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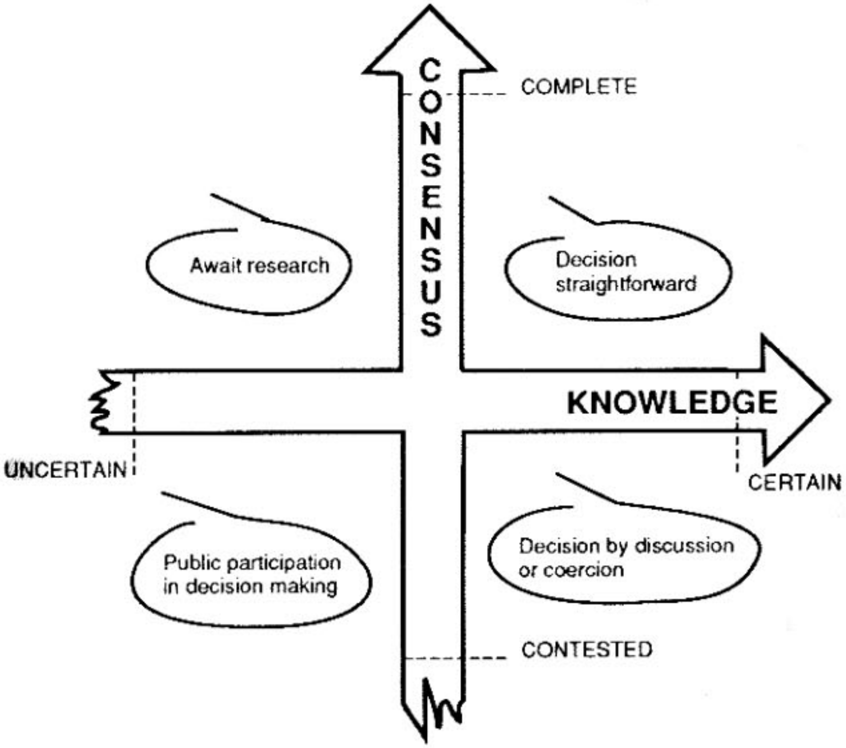
Risk analysis and safety rationale



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Risk analysis and safety rationale

Final report of a joint Nordic research program in nuclear safety

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Abstract

Decision making with respect to safety is becoming more and more complex. The risk involved must be taken into account together with numerous other factors such as the benefits, the uncertainties and the public perception.

Can the decision maker be aided by some kind of system, general rules of thumb, or broader perspective on similar decisions?

This question has been addressed in a joint Nordic project relating to nuclear power. Modern techniques for risk assessment and management have been studied, and parallels drawn to such areas as offshore safety and management of toxic chemicals in the environment.

The report summarises the findings of 5 major technical reports which have been published in the NORD-series.

The topics include developments, uncertainties and limitations in probabilistic safety assessments, negligible risks, risk-cost trade-offs, optimisation of nuclear safety and radiation protection, and the role of risks in the decision making process.

Key words Cost benefit analysis, decision making, environment, human factors, management, nuclear power, nuclear safety, optimisation, probabilistic estimation, radiation protection, regulations, reviews, risk assessment, safety analysis

Summary

The safety of nuclear energy installations depends critically on the assessment of the risks involved, and on the subsequent decisions taken by designers, operators, regulators and politicians. A multitude of methods have been developed to aid the assessment and decisions. This report describes the use and further development of some such methods in the Nordic countries, which have already contributed to improvements in nuclear safety and radiation protection.

The program has shown, however, that in large decisions, there are no simple rules for balancing risks versus benefits and other factors involved in a decision. Risk comparisons can give some perspective but the public tends to handle the ethical issues involving risk in a way that is particular to each risk. Risk perception plays a large role, but is governed by many factors in a complicated interplay. These may lead to exaggeration of risks as well as indifference to them. Despite these problems, simple economic valuations of health effects are still used for decision making and seem to have some impact on the decisions.

The study has also concerned the possible trade-off between risks for health effects from low probability, high consequence events such as nuclear accidents, and from certain exposures such as normal releases. At present, such a trade-off is surrounded by controversy, and no generally acceptable rules for it have been found. This is not surprising but is consistent with the concept of incremental decision making which is explained below.

Generalisations are, however, emerging when it comes to valuations of what are negligible risks and what are tolerable risks. A lively discussion is going on both with respect to various occupational hazards and concerning exposures to carcinogenic substances in the environment.

Perspective on decisions involving risks

Mankind has always been exposed to risks, i.e. the possibilities of unwanted outcomes of an action or a situation. The situation has, however, improved. In the last few centuries, our expected length of life has doubled. One reason for this is the increased awareness of risks and the large efforts spent on preventing risks from diseases and other major hazards.

Today's large efforts spent on risk reduction are not a reflection of increasing risks to human health but rather show that we are prepared to continue reducing risks despite the law of diminishing returns.

`Synoptic and incrementalistic approaches to decision making

A *synoptic* approach towards decisions which entail risks requires

□ the definition of alternative possibilities for decisions

□ an analysis of the consequences of these alternatives in terms of costs, risks and benefits, and

□ a decision based on the results of the analysis.

The decision involves a weighting of the consequences which reflects the decision maker's set of values. In one technique for aiding the decision, monetary values are assigned to all parameters involved. The technique is called cost-benefit analysis.

Many other decision aiding techniques have been tried, usually involving other types of quantification on a single scale based on the decision maker's set of values. Examples include multiattribute utility analysis and multicriteria analysis. These are fairly complex techniques which often are computer based.

It is obvious that in many complex decisions, much relevant information will not be available to the decision maker at the time of decision. An alternative way of arriving at decisions in the face of uncertainties has been developed. It is called *incrementalism* and is based on an assessment of the uncertainties in the factors involved, and the degree of consensus about the decision to be taken. The basic rule of thumb is that small uncertainties and a high degree of consensus justify far-reaching decisions while large uncertainties and lack of consensus justify research efforts in combination with a little step or increment forward in the area subject to the decision.

Hazards from radiation and chemicals

The *hazards* in our definition are the outcomes in the form of injuries following exposure to an agent. Hazard analysis means the study of the relations between exposure and hazard. Some hazards are directly noticeable following high level exposures. Delayed hazards may occur after higher or lower eposures, e.g. cancer and hereditary disease. These are often starting with an injury to the hereditary material, DNA. Agents that can cause such injury are called genotoxic. The principal interest in hazard analysis within the Nordic program has concerned such agents. Ionising radiation can be genotoxic. Tens of chemicals are known to cause human cancer, hundreds animal cancer, and thousands cell DNA injury.

Within the Nordic program, a comparison has been made of genotoxic risks from radiation and chemicals. There is an emerging international consensus that cancer initiators such as radiation and benso(a)pyrene may cause cancer with a frequency that increases with the integrated exposure (concentration times time) even at low doses. Authorities often assume for regulatory purposes that the relationship is linear and has no threshold.

It is generally difficult to establish the real hazard that follows from exposures to genotoxic agents e.g. because the time prior to clinical manifestation of an injury may amount to decades, and individuals may have quite different sensitivity. To establish the risk, one may use the fact that genotoxic injury to a cell may create molecular attachments (adducts) to DNA, which can serve as indicators of carcinogenic potential. This may enable extrapolation from radiation to chemical hazards. In a promising application, this method has been used to predict leukemia risks from ethylene oxide exposures.

Probabilistic safety analysis

In our terminology, *risk analysis* means the assessment of various hazards associated with a given source such as a nuclear power plant, or a given situation such as the exposure situation in a country with respect to radiation.

The risks related to Finnish and Swedish nuclear power plants have been studied using Probabilistic Safety Analysis, (PSA). By this method, complex systems are assessed with respect to the likelihood of accidents. The contributions to system failure by all component and human failures are summed in a systematic way. Exercises to compare the models used and clarify their limitations have resulted in improved knowledge of the realisation of such exercises, as well as in improvements in the modelling of common cause failures and human interactions. The new findings have directly influenced the probabilistic safety analyses in the Nordic countries and helped in setting research priorities.

Probabilistic safety analyses may help in identifying possible weak spots in the design and operation of nuclear power plants and other complex industries, and in ranking the dominant risk contributors. Systematic analyses have resulted in significant improvements in plant safety. The techniques of probabilistic safety analysis, however, have limitations. Such limitations have been studied with respect to several important risk contributors such as human interactions and multiple failures having the same origin (common cause failures). The associated uncertainties have been discussed.

It has been concluded that probabilistic safety analysis is not mature enough for stringent comparisons of quantitative estimates with prescribed safety goals.

Another judgment holds that the uncertainties in the treatment of external events, especially earthquakes, are much larger than the uncertainties in the treatment of internal events such as loss of coolant accidents and transients (sudden changes in e.g. reactor power).

Value judgments and decision making

As previously mentioned, the decision involves applying value judgments to the results of consequence assessments. This procedure is surrounded by controversy, mainly because value judgments may be very different between individuals.

The word ethics may mean a set of values adhered to by a group and expected to govern their actions. The sets of values depend strongly on such factors as religious and cultural heritage. The discipline of ethics does not help by stating that a set of values is right or wrong. Rather, it puts the spotlight on the ethical dilemmas facing the decision maker:

□ competing values
□ conflicting obligations
□ trade-off between costs and benefits in alternative outcomes.

For the resolution of such dilemmas in Western societies, there is not a fixed set of values available but an agreed process, the democratic process. This is influenced by the changing values of the population. The elected representatives of the people have the difficult task to interpret these values.

It was concluded that the discussion on ethical problems related to nuclear energy production has to be carried out without any help from similar debates in other sectors. This also holds for the particular issue of allocation of resources to different categories of safety and health measures. The reason is that the populations involved on the whole will not accept any comparisons between different types of threats to life.

On the issue of risk perception, indifference to risks has been studied rather than sensitivity. An earlier study on home owners indicated that about two thirds of those who were informed about potentially high radon levels in their houses were indifferent to the risk. This may be one factor behind the experience in Sweden that mitigating measures against radon are neglected by a large share of those who know they have rather high levels in their homes.

A special study has been performed in a Swedish community to explore the willingness of home owners to take mitigating actions against radon. The results show that the willingness to take action is higher if the individuals involved are younger, have a higher income, and face a cheaper countermeasure or a higher radon level.

What is a low risk?

Judgments on when a risk is negligible were studied. A consensus seems to be emerging, both among countries and between the regulators of chemical and radiation risks.

An annual exposure committing 0.01-0.1 persons per million inhabitants to cancer or death has been characterized as negligible The lower limit for risks of concern often lies in the interval 1-10 cases of committed serious injury or death per million exposed during one year.

Economic valuation of health detriment

In most basic cost-benefit analysis, all consequences involved in a decision are put on a common monetary scale. This means that for instance environmental and health effects are given in monetary terms.

Many studies have tried to estimate the resources spent to prevent the loss of a human life. They tend to fall in the range between 1 and 10 times the value of the production time which would be missed through the loss of life. In the field of nuclear safety they often exceed this range, and in the field of medical measures they often fall below the range. In the study of home owners' willingness to mitigate radon problems, the implied value was also well below the range.

An empirical study was undertaken concerning the valuation of the health risk associated with living in a home with high radon levels. The selling prices of these homes were compared with the prices of homes with less radon. The preliminary results showed no influence of high radon levels on the price, but the uncertainties were rather large.

Optimisation of radiation protection at nuclear power plants

The International Commission on Radiological Protection, (ICRP) recommends that optimisation analyses should be carried out to establish whether exposures are kept As Low As is Reasonably Achievable (ALARA), social and economic factors being taken into account.

A study was made on the implementation of this recommendation in the Finnish and Swedish nuclear power industry. The main conclusion of the study was that optimisation in a strictly formal sense had not been used in any of the three areas studied. Instead, practical optimisation based on operating experience was applied particularly concerning *in-service inspections*. When applied to the *use of protective clothing and equipment*, it turned out that the decisions actually taken were on the whole consistent with the results of simple cost- benefit considerations. This did not hold true in the more complex case of *changes in plant systems and constructions*. More than 100 actions were studied, ranging from small modifications justified on radiation protection grounds to larger new constructions. Other factors than dose reductions and the concomitant costs were as a rule the decisive factors.

A general conclusion was that more complex optimisation procedures must be aided by techniques which are easily understandable and simple to use, if the practitioners are to employ optimisation. Such methods could include data bases and computerised decision support systems.

Optimisation of nuclear safety regulations

In the field of nuclear safety in Finland and Sweden, the political decision makers have set boundary conditions for how far it is permitted to carry attempts at optimisation of the safety level. A lowering of the level of safety is not permitted even if it would be the result of a cost-effective trade-off against e.g. the energy availability of the reactor. The alternatives that remain to attain greater cost-effectiveness in plant operation are either to lower the cost at a constant safety level or to increase the safety at a constant cost.

Ways of achieving these goals in the plant operation have been studied in a joint Finnish-Swedish project. The main results of this project are the following:

□ Probabilistic safety assessment techniques can be used to compare alternative schemes for plant operation when there is a defined failure of a safety system, and to search for the scheme with the minimum risk, e g the minimum probability that a safety function is not available when called for.

□ They can also be used to justify changes in the rules which govern preventive maintenance and repairs in safety systems during power operation.

The results treat the requirements on plant shutdown when different failures occur, temporary risk increments when components fail but are still retained during power operation, and the effectiveness of tests for safety systems.

Their application can make operation and maintenance at the plant more flexible at a constant safety level, and often also the safety level can be increased.

Interaction of probabilistic safety analysis and radiation protection

Over the last decade methods have been sought for a systematic trade-off between costs and risks in radiation protection versus nuclear safety. From the discussion on probabilistic safety analysis above, it is obvious that predictions of accident probabilities have large uncertainties. Therefore, the use of such predictions for stringent comparisons with general quantitative safety goals at the plant level is discouraged by top level regulators.

A consequence of the uncertainties is that one should not encourage formal optimisation involving trade-off between say health effects from nuclear accidents and resources spent to prevent accidents. Further support for this view comes from the wide-spread recognition in the operating organisations of Nordic power plants that any nuclear accident may lead to the shutdown of other plants for extended periods. The economic consequences would thus go beyond the plant in question. These views on the possibilities for trade-offs are, however, still subject to international debate. They are consistent with the incrementalistic decision making model.

Summary in Swedish

Detaljerad sammanfattning

Till stor del beror säkerheten i kärnenergianläggningar på hur de tillhörande riskerna analyseras och vilka beslut som fattas av konstruktörer, anläggningsinnehavare, myndigheter och politiker på grundval av dessa analyser. En mängd metoder har utvecklats för att underlätta analys och beslut. Denna rapport beskriver tillämpning och vidareutveckling i Norden av en del sådana metoder.

Forskningsprogrammet har visat att när besluten är komplicerade finns inga enkla sätt att väga risker mot nytta och andra faktorer som påverkar beslutet. Riskjämförelser kan ge en del perspektiv, men allmänheten tycks värdera riskerna på olika sätt beroende på vilken situation risken förekommer i. Riskuppfattning spelar stor roll men styrs av många faktorer i ett komplicerat samspel. Både överskattning och underskattning av risker förekommer. Trots svårigheterna tycks beslut som berör risker dra viss nytta av de enkla ekonomiska värderingar av hälsorisker som tillämpas i en del metoder avsedda som beslutshjälpmedel.

Denna studie har också behandlat möjligheten att väga samman hälsorisker från osannolika stora olyckor med sådana som beror på normala utsläpp från drift av anläggningarna. För närvarande pågår internationellt en omfattande debatt om huruvida en sådan sammanvägning är lämplig och möjlig, och några allmänna regler för sammanvägningen har inte kunnat anges. Slutsatserna kan emellertid belysas med hjälp av den inkrementalistiska beslutsmodellen som förklaras längre fram.

Däremot tycks vissa tumregler vara på väg när det gäller värderingar om vad som är försumbara risker och vad som är risker som kan tolereras. Debatten förs här både beträffande arbetsmiljörisker och beträffande risker i den yttre miljön från såväl strålning som cancerframkallande kemikalier.

Perspektiv på beslut som berör risker

Mänskligheten har alltid varit utsatt för risker, dvs möjligheter till oönskade utfall av ett handlande eller en situation. Läget har dock förbättrats. Vår livslängd har fördubblats under de senaste århundradena. En av anledningarna är att man blivit mer medveten om olika risker och ägnat stora resurser åt att förebygga risker från sjukdomar och andra stora riskkällor. När man idag ägnar stora resurser åt riskminskning beror det inte på att hälsoriskerna ökat utan på att vi vill fortsätta minska risker trots att de mest lättköpta vinsterna redan hämtats hem enligt lagen om den avtagande gränsnyttan.

Synoptisk och inkrementalistisk syn på beslut

En *synoptisk* syn på beslut som berör risker förutsätter

□ definition av alternativa beslutsmöjligheter
□ analys av kostnad, risk och nytta i dessa alternativ
□ beslut utgående från analysen.

Beslutet kräver att beslutsfattaren lägger sina värderingar på de faktorer som analyserats. I en metod för att underlätta beslut, kallad kostnads-nytto- analys, värderas alla faktorer i pengar. Många andra beslutshjälpmetoder finns. På något sätt försöker man placera varje faktor på en gemensam skala utgående från beslutsfattarens värderingar. Flerkriterieanalys och nyttoanalys med flera attribut är exempel på komplicerade beslutshjälpmedel.

Ofta finns inte tillräckligt underlag för beslut vid den tidpunkt när de måste fattas. Ett alternativt synsätt, *inkrementalism,* har utvecklats för beslut under osäkerhet. Det grundas på att man bedömer osäkerheterna i de faktorer som är intressanta och enigheten hos berörda aktörer. En tumregel är att vid små osäkerheter och stor enighet kan långtgående beslut fattas, medan stor osäkerhet och splittring bör mötas med en satsning på forskning i kombination med små steg eller inkrement framåt på beslutsområdet.

Faror från strålning och kemikalier

Faror definieras här som skador efter exposition för ett agens. Faroanalys avser studiet av sambandet mellan exposition och fara. Vissa faror märks direkt efter exposition vid höga nivåer. Fördröjda faror kan förekomma både efter höga och låga nivåer. Exempel är cancer och arvsskador. De startar ofta med en skada till arvsmassan, DNA. Agens som kan ge sådana skador kallas genotoxiska. Faroanalysen i det nordiska programmet har huvudsakligen avsett genotoxiska faror. Joniserande strålning är genotoxisk och kan orsaka cancer. Man vet att tiotals kemikalier kan orsaka cancer hos människor, hundratals cancer hos djur, och tusentals skada på DNA. Inom det nordiska programmet har genotoxiska risker från strålning och kemikalier jämförts. Det börjar bli internationell enighet om att cancerinitiatorer som benso(a)pyren och strålning kan orsaka cancer med en sannolikhet som ökar med ökande dos (koncentration gånger tid). Myndigheterna antar ofta att sambandet är linjärt och inte har någon tröskel.

Den exakta storleken av faran från en exposition för genotoxiska agens är svår att uppskatta eftersom det kan gå decennier innan en skada blir kliniskt observerbar och olika individer kan vara olika känsliga. För att komma åt riskens storlek kan man utnyttja att en genotoxisk skada kan leda till påhängsmolekyler (addukter) på DNA. Dessa kan vara indikatorer på den cancerframkallande förmågan hos ifrågavarande agens. De kan möjliggöra att erfarenheter av cancerrisk från strålning kan användas för bedömning av cancerrisk från kemikalier. I en lovande tillämpning har svenska forskare förutsagt cancerrisker hos arbetare som varit utsatta för etylenoxid.

Probabilistisk säkerhetsanalys

Riskanalys betyder här bedömning av de faror som hänger samman med en given källa som ett kärnkraftverk eller en given situation som expositionssituationen för strålning i ett land. Riskerna från finska och svenska kärnkraft- verk har studerats med hjälp av probabilistisk säkerhetsanalys PSA. Med hjälp av denna bedöms sannolikheten för olyckor i komplexa system. På ett systematiskt sätt summeras alla bidrag till att ett system felfungerar, vare sig orsaken är komponentfel eller mänskligt felhandlande. Försök har gjorts att jämföra alternativa modeller och kartlägga deras begränsningar. De har lett till bättre kunskap om hur sådana försök bör läggas upp och om modellerna för mänskligt ingripande och för fel med gemensam orsak. Resultaten har direkt påverkat de probabilistiska säkerhetsanalyser som görs i Norden och har underlättat prioriteringen av forskningsprojekt.

