Methods for comparative risk assessment of different energy sources
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The environmental and health impacts of different energy systems, particularly those associated with the generation of electricity, are emerging as significant issues for policy formulation and implementation in the coming decades. This, together with the growing need of many countries to define their energy programmes for the next century, has provided the basis for a renewed interest in the comparative risk assessment of different energy sources - fossil, nuclear, renewables - in order to account for their effects on health and the environment in decision making as an integral part of energy planning.

The IAEA has developed knowledge and expertise concerning the overall concept of comparative risk assessment including data requirements, methodological and procedural issues, scope and range of practical applications. Emphasis is being placed on the co-ordination of research on the development of relevant databases and on improvements to methodological and procedural approaches.

Methods of comparative risk assessment entail determining (quantitatively and qualitatively) the health and environmental risks of different energy sources and, where appropriate, comparing such risks on a normalized per unit basis. Although these methods are extensive and are now generally accepted as useful tools, a number of procedural and methodological uncertainties remain for which improvements are desirable, in order to strengthen the applicability and credibility of these techniques.

This document is the outcome of a Specialists Meeting held in Studsvik, Sweden, 27-30 August 1991 on the procedural and methodological issues associated with comparative health and environmental risks of different energy sources for the generation of electricity. The meeting was hosted by KSU, Studsvik, and was attended by 19 participants, representing 13 countries and 3 international organizations. The main objectives of the meeting were to identify, consider and reach conclusions on the main methodological and procedural issues associated with the comparative risk assessment of health and environmental impacts from different energy sources, particularly those associated with the generation of electricity.

This document presents and reviews methods for comparative risk assessment of different energy sources determining (qualitatively and quantitatively) the health and environmental risks.

The first part of this document presents an identification and analysis of the methodological and procedural issues, with relevant conclusions and recommendations.

The second part of this document contains the technical papers presented at the Specialists Meeting held in Studsvik.
EDITORIAL NOTE

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METHODS FOR COMPARATIVE RISK ASSESSMENT OF DIFFERENT ENERGY SOURCES:

ISSUES IN REVIEW
1. IDENTIFICATION OF ISSUES

An overall review of the current status of the methods used for comparative health and environmental risk assessment of different energy sources was undertaken\(^1\). These methods, which entail determining the health and environmental impacts of different energy systems and, where appropriate, comparing such impacts on a normalized per unit basis, have experienced important developments in the late 1970s and early 1980s. The main purpose of the review was to identify the methodological key issues to ensure a credible comparison to be made and suggest directions for the resolution of those issues or for further research in particular areas. The main methodological issues can be summarized in eight points as follows:

(i) The delineation of consistent and comparable boundaries for different fuel cycles. The definition of principles and delineation of "reference fuel cycles" for risk comparison purposes is a priority issue in this regard.

(ii) Methods and dose-effect relationships for the risk assessment of the health effects of different energy systems (for electricity generation) including in particular the deviation of consistent indicators of health risks for comparative assessment.

(iii) Methods and relationships for the assessment of impacts of different energy sources (for the generation of electricity) on the natural environment and associated ecosystems, and particularly the derivation and application of indicators of environmental risks for comparative assessment.

(iv) How to deal, in the comparative risk assessment process, with the time and technological dependencies of risk estimations, given variations in technologies and in the state of technological development (over time). Can the principles of "risk discounting" be used to compare existing risks by postulating and accounting for possible future technological development. How can future technological development be accounted for in the comparative risk assessment process.

(v) How to deal in the comparative risk assessment process with the issue of "uncertainties". Such uncertainties exist in particular in the type, nature and extent of various impacts and with the variable nature of some impacts over time. Uncertainties also exist in the estimation (both qualitatively and quantitatively) of the various risks, both in terms of consequences and probabilities.

(vi) Comparative risk assessment for severe accidents in different energy systems. The main issues here relate to the tools and criteria for comparison; the methods for presenting the results and the comprehensiveness of the comparative results, particularly in relation to environmental impacts from severe accidents.

The integration of the different elements of risks, including: the question as to whether one overall integrated indicator of risk is possible or feasible; the applicability of comparative risk assessment studies at a global, regional or country level; the weighting of the various dimensions of different risks in the comparative risk assessment process.

Methods and tools for the presentation of the results of comparative risk assessment.

2. ANALYSIS OF ISSUES

2.1. FUEL CYCLES AND SETTING OF BOUNDARIES

The definition of consistent boundaries for the different fuel cycles is an essential requirement for a credible comparative risk assessment. The fuel cycle boundaries for different energy sources have not been defined consistently in most comparative risk assessment studies. In some studies, the impacts of constructing power plants or of waste disposal are incorporated whilst not in others. The difficulties faced in delineating the boundaries of fuel cycles are a major issue in the comparative risk assessment process.

The definition of the boundaries of various energy systems for comparative risk assessment purposes is not straightforward. The main issue here is whether the boundaries should be limited from the point of fuel gaining and mining to the point of electricity production and waste storage and processing, or should the boundaries be extended to encompass, say, the gaining of resources for the building and operation of the generating plant facilities.

There is obviously a need to agree on some boundaries. Figures 1 to 11 present guidelines on proposed boundaries and different steps of the various fuel cycles.

The principles for setting boundaries are as follows:

(i) The setting of boundaries has to be adapted to the purpose of the assessment (e.g. new system or extension of existing system).

(ii) The boundaries should be set taking into account:

- time (horizon)
- space (workers and public exposed, environment)
- phases of the systems under investigation
- impacts to be considered
- material balance considerations in terms of risk per net energy output
- acceptable threshold criteria.

(iii) The boundaries should be clearly defined and should be consistent for all systems to be compared in terms of quality (e.g. availability) and quantity of the net electricity output.
FIG. 1. Municipal waste incineration fuel cycle.

FIG. 2. Coal fuel cycle.
FIG. 3. Oil fuel cycle.

FIG. 4. Gas fuel cycle.
FIG. 5. LWR fuel cycle with recycle of uranium.

FIG. 6. Hydropower cycle.
FIG. 7. Geothermal fuel cycle.

FIG. 8. Photovoltaic cycle.

FIG. 9. Solar (thermal) fuel cycle.

FIG. 10. Wind fuel cycle.
At a national/regional level, the setting of boundaries will greatly benefit from a structured public scoping/participation process, so that all concerned could be involved in boundary setting. This process would greatly enhance the credibility and acceptance of the study process.

(v) Operational principles. The detailed analysis should focus on the complete energy cycle:

- extraction
- transportation
- treatment
- storage
- conversion to electricity
- electricity transmission and delivery
- waste treatment and disposal.

Impacts and construction and dismantling of installation used in the auxiliary life cycle should be included for single use, dedicated plants only. For non-specific installations a more general, less detailed impact assessment could be sufficient.

(vi) Depending on the purpose of the assessment, a number of reference cases have been identified:

Stock related systems (nuclear and fossil)

- new systems
- additional facilities of existing systems:
  - centralized
  - decentralized
Energy flow systems (renewable)
- centralized
- new systems
- additional systems
- decentralized.

For each of these reference cases a reference system structure has to be set up as a starting point for the assessment.

2.2. ASSESSMENT OF ENVIRONMENTAL IMPACTS

2.2.1. Overview

Electricity generation processes are very diverse due to the different fuel conversion chains and to the variety of technologies at various stages of the fuel cycle. A large number of compounds are released into the atmosphere and water and disposed of on land with associated environmental impacts. These impacts may be immediate or long term. Implicit "environmental impacts" are often a direct or indirect "inference" of "health impacts". Figure 12 shows a generalized environmental transfer model outlining the various essential components of health and environmental risk estimations.

A linear pollutant pathway model indicating the amount reaching the receptor (target) as a function of the amount emitted, altered by dilution and removal and enhanced by environmental accumulation factors, is shown in Figure 13. Two parameters along the pathway are critical to an environmental impact assessment, namely the distance (space) and the rate of movement (time). The feedback mechanism in the system arises when effects produced at the target modify transport or removal rates. The complex interdependencies between time, space and feedback mechanisms (the degree of resilience of a given environment to external factors) are not fully known; very often it is difficult to normalize them on a common scale for comparison.
2.2.2. Methods for assessment of environmental impacts

The exposure-damage relationship is difficult to be demonstrated in many situations (e.g. impacts affecting or destroying local species of animals or plants which sometimes could be irreversible). When one develops dose-effect models, one deals with hypotheses rather than facts. No definite proof exists that such relationships are totally correct. It is considered that there are good chances of agreeing on some basic hypothesis in calculating environmental risks from electricity generation. Due to the diversity of activities on the electricity generation fuel cycle and also emissions and effluents associated with them, it may not be possible to identify a common (unique!) criterion by which to assess and compare environmental impacts.

In comparative risk assessment one has to "compare risks", which may be different in a subjective way from impacts, effects, emissions, etc. Two major limitations have to be considered when dealing with the assessment of environmental impacts of electricity generation, namely:

- the effects are not always susceptible to quantification;

- there is no general agreement on what should be quantified.

Methods of relevance for making comparisons of environmental impacts are: ranked environmental assessments, emission values and ambient quality indices, critical loads and critical levels.
A matrix approach is a ranking method to quantification of environmental impacts attempts to relate dose to response.

The emission values method is a dose oriented approach.

Critical load model whilst being dose based, in fact is essentially of a response type the response being the outset of (often unspecified) damage systems.

The **Critical Loads** concept provides an adequate scientific basis to set limits to environmental impacts above which damage would occur.

**Critical Levels**: expresses the concentration of pollutants in the atmosphere above which direct adverse effects on receptors such as the ecosystem, may occur, according to present knowledge.

**Critical Loads**: is a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment which do not occur, according to present knowledge.

The **Critical Loads** approach is a procedure for developing optimized abatement strategies by which levelized emission reductions are obtained on the basis of scientifically derived critical values. Additional concepts associated with the critical loads and levels for comparative risk assessment are: target levels and loads and actual loads and levels.

The critical loads approach for environmental impact assessment requires the following information: inventories of current emissions and projections of future emissions rates, estimates of the potential emissions reductions, long range transport models, maps of critical loads and target loads, integrated assessment modelling. Large scale renewable technologies are a source of negative environmental impacts (e.g. tidal power plants). Adequate methods and associated models for describing and evaluating the environmental/health impacts of such technologies at the different stages of the fuel cycle are needed.

In general it is considered that large scale electricity production systems have an exponentially increased value for the environmental impacts due to the "effect of scale"; appropriate methodological tools for comparative risk assessment should be developed for use in such cases. There are economic and technological limitations to the elimination of emissions or waste products and their associated impacts. There will always be residual environmental risk as a result of electricity generation by any fuel cycle. No energy technology is completely environmentally benign; their contribution to different environmental impacts is not zero when all stages of the fuel cycle are considered. The use of different methods for environmental impacts, reflecting the whole range of risks and impacts over the entire cycle of different energy systems and technologies is presently limited. A systematic database does not exist at present.

- Related information is scattered in a number of studies compiled over the past two decades;
There is a lack of uniform standards, including environmental quality standards, critical loads for different ecosystems (soil, water) harmonized mode routines and measurement methods;

There is a need for more and better dose-risk relationships for the assessment of different environmental impacts.

2.2.3. Indicators of environmental risks

The nature of the indicators have been discussed at length; source options were considered for environmental impact indicators. Qualitative and quantitative indicators could be equally used for describing a large variety of environmental impacts of the electricity generation at different stages on the fuel cycle.

The experts from the meeting considered that it is not meaningful to define single indicator as environmental indicators are: site specific, society specific, value judgement dependent. More data are needed in order to understand the synergistic effects in comparative environmental impact assessments.

Special distinctions have been made for the use of different aspects related to indicators and impacts evaluation. There are some environmental performance measurements already accepted by international organizations, such as:

- environmental performance indicators (e.g. river quality, air quality, soil quality etc.),
- environmental goals (critical loads, sustainability index, etc.),
- environmental emissions (SO\(_x\), NO\(_x\), CO\(_2\), Trade in Forest Products, etc.).

The experts in the meeting seem to believe that the best, if not only, was to perform comparative environmental impact assessments are by using a systematic semi-subjective approach by means of models where appropriate and accessible one can use "Expert Systems" and "Human Experts".

2.2.4. Environmental impacts in the structure of a database

In contrast with human health, where impacts relate to relatively straightforward indicators (e.g. mortality, morbidity) from one receptor (i.e. man), environmental impacts arise from highly complex pathways in turn affecting a diverse array of receptors (i.e. ecosystems with their structure and function). Moreover, both the pathways and environmental units which are "at risk" differ between different stages of any given fuel cycle, and between the different fuel cycles.

Environmental perturbations from a given fuel cycle might involve direct losses of agricultural land at the site of an operating plant, or they might involve the discharge of particulate material to surface water during fuel extraction. Other environmental perturbations could refer to the release of SO\(_x\) over the region in which the plant operates, or additions to the global concentration in CO\(_2\). These examples operate at different scales (local to global) through different perturbations (physical damage, gaseous and particulate emissions) in different media (land, air and water) where
different environmental systems are placed at risk (e.g. agriculture, aquatic ecosystems, terrestrial ecosystems). Some complexity limits are to be considered: within these systems a wide variety of organisms are linked through a variety of processes and functions. Such organisms and processes will vary in sensitivity to the perturbations which are imposed. Further complexity arises because of the likelihood of indirect effects on other systems, for example the deposition of SO$_2$, leading to the acidification of soils and water. Synergetic effects between perturbation are possible.

The complexity of such environmental impact mechanisms limit the development of environmental indices which allow comparison between different energy systems. There is a limited number of approaches to exposing environmental impacts and allowing for some quantitative assessment:

(a) a semi-quantitative approach based on the impacts ranking procedure; this is subjective by nature;

(b) calculation of indices of environmental quality or some other environmental feature (e.g. biological diversity, productivity);

(c) use of the critical loads and critical levels to compare the "sensitivity" of ecosystems to a particular perturbation (e.g. sulphur or nitrogen depositions).

A critical load is "the highest load (of a pollutant) that will not cause chemical changes leading to long term harmful effects in the most sensitive ecological systems". Using environmental criteria, measured characteristics or modelled processes, a concentration of rate of deposition value is set below the critical value at which no damage will occur over a specified period of time. A critical load could be considered as a measure of the risk to the ecosystem (a qualitative measure of the impact).

The use of quantitative (or semiquantitative) data on health and environmental risks associated with fuel use and electricity generation has prompted consideration of a computerized database system to hold and allow efficient access to the information. On the design of an adequate database two aspects have to be considered:

- those relating to the structure of the database;
- those relating to the form and availability of the data to input and retrieve.

One possible database could have a hierarchical structure; it will be utilized for the data input and interrogation.

The structure and the use of the database suggests that pathways through the components of the database will have to be established by using a "perturbations schedule". Perturbations resulting from a particular pathway or set of pathways will have the following form: pollutant emissions, vegetation and soil loss, effluent production (to aquatic or terrestrial systems) and solid waste production. These perturbations will variously have local, regional and global effects and these will have to be specified before the environmental impacts can be linked to the perturbations and stipulated in a qualitative form.

A distinction has to be made between a particular emission perturbation and that of an impact. An activity resulting from the use of a particular fuel may give rise to SO$_2$
emission which raises the ambient level of atmospheric SO₂ emissions which in turn raise
the ambient level of atmospheric SO₂ regionally, for a period of time. This is the
perturbation. The impact of perturbation may be the reduction of the annual production
of a forest area, or the mobilization of soil aluminum from sulphur deposition, so that
concentrations rise in associated watercourses and fish deaths eventually result.

2.3. COMPARATIVE HEALTH RISK ASSESSMENT OF DIFFERENT ENERGY
SOURCES FOR THE GENERATION OF ELECTRICITY

2.3.1. Overview

Electricity generation leads to the production of potentially hazardous materials,
although largely controlled and accounted for, give rise to direct exposure to the work
force, routine and accidental emissions to the public via releases to the environment.
Figure 14 indicates the main elements that need to be considered in the assessment of
the total health impact from the various fuel cycles involved in electricity generation.
The various categories of health risks are established as follows:

- Source: Risk from routine operations or accidents
- People at risk: Workers or public
- Exposure: Short or medium and long term
- Effects: Fatal (immediate/delayed);
  Non-fatal (immediate/delayed).

It is agreed that these various dimensions of health risk should be considered and
compared separately. The assessment of health risk is usually based on:

(a) Data from epidemiological studies for particular situations. Relatively few such
    studies have been undertaken, particularly for non-nuclear energy systems and
    accounting for the synergetic effects of the combined effects of a number of
    chemical pollutants;

(b) Estimations based on dose-effect relationships for different levels of exposure.
    Mathematical models enable the determination of ambient concentrations of
    pollutants in different media, and the prediction of health effects through dose-
    effect relationships. The state of knowledge concerning exposure paths, dose-
    effect relationships and health risks for different energy systems varies amongst
    different systems. The nuclear option seems to be the highest researched in this
    regard.

<table>
<thead>
<tr>
<th>Source</th>
<th>People at risk</th>
<th>Exposure</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routine or accidents</td>
<td>Workers and public</td>
<td>Short or medium and long term</td>
<td>Fatal and non-fatal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Immediate/delayed</td>
</tr>
</tbody>
</table>

2.3.2. Methodological issues

(i) Both approaches to estimate health effects of different energy systems, as referred to above, only rarely deliver quantitative risk coefficients with high confidence intervals. For many energy systems, many of the necessary steps in the estimation process are so poorly defined that uncertainties in the range of several orders of magnitude may arise in the postulated health detriment. However, because some of the potentially larger sources of error, such as dose-effect relationships near the zero dose, apply similarly to all the systems under consideration, comparisons and ranking may still be possible.

(ii) Dose-response relationships for many chemical pollutants are not available or in need of further research and development. Dose-effect relationships along similar lines to those available for radiation should be developed for chemical pollutants. In these cases, the issues are more complicated than with the case of radiation, due to the large number of chemical substances.

(iii) There is a particular lack of data concerning the delayed (chronic) health effects of many chemical pollutants. The health effects at the low spectrum of continuous exposure need particular attention in this regard. Another issue of research need relates to the indirect health effects of pollutants where relatively little information is available.

(iv) The dose-response curve for radiation exposure, as recommended by the International Commission on Radiological Protection (ICRP), may need careful interpretation. It was noted at the meeting that, at low doses to the individual, the ICRP refers to the cumulative risk as a "detriment" and does not necessarily equate it to the number of delayed fatalities. It may therefore be inappropriate to use it to assess risks other than those referred to as "hypothetical risks". It was also noted that the ICRP curve was designed for the purpose of radiation protection and not for risk assessment. It was therefore conservative. However, risk assessment requires the use of "realistic" dose-response functions.

2.3.3. Indicators of health risks

In compiling a list of health risk indicators, the various dimensions of health impairment should be considered. These can be identified as prompt loss of life, loss of life years due to delayed or premature death, partial impairment as a result of injury or disease which might result in reduced ability to function as a worker or in society, psychological detriment, permanent impairment, disability and genetic effects.

A short list of parameters, being used as indicators of health risks, covering the above dimensions (as far as possible), includes:

- number of fatalities (acute)
- number of fatalities (delayed)
- incidence of injury and disease
- projected incidence of genetic effects
- years of lost life (YOLL)
- relative utility loss (RUL).
The first four indicators have been orderly used and are self explanatory. The last two are newer developments but permit some consideration of the multi-dimensionality of health impairments. YOLL, for example, recognizes the difference between acute and delayed fatalities. RUL is a further development which places a utility value (usually between zero, equivalent to death, and unity, equivalent to full health), on a health state of specified duration, say, one year. RUL may incorporate dimensions of physical and mental impairment, distress, pain, dependence upon others, etc. RUL values may be integrated over various time periods to track the course of an injury or disease.

The following additional comments are offered in relation to the use of indicators:

- Although compound indices such as YOLL and RUL offer the prospect of improved reliability in assessing and comparing health detriments, simple indicators such as numbers of fatalities and serious injuries should continue to be used in parallel, at least for the time being;

- Some classes of detriment should not be aggregated. For example, prompt and delayed fatalities;

- Health risks to different groups (e.g. the public and workers) and of different types (e.g. from "normal" operations and severe accidents), should be distinguished, although it may in addition be permissible to aggregate in some cases providing the basis and any value judgements are made explicit.

