysis to determine which sequences are important to include in the methodology. None-the-less the criteria provide guidelines on which risks the methodology aims to investigate.

A concept of a methodology for low probability and severe consequence risks was created and described. Even though the methodology is based on the existing EKS risk management process some significant differences and challenges exist. One challenge is the input information from the OKG department TR. This information has so far not been adapted to a risk management appropriate format and a method on how this should be done, without adding unnecessary new functions, could become a challenging task. One of the most significant differences is that the consequences are not only determined by the expected business interruption, but also by the radioactive release and by the property damage. This complexity of the risk analysis provides a high demand on the tools and the information which should help the risk manager to assess the risk.

Suggestions on the implementation of the methodology have been investigated and are described in the report. The implementation includes three work processes connected to functions at OKG, EKS, and ESV. This will involve a challenge in the possibly increased and adapted communication between the OKG TR and the risk managers, the EKS risk manager, the ESV risk manager, and the legal and insurance experts at ESV and OKG. When an update and analysis has been initiated all parties need to collaborate in order to provide high quality risk report material. It needs to be described more in detail how this should be performed in further developments of the methodology. A large part of the work in to the analysis is connected to the preparation of the consequence sequences that provide the input to the methodology. This is suggested to be performed at the OKG TR, which means that the methodology needs to be created in consideration of and collaboration with the department.

The update and analysis are suggested to be performed simultaneously each third year by initiation from the release of new APRI report. It may however be appropriate to update and perform the analysis if large reconstructions are performed at the power plants and the next planned update and analysis is far in the future.

8.2 Further Development and Future Study

This section describes some possible future developments of the methodology and implementation as well as some suggestions on areas which would be interesting to continue to investigate in further studies.

8.2.1 Further development of methodology

In general the concept of methodology needs to be optimized to EKS needs and be further developed into a complete methodology, which can be implemented into the organization. This will require work and collaboration between the involved parties as well as approval in the organization.

In order to create a complete methodology the cost categories need to be connected to monetary values. By creating a database on specific monetary values for the cost groups and the cost subgroups and the total economic impact could be estimated.

When developing the methodology it is very important to collaborate with OKG on how the sequences can be evaluated and how they are connected to probabilities and initiating events. The connections between the sequences and initiating events are important to include when considering possible treatment of the risks. However, if it should be included in the analysis as such, or simply be included in the discussions related to the analysis will need to be determined as the methodology is further developed. This study has focused on the consequences and how these can be structured and interpreted, but in further studies it is important to also include probabilities; both in terms of the total probability of core damage and the conditional probability for specific sequences. It is important to include the probability along with the consequence in order to provide a complete description on the risks.

In this study delimitations have been set to exclude risks including failure of more than one reactor at the same site. Considering the Fukushima accident it would be recommended to include simultaneous reactor failure in order to analyse these risks as well. In a future development it would also be recommended to include non-nucleate accidents, which in this study have been excluded, since these may lead to large economic impact even though they may not affect the reactor core. It could finally be interesting to study political and trademark issues related to the occurrence of the low probability severe consequence risks.

8.2.2 Enhancing connection between risk management and safety analysis

As previously described the study includes suggestions on how the methodology can be implemented in the organisation. These suggestions specify that collaboration is needed between the TR department at OKG, the OKG risk manager as well as the EKS and the ESV risk managers. Especially important is the development of format for how to transfer the knowledge on low probability severe consequence risks and their properties from the TR department to the EKS risk management process. This transfer will gain from an increased collaboration between the processes and may lead to a general gain in knowledge on these risks. Therefore the inclusion of low probability severe consequence risks into the risk management and enhanced collaboration between the safety analysis and risk management is recommended. This inclusion will need collective measures to increase the interaction between the risk management function and the TR department.

8.2.3 POSSIBLE FUTURE EFFECTS FROM THIRD PARTY LIABILITY

In this study not much focus has been given to the coming update of the TPL law and the corresponding reviewed TPL insurance, since much is still uncertain on the characteristic of these. However, when these are implemented into the legal and insurance system, the methodology needs to be updated to include the new characteristics. One aspect of including the “new” law is the possibility of complete liability in case of an accident initiated by a natural disaster. In the current law such events fall under Force Majeure and will not lead to third party liabilities. The TPL insurance is valid for severe natural events with exception to earth quakes. However in the “new” law nothing is mentioned on severe natural disasters, which implies that these are not included Force Majeure events, and could lead to large uninsured third part liabilities. It is unclear how this will be approached in the corresponding insurance, but if they will not be covered by the insurance, this type of accident would mean a substantially higher economic impact for the operator. It is recommended that topic is further investigated.