Probabilistiska säkerhetsanalyser kan hjälpa till att hitta svagheter i konstruktion och drift av kärnkraftverk och att rangordna deras viktigaste orsaker. Systematiska analyser har lett till betydande säkerhetsförbättringar. Tekniken har dock begränsningar. Dessa har studerats, t ex mänskliga ingripanden och fel med gemensam orsak. De tillhörande osäkerheterna har diskuterats. En av slutsatserna är att probabilistisk säkerhetsanalys inte har tillräcklig mognad för att man strikt skall kunna bedöma resultaten mot uppställda kvantitativa säkerhetsmål. En annan slutsats är att osäkerheter i behandlingen av yttre händelser, särskilt jordbävningar, är mycket större än osäkerheterna i behandlingen av inre händelser som transienter (snabba ändringar i t ex reaktoreffekt) eller kylmedelsförluster.

Värderingar och beslutsfattande

I beslutsprocessen tillämpar beslutsfattaren sina värderingar på resultatet av konsekvensanalyser. Detta är omtvistat eftersom olika individer har olika värderingar. Ordet etik kan betyda en uppsättning värderingar som omfattas av en grupp och väntas styra deras handlande. Värdeuppsättningarna beror starkt på sådana faktorer som religiösa och kulturella arv. Läran om etik anger inte vilka uppsättningar av värderingar som är rätt eller fel. Istället granskar den kritiskt de etiska problem som beslutsfattaren står inför:

□ värderingskonflikter
□ åtaganden som står i konflikt med varandra
□ avvägning mellan kostnad och nytta i olika alternativ.

I västvärlden löses inte sådana problem genom att man tillämpar ett givet värdesystem utan genom att man utnyttjar den demokratiska processen. Denna påverkas av befolkningens värderingar, som ändras med tiden. De valda ombuden för folket har den svåra uppgiften att tolka befolkningens värderingar.

I programmet drogs slutsatsen att diskussion om etiska frågor kring kärnenergi inte kan luta sig mot etiska avvägningar gjorda på andra områden. Detta gäller bl a avvägningen mellan förebyggande och konsekvenslindring för stora olyckor. Orsaken är att de berörda människorna i stort sett inte godtar att man jämför olika hälsofaror.

Beträffande *riskuppfattning* har okänslighet för risker studerats snarare än överkänslighet. En tidigare studie av villaägare visade att omkring två tredjedelar av dem som fick veta att de kunde ha höga radonhalter i villan inte oroade sig för detta. Det kan vara en av förklaringarna till den svenska erfarenheten att en stor del av dem som har höga radonhalter i bostaden inte åtgärdar dem. En särskild studie i en svensk kommun undersökte villigheten att åtgärda radon. Resultaten visade att villigheten att åtgärda ökade om de berörda människorna var yngre, hade högre inkomst, var utsatta för högre radonhalter eller bedömde att kostnaden var låg.

Vad är en liten risk?

Bedömningar av vad som är små risker har studerats. Internationellt börjar man bli överens både för strålning och kemikalier att en årlig exposition som leder till en riskinteckning av 0,01 till 0,1 dödsfall eller cancerfall per miljon exponerade invånare är försumbar och inte kräver myndighetsreglering. Den undre gränsen för vad som bör föranleda reglering ligger vid 1 till 10 fall per miljon exponerade.

Ekonomisk värdering av hälsorisker

I grundläggande kostnads-nytto-analys åsätts alla faktorer i ett beslut ett värde i pengar, t ex miljö- och hälsoeffekter. Många forskningsprojekt har ägnats åt frågan om hur mycket resurser som bör läggas på att förebygga ett dödsfall. Ofta ligger resultatet i intervallet 1 till 10 gånger värdet av den produktiva tid som förloras genom dödsfallet. Inom kärnenergiområdet ligger man ofta över intervallet och inom medicinområdet under. I studien av villaägare låg det värde som härletts också under intervallet.

Ett annat försök har gjorts att se hur villaägare värderar den hälsorisk som är förknippad med höga radonhalter. Försäljningspriserna på radonhus jämfördes med försäljningsvärdena på andra hus. De preliminära resultaten visade ingen inverkan av radonhalten, men osäkerheterna var stora.

Optimering av strålskydd vid kärnkraftverk

Internationella strålskyddskommmissionen ICRP rekommenderar att optimeringsanalyser skall göras så att man kan se om stråldoserna är så låga som rimligt möjligt (As Low As Reasonable Achievable, ALARA) med hänsyn till sociala och ekonomiska faktorer. Tillämpningen av denna rekommendation i svensk och finsk kärnenergiindustri studerades. Huvudresultatet var att formell optimering inte hade använts på de tre områden som studerats. Istället användes en praktisk optimering grundad på drifterfarenheter, särskilt när det gällde inspektioner under drift. De beslut som fattades beträffande användning av skyddsutrustning och skyddskläder stämde överens med enkla kostnads- nyttoanalyser. Så var inte fallet vid ändringar i konstruktioner eller system. Mer än 100 sådana studerades, från små ändringar av strålskyddsskäl till stora nykonstruktioner. Avgörande i dessa fall var andra faktorer än minskning av stråldoser och de tillhörande kostnaderna.

En allmän slutsats var att mer komplexa optimeringsöverväganden behöver få stöd genom enkla, lättförstådda hjälpmedel om personalen i praktiken skall tillämpa optimering. Sådana metoder kan ha nytta av databaser och datorstöd.

Optimering av säkerhetstekniska föreskrifter

Optimering beträffande kärnsäkerhet i Finland och Sverige är föremål för politiskt satta begränsningar. Säkerheten får inte minskas även om detta skulle vara kostnadseffektivt t ex med tanke på reaktorns tillgänglighet. Bättre kostnadseffektivitet får bara uppnås genom lägre kostnad vid oförändrad säkerhetsnivå eller ökad säkerhet vid oförändrad kostnad. Sådana förbättringar har studerats i ett finsk-svenskt projekt. Huvudresultaten var:

- □ Probabilistisk säkerhetsanalys kan användas för jämförelser av olika driftssätt med avseende på en viss sorts felhändelse och för att hitta det sätt som innebär minst risk, dvs minst sannolikhet att en säkerhetsfunktion är otillgänglig när den behövs.
- □ Analysen kan också vara underlag för ändringar i reglerna för föebyggande underhåll och reparationer under drift, och för ökad effektivitet i inspektioner.

Därmed kan drift och underhåll bli mer flexibla, och säkerheten kan ofta ökas.

Andra resultat gäller kraven för avställning vid olika fel, tillfälliga riskökningar vid komponentfel under drift och effektiviteten i prov av säkerhetssystem.

Samspelet mellan probabilistisk säkerhetsanalys och strålskydd

Under de senaste decennierna har man sökt efter enkla regler för avvägningar melan strålskydd och kärnsäkerhet. Diskussionen ovan om probabilistisk säkerhetsanalys visade att förutsägelser om sannolikheter för olyckor fortfarande har stora osäkerheter. Framträdande myndighetsrepresentanter har därför avrått från bedömningar av sådana förutsägelser i förhållande till kvantitativa säkerhetsmål. Osäkerheterna leder också till att man bör avråda från optimering grundad på formell avvägning mellan t ex hälsorisker från olyckor och resurser för olycksförebyggande verksamhet. Denna slutsats är visserligen föremål för internationell debatt men ligger väl i linje med den inkrementalistiska beslutsmodellen.

List of contents

Preface

This is the final result of a research program which formed part of a major joint Nordic research effort in nuclear safety. The effort comprised the following five program areas:

□ activity releases in the case of nuclear accidents and their dispersion and impact in the environment
□ nuclear waste management
□ risk analysis and safety rationale
□ reactor material properties
□ use of advanced information technology to support decisions in the case of accidents in complex systems such as reactors

The overall aim of this effort has been to contribute to maintaining the high safety level of nuclear installations in the Nordic countries, and to provide decision makers with background information to enable them to realistically judge the impact of nuclear power and the precautions undertaken to maintain its safety.

The program on risk analysis and safety rationale

This report deals with the third program area, which has been divided into five projects:

□ optimisation in nuclear power radiation protection
□ comparisons of radiation risks and others
□ methods for probabilistic safety analyses and their limitations
□ development and optimisation of nuclear safety regulations
□ principles of risk assessment and management.

These projects have in turn been divided into various subprojects.

The project reports and the underlying extensive documentation are referenced in Chapter 7. In this report, the five project reports are summarised in Chapters 1 – 5. Chapter 1 also contains other material to provide a broad overview of the whole risk analysis research program.

Aim of the risk research program

The aim of research in this area has been to review methods for risk assessment and management with respect to nuclear safety, in order to

□ give an overview of the methods available
□ demonstrate to what extent these methods fit into a common framework and reflect general principles.
□ provide background material for decisions, e.g. on safety regulations.

The overall purpose has been to aid decision makers by trying to find systematic approaches or rules of thumb for decisions. Nuclear safety and radiation protection were the primary areas of research, but a cross- fertilisation was intended with such areas as offshore safety and decision making with respect to toxic chemicals in the environment.

International cooperation

The work has been coordinated with and has drawn upon similar international work in organisations such as the Nuclear Energy Agency (NEA) of the Organisation for Economic Cooperation and Development, the International Commission on Radiological Protection (ICRP), the Commission of the European Communities (CEC) and the United Nations Scientific Committee on the Effects of Atomic Radiations (UNSCEAR). Project personnel have been directly engaged in contacts with the International Atomic Energy Agency (IAEA) in its Coordinated research programmes on "Comparison of cost-effectiveness of risk reduction among different energy systems" and on "Reference studies of probabilistic modelling of accident sequences".

The work was carried out at institutions in the Nordic countries of Denmark, Finland, Norway and Sweden. A reference group with one person from each country followed the work and suggested directions of research. The whole research effort was coordinated by the Nordic liaison committee for atomic energy, aided in this particular area by two research coordinators from Sweden.

The report has been compiled by Gunnar Bengtsson, Sweden after extensive consultations with the project managers and others. It is being distributed to scientists and to individuals working in national and regional authorities and in companies dealing with industrial risks. The main distribution is to the Nordic countries, but the report is also distributed outside of the Nordic region.

System for referencing

Refences to parts of this report are given in parenthesis using the numbering of sections and subsections, e.g. (4) or (4.3.2). Literature references are given using a capital and a number. e.g. (H1) or (H10). The letter is the initial of the family name of the first mentioned author, editor or organisation, or in a few cases of the book title. For each initial, the references are arranged in alphabetical order and then numbered consecutively.

1 Principles for risk assessment and decision making

Project report 490

1.1 Structuring of decisions involving risks

Risk is a vague term related to unwanted outcomes of an action or a situation. In this report, risk is used as a loose term and more specific terms are used when precision is necessary. The relevant outcomes are then specified, e.g. cancer, and the probability of each outcome is given.

Mankind has always been exposed to risks. In the last few centuries, the risks to human health have decreased significantly in Western societies. Our expected length of life has doubled. One reason for this is the increased awareness of risks and the large efforts spent on preventing risks. Despite the significant achievements in risk reduction, large segments of the public are very concerned over the new types of risk which have replaced the old ones. A simplistic reaction is to demand the abolishment of new practices that entail risks. This is not tenable since all practices involve some risk. The general level of well-being would be better nursed if one could find ways of assessing the different types of risk, and then eliminating all exposures to risk for which the cost of the countermeasures is reasonable in relation to the magnitude of the risk reduction. The combined processes of risk assessment and reasonable risk reduction are the subjects of this report and jointly called optimisation of protection.

1.1.1 Synoptic approaches to decision making

The skeleton on which the report is based is a suggested rational scheme (B6) for decisions involving risk. This scheme (figure 1.1) requires the definition of alternative possibilities for decisions, analysis of consequences of the alternatives such as costs, risks, and benefits, and an evaluation of the result which leads to a decision. Such a comprehensive scheme is sometimes referred to as a synoptic approach.

Synoptic means just comprehensive, or characterised by breadth of scope.

The evaluation for decision is a complex process which reflects the values of the decision maker. The ultimate decision is often more influenced by the public perception of the risks than by the estimates of risk established from the analysis.

In one technique for aiding the decision, monetary values are assigned to all parameters involved. The technique is called cost-benefit analysis. Simpler forms of cost-benefit analysis have been used extensively in the field of nuclear radiation protection, and have been further investigated in this report.

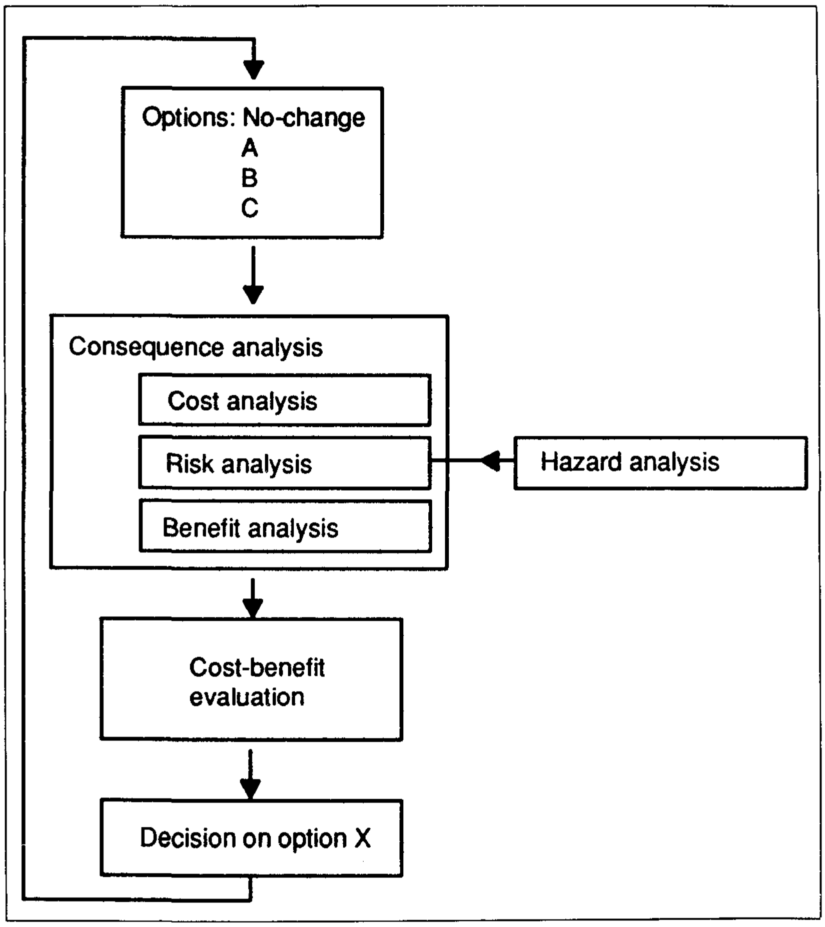

Figure 1.1. A synoptic schedule for risk management. The alternatives to be considered should include the no-change alternative. The hazard analysis is performed independently of whatever alternatives are considered. It pertains to the relation between exposure and injury. Results from hazard analyses can be used to calculate risks from the alternatives considered.

Many other decision aiding techniques have been tried, usually involving other types of quantification on a single scale based on the decision maker's values (I3). Examples include multiattribute utility analysis and multicriteria analysis.

1.1.2 Incrementalism

It is obvious that in many complex decisions, much relevant information will not be available to the decision maker at the time of decision. The scheme accounts for this problem by allowing for a reconsideration of the decision when new information has become available.

In political science an alternative way of arriving at decisions in the face of uncertainties has been developed (B6). It is called incrementalism and is based on an assessment of the uncertainties in the factors involved, and the degree of consensus about the decision to be taken. The basic rule is that small uncertain-

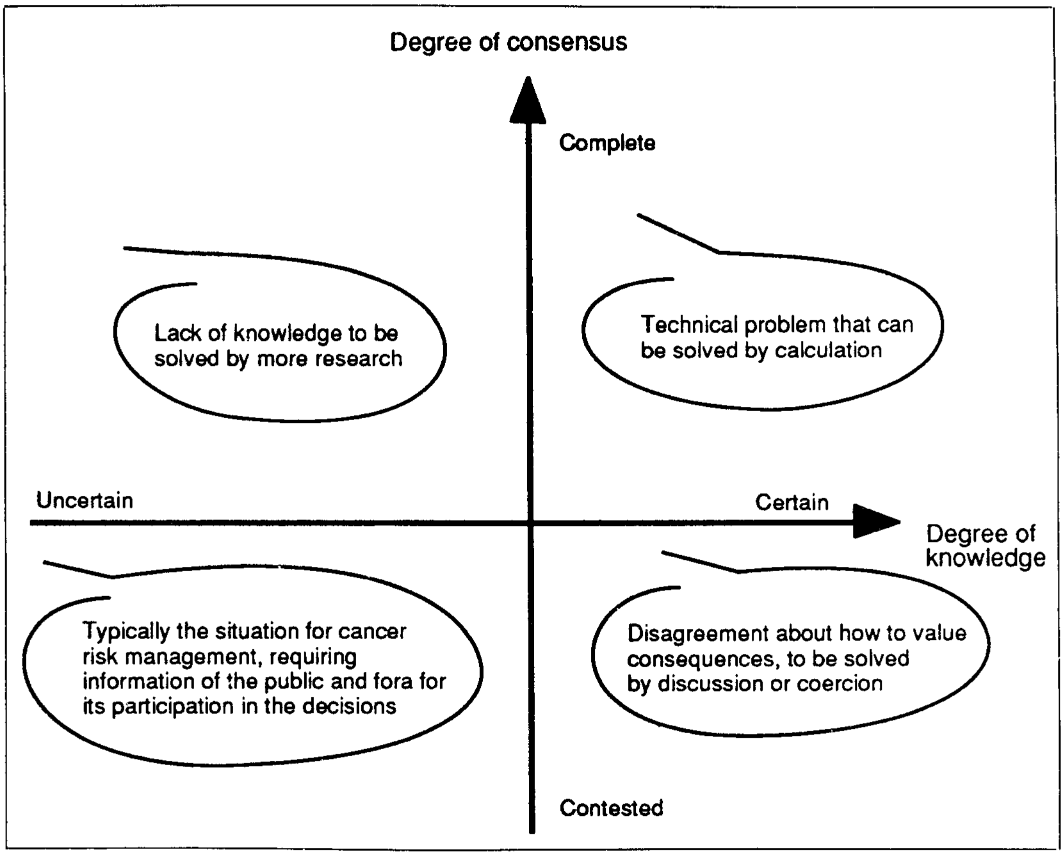
Degree of consensus
Complete
Lack of knowledge to be solved by more research
Technical problem that can be solved by calculation
Uncertain
Certain
Degree of knowledge
Typically the situation for cancer risk management, requiring information of the public and fora for its participation in the decisions
Disagreement about how to value consequences, to be solved by discussion or coercion
Contested

Figure 1.2. Management options in cases of different levels of consensus about the most desired prospects for the future and different knowledge about the future. Adapted from (D2).

ties and high degree of consensus justify far-reaching decisions while large uncertainties and lack of consensus call for research efforts in combination with a little step or increment forward in the area subject to the decision. This is illustrated in figure 1.2.

The difference between the two methods is mainly in the treatment of uncertainties. In the synoptic approach there is more of a belief that uncertainties can be assessed and considered in the decision, whereas in incrementalism there is' an explicit recognition that the decision should be deferred as far as possible until the uncertainties have been resolved.

In this report, the synoptic approach has been chosen as the backbone of the presentation because it illustrates clearly the factors involved. A survey (V1) showed that cost-benefit analysis, a technique with a synoptic flavour, is indeed used as a practical tool by several Nordic safety authorities. On the other hand, the management of high level radioactive waste in Finland and Sweden bears many of the marks of incrementalism, for instance the deferral of a final decision and the determined efforts devoted to research.

The rest of this chapter is based upon the structure of figure 1.1 and discusses hazard and risk analysis, and evaluation for decision making. The Nordic results are put in an international perspective and are briefly summarised.

More detailed discussions follow in Chapters 2 to 5.

1.2 Hazard analysis

The hazards in our definition are the outcomes in the form of injuries following exposure to an agent.

Hazard analysis means the study of the relations between exposure and hazard. Some hazards are directly noticeable following high level exposures. Delayed hazards may occur after higher or lower eposures, e.g. cancer and hereditary disease. These are often starting with an injury to the hereditary material, DNA.

Agents that can cause such injury are called genotoxic. The principal interest in hazard analysis within the Nordic program has concerned such agents. Ionising radiation can be genotoxic. Tens of chemicals can cause human cancer, hundreds animal cancer, and thousands cell DNA injury.

Within the Nordic program, a comparison has been made of genotoxic risks from radiation and chemicals (B3). There is an emerging international consensus that cancer initiators such as radiation and benso(a)pyrene may cause cancer with a frequency that is proportional to the integrated exposure, even at low doses. It is a common hypothesis that the dose-response relationship is a linear, non-threshold one, and authorities often assume such a relationship for regulatory purposes.

It is generally difficult to establish the real hazard that follows from exposures to genotoxic agents. This is because e.g. many decades may lapse between exposure and the clinical manifestation of an injury, and individuals may exhibit different sensitivities depending on such factors as sex, age and hereditary disposition. To establish the risk one may use the fact that some promising techniques are emerging, as discussed at a symposium related to the Nordic program (M1).