A hierarchy of proposed health indicators is shown in Figure 15.
2.3.4. Research needs

- There is an urgent need for an international agreement on a methodology for the assessment of the health detriments associated with effluent from fossil fuel plants in particular;

- In Europe, and on an international level, moves to harmonize statistical databases should take account of user requirements;

- Further work is required on more sophisticated indices such as RUL which have been examined in relation to health case programmes, consumer and transportation accidents.

2.4. TIME DEPENDENCE IN COMPARATIVE RISK ANALYSIS

Risk is a product of two time dependent factors, summed over all scenarios:

\[
\text{Risk} \, (t) = \sum \text{Probability} \, (t) \times \text{Consequence} \, (t)
\]

Probabilities can be influenced by preventive measures while consequences can be influenced by mitigating measures. Risk from energy systems changes over time as a result of maturation of (i) technology (e.g. flue gas scrubbers, ventilation of mines), (ii) new generations of energy systems and (iii) knowledge and understanding of design and handling of complex technological systems (e.g. automation, advanced design procedures, new methods of manufacturing equipments with higher tolerance and precision, new environmental standards). Delayed effects due to electricity production emissions and effluents may manifest themselves in future risks (e.g. latency period for cancer induction or genetic effects in descendants).

An energy system can never be brand new. One has to build new infrastructures on previous energy technologies to meet the growing needs of consumers. In a society, old and new technologies will coexist and contribute differently to the overall risk. The energy system has an internal clock and technologies do experience a complex substitution process over a span of time. The relative risks of these technologies must be incorporated into comparative risk assessment (e.g. automation and fail-safe systems, coal and nuclear power, renewables, etc). The reliability of models which make predictions far into the future is open to question in their theoretical assumptions and results. Such models require peer review by experts and unique validation approaches. They should be updated as knowledge on data and mathematical modelling of the fundamentals of the predicted processes improve (e.g. bioaccumulation of contaminants over long time periods). The time-space relationships require special modelling techniques (e.g. finite element models).

In comparative risk assessment (CRA), appropriate time frames must be defined for different stages of different fuel cycles (e.g. impacts of thousands of years). In this respect one can consider microtime (e.g. fraction of seconds) and macrot ime (e.g. decades, centuries) as possible concepts to be used in comparative risk assessment.
Many recent studies consider that environmental impacts reflect unanticipated long term consequences of energy and other related development activities undertaken for their short term benefits. Analysis of the interplay between energy systems and environmental processes indicate a time horizon of one century into the future and at least two centuries into the past.

Recent work deals with cumulative environmental impacts, where sources of perturbation are clustered sufficiently close in space or time so that they exceed the natural system's ability to remove or dissipate the resulting disturbance (see Figure 16). The abscissa indicates the residence time into the environment of some chemicals while the ordinate indicates the space environmental impacts. The scale of environmental impacts resulting from the utilization of different fuels varies from local, through regional, national, continental, to global.

Risk analysis for the entire energy fuel cycle is a complex and cumbersome activity. More research is needed for the integration of risks of different time-space elements of the fuel cycle.

Due to varying levels of technological developments for similar stages of different fuel cycles (e.g. coal mining vs. uranium mining) and the site specific character of such activities, comparative risk assessment studies should clearly state all assumptions concerning the applicable technologies. Every attempt must be made to at least qualitatively account for the effect of future technological development on risk estimate.

2.5. UNCERTAINTIES IN COMPARATIVE RISK ASSESSMENT

In comparative risk assessment, uncertainties occur in the prediction of scenarios, models and data.

(a) Uncertainty in scenarios

   Erroneous probabilities;
   Factors not considered;
   Factors screened out;

(b) Uncertainty in models

   Imperfect conceptual model;
   Imperfect mathematical model;
   Imperfect computer model;

(c) Uncertainty in data

   General vs. site specific data;
   Measurement errors;
   Data reduction.

Expert judgement is inherent in the evaluation of uncertainties. Uncertainties must be delineated and exposed whenever appropriate and attempts made to deal with them. Uncertainties take many forms and it is essential that a coherent and clearly visible approach is adopted, both in the computational process and in the interpretation of results.

Uncertainty analysis should be performed for each stage of the fuel cycle. The uncertainty results from an entire fuel cycle do not represent an arithmetic summation of those associated with each stage.

Uncertainties arise from a number of sources:

**Data:** all data are subject to sampling errors. Statistical uncertainty requires the reporting of range or confidence intervals. Very often comparative risk assessment is done by using historical data or by using data for similar situations, sometimes developed in a different technical and environmental space frame.

**Models:** estimates of risks through scientifically based models (lack of direct observations) brings additional uncertainty in a comparative risk assessment. When models are the only tool to be used for risk assessment, uncertainty analysis of the results should be exposed and taken into account.

**Knowledge:** lack of knowledge or uncertainty in the foundation of basic physical phenomena can lead to erroneous results and faulty predictions. At the present time, this uncertainty in results due to knowledge is solved by using simulation procedures or intercomparative computer exercises.
There are some techniques already in use which can help to evaluate uncertainties; among them are sensitivity analysis, inferential statistics (Bayesian methods), complex statistical and probabilistic analyses, Monte Carlo simulation.

In cases of lack of knowledge bounding calculation and conservative assumptions can be used. As a rule of thumb, one can consider that risk assessments should be realistic and, if this is not possible, then the results should be considered as conservative.

Model validation is necessary in many cases and involves comparison of prediction of the model's results based on existing or future observations. Confidence in comparative risk assessments can be significantly increased by model validation, calibration and verification exercises.

Some uncertainties in results do arise because of the different types of technologies considered and their associated economics. For "objective" comparative risk assessment, economic factors, such as work productivity, should also be considered. Remote control technologies in advanced mining systems with high productivity values is just one example where one has to objectively compare different energy fuel cycles.

There are different mathematical approaches to dealing with uncertainty: probability theory, Markovian models, possibility theory (fuzzy sets), event trees, influence diagrams, heuristic models.

The fact that uncertainties exist does not invalidate the use of comparative risk assessment as a useful tool for overall assessment of the impacts of electricity production, as long as such uncertainties are clearly understood, exposed and acknowledged in the presentation of the results.

2.6. METHODOLOGICAL ISSUES IN COMPARATIVE RISK ASSESSMENT FOR SEVERE ACCIDENTS FROM DIFFERENT ENERGY SOURCES FOR ELECTRICITY GENERATION

It is now well accepted that the potential for major accidents exists for most energy systems at various stages of their fuel cycles. Traditionally, the assessment and hence comparative risk assessment of different energy sources as regard major accidents, focused almost entirely on estimating acute fatalities to people from historical records or using techniques of Probabilistic Safety Assessment as a predictive tool. With the exception of nuclear energy, methodologies for the estimations of late health effects to people and of the environmental impacts from major accidents are limited or in need of significant development and applications.

The following methodological issues are particularly significant and should be addressed/resolved in order to ensure a credible comparative risk assessment:

(a) Definition of "severe accidents"

Severe accidents have been defined as, "accidents with the potential for or associated with significant off-site risk to people, property or the environment". Attempts
have also been made for a quantitative definition in terms of "accidents that will cause 10 or more immediate fatalities". The main issue, however, is that to date no universally agreed international definition of what constitutes a severe accident has been developed. The need for the formulation and agreement on such a definition is important in order to ensure improved reporting, assessment and management. A definition for severe accidents should encompass all the elements of health, environmental risks and damage to plant, equipments and buildings. The definition should also be expressed in terms of both the potential as well as the actual damage and risk.

(b) Risk indicators of severe accidents

The most commonly used risk indicator for severe accidents is in terms of number of immediate (acute) fatalities. Other risk indicators may include: years of lost life; number of injuries and/or diseases; number of genetic effects.

No indicators of environmental risk for severe accidents have been proposed to date. Assessment is presented in terms of emissions in most cases. For comparative risk assessment, it is necessary to relate the risk to a common unit for the different electricity generation systems. Three comparative indicators (all related to immediate health effects) have been used:

(i) For a given period of time and for the different energy systems, a comparison may be made on the basis of the immediate number of fatalities per accident. (Total number of fatalities for the period of interest divided by the corresponding total number of accidental events for the same period).

(ii) Number of fatalities per unit of electricity generated for the different sources of electricity generation (Number of fatalities/GW(e).a).

(iii) Frequency distribution curves, representing the cumulative frequency distribution of acute fatalities per GW(e) per year of electricity energy production (i.e. plots of number of acute fatalities (X) per accident vs. probability of accidents per GE(e). a, with X or more number of fatalities).

Comparative risk indicators based on delayed health effects and/or indirect health effects have not been generally advanced to date, particularly for non-nuclear energy systems. No comparative risk indicators for environmental risk are available and qualitative comparisons can only be performed at this stage.

(c) Methods and tools of comparative risk assessment for severe accidents

The principle tools for health and environmental comparative risk assessment rely on historical data analysis/assessment and/or the use of probabilistic safety assessment (PSA) or quantitative risk assessment (QRA). The following methodological issues are of particular relevance:

(i) The comparison cannot be made on the basis of the consequences of such accidents in isolation. The likelihood (or probability) of occurrence should also be taken into account. Hence, estimation of the frequency of such accidents is relevant. Such estimations necessitate reliable information on the past records of such accidents and their effects and/or the application of probabilistic methods that predict the likelihood of their future occurrence.
(ii) It is difficult to assess and compare the frequency and the health and environmental damages caused by severe accidents because such data are not systematically collected by a single national or international agency. This applies particularly to the non-nuclear energy systems. Data on incidents and accidents for the nuclear fuel cycle are more readily and systematically available.

(iii) There are virtually no data on the delayed effects on health from severe accidents for non-nuclear energy systems in particular. All health effects in such cases are reported in terms of immediate fatalities, with immediate injuries reported in a few cases. This makes complete comparison difficult, since the total impact may be underestimated, especially for the non-nuclear energy systems.

(iv) The ultimate long term environmental effects, particularly from severe accidents, are difficult to establish. Because of the one-time or infrequent exposure of ecosystems to accidental emissions, it may be difficult to establish whether the effect is irreversible or whether a recoverable effect is possible.

Another issue of growing importance relates to the need to account for variations in technologies and possible future technological developments of different energy systems in the assessment and comparative assessment for severe accidents. PSA and QRA studies should attempt to include the effect of such future developments in the comparative results.

(d) Presentation of results of comparative risk assessment for severe accidents

In presenting the comparative risk assessment results for severe accidents, the following principles should be adopted:

(i) Risks from severe accidents should be presented and compared separately from the risks resulting from routine operations.

(ii) Data based on historical (actual) occurrences should not be compared directly with data based on probabilistic predictions of likely future events.

(iii) The comparative results should not be presented in terms of aggregate risk in isolation. The various risks associated with the different steps of each fuel cycle should be separately highlighted.

(iv) All dimensions and elements of environmental and health risks should be exposed and presented. The presentation of results in the form of F-N curves (frequency distribution) is a useful presentation technique. However, the values usually presented without additional information may not by themselves be sufficient since other dimensions of risks may not be exposed. Another method of presenting the results in tabular form should ensure the completeness of all relevant dimensions of risk rather than relying on isolated information, on fatalities for example.
2.7. INTEGRATION OF THE DIFFERENT ELEMENTS OF RISK AND THE ROLE OF COMPARATIVE RISK ASSESSMENT IN ENERGY PLANNING AND PRODUCTION

2.7.1. Lack of a single integrated risk indicator

The various elements of risks from energy generation systems can be broadly categorized as indicated in Figure 17. The following comments are made concerning attempts to integrate those different categories into one overall indicator of risk:

- The various elements and dimensions of environmental and health risks cannot be integrated into one overall indicator of total risk. No comparison on the basis of a single indicator is possible. The comparative risk assessment process must specify on which basis (indicator) the comparison is being made.

- It is necessary to expose all the dimensions and elements of health and environmental risks in the comparative process. Differences between regions and societies make the development of one overall indicator meaningless. There is no 'global' risk value. Comparative risk studies are best undertaken at the national or regional levels. The results should not be transferred from one study to another without appropriate investigations of differences between regions and countries.

FIG. 17. Elements of risk from energy generating systems.
• One approach/attempt to develop an overall indicator is the estimation of 'external costs' of impacts in terms of monetary value. This approach is arguable (as a tool to develop a single indicator of comparative risk assessment) as it has not been established whether all impacts can be allocated an acceptable monetary value.

• The integrated approach to health and environmental risk means that all risks should be identified, assessed and considered in the comparative risk and management process.

2.7.2. The role of comparative risk assessment in the energy planning and development process

Comparative environmental and health risk assessments of different energy systems provide decision makers with an important and useful tool in energy planning and development. The following highlights the most appropriate applications of these tools:

(i) The most appropriate role for comparative risk assessment relates to the incorporation and integration of health and environmental impact considerations into electricity generation choices. In particular, the concept can be used to assist in more detailed selection of the appropriate energy mixes within the broader framework of energy scenarios.

(ii) Comparative risk assessment cannot be expected to provide an overall ranking of the different electricity generation systems on the basis of a single integrated risk indicator. It is possible, however, to derive ranking of options on the basis of individual (separate) risk indicators - based on health and, to a much lesser extent, environmental considerations.

(iii) The integration of health and environmental factors through the comparative risk assessment of these factors - before the start of the study process - through appropriate scoping. The scoping process should involve all factors concerned and consider all possible impacts to help determine the scope of the comparative risk assessment so that no important facts are neglected.

The involvement of independent experts (or experts body) in the decision process is necessary. The independent experts could come from an environmental assessment board or belong to an international experts group. This procedure of using independent experts should be encouraged internationally.
PAPERS PRESENTED AT THE
SPECIALISTS MEETING ON
METHODS FOR COMPARATIVE RISK ASSESSMENT OF
DIFFERENT ENERGY SOURCES

STUDSVIK, SWEDEN, 27–30 AUGUST 1991
COMMENTS ON ENERGY RISK ANALYSIS*

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Abstract

The aim of energy risk analysis is to determine the magnitude of the various categories of risk as objectively as possible. The present state of the analysis of health risks is rather heterogeneous. The paper identifies and discusses the most significant issues concerning the present status of risk analysis for energy systems. Such issues include the specification of the boundaries which define the fuel cycles to be analysed and the formulation of a rational basis for their comparison. For meaningful comparisons to be possible, health detriments which are valued differently must be carefully distinguished and not aggregated artificially into some synthetic risk indicators. Rare but severe accidents must, for the same reason, be considered separately. Policy decisions, which always imply value judgements as to the relative weight to be given to the various categories of risk, are possible on this basis only. Most health risks of the conventional fuel systems and for nuclear energy have a relatively sound statistical basis. A main problem is the determination of the risks to the public of atmospheric pollution. For the most renewable energy systems risk analysis is still at an early stage of development.

A METHODOLOGY FOR QUANTIFICATION OF HUMAN HEALTH EFFECTS DUE TO ELECTRICITY PRODUCTION FROM COAL*

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Abstract

The paper presents the development of a consistent methodology to estimate human health impacts of energy systems; examples are given from the field of coal energy technology. An adequate framework of standardized mathematical procedures and the required input data for the entire fuel cycle are defined and integrated into a comprehensive approach. The paper claims that the standardization of risk calculation is a determinant step in the development of comparative risk assessment studies. As there are no reliable dose-effect relationships available to calculate public risks from air pollution, the paper proposes the "critical level" approach to estimate the potential health risks caused by power plant emissions. Numerical examples are given for a typical coal fired power plant located in Baden-Württemberg (Germany).

COMPARATIVE RISK ASSESSMENT OF VARIOUS ELECTRICITY GENERATING SOURCES — THE GREEK EXPERIENCE

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National Research Centre for the Physical Sciences Democritos,
Athens, Greece

Abstract

The analysis starts from the observation that the electricity production in Greece is based mainly on lignite fired and hydropower plants while oil fired power plants contribute only to a small extent. Renewable energy sources (e.g. wind power) have a limited part in the Greek energy system. The paper highlights that in the past only limited interest was paid in the country to comparative risk studies for electricity generation; only lately a resurgence of interest was observed. The case study reported in the paper deals also with nuclear power and natural gas, since these energy sectors were considered by energy planning specialists in addressing the increasing demand for electricity in Greece. The paper points out that the resulting assessments should be considered as first approximations to a more detailed and realistic analysis.

INTRODUCTION

The utilization of electricity is historically one of the principal factors that improved the standard of living of humankind. However the production of electricity and energy in general implies some social cost, that should not be ignored. The risks of electricity production have been extensively studied in many countries, and the results of these studies cover a wide spectrum of environmental and health impacts, resulting from different energy sources. However in Greece such studies were performed fragmentarily in the past, due mainly to a lack of interest from both the authorities involved in electricity production and regulation, and the general public. The latter was rendered sensitive only for a small period of a few years in the late seventies - early eighties, when an intention was expressed by the government of that time to introduce nuclear power in Greece. Another reason was the very limited nature of the existing data base related to the risk of electricity production, and the difficulty of getting access to these data, that were used practically as proprietary information. When the planned nuclear power programme of Greece was frozen in 1982, the interest that concerned issues of risk from the Greek power plants of both the public institutions involved and the general public started to wane.
The studies performed at that time included nuclear power and natural gas, since a decade ago these were among the options that were considered to cope with the increasing demand for electricity. The data used for nuclear power, natural gas, and for the indigenous sources in many instances as well, were adopted from foreign literature and were applied to the Greek conditions by some rough approximations. The resulting assessments should therefore be considered as a first approximation to a more realistic analysis. There were also some qualitative analyses for lignite power plants that were based exclusively on indigenous data, while similar quantitative analyses could not be performed due to the lack of a complete indigenous data base. The risk of wind power that is used in some Greek islands, was also estimated.

INDIGENOUS FOSSIL FUELS

Lignite Fired Power Plants. Lignite is the main energy source used for electricity production in Greece and lignite fired power plants furnish about two thirds of the total electricity produced. Most of the plants have a rating of 300 MW consuming slightly more than 500 t/hr of lignite during maximum load. A typical composition of Greek lignites is given in Table I({eq}^{1}\). The fly ash produced by the burning of lignite is reduced by 10% in the burner due to gravitational setting, and then passes through electrostatic filters, where it is withheld by 99.5%. The remaining 0.5% is released into the environment. The total yearly release of fly ash from a 300 MW lignite fired power plant amounts to about 2000 t, for an average load factor of 75%. The typical composition of lignite fly ash is presented in Table II({eq}^{1}\). Fly ash includes additionally some radioactive substances, such as Ra-226. These substances have been measured by various environmental radioactivity laboratories and the results of the measurements are shown in Table III({eq}^{2,3,4}\).

Lignite fired power plants like coal fired ones release additionally into the environment oxides of sulfur and nitrogen, carbon monoxide, hydrocarbons and particulates. Table IV presents some characteristic data concerning the releases of a coal fired power plant({eq}^{5}\).