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Appendices A: Examples of Previous Accidents and Accident Simulations

In order to provide a general view on how risk of events with severe consequences can evolve into full scale accidents four nuclear accidents have been studied. In complement to the accidents the results from the Swedish simulation of a nuclear accident at OKG, SAMÖ/KKÖ, has also been studied. The study aimed to provide a general view on the accidents in terms of accident sequence, radioactive release and effects from the radioactive release. The economic impact of the accidents has been studied from an owner and operator perspective. The economic impacts from the accidents are presented in chapter 4. The studied accidents are Windscale, Three Mile Island, Chernobyl, and Fukushima Dai-ichi. Due to the variation in available information on the accidents the descriptions below may vary in content between the accidents. However they all provide useful information in order to understand the effects of a nuclear accident.

A.1 Windscale, UK, 1957

In the Windscale accident in October 1957 a fire took place in the core of a graphite-moderated reactor used for plutonium production in United Kingdom. The fire led to partial destruction of the core and release of radioactive material. The fire was put out the day after the accident by flooding of the reactor core with water.(34) The fire in the graphite material occurred when unexpected Wigner energy was released.(76) The Wigner energy produced by a change in the graphite structure due to irradiation with neutrons.(77) The accident led to off-site effects, but not to the same extent as the Chernobyl or the Fukushima accidents. The accident is classified as a Level 5 accident on the INES-scale. INES level 5 means that damage has occurred to several safety barriers and that a limited radioactive release has occurred.(78)

The reactor was completely destroyed and is still not fully decommissioned (29). The Windscale accident led to an outlet of $7.4*10^{14}$ Bq of ^{131}I and the radioactive material was spread over UK as well as other parts of Europe.(76) The main off-site action at the Windscale accident was the disposal of cow milk from the affected area. The milk contained alarming levels of ^{131}I and the Medical Research Consul enforced guidelines on iodine levels in milk; the maximum level set to 0.1 µCi L^{-1}. 5 days after the accident an area of approximately 600 km^2 still showed levels of iodine in milk exceeding the maximum level.(34) For several weeks after the accident the British government banned the consumption of milk from the area around the Windscale plant. The reactor remained sealed until 1980 when the process of clean-up the reactor area was initiated. The clean-up is expected to proceed until 2015.(79)

A.2 Three Mile Island (TMI-2), USA, 1979

The Three Mile Island accident (TMI) occurred in block 2 of the Three Mile Island Nuclear Station situated in Pennsylvania, USA. The reactor was a PWR with a rated capacity of 880 MWe and a thermal output of 1 800 MW (33). The accident can be described as a small leakage of coolant-accident (Small LOCA), but also as a bypass accident. The leakage occurred in a PORV (Pilot-Operated Relief Valve), which should prevent high pressures to release the safety valves. For some time the leakage remained unknown to the operators and several inappropriate decisions lead to the core becoming dry, overheated, and partly melted. However the pressure vessel remained intact. The system also experienced a hydrogen explosion when hydrogen was let out of the pressure vessel in order to decrease the pressure in the reactor. Some of the contaminated water found its way into the auxiliary and fuel handling building, but also outside the reactor containment and into the surroundings. Even though the accident led to a substantial core melt and a migration of molten core into the lower head of the vessel, the reactor vessel integrity was not breached and the molten material did not leak into the containment.(23) Because the integrity of the containment stayed intact, the spread of radioactive materials was limited and the radioactive releases were comparably small.(33) After one month the natural circulation was re-established.(23)

Even though the accident at TMI-2 led to severe core impact as well as hydrogen detonation the release of radioactive material was rather limited.(23) The accident is classified as a Level 5 accident on the INES-scale. INES level 5 means that damage has occurred to several safety barriers and that a limited radioactive release occurred.(78) The severe core impact lead to a complete destruction of the reactor and the permanent loss of energy production. The TMI site is still in use with power production in the TMI-1 reactor.(29)

Within the first days of the accident, sheltering was recommended to people within a radius of 16 km round the TMI site. Evacuation was recommended to pregnant women and children within an 8 km radius. However, the accident led to a spontaneous evacuation within an area for approximately 8 km including around 144 000 people. The evacuation (both official and spontaneous) was lifted after a week.(23)