One of these techniques has been described in detail at a Nordic seminar on genotoxic agents. Its basis is that one consequence of a genotoxic injury to a cell may be the creation of adducts to DNA, which can serve as indicators of carcinogenic potential. Such adducts are also traceable in hemoglobin in human blood cells. It seems possible to establish well defined relationships between the frequencies of adducts due to radiation and to alkylating chemical agents. If this is verified, the adducts will provide a mean for estimating cancer risks from chemicals by combination of the adduct frequency in hemoglobin with the corresponding frequency per unit radiation dose and the cancer frequency per unit radiation dose (E2, E3). In a promising application of this method (D3), leukemia risks from ethylene oxide exposures have been predicted.

1.3 Risk analysis

In our terminology, risk analysis means the assessment of various hazards associated with a given source such as a nuclear power plant, or a given situation such as the exposure situation in Nordic dwellings with respect to radiation.

The risks related to Finnish and Swedish nuclear power plants have been studied using Probabilistic Safety Analysis, PSA (4,5). By this method, complex systems are assessed with respect to the likelihood of accidents. The contributions to system failure by all component and human failures are summed in a systematic way. The development work has been concentrated on comparing the models used and clarifying their limitations.

PSA has several merits. It may help in identifying weak spots in the design and operation of nuclear power plants, and in ranking the dominant risk contributors. These insights have resulted in numerous modifications of design or operation, and thus in increased safety. They have also helped in setting research priorities. PSA techniques are increasingly being applied outside the field of nuclear power.

There are, however, also serious limitations in the present state of PSA techniques which have been studied (4), e.g. in the treatment of common cause failures and human interactions. A significant conclusion is that PSA is not mature enough for stringent comparisons of quantitative estimates with prescribed safety goals. Another judgment holds that the uncertainties in the treatment of external events, especially earthquakes, are much larger than the uncertainties in the treatment of internal events such as transients and loss of coolant accidents.

1.4 Decision making

As previously mentioned, the decision involves the application of value judgments to the results of consequence assessments. This procedure is surrounded by controversy, mainly because value judgments may be very different between individuals.

Several factors have been studied in order to clarify where there is room for value judgment and whether there are any general rules governing these judgments.

1.4.1 Ethical questions

The word ethics may have two meanings. It may mean a set of values adhered to by a group and expected to govern their actions. Alternatively, it may mean the discipline which concerns itself with critical reflections over such values and norms. The sets of values depend strongly on such factors as religious and cultural heritage.

For instance, one group may wish to maximise collective wealth without regard to distribution while another may wish to distribute the wealth equally. Once the set of values is postulated, economic scientists may suggest policies which are likely to lead to fulfilment of the goals associated with the particular set.

The discipline of ethics does not help by stating that a set of values is right or wrong. Rather, it puts the spotlight on the ethical dilemmas facing the decision maker:

□ competing values
□ conflicting obligations
□ trade-off between costs and benefits in alternative outcomes.

For the resolution of such dilemmas in Western societies, there is not a fixed set of values available but an agreed process, the democratic process. This is influenced by the changing values of the population. The elected representatives of the people have the difficult task to interpret these values.

Since decision making involves value judgments, it is obvious that ethical considerations must come into play. These are dealt with in the following subsections. A special seminar with Nordic participation concerning ethical aspects on nuclear waste (E6) provides additional guidance.

Ethical issues with respect to nuclear power production have been discussed (E1). One dilemma lies in the relative assignment of resources for prevention of accidents and for planning to provide efficient mitigation once an accident has occurred. The main conclusion was that the discussion on ethical problems connected with nuclear energy production has to be carried out without any help from similar debates in other sectors. This holds also for the particular issue of allocation of resources to different categories of safety and health measures. The reason is that the populations involved on the whole will not accept any comparisons between threats to life. The resources actually allocated for prevention in the nuclear field seem to be very high indeed (1.4.10).

1.4.2 Risk perception

Recent international research, including a major Swedish project (S2) suggests that strong reactions to risk are tied with moral indignation and the existence of credible experts who support alarm signals. Much research has been devoted to these and other factors responsible for risk reactions, with emphasis on exaggerated risk perception.

Less work has been done on indifference to risk. An earlier study on home owners indicated that about two thirds of those who were informed about potentially high radon levels in their houses were indifferent to the risk. This may be one factor behind the experience in Sweden that mitigating measures against radon are neglected by a large share of those who know they have rather high levels in their homes. A special study has been performed in a Swedish community to explore the willingness of home owners to take mitigating actions against radon (B10). The results of this study show that the willingness to take action is higher if the individuals involved are younger, have a higher income, and face a cheaper countermeasure or a higher radon level.

1.4.3 Risk comparisons

Risk comparisons are always unsatisfactory. The items compared are by definition different, and the valuation of the differences is very personal and dependent on the same factors as the risk perception. Attempts to characterise and compare risks must therefore be sensitive to personal valuations and try to emphasise in what respects there are differences between the items compared. Still, with such reservations, there is much perspective to be gained from comparisons of risks.

Information has been compiled about radiation levels and risks in the Nordic countries (3). Attempts have also been made to compare radiation risks and chemical risks (B3, B4, Project report 430, E2, E3), and long-term risks from different energy systems (B7).

Some of the main results are the following:

Comparison of risks from radiation sources

Radon provides the dominating contribution to the nation-wide averages of indoor radiation exposures in the Nordic countries, which by far surpass any outdoor exposures. It also represents the largest fraction, 30-70 %, of the radiation doses from natural radiation levels which have been enhanced due to human activities.

Comparisons of risks from radiation and chemicals

The hazards from ionising radiation seem to be more thoroughly evaluated than those of any single chemical compound. Due to lack of data, no definite conclusions can be drawn about the relative risks from radioactive and chemical substances in the enviroment. There is, however, an emerging consensus on the analysis of hazards from genotoxic chemicals and radiation (1.2), and on the management of risks associated with these agents (1.4.5).

Many types of power plants release toxic substances to the environment. In many cases, the potential long-term risks to humans seem to be determined by releases from the storage of the waste from the plants. Generally, nuclear waste is stored in a safer way than chemical waste from fossil fuel power production.

Comparison of long-term risks from different energy systems

The very long time perspective which is conspicuous in matters of radioactive waste raises the question of risk management over times much longer than the interval preceding the next ice age. In such a long time perspective, it is not possible to assess consequences of environmental pollution with any certainty.

It has been suggested that a suitable management rule would be to make sure that the concentrations due to pollution would add only small risks in comparison with the risks from the natural levels of hazardous agents. This has been investigated for energy systems based on nuclear power, fossil fuels, and biomass (B7).

Nuclear power risk management was judged to be compatible with this rule of the natural levels, with local exceptions in case of major accidents. The present use of fossil fuels was deemed grossly out of balance with this rule, mainly with respect to emissions of carbon dioxide and acidifying substances. In the case of coal, leakages from waste heaps of current design constitute an even worse long-term threat to the environment than the emissions mentioned.

1.4.4 Economic valuations

In the most basic cost-benefit analysis, all consequences involved in a decision are put on a common monetary scale. This means that for instance environmental and health effects are given in monetary terms. The theoretical basis has been reviewed (B9). Many studies have tried to estimate the resources spent to prevent the loss of a human life. They tend to fall in the range between 1 and 10 times the value of the production time lost. In the field of nuclear safety they often exceed this range, and in the field of medical measures they often fall below the range (B1).

An empirical study has been undertaken concerning the valuation of the health risk associated with living in a home with high radon levels (B10). The selling prices of these homes were compared with the prices of homes with less radon. The preliminary results showed no influence of high radon levels on the price, but the uncertainties were rather large.

1.4.5 What is a low risk?

A literature survey has been made regarding risks considered to be small (Project report 490). This would imply either being at the lower limit of risk levels being of concern, e. g. important enough to be regulated, or being low enough to be very generally uninteresting for regulation. There is an interval between these two risk levels, where a risk may not be directly of concern but action may be very simple and cheap, and thus implemented through regulation.

The review indicates that a consensus seems to be approaching, both between countries and between radiation and chemical risk regulation. The definitions of what the levels or limits pertain to are different, but the consensus contains the following intervals:

□ 0.01-0.1 committed cases per million persons exposed during one year is a negligible risk, and 1-10 a risk of little concern.

□ Major accidents are definitely of concern if the annual expectation value of the number of victims exceeds 0.01.

Some narrowing of the intervals might be possible with harmonised definitions for the different areas. For major accidents affecting many persons additional tolerability criteria are under discussion.

1.4.6 Decision aiding principles and techniques

A review (B6) has been made of the two approaches mentioned in Section 3.1: the incrementalistic and synoptic ones. It was concluded that quantitative decision aiding techniques are seldom useful in political decisions when controversy surrounds the issues of risk, and thus not applied.

Within the program, an economist has analysed the possibilities and limitations of cost-benefit analysis for health risk management (B9). The report ended with the following conclusions:

● In practice, decisions involving the value of changes in risks to human health are unavoidable. Cost-benefit analysis has a sound theoretical backing in central economic theory and is a natural candiate for the generation of background material for such decisions.

● There are no economic principles that would impede the employment of cost-benefit analysis to study risk reducing measures. In particular, it is in principle possible to assess changes in health in monetary terms. The obstacles encountered are of a practical nature, mainly with respect to the difficulties of obtaining relevant data on the preferences of the individuals concerned.

● Methods to assess such preferences are available and have been tested, in particular following the new guidelines for environmental policy making in the United States.

● Empirical studies have been made on the economic valuation of reduction of risks to human health. These have given valuable insights, but the results show a considerable spread.

● Application of cost-benefit analysis should lead to the recommendation to institute a protective measure if the cost of saving a statistical life is below 3 MSEK, and not to institute it if the cost is above 50 MSEK, subject to a number of reservations with respect to the absence of reliable data.

The use of cost-benefit analysis in the Nordic countries has been reviewed in a preliminary study (V2). Wide applications where the authorities used cost-benefit analysis were found in road safety, in radiation protection and the evaluation of new technology within the health care sector. Some examples were also found in off-shore oil exploration activities and in the manufacture of explosives. The use of cost-benefit analyses has recently been required by both the Swedish and the US governments to be provided as an input when authorities are suggesting new regulations.

Finally, environmental protection policies in several European countries, Japan and the United States have been reviewed (B11). In general, statements of environmental policy and objectives were qualified by phrases to the effect that economic implications must be taken into account when planning pollution abatement and other protection measures, and that costs must be considered in relation to the expected benefits. Several practical difficulties were discussed in this report, e.g. the difference between business economics and national economics, and the assessment of the value of improved quality of life. Of the countries reviewed, only the Netherlands had made full estimates of the costs of a comprehensive environmental programme, but without matching them with benefit estimations in comparable detail.

The results witin the program thus indcated that cost-benefit analyses outside the field of nuclear safety and radiation protection is a young technique beset with many difficulties, but still being actually applied as a decision aid in many areas in many different countries.

1.4.7 The handling of uncertainties in probabilistic assessments (PSA)

The various sources of uncertainty encountered in a PSA (1.3) quite naturally fall into one of the following categories (V1).

1. Parameter uncertainties. Data in PSAs on failures have uncertainties due to e.g.

□ limitations of the database
□ diverging expert opinions
□ limited applicability of available data
□ interpretation of the analyst
□ applicability of data analysis methods used.

2. Modelling uncertainties. Models have uncertainties due to limitations in either

□ coverage of the model or
□ representativity of the model.

3. Completeness uncertainties. Completeness uncertainties are frequently closely related to modelling uncertainties. They may originate from:

□ contributor uncertainty (identification)
□ relationship uncertainty (interaction).

In recent PSAs, Bayesian methods have generally been used to describe the parametric uncertainties. By these methods it is relatively easy to utilize "learning from experience". The Bayesian thinking presupposes the acceptance of the concept of subjective probability. This type of probability can be assigned also to nonstatistical events, a feature which is of great importance in the context of uncertainty handling in risk analyses. In the future one can foresee a further development where subjective probabilities more and more will be used to describe even modelling uncertainties.

The completeness problem touches upon the limits of our knowledge which in practice make rigorous treatment impossible, while modelling uncertainties are best studied by the application of sensitivity analysis.

The role and practical applications of sensitivity analysis have been discussed in (H12). Two important reasons for performing sensitivity analysis are that:

- They are used to estimate the firmness of the conclusions, or rather, of the foundation upon which the conclusions are built. Sensitivity analysis will shake this foundation and assess the effects.
- They are necessary in order to give a many-faceted picture of PSA results to decisions-makers. Any user of PSA should have a general understanding of the models and assumptions upon which the conclusions are founded. A study of the impact which changes in models and assumptions may have on final results usually gives a better perspective on the conclusions.

Decision making in view of uncertainties has been addressed in (P6).

Because probability is a measure of uncertainty, there is no room for "probability of probability". According to basic probability laws one can express the total uncertainty with integral probability values, i.e. without any further uncertainty bounds. This will greatly facilitate the decison making process, where one tries to find the action alternative that corresponds to the minimum expected risk. An important step in all uncertainty analyses is also to find the areas where additional information would be of greatest value.

1.4.8 Principles for managing nuclear safety

Present industrial practices for potentially dangerous processes rely on the concept of defence in depth. This concept means that several independent barriers are established against unwanted events. The required level of safety of the plant can thus be achieved with barriers which alone are not completely reliable, since the probability of a concurrent failure of all of the barriers will be sufficiently small. According to this approach, safety is assessed using a probabilistic safety analysis (PSA) (1.3, 4). In this analysis, possible chains of events with safety implications are evaluated using probabilistic arguments.

The analysis of recent industrial disasters indicates that the main contribution to risk is from chains of events having very low probabilities of occurrence. Such risks can be dealt with by treating safety management as a control problem and including operational experience in the safety analysis (W2, W3). By also studying well defined performance indicators and safety oriented organizations, it should be possible to develop managerial tools by which low probability chains of events can be avoided.

1.4.9 Optimisation of radiation protection

The ICRP recommends that optimisation analyses be carried out to establish whether exposures are kept as low as reasonably achievable (ALARA), social and economic factors being taken into account.

The implementation of this recommendations in the Finnish and Swedish nuclear power industry has been studied (2). Besides a general review of optimisation procedures, three areas were studied, concerning radiation protection in:

□ in-service inspections
□ use of protective clothing and equipment
□ modifications of plant systems and constructions.

The main conclusions of the studies were that optimisation in a strictly formal sense had not been commonly used in any of the three areas. More complex optimisation procedures must be aided by techniques which are easily understandable and simple to use, if the practitioners are to employ optimisation. Such methods could include data bases and computerised decision support systems.

Optimisation in the management of the consequences of an accident was also studied (B8). It was concluded that many factors enter the decisions, and simple optimisation can not be demonstrated, although optimisation in a wide sense is a factor behind the decisions.

Finally, the costs of protection for the management of a range of radiation hazards were studied (B5, B2). It was concluded that cost estimates are very uncertain. Within these limitations, prevention of skin cancers from solar exposures was judged to be extremely cheap, of cancers in patients from x-ray diagnostic procedures moderately expensive, of lung cancer from radon expensive, and of cancers from environmental pollution due to a nuclear accident very expensive.

1.4.10 Optimisation of nuclear safety regulations

In the field of nuclear safety in Finland and Sweden, the political decision makers have set boundary conditions to attempts at optimisation of the safety level. A lowering of the level of safety is not permitted even if it would have very great economic advantages. The alternatives that remain to attain greater cost-effectiveness in plant operation are either to lower the cost at a constant safety level or to increase the safety at constant cost.

The management of nuclear safety follows the principles outlined in 1.4.8. The primary emphasis is on the prevention of accidents, particularly accidents which could cause a severe damage to the reactor core. The possibility of such accidents is a significant economic risk for the utility, and also indirectly for the whole industry since an accident in one plant may lead to consequential shutdowns in other plants for extended periods. This economic risk adds to the motivation of the Nordic utilities to reduce the accident probabilities to very low levels, and supports the mentioned boundary conditions set by politicians. The utilities also desire flexibility in the operation of a plant, although its effect may not be directly measurable in economic terms.

Optimisation of this balance between safety, flexibility, energy availability and economy with the boundary conditions mentioned, was studied in a joint Finnish-Swedish project (5) centered on the operational safety rules, called technical specifications. These define the allowed conditions for plant operation from a safety point of view. The main method used in the studies was probabilistic safety assessment, PSA.

The project has by and large met the goals concerning safety, flexibility and economy, e. g. through the following results:

□ In the case that given safety related components cannot be operated, PSA techniques can be used to compare alternative modes for plant operation. The scheme with the lowest risk can then be searched for, e. g. the one with the minimum probability that a whole safety function is not operable when called for. The result can be used to justify changes in safety-motivated requirements on plant shut-down.

□ PSA techniques can also be used to justify changes in these requirements concerning preventive maintenance as well as repairs during power operation. PSA may further be used to control temporary risk peaks in plant operation, and to evaluate the efficiency and coverage of surveillance tests.

PSA has the potential to improve the understanding of complex operating situations and thus reduce the uncertainty in decisions related to safety and availability. This can only be realised, however, if decision makers and plant personnel strengthen their understanding of the methods for risk analysis.

The methods and principles developed can also be modified for use in other safety and reliability applications in e. g. complex process and offshore plants.

In another project, the costs of preventing nuclear accidents were studied (B8). It was concluded that such costs are difficult to distinguish from costs expended to maintain a high availability of the nuclear power production. The costs spent to prevent accidents, however, seemed very high in relation to the health and economic effects evaded by the preventive measures.

1.4.11 Interaction of nuclear safety and radiation protection

Over the last decade methods have been sought which may facilitate a systematic trade-off between costs and risks in radiation protection versus nuclear safety. From the discussion on probabilistic safety assessments (3.3), it is obvious that predictions of accident probabilities have large uncertainties. This has now also been recognised insofar as the setting of quantitative safety goals is discouraged by top level regulators (O2).

A consequence of the uncertainties is that one should not encourage optimisation involving trade-off between say health effects from nuclear accidents and resources spent to prevent accidents (B8). This was also the consensus of a recent expert meeting (O1). In spite thereof, a recent IAEA document (I1) takes an optimistic approach towards the possibilities for trade-offs. Obviously, there is still no international consensus on this issue.

1.4.12 Conclusions for decision making

Many methods have been developed in the Nordic program which permit a structured analysis of decisions involving risks. They have contributed to improvements in nuclear safety and radiation protection.

The evaluations of risks versus benefits and other factors involved in a decision can not, however, be expected to follow any given patterns. Risk comparisons can give some perspective but the public tends to handle the ethical issues involving risk in a way that is particular to each risk. Risk perception plays a large role, but is governed by many factors in a complicated interplay. These may lead to exaggeration of risks as well as indifference.

Despite these problems, simple economic valuations of health effects are still used for decision making and seem to have some impact on the decisions.

The study has also dealt with the possible trade-off between risks for health effects from low probability, high consequence events such as nuclear accidents, and from certain exposures such as normal releases. At present, such a trade-off is surrounded by controversy, and no generally acceptable rules for it have been found.

Generalisations are, however, emerging when it comes to valuations of what are negligible risks and what are tolerable risks. A lively discussion is going on both with respect to various occupational hazards and concerning exposures to genotoxic substances in the environment.

1.5 Follow-up of a decision involving risk

In practice, it is very common that decisions are modified after a follow-up. This is also recommended by the ICRP for radiation protection decisions based on optimisation.

The possible change of risk factors for radiation induced cancer (3.2) provides an example of a revised input which should lead to a re-appraisal of many optimisation results.

2 Optimisation of radiation protection at nuclear power plants

Project report 410

2.1 What is optimisation of radiation protection?

Optimisation was defined above (1.1) as assessment of various types of risk and then elimination of all exposures for which the cost of the countermeasures is reasonable in relation to the magnitude of the risk reduction.

Optimisation should be applied in radiation protection according to international recommendations. The International Commission on Radiological Protection (ICRP) has summarized its recommended basic system of dose limitation as follows:

"The system has three components which are necessarily interrelated.

1) No practice shall be adopted unless its introduction produces a positive net benefit (The justification of the practice).

2) All exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account (The optimization of radiation protection).

3) The dose equivalent to individuals shall not exeed the limits recommended for the appropriate circumstances by the Commission (The limits of individual dose equivalent)."

The ICRP has also published detailed guidance on optimisation of radiation protection (I1, I2), in jargon called ALARA (As Low As Reasonably Achievable). The main ideas rest on a working hypothesis, according to which the relationship between small radiation dose contributions and the resultant increase in risk is linear.

Optimisation of radiation protection is an aid for decisions in matters where radiation protection issues enter. It is intended to clarify and to quantify radiation protection factors and to systematise tradeoffs between the factors. Both the design and the operation of facilities should be optimised from the radiation protection point of view.