Oil Fired Power Plants. The releases of oil fired power plants are similar to those of lignite/coal fired power plants. A typical case of oil fired power plant effluents for a consumption of $10^8$ barrels of oil is presented in Table V({eq}^{5}\).
Table I. Typical Composition of Greek Lignites

<table>
<thead>
<tr>
<th>Substance</th>
<th>Weight Composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>57.2</td>
</tr>
<tr>
<td>Fly ash</td>
<td>13.0</td>
</tr>
<tr>
<td>C</td>
<td>18.2</td>
</tr>
<tr>
<td>H₂</td>
<td>1.5</td>
</tr>
<tr>
<td>O₂</td>
<td>8.8</td>
</tr>
<tr>
<td>N₂</td>
<td>0.4</td>
</tr>
<tr>
<td>S</td>
<td>0.35</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table II. Composition of Fly Ash

<table>
<thead>
<tr>
<th>Substance</th>
<th>Weight Composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>25-35</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>10-16</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>6-10</td>
</tr>
<tr>
<td>TiO₂</td>
<td>traces</td>
</tr>
<tr>
<td>CaO</td>
<td>25-40</td>
</tr>
<tr>
<td>MgO</td>
<td>6-8</td>
</tr>
<tr>
<td>SO₃</td>
<td>12-14</td>
</tr>
<tr>
<td>K₂O, Na₂O</td>
<td>0.5-1.5</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.1-0.3</td>
</tr>
<tr>
<td>MnO</td>
<td>traces</td>
</tr>
</tbody>
</table>

The releases of thermal power plants include two groups of substances that are considered as carcinogen agents. These are: (a) the radioactive substances contained in the fly ash, and mainly (b) the aromatic hydrocarbons, especially benzo(a)pyrene. The first group has been extensively studied, in connection to nuclear power, more than any other carcinogen agent. Besides these two groups, there are other pollutants
Table III. Radioactivity of Fly Ash (pCi/gr)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Ra-226</th>
<th>U-238</th>
<th>Th-232</th>
<th>K-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab A</td>
<td>10.4±0.9</td>
<td>23.2±3.3</td>
<td>0.192±0.014</td>
<td>-</td>
</tr>
<tr>
<td>Lab B</td>
<td>26.63</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lab C - 1</td>
<td>7.4±0.3</td>
<td>9.9±2.0</td>
<td>1.2±1.2</td>
<td>7.1±1.2</td>
</tr>
<tr>
<td>Lab C - 2</td>
<td>16.0±0.2</td>
<td>20.6±1.5</td>
<td>1.3±1.9</td>
<td>6.2±1.9</td>
</tr>
</tbody>
</table>

1 pCi/gr = 37 Bq/kg

Table IV. Effluents from a Coal Fired Power Plant

<table>
<thead>
<tr>
<th>Substance</th>
<th>Pollutants Released (t) (1Mt of fuel consumption)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxides of sulfur</td>
<td>60000</td>
</tr>
<tr>
<td>Oxides of nitrogen</td>
<td>9000</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>230</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>90</td>
</tr>
<tr>
<td>Aldehydes</td>
<td>24</td>
</tr>
</tbody>
</table>

Table V. Effluents from an Oil Fired Power Plant

<table>
<thead>
<tr>
<th>Substance</th>
<th>Pollutants Released (t) (10^8 barrels of oil consumption)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxides of sulfur</td>
<td>11400</td>
</tr>
<tr>
<td>Oxides of nitrogen</td>
<td>4700</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>2</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>145</td>
</tr>
<tr>
<td>Aldehydes</td>
<td>25</td>
</tr>
<tr>
<td>Fly ash (97.5% removed)</td>
<td>160</td>
</tr>
</tbody>
</table>
produced secondarily such as ozone and sulfuric and nitric compounds, that have also a specific impact on human health\(^5\). The biological impacts of the releases from thermal power plants have been analyzed in many studies. However the quantitative estimations of most of these studies contain large margins of uncertainty.

Table VI. Work Days Lost in Energy Production (Days/MWyr)

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Occupational</th>
<th>Public</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite/Coal</td>
<td>4.68-12.40</td>
<td>5-1080</td>
<td>9.7-1092</td>
</tr>
<tr>
<td>Oil</td>
<td>0.78-5.91</td>
<td>1-1080</td>
<td>2-1086</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.64-2.7</td>
<td>-</td>
<td>0.64-2.7</td>
</tr>
<tr>
<td>Hydro</td>
<td>11.0</td>
<td>0.04-0.39</td>
<td>11.0-11.4</td>
</tr>
<tr>
<td>Nuclear Power</td>
<td>0.25-0.90</td>
<td>0.022-0.039</td>
<td>0.28-0.95</td>
</tr>
<tr>
<td>Wind Power</td>
<td>125.9-145.9</td>
<td>8.6-280</td>
<td>134.5-426</td>
</tr>
</tbody>
</table>

Table VII. Fatalities in Energy Production (Deaths/MWyr * 10\(^3\))

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Occupational</th>
<th>Public</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite/Coal</td>
<td>3.0-12.5</td>
<td>2.3-156</td>
<td>5.3-168</td>
</tr>
<tr>
<td>Oil</td>
<td>0.2-1.9</td>
<td>1.4-140</td>
<td>1.6-142</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.1-0.4</td>
<td>-</td>
<td>0.1-0.4</td>
</tr>
<tr>
<td>Hydro</td>
<td>2.0-4.2</td>
<td>1.3-2.0</td>
<td>3.3-6.2</td>
</tr>
<tr>
<td>Nuclear Power</td>
<td>0.23-1.32</td>
<td>0.04-0.24</td>
<td>0.27-1.56</td>
</tr>
<tr>
<td>Wind Power</td>
<td>26.7-39.8</td>
<td>2.2-39.8</td>
<td>29-80</td>
</tr>
</tbody>
</table>
ESTIMATIONS OF THE RISK OF SOME ENERGY OPTIONS

In this section some quantitative results are presented for the different energy sources that are used in Greece, based on some preliminary assessments that were performed. Nuclear power and natural gas are also included. The risk of wind power was relatively high since the estimations were based on the Inhaber approach\(^6\). Two risk indicators were utilized, namely the number of deaths and the number of working days lost per unit energy produced. Furthermore the distinction between occupational and public risk was used.

As was explained previously the assessments performed can be only considered as a first approximation to realistic estimates due to the lack of appropriate reliable data bases. The results of the analyses are presented in Tables VI and VII\(^7\).

The estimations of these studies were in agreement to most similar studies performed in other countries during the last two decades, favoring nuclear and hydroelectric power over lignite and oil, while natural gas was found to be the least risky energy option.

ENVIRONMENTAL LEGISLATION

Recently some changes were introduced into the environmental legislation of Greece, in order to harmonize the existing legislation to the directives of the Council of the European Communities. The main requirement instituted concerns the submission of an Environmental Impact Assessment report for a broad spectrum of industrial installations, including explicitly thermal power plants with a power rating of 300 MW or more, hydroelectric power plants, nuclear power plants, and in general terms all other industrial electricity generating installations. The report required must include an estimation of the consequences to the environment of the installation involved from both normal operation and accidents. However the legislation does not provide guidelines for intercomparison and/or integration of the various consequences. The assessment of the consequences and the implied uncertainty assessment for accidents constitute the first step towards the assessment and management of risk.
CONCLUSIONS

The limitations of the results presented in the previous sections indicate that a more systematic approach should be adopted in Greece concerning the area of comparative risk assessment of different electricity generation sources. This necessity is well understood today by most of the institutions involved in risk assessment activities, and efforts are already underway for a more integrated approach. The recent changes in Greek environmental legislation facilitate somehow the accomplishment of this purpose. Reliable estimations of the risk of the Greek electricity generating stations are expected in the immediate future.

REFERENCES

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THE PROBLEM OF RISK PERCEPTION:
A PRELIMINARY STUDY ON SOME
UNDERESTIMATED ASPECTS OF THE
SOCIAL PHENOMENON

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Abstract

The paper examines the psychological and social aspects of the preponderant determinant of modern energy policy, i.e. the risk perception. The rational, optimum and at the same time socially acceptable energy policy is, in democratic systems, determined by public opinion. The intensity of common concern on this point makes social acceptance the necessary condition of any realizable energy policy. The decisive factor for acceptance is the public perception of the risks associated with a given energy source. It is obvious that, especially in the case of nuclear energy, this issue is of outstanding importance. In view of the deeply emotional worldwide reactions against nuclear energy, the need for effective counteractions to be undertaken obliges the competent scientists not to confine research to mere risk assessment related problems but also to take account of the risk perception by society. It is reminded that the common feelings on energy related risks do not correspond to the reality, therefore an attempt of explanation of respective human attitudes is needed. It is indicated that the modern man living in the civilized world - thus, in a much safer one than in prehistoric times - shows a distinct demand for stronger stimuli. The mass media in turn, following the rules of market economy, successfully try to satisfy this need. The well known properties of nuclear energy predetermine it to become a perfect source of such a stimulus, which results inevitably in social reaction against the nuclear power. Finally, in the difficult task to find an efficient counter measure, the shift is suggested of a minute fraction of the means spent for very expensive improvements of (already high) nuclear safety to the enlightenment of the society on the true ranking of energy related risks. It might prove to be the most cost-efficient action for mankind sake in the field of energy issues.

1. Introduction

One of the most important political and economical objectives on the national scale - the rational, optimum and at the same time socially acceptable energy policy is in democratic systems determined by the public opinion. The intensity of common concern in this point makes of the social acceptance the necessary condition of any realizable energy policy. The decisive factor for this acceptance is the public perception of the risk associated with the particular energy sources. It is obvious that in the case of nuclear energy this issue is of outstanding importance. Simultaneously, it seems that just this aspect for years used to be generally neglected or at least underestimated by the nuclear community and only since a relatively short time it has been drawing the well deserved attention. The formerly prevailing attitude made the impression that the community assigned to the public the same capability
of understanding complexed technological questions of the modern world as their own one. Meanwhile, the deeply emotional worldwide reactions against the nuclear energy proved exactly the opposite. Obviously, the problem of hazard associated with the nuclear power has been the main factor motivating these movements. At the same time, the rather general lack of experience of the nuclear community in the questions of public relations makes the situation even harder.

In view of all the above the need for effectiveness of counteractions to be undertaken obliges the scientists in question not to be confined to the mere risk assessment related problems but also to put some stress on the risk perception by the society. The present study tries to fill up this deficiency.

2. Analysis of the Problem

The opinion that the common perception of various risks does not reflect real dangers associated with the respective sources does not give rise to serious doubts. For instance, we are afraid more of flying than of driving, in spite of the well established evidence that the risk of travelling by car is by one order of magnitude higher than that of using a plane. In the everyday life we are continuously undertaking certain risks and we have got used to many of them. We are smoking cigarettes, choosing dangerous professions, exercising hazardous sports, though we have (usually) no feeling of being endangered. Yet everything we do involves risk [1,2]. The late Polish humorist S.J. Lec, concluded plainly: "Life is unhealthy - who lives - dies".

Below we will try to throw some light on the sophistication of human attitudes towards the hazards of modern civilization.

2.1 Psychical determinants

At the very end all the factors determining the feeling of fear might be classified as the psychical ones, nevertheless, we now leave those involving other aspects, e.g. social ones, to be discussed later.

The main problem can be reduced to the question what makes the common perception of anthropogenic risks distorted that much?
Why people can be so indifferent to some dangers and simultaneously react that allergically to anothers? It is obvious that there are no univocal exhaustive answers to these questions particularly since there are many reasons that provoke this result. We start from those genetically built-in properties of the human psyche.

2.1.1 Inborn factors
In order to explain the behaviour of a man in the contemporaneous world we recall the fact, with the words of Desmond Morris [3], that he is "a primitive tribal hunter, masquerading as a civilized, super-tribal citizen and desperately struggling to match his ancient inherited qualities with his extraordinary new situation."
In a deep contrast with the pre-civilizational world the modern man enjoys, among others, incomparably higher degree of security from nearly any point of view. The level of medical sciences and care made many lethal diseases quite exceptional or curable, the specialized social formations (police, army) assure our physical safety, the systems of social security take care of the weak members (unemployed, ill or old ones) of the society. In addition to this, thanks to the enormous productivity achieved practically only in this century, the amount of free time remaining at man's disposal surpasses everything what for our close ancestors could remain only a dream. Many grave consequences result from these two simple facts (e.g. the more and more common drug abuse); here, however, we confine ourselves to those pertinent to the question of risk perception, with a special stress put on the nuclear energy perception.
Therefore, in this incomparably safer life than it was during those millennia which finally shaped our nature, the modern man experiences a significant lack of stimuli [3]. In other words we are genetically prepared for a much more hazardous life than on the average we have at the end of the XX-th century. We are thus simply equipped with a certain surplus of adrenaline and we need a reason to release it. Simultaneously, the gap between the mysterious, sophisticated and abstract modern science and the opinion-making elites has significantly increased since the
birth of modern physics. The golden age of a Renaissance man
categorized, among others, by its capability to master all
the knowledge of his times has irrevocably gone. The comfort of
the educated, self-confident elite, which produced on one hand
the rationalist philosophy of XVIIth century and the XIXth
century Marxism on the other, gave way to the anxieties of our
contemporaries surrounded by the poorly understood,
technicized, present world of machines. This relative
intellectual weakness of educated people, not even mentioning
the uneducated ones, results in a noticeable increase in
popularity of various pseudo-scientific theories and beliefs.
That peculiar demand for irrational explanations is subject to
the market rules and as such finds its supply in performances
of individuals frequently deserving to be named simply
charlatans. Their ideas often expressed in a showy
pseudo-scientific thus convincing jargon result at the end in a
further loss of authority of the official science. Facing the
incomprehensible (for him) phenomena our contemporary is, in a
way, recurred to a childlike position in his search for simple
and decisive explanations. Therefore, more or less consciously,
he is expecting sometimes fairy stories. He likes the tales
with their bipolar valuation scale - black or white characters
- with positive heroes and incorporated evil which should (and
always does) lose. He likes watching thrillers on the TV
screen, while those of a bit more developed imagination are
able to find satisfaction also in reading similar paperbacks.
It seems however, that the fictitious world of horror books or
movies created by the pure phantasy is less convincing than the
real, non-fiction phenomena. Though the modern civilization
brought about an immense increase in life expectancy of man, it
certainly could neither eliminate all ancient risks nor avoid
to produce completely new ones. It is obvious that not all the
present sources of real or potential danger can match that
refined psychological needs of a former hunter-gatherer thrown
into the middle of steel-glass-concrete desert of our
over-urbanized world. The best source of his stimulus must
fulfill certain requirements. It seems that it should be
spectacular, uncommon, mysterious, moving and not dull. Such
conditions of attractiveness of the stimulus sources can at
least in part be explained by the properties of information we
are daily subject to. The lion’s share the informations about any kinds of disasters are always getting in the news is worth to notice. It is absolutely disproportionate to the real significance of the event. I am not going to deny the personal tragedies of the people involved in the misfortune we used to be told about, but we should not forget that in an average country of, say, 50 millions inhabitants, ca. 1500 persons die each day and 150 000 in the whole world. Meanwhile, the mass media draw our attention to some fires, drownings, crashes, murders in which perish less than 0.1% of daily decease rate without any further significant consequences. It should be underlined in this place that this astonishing hierarchy of news value is not at all an exclusive feature of the gutter press; to the contrary, the world best information agencies are spreading out in their news services the relations of the most important political events together with thrilling stories of no importance. Obviously, it has to be admitted that a violent death is something less natural than a peaceful passing away of an old man. Nevertheless, it cannot justify the strikingly high rank this sort of news enjoys in the mass media.

It is suggested hereby that the demand for such sensations stems from the inborn human need for a stimulus we are lacking at the present level of life safety.

It proves that the modern technology can be helpful in this quest for stimulus providing us with its by-product in the form of various technology related disasters. Among many of those anthropogenic hazards there are also energy sources. However, not all of them satisfy the above mentioned requirements for a good stimulus source. Those ones based upon the pre-civilizational process of burning can hardly give rise to a stronger emotional reactions.

One can easily guess that, unfortunately, just the nuclear energy is predetermined to play this role.

Among the inborn determinants of the human psyche there are also those much less precised, more or less hidden, dim and valid rather as general characteristic of human beings than as a certain feature obligatory for each individual. Nevertheless, since they appear in various circumstances, amidst distant and mutually isolated peoples no one would deny their existence.

Obviously, there are very many such significant properties of
man which belong to the field of psychoanalysis. Here, naturally, we confine our considerations to the qualities pertinent to the question of the risk perception. Therefore, we concentrate on certain tendencies emerging from our unconsciousness - tendencies in our way of perceiving and thinking, in our desires and emotions named by Carl Gustav Jung - archetypes. Of course, not all Jung’s archetypes are of interest for us, too. But certainly, several deserve some attention. These are: the universal punishment myth and the closely related to it lost paradise myth [4]. The punished for their audacity Icarus and Prometheus, the Tower of Babel constructors and Adam and Eve for eating the forbidden apple incorporate these archetypes. Thus similarly, somewhere in the unconsciousness of our contemporaries a feeling of deserving punishment for the original sin of creating modern technology may arise. It seems that just this archetype significantly contributes to the psychological basis motivating (sometimes fanatically) environmentalist movements. It is really unfortunate, but in view of the qualities of radioactivity (invisible, inaudible, insensible yet noxious) just the nuclear energy can best embody the challenge thrown to the Almighty by the mankind. As a result, an enemy is created and all the negative feelings like the accumulated, technology related stress, are redirected and transferred on the selected target. Then such a target as being simple and well-defined evil evokes allergic fear reactions thus distorting completely the true risk estimations. Psychology knows also a phenomenon called "horror novi" - the fear of something new or unknown. Again from this point of view the nuclear power seems to focus on itself all the respective phobias.

2.2 Social issues

The social aspects, though treated here separately, remain in a very close connection to the discussed above purely psychological questions. Now, however, some stress will be put on the role of particular social elements and mechanisms.
2.2.1 The mass media
The modern man in the present world is daily overflown by a Niagara of information produced by the media of mass communication. These, in fact, have grown to become the fourth component of power in democratic systems, besides the well-known Montesquian ones: the legislative, the executive and the juridical ones. There is little exaggeration in the statement that it is just the mass-media that control the people’s minds. It should be underlined that this opinion is not a bit less valid in circumstances of undisturbed deployment and availability of information. Leaving apart the view that an absolute liberty does not exist even the perfect freedom of mass media does not signifies the lack of any rules they are subject to. Anyway, the concluding observation is that the mass media are operating on the information market and thus they must subject to the rules of market economy. It causes, among others, that a higher rank will obtain the information which is more attractive and sensational but not necessarily (quite) true. Not at all the information of highest reliability and accuracy enjoys the highest demand. Following the rules of economy, the last one is shifted towards this what people like to get to know, since this can be best sold. In consequence, as one may expect, the mass media are supplying society with the informations that could satisfy its quest for such stimulus, which could confirm its deeply rooted prejudices and phobias [5].

2.2.2 Effects of mass psychology
Strong negative feelings (e.g. of fear) shared by a large part of society can fulfil a complexed social role. In addition to the mentioned above satisfying of the quest for stimulus and the universal punishment myth, when separately influencing each individual, they create a significant element of social mechanisms. In the modern, television dominated society they create a unifying basis for our atomized, thus lacking social bonds super-tribe. At this point one should notice an interesting phenomenon of the amplification of emotions shared by many as compared with a singular case, which is taking form of a typical synergic effect [6]. There is no place here to discuss more exactly the ideas of synergetics, but it is
intuitive that the non-linearity of collective phenomena leads to qualitatively new effects which e.g. in the social area can mobilize enormous resources of human energy. As a matter of fact, the last effect had been utilized, for instance, in totalitarian regimes in the form of various mass meetings - parades, marches, singings etc. - long before the concept of synergetics was proposed. At present, the environmentalists movements try to move the public with the use of analogue effects based upon common fears and phobias. Obviously, not any risk source is suitable to play such role. It is hard to expect that e.g. the cigarette smoking though responsible for 6-8 years of loss of life expectancy would supply a sufficient mass bonding stimulus. The habit of smoking is far too common, (they say) too pleasant, neither terrific, nor mysterious enough. Unfortunately, again, the nuclear power related feelings enhanced by the associations with nuclear weapons (so called Hiroshima’s syndrom) can satisfactorily fulfil this integrating task.

2.2.3 Political aspects
The public opinion is always of great concern of politicians in democratic systems. Thus the attitudes of the people towards various energy sources determined principally by the perception of the energy associated risk become very important. It is clear, that the authorities cannot neglect the (subjective) feelings of their electorate. In consequence in spite of their much better knowledge of the true risk ranking, the energy policy realized in practice is frequently non-optimum as being strongly biased by the "vox populi". Also the opposition to the government in its efforts to get more votes in the next elections is rather not guided by the scientific truth but by the subjectivity of the voters.