A.3 Chernobyl, Soviet Union (now in Ukraine), 1986

The Chernobyl accident happened in the Chernobyl-4 reactor on the Chernobyl site located in Ukraine 120 km north of Kiev. The reactor was of the type RBMK, i.e. graphite moderated channel-type boiling water reactor, with a thermal power output of 3200MW.(33) The Chernobyl-4 reactor was designed to have a positive void coefficient of reactivity, which means that an increase of boiling will lead an increase of reactivity. Another feature of the reactor was slow-moving control rods that even had some delay in the insertion command. The accident happened when safety experiments was performed at the reactor. In the experiments the power accidently became too low and in the attempt to force the reactivity up the reactor became prompt critical and several explosions led to complete destruction of the reactor and the reactor building.(23) All barriers and the reactor building were destroyed creating an unhindered radioactive release. The accident generated a large spread of radioactive material to the surroundings and at large distances. The accident led to health effects on a large geographical area. The accident is classified as a Level 7 accident on the INES-scale. An INES level 7 accident means that no safety barriers remain intact and a major radioactive release has occurred.(78)

The area within 30 km from the accident was evacuated but the evacuation started days after the accidents and continued until approximately ten days after the accident. Cattle within the area was killed and stored in special facilities.(34) Srinivasan et al. (17) claim that 116 000 inhabitants within a 30 km zone were evacuated followed by another 230 000 people in the following years.(17) The radiologic effects from the Chernobyl accident did not only affect the on-site personnel and habitants of an area at 30 km from the reactor, but also other parts of the Soviet Union and European countries outside the Soviet Union.(34)

A zone, within which levels of ^{137}Cs were considered extremely high, became restricted in the aftermath of the accident. The zone was approximately 150 000 km^2 and a population of approximately 6 million people is believed to have been affected by the restriction. The population in the affected region experienced both external and internal radiation. The internal radiation dose came from consumption of contaminated goods.(24) The Chernobyl accident affected large areas, approximately 45 000 km^2, of agricultural land, which demanded prolonged actions focusing at first on monitoring and rejection of goods as well as restriction of land-use and later on remediation of soils and increasing fertility in order to lower the internal contamination risk for the goods.(24)

The Chernobyl accident affected large forest areas; approximately 40 000 km^2 with inhabitants of around 50 000 people became contaminated.(24) Some forest areas were completely destroyed and has become known as “red forests”.(34) Forest areas are important to protect the environment as a whole by lowering the dispersion of radionuclide, but in may also contribute to internal radiation from forest products such as berries, mushrooms and game. Countermeasures for contaminated forest areas are difficult to carry out due to high costs or poor availability of suitable technologies and often the actions are left at a general ban on collection of forest products as well as fire protection.(24)

The fate of the 30 km-zone, which is still under restriction, has been debated. There are suggestions of making the zone into a final storage area for nuclear waste or to simply use the area for study of long-term effects from radioactive exposure.(24)

A.4 Fukushima Dai-ichi, Japan, 2011

On March 11 Japan was hit by an earth-quake of the magnitude 9.0 that also lead to creation of a number of tsunamis, which hit the Japanese coastline with waves reaching up to 15 meters. Several nuclear power stations are located on the coastline and some were affected by the earth quake and tsunami. One of these power plants was Fukushima Dai-ichi including 6 BWRs.(72) The accident was initiated when the earth-quake disabled the external AC support to all six reactors and units 1-4 became the most affected.(72) Unit 1 had a rated thermal power of 1 380 MW and units 2-4 had a rated thermal power of 3 880 MW.(33) In reactor 1 the tsunami lead to loss of support power from the diesel generators as well as loss of the coolant pumping, which in turn led to overheating and melt of fuel. The fuel propagated through the reactor vessel into the containment, which experienced a pressure increase. The pressure increase led to cracks in the containment wall and leakage of hydrogen to the reactor building. The mix of hydrogen and oxygen led to a hydrogen explosion and the destruction of the reactor building. The scenario in reactor 3 was rather similar, except that reactors 2 and 3 had a passive core cooling system. After some time, however, the passive cooling failed and reactor 3 experiences a hydrogen explosion leading to the destruction of the reactor building. The hydrogen produced in reactor 3 spread into the building of reactor 4 which also experienced a hydrogen explosion. Reactor 4 was emptied on fuel, but the spent fuel in cooling pools was of great concern due to their high decay heat. The passive cooling system failed in reactor 2 as well and the reactor is believed to have experienced a failure of the reactor vessel and fuel melt propagation into the containment. On reactor 5-6 a cold shut down could be performed on the 20th of March.(72) The accident is classified as a Level 7 accident on the INES-scale. INES level 7 mean that no safety barriers remain intact and a major radioactive release has occurred.(78)