The ideas of the ICRP Publication 37 (I1) have been extended by the National Radiological Protection Board (NRPB) in Great Britain. One purpose of this work has been to give advice on the monetary values associated with the detriment from radiation exposures, measured in terms of collective dose equivalents (N1). The NRPB recommends that its base-line cost of unit collective dose equivalent should be increased for those parts of the collective dose equivalent which are due to higher individual dose equivalents.

Many scientific evaluations have described the application of cost-benefit analysis to radiation protection. In addition to utilising cost-benefit procedures for optimisation, organisations in some countries (e.g. the Research center for nuclear risk assessment and management (CEPN) in France) have in more detail examined the use of decision theory and thereby also the use of multiattribute and multicriteria analyses as tools for decision-making purposes.

2.2 What have been the practical applications of radiation protection optimisation at nuclear power plants world-wide?

At a nuclear facility, the radiation exposure of workers can be reduced:

a) by reducing the dose rate in workplaces; the contributing factors and the corresponding means include

□ the radiation sources (selection of materials, filtering, cleaning, corrosion monitoring, water chemistry, decontamination etc.)

□ shielding/protection (radiation shields, tools, robotics, protective equipment etc.)

b) by reducing working time; the contributing factors and the corresponding means include

□ technical solutions (selection of components, maintenance and operational measures, etc.)

□ detailed planning of work

□ training/mock-up procedures.

The main radiological issues are often connected with major modifications at a nuclear power plant. Radiation protection is then inherently associated with e.g. engineering, production and nuclear safety.

Decisions have in many cases been based on rather simple optimisation methods, primarily cost-benefit or cost-effectiveness analysis.

In Europe, optimisation of radiation protection dealing with nuclear installations has been applied e.g. in some European Community countries, Sweden and Finland. This work has been reported at scientific seminars, the latest held in 1988 (C3, O1). The practical applications describe many interesting details of radiation protection, dealing e.g. with maintenance, work management and robotics at nuclear power plants.

In the USA, collection of data from special radiation work at nuclear power plants is partly systematised. Data are searched in a special radiation protection data base operated by the Brookhaven National Laboratory. It is used primarily for research and development concerning control of occupational dose.

A project for the development of a system for collection, retrieval and analysis of data relevant to occupational exposure is under way at the OECD/NEA. The purpose is to facilitate exchange of information between the participants in the system concerning dosimetric data and dose reduction methods.

2.3 Objectives and results of the Nordic project

The objective of the Nordic research project was to investigate how optimisation could be applied to radiation protection of workers at the Nordic nuclear power plants. This objective was to be reached by utilizing the existing knowledge and experience of the project members, who were representatives of nuclear power plants and companies as well as of safety authorities. The Nordic project studied applications of radiation protection in:

□ in-service inspections
□ the use of protective clothing and equipment
□ modifications of plant systems and constructions.

In addition, the optimisation procedure was more generally evaluated. The main results are presented in the following.

In-service inspections

In-service inspections are considered to be of great importance to plant safety and reliability. The study collected information on regulations and practices for in-service inspections, radiation dose statistics, radiation protection measures, and decision criteria for the optimisation of radiation protection at the Nordic power plants.

One of the findings was that exposure of workers during in-service inspections contributed about 15 % to the annual collective dose. The individual doses are sometimes high, and protective actions must be continually considered, particularly for the insulation personnel and for those of the inspection personnel who work at several different plants during maintenance periods.

Optimisation in the strict formalized sense had not been used at the plants. Instead, practical optimisation based on operating experience was applied. Besides dosimetry and other direct radiation protection measures, one of the most important actions for controlling doses during in-service inspections seemed to be an active work management programme.

Automation of some parts of the inspections is considered a step forward from the radiation protection point of view. Re-consideration of the frequency and extent of the traditional inspection program would mean additional progress. To enable an adequate analysis, data must be collected and evaluated systematically, e.g. concerning the radiation doses and the costs of the protection alternatives possible with the new methods.

Protective clothing and equipment

Information from the Nordic nuclear power plants was obtained and presented concerning the use of i.a. boundaries for contaminated areas, protective clothing, respirators, and temporary shielding.

In addition a cost-benefit formalism was developed as a decision aid for the use of temporary protective equipment. Some examples of the result of its use are given in figures 2.1 to 2.3. Figure 2.1 shows the cost effectiveness of lead blankets with dose reductions of 33 % and 50 %, respectively. The cost of the dose reduction per unit dose equivalent is given as a funtion of the initial dose equivalent rate, with the time the blanket is used as a parameter. In Nordic radiation protection, it has been considered appropriate that the radiation protection authorities advocate an expense of at least 20 000 USD per mansievert averted, or about 100 000 FIM. If this is applied, it is e. g. advisable to use lead blankets with a dose reduction of 33 % for a work operation of 1 hour if the initial dose rate exceeds 1.2 mSv per hour. In the case of the respirator with a decontamination factor of 30, the corresponding air contamination level should exceed 5 times the derived air concentration, DAC, for the respirator to be used.

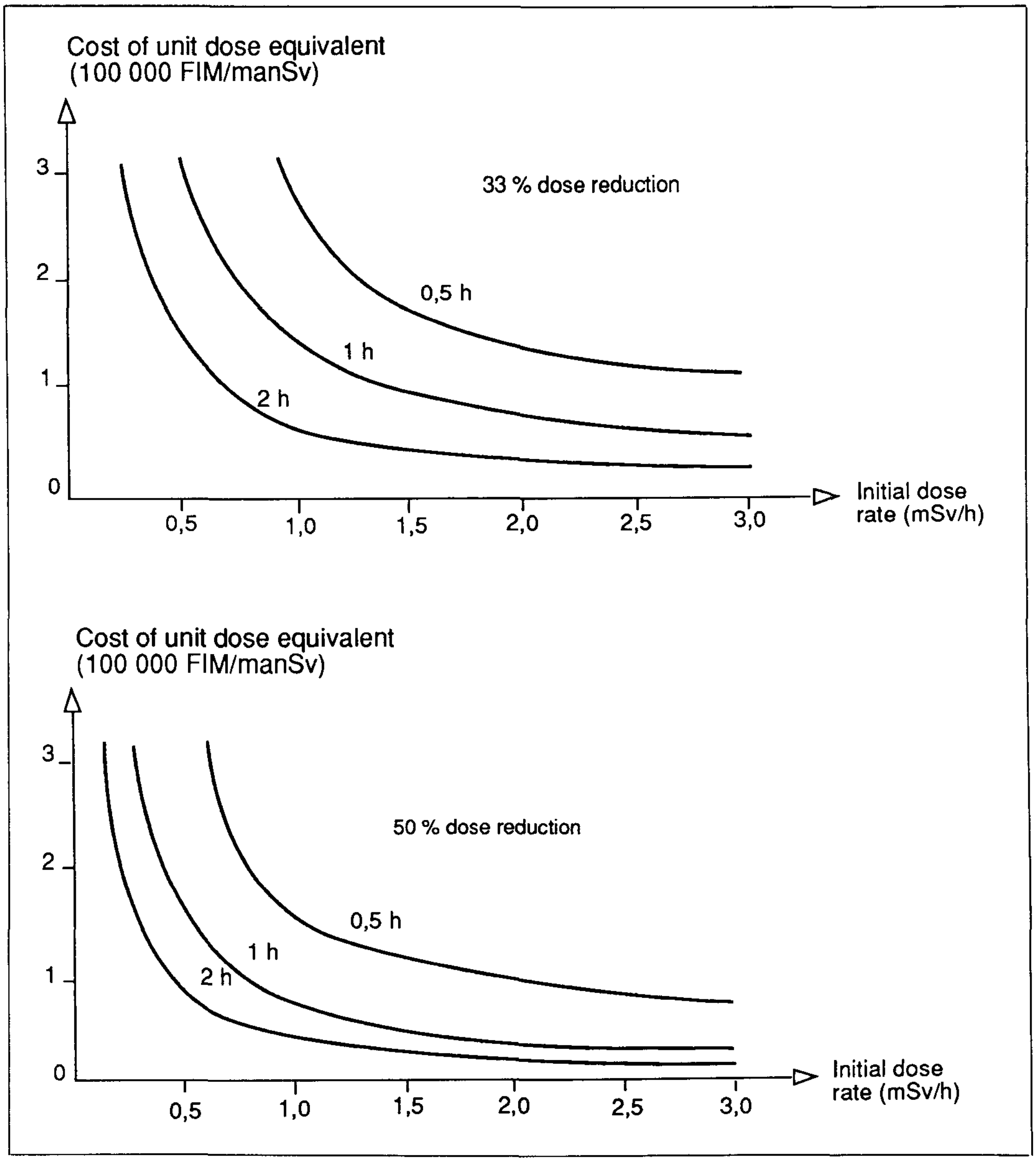

Figure 2.1. The cost per unit dose equivalent averted when one lead blanket is used and its dependence of dose rate and working time. The total costs caused by the use of the blanket are 40 FIM for each time it is used. The dose reduction achieved through lead blanket use is 33% (upper diagram) or 50% (lower diagram) of the dose received without the blanket. 1 FIM is about 0.2 USD.

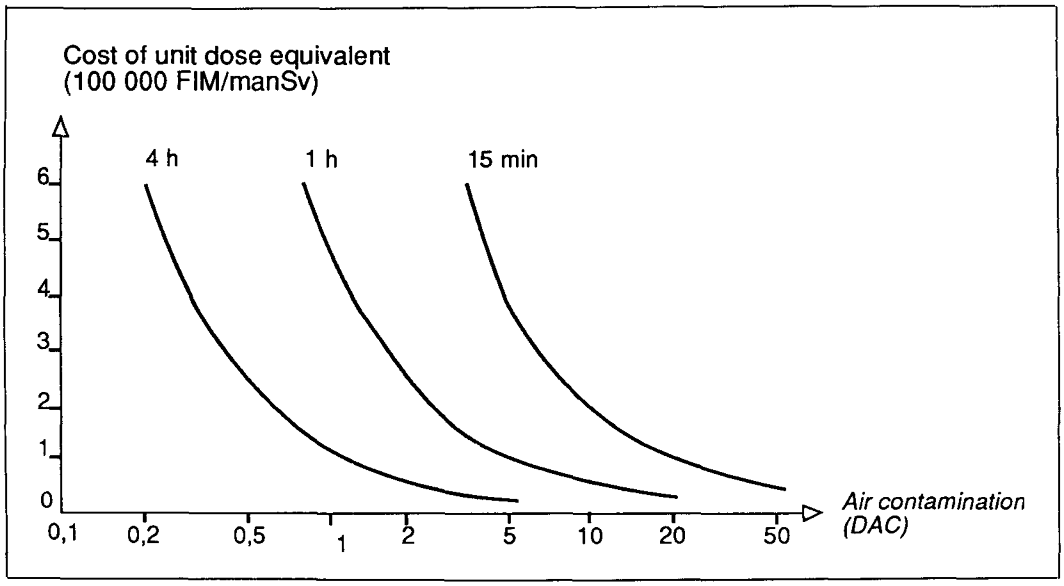

Figure 2.2. The cost per unit dose equivalent averted when a half mask provided with a dust filter is used, and its dependence of the air contamination level and the time of use. The decontamination factor of the half mask respirator is 30 and the total cost for one use is 12 FIM.

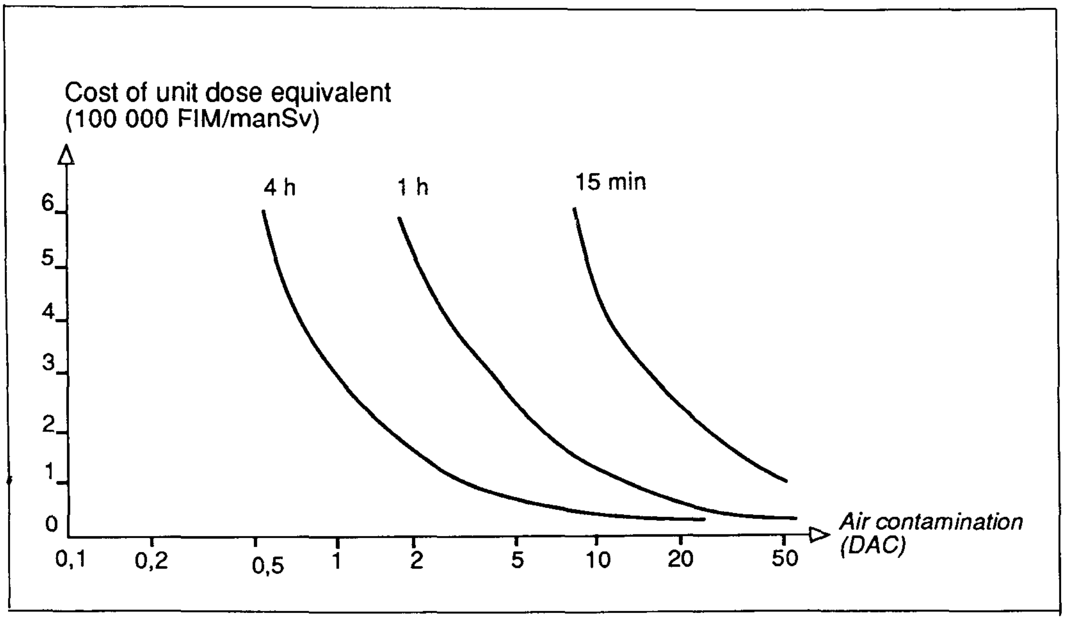

Figure 2.3. The cost per unit dose equivalent averted when a full mask provided with a filter is used, and its dependence on the air contamination level and the time of use. The decontamination factor of the full mask respirator is 100 and the total cost for one use is 35 FIM.

A calculation model for the spreading of radioactive contamination at a nuclear power plant was also developed.

The results show that the protective measures applied today at Nordic nuclear power plants are fairly compatible with the internationally recommended principles and guidelines for optimisation. This implies that they are near optimal.

2.3.3 Modifications of plant systems and constructions

The radiation doses to the personnel at Nordic nuclear power plants are generally low. Possible common factors behind the low doses were sought in a review of dose reduction actions and optimisation practices. More than 100 actions were studied, ranging from small modifications made just to improve radiation protection, to larger new constructions. The resulting view was that actions to reduce doses were based on more direct needs than optimisation considerations. Such needs could concern e.g. high local or general dose rates, or operational or safety related factors. Optimisation was hardly ever done quantitatively. Instead, it had been more like an intuitive process, based on the experience and skill of the radiation protection staff.

Actions were generally considered to be cost-effective. The study revealed that some of the actions involve rather high costs, reflecting the relatively large weight given by the plant operators to other factors than the objective health detriment.

It was concluded that a crucial factor from the practitioner's point of view is the ease of the optimisation procedure. This calls for clear, simple (although based on advanced models) and fast methods for routine production use. Such methods could include data bases and computerised decision support systems.

2.4 Discussion and conclusions

The optimisation of radiation protection must be an overall state of thinking in the minds of all employees. Optimisation of protection in a practice is an aid to support decision making, and should be considered as just one part of the optimisation of the practice itself.

General guidance on the selection of formal optimisation methods can be given. However, there are many things to be considered which have a bearing on the choice. There is a need for rules of thumb or some type of standard to be used in decision-making on the basic level of operational radiation protection work at a nuclear power plant. In more complex cases, data bases and computerised decision support systems are also needed.

If the optimisation problem can be confined to cover only the radiation protection of workers at a nuclear power plant, the procedure is normally quite well defined. The optimisation criteria are accepted, and inaccuracies in doses, costs, etc. set the boundaries for decision-making. The optimisation of radiation protection and the decision-making should be based on good technical competence and thorough preparation. Special emphasis should be put on the search for options as well as on the assessment of the doses and costs involved.

The level of ambition in radiation protection decisions at Nordic nuclear power plants is high. Indeed, in many practical situations and routines it seems as though the entire costs of protection options are not in detail recognised or assessed.

The following are some suggestions to further study the basis for optimisation of radiation protection at the Nordic nuclear power plants:

□ thorough evaluation of occupational radiation doses, general as well as task specific, and the radiation protection work normally carried out at the plants,

□ survey of the relations between radiation protection and operation of the plants,

□ assessment of potential contributions available in special cases for radiation protection at the plants,

□ more comprehensive monetary valuation of occupational radiation doses at the plants.

The validation of a model for estimating the monetary equivalent of occupational doses, in line with that developed by the NRPB could possibly be studied as a special issue.

In countries such as the USA and the UK, optimisations assessments are formally required by the authorities. If this were required also in the Nordic countries, the optimisation assessments are likely to be better founded than the present ones.

3 Comparisons of radiation risks and others

Project report 430

3.1 Background

We have always been exposed to natural radiation. The radiation level is quite variable and depends on e.g. the geology of the place considered. A large number of human practices may increase or decrease the natural radiation dose.

The use of nuclear power obviously leads to some form of radiation exposure. The Nordic countries have experienced a debate about the use of nuclear power and a search for alternatives. In this type of debate, the risks to health and the environment play an important part. Radiation is one source of risk among many, and several types of energy sources including nuclear power can lead to radiation exposures. Therefore an ideal goal for the studies of risk from power production should include a quantification of all associated risks, both from radiation and from other agents. A first step towards this ideal has been a project concerned with comparison of nuclear radiation risks and others.

3.1.1 Risk factors

The following types of risk are included:

- □ risks from natural radiation (these risk factors include consequences of exposure to radiation from cosmos, cosmogenic radionuclides, terrestrial gamma radiation, radon, thoron, and long lived radionuclides)
- □ risks from industrial modification of the natural radiation (among human activities inducing these types of risks are mining, non- nuclear energy production and the production, and use of fertilizers)
- □ risks due to predicted and potential releases of radionuclides into the biosphere from a final disposal of used nuclear fuel
- □ risks due to releases of chemical pollutants from fossil fuel waste.

This part of the study has been limited to potential risks contributed by release from energy production. Risks from both carcinogenic and noncarcinogenic substances are taken into consideration.

This part of the study has been limited to potential risks contributed by release from energy production. Risks from both carcinogenic and noncarcinogenic substances are taken into consideration.

3.1.2 Objective

The objective of the study was to provide data for comparisons of various risks, with those from the natural radiation as a reference.

Risks induced through human activities, particularly the final storage of nuclear waste, can thus be put into perspective. A way of reducing some of the risks mentioned in 3.1.1 is to save energy. Therefore the radiological impact of energy conservation has been studied. Chemical risks from effluents from power plants fired by fossil fuel are of a totally different nature than radiological risks.

It was an objective of the present study to suggest a method for comparison between these very differently acting risk factors and also provide a discussion of the limitations of such risk comparisons.

3.1.3 General outline of the study

The natural radiation doses to the population in the Nordic countries have been estimated, as well as their modifications by human activities. Both individual radiation doses (effective dose equivalent in millisievert, mSv) and collective radiation doses (collective effective dose equivalent in mansievert, manSv) have been assessed. The collective dose is the sum of all individual doses in a group.

Generally, the collective dose equivalent from a source is assumed to be proportional to the collective long-term risks (compare 1.2). This means that the risks are the same if 10 persons get 100 mSv each, or 100 persons get 10 mSv each. In both cases the collective dose is 1000 man-mSv = 1 man Sv.

Any releases from final repositories of high level nuclear waste will, according to present judgments, not start until about one million years from now. It is impossible to determine the risk to a human population in the very distant future, since the development probably will bring about both social, environmental, and biological changes in the next one million years. Therefore it is only possible to estimate the potential of the waste from a repository to increase the radiation exposure of future human beings. This potential may be compared to that from present activity sources which are found in other contexts. Thereby an indication of the relative risk potential from the repository is obtained.

All types of energy production from fossil fuels produce various toxic chemicals. Since the use of fossil fuel is an alternative to nuclear power generation, it is tempting to try to present the contributions to the risks from energy production on a common scale. No definite conclusions can, however, be drawn in this report with regard to the risk from chemical substances released to the environment compared to the risk from radiation. Some of the problems of finding a common scale are the following:

□ Chemical species may be transformed through chemical reactions in the environment or in the body, with widely varying time scales.

□ Radiation and some chemicals have mainly genotoxic effects, which are difficult to compare with non-genotoxic effects of chemicals.

□ Some chemicals may cause environmental damage that leads to secondary effects on human health, e.g. acidifying substances that may mobilise metals in the ground.

□ It is difficult to measure and get data on the very large number of chemicals in effluents.

□ One substance may enhance or weaken the effect of another.

Final disposal of the waste products from energy production may be an important source of potential hazards to human beings. Generally, nuclear waste has much smaller volume and is much more safely deposited than chemical waste. This reflects the general finding that radiation is under more strict control and is more thoroughly evaluated as a contributor to the total risk posed to humans from hazardous agents than any single chemical compound.