2.3 Ethical aspects
As it might be already expected, in connection with the mass-media and politics also certain nonnegligible moral questions appear. In short, it can be reduced, as in most ethical problems, to the question of widely understood responsibility.
2.3.1 Journalist ethos
A particular burden lies upon the conscience of journalists being in authority over hundreds of millions minds, having each day a numbering millions audience, thus of the size no teacher can even dream of. Unfortunately, the journalist community seems to be interested merely in "selling" its information in a wide sense (news, views, commentaries etc.), paying little attention to further consequences of this professional activity. What counts, is whether the information is successfully sold. As compared with other professions - surgeons, physicians, engineers etc. the extraordinary tolerance the journalists enjoy, is striking. Pretending to be experts in any field they rarely hesitate to spread out informations of doubtful value - unconfirmed news and documents (e.g. the famous Hitlers memoirs) and various semi-truths, provided that they can be well sold.

The above opinion may sound like an attack against market economy but in totalitarian regimes the situation of mass-media is incomparably worse. According to the words of Goebbels: "Decisive is the plausibility of a statement, instead its content of truth remains meaningless" [4] the journalists being reduced to obedient servants under dictatorships spread out still less reliable information.

2.3.2 Politician ethos
The sole person of author of the above citation might provoke the question of politicians ethic. Unfortunately, even when having put aside all the crimes of genocide committed by those who can be classified as politicians, their ethic give rise to even more serious doubts than that of journalists, what should not be a surprise. The obvious and common need for efficiency of action obliges politicians to a well-advanced pragmatism. Thus, if the end justifies the means, certainly the average politician horizons cannot be excessively distant and the objective truth will lose in competition with the immediate advantages.

2.3.3 Environmentalist ethos
The ambitious, quasi messianistic role of contemporary saviours of the Earth which the environmentalist movements have taken
upon, brings them particular moral obligations. Meanwhile, surely even not being conscious of that, they prove not to cope with this duty. Most often their excessive political ambitions and thus sometimes desperate efforts to draw the public attention at any price together with their frequently very leftist inclinations throw a shade on the honesty of their intentions. This is very unfortunate since the civilizational impact on the environment is enormous and prospectively very dangerous, thus, the nature requires an institutional reliable protection. Yet, the "green" put themselves voluntarily on the exotic fringes of social life. The results of last elections in Germany may illustrate this opinion.

2.3.4 Scientists ethos
The bitter estimation of the ethic of journalists, politicians and environmentalists to a high degree is valid also for the scientific community. The problem of decisions regarding the distribution of means for research makes scientists not to be free from opportunism. Though this opinion may concern first of all the scientists of humanities field, (esp. in totalitarian regimes), it seems that not to follow the interest of the sponsor may prove difficult for anybody. Also scientists in their quest for publicity not always observe the strictness necessary for assuring the reliability of research. Sometimes they even join various movements supporting them with arguments of doubtful value but armoured with scientific authority. Particularly sensitive are those disciplines where e.g. certain discrepancies in experimental results are unavoidable and thus the differences in opinions are somehow justified. The risk evaluation as being based upon the estimation of probabilities and numerous, sometimes arbitrary assumptions, unfortunately, belongs also to this category.

3. Positive Countermeasures
The presented above picture of the conditionings of risk perception does not provide grounds for optimism. However, first of all, we must be well-conscious of all these factors which are inherent properties of human nature thus making the struggle against them so difficult. Therefore, we should look for analogue weapons and also utilize some human features. E.g.
this one that human beings, especially at young age, show a powerful instinct of learning and simultaneously a great adaptative capabilities.

3.1 Social Education

Consequently, it seems that only with an adequate, rational, enlightenment policy that false and noxious ranking of risks can be modified. The pertinent education should start already possibly early, at elementary school. But the environmental education should not be left to fanatics depriving our civilization of any merits. The educational programs should stress the fact that there is no life without risk and that an absolute safety is inachievable. The ALARA principle should be widely known. Finally, the ethical aspects also should not be omitted. Among others, that the end does not justify the means.

In this outreach efforts a special attention should be paid to journalists. Something poorly known, incomprehensible, but which they are forced to deal with, will provoke certainly most negative attitudes. Therefore, the magic words - radioactivity, nuclear etc. should be demystified. Everyone should know that his (her) own body is radioactive, or jokingly saying - is a low level radioactive waste. An intensive action should be undertaken in order to make society (and its more influential members like journalists) more familiar with the problems of risk and safety.

Obviously, such action will require a financial support.

3.2 Economics

It seems that the inevitable costs of educational actions could be covered by the industry and institutions interested in changes in public attitudes. It is well-known that the large scale modern technology is in no case cheap. The expenses for additional (often not absolutely necessary) safety measures are out of any comparison with the costs of outreach actions. Especially the delays in construction course of power plants caused by public protests cost incomparably more than any profilactic educational action. Seeing this, its neglect by the respective industry looks at least like short-sightedness.

Therefore, the optimum economical policy should less privilege the technology and concentrate more means on the issue of
public relations. Naturally, the scientific community feels rather less familiar with this subject. Thus some help of professionals may prove necessary. But certainly, no savings in this item can be advantageous, on the contrary, even minor expenses might prove to be the most cost-efficient action for mankind sake in the field of energy issues.

The author would be very happy if the present remarks could contribute to this important cause.

References

COMPARATIVE RISK ASSESSMENT WITH DUE REGARD TO HUMAN FACTOR UNCERTAINTIES

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Abstract

Human activities have to be considered at all fuel and life cycle stages of an energy source. Two kinds of human errors should be considered: anthropogenous accidents initial events and anthropogenous common cause failures. The paper presents a mathematical model of human factor uncertainties based on a large number of input parameters and on expert estimation of some uncertainties which can be expressed in terms of the informational entropy of Shannon. An analytical expression for such an indicator is given in the paper with reference to the case of a nuclear fuel cycle.

1. Basic Assumptions

1.1. There are three main dangerous impacts on the environment and people health from energy sources. First, ever-increasing expansion into natural resources. Second, continued pollution. And, finally, accidents.

Since Chernobyl disaster, the risk of severe accidents is of the most concern in this country when an optimum energy source is selected. That is why we have concentrated our attention on the human factor uncertainties in accidental conditions first of all.

1.2 In view of modern concepts of loss prevention, there are three main areas of human activities in this field:

- Prevention of emissions and accidents.
- Mitigation of consequences of accidents:
  (a) pre-accident measures;
  (b) post-accident measures.
- Post-accident recovery.

The human factor risk and uncertainties have been yet accounted for in two items only.
1.3 The human activities are considered at all phases of fuel and life cycle stages of an energy source. For example, as fuel cycle phases for a nuclear power plant (NPP) the following are investigated: mining, enrichment, fabrication, transportation, operation, storage, reprocessing and long-term storage. The life cycle stages are: research and development, project making, production/construction, operation and decommissioning. Each phase of fuel cycle is unavoidable without human activity on all the above-mentioned life stages, with unavoidable human errors whichever the stage is involved. The total sum of the unrevealed errors is an uncertainty. It is supposed to be so large that risk assessment by conventional techniques is invalid, as comparative risk assessments for different energy sources.

1.4 Two kinds of human errors are considered only in this context, viz., the so-called anthropogenous initial events of accidents (IE_A) and anthropogenous common cause failures (CCF). To this end, all stages of the life cycle i.e., the object of human activities, are represented as inputs/outputs similar to the theory of management. In this case, outputs characterise the object state, with the inputs subdividing into disturbances and control/protection. Among the disturbances we distinguish those that potentially can be a source of accident, - IE_A. The failures (or absence) of control/protection input also may the the cause of an accident or substantially increase the scale of its affect. If such failures result in a complete loss of a safety function, or the necessary function is not envisaged, then CCF or Common Mode Failure (CMF).

CMF are defined as simultaneous - or almost simultaneous - multiplicative failures in the same mode of safety
important technical systems (or elements thereof) that happen as a result of personnel's errors, a chance technical failure, inner or outer impact. The initial event - IE - is such a violation of normal conditions of safe exploitation that can be caused by the personnel's errors, chance technical failure, or an outside effect.

1.5. The sources of human inadequacy lie in the three main spheres of human activity. Firstly, in the sphere of professional knowledge and skills. Secondly, in the sphere of social and psychological objectives, i.e. motives that determine the actual orientation of the specialist's activity. And, thirdly, in the organisational structure and the method of functioning of groups of specialists in energy industrial process.

2. Qualitative Assessment of Human Factor Uncertainties

Estimation of human contribution into the life cycle of NPP was envisaged with regard to severe accidents at two NPPs - TMI-2 and Chernobyl, in strict compliance with the assumptions made in 1.1.

The analysis area incorporated the operation phase of the fuel cycle only but at all stages of the life cycle (assumption 1.3). In accordance with assumption 1.4, two kinds of human errors have been taken into account, viz. IE and CCF, and with 1.5 - three areas of their performance.

Graphically, the analysis is illustrated in Fig.1 Here, major components of the sphere of professional qualities are shown where \( \Pi_i, M_i, O_i, Y_i \) - being specific solutions, actions (or lack of actions) of the specialists working in the given industry. These can take place in the course of project-making (\( \Pi \)) production and assembling of equipment.
(M), maintenance safety related systems (O), and also in the process of immediate control over the technological process (Y). These may instantly or after a certain period of time result in CCF or IE. In the diagram: II1 - the mistakes in NPP siting, II2 - is inadequately calculated safety in designing industrial installation, for example, as a result of deficiency in the course of the preliminary analysis sources of potential danger; II3 - are mistakes in calculations and design of the safety control systems of the same installations; II4 - inadequacy of the control and diagnostics means in respect of potential conditions of the installation and its safety systems; II5 - design-making under limited conditions for taking decisions relating to material and technological possibilities that best meet safety
demands; M1 - violation of technological requirements in the process of production and installing safety-related systems and equipment of the industrial installation, including deviations from the original blueprint; M2 - poor quality of inspection; M3 - poor quality output control in the course of producing and installing safety systems; 01 - violation of shedule while servicing and repairing the safety-related systems, and also the poor quality of 02 - tuning, 03 - testing, 04 - output control, 05 - prescheduled check-ups of the system in question; Y1 - single blunders (single errors) of the operation personnel; Y2 - actions violating the set schedule (including delays in decision-making); Y3 - inadequate assessment by the personnel of condition of the safety-related systems, and also of the condition of the industrial installation as a whole; Y4 - actions taken following imperfect technological instructions.

We applied this scheme of anthropogenic (human) CCF-IE to the analysis of the set problem in case of nuclear power industry (NI) as one of the most "dangerous" industries. The actions of the NI specialists leading to CCF or IE will be described by corresponding points in Fig.1. The scheme of anthropogenie CMF-IE was shown one thing which is extremely important for our understanding of how the accident originated. Mistakes made by the specialists of the nuclear plant at the pre-operational stages (Π, M, O) under certain conditions can be sped up by the operational personnel and add to the disaster becoming irreversible. In case of TMI-2 power plants this implies the following: as a result of previous mistakes the nuclear plant operated at rated capacity and closed valves of emergency water supply to steam generator(01). At the initial stage of the accident the TMI-2
operators were misled by the erroneous readings of some malfunctioning instrumentation. Using false information the operators made a wrong decision to switch off the emergency cooling system of a reactor (ECCS) (Y3) and the system of forced coolant circulation through the reactor (Y2). These actions "prepared" the accident.

A similar situation was observed at Chernobyl nuclear plant-4 in terms of its antropogenic origin. The "design sources" of the accident were described many times. However, only the final contribution to the accident was made by the operational personnel - again similarly to TMI - 2 case.

Besides, we have found that to cope with the problem, a socio-psychological category of motivation factor which stimulates human activity is required to explain the Chernobyl phenomenon. It is assumed that the agitation force of a motivation at the given time is determined by the following three components which are assessed and "weighed up" by an individual: (a) mP - a priori probability of safely achieving the goal, (b) mC - labour and material losses to be suffered from achieving the goal, (c) mV - relative significance of the goal in a system of priorities belonging to an individual, the level of his or her personal ambitions. It was proved that the agitating force of a motivation is in direct proportion to mP and mU - components and in inverse proportion to mC. Apparently, these parameters are specific features of a particular individual. However, they are reflected at a quite objective basis of professional and psychological training of specialists and they are also reflected within an organizational structure of a team of specialists working in any industry.
For example, the pre-Chernobyl period in the USSR was marked with the lack of transparency in respect of accidents and incidents in general in the sphere of nuclear power production. The lack of information concerning the accidents contributed to forming in erroneous conception of safety at nuclear power plants in general. Consequently, the level of mP motivations components appears higher as compared with a realistic one. While, mC component was undoubtedly formed under the influence of some specific conditions related to control over reactors of this type (RBMK-1000) which are of more artistic, rather then scientific nature. The literature shows that regulations concerning maintenance of power units RBMK-1000 have been often violated. Therefore, the relevant personnel developed a concept of negligible risk of accident due to this kind of violations.

Importantly, the risk resulted from such "motivated" actions, as we see in case of Chernobyl - 4, usually many times exceeds the risk of accident caused by a chance professional mistake (cf. TMI-2). The given examples throw light at potential objective sources of motivation components. As we see in this case, such components may include technological features and operating regime of this type of power units, as well as a system of material and moral values typical of the industry, the degree of personnel awareness in respect of an accident risk, etc.

The failure-event-motivation approach to evaluating personnel actions makes it possible to clarify a HF phenomenon not only in case of TMI -2 or CNP-4; it can be applied to other energy industrial accidents. As we stated before, this failure-event-motivation approach forms a basis
for making a qualitative comparative hazard assessment and a programme of early preventive measures.

The detailed results of the qualitative assessment and the measures for decreasing the uncertainties and hazards dealt with human activities have been reported in /1/. Here we shall pay attention only to one of components - seemingly a key one - lying in the context of the above-analysed problems. That is an optimal organizational form of expert teams and collectives activities, making up a kind of safety filter. Safetywise, the only strucrural form of a team (shift; command; shop; industry) that can be called optimal is the one that blocks (filters out) unprofessional or ill-motivated actions. We can scrutinise in this respect both individuals and groups of experts working at the factories which maintain the operational cycle of the industry. Fig.1. illustrates the idea which underlines the organisational form -filters which complete the three-stage approach to the analysis of HF role regarding safety standards in hazardous industries, exemplified with nuclear power plants in the paper. These forms are shown in the picture as shells enveloping certain production stages, industrial enterprises, and industry as a whole. This is to underline their functioning as filters.

The present-day state of domestic organisational structures is far from being optimal. For this reason, symbols of reducing "<" or intensifying ">" safety related HF properties are placed where vectors, corresponding to professional or motivation components, pass through the shells, i.e. organisational structures. The results of the qualitative human activity assessment can not be used directly for the comparative risk analysis. But they revealed
the human deficiency areas where we could derived the data for quantitative estimations.

3. Mathematical Representation of Human Factor Uncertainties

The multitude of human activity operations expressed in Section 2 by submultitudes \( \Pi_1, \Pi_2, ..., M_1, M_2, ..., 0_1, 0_2, ..., Y_1, Y_2, ... \) is subdivided into two groups: 
\( (\Pi_1, \Pi_2, ..., M_1, M_2, ...) \subseteq U_1 \) and 
\( (0_1, 0_2, ..., Y_1, Y_2, ...) \subseteq U_2 \), where \( U \) denotes group of multitudes. The most simple characteristics of such groups is their dimension \( N \).

The multitudes of the first group are formed as has been stated above in NPP site selection, safety feasibility studies, project making, etc., i.e., at pre-operational stages of life cycle.

By the time of commissioning, the dimension of the multitude \( U \) is a definite magnitude and, after commissioning, tends to decrease only. Thus, the dimension of this group of multitudes at the pre-operational stage of the life cycle can be described by monotonously increasing function. After commissioning, this function becomes the monotonously decreasing, which corresponds to the process of detection, identification and correction of the errors at pre-operational stages. The possible exceptions are dealt with human activities in retrofitting, repowering, etc. at operational stage. In this case, the nature of the function change may differ, which is beyond the context of the paper.

A quite another picture is observed for the excursion of the \( U_2 \) multitude. At commissioning, their dimension is minimal or even zero. After commissioning, it changes in a complex
manner, first increasing and then decreasing. Besides, such changes may be of a periodic nature, having shift, week, month, year, etc, harmonics. An illustration, Fig.2 shows possible shapes of $U_\text{I}$ and $U_\text{II}$ function curves.
For mathematical description of such curves, the information is required on the professional ability, motivation and structures of R&D, project-making, etc. teams associated with the appropriate life cycle. As such information, previous, pre-operational, operational and post-operational experience with symmetrical plants capable of revealing anthropogenic CCF-IE can be used. Also, expert estimates of $U$ and $U$ multitudes parameters can be used for the purpose.

Let us assume that each of the submultitudes $X_i \in U_{\infty}$, $i = 1, 2, \ldots m$, comprises finite/countable number of elements $X_{i,j}^{(j)}$, $j = 1, 2, \ldots$. Also, the personnel actions are supposed to influence the origination of CCF and IE, after $t = 0$. The $X_j$ is supplemented with the state $X_0^{(j)}$ which corresponds to the situation with no CCF -IE.

Let $0 < T_1^{(1)} < T_2^{(1)} < \ldots < T_n^{(1)} < \ldots$ is the sequence of random time moments of recording the initiation of events (elements) of multitudes $X_i$. Since the elements of $X_i$ do not coincide in time, the following sequence of the time moments can be written:

$0 < T_1^{(1)} < \ldots < T_n^{(1)} < T_1^{(2)} < \ldots < T_n^{(2)} < \ldots < T_1^{(m)} < \ldots < T_n^{(m)}$

Now, let us introduce the function \( \psi^{(i)}_t \), \( t \geq 0 \)

$$\psi^{(i)}_t = \sum_{j=1}^{\infty} \mathbb{I}_{T_j^{(i)} < t}$$

whose initial state is \( \psi^{(i)}_0 = 0 \), $i = 1, 2, \ldots m$

The random process is represented in $Z^+ = \{0, 1, 2, \ldots\}$ and $\psi^{(i)}_t = n$, with equatily $n$ of random values of $T_j^{(i)}$ less or equal $t$, i.e., the events occurred not later than $t$. It means that not later than $t$, the equatily $n$ events out of the multitude $X_i$.  

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The mechanism of a probable accident may be described either by the vector random process \( \mathbf{v}_t = (v_t^{(1)}, v_t^{(2)}, \ldots) \) or by its scalar equivalent \( \eta_t \):

\[
\eta_t = \sum_{i=1}^{K} \alpha_i t^{(i)}
\]

where \( \alpha_i \) is the weight coefficient, relating to the significance of the personnel errors in the formation of CCF or IE: \( 0 < \alpha_i < 1, \sum \alpha_i = 1 \). In this case, for \( \Pi_1, \ldots, M_2, \ldots \) all \( \alpha_i \) are \( >0 \) or all \( \alpha_i \) are \( <0 \), while for \( 01, \ldots, Y_2, \ldots \) \( \alpha_i \) may be negative or positive.

Thus, a possibility arises for quantitative expression of safety uncertainties due to human activities at pre-operational stages. As has been stated above, after commissioning, the uncertainty level can be reduced to finally arrive at decision-making using PSA, HAZOP, and the like. The indication for such a possibility is represented by the event where random process achieves a certain threshold value \( N \) (or time moment of this threshold value). This situation can be predicted with known \( T_{i,j}^{(i)} \) distribution or, which is equivalent, the following interval time distributions:

\[
\xi_{i,j} = T_{i,j}^{(i)}, \quad \xi_{m} = T_{m+1}^{(i)} - T_{m}^{(i)}, \quad m \geq 2
\]

There are all grounds to state that the probability structure of and is of the form characteristic of the Markov processes.

If the random process \( \eta_t^Z, t = P (\eta_t < Z) \), has its distribution function \( F_{\eta}^Z (Z, t) \), then the uncertainty measure can be expressed as follows:

\[
H_{\eta}^Z (Z, t) = -\ln F_{\eta}^Z (Z, t), \quad \text{where} \quad H_{\eta} \quad \text{is entropy (see Fig.2).}
\]
The entropy quantifies our ignorance with respect to hazard or anthropogenic risk of a given energy source at a pre-operational stage. The entropy has its maximum value at the end of the pre-operational stage and, as has been said above, the information level about the professional teams directly specifies the entropy value. Incorporation of the human activity data into the mathematical model may substantially decrease the entropy level.

Presently, developments have been underway to incorporate $U_{\text{H}}$ into the model which will allow current safety estimates regarding to human factor uncertainties.