The accident led to a core melt and migration to bottom of reactor vessel and partly into the containment in three reactors, resulting in integrity breach of all safety barriers. The accident led to large airborne radioactive releases. The releases are believed to have reached levels of iodine equivalence up to $7.7*10^{17}$ Bq. Large releases were also detected by leakage of contaminated water both from the core cooling and water from storage volumes. The releases are expected to lead to large impacts and long term monitoring of the land and marine environment.(72) The radioactive release was approximately 15 % of that at Chernobyl.(17) The release has led to monitoring of the environment, agricultural products, water etc. in the surroundings. Some clean-up actions have been taken in the most contaminated off-site areas.

The protection of the surrounding residents was at first performed by evacuation of residents within a radius of 3 km and a recommendation to stay indoors within a radius of 3-10 km around the power plant. This was, however, later expanded to evacuation within 20 km and a recommendation to stay indoors within 20-30 km. In the end around 120 000-150 000 people were evacuated from an area of approximately 1 100 km^2.(72)(33) Some difficulties were experienced during the evacuation, especially in connection to the hospitals within the evacuation area. It is estimated that 60 hospitalized patients died during the evacuation.(33)

In April 2011 the Japanese government followed the Nuclear Safety Commissions (NSC) recommendations and set up three different zones in the area. Zone I, the Caution zone, reached 20 km in radius around the power plant and was prohibited to enter. Zone II, the Planned evacuation zone, stretched north-west of the power plant in the direction of the large radioactive spread and was planned to be evacuated for a month. Zone III, the Emergency evacuation preparedness zone, reached around the power plant at a 20-30 km radius. Zone II was recovered in September 2011 and could be re-habitated.(72)

A.5 SAMÖ/KKÖ

In 2-3 February 2011 a simulation and coordination exercise was performed; including a number of local, regional, and national actors to simulate and study the overall society response in case of a nuclear accident at OKG. The focus of the simulation was to combine collaboration simulation, “Samverkansövning” (SAMÖ), and nuclear simulation, “Kärnkraftsövning” (KKÖ), into one simulation, which was intended to focus on both the short-term and long-term effects from a nuclear accident.(36) Both SAMÖ and KKÖ are simulations that have been performed several times, however separately. The previous SAMÖ simulations have been performed by the Crisis Response Authority and the simulations focus on studying large geographically effects and the effect on society in case of a crisis. KKÖ simulations have been performed in all three of the nuclear counties. The KKÖ simulations involve actors on local, regional and national level, who are affected by the nuclear accident response.(80)

The simulated scenarios included a large release of radioactive material into the surroundings. The aim was to set high demands on communication and information in order to create a scenario were the affected units needed to have high performance on collaboration and coordination. The simulation was divided in three parts. The initial step consisted of the acute events the first two days and included the radioactive release. The second step consisted of an analysis of the effects on society and the long-term effects from the nuclear accident simulation performed in step 1. The third step consisted of two seminars focusing on the analysis of step 2 with the key question: How does society recover after the crisis? (Hur återställs samhället efter krisen?) (36)

The first part of the simulation consisted of the accident scenario. The scenario started with problems to cool two of the reactors at OKG outside Oskarshamn. The power plant decided to issue a “high readiness” alarm (“hög beredskap”). The next step was a fire in the waste facility leading to the evacuation of the personnel at OKG and SKB (Svensk Kärnbränslehantering AB) that is closely situated. Later the external electricity became inaccessible and the back-up cooling of the reactors malfunctioned. The scenario lead to a release through the scrubber filters, which also malfunctioned, and resulted is an unfiltered radioactive release. The accident is graded as a level 5 accident on the INES scale. INES level 5 means that damage has occurred to several safety barriers and that a limited radioactive release occurred (78). After four weeks the situation was assumed to have stabilized but all reactors on the site stands still. 12 000 people had to evacuate and be temporary accommodated outside the most affected zone. (80)