3.2 Comparisons of doses and risks

3.2.1 Natural radiation in the Nordic countries

The doses from the different sources may be grouped as shown in figure 3.1. In the figure, collective doses to the whole Nordic population are shown (Denmark, Finland, Iceland, Norway and Sweden, in all about 22 million inhabitants).

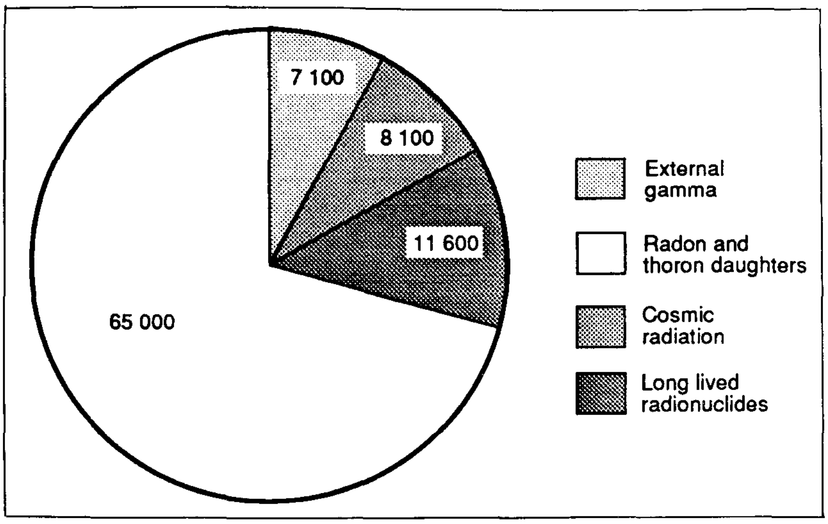

Figure 3.1. Collective effective dose equivalent (manSv per year) from different natural radiation sources in all of the Nordic countries. The total collective dose is 92 000 manSv per year.

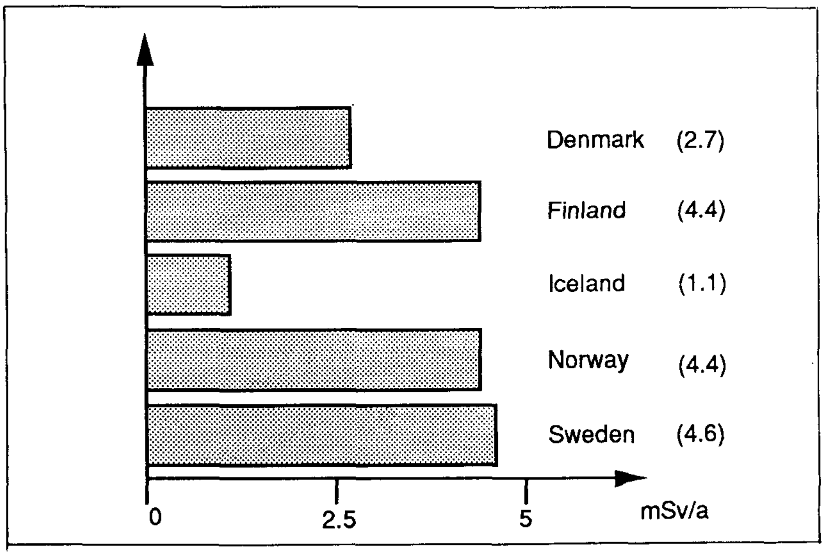

Figure 3.2. Average effective dose equivalents from natural radiation to individuals in the Nordic countries.

There is a considerable difference in the individual dose to an average member of the population in the five countries. The Nordic countries seem to group themselves at three different dose levels, Iceland whith a relatively low dose, Denmark inbetween, and Finland, Norway and Sweden with a higher and similar dose level, as shown in figure 3.2. Exposure to terrestrial gamma radiation and radon are the main causes of variation between the countries, due to variations in geology and climate.

3.2.2 Modifications of the level of natural radiation by human practices

As shown in figure 3.1, the natural radiation gives rise to a total collective dose equivalent of roughly 100 000 manSv per year for the Nordic area.

In the following a number of practices will be described and their additions to the collective dose equivalent will be estimated. It should be noted that their relative collective radiation risk follows the relative collective dose equivalents under the linearity assumption (3.2).

Mining

The most important radiological consequence of non-uranium mines is the exposure of the workers to increased concentrations of radon in the air.

Since only a small group of workers is exposed, the collective dose equivalent contribution is small. Individual dose equivalents are on the order of 3-10 mSv/year and the contribution to the collective effective dose equivalent in the Nordic countries has been estimated to about 40 manSv/year.

Production of energy

The emissions of radioactive material from combustion at coal and peat fired power stations may cause different forms of exposure: internal through inhalation and food intake, external from radionuclides in the air and from radionuclides deposited on the ground. Our estimates indicate that these forms of exposure lead to an increase in the collective effective dose equivalent in the Nordic countries of less than 100 manSv/year.

Some of the ashes from power production are used as a constituent of concrete. This may lead to a slight increase in the exposure to terrestrial gamma radiation of inhabitants in houses built from such material (approximate individual dose 0.1 mSv/year). It is difficult to estimate the dose contribution to the total population, but it may be larger than that from the radionuclides emitted from combustion.

The use of geothermal energy in Iceland and production in underground hydroelectric power stations in Norway can increase the exposure to radon slightly, but to an extremely low degree in terms of collective doses, at most a few manSv per year. The same conclusion can be drawn about contributions from radon in gas for domestic use and from exposure of workers due to scaling (selective accumulation of contaminating materials) on equipment used in the production of oil and gas.

Use of fertilizer

Certain fertilizers may contain radioactive substances and thus contribute to the doses to the population through internal and external irradiation. Production of fertilizer may lead to byproducts which are radioactive. Certain forms of gypsum byproducts from such production may in some cases cause significiant individual doses when used for building material. The contributions from the use of fertilizer are, however, small and a total of about 100 – 200 manSv/year is a reasonable estimate.

Energy conservation

In recent years the public has been saving energy mainly by improving the insulation of houses. The energy supplied for heating has been reduced by about 30 – 40 %. The energy actually used in the dwelling may have been less reduced, however, since there has also been a parallel switch from oil heaters to electric radiators which have practically no immediate losses to the outside. The conservation has often been achieved by using a lower ventilation rate which causes an increase in the indoor radon concentration.

Would it be reasonable for radiation protection purposes to increase again the air exchange rates (and the energy consumption) in Nordic dwellings?

As a yardstick, a cost of about NOK 150 000 per manSv is often used as a reasonable expenditure in radiation protection.

A theoretical study shows that compared to this, the heating costs from increasing the ventilation in dwellings will be very expensive in relation to the dose reduction. This is not an argument for refraining from radon reduction in the case of high radon levels, since in this case the optimisation criterion is overruled by the individual dose limitation criterion (2.1).

There are also today other methods for radon reduction that are very effective. For the sole purpose of radiation protection, such methods should be used rather than a general increase in ventilation. There are however other negative effects of low air exchange rates, and if such effects also are taken into consideration, increased general ventilation is probably recommendable, especially if heat exchangers can be used. Actually, these are often profitable in countries with high energy costs, and the cost estimates therefore can only be seen as crude examples.

3.2.3 Waste from nuclear and fossil fuel plants

Many chemicals that are released as by-products from energy production are genotoxic, as is radiation (1.2). It would have been interesting to include chemical risk factors in the estimations of risk from energy production. The amount of each chemical emitted and its associated hazard are among the unknown factors that make such comparisons difficult. Furthermore the population may be exposed to the hazardous materials during totally different time periods in the future (3.2.4). Therefore several questions of facts as well as values have to be resolved before an actual risk comparison can be performed.

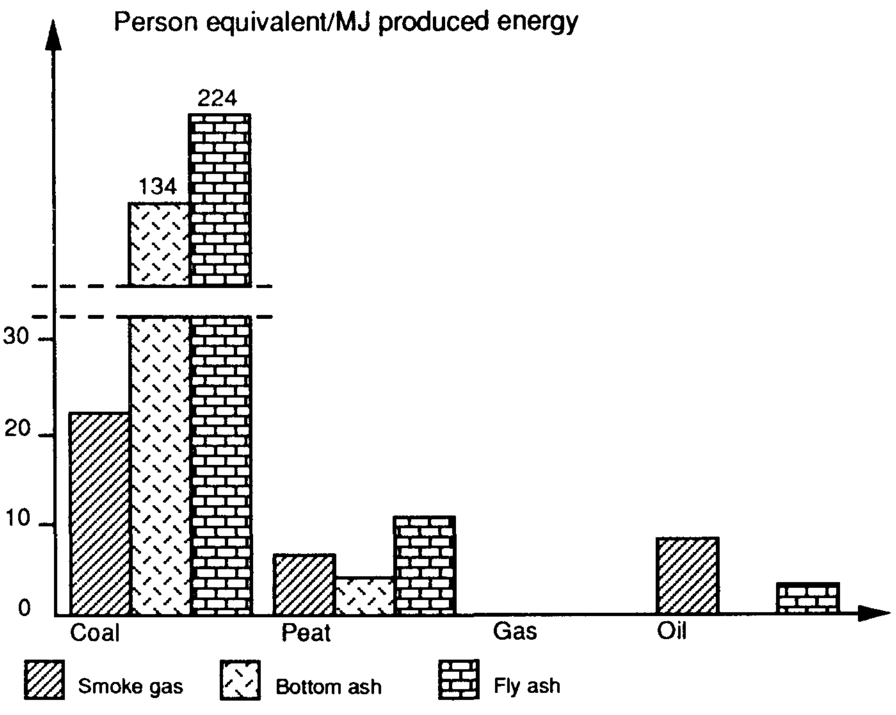

Figure 3.3. Person equivalents (see text for definition) from different exposure pathways caused by radioactive and chemical waste products from the combustion of fossile fuels. All releases are assumed to go to water pathways. For coal, the bottom ash gives 134 and the fly ash 224 person equivalents per MJ.

As a first step, we have tried to estimate the toxic potential of waste from nuclear power plants and from power plants burning fossil fuel. One may as an example express the potential risk in terms of person equivalents as shown in figure 3.3.

The person equivalent is a purely theoretical unit. It may be depicted as the number of persons that can be exposed at a concentration corresponding to the annual limit of intake if the waste is distributed equally among them. Todays maximum limits are used and the dominating compounds have been shown to be the ones that are genotoxic (metals). These chemicals are assumed to have a linear dose-response curve (see section 1.2).

From figure 3.3 it can be seen that the highest risk potential is associated with the burning of coal. The waste from nuclear power plants has been found to have a risk potential corresponding to 80 person equivalents if an exposure to 1 mSv/year is accepted. The number of person equivalents increases in inverse proportion to the annual limit of intake.

In order to obtain the actual risk from the potential risk, the dispersion of the waste in the environment and its uptake in man must be calculated. The degree of human exposure is associated with the character of the repository and the environmental transfer of the releases which have not been assessed here. Our calculations can possibly give a first idea on the requirements on safe storage of waste from the different forms for energy production.

3.2.4 Radioactive releases to the environment

In order to assess how the release of high level radioactive waste from repositories can add to the levels of natural radionuclides, model calculations have been performed. They indicate that even under unfavourable conditions, the release will not take place until after at least one million years.

At that time the activity concentration of the released radionuclides will reach a level normally several orders of magnitude lower than todays activities in the same type of environments. The model calculations assume a possibility of leakage from the storage through ground water directly to well water used for human consumption. Even in the "special case" where the ground water is assumed to be oxidizing, one will not be able to find more than a limited increase in the activity concentration (or danger index) in well water compared with todays very low activity in most Nordic wells. But, again we do not know whether humans will drink well water, particularly not if the ground water is oxidizing, a million years from now.

Our calculations thus indicate that a risk potential (3.2.3) will not be expressed unless an accident or other totally unexpected events take place.

3.3 Conclusions

The collective effective dose equivalent to the Nordic population from natural radiation constitutes a much larger fraction of the overall collective dose equivalent than that from any other human activity studied. Among the natural sources, indoor radon gives the largest exposure.

Indoor radon has some features common with man-made sources, since its levels can be influenced by human practices, e.g. by energy conservation based on reduced ventilation rates. Lowering of the ventilation rate in houses causes increased doses due to radon which by far offset the dose reduction gained since less energy need be produced.

Storage of nuclear waste will cause only small increases in the natural activity concentrations in the environments studied, and only after time periods of the order of 1 million years.

Chemical risk factors may contribute significantly to the health risks connected to energy production. Although it is not at present possible to estimate the magnitude of the risk, one may easily estimate the potential risks related to some chemical and radioactive waste products. Such estimates lead to the conlusion that the control of effluents from all types of energy production is important for human health and the global environment.

The lack of data on release, distribution, uptake, health effects and acceptable concentrations of different chemical and also some radioactive effluents is striking.

4 Limitations and method development in probabilistic safety analysis

Project report 470

4.1 What is probabilistic safety analysis?

The main objective of safety analyses of industrial facilities is to give knowledge that may be used to minimize the potential for accidents which can cause injuries and loss of human life, negative impact on the environment and damage of the facility itself.

The basic steps in a safety analysis include:

□ identification of events that can initiate an accident (primary disturbances)
□ analysis of how selected disturbances proceed, with due regard to responses from those who operate the plant
□ analysis of potential releases of toxic substances
□ analysis of the environmental transport of these substances and their impact on health and on the environment including the plant itself.

These steps are carried out in any type of safety analysis. However, in a deterministic safety analysis, pessimistic assumptions are made and criteria for safety functions are consistently chosen on the safe side. Components and operators are assumed to act in a determined way (deterministically), and accidents also occur deterministically. Different protection barriers are analysed one at a time with pessimistic assumptions. Hence, the safety level is not expressed quantitatively in a deterministic safety analysis. Such an analysis cannot give a realistic picture of the accident propagation and of the associated environmental consequences. In addition, it cannot reflect the relative importance of different accident sequences.

By definition deterministic analyses focus on the worst possible cases. They are likely to overlook less dramatic sequences of events and the simultaneous failure of several safety related components.

Verification of the safety of plants has traditionally been obtained through a deterministic analysis of selected postulated incidents that challenge safety. The criterion of safety of a nuclear plant has been that it can be brought to a stable and safe state given a predetermined set of accident conditions.

A supplementary and more balanced picture may be obtained by superimposing a probabilistic perspective on the main steps of the safety analysis. This is a natural approach since components fail and accidents start in a seemingly random way, and human interactions with the systems are hardly deterministic.

Probabilistic safety assessment (PSA) provides a structured and logical approach to identify credible accident sequences, assess the corresponding likelihood and delineate the associated consequences.

In nuclear power applications, three *PSA levels* can be distinguished.

Level 1 PSA comprises identification and quantification of accident sequences leading to core damage.

Level 2 PSA includes analysis of core melt progression and containment response, which combined with Level 1 results leads to determination of the magnitude and frequency of radioactive releases.

Level 3 PSA together with results of Level 1 covers environmental transpoıt of radionuclides and assessment of radiation doses to the population. Hereby an estimate of the public risks is obtained.

The exposure and risks for plant personnel are normally not directly assessed in PSA.

Within the nuclear sector in Finland and Sweden, the use of PSA-techniques is today regarded as a natural element in everyday safety work. The principal merits of PSAs include the potential to identify possible weak spots in the design and operation of the plants, and to rank the dominant risk contributors. These insights may directly lead to safety improvements at the plants by means of design modifications or procedural changes.

Swedish PSAs have resulted in implementation of numerous significant improvements (E4, H9).

At the same time the PSAs have the potential to increase the operators' awareness of the safety significance of various tasks in operation and maintenance, and consequently make them better prepared for possible emergency situations.

The state-of-the-art in PSA has reached a certain degree of maturity. Several comprehensive PSAs are now available for nuclear power plants in a number of countries. There is a general agreement that the studies should be used as an important tool in the process of decision-making.

Practical applications of PSAs involve planning and reviewing of plant modifications, establishing the basis for a systematic evaluation of operating experience by analysis of disturbances and incidents, and supplying input for decisions on research project priority. Also in the non-nuclear field there is a clear tendency of a growing number of applications of PSA-techniques (P1).

4.2 What are the limitations of probabilistic safety analysis?

The merits of PSAs are thus indisputable, given that the analysts are aware of the limitations and the practitioners use the results within the intended frame. At the same time there are many remaining problems and limitations in using probabilistic techniques (L3, P4, H12). Some of them are intrinsic and difficult or impossible to overcome, while other are matters of practice and thus bound to be resolved as understanding of analytical methods becomes more widespread (L3).

The limitations of the PSA techniques contribute to the overall uncertainty of the results of PSAs. It is of great importance to point out the main limitations and hereby facilitate decision-making and prevent possible misuse of PSAs.

Examples of the intrinsic and practical limitations (L3, P4) are given below. Sometimes both types of limitation may affect an aspect of a PSA.

4.2.1 Intrinsic limitations

Incompleteness

Incompleteness of PSA originates from the technical complexity of large systems, from difficulties to identify, model and quantify all potentially significant internal interactions between systems, components, human beings and corresponding external interactions with environment, and from possible misses in the use and review of PSA.

Obviously, there are no guarantees that all significant accident sequences can be identified, but credibility of the studies is expected to increase with time. Integration of new operating experience, i.e. calibration based on the real world, within the concept of living PSA will contribute to reduce incompleteness uncertainties. Sensitivity analysis may also be employed to some extent in this context (H12).

Finally, a well-structured review process will contribute to assure that the PSA is satisfactorily complete.

Data base

The data bases will always be inadequate. This applies also to the information on relatively frequent failures, at least with respect to detailed knowledge.

Other, more serious failures might never occur and associated failure probabilities are bound to be based on judgement and extrapolations from other applications.

Human interactions

Human reliability is quite different in nature from component reliability. The spectrum of possible human errors is very wide. The same applies to the ability to act innovatively, to solve problems and to correct mistakes.

When plant systems are designed, procedures formulated, work organisation established and training carried out, the overall goal is to take into consideration both abilities and limitations of human beings. Despite this, there is always a possibility that human beings will make mistakes. These are difficult to predict, and there are no PSA models which can fully represent human behaviour.

Common cause failures – a subset of dependencies

Components or systems may for their function depend on the function of other components or systems. The potential for such dependencies may be due to e. g. design complexity, involvement of human beings or the influence of environmental factors. The dependencies imply a potential for multiple failures. Most types of dependencies can be explicitly modelled, which constitutes one of the main advantages of PSA methods. Common cause failures, however, represent a subset of dependencies which due to scarceness of data or lack of knowledge are not represented in detail in the analytical models (event trees and fault trees).

The common cause failures are very important in the case of redundant safety systems or components – a common cause failure may mean that all systems or redundant trains within a system are becoming inoperable at the same time, and the redundancy is thus lost. A variety of different causes may be hidden behind each common cause failure contribution, and the analysis of common cause failures is quite complex.

Similarly to human failures, common cause failures may result from an infinite spectrum of possible scenarios based on hypothetical root causes and coupling mechanisms. It is not possible to model and quantify unknown failures, and this shortcoming is closely related to the problem of completeness.

Uncertainty

Uncertainty is an inseparable characteristic of probability. It is often forgotten that the corresponding uncertainties are hidden also in deterministic analyses. In a PSA they are easier to identify and quantify.

4.2.2 Practical limitations

Consistency

Experience shows both similarities and differences between the PSAs performed.

Efforts have recently been made in Sweden (C2, C3) to separate those discrepancies which reflect differences in design and operation from those which are due to differences in modelling approaches. The study (C3) showed that better consistency can be achieved.

Realism

The objective of a PSA is to provide a plant-specific realistic model of accident propagation. This means that unduly pessimistic assumptions should be avoided.

In reality the uncertainties are frequently handled by means of safety margins, the magnitude of which is not known. In addition, proper credit is not always taken for normally operating systems which can prevent or mitigate the accident. The final quantitative result might then be of no value and the relative importance of different sequences might be distorted.

Uncertainty

Numerous examples can be given of careless treatment of uncertainties. No clear distinctions are usually made between the parametric, modelling and incompleteness uncertainties and their relative importance.

The analysts are not always aware of which type of framework (frequentist or subjectivist, i.e. Bayesian) they actually apply, and this may lead to inconsequences.

Human interactions

Apart from having intrinsic limitations, modelling of human interactions is subject to shortcomings which can be improved. This applies in particular to qualitative modelling of operator tasks in the control room, where depending on the particular situation different types of behaviour (skill-, rule- and knowledge-based) may be expected (R1).

Understanding of cognitive aspects of operator behaviour is limited among PSA analysts, and bridging of the gap between technicians and psychologists is desirable. There is frequently a pessimistic or lacking treatment of recoveries in the PSAs, that is, of the restoration and successful operation of equipment which was initially unavailable. The available data for human interactions apply only to well structured tasks. The modelling of human behaviour has not yet reached the level where any accurate predictions of error probabilities can be made (W1). Structured procedures are, however, available for use of expert judgement in a systematic way.