4. Comparative Risk Assessment of Energy Sources with due Regard to Human Factor Uncertainties

Using the above-disclosed methodology, let us try to achieve a rough solution in the field of the comparative risk assessment based on the available findings. With such a tradeoff, we propose to compute a special criterion for an accidental risk for each energy source: $R_{\text{NUCL}}^{\text{Acc}}, R_{\text{GAS}}^{\text{Acc}}, R_{\text{OIL}}^{\text{Acc}}$.

Let us use a simple formula which is a combination of two types of summands.

First summand will represent the accidental risk with due account for human factor uncertainties in the accident prevention area.

Second summand is similar to the above but relating to accident mitigation area.

A risk, which is a common practice, is expressed by the product of the accident frequency probability $A_A$, and the probable loss resulting from the given accident, $A$, i.e., $A_A \times A$. 
The accident frequency should be determined for maximum entropy, i.e., at the end of the pre-operational stage.

It should be noted that the above elements of multitudes $X_i (m_1, M_2, \ldots, \text{etc.})$ are very difficult to be observed in reality, so that CCF and IE must be related to the category of "latent failures". Rigorously speaking these are the failures which could not be detected and eliminated at the pre-operational stage of life cycle.

The problem cannot be solved directly without intervention into the operational stage. The indirect solution, in our opinion, may be as follows. First, the maximum probable number of accidents for the given plant is estimated whereupon those accidents are canceled from the "list" for which trustful measures to eliminate CCF and IE have been taken at pre-operational stages.

Given are certain magnitudes of $K$ and $Q$ of CCF number, canceled in the elements of the $U_T$ multitudes. Let us use different values to quantify CCF relating to safety functions (accident prevention area) and CCF associated with mitigation functions $-K$ and $Q$, respectively.

One can assume that with $K = 1$ the intensity of accidents is approximately equal to that of the initial even causing the accident: $\Lambda_A = \Lambda_I$. Indeed, if even single safety function is absent, the initial event safety is not fulfilled: the accident frequency may be assumed equal to that of the occurrence of the initial event. Accordingly, at $K > 1$, we have:

$$\Lambda_A = \sum_{j=1}^{K} \Lambda_{I_j}; \quad \Lambda_A = \sum_{j=1}^{\max} \Lambda_{I_j}.$$  

Similarly, at $Q > 1$, if the accident does take place, its scales or resulting loss will increase in proportion to the
number of disconnected or not envisaged safety mitigation
devices.

With this in view, the loss parameter can be represented
by two components, viz., \( A \) and \( \overline{A} \), where \( A \) accounts for the
accident mitigation due to the appropriate measures both
taken at pre- and post-accident stages, while \( \overline{A} \) disregards
these measures.

Now, the criterion for relative assessment of accidents
for different energy sources can be obtained, and in case of
an nuclear source, it is:

\[
\begin{align*}
\text{Acc}_{\text{nucl}} &= \left\{ \sum_{m=1,2,\ldots,K_m=Q_m} A_m \left( A_m + \overline{A}_m \right) \right\} + \left\{ \sum_{e=1,2,\ldots,K_e=Q_e} A_e \left( A_e + \overline{A}_e \right) \right\} + \\
&+ \left\{ \sum_{f=1,2,\ldots,K_f=Q_f} A_f \left( A_f + \overline{A}_f \right) \right\} + \left\{ \sum_{r=1,2,\ldots,K_r=Q_r} A_r \left( A_r + \overline{A}_r \right) \right\} + \\
&+ \left\{ \sum_{o=1,2,\ldots,K_o=Q_o} A_o \left( A_o + \overline{A}_o \right) \right\} + \left\{ \sum_{s=1,2,\ldots,K_s=Q_s} A_s \left( A_s + \overline{A}_s \right) \right\} + \cdots
\end{align*}
\]

Analogously, the criteria may be obtained for other
energy sources. The comparison of such criteria would allow
decision-making based on the information characterizing,
apart from other factors, technological level, social
orientation and production management not only in the given
branch of the industry but in the given country as a whole.

Thus, to conclude, a criterion is proposed to account
for the human factor, which according to the previous
experience, is responsible for the sources and sizes of most
large accidents in the power industry.
Reference

RADIOACTIVE RISK ASSOCIATED WITH MINING ACTIVITIES

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Abstract

The majority of human activities involve some degree of risk and the mining activities are no exception. Mining activities are independent of the open ends of the nuclear fuel cycle, that are by themselves a problem, can result in technologically enhanced environmental radioactivity. The high naturally radioactive areas in Brazil are usually associated with peculiar geological formations, as for example: monazite sands (Guarapari, ES), pyrochlore and apatite (Araxa, MG), uranipherous phosphate rocks (Araxa, MG and Itataia, CE) and black shales (Amazon Basin, AM). Mining and milling activities are not necessarily related to the nuclear fuel cycle industry. However, these activities can produce radioactive wastes that can enhance the naturally high radioactive background occurring in the country. Taking into account that uranium and thorium are always present in the areas of naturally occurring radioactivity, the wastes will contain significant activities of $^{226}$Ra, $^{228}$Ra and $^{222}$Rn in addition to uranium, thorium and their parents. The radioactive risk associated with mining activities in the world are not, in general, borne by the same populations that receive the benefits. As a consequence, actions should be taken to cope with this situation.

I. Introduction

The majority of activities of man involve some degree of risk and the production and use of energy are not exception. However, the term risk has different meaning for different persons. As consequence, the International Commission on Radiological Protection (ICRP) decided recently "to abandon its practice of always using risk with the specific meaning of probability and to attempt to use, where practicable, the more direct term probability" (1).

When one thinks about risk assessment related to Nuclear Energy in general, Nuclear Power Plants come to mind. Immediately after, the mushrooms resulting from the nuclear attacks to Hiroshima and Nagasaki come also into the mind. As far as Nuclear Power Plants are concerned accidents like TMI and Chernobyl are always in the public’s mind perception. It is important to observe that in normal operation conditions the open ends of the nuclear fuel cycle can bring higher risks to human health and produce more damage to the environment than a nuclear reactor.

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One item that normally is not considered, because of the low radioactivity levels involved is uranium mining, milling and tailing management.

In general the mineral ores for uranium production contain from 0.1 to 0.6% of $\text{U}_3\text{O}_8$. In most cases around 85,000 t of lower grade uranium ore need to be handled in order to feed a 1,000 MW reactor (2).

Another very important point to be mentioned is that a series of several mining activities can result in environmental radioactive contamination even though such activities are not part of the nuclear fuel cycle. High natural radioactive regions are usually associated with specific geological formations such as: monazite sands (Guarapari, ES/BRAZIL), alkaline volcanic intrusions (pyrochlore and apatite, Araxá, MG/BRAZIL), uranipherous phosphate rocks (Araxá, MG/BRAZIL and Itataia, CE/BRAZIL), black shales (Amazon basin, AM/BRAZIL). So mining and milling activities not related with the nuclear industry can produce, after concentration, radioactive wastes that can reach 2 or 3 times the highest natural radioactive background. Even though some national authorities do not consider this enhanced radioactivity as a problem, in Brazil it is considered that such activities should be under control. As a consequence the treatment and final destination of the radioactive wastes resulting from non nuclear industries are in the process of being regulated.

In the map below (Fig.1) the main orebodies bearing radioactive minerals in Brazil are shown, in order to give an overview of how spread such activities are in the country.

Figure 1: The main orebodies bearing radioactive minerals in Brazil.
It can also be seen in Fig. 2 the localization of the phosphate rocks in Brazil (3).

II. Uranium Mining Activity

The environmental resulting detriments associated with uranium exploration, mining, milling and tailing management can be summarized as follows (4).

a) Uranium Exploration

There are potential ways through which the level of natural radiation in the environment can be enhanced by uranium exploration:

- bringing radionuclide bearing material to the earth surface;
- spreading radioactive material through blowing dust;
- interconnecting previously separated aquifers via drill holes; and,
- introducing radioactive material into ground water via the loss of drill fluids during drilling.

b) Uranium Mining

The type of mining method used at one specific location is influenced by many factors; including nature and grade of ore bodies, its depth, geological state of the surrounding rock, and
the presence or absence of groundwater. The potential radiological concerns from uranium mining may include:
- discharging minewater that contains radioactive contaminants;
- releasing radon and dust in the exhausted air from underground mines; and,
- emitting radon and dust from open pit mines.

c) Uranium Milling

Mill processing typically involves grinding the ore to a very fine flour-like consistency. The ground ore is then subjected to a leaching process in either highly acidic or alkaline solutions, depending on the ore. Due to the nature of the milling operation, the majority of the potential environmental and radiological contaminants remain in the liquid phase and are sent to the tailing management area.

The amounts of radon and dust released from the milling operation are small in comparison to those associated with the tailing management area.

d) Uranium Tailings Management

Tailings are the waste materials produced during milling of ore. Consists of ground rock particles, water and various amounts of mill chemicals. Tailings management areas often include one or more dams which help to form a basin into which the material is placed. There are, in general, three basic types of tailing management areas:
- dry land sites;
- land/shallow water combination sites; and,
- underwater deposit sites.

Concern is often expressed over the possible effects of radionuclides that can be released from uranium tailings. One and probably the most important radionuclide released is radon. Radon is a gas, but its daughters are solids and have chemical and biochemical properties of such nature that they can be deposited in the lungs and bronchi, where they can induce cancer. Radon-222 comes indirectly from the decayment of thorium-230 that has a half life of 80,000 years and produces the $^{226}\text{Ra}$ with a half life of 1,620 years.

Some amount of radon will migrate to the tailings surface and then will be dispersed in the atmosphere. Radon emission rates from tailings areas have been established, both by field
measurements and theoretical calculations. It is typically found that radon concentrations is of the order of the background levels within one to two kilometers around the tailing area.

Table I shows the uranium annual dose and radon exposure for some uranium mining areas.

In addition to this, in general, uranium is in many cases associated with thorium. Thorium-232 produces the radium-228 (mesothorium), 6.7 years of half-life, that constitutes also a problem as far as wastes are concerned.

The uranium tailings are for all those reasons the main source of concern from the radiological point of view. Mining and milling wastes must be treated before returning to nature, because even though such wastes have been originated in nature, they have technologically enhanced activity concentrations.

A deposit of such a kind is located in Poços de Caldas, Brazil, where uranium mining and milling facility has been active for several years, at production rate of 420 t U₃O₈/y, since 1982. This facility is not producing at this date. Radioactive contamination of water used in uranium mining and milling may occur due to ²²⁶Ra release to spring head waters of the hydrographic basin near a uranium mine. The increase in the ²²⁶Ra concentration in the hydrographic basin of the rivers Antas and Verde that are horn in the Poços de Caldas plateau near the uranium mining and milling site has been measured.

Many of these potential hazards are of little consequence in uranium exploration, mining and milling. The uranium tailings are
particularly difficulties to restore to a good environmental condition. This difficulties has been partially due to the nature of the waste itself, in addition to the lack of preparation of the operation to deal with the magnitude and complexity of the waste problem. The major problem is the total containment of low-level hazardous radionuclides for the long term (up to 1,000 years). Adequate technology is now available to deal with uranium mining and milling, although costs may be high.

III. Monazite Sands

Monazite sands found at the sea shore of Brazilian states of Rio de Janeiro (RJ), Espírito Santo (ES) and Bahia (BA), and in the alluvial beds of rivers at the Sapucaí region in Minas Gerais, contains high concentrations of ThO₂ equivalent.

NUCLEMON Minero Química Ltda benefits heavy sand taken from the Brazilian sea-shore of the states RJ, ES and BA. Such sands contain among other constituents, ilmenite (iron titanate), zirconite (zirconium silicate), rutile (titanium oxide) and monazite (rare earth orthophosphate containing uranium and thorium oxides). Thorium and uranium are present with 6% and 0.3% respectively.

The heavy sands constituents are concentrated in the installations of Usina da Praia (UPRA) in Buena, RJ. Ilmenite is commercialized directly by UPRA, and the other mineral concentrates are sent to the Usina Santo Amaro (USAM), located in the State of São Paulo. In USAM the concentrates are further submitted to physical and chemical processing, in order to achieve the purity grade necessary for trading zirconite, rutile and rare earth chlorides.

The chemical processing of monazite is necessary to produce rare earth chlorides. This processing is responsible for the generation of radioactive wastes, where the ²²⁸Ra constitutes the most relevant problem. However, the chemical processing is also responsible for a byproduct that contains uranium and thorium concentrate, called "Torta II". The byproduct "Torta II", can be used to extract uranium and thorium, but the development of the methodology poses an additional problem, not completely solved being at the laboratory level.
IV. Pyrochlore

Brazil has the largest world reserve of niobium as pyrochlore(5). Around $5.00 \times 10^8$ t with average concentration between 1.3 to 2.5% $\text{Nb}_2\text{O}_5$, 0.13% $\text{ThO}_2$ and 0.008% $\text{U}_3\text{O}_8$. The Brazilian production of niobium comes from Araxá, Minas Gerais (MG) and Catalão/Ouvidor, Goiás (GO). The production of niobium concentrates is around 46,000 t/y. As an unwanted consequence of the niobium production 60 t of $\text{ThO}_2$ are deposited annually in wastes dam. In addition, the $^{226}\text{Ra}$ concentration in the waste dam is 20 kBq/m$^3$ (540 Ci/l) (6).

V. Phosphate Rocks

The national reserve of phosphatic rock contains around 350,000 t of $\text{U}_3\text{O}_8$ that may be partially extracted during industrialization of the phosphates. Such uranium has a concentration distributed from 30 to 200 ppm, consequently can not be characterized as an uranium orebody. The amount of $\text{P}_2\text{O}_5$ in the phosphate rocks ranges from 5 to 30%. Table II lists the average $\text{U}_3\text{O}_8$ contain of the main ores of phosphate rock in Brazil(7).

<table>
<thead>
<tr>
<th>Place *</th>
<th>ppm $\text{U}_3\text{O}_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Itataia (CE)</td>
<td>1,800</td>
</tr>
<tr>
<td>Itambé (BA)</td>
<td>50</td>
</tr>
<tr>
<td>Catalão (GO)</td>
<td>200</td>
</tr>
<tr>
<td>Turiaçu (MA)</td>
<td>80</td>
</tr>
<tr>
<td>Araxá (MG)</td>
<td>160</td>
</tr>
<tr>
<td>Patos de Minas (MG)</td>
<td>10</td>
</tr>
<tr>
<td>Tapira (MG)</td>
<td>80</td>
</tr>
<tr>
<td>João Pessoa (PB)</td>
<td>100</td>
</tr>
<tr>
<td>Iguarassu (PB)</td>
<td>200</td>
</tr>
<tr>
<td>Olinda (PE)</td>
<td>130</td>
</tr>
<tr>
<td>Paulista (PE)</td>
<td>130</td>
</tr>
<tr>
<td>Jacupiranga (SP)</td>
<td>30</td>
</tr>
</tbody>
</table>

* BA - Bahia; CE - Ceará; GO - Goiás; MA - Maranhão; MG - Minas Gerais; PB - Paraíba; PE - Pernambuco; SP - São Paulo
Considering the production of superphosphates through the sulfuric acid attack developed for the orebodies of Araxá, Tapira and Catalão one can obtain the concentrations per ton of ore presented in Table III.

<table>
<thead>
<tr>
<th></th>
<th>Araxá</th>
<th>Tapira</th>
<th>Catalão</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{P}_2\text{O}_5$ (kg)</td>
<td>300</td>
<td>350</td>
<td>300</td>
</tr>
<tr>
<td>$\text{U}_3\text{O}_8$ (g)</td>
<td>285</td>
<td>332</td>
<td>291</td>
</tr>
<tr>
<td>$^{226}\text{Ra}$ (µCi)[MBq]</td>
<td>(84)[3.1]</td>
<td>(95)[3.5]</td>
<td>(83)[3.1]</td>
</tr>
</tbody>
</table>

One can then claim that the presence MBq levels of $^{226}\text{Ra}$ per ton of superphosphate can potentially give origin to a radioecological problem. As have already been demonstrated such amounts of uranium and radium in phosphate fertilizers can contaminate the food produced in fertilized soils (8,9).

It is well known the bioavailability of $^{226}\text{Ra}$ for plant uptake. Figure 3 shows schematically the critical pathway of $^{226}\text{Ra}$ from fertilizers to human beings.

![Figure 3: Cycle of Fertilizers](image)

On the other hand, during the phosphoric acid production, even without the $\text{U}_3\text{O}_8$ recovering, high levels of $^{226}\text{Ra}$ are usually not present because this radionuclide is incorporated into the gypsum resulting from the treatment. In some cases, gypsum concentrates such a high amount of $^{226}\text{Ra}$ that becomes necessary to keep it in a waste basin, to avoid polluting the environment so easily.
VI. Coal

The Brazilian coal presents natural uranium concentrations ranging from 30 to 2,000 ppm. The highest concentrations being that of coal from Paraná state. The uranium present in the Brazilian coal is mostly concentrated in the ashes with values that range from 8 to 65 % (10).

The amount of equivalent tons of uranium produced per year in coal is around 1,000 ton and the annual burning of $5.5 \times 10^6$ t of coal will generate $2.2 \times 10^6$ t of ashes, giving rise to 270 ton of $U_3O_8$ equivalent spread in the environment. The Brazilian reserves of mineral coal are shown in Table IV.

<table>
<thead>
<tr>
<th>State</th>
<th>Ton ($x 10^6$)</th>
<th>Ashes (%)</th>
<th>$U_3O_8$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>São Paulo</td>
<td>10</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Paraná</td>
<td>128</td>
<td>25</td>
<td>300</td>
</tr>
<tr>
<td>Santa Catarina</td>
<td>1,916</td>
<td>32</td>
<td>30</td>
</tr>
<tr>
<td>Rio G.do Sul</td>
<td>20,916</td>
<td>40</td>
<td>80</td>
</tr>
</tbody>
</table>

VII. Tin

The cassiterite ($SnO_2$) is not radioactive per se, however, it is almost always associated with zirconite ($ZrO_2$), columbite/tantalite ($Nb/Ta$) and xenotime ($YPO_4$). Each of these minerals contain uranium and thorium in different amounts (11).

The most significant tin ores in Brazil occur in Rondônia, Amazon and Pará.

As an example, one can describe the current situation of the Pitinga mine. The ore contains cassiterite, zirconite, tantalite/columbite and xenotime, but is not characterized as an uranium mine. The average amounts of $U_3O_8$ and $ThO_2$ are around 200 ppm and 1,700 ppm respectively. Thus, in the overall one can infer amounts around 57,000 ton $U_3O_8$ and 133,000 ton of $ThO_2$ present in the mine. Uranium and thorium are preferentially associated with niobium and tantalum, and secondarily with zirconite. Table V shows the annual production expected in Pitinga.
### Table V

**Annual Production Expected from Pitinga Mine**

<table>
<thead>
<tr>
<th></th>
<th>ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore</td>
<td>6,144,000</td>
</tr>
<tr>
<td>Tin concentrate</td>
<td>12,667</td>
</tr>
<tr>
<td>Ta / Nb</td>
<td>17,420</td>
</tr>
<tr>
<td>Zirconite</td>
<td>67,800</td>
</tr>
<tr>
<td>U$_3$O$_8$</td>
<td>500</td>
</tr>
<tr>
<td>ThO$_2$</td>
<td>1,500</td>
</tr>
<tr>
<td>Waste</td>
<td>(700 \text{ ton } U_3O_8)</td>
</tr>
<tr>
<td></td>
<td>(8.9 \times 10^3 \text{ ton } ThO_2)</td>
</tr>
</tbody>
</table>

The values presented in Table V reflects the fact that during the physical processing 30 to 40 % of uranium are thrown in the waste basin. After ending the orebody exploration, about 17,000 ton U$_3$O$_8$ and 40,000 ton ThO$_2$ will be found in the waste basin. These amounts will constitute a future environmental problem.

### VIII. Other Minerals

- **Copper** - The uranium concentrations in rocks of Carajás mine (PA) lie between 50 and 500 ppm U$_3$O$_8$, presenting as a consequence abnormal radon concentrations in the Salobo area.