Dependencies

Treatment of dependencies is not always well structured and consequent. Some common cause failure models are based on questionable assumptions or are being applied without proper regard to their limitations. Frequently, available methods for quantification of common cause failure contributions are not compatible with the amount and quality of information available from data sources.

Recent developments (e.g. M5) provide, however, a framework for performing different stages of common cause failure analysis.

External events

The lack of relevant data and the complexity of the problem create large uncertainties. The treatment of seismic hazards appears to be most difficult. These hazards are sometimes the dominant risk contributors.

Progress in this area is expected due to increasing knowledge about seismicity, fracture mechanics and seismic response.

Time dependencies

The basic logical models of PSAs (event trees, fault trees) can only to a limited extent simulate the numerous types of time dependencies which are involved (S1) and which may be important. Supplementary analyses of these aspects are seldom made within the PSAs.

Documentation

There is a substantial potential for improvements in documentation. Many PSAs are badly structured or written by and for PSA specialists. This limits significantly the use of PSAs and creates difficulties in PSA based decision-making.

4.2.3 Validity of absolute estimates

PSA provides a frame to identify systematically chains of events which may lead to accidents, and to assess realistically the associated frequencies. Dominant risk contributors are thus identified.

There are many examples of design and procedural deficiencies which have been disclosed as a result of PSA work. Modifications are then often made at the plants in order to achieve a more balanced risk profile. Such use of PSA techniques has indisputable advantages, and the validity of analysis results is frequently moderately sensitive to the uncertainties due to intrinsic and practical limitations.

In this context the use of PSA results for decision-making is based on relative criteria. These are, as opposed to absolute criteria, not totally dependent on the exactness of predictions and consequently less sensitive to uncertainties.

In contrast, considerable controversy surrounds the reliance on the bottom-line results of PSAs in an absolute sense and, consequently, the use of formal quantitative safety goals in the regulatory process. "One should resist one-digit statements about safety." (L3).

In some countries the introduction of safety goals has been considered a possible solution to the regulatory dilemma concerning demonstration of the level of safety. A good review of safety goals for nuclear power plant regulation may be found in reference (L2).

Current research projects carried out in Nordic countries (C2, C3, H13) clearly demonstrate the spectrum of problems encountered when comparing different PSAs. Thus, direct use of plant-specific numerical results in the absolute sense should be made with great caution, having in mind a wide spectrum of intrinsic and practical limitations as well as the involvement of subjective judgement in almost all tasks of a PSA.

A new major comparative study (U1) has made the importance of expert opinions in the PSA-context very visible.

Intuitive use of PSA-based goals is frequently employed on a system/subsystem level, e.g. for evaluation of design trade-offs. This is rather straight-forward and certainly beneficial with respect to public safety as well as plant reliability. Introduction of formal criteria for licensing is, however, hardly motivated in view of the problems outlined and in view of the inadequate precision of presently available safety goals. Implementation of such goals would require detailed specification of analysis procedures, a formidable and practically impossible task, the realisation of which would not encourage future developments and hardly promote safety improvements.

A compromise solution is suggested in (M6):

"The safety goals should not be used within a regulatory framework of strict acceptance or nonacceptance criteria but should be considered as one factor in arriving at regulatory judgement."

Individuals other than specialists in nuclear safety have very differing views on the value of alleged probabilities resulting from PSAs.

View of the economist

Economic scientists have developed models to compare the expected value of imperfect information and that of perfect information (F1). The implication is that with the aid of computer codes, decision makers can compare predictions of varying uncertainty.

View of the layman

Lay people have widely different attitudes to safety. Many people believe that anything that can happen will happen.

Many studies have shown that the catastrophic potential is a major factor in the explanations of why a risk is perceived as large (F2). Greater weight is thus given the same number of fatalities if it was obtained from a catastrophic event. The result of a PSA may therefore reinforce the layman's prejudice that the analysed low probability events are as threatening as the events with higher probability.

View of the political decision-maker

Politicians may have limited interest in the results of PSA. This is the conclusion of a major study in five countries where risk studies have been considered in political decisions about nuclear power (K2).

A party's political stance on overall energy policy is likely to colour political response to particular risk studies, according to this investigation. The results of particular studies may be far less important than for instance a previous position on the use of coal or renewable energy sources. It is interesting that in this respect the politicians may not reflect the concern of the lay people over risk studies.

4.3 Objectives and results of the Nordic project

The applications of PSA-techniques in Nordic countries are continuously supported by an extensive research program.

Of particular interest in the context of PSA limitations are benchmark exercises and reference studies (H3), and parallel comparative analyses of PSAs (C2, C3, H6, P7, P8, H8).

4.3.1 Objectives of the Nordic project

The following objectives were specified for the Nordic project:

1. Review and evaluate the current state of PSA-techniques with special emphasis on the treatment of dependencies, human interactions and uncertainties, which should lead to the identification of significant differences in analytical approaches of selected PSA-studies.
2. Investigate the sensitivity of results obtained from PSA-studies to basic assumptions, to data assignments and to choices of methods for analysis of selected topics.
3. Identify weak points and suggest improvements of current approaches.
4. Exchange new ideas and supply methodological support to current and planned projects related to topics mentioned above.

The largest share of the research resources was devoted to common cause failures. These are responsible for one of the most serious limitations of level 1 PSA and contribute significantly to the overall uncertainty.

4.3.2 Studies of dependencies

The studies of dependencies comprise a common cause failure data benchmark exercise (H7), and retrospective qualitative analyses of treatment of dependencies in Swedish (H6) and in foreign (P7) PSAs.

The Nordic perspective on this subject has been summarized in (H2).

Common cause failure data benchmark exercise (H7)

Motor operated valves in Swedish boiling water reactor plants have been chosen as the object of the study. The main findings of the benchmark exercise concern:

□ recommendations on suitable procedures for search of common cause failures
□ suggestions for improvements of the current failure reporting system
□ merits and drawbacks of classification systems
□ which are the most uncertain elements in the process of common cause failure quantification
□ evaluation of parametric models and use of direct assessment in the context of common cause failure quantification.

In total, 17 common cause failure candidates have been identified. The results are considered encouraging and indicate that basic identification can be reasonably well performed with the available raw data. Several different methods of analysis were used and their relative merits discussed.

Most of the observed discrepancies between the results from different models may be explained by differences in scope, bounding conditions and type of approach.

The quantitative analysis has shown that direct assessment (DA) of common cause failure contributions is possible, given comprehensive information including system flowschemes for identification of redundancies, and number of actuations and failures of relevant components.

Simple parametric methods, e.g. Additive Dependence (ADDEP) model and Multiple Greek Letter (MGL) method, are still of major interest. They may be directly combined with data on single failure probabilities given in the Swedish Reliability Data Book (R2), are easy to apply, are suitable for checking the impact of modified assumptions, and represent in practice the only option which may be applied to components which are not as common at the plants as valves.

On the other hand, the Binominal Failure Rate (BFR) model is complex and its use may result in arbitrariness. The Multinomial Failure Rate (MFR) method needs as input the same type of information as direct assessment.

Figure 4.1 shows the estimated probabilities of observing exactly i ($i = 1, 2, 3, 4$) failures per demand and corresponding 90 % confidence intervals, obtained for a set of redundant motor operated valves at Forsmark plants. As expected the uncertainties become larger with growing failure multiplicity.

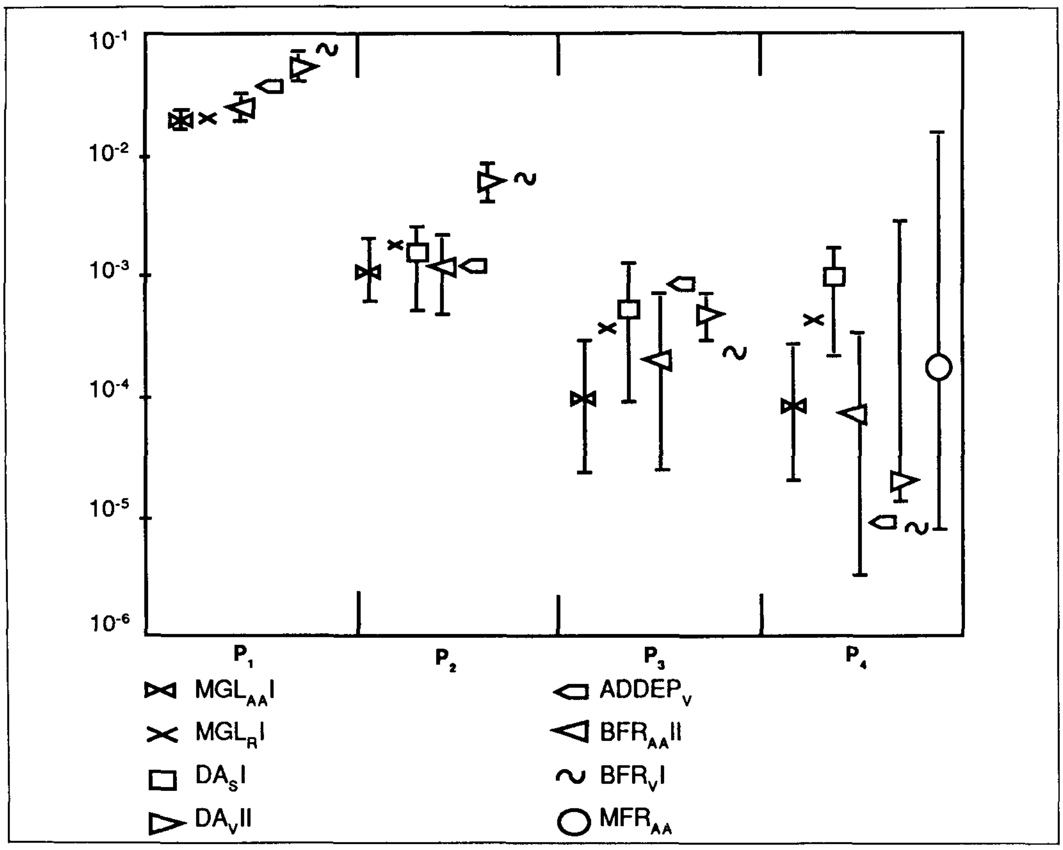

Figure 4.1. Estimated probabilities P of observing exactly i (i=1, 2, 3, 4) failures per demand and the corresponding 90 % confidence intervals for a set of redundant motor operated valves at the Forsmark plants. The results were obtained by four different teams of analysts (indexed AA, R, S and V) using different estimation methods explained in the text (MGL, DA, ADDEP, BFR, MFR).

Retrospective qualitative analysis of treatment of dependencies in Swedish PSAs (H6)

This in-depth qualitative overview concerned equipment-related common cause initiators, intersystem dependencies and intercomponent dependencies. The two last mentioned groups were in turn divided into functional, shared-equipment, physical and human interaction dependencies. Due to their special nature and importance, common cause failures were treated separately.

The overall impression from the retrospective analysis is positive due to the high degree of detail in modelling of accident sequences (event tree analysis) and in modelling of safety systems (fault tree analysis).

The Swedish PSAs have been successful in identifying different types of dependencies. In several cases design deficiencies have been observed, leading to modifications of the plants. The differences between the performed analyses are, however, significant and concern: degree of detail, scope, choice of qualitative (identification) methods, representation of dependencies in the plant model, quantification models, sources of data and documentation.

Recommendations from the qualitative phase comprise a list of specific cases to be analysed in sensitivity studies, proposals for future Nordic research projects and suggestions for improvements or supplements to existing analyses.

Retrospective qualitative comparison of treatment of dependencies in foreign PSAs (P7)

The study covers five PSAs for the German plant Biblis B, British plant Sizewell B and U.S. plants Calvert Clift 1, Oconee 3 and Seabrook. These PSAs were selected since they were publicly available and are representative for PSA-work in different countries.

The comparative study is much more superficial than the study concerning Swedish PSAs. This is natural since in the case of foreign studies it was not possible to perform a detailed analysis of the system models. This would require access to background information and close cooperation with analysts who performed the PSAs. However, on a superticial level the conclusions of this comparative review are in line with those of the Swedish study (H6), i.e. differences in scope and apCroaches used are significant.

It was not possible to assess to what extent the observed discrepancies in the impact of various types of dependencies on the results of the PSAs can be attributed to specific differences in design and operation of the plants.

4.3.3 Studies of human interactions

Studies of human interactions include a reference study (H5) and retrospective qualitative analyses of treatment of human interactions in the Swedish PSAs (H6) and in foreign PSAs (P8).

Reference study on human interactions

Manual depressurization following loss of the main and auxiliary feedwater systems is an important interaction between the operators and the plant. This has been studied for the Forsmark 3 plant by the four working groups. The analysed operator action is part of the most dominating core damage sequence for Forsmark 3 according to the PSA for this plant.

The study used very limited resources and boundary conditions were not specified in detail, thus giving the working groups rather free hands for handling of the problem. The main objective was to investigate the importance of assumptions behind the boundary conditions, rather than to compare in detail models for treatment of human interactions. Particular operator actions were qualitatively analysed and their failure probablity was assessed.

The PSA-study for the Forsmark 3 plant constituted the main background material for the reference study. In addition, a simulator exercise was carried out in order to provide practical insights into the situation of the operators during accident conditions. However, the simulated case did not correspond exactly to the situation to be analysed.

The available time for carrying out of the manual depressurization (i.e. for diagnosis, performance of necessary operations and possible recovery) was regarded by all groups as a critical factor in the context of quantification.

The discrepancies between the numerical results, which in some cases were substantial, could be attributed to different interpretations of the simulator exercise and of information contained in the emergency procedures (and consequently to differences in the choice of time windows), and to different approaches to data assignment.

Specific recommendations were made to improve factors which may influence operator performance in emergency conditions. In addition, the use of training simulators in analysis of human interventions in complex industrial systems has been discussed (P2).

As a follow up to the reference study on human interactions, one institution applied an approach based on influence diagrams for the estimation of operator failure probabilities (P9). The use of influence diagrams proved to be an effective tool in the modelling and identification of major uncertainties.

Retrospective qualitative analysis of the treatment of human interactions in Swedish PSAs (H6)

Contrary to the treatment of dependencies, the analyses of human interactions in the Swedish PSAs are relatively superficial. This is due to the fact that for various reasons the main emphasis in the first generation of Swedish PSAs was focused on hardware performance.

The qualitative overview covered six Swedish PSAs. The analysis concentrated on routine and dynamic human interactions including recoveries. The topics addressed include assigned human interaction probabilities, human interaction dependencies, sensitivity studies within the PSAs and impact of human interactions on dominant accident sequences.

A wide spectrum of differences between the analyses performed has been observed. These differences may concern level of ambition, approach to modelling and quantification, and documentation of the studies. In principle, only the Ringhals 1 PSA contains a thorough, well documented, plant- and situation-specific analysis of human interactions. None of the studies addressed errors of commission, i.e. active operator errors which may aggravate the accident situation.

Data on the probability of human errors in most cases came from simple assumed relations between the time available for diagnosis and the probability of operator failure. The numerical differences are large and can hardly be explained by differences in factors which are specific for the various plants. In fact, the Swedish boiling water reactors are quite similar with respect to the times available for crucial operator actions.

Based on conclusions of the study, recommendations have been made concerning cases to be studied in sensitivity analyses, possible improvements/supplements to existing PSAs and proposals for future Nordic research projects within the field on human interactions.

Retrospective qualitative comparison of the treatment of human interactions in foreign PSAs (P8)

The analyses of human interactions in PSAs were compared for the same five plants that were considered in the review of dependency analyses (P7). The limitations described earlier still apply.

The main areas of the study are: scope and objectives of the human action analyses, identification and classification of human errors, treatment of maintenance versus operational activities, impact of recovery actions, inclusion of psychological factors, human actions modelling, data sources used, and impact of human actions on the core melt frequency.

In addition, the uncertainty analyses connected with human reliability were reviewed.

The quality of human action analysis documentation varies significantly. Also the extent to which commission errors are taken into account is usually low. The models utilised are mostly simple logical models suitable for calculation.

Data for human reliability estimates were mainly taken from subjective sources. This, however, does not explain all the differences in the results since the degree of inclusion of recovery also plays an important role. Human actions have a significant impact on the results of each study in which they are extensively addressed.

4.3.4 Sensitivity and uncertainty analysis

The work in this area includes the Nordic reference study on uncertainty and sensitivity analysis (H11, H10), sensitivity studies of common cause failures and human interactions in Swedish PSAs (H8) and reflections on decision-making in view of uncertainties (P6).

Nordic reference study on uncertainty and sensitivity analysis (H11, H10, P6)

The Swedish PSAs are limited to point estimates of accident sequence frequencies. Thus, formal studies of parametric uncertainties have not been included. With the exception of the Forsmark 3 PSA, no comprehensive sensitivity studies have been performed. In order to obtain a better perspective on the results, supplementary uncertainty and sensitivity analyses are of interest.

The most dominant sequence from the Forsmark 3 PSA has been selected as the object of the study. The sequence is dominated by common cause failure contributions for motor-operated valves, previously studied within the common cause failure data benchmark exercise (H7), and by operator failure to initiate manual depressurization, previously studied within the reference study (H6).

It should be observed that the selected sequence is not typical for the Swedish PSAs. Due to the involvement of common cause failure contributions with high failure multiplicities combined with an operator action, the associated uncertainties are expected to be very large.

The reference study comprised three phases:

1. Generation of uncertainty distributions for the studied accident sequence. Methods and data quantifying common cause failures and human interaction errors were selected quite freely by the participating groups of analysts
2. Comparison of computer codes for uncertainty analysis using a common model and common data for all types of events involved.
3. Use of models, data and computer codes considered optimal by the participants.

Figure 4.2 shows some results obtained by the different groups. All groups used Monte Carlo simulation codes for the propagation of uncertainty distributions.

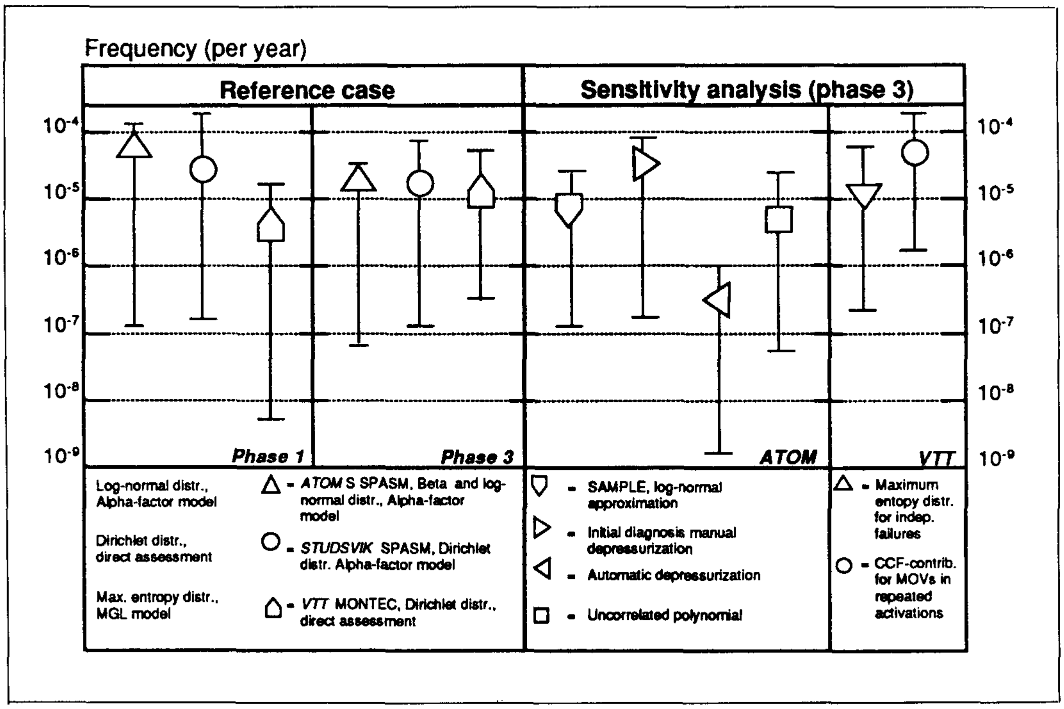

Figure 4.2. Reference case results in Phase 1 and Phase 3 of uncertainty analysis, and sensitivity analysis of Phase 3 results for the selected sequence (see text). The sensitivity analyses include manual vs. automatic operator action, different uncertainty distributions for the basic event, and different assumptions concerning the treatment of time dependent phenomena.

The estimated uncertainty interval for the analysed accident sequence is large. Also the estimated frequencies differed substantially in phase 1 but were more consistent in phase 3 as a result of modified approaches. The relative merits of a variety of models and computer codes were demonstrated. From a practical point of view, replacement of the existing manual depressurisation by an automatic one would reduce the estimated frequency by a factor of 20.