- **Lead** - The concentration of uranium and thorium in the lead orebody of Boquira (BA) is around 1,000 ppm of U$_3$O$_8$, resulting also in abnormal radon concentrations in the underground galleries.

- **Gold** - Uranium concentration associated with the auriferous conglomerate that occurs in the Quadrilátero Ferrifero (MG) and Jacobina (BA) reach values between 50 and 250 ppm of U$_3$O$_8$.

- **Barium** - Abnormal concentration of radionuclides from the $^{226}$Ra family is associated to niobium and barium mining in Araxá (MG).

### IX. Conclusion

Mining and mineral processing are often associated with radioactive waste materials, in addition to the overall environmental impact of such operations. The value and
significance of environmental impact assessment throughout the world have been interpreted by Coppin (12) as providing a:
- growing emphasis on anticipating environmental planning requirements as means of reducing environmental problems;
- closer integration of environmental planning with other forms of economic and social planning;
- more systematic and comprehensive interdisciplinary environmental study which incorporates economic, technological and environmental considerations.

Peter Wood (13) in his article "Meeting on the Environmental Challenge", about the future trends in regulation for the mining and mineral processing, indicates:
- an increased community pressure for reduced environmental impact,
- more stringent standards for pollutants or potential pollutants in waste streams,
- greater enforcement of standards with decreased community tolerance of levels in excess of them.

It is of paramount importance inviting efforts to develop experimental technics and theoretical models in order to evaluate the risk assessment inherent to mining activities. This will allow the society to have a better understanding of the real impact of mining activities in the environment.

Another important point to be mentioned is that the risk from mining activities are, in general, in a different place from those where the benefits can be found as it has already been discussed by Paschoa (14,15). Some actions should be taken in order to cope with this fact. The authors suggest that in the same way it has been presented elsewhere by Goldemberg (16), for fossil fuel, a preventive strategy has to be adopted in order to try to minimize the global consequences of mining activities. It should be added to these mining activities the costs the country will pay in dealing with the wastes left in order minimize the risks for the population and the environment. This might not be a solution to eliminate these tailings management effects but at least will reduce the local risks resulting from mining activities.

Environmental protection is no longer an option for certain areas. It is today part of all human activities.
References


ASSESSMENT OF RISKS FROM HAZARDS ASSOCIATED WITH INDUSTRIES AND ENERGY SYSTEMS

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Abstract

Probabilistic risk assessment (PRA) is used in the present study to analyse and assess the safety of complex industrial plants as well as energy systems. The work is conducted within the framework of the International Atomic Energy Agency (IAEA) Inter-agency project on health and environmental risks in heavily industrialized areas. El-Amryia industrial area (west of Alexandria,) was chosen as a case study for this project in Egypt. The major industries in the area comprise petrochemical and oil refinery plants, chlorine production plant, cement production plant, and iron and steel production and forging plants. It is projected to construct a coal fired electric power plant in the area by the year 2000. The analytical approach adopted in the present study is the failure mode and effect analysis (FMEA). In this approach, the critical components to plant safety are identified and an engineering judgement is employed to assess plant safety. A first phase of the study was conducted to assess the accidental releases from the chlorine plant. The most severe accidents with potential off-site consequences are identified as rupture or break in liquid chlorine storage tanks. Five break sizes are postulated which simulate possible break size ranging from 2 inches to 0.1 inch. A relevant software package obtained from the IAEA Safety Assessment Section is used to account for the duration and rate of discharge of liquid chlorine. Plume width and concentration of chlorine gas in the downwind direction are calculated. Results are given and relevant conclusions are drawn.

1. INTRODUCTION

The rapid development in early sixties in Egypt led to the creation of unplanned new urban areas around the big cities of the country: Cairo and Alexandria. More than 70% of the total industrial activities of the country are invested near and around these two cities. The major industrial area were grouped into four areas namely; Helwan and Shubra El-Kheima in Cairo and El-Amryia and Abu-Kir in Alexandria. These four areas have been subjected to preliminary analysis to chose one candidate area as a case study for the current project [1].
The study is conducted within the framework of the International Atomic Energy Agency (IAEA) Inter-Agency project on health and environmental risks in heavily industrialized areas.

El-Amryia industrial area (west of Alexandria-Egypt) was chosen as a case study for this project in Egypt. The major industries in the area comprises chlorine production plant, petrochemical plant, cement production plant, oil refinery plant and iron and steel production and forging plant. It is projected that a coal fired electric power plant shall be constructed in the area by the year 2000. The probabilistic risk assessment (PRA) technique was largely developed to analyze the safety of nuclear power plant. It is successfully used to analyze the safety of complex industrial and energy systems. Hazard identification as well as qualitative and quantitative analysis are emphasized. The analytical approach adopted in the present study is the Failure Mode and Effect Analysis (FMEA). In this approach, the critical component to plant safety are identified and an engineering judgement is employed to assess plant safety [2],[3].

The first phase of the study was conducted for accidental releases of chlorine gases in Misr Chemical Industries company (MCI). The most severe accidents in the chlorine plant of MCI with potential offsite consequences are identified as rupture or break in liquid chlorine storage tanks. Five break sizes are postulated which simulate possible break size ranging from 2 inches to 0.1 inch. A relevant software package obtained from IAEA - safety assessment section is used to account for the
duration and rate of discharge of liquid chlorine. Plum width and concentration of chlorine gas in the downwind direction are calculated.

2. CHLORINE PLANT SAFETY ANALYSIS

Information about MCI plat location and site characteristics are given in reference [4]. The plant produces more than 40 tons of liquid chlorine per day and many other chemical products such as caustic soda, hydrochloric acid, sodium and calcium hypochlorites. The production process is based on multiple mercury electrolysis cells. Description of process systems, instrumentation and piping (I & P) line diagrams and other plant systems are given in reference [5]. An evaluation of pollution abatement plan was conducted through the Government of USA aid programme [6]. Plant safety systems were consequently subjected to necessary modifications and upgrading. The chlorine plant instrumentation and piping line diagram is subdivided into 12 main components or items. Each component is checked against its failure modes, their causes, detection method and effects on plant safety. Then a risk assessment map proposed by Raafat [7] was adopted, which provides proper ranking of the individual failure modes of components and subcomponents. The results of analysis are given in table 1. The last three columns in this table entails definition of severity, probability level and risk probability code "RPC" for each component failure mode. Using standard tables and graphs [7] and engineering judgement, one can determine RPC which appear in the last column. This RPC is assigned three values only; RPC = 1 for
<table>
<thead>
<tr>
<th>ITEM</th>
<th>Component function</th>
<th>Failure mode</th>
<th>Failure effect</th>
<th>Failure detection method</th>
<th>Risk Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Storage tank of pure brine</td>
<td>Rupture in tank 1.1</td>
<td>Release of brine solution</td>
<td>Observation</td>
<td>I  D  3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture in Pipe 1.2</td>
<td>Release of brine solution</td>
<td>Observation</td>
<td>I  D  3</td>
</tr>
<tr>
<td>2</td>
<td>Head tank</td>
<td>Malfunction Pump 2.1</td>
<td>No feed of brine</td>
<td>Monitoring</td>
<td>I  C  3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture in Pipe 2.2</td>
<td>No feed of brine</td>
<td>Observation</td>
<td>I  D  3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malfunction of valve 2.3</td>
<td>Break down of production</td>
<td>Observation</td>
<td>I  D  3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture in tank 2.4</td>
<td>Brine leakage</td>
<td>Observation</td>
<td>I  D  3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malfunction of valve 2.5</td>
<td>No brine feed to cell</td>
<td>Observation</td>
<td>I  D  3</td>
</tr>
<tr>
<td>3</td>
<td>Electrolysis cell</td>
<td>Blocking of valve 3.1</td>
<td>Explosion in cell</td>
<td>Automatic stop</td>
<td>I  D  3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contact of cell poles 3.2</td>
<td>Explosion</td>
<td>Observation</td>
<td>II  E  3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wear in the wall of the cell 3.3</td>
<td>Break down of production</td>
<td>Observation</td>
<td>II  E  3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impurities in brine solution</td>
<td>Hydrogen explosion</td>
<td>Observation</td>
<td>II  D  3</td>
</tr>
<tr>
<td>4</td>
<td>Receiving tank of depleted brine</td>
<td>Blocking in valve 4.1</td>
<td>Explosion in cell</td>
<td>Observation</td>
<td>II  D  3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture in pipe 4.2</td>
<td>Leakage</td>
<td>Observation</td>
<td>I  E  3</td>
</tr>
<tr>
<td>ITEM</td>
<td>Component function</td>
<td>Failure mode</td>
<td>Failure effect</td>
<td>Failure detection method</td>
<td>Risk Assessment</td>
</tr>
<tr>
<td>------</td>
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<td>--------------</td>
<td>---------------</td>
<td>-------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>4</td>
<td>Continued</td>
<td>Rupture in tank 4.3</td>
<td>Explosion in cell</td>
<td>Observation</td>
<td>I E 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malfunction in pump 4.4</td>
<td>Explosion in cell</td>
<td>Observation</td>
<td>I D 3</td>
</tr>
<tr>
<td>5</td>
<td>Dilute chlorine line</td>
<td>Blocking of valve 5.1</td>
<td>Explosion in cell</td>
<td>Monitoring</td>
<td>II D 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malfunction of pump 5.2</td>
<td>Explosion in cell</td>
<td>Monitoring</td>
<td>II C 2</td>
</tr>
<tr>
<td>6</td>
<td>Concentrate chlorine line</td>
<td>Blocking of valve 6.1</td>
<td>Explosion in cell</td>
<td>Monitoring</td>
<td>II D 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture in Header pipe 6.2</td>
<td>Leakage of chlorine</td>
<td>Monitoring</td>
<td>II D 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malfunction of automatic valve 6.3</td>
<td>Break down of production</td>
<td>Monitoring</td>
<td>III D 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malfunction cooler/separator 6.4</td>
<td>Impurities in chlorine</td>
<td>Analysis</td>
<td>II D 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malfunction of compressor pump 6.5</td>
<td>Break down of production</td>
<td>Observation</td>
<td>II C 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture of Liquid chlor. pipe/tank 6.6</td>
<td>Release of chlor. gas</td>
<td>Observation</td>
<td>IV D 1</td>
</tr>
<tr>
<td>ITEM</td>
<td>Component function</td>
<td>Failure mode</td>
<td>Failure effect</td>
<td>Failure detection</td>
<td>Risk Assessment</td>
</tr>
<tr>
<td>------</td>
<td>-------------------</td>
<td>--------------</td>
<td>----------------</td>
<td>------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>7</td>
<td>Decomposer</td>
<td>Rupture in Decomposer 7.1</td>
<td>Explosion and fire</td>
<td>Observation</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blocking of outlet valve 7.2</td>
<td>Explosion</td>
<td>Observation</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture in pipes 7.3</td>
<td>Release of mercury</td>
<td>Observation</td>
<td>II</td>
</tr>
<tr>
<td>8</td>
<td>Receiving tank of Na OH</td>
<td>Rupture in tank 8.1</td>
<td>Release of Na OH</td>
<td>Observation</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malfunction of valve 8.2</td>
<td>Break down of production</td>
<td>Monitoring</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malfunction of pump 8.3</td>
<td>Break down of production</td>
<td>Observation</td>
<td>I</td>
</tr>
<tr>
<td>9</td>
<td>Mercury</td>
<td>Malfunction of pump 9.1</td>
<td>Explosion in cell</td>
<td>Automatic stop</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blocking of valve 9.2</td>
<td>Explosion in cell</td>
<td>Automatic stop</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture in pipe 9.3</td>
<td>Release of mercury</td>
<td>Observation</td>
<td>II</td>
</tr>
<tr>
<td>10</td>
<td>Hydrogen gas</td>
<td>Rupture in cooler 10.1</td>
<td>Leakage of cooling water</td>
<td>Observation</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malfunction of pump 10.2</td>
<td>Pressure increase</td>
<td>Monitoring</td>
<td>II</td>
</tr>
</tbody>
</table>
Table 1: Continued

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Component function</th>
<th>Failure mode</th>
<th>Failure effect</th>
<th>Failure detection method</th>
<th>Risk Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sever.</td>
</tr>
<tr>
<td>10</td>
<td>Hydrogen gas</td>
<td>Rupture in pipe 10.3</td>
<td>Release of hydrogen</td>
<td>Monitoring</td>
<td>I</td>
</tr>
<tr>
<td>11</td>
<td>Demineralizer</td>
<td>Rupture in tank 11.1</td>
<td>Leakage of water</td>
<td>Observation</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malfunction of valve 11.2</td>
<td>Explosion</td>
<td>Observation</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture in pipe 11.3</td>
<td>Leakage</td>
<td>Observation</td>
<td>II</td>
</tr>
<tr>
<td>12</td>
<td>Cooling water</td>
<td>Rupture in tank 12.1</td>
<td>Temperature increase in decomposer</td>
<td>Monitoring</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture in pipe 12.2</td>
<td>Leakage of hydrogen</td>
<td>Monitoring</td>
<td>I</td>
</tr>
</tbody>
</table>

high risk, RPC = 2 for medium risk, and RPC = 3 for low risk.

A summary sheet of FMEA results are given in Table 2 which indicate the critical components to system safety. The most severe accident with potential off-site consequences is recognized to be the rupture or break in a liquid chlorine storage tanks. There are 6 tanks (each has 60 tons capacity) 4 tanks are usually in operation and the remaining are standby or at maintenance. The liquid chlorine coming from the electrolysis plant after liquidation is temporarily

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Table 2: FMEA SUMMARY SHEET (Potential Accidents)

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Component</th>
<th>RPC</th>
<th>Action Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3</td>
<td>Automatic valve</td>
<td>1</td>
<td>Adding pressure monitor, periodic test and inspection.</td>
</tr>
<tr>
<td>6.5</td>
<td>Compressor pump</td>
<td>1</td>
<td>Periodic inspection and leak tightness test.</td>
</tr>
<tr>
<td>6.6</td>
<td>Liquid Chlorine tank</td>
<td>1</td>
<td>Regular inspection and monitoring of leakages and releases from the tank.</td>
</tr>
<tr>
<td>5.2</td>
<td>Dilute chlorine pump</td>
<td>2</td>
<td>Redundant Pump and insuring reliable power supply.</td>
</tr>
<tr>
<td>6.2</td>
<td>Concentrate chlorine pipe line</td>
<td>2</td>
<td>Monitoring and preventive maintenance.</td>
</tr>
<tr>
<td>9.1</td>
<td>Mercury pump</td>
<td>2</td>
<td>Redundant pump and insuring reliable power supply.</td>
</tr>
<tr>
<td>10.2</td>
<td>Hydrogen gas pump</td>
<td>2</td>
<td>Redundant pump and insuring reliable power supply.</td>
</tr>
</tbody>
</table>

stored in these tanks until it goes to the unit of filling in cylinders of appropriate sizes.

3. ACCIDENT SIMULATION

Large release of chlorine gas could be accidentally possible due to rupture or break in the body of liquid chlorine storage tanks or connected pipings. However, rupture or break in the pipings might be less dangerous unless the closure of safety values is not successful. This accident may be initiated due to propagation of small cracks
Table 3: Results of chlorine gas accidental release [Weather conditions: Wind speed = 3 MPH $\approx 1.4 \text{ m/s}$]

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Accident Description</th>
<th>Hole Diameter (Break Size) (Inches)</th>
<th>Discharge rate (LBS/Min)</th>
<th>Duration of Discharge (Min)</th>
<th>Down-Wind Plume Width (Feet)</th>
<th>Plume distance For Chlorine Concentration (200 PPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Storage tank/Pipe Break at elevation 10 meters from ground level</td>
<td>2</td>
<td>9661</td>
<td>13.9</td>
<td>9113</td>
<td>18230</td>
</tr>
<tr>
<td>2</td>
<td>Storage tank rupture or pipe break</td>
<td>1</td>
<td>2415</td>
<td>55.6</td>
<td>9113</td>
<td>18230</td>
</tr>
<tr>
<td>3</td>
<td>Storage tank rupture</td>
<td>0.5</td>
<td>603.8</td>
<td>222.6</td>
<td>3816</td>
<td>7633</td>
</tr>
<tr>
<td>4</td>
<td>Storage tank rupture</td>
<td>0.25</td>
<td>151.0</td>
<td>890</td>
<td>1518</td>
<td>3037</td>
</tr>
<tr>
<td>5</td>
<td>Storage tank Small crack</td>
<td>0.1</td>
<td>24.15</td>
<td>5564</td>
<td>462</td>
<td>925</td>
</tr>
</tbody>
</table>
in the body of the tank or falling objects or missiles. Also it might be initiated due to higher seismic activities or explosions near the area or violations or terroristic actions near the area. The software package (CHEMS-code) [8] is used to account for the duration and rate of discharge of liquid chlorine from the failed tank. Chlorine vapour evolution duration, plume width, and distribution of chlorine gas concentration in the downwind direction are determined.

Five possible break or rupture sizes (hole diameter) simulating possible accidents ranging from 2 inches to 0.1 inch are postulated. The results are summarized in table 3. The downwind chlorine gas concentration for the postulated accidents are shown in Fig. 1.
4. DISCUSSIONS AND CONCLUSIONS

4.1 For all sizes of break or rupture, the spill of liquid chlorine is more than 90% of the total mass of liquid chlorine. Less than 10% of liquid chlorine evaporate during the release assuming that the compressed air pressure is 12 atmosphere (nominal working pressure in the tank).

4.2 The liquid chlorine spilled from the tank will form a pool beneath the tank, the area of such pool reached about 10000 feet square and with depth of 1.6 inch for the concrete floor considered. The evaporation evolution duration is 63 minutes or more depending on the hole diameter. In fact for smaller hole diameter (< 1 inch) the discharge duration is equal to vapour evolution duration.

4.3 The length and width of chlorine gas plume depends on the weather conditions. The results are summarized in Table 3. The worst conditions with respect to nearby populated areas might be in the winter season when the prevailing wind directions are west and southwesterly.

4.4 In order to reduce or mitigate the accident consequences; the following recommendations may be considered:

- To carry out regular inspection and surveillance for the tanks and their joints to avoid the propagation of small cracks.
- To construct a concrete walls and ceiling with sufficient thickness for housing the storage tanks.
- To install reliable safety valves and establish the capabilities for quick discharge of liquid chlorine from a damaged tank to another standby one.
ACKNOWLEDGEMENT

The Authors wish to express their thanks and appreciation to the working team of the project for their sincere co-operation and devotion. Special regards are due to Zeid A. and Walliam M. from Misr Chem. Industry, and to Hebba A. and Seliem S. from Occupational Safety and Health administration. They are also indebted to Dr. Haddad S. and Dr. Donne R. from the Nuclear Safety Division of the IAEA for providing the computer codes and their fruitful and valuable discussion during the initial phase of the project.

REFERENCES


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HEALTH RISKS OF ELECTRICITY GENERATION:  
A VIEW OF THE SITUATION IN THE UNITED KINGDOM

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Abstract

The traditional reliance upon indigenous coal reserves for electricity generation in the United Kingdom has been partially supplanted by a significant nuclear, capacity and, for a period, oil fired capacity. The future may see the introduction of gas fired plants and additional nuclear capacity. A number of renewables could also contribute. In this respect the main options for the United Kingdom are on-shore wind, tidal power and off-shore wind. The paper summarizes progress on the evaluation of the health risks associated with each of these options. Risk estimations relate to circumstances as envisaged for large, new generating facilities.

1. Introduction

In the early 1980s two reports were prepared on the comparative risks of electricity generation as it applied to the United Kingdom (Cohen and Pritchard, 1980; Ferguson, 1981). Since then there have been many significant changes including the sources and types of fuels available, the status of renewables, advances in conventional technology, and new legislation and changing approaches on environmental protection and health and safety at work.

This paper describes preliminary stages of a new study of the comparative health risks of electricity generation as would apply to large, central generating systems within the UK context, which takes account of these changes. Ultimately, a full systems approach will be adopted covering the relevant stages of each fuel or generating cycle. This should not disguise certain practicalities associated with the analyses, some of which will be pointed out in this contribution.

2. UK Electricity Options

The UK is rich in electricity generating options. The present situation is illustrated by the following: of the 253 TWh supplied in Great Britain in 1987/88 by steam plant, 43 TWh originated from nuclear plant, 10 TWh from oil-fired plant, and 200 TWh from coal-fired plant. Natural flow hydro contributed an additional 4 TWh (D.En., 1989; CEGB, 1987/88), with other renewables and natural gas figuring only to a very limited extent.

There are, however, pressures at work which will lead to gradual change. For example, National Power (1990) has recently announced that investigations into the suitability of sites for combined cycle gas turbine (CCGT) stations will be expanded. One motivation for this is to contribute to the achievement of atmospheric emission
reduction targets set by the European Community. Thus it is likely that coal will, to some extent, be replaced by natural gas as a fuel for use in power stations. This may influence the extent to which FGD plant, with its associated risks, is introduced.

Secondly, it is now believed that renewables could contribute as much as 18% of the nation's electricity supply by the middle of the next century (Chester, 1989). So far as Britain is concerned, prime candidates are tidal and wind power. There are now 22 estuaries around Britain which are the subject of barrage proposals. The largest of these is undoubtedly the Severn Estuary which is one of the best sites in the world for this purpose. Peak installed capacity is projected to be 8640 MW with an annual output of 17 TWh, equivalent to about 7% of UK demand. The associated electricity price, however, is closely linked to the discount rate applied (3 p/kWh at 5%, 6 p/kWh at 8%), and the go-ahead is said to be dependent upon at least partial government support (R. Clare, 1990).

It has been estimated that onshore wind power in Britain has a technical potential of 45 TWh/y and that the contribution realised by 2025 would be in the range up to 30 TWh/y (D.En., 1988). The offshore potential is estimated to be much greater, 140 TWh/y, but its development in the near future is considered unlikely unless there are 'dramatic improvements in costs, performance, or if fuel prices increase sharply' (D.En., 1988). So far as land-based wind generators are concerned, it is estimated that 2000 MW equivalent plant capacity could be supported in Britain, most of which would compete economically with coal-fired power stations. Plans are underway to establish demonstration wind parks at Langdon Common (Durham), Cold Northcott (Cornwall) and Capel Cynon (Carmarthen), which could offer the opportunity for commercial extension even by 1995.

3. Scope of Project

The primary aim of the project is to assess, using current information, the comparative health risks of new electricity generating options which are practicable within the UK during the next 30 years. Environmental impacts, and secondary health impact mechanisms via e.g. 'acid rain' and global greenhouse gas accumulation, do not form part of this study. The main cycles to be considered are coal, oil, gas, nuclear, hydro, on-shore and off-shore wind, and tidal. As far as possible, the marginal risks of new facilities adding on to the UK national grid will be sought, up to the point at which the electricity enters the national grid. Thus, risks of transmission and risks further downstream are excluded from the analysis.

4. Preliminary Comments on Cycles Examines

4.1 The Coal Cycle

The main risks associated with the coal cycle, or which figure most highly in the public perception, are:

- occupational accidents of mining
- lung diseases of mining
- transport-related risks
- power plant construction and operation risks
- public exposure to combustion-derived air pollution
- radiological impacts on the public

The first two of these will be discussed here.
Coal mining has traditionally been regarded as one of the most dangerous occupations. Fifty years ago some 800 to 900 persons were killed each year in British mines, equivalent to an accident rate of some 14 fatalities per GW(e)-a. There has, however, been a continual improvement in the safety record of British Coal (Figure 1), and the number of fatal accidents is now at a level where it can be influenced by incidents far removed from the coal face, for example, surface incidents involving contractors. Likewise, though less easy to discern, there have been improvements in the rates of non-fatal accidents which result in serious injuries.

Lung disease in miners typically relates to exposure to dusts and/or exposure to radon and thoron. Both the British Coal Corporation and its predecessor, the National Coal Board, have been active in seeking to reduce the incidence of simple pneumoconiosis in miners, primarily as a means of reducing the risk of complex pneumoconiosis, or progressive massive fibrosis (PMF) as it is also known. The reason for this is that while simple pneumoconiosis may be associated with some impairment of pulmonary function, in general it causes only minimal clinical disease, whereas PMF commonly causes serious disease and reduces life expectancy. To achieve this goal various measures
have been introduced including statutory limits for airborne dust levels based on dose-response relationships between dust exposure and pneumoconiosis risk, together with dust control measures, and periodic medical surveillance. While some caution in interpretation is warranted, there is good evidence that these measures have been effective. Figure 2, for example, shows how the prevalence of pneumoconiosis has varied at 16 British collieries since 1962 (BCMS, 1990). These results clearly demonstrate the decline of simple pneumoconiosis and PMF from one survey round to the next. In absolute terms in 1959-63, 56,009 working men were identified with either simple pneumoconiosis or PMF in the industry. In contrast, by March 1990 only 31 certified pneumoconiotics were to be found in the industry.

Although there have been major advances in understanding the factors influencing the occurrence of PMF, calculation of the level of risk under modern mining conditions remains difficult. Studies of miners in Britain have shown that incidence is related to age, cumulative dust exposure, simple pneumoconiosis category, the carbon content of the coal being mined, and physique. In addition, pneumoconiosis takes many years to develop and the present incidence of the disease is an indicator of dust exposure in mines 30 or more year earlier, long before modern dust suppression and health management methods were introduced.

Ferguson (1981) estimated the future incidence of pneumoconiosis which might be attributable to present mine conditions by logarithmic extrapolation of the historical record. This clearly is not an ideal technique. It would be far preferable were it possible to predict on the basis of present dust exposures and established dose-response relationships. This now seems feasible, although uncertainties still remain. Hurley and Maclaren (1987) have, for example, published risk factors for pneumoconiosis and PMF as a function of mean working lifetime dust exposure. At dust levels of 3 mg/m$^3$ these suggest a risk factor for PMF of about 1%.

Radiation exposure arising from radon and thoron concentrations in British mines have been the subject of a recent study by Dixon et al (private communication) using passive radiation monitors. For British Coal Corporation mines the average individual dose was found to be about 1 mSv/a. It is relatively straightforward to convert this to a risk based on ICRP factors. However, such results need to be interpreted with caution since they presume a linear, no threshold, relationship at low doses which, while it may be appropriate for radiological protection purposes, introduces an undefined level of conservatism into the calculation.

4.2 The Nuclear Cycle

Although some uranium has been mined in Britain, the present requirement of some 850 tonnes per year is imported from Canada, Australia and the USA. Imports are likely to continue to be the main source of the UK's uranium requirement. It is therefore necessary to examine data bases on health and safety from a variety of nations in order to assess the risks. It should be noted that this will immediately introduce uncertainties since even quite subtle variations in definitions will affect the figures, and these variations are almost inevitable wherever transnational data bases are compared.

At the beginning of the uranium fuel cycle the main risks, as with the coal cycle, are associated with mining. While most of the early uranium was mined by open-cast techniques, conventional underground mining is now employed at depths between 300 and 3000 m. The uranium is recovered from the ore by crushing and grinding followed by dissolution, which leaves behind all unwanted constituents in the milling tailings.
The predominant occupational risks at this stage of the fuel cycle arise from conventional mining accidents and disease, and an increased risk of lung cancer attributed to exposure to gamma radiation and inhalation of radon, radon daughters and radioactive dusts. In comparing the risks of alternative fuel cycles it is common practice to scale the risks to an electricity production of 1 GW(e)-a, or similar. While this is straightforward with the coal cycle, it is less so for the nuclear cycle because uranium ore grades vary widely and the level of international demand will be a key factor in determining which grades and hence which ore bodies are exploited. Currently, for example, the uranium demand is depressed and only the richer ore bodies are being worked (Bromley, 1988). This means that smaller tonnages of ore are required per GW(e)-a and this in turn has the effect of reducing the effective risk per GW(e)-a. This situation may change, however, if demand increases. Nonetheless, the quantities of uranium ore required per GW(e)-a are substantially below those of coal. For ores containing 0.05 or 1% uranium oxide, the quantities involved are 400,000 tonnes and 20,000 tonnes respectively, both well below the 3 million tonnes or more equivalent coal requirement.

A further difficulty is that uranium mine accident statistics are less well documented than for coal and other minerals. This is not surprising given the short history of the industry. There is some evidence, however, that acute mortality rates in the uranium industry are similar to those in other mining industries and in some circumstances it may be possible to transfer risk factors.

So far as radiation exposure in uranium mines is concerned, UNSCEAR report that the average annual effective dose equivalent for uranium miners is 10 to 12 mSv for underground ore bodies and 5 mSv for opencast. However, to convert this to a risk per GW(e)-a requires a knowledge of, amongst other things, worker productivity rates. These are clearly a function of the geology of the ore body being worked, the ore grade, degree of mechanisation which in turn will be affected by the level of world demand for this fuel.

When it comes to assessing public risks associated with the nuclear cycle, assumptions are required on the particular type of reactor. So far as the UK is concerned, it is unlikely that anything other than PWRs will be contemplated in the near future. The risks of normal operation of projected PWRs in the UK environment have been studied in some depth at the Hinkley Point 'C' and Sizewell 'B' public inquiries and provide valuable sources of information. Various agencies were involved in calculating collective effective dose equivalent commitments as a result of atmospheric and liquid discharges during routine operation and these can, of course, be converted to health risks using the ICRP risk factors. However, one is faced with the philosophical questions of whether the dose commitment should be based on integration for the entire globe to infinite time, or whether some form of truncation should be applied. The validity of the former would rest in part upon the legitimacy of the extrapolation of the linear no-threshold relationship for radiation exposure to very low doses indeed. Were it decided, nonetheless, to follow this route, then it could clearly be argued that a similar, conservative approach should be applied in the case of public exposure to air pollutants from fossil fuel fired plant. In this arena, however, it has been standard though not universal practice to presume a no-effects threshold. Clearly, these approaches are not consistent. In the cases of gaseous, non-carcinogenic emissions, it may be appropriate to assume a threshold if there are sound scientific reasons for this, but it should not be presumed that this is necessarily the case. Certainly, attitudes to air pollution in Britain have been much shaped by historical experiences such as the long history of smogs which persisted up until the 1960s (Schwar and Ball, 1983). Exposure to gross pollution of this kind has a tendency to influence attitudes to the much more modest exposures resulting from modern power plant emissions, even amongst the scientific community. It is suggested that serious consideration needs to be given to the nature of the relationships.
used to estimate the risks of public exposure to the radiological and non-radiological impacts of power plant emissions to ensure, so far as possible, that these are placed upon an equitable footing.

4.3 Renewable

As noted, the main renewables to be considered in this project will be on-shore and off-shore wind and tidal (or lunar!) power. The main risks associated with these cycles arise at the materials provision, fabrication and construction stages. The Severn tidal barrage, for example, would require 1 M tonnes of steel reinforcement and 16 M tonnes of concrete alone. The risk to the work force engaged upon the project, estimated as 200,000 man-years, will depend upon the sources of materials, types of quarries, transportation modes, site conditions and the type of management. The construction industry generally exhibits comparatively high risks, but this may be tempered in the case of major projects such as the Severn barrage where the management structure and experience can be expected to differ substantially from that of the more conventional building site. Countering this, however, will be the more difficult working environment in the case of off-shore installations, as well as the growing tendency to use subcontractors.

5. Concluding Remarks

There is clearly a need to review the risks of electricity generating options as one aid in future planning and decision making, and this should be conducted on a full cycle basis if useful comparisons are to be made. In this respect, a systems approach is a useful one. However, it should not be overlooked that there are 'systems within systems' and that inconsistencies and disparities in methodologies, which exist at a more fundamental level and which may have a profound influence upon the results, should be fully addressed. This applies both in the comparison of routine operational risks, but especially in relation to high consequence risks where construction of a systems approach requires additional care.

Acknowledgements

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RISK COMPARISON OF SOME ENERGY SOURCES

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Abstract

The paper focuses on energy sources of significance to the Swedish energy supply: hydro, nuclear, coal, natural gas, and oil. It describes severe multiple fatalities having occurred throughout the world during the last decades. The different phases of the whole energy cycle are covered. As exemplified in the paper, the "pure" society with total protection and no risk is unfortunately an utopian ideal. This is especially true for the different energy sources available and required for the development of any healthy society. Illustrated by the jogger's dilemma, society must develop an integrated and comparative view on health and environmental risks associated to its main activities, one of the most important being energy supply.

1 Introduction

It is a common view that the modern society is more riskful than for some decades ago. This judgement is probably reinforced through the alarming articles published recurrently in the media concerning new dangers and risks. At the same time, statistics on demographic data shows that the mean life expectancy in the western countries has increased with 30 years since the beginning of the industrialization era, for about 100 years ago. The three factors responsible for this unprecedented result are:

- energy consumption (a necessary condition for economical growth)
- education (primarily reading and writing capability)
- medical development (the contribution of which is judged less than the one from energy consumption and education respectively).

"Risk" is often treated as something exclusively negative which should be avoided. Reality is more complicated as exemplified by the high safety level obtained in the modern society, in spite of all new risks emerging in the wake of the socio-technical development.

The jogger's dilemma illustrates the relation between risk and safety, actually the two sides of the same coin. Too much or too strenuous exercise is unhealthy. Too infrequently, too little exercise is also bad. The relationship seems easy so far. The complication is that the risk for heart attack increases during the limited time of strenuous exercise, meanwhile regularly vigorous exercise results in an overall decreased risk of primary cardiac arrest. The jogger's dilemma is to conscientiously expose himself or herself to calculated health risks in order to develop a safer organism. To stay in bed is not the solution to the jogger's dilemma.

The jogger's dilemma can be transposed to the society. With knowledge that risks can not be eliminated in practice - the absolute safety is an utopia - each society should continuously assess relative risks, and risk related to benefit for the activities vital for the society, i.e. energy supply, transportation, food production etc. This can be formulated as a society should not disregard significant real benefits and at the same time be led by insignificant or even hypothetical risks.

2 Definition of risk

Risk is defined, in the context of this paper, as the product of two factors. The first factor is the "probability" for an undesired event to occur. The second factor is related to the "consequence(s)" the undesired event results in.

It must be pointed out that a probability, how big it can be, can never be more than 1. The probabilities of concern in technical considerations are usually small numbers, often part of a thousandth. These small numbers are consequently near zero but never zero, which explain why the absolute safety does not exist.

"Conditional probability" is the probability that an event will happen given that another event has already happened. Conditional probability is usually denoted by P(A|B).

Finally, risk assessments are not made easier when economical, political or ideological interests enter into the picture.

The second factor "consequence" can represent acute death, late fatalities, economical or environmental losses etc. It follows that certain consequences can be assessed with greater confidence than other consequence categories. As such, the quantification of acute deaths resulting from low probability industrial accidents is often more easy to perform than similar calculation concerning later diseases. This is true also if both the former and the latter are afflicted with significant uncertainties.

The notion of "risk" has thus, in its simplest definition "probability x consequence", all ingredients necessary for a given risk, real or hypothetical, to be assessed differently by different individuals or groups of individuals.

Finally, risk assessments are not made easier when economical, political or ideological interests enter into the picture.

3 Risk comparison of different energy sources

3.1 Background

Since life began there have been catastrophic hazards which have resulted in severe multiple fatality accidents. In the early days these catastrophes were usually, as today, as a result of natural disaster such as earthquake or flood. With the industrial revolution several man made risks have added to the risk topography.

The contribution of energy risks started when the growing industry demanded energy in the form of coal. Coal mines accidents have resulted in several 10 000 acute deaths over the years. Later fatalities have never been estimated. Then came hydropower, also resulting in many catastrophes and losses of human lives. Followed oil and gas energy industry. Its tribute in acute fatalities is expressed in more than 1 000 lives lost. No estimate is available concerning later fatalities. Latest in the list is commercial nuclear power, badly illustrated by the Chernobyl accident resulting officially in 31 acute fatalities, 145 latent fatalities and 135 000 evacuated individuals. Other health injuries resulting from, for example, radiophobia are not possible to quantify.
Summarizing the above background, all energy sources represent some risks, highly depending on different countries (safety culture and economics. These risks have to be assessed and minimized, and should be part of an integrated view on the risks in the society.

3.2 Risk comparison of energy sources

All major energy sources, be it coal, oil, natural gas, nuclear or hydro power, have a potential health and environmental impact.

A consequent risk comparison between different energy sources has to include all phases of the whole energy cycle. That means, extraction, conversion, transportation, production (normal operation and accidents), waste management and disposal.

Hereby, an obvious condition should be that the normal operation, including the produced wastes, of each energy source must be acceptable for the society as regard both acute and late fatalities, and environmental impact. Against the threat of global climate changes caused by carbon dioxide and other "green house gases" emissions in the atmosphere, the above condition should normally be limitative for certain energy sources.

Another condition should be that the consequences, for the public and the environment, of hypothetical accidents can be avoided or limited to acceptable levels through consequence limiting systems and through administrative actions.

Many quantitative risk comparisons between different energy sources have been published in the western countries. From this abundant literature appears an overwhelming concordance concerning the risks the different energy sources expose the individual, the society and the environment for.

The following presentation is limited to - for the Swedish conditions potentially significant energy sources - a short review of accidents having occurred during the last decades.

3.3 Hydropower

Water has been used by man to locally generate energy for hundreds of years. The industrial era led to the expansion of hydropower by building large dams storing huge amounts of water needed for a reliable hydro-electric power production. Throughout the world tens of millions of people live in the flood plains and valleys below large dams and thus face the risk of sudden dam failure. Dams can fail as the result of earthquakes, faulty construction, undermining of the reservoir rims, avalanches of material into the reservoir, over topping of the dam etc.

The Swedish dams are built for the hypothetical and extremely abundant so-called "10 000 years rain". For hydropower, the most severe risk exists when the water inflow to the reservoir is bigger or much bigger than the water outflow possible to release downstream the dam.

The consequences of a catastrophic dam rupture in connection to the "10 000 years rain" result in important damages including the flushing down of downstream hydro-electric power stations, villages and cities. For the Swedish conditions, such a catastrophic accident can result in between 1 000 and 3 000 deaths. The environmental and economical consequences of the flood wave would be very significant. The probability of such an event with the mentioned consequences has been calculated to be slightly less than 1 per million dam x year. The most probable sequence of a Swedish dam failure is however assessed as resulting in no acute fatality.

During the last 30 years, some few dam catastrophies have occurred throughout the world, each of them resulting in more than 1 000 deaths (Vajont, Italy, 1963, 1189 deaths; Machhu, India, 1972, 2 000 deaths; Gujarat, India, 1979, 15 000 deaths). Others accidents have occurred during the same time period resulting in several hundred deaths. Furthermore accidents have occurred where an effective warning system has resulted in early evacuation of the endangered population, thus drastically limiting the losses of human lives (Teton, USA, 1976, only 14 deaths, 30 000 people without housing).

As a severe example of hydro-electric power risks, a brief summary of the Vaiont catastrophe is presented here. The Vajont dam in the Italian Alps was among the highest concrete dams in the world and almost 300 m high. The dam was put in operation 1960. In September 1963 geologists noted that a large mass of land was slipping slowly toward the reservoir valley upstream the dam, due to heavy rain. On 8 October, dam engineers estimated that the land masses could reach the reservoir within a few weeks and started consequently the reduction of the dam water level. The same day warnings were send to the population drawing its attention to the danger of being on the reservoir shores. On 9 October a gigantic and sudden landslide occurred sending almost 200 millions tonnes of material into the reservoir. The resulting wave over topped the dam by about 125 m. The water entered the narrow Piave River valley and a wave of water, mud and rocks, 60 m high, continued downstream, devastating the town of Longarone and several villages. The official figure of the death toll was 1 189. Higher figures have also been published. Ironically the dam remained almost intact with only minor damages to the top of its retaining wall. The avalanche resulted in a reduction of the reservoir by 2/3, thus rendering it useless for hydro-electric power production. The plant was consequently closed down.

3.4 Nuclear power

Health and environmental effects during normal operation of the Swedish nuclear power plants are negligible. The collective dose to the population resulting from the normal operation of these plants is a minor fraction of the natural background radiation collective dose.