Finally, the impact of uncertainties on decision making has been treated (P6).

Retrospective quantitative analysis of common cause failures and human interactions in Swedish PSA studies (H8)

Following the recommendations from the qualitative analyses described above, comprehensive sensitivity studies have been carried out on the treatment of common cause failures and human interactions in available Swedish PSAs for boiling water reactor plants.

An example of a sensitivity study, concerning manual reactor shutdown is shown in figure 4.3. For comparison, the values used in each PSA, respectively, are indicated. Apparently, the core damage frequency for two of the plants is sensitive to the assigned probability of this operator action.

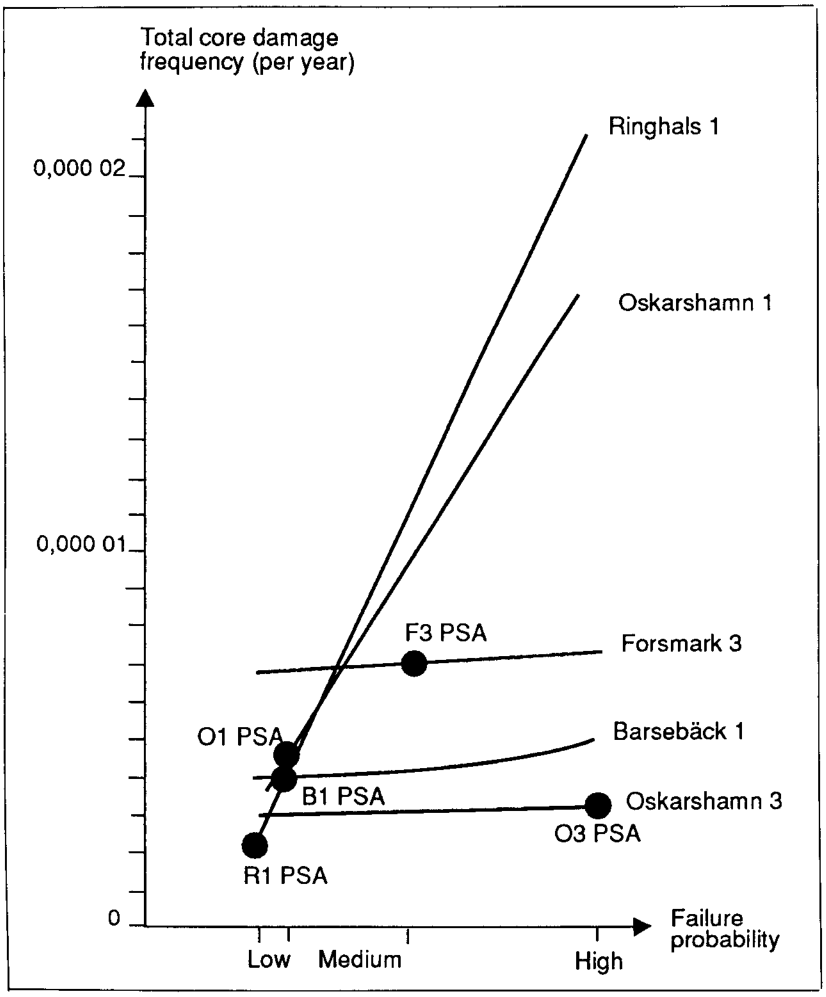

Figure 4.3. Sensitivity analysis of manual reactor shutdown showing the frequency of core damage as a function of the probability (low, medium, high) of operator interaction error.

Sensitivity analysis proved to be an efficient tool for demonstrating the impact of different assumptions, methods and data on the results of the studies. Specific recommendations were given with respect to the treatment of common cause failures and human interactions within those plant-specific reference plant models which are about to be generated in the near future. Further studies were also suggested.

It should be remembered that within sensitivity studies, one aspect at a time is studied. Integration of the corresponding recommendations concerning other PSA-elements might lead to a different overall picture, and this may influence priorities for future research.

4.3.5 Studies of selected modelling topics

Time-dependent phenomena in PSA (S1)

The nature of some essential time-dependent phenomena which should be incorporated into the models of PSA has been reviewed, and the probabilistic methods for analysis of such phenomena have been discussed. Among a wide spectrum of time-dependencies of interest in this context we may mention ageing of equipment, time-dependent unavailabilities of standby components and the time related behaviour of accident sequences.

The problem of component ageing has been addressed in two case studies concerning (1) statistical analysis of ageing of motor-operated valves at Swedish nuclear power plants and (2) models for evaluation of ageing of piping.

The statistical analysis demonstrates the use of a nonhomogeneous poisson process model and its results may serve as a guideline for continued qualitative and quantitative analyses. In particular the importance of qualitative analyses at the component and the system level is emphasized.

Combination of several data sources (P5)

The problem of combining several uncertain data has been studied. The need of such combinations is evident in the analyses of e.g. common cause failures and human interactions where plant specific data are scarce.

Two methods based on subjective Bayesian analysis and on the Shafer-Dempster theory were proposed.

Application to some cases illustrated the uncertainties of the resulting estimates.

It was concluded that much research is needed to enable future use of the method based on Shafer-Dempster theory, which has some links to the theory of fuzzy sets. This is due to computational requirements and conceptual difficulties. On the other hand, the applicability of a Bayesian framework has been confirmed. The Bayesian approach is characterised by conceptual clarity and the possibility to include judgement in a transparent and explicit way.

4.4 Conclusions

The merits of Probabilistic Safety Assessment (PSA) are indisputable and have been demonstrated in numerous applications. PSAs may help in identifying possible weak spots in the design and operation of nuclear power plants, and in ranking the dominant risk contributors.

On the other hand, many limitations both of intrinsic and practical nature are associated with the use of a probabilistic approach. This complicates an implementation of PSA in the process of decision-making. In particular, the difficulties encountered in applying absolute probabilistic criteria as an acceptance standard are overwhelming. This is due to existing parametric, modelling and completeness uncertainties, differences in scope and level of ambition of PSAs, and lack of consensus with respect to the modelling of critical issues, i.e. there is no clear preference as to the choice among several available models which give different results.

The work performed has contributed to improvements with respect to some of the most important practical limitations of PSA. Use of the findings of the project will hopefully support a more disciplined, complete and credible treatment of dependencies and human interactions. In addition, a better perspective on the uncertainties involved has been obtained. Uncertainty analysis should be an integral part of any PSA.

Several recommendations have been made concerning the need for future research work. In the context of dependency analysis (H4), the most urgent needs concern in-depth studies of common of cause failure data with due regard to the defensive measures being applied (H14), and common cause failure modelling in systems with a non-standard level of redundancy. The modelling of human interactions should be subject to overall improvements. Better integration of technical information about the systems is desirable as well as knowledge about mental processes influencing operator behaviour during accident conditions.

PSA has the potential to improve the understanding of complex operating situations and thus reduce the uncertainty in decisions related to safety and availability. This can only be realised, however, if decision makers and plant personnel strengthen their understanding of the methods for risk analysis. The PSA should be integrated in a framework of operating experience, and incidents should be analysed to indicate improvements either in the plant or in the PSA.

5 Development and optimisation of safety regulations

Project report 450

5.1 How are safety regulations designed?

The limits and conditions for the safe operation of a nuclear power plant are defined in the so-called technical specifications. Their ultimate goal is to prevent radiological accidents which can affect the plant and the environment, and thereby protect the health and safety of the public and the plant personnel. The technical specifications can therefore be seen as a set of operational safety rules and criteria, which define the allowed operational range for the nuclear power plant from the safety point of view.

These operational safety rules and criteria have been set on the safe side using mainly analyses prepared in the Final Safety Analysis Report of the nuclear plant and engineering judgement. The technical specifications are prepared by the operating organizations and approved by the regulatory authority.

The following descriptions on the background and criteria for the requirements in the technical specifications are based especially on the Swedish Forsmark and Finnish TVO plants.

A general overview of the structure and contents of the technical specification in the Nordic ABB Atom boiling water reactor plants follows in table 5.1.

The *limiting conditions for operation* shall assure that the safety systems are either ready for use or functioning on demand, e.g. at incidents involving loss of off-site power. The *action statements* require the plant to be brought into a safer operational state, usually shutdown, if the faulty equipment cannot be restored within its allowed outage time. The *surveillance requirements* prescribe periodic tests for detection of faults and verification of the operability of safety equipment. Limiting conditions for operation and periodic testing have been studied in the Nordic project. The practical part of the studies have concerned standby systems and functions (N2).

Those primary safety systems which have active functions are divided into four redundant subsystems in the TVO and Forsmark units. The subsystems are separated from each other by physical separation and they each have a separate electrical supply bus. Each subsystem has 50 % of the total capacity required according to design criteria. This creates excess margin if one subsystem fails and makes it possible to justify power operation even if one subsystem is inoperable due to planned maintenance actions or to a repair of a fault.

Table 5.1. General contents of Chapters 1 – 8 in Nordic boiling water reactor technical specifications (B12)

1. Introduction and definitions
2. Safety limits
   - □ concerning fuel cladding integrity
   - □ concerning primary circuit integrity
3. Limiting conditions for operation
   - □ requirements on the operability of equipment at the system/component level for the operational states hot shutdown, nuclear heating, hot standby and power operation
   - □ allowed outage times for equipment
   - □ action statements in failure situations
4. Periodic testing
   - □ requirements and acceptance criteria at the system/component level
   - □ test intervals
5. Administrative instructions and rules
6. Background for the conditions and limitations in chapters 2 and 3
7. Conditions and limitations för cold shutdown and refuelling
8. Background for conditions and limitations in chapter 7

5.2 Objectives of the Nordic project

Developments in probabilistic safety assessment (D1, C1, V3), and increasing operating experience have enabled further development of the safety regulations. This has been pursued in a joint Nordic research project with the following objectives:

1. To identify *areas* for future development of technical specifications, in which there is potential for applying probabilistic methods to identify and evaluate possible improvements.

2. To examine and develop probabilistic *methods,* and plan experience data bases, to be used by utilities and authorities in their assessment of present and future requirements in technical specifications.

3. To develop the general *philosophy* and principles for further improvement and optimisation of technical specifications taking into account both the plants' safety and economical risks. To improve the understanding and application of these principles.

4. To perform practical *case studies* for specific nuclear power plants for testing and verification of the methods and principles developed.

The development work (N2) has included the following main subtasks:

- □ development of risk-based general principles and criteria for balancing (M3, P3, K4) of the technical specifications by use of probabilistic techniques
- □ development of methods for the evaluation of repair arrangements and action statements, preventive maintenance and test arrangements
- □ case studies (TVO and Forsmark nuclear power plants).

International developments in this field have also been surveyed and information exhanged with e.g. IAEA (International Atomic Energy Agency) OECD/-NEA (Nuclear Energy Agency), and EPRI (Electric Power Research Institute).

5.3 Development of principles, criteria and methods

5.3.1 Risk-based evaluation principles

The typical analysis cases are:

□ evaluation of the impact of proposed permanent modifications of the technical specifications

□ evaluation of the safety significance of temporary exemptions from the technical specifications.

The uses of probabilistic methods in optimising technical specifications concentrate on two main issues:

Baseline risk of the plant

This is the risk level during normal power operation with the condition that no unavailabilities due to failures or planned maintenance activities in the safety systems are known. Obviously the reliability of systems with safety- related tasks (standby or operating) is essential.

The way to assure the reliability is to search for faults at tests, to monitor processes and system condition and to make preventive maintenance during revision outages.

Temporary risk increases

Outages of parts of safety systems during power operation will temporarily increase the total plant risk over the baseline risk level. Such additions may be caused by forced or planned unavailabilities, e.g. due to component failures discovered at tests, or due to isolation of parts of safety systems for preventive maintenance or testing (K3, M2).

The total plant life-time risk should also be evaluated by adding the sum of the recurring temporary risk increases to the integrated baseline risk (M2).

5.3.2 Levels of optimisation, optimization criteria and methods

Optimisation may be carried out at any of a series of levels with increasing complexity, e.g. at a component, a system or a plant level.

An approach is suggested that makes use of a plant level safety model, such as a probabilistic safety assessment, to derive the relative importance of safety functions and systems, from a core damage risk point of view. Thus the optimisation for systems with a very limited importance at the plant safety level may be mainly governed by considerations for effectiveness and economy of plant operation and maintenance.

The results of probabilistic safety assessments should aid to focus interest on those parts of the technical specifications where test arrangements and limiting conditions for operation should be investigated from the safety point of view.

The optimum found from analysis at a low level (e.g. the component level) may significantly differ from the optimum found at a higher level of analysis, e.g. the plant level. The magnitude of such differences depends on how the plant systems are interrelated. Such coupling cannot be adequately considered in a system or component level model.

On the other hand, it is desirable to treat problems isolated – or at a lower level – when possible, because this limits the model complexity and enchances possibilities of managing uncertainties.

In applications of the technical specifications, the optimisation can often be based on the simple criteria of comparing relative differences and changes, with the current practice as the reference point. This enhances the understanding of the results. Furthermore, by use of relative results the risk acceptability issue may be avoided.

Optimisation often relates to how the unavailability of a safety function or system depends on the test interval or allowed repair time of a component. The optimum at the safety function or plant level (K5, see also M2) may depend on criteria limiting the additional risk during the component outage time and the instantaneous risk caused by stated operational actions.

Due to a strong influence of uncertainties, it is reasonable to find an optimum interval rather than an exact optimum point value in the interpretation of analysis results. It should also be emphasized that the analytical models need to be coherent with the real world. Systematic analysis of operating experience should hence be a primary element in model considerations.

5.4. Presentation of results and treatment of uncertainties

Actual results and conclusions from case studies are seldom transferrable between different plants, because small differences in designs and procedures may be important. Available models and data can often be utilized in a new application after reasonable modifications.

Risk importance measures, e. g. an increased risk ratio, are valuable tools for processing of the risk analysis results into a form more suitable for drawing conclusions and making decisions. These measures may facilitate a gross ranking in order to focus interest on those plant functions and systems where test arrangements or limiting conditions for operation should be investigated.

In this way importance measures provide a bridge between the plant probabilistic safety assessment results and those considerations concerning the technical specifications which are to be performed with more developed methods (P11).

5.5. Test arrangements

The surveillance requirements in the technical specifications prescribe periodic tests and inspections for detection of latent faults and verification of the operability of standby safety equipment.The specifications include requirements con-

concerning test intervals as well as the procedure for and the acceptance of the single tests performed.

5.5.1 Test arrangements, choice of the level of optimisation

Not only the frequency of testing should be considered. Other properties of the surveillance tests to be balanced are e.g. the relative order of test times (sequential vs. staggered) in redundant subsystems, the test quality and procedures, substition of testing (wholly or partly) with component diagnostics and use of preventive maintenance.

When this kind of properties are considered, different optima may well be obtained at different levels of optimisation (component, system, safety function or plant). Test arrangements should thus be optimised on the level covering all significant influences.

5.5.2 Surveillance tests of standby components

The surveillance tests do not always seem to correspond to actual demands. The use of functional block techniques show encouraging results in evaluation of test coverage at component and system level (K1).

The coverage of the test procedure is of central importance because it determines which faults and failure modes are detected. Often surveillance tests are limited component tests such as:

□ starting up diesel generators without the loading sequence relevant for emergency situations

□ closing and opening valves in standby lines without real pressure and temperature conditions.

A systematic procedure for a qualitative identification of significant differences between test conditions and anticipated accident conditions has been developed and applied for motor-operated closing valves (E5).

The analytical considerations of component tests are restricted to relatively simple models and much effort needs to be devoted to obtaining a relevant empirical data base (M4).

5.5.3 Comparison of alternative test schemes and influence of common cause failures in redundant subsystems

Practical applications and model studies show that the currently used test intervals and staggering of test times in redundant subsystems seem to be reasonably near to the optima, when the mean unavailability is considered at the system level.

Considering the reliability at the system level or higher levels, the dependencies (common cause failures) between redundant equipment need to be taken into account.

5.5.4 Evaluations at the plant or public risk level

As already mentioned (4.2), there are many limitations in the techniques of probabilistic safety assessment, PSA. The dominant accident sequences of present

PSAs at the plant level seldom include adequate account of the components which are regulated via the technical specifications. Changes in the latter will thus not be accurately reflected in the PSAs, and significant efforts are required to make the models more accurate (K5).

Sometimes a change in the technical specifications may lead to an increase in the frequency of some core damage sequences and a decrease in others. An analysis of the consequences of a core damage (at levels 2 or 3, see 4.1) is then required. It may ensure that any decreases in core damage frequency are not traded off against an increase in other damage sequences for which the accident consequences are more severe.

5.5.5 Experience from unplanned plant transients

Information on risks at the plant level can also be obtained if the safety system is called for in the normal course of the plant operation. This may be very useful since in practice the surveillance tests cannot be perfect.

A real demand situation such as an unplanned plant transient forms an integrated test of some safety functions if it is well recorded and analysed (L1). Such transient events can substitute some periodic tests at lower levels.

5.5.6 Influence of human understanding

The quality of the testing depends on the communications between individuals responsible for e. g. the development, updating and training concerning technical specifications, the planning, follow-up and acceptance of tests and maintenance, and the performance of tests and maintenance. Lacking understanding of the test and maintenance objectives may lead to reduced motivation and poor performance, and restoration of the equipment to an operable mode after testing could then be omitted.

A method for identification of human originated test and maintenance failures has been developed and preliminarily tested (P10).

5.6 Allowed repair and maintenance times during power operation

As mentioned, the primary safety systems, which have active functions, are divided into four redundant subsystems in the reactors studied.

The criteria for allowed outage times for repair of components are specified per failure event. Thus the allowed outage time is limited to 30 days for single failures (one subsystem) and to 3 days for double failures (two subsystems) in the four redundancies.

A budget principle is in turn introduced for the times during which subsystems are allowed to be unavailable because of preventive maintenance during power operation.

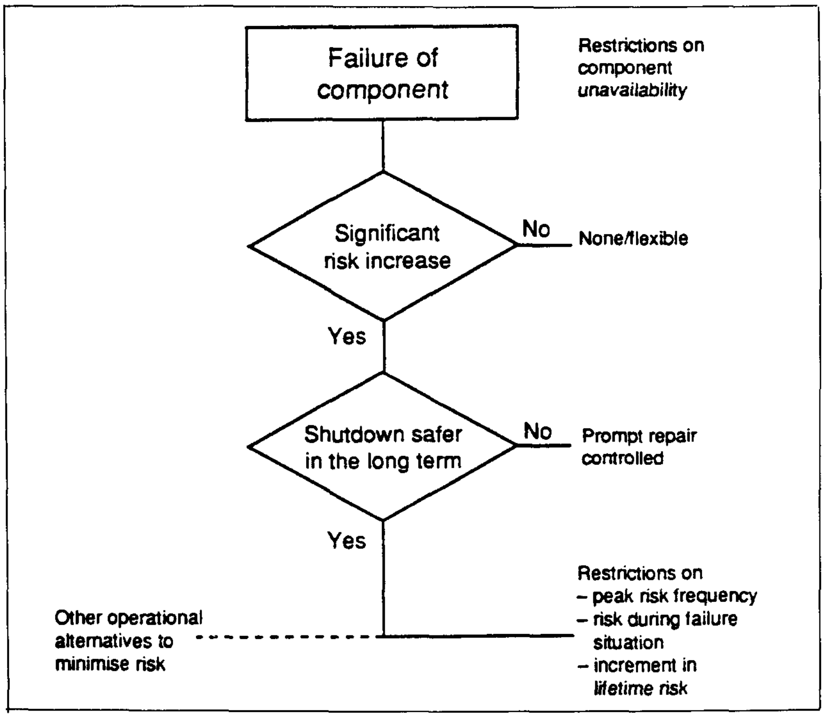
Failure of component
Restrictions on component unavailability
Significant risk increase
No
None/flexible
Yes
Shutdown safer in the long term
No
Prompt repair controlled
Yes
Restrictions on
- peak risk frequency
- risk during failure situation
- increment in lifetime risk
Other operational alternatives to minimise risk

Figure 5.1. Simplified decision tree when a failure has been detected in a safety system. To the right in the figure are given the restrictions or criteria for the time during which a component is permitted to be unavailable during power operation. These are part of the limiting conditions for operation (Table 5.1).

5.6.1 Outline of probabilistic approach for assessment of limiting conditions for operation

A systematic treatment of the question of allowed outage times and related action statements presupposes the comparison of operational alternatives. If a failure or a multiple failure is detected in a safety system during power operations the operator faces different alternatives to proceed, as illustrated schematically in the decision tree in figure 5.1. The main decision is whether:

- □ to continue power operation over the repair time of the fault or
- □ to shut down the plant, or proceed to some other operational state, where the inoperability of the faulted components has a smaller impact on plant safety.

The behaviour of the risk level is illustrated in figure 5.2. The change of the operational state usually involves a risk peak arising from the:

- □ possible failures of those systems which are needed during the state change operations or which must be started up from the standby state
- □ the possibility to initiate a plant transient by the operational change itself.

A method for quantitatively comparing the risks of continued power operation with those of plant shutdown will permit a more objective evaluation of the action requirements of the limiting conditions for operation especially in multiple failure situations (K5, M2).

The choice between the operational alternatives should be made with regard

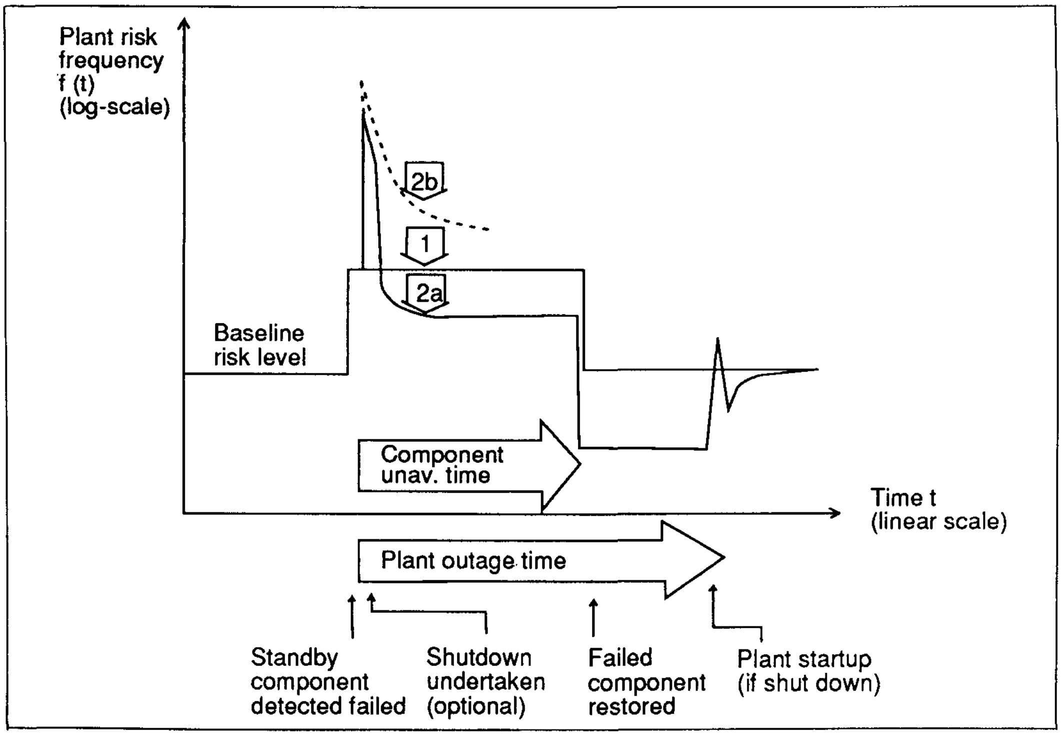

Figure 5.2. Risk of core meltdown after detection of a failing component in a standby system. The frequency given is the conditional frequency given that the component has failed. Case 1 indicates the elevated but constant risk level until the component has been restored, with continued plant operation. Case 2a shows the transient risk increases when the plant is shut down and then restarted. Case 2b shows a similar but higher risk in a shut-down alternative with a high failure-to-run frequency.

to both the instantaneous risk, the expected risk over the failure situation, and the influence of the adopted rules on the integrated risk over the plant lifetime.

5.6.2 Criteria for allowed repair times for components during power operation

The probabilistic approach can be used (K5) to determine more balanced allowed outage times for components. In systems where failure states contribute only marginally to the risk at the plant level, relatively flexible rules could be justified (figure 5.1). In more critical failure situations e.g. multiple failures, risk analysis methods can be used to identify the operational alternative which gives the minimum risk.

It is highly important from the safety point of view to avoid failures by keeping failure rates low through reliability and quality assurance of the equipment.

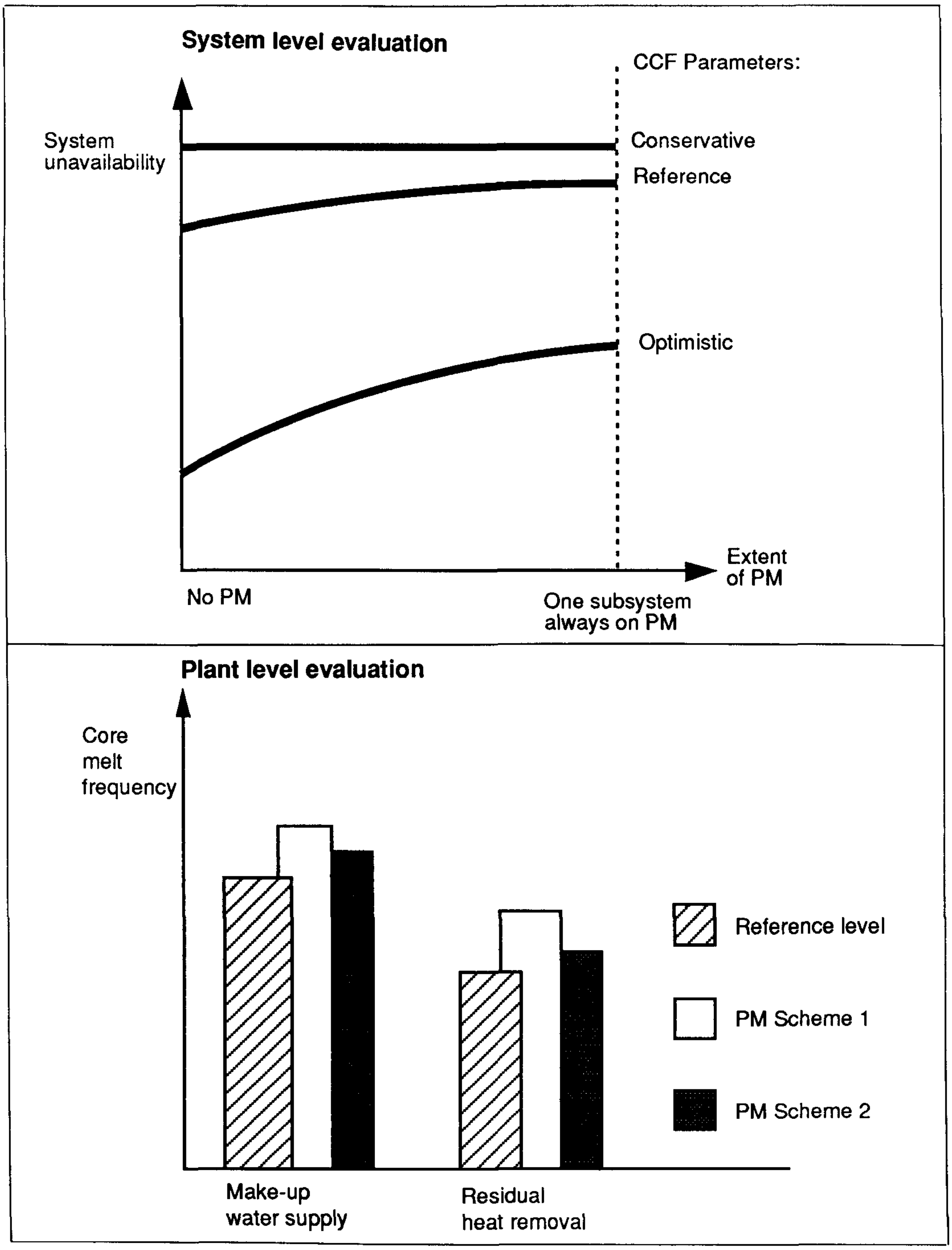

Figure 5.3. Analysis of preventive maintenance during power operation. The figures show examples of the unavailability at the system level and of the core melt frequency at the plant level. CCF = Common Cause Failure, PM = Preventive Maintenance. At the plant level, the preventive maintenance schedule 2 gives a lower core melt frequency, but the reference alternative is still the safest.

5.6.3 Criteria for preventive maintenance during power operation

The criteria specify the annual time budget of preventive maintenance during which the subsystem levels are unavailable. At the system level the probabilistic methods can be used to evaluate quantitatively the impact of preventive maintenance unavailabilities on the safety system failure probability (H1, H13).

At the plant level, the impact of preventive maintenance on the relative increase of the total baseline core damage frequency is evaluated. Also the risks related to different preventive maintenance schemes within given volume and time restrictions can be compared (K4). The type of results is illustrated in figure 5.3.

5.7 Requirements on data

The need for data and other information for optimisation of technical specifications is larger than in ordinary reliability analysis. In addition to "normal" reliability data, other information is needed, both concerning lay- out and performance of activities related to the technical specifications (test, maintenance, repair and operational).

Adequate data on operating experience for analysis of surveillance test and maintenance efficiency, and on the proneness to introduce human errors in the test an maintenance activities, seem to be very hard to obtain from the empirical data collected this far. Attention must be paid to data collection and analysis at the plant, but also to partial extraction of such data to central organisations for further use.

5.8 Case studies

In order to test and verify the methods and criteria developed and evaluated, practical case studies have been performed during the development work. The objective of the case studies was also to provide an aid for present and future decisions by utilities and authorities on modifications of the technical specifications.

At the TVO nuclear power plant there is after several years completed an application (K5), which is concerned with failures in the residual heat removal function and with plant shut-down risk analysis. This study has as an objective to compare the additional transient risk of plant shutdown with the risks of continued power operation, given specific failure combinations in the safety systems. The present technical specifications state that if three or four subsystems are inoperable, cold shutdown must be reached within 24 hours. The results of the study justify reconsideration of the TVO plant shutdown requirements in situations with multiple failures.

The unavailabilities caused by preventive maintenance in safety systems during power operation in Forsmark 2 have been studied (K4, K3). The probabilistic safety assessment of the plant Forsmark 3 was applied and the system models were very slightly modified in order to account for differences between the two plants. The plant level analysis has made it possible to study:

□ the temporary risk increases caused by isolation of equipment for preventive maintenance at the subsystem level

□ the safety impact from performing preventive maintenance on shared support systems (cooling systems, diesels)

□ the comparison of different preventive maintenance layouts from the relative reactor core damage risk point of view.

Studies on safety systems and components in the Forsmark units have included:

□ an analysis of the functional coverage of the test arrangements in an auxiliary feedwater system (K1)

□ an analysis of the impact of differences between the test conditions and anticipated real accident conditions on the reliability of motor operated closing valves (E5).

□ a study concerning a rearrangement of the diesel generator test scheme at the Forsmark reactors 1 and 2.

5.9 Discussion and conclusions

The technical specifications are now well established documents. The project has had the purpose to identify possible modifications, and justify and evaluate these. Both temporary exemptions and permanent modifications have been studied.

The probability of an accident may increase temporarily when a safety related system fails or is unavailable because preventive maintenance is made during power operation. By systematic inspections one tries to increase the probability that the system is available when it is called for. The risks resulting from this complex interplay of maintenance, tests, failures and repair have been successfully studied by probabilistic safety assessment techniques.

It has for example been possible to identify and analyse temporary high risk situations in advance, and to modify requirements that were excessively stringent but not safety-efficient. This has resulted in more flexible operation and maintenance of plants in Finland and Sweden, and often the safety level has been increased. The results have been useful both for power companies and regulatory authorities.

The main results are the following:

□ Probabilistic safety assessment techniques can be used to compare alternative schemes for plant operation when there is a defined failure of a safety system, and to search for the scheme with the minimum risk, e.g.the minimum probability that a safety function is not operable when called for.

□ They can also be used to justify changes in the rules which govern preventive maintenance and repairs in safety systems during power operation, and to enhance the efficiency of surveillance tests on standby equipment and redundant subsystems.

The safety could be further increased if experiences from operation and maintenance were more efficiently introduced in the probabilistic safety assessments to make them "living". A high degree of such feed-back would facilitate efficient and timely control of situations with incidents, failures or other forms of degrade safety performance.

The results of the project would be most fully exploited if decision makers and plant personnel would increase their understanding and use of the methods of reliability and risk analysis.

6 Discussion and conclusions

At the outset of this program, it was hoped that some general principles would be found for the assessment of risks and for making decisions where risks are involved. These would then be applicable for both radiation protection and nuclear safety management.

On the whole, these hopes have been in vain.

This is not surprising since the issues studied are fundamentally different with respect to the parameters of importance for decision making according to the incrementalistic – synoptic model for decisions (1.1.1, 1.1.2, Figure 1.2).

Radiation protection for normal situations is based on fairly good knowledge about the hazards and exposures, and there is mainly a lack of consensus on the valuation of the risks. The case study on radon (1.4.2) showed that age and income were important for the valuation.

In the case of nuclear power there is no doubt that many other factors influence the valuation, as discussed in the report on ethics (1.4.1). Classical ethics cannot provide sets of value judgments that are generally applicable, i. e. can be transferred from one area to another. There is thus no simple way of evaluating how the radiation risks related to nuclear power will influence decisions of which they form part.

In cases where there is consensus about the value judgments, general models can be used for radiation protection decisions. This is the case for instance when decisions of a technical character are taken in the nuclear power industry. The lack of consistent optimisation application in nuclear power radiation protection (2) should thus not be due to principal difficulties but rather lack of good practical tools.

The situation in nuclear safety has similarities and differences to the radiation protection case. On the technical level, safety assessment techniques are not subject to different value judgments. Consequently, they are used for safety improvements by the plant operators and by the authorities (4, 5).

When it comes to absolute estimates of the frequency of accidents, however, even technical analysts agree that these have very significant uncertainties (4.2).

When this is combined with the very diverging valuations of nuclear accident risks, it is obvious according to the incrementalistic decision making model (Figure 1.2) that decisions cannot be based on the present scientific knowledge. This is also recognised by top regulators who advise that absolute frequency estimates should not be used for direct comparisons with quantitative safety goals. The decisions will instead emphasise research, rejection of trade-offs between safety and economy (1.4.10), and absorption of uncertainties by using independent barriers against releases to the environment. Decisions along these lines fit well with the incrementalistic decision model.

Against this background, it appears very difficult to compare risks from direct radiation exposures with risks from potential exposures at large accidents having low probabilities of occurence. The uncertainties also prevent trade-offs between improvements in nuclear safety and radiation protection.

The program has, however, achieved some other important goals.

6.1 What is the safety level in nuclear power and how has the program contributed?

The program has elucidated the radiation doses due to nuclear power and put them in the perspective of other radiation doses and of chemicals which produce similar effects, e.g. cancer. It has turned out that nuclear power is associated with low risk levels in most of these comparisons (1.2; 3), but the large consequences of nuclear accidents have justified high expenditures for accident prevention (1.4.10).

Indeed, the collective dose to the Nordic population from the natural radiation constitutes the dominating contribution to the radiation risk and is higher than those of all the human activities studied (3.2). This contribution has a wide spread between different places in the Nordic countries. Indoor radon represents the highest risk from radiation exposure, and energy conservation by reduced ventilation will increase the risk from indoor radon (3.2.2.d).

Disposal of high level waste will cause only small increases compared with natural activity concentrations in the environments studied, and only after time periods of the order of 1 million years (1.4.3).

Many chemicals may cause concern and hereditary disease, just like ionising radiation. The potential risk for such injuries from waste genesated at combustion of coal for energy production is higher than the potential risk from waste due to nuclear energy production (3.2.3).

The program has also elucidated the radiation protection of personnel at Nordic nuclear power plants (2). High costs are spent for personnel protection in comparison with the rule of thumb for optimisation established by the Nordic radiation protection authorities. There are formal methods for optimisation of protection available, but wider use requires better data bases and computerised decision support systems.

The program has also addressed the assessment of the risk of large accidents. It has contributed to improving the methods of assessment (4). It is clear that basic common cause failures can be identified and acceptably quantified using two different methods (direct assessment and alpha-factor).

A third, widely used method (multiple greek letter) may lead to underestimation. The probabilities assigned to errors in human interactions still depend highly on subjective judgements.

It has been shown that the uncertainty in probabilistic safety assessments can be analysed at reasonable cost using available computer codes. The uncertainties are quite large in cases where common cause failures and human interactions are involved.

The methods of probabilistic safety assessment have been demonstrated to improve the efficiency of the operation of nuclear power plants while maintaining or improving the safety level (5). The methods have for instance helped to identify and evaluate temporary high risk situations in advance.

A rewiev (4) shows that the Nordic work in the area has been successful in identifying major dependencies. This is one of the most important merits of probabilistic techniques.

These techniques enhance the understanding of complex situations involving maintenance and failures, and are important tools for comparing alternative improvements of design and operation. Still there are large uncertainties in the estimated frequencies of some of the postulated accident sequences. Thus, the results do not permit stringent comparisons with prescribed safety goals.

6.2 What experiences have been gained on safety in other areas?

The program has demonstrated that similar management philosophies are emerging for genotoxic chemicals as for radiation (1.2). These include e. g. the assumption of a non-threshold linear dose-response curve, and similar levels of risks that are of little concern or negligible. Attempts at simple cost- benefit analyses are being made both in nuclear radiation protection and such areas as road safety and health economics (1.4.6).

Probabilistic safety assessment is applied in off-shore safety. Many problems surround these applications, and further development is required.

6.3 What do decision makers know about these safety issues and how do they use what they know?

In general, safety issues are only one component in political decisions, and often not given much weight by the political decision makers (1.4.6).

Decision makers at the plant and authority levels are the real users of advanced methods of safety analyses, and do use them to improve safety in various ways.

6.4 What are the most urgent needs for further research?

During the Nordic program, some areas have been identified where more research is required. The following areas have been judged as particularly important.

Methods for early monitoring of late health effects such as cancer and hereditary disease are needed. This applies both to radiation and chemicals. Indicator systems in the body are particularly interesting. The corresponding need for effects on the environment might be met by research on indicator organisms.

Dose-response relationships for genotoxic chemicals should be studied, as well as the distribution in the body and the metabolism of the latter.

Indirect effects such as synergism between different exposures and secondary effects of environmental contamination with chemicals should be studied.

The practical implementation of many studies on optimisation of radiation protection for personnel at nuclear power plants requires the development of specific guidance and of task related data bases on radiation doses.

Methods and data are needed for a better treatment of human interactions in probabilistic safety analyses for nuclear power plants.

Data on common cause failures are needed, as well as studies of their significance in systems with non-standard levels of redundancy. The influence on common cause failures by defensive measures should also be considered.

In the long run, one should try to attain *the living probabilistic safety assessment* by continuously using new experience from operation and maintenance of nuclear power plants to update the assessment models.

The prevention of rare, large accidents in plants involving genotoxic chemicals should be studied.

Studies in political and social sciences should explore how opinions are formed and decisions actually made.

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These final reports from the NKA/RAS program 1985-1989 with the project numbers 410, 430, 450, 470 and 490 will all be published towards the end of 1989 or later. They will be given a number in the NORD series of the Nordic Council of Ministers. The addresses of the editors are given in chapter 8 below.

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430 *Weighting of radiation consequences at parts of nuclear energy production against the consequences of natural radiation* (In Norwegian). Editor: Terje Christensen

450 *Optimisation of technical specifications using probabilistic methods – A Nordic perspective.* Editor: Kari Laakso

470 *Dependencies, human interactions and uncertainties in probabilistic safety assessment.* Summary report of the Nordic NKA-project Risk Analysis. Editor: Stefan Hirschberg

490 *Principles for decisions involving environmental and health risks.* Editor: Gunnar Bengtsson

Detailed references

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Report within the NKA program are usually available from the author, from the secretariat of the Nordic Council of Ministers, St Strandstrade 18, DK-1255 Copenhagen, Denmark, or from the technical research libraries in Denmark, Finland, Norway or Sweden: Riso National Laboratory, DK-4000 Roskilde, Denmark; Technical Research Centre, SF-02150 Espoo, Finland; Institute for Energy Technique, Postboks 40, N-2007 Kjeller, Norway; Studsvik, S-611 82 Nyköping, Sweden

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9 Subject index

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Risk analysis and safety rationale

Decision making with respect to safety is becoming more and more complex. The risk involved must be taken into account together with numerous other factors such as the benefits, the uncertainties and the public perception.

Can the decision maker be aided by some kind of system, general rules of thumb, or broader perspective on similar decisions?

This question has been addressed in a joint Nordic project relating to nuclear power. Modern techniques for risk assessment and management have been studied, and parallels drawn to such areas as offshore safety and management of toxic chemicals in the environment.

The report summarises the findings of 5 major technical reports which have been published as NORD-publications.

The topics include developments, uncertainties and limitations in probabilistic safety assessments, negligible risks, risk-cost trade-offs, optimisation of nuclear safety and radiation protection, and the role of risks in the decision making process.

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