Uranium extraction in the world became a matter in debate around year 1980. The criticism pointed out welfare states in Europe, among other Sweden, as causing environmental damages in Canada and Australia, due to uranium mining there. After (Swedish) governmental inquiries and hearings, the conclusion was reached that the accusations were of such character that no further governmental actions were motivated. The reality is in fact that uranium is today extracted in modern mines where the environment has been successfully taken into consideration.

The question of nuclear wastes has also been a matter in debate in Sweden. A safe acceptable solution to this question was a governmental requirement, at the beginning of the eighties, for the Swedish nuclear utilities to obtain the operation permit for the two latest nuclear units (Oskarshamn 3 and Forsmark 3).

The waste volumes from one year operation of a 1000 MW power plant are as follow:

<table>
<thead>
<tr>
<th>Type of waste</th>
<th>Before treatment (m³)</th>
<th>After treatment (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High radioactive</td>
<td>17</td>
<td>3</td>
</tr>
<tr>
<td>Medium &quot;-&quot;</td>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>Low &quot;-&quot;</td>
<td>800</td>
<td>120</td>
</tr>
</tbody>
</table>

These values are extremely small compared with the volumes resulting, for example, from coal burning (about 60 tonnes slush and ashes per hour, and about 950 tonnes gaseous waste per hour for the same produced power). A conclusion is that the above small volumes make it possible to manage nuclear wastes in a safe manner.

It must be pointed out that the toxicity of nuclear wastes decreases as its radioactivity decreases with time. The medium and low radioactive wastes have, after 500 years, the same radioactivity level as the natural radiation background. The high-radioactive wastes are still toxic several thousand years. As a comparison one can mention that after 1 000 years the toxicity of wastes from coal burning is higher than the nuclear wastes. This is due
to the fact that the heavy metals (arsenic, mercury, nickel, cadmium), contained in the coal slush and ashes, have a permanent and non-decreasing poisonous effect.

Concerning the risks for severe accidents, the Swedish nuclear utilities are under the obligation to render account of recurring safety analyses of their nuclear plants for the regulatory body. These safety analyses point out that the probability for core melt is slightly less than 1 per 100 000 reactor x year.

All Swedish nuclear units are equipped with consequence mitigating systems, the function of which is to prevent the release of radioactive material into the surrounding environment, should a core melt occur. The containment represents the most important consequence mitigating barrier. The TMI-accident in USA demonstrated clearly the importance of a tight and resistant containment. The dose level outside the plant was negligible. No acute fatality occurred. The risk for later fatalities is negligible.

A further step taken in the development of public safety in Sweden was the installation of the "safety filter" connected to the containment of each operating unit. With such filters in place, in the improbable event of a core melt, the resulting radioactive releases and land contamination will be so low that an evacuation of the surrounding population will not be necessary (the Swedish utilities are under the obligation to render account of recurring safety analyses of their nuclear plants for the regulatory body. These safety analyses point out that the probability for core melt is slightly less than 1 per 100 000 reactor x year.

As mentioned earlier, the TMI-accident showed that a core melt in a western light water reactor is not similar with environmental nor human catastrophe. The highest radiation dose someone could obtain staying continuously outdoor near the TMI-plant was equivalent to one year natural radiation dose. The TMI-accident is the only core melt accident having occurred in a commercial light water reactor. Until now an operational experience of about 5 000 reactor x years has been accumulated with such light water reactors.

About seven years after TMI occurred the catastrophe in the graphite moderated, light water cooled reactor Chernobyl 4. Important contributing causes to the accident were major deficiencies in the reactor construction (unsuitable physical properties in combination with ineffective shut down system) and in the safety philosophy (lack of tight and strong containment). Soviet officials confirmed in April 1991 in Paris that the total death toll is 31 (these persons died within two months after the accident). 145 persons show sign of radiation induced illness (later injury can be expected for those persons). 145 000 persons were evacuated days after the accident. Some more local evacuations have been actual. A land area with a radius of 30 km is commonly inhabitable for decades. The psychological consequences are important into the public due to radiophobia (not only in the contaminated areas but also in countries outside USSR). The total economical consequences of the accident have been estimated at 25 billions roubles including the relocation of about 200 000 people.

3.5 Coal

Unlike hydropower and nuclear power, it is the daily operation of coal fired power plants which constitutes the most significant health and environmental risks.

Accident risks in a coal fired power plant are, from the health point of view, limited to the plant personnel (i.e. death risk in connection to fire or explosion). For the environment, the consequences of an accident will affect only the plant's vicinity.

The risks related to coal mining are brought to the fore, in Sweden, from time to time when an explosion or slide occurs in some distant mine in a foreign country. The three worse mining accidents recorded in the openly published literature count more than 1 000 deaths each (Courrières, France, 1906, 1 060 deaths; Fusun, China, 1931, 3 000 deaths; Honkeiko, China, 1942, 1 549 deaths). Relatively often the death toll of mining accidents exceeds 100 victims. The number of non-fatal injuries in coal mining accidents is about 10 times higher than the respective death toll. American statistics shows that coal mining accidents in the USA have contributed to half the death toll in working accidents until year 1960. The coal mining industry still constitutes today the most injuries affected industry in the USA. The same is probably valid for all countries mining coal below ground.

Later health risks for miners are well documented. The mean life expectancy for miners is significantly lower, up to decades, than the one for the average person living in respective country.

Another risk with coal mining is related to the wastes, as depicted in the following. Waste generated at coal mines is generally piled into huge slag tips. Occasionally there are landslips on these tips. One such slip occurred at Aberfan, South Wales, October 1966. A large part of a slag tip, lubricated by groundwater and heavy rains, slipped down a 200 m slope and engulfed a primary school and eight other buildings. 144 people died in this accident, 116 of them were young children.

The health and environmental risks related to the normal operation of a 1 000 MWe coal fired modern power plant are exemplified below. Hereby the assumption is made that high quality coal is used, with a maximum sulphur content of 0,8%. It is further assumed that the plant is equipped with an efficient (90%) purification system for the treatment of the effluent gases with regard to sulphur dioxide and nitrogen oxide. Observe that the values below are given per hour.

<table>
<thead>
<tr>
<th>Coal consumption</th>
<th>330 tonnes per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Releases:</td>
<td></td>
</tr>
<tr>
<td>- Sulphur</td>
<td>270 kg</td>
</tr>
<tr>
<td>- Nitrogen oxide</td>
<td>450 kg</td>
</tr>
<tr>
<td>- Carbon dioxide</td>
<td>950 tonnes</td>
</tr>
<tr>
<td>- Dust, heavy metals</td>
<td>130 kg</td>
</tr>
<tr>
<td>- Slush, ashes</td>
<td>60 tonnes</td>
</tr>
</tbody>
</table>

The above presented values depends obviously on the quality of the burned coal, its energy content, and the efficiency of the filter system. It must here be pointed out that desulphurisation of the combustion gases has caused many operational disturbances in among other American coal fired power plants. These incidents have been used in the debate by the involved utilities in order for their plants to be spared from the requirement for such filter systems. Many have furthermore emphasized neither the techniques is fully developed with respect to commercial operation.

Operating experience from foreign coal fired power plants equipped with only electro-filters shows order of magnitude higher releases. Some values are presented below, valid for an Hungarian coal fired power plant, using low quality coal ( lignite) with 1,6% sulphur. Normalized to a 1000 MWe plant the values are:

<table>
<thead>
<tr>
<th>Releases</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Sulphur</td>
<td>29 000 kg per hour</td>
</tr>
<tr>
<td>- Dust, heavy metals</td>
<td>5 400 kg</td>
</tr>
</tbody>
</table>

The metals released with the gaseous effluents are principally mercure, cadmium, chrome, nickel, lead and arsenic. The potential environmental threat caused by these metals and by the carbon dioxide releases has been recognized as serious. Many countries have agreed on a reduction of the releases into the environment of sulphur (with 65%), nitrogen oxide (with 30%), mercure and cadmium (with 50%), and on a limitation of the carbon dioxide releases to the year 1988's value.

It must be pointed out that in order for this agreement to be fulfilled rigourously, all new use of coal and other fossil fuels should be banned.

The volumes poisonous solid wastes produced during the normal operation of coal fired power plant are exemplified in the figure below. For the sake of comparison, the produced wastes from the operation of two 900 MWe nuclear power units are shown on the figure.
Aside the daily releases of airborne particles and gases, the deposition of ashes and wastes from the desulphurisation process represents a difficult problem. After 30 years of operation of a coal fired plant, the wastes will contain tens of thousand tonnes of constantly poisonous matters. The potential health and environmental risks are significant.

This risk potential leads one to think about the so called "conditional law" governing the management of high radioactive nuclear wastes. In the same way and because of their toxicity, ashes and wastes from a coal fired power plant should be subject to the same rigorous law, and management. The gigantic waste volumes in question can be prohibitive in this respect.

3.6 Natural gas

The health and environmental risks from the normal operation of large scale burning of natural gas are dominated by the carbon dioxide releases to the atmosphere. Calculated per produced energy unit, natural gas burning results in half the carbon dioxide releases compared to coal burning.

Considering the greenhouse effect, this relative saving can be fully cancelled by the liberation of methane to the atmosphere during the phases of gas extraction, handling and combustion. The methane is in fact about 25 times more aggressive than carbon dioxide for the ozone layer.

The releases of nitrogen oxide from the combustion of natural gas are about half those resulting from the equivalent oil combustion.

Later health and environmental consequences from the normal operation of large scale natural gas burning have not been found analyzed in the literature.

Another matter not analyzed in the literature is the waste production at the extraction sites. Natural gas has to be separated and purified from oil and other impurities as hydrogen sulphide. This involves both a chemical process and large volumes.

The acute health risks resulting from the widespread use of natural gas are dominated by catastrophes during extraction (exploration/drilling/production), important gas leakages in the distribution network, compressor and monitoring stations, fire and explosion in areas with high population density. The last issue includes potentially very significant risks in harbour cities due to ship transport of LNG (Liquefied Natural Gas).

An idea of the risks related to the extraction of natural gas can be obtained through the world-wide statistics that the Norwegian "Det Norske Veritas" compiles on accidents in the off-shore gas and oil industry (a weakness of this data bank is the difficulty to differentiate and identify the platforms extracting only gas or oil). This comprehensive data bank indicates that almost 100 platforms have been totally lost (i.e. suffered catastrophic damages) during 1970 - 1987. The related economical losses exceed tens of billions of dollars.

In the early days of the gas industry, the accidents usually affected a limited number of people, due to blow-outs and fires on land-based installations. With the development of off-shore exploration, especially at sites distant from land, large exploration and accommodation platforms were built, often located in adverse environment, as the North Sea. Two accidents are summarized below, illustrating the potential severity of off-shore catastrophes.

The capsizing of Alexander Kieland in March 1980 is probably the worst accident having affected an accommodation platform. It capsized in storm force weather in the Ekofisk field, and was found upside-down. Of the 225 persons on board, 123 died, many of the bodies were never recovered.

In July 1988, the Piper Alpha platform was totally destroyed by fire and explosion. This platform was an oil production installation. As a result of a major gas leakage in the compressor system, a fire started and explosions occurred disabling among other both the control room and all electrical power supply. The fire fighting system was ineffective and the fire escalated rapidly. The main gas pipeline to land failed without any possibility of isolating the natural gas leakage. Gigantic gas bubbles went to
the sea surface and caught fire. The subsequent fire balls engulfed the entire platform, leading to its collapse and total destruction. This catastrophe resulted in 167 deaths. The economical loss exceeded 1 billion US dollars.

A specific problem with natural gas is, as indicated above, that the production sites are often at large distances from the important consumption areas. This situation, connected to the fact that natural gas both in normal condition and in liquefied form is highly explosive and inflammable, means that transportation, distribution and storage of natural gas have a significant risk potential.

Catastrophic natural gas risks originate from the risks for important leakage followed by the deflagration of the gas cloud. When a gas cloud has formed and drifted over a populated area, the probability is high that the cloud will ignite. In such a case, the ignition will be followed by a deflagration of the gas cloud resulting in acute death for the majority of people below the cloud.

The ignition of a natural gas leakage can result in a significant death toll up to a distance of some ten kilometres from a failed LNG-tanker, and up to some kilometre from a leaking gas pipeline.

Relevant statistics which thoroughly describes the probability and consequences of occurred natural gas catastrophes does not exist. This is valid for both land based installations and LNG-tankers.

The following descriptions give an indication of the consequences of natural gas accidents.

In October 1949 occurred a LNG-leakage at the East Ohio Gas Company, Cleveland, Ohio, USA. The leakage was 2 900 m³ LNG or 1 600 000 m³ NTP (Normal Temperature and Pressure). The gas cloud ignited promptly and deflagrated. Some gas entered the sewage system and ignited there. The flames reached 900 m in altitude and a fire ball 300 m in diameter formed. The whole installation was destroyed. 128 persons died and 400 suffered severe injuries. As a consequence of the Cleveland catastrophe a massive opinion grewed up in USA against the use of natural gas. Use of similar installations was stopped for almost 30 years.

Year 1973 occurred in USA a new catastrophe during repair work on an empty 95 000 m³ large LNG-storage tank in the New-York state. The tank had been drained one year earlier and had also been flushed from inflammable gas. 42 persons were working inside the storage tank, some of them doing welding repair work. Suddenly an explosion occurred which blowed off the steel and concrete tank top. Its subsequent fall and the explosion killed altogether 40 workers. The most credible cause of the accident was that some natural gas was still present in the tank despite the earlier flushing. This fact was never officially recognized against the background of the Cleveland catastrophe and the prevailing opinion.

Concerning the risks associated with the large scale distribution of natural gas through pipeline, these are documented in both American and European statistics. The probability for leakage of a gas pipeline is between 1 000 and 10 000 per km and year. The larger the diameter the lower the leak probability. The main causes of pipeline failures are subsequent excavating works, aside corrosion and weld failures. The consequences of a gas pipeline leak depend on leak duration time, distance to and population density, etc.

During the severe winter 1987, several accidents occurred in Europe due to leaking gas pipelines being torn by earth movements because the cold weather. The resulting leak points were difficult to localize in the densely populated cities. Explosions and fires resulted in several deaths.

Finally an indication is provided below of the huge amounts of energy contained in the pressurized gas transportation pipelines. This indication refers to the catastrophe in June 1989, in Ural, USSR, when a leaking gas pipeline resulted in the worse train catastrophe ever in USSR. A gas leakage had been in progress for 5 hours. The gas escaped up to some kilometres from the leakage point. A spark, from one out of two trains circulating some kilometre from the pipeline, ignited the gas cloud. The following explosion overturned the wagons. The heat resulting from the gas burning was so intense that two wagons melted partly and became welded together. Between 600 and 800 persons died, a majority of the offers being children on the way to vacation centers. All trees were wrecked inside a radius of 4 km. The explosion has been calculated as equivalent to 10 kilotons TNT, or the strength of a small atomic bomb.

3.7 Oil

Health and environmental impacts resulting from large scale oil burning, either for the production of electricity or house warming, should today be well known for politicians and the public. The evident effects of a widespread acidification of soils and lakes can hardly remain unnoticed for anybody.

Measurements of the air samples taken in Swedish cities show that 90% of the sulphur dioxide originate from the burning of oil for house warming purposes. SO2 concentration in the air 800 - 1000 times higher than the natural background concentration have been measured in several cities during special weather conditions (i.e. inversion).

In the Netherlands, an acid deposition equivalent to 5 600 moles H+ per hectare has been measured. Normal soils and plants tolerate a maximum equivalent to 4 400 moles H+ per hectare. Sensitive soils and plants tolerate not more than an equivalent of 500 moles H+ per hectare.

The releases from an oil fired power plant are comparable to the ones from a coal fired power plant with the same power output. An exception is the releases of heavy metals which are about 5 times less for oil burning. The solid wastes from an oil fired power station are, in volume, comparable with the ones from a coal fired plant. Hereby, the desulphurisation process of the combustion gases contributes to 99% of the total volume of wastes.

The health and environmental risks connected to the extraction, transportation and storage of oil are dominated by the risk for explosions and fires, and significant oil leakages.

What has been said above for natural gas, concerning some hundred of totally lost platforms, is also valid for oil extraction. An environmental risk which is rarely touched upon is the risk for uncontrollable oil leakages during prospecting or extraction. Disregarding such leakages caused by acts of war, like in the Persian Gulf this year, one has to remember the important oil leakage in the Mexican Gulf, in the late seventies. Almost six months were needed to stop the leakage which finally amounted to about 300 000 tonnes of crude oil released into the aquatic environment.

The oil industry has also caused disasters, both to man and the environment, during the transportation and loading/unloading of its products.

A serious accident occurred in Eire, January 1979, and involved the supertanker "Betelgeuse", moored at a jetty at Whiddy Island and unloading its crude oil. A faulty repartition of the in-pumped oil caused a huge explosion which destroyed the entire installation, resulting in 128 persons died and 400 suffered severe injuries. As a consequence of the Cleveland catastrophe a massive opinion grewed up in USA against the use of natural gas. Use of similar installations was stopped for almost 30 years.

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The oil industry has also caused disasters, both to man and the environment, during the transportation and loading/unloading of its products.

A serious accident occurred in Eire, January 1979, and involved the supertanker "Betelgeuse", moored at a jetty at Whiddy Island and unloading its crude oil. A faulty repartition of the in-pumped ballast caused the tanker to break mid-ship. Due to unknown reason the tanker caught fire and several explosions followed. The entire crew, two passengers and the shore staff on the jetty lost their lives, with a final death toll of 50. The tanker was totally destroyed, the jetty severely damaged. An indication of the energy released during the explosion was obtained when a 500 kg heavy steel plate from the tanker was found 600 m from the accident point.

The transportation of crude oil with supertankers has recorded a significant number of catastrophes where very large quantities of oil leaked and resulted in severe ecological damages. A majority of these catastrophes has occurred in relatively narrow straits.
At the end of the sixties the crude oil tanker Torrey Canyon ran aground in the English channel. 100,000 tonnes of crude oil were spilled. About ten years later, in 1978, the crude oil tanker Amoco Cadiz ran aground off Brittany, France. 250,000 tonnes of crude oil were spilled and swept more than 350 km of the coastline, ruining the marine ecosystem for decades. More recently, in 1989, the crude oil tanker Exxon Valdez grounded in the Prince William Sound, Alaska. About 40,000 tonnes of crude oil were spilled contaminating about 1,600 km of coastline.

Oil products

Some oil products as LPG (Liquefied Petroleum Gas) are commonly used in many industries, households, etc. The production, storage, handling and transportation of these highly inflammable and explosive oil products can result in severe catastrophes mainly due to the risk for uncontrolled leakages.

The catastrophe in Mexico City, 1984, provides an idea of the consequences of such catastrophes. The catastrophe occurred at the San Juanico PEMEX (Petroleos Mexicanos) factory, mainly dealing with production, storage, and distribution of LPG (especially handling of gas bottles used for warming purposes). About 5,000 m³ or about 3,000 tonnes LPG (80% butane, 20% propane) were handled daily. The cause of the disaster was a leak on a gas pipeline, 200 mm in diameter. A gas cloud formed, 30,000 m² in surface and 2 m in height. Early in the morning, the cloud ignited resulting in a fireball 300 m in diameter, and generating high thermal radiation levels. Several explosions lasted for about 20 hours, resulting mainly from the explosion of LPG and LNG storage tanks. The total amount of gas involved in this catastrophe was 12,000 m³. At least 500 acute deaths occurred. Over 7,000 people were injured seriously, 144 of them died later. The entire installation was destroyed and 39,000 lost their housing.

Concerning LPG transportation risks, a serious accident happened in 1978 in San Carlos, Spain. An articulated road tanker carrying liquefied propylene was travelling on the coast road (in order to avoid paying toll charges on an inland highway!). The tanker was carrying 23.5 tonnes of propylene, overloaded by 3.5 tonnes. Due to the sun heat, a significant overpressure developed in the almost solid-filled tanker. A gas leak occurred followed by a fire and a catastrophic explosion. The tanker was torn in four major pieces. The driver's cab and the rear end of the tank ended at almost opposite locations, some 300 m from the explosion point. The thermal effect of the fire was devastating. 215 persons died from burns, 100 of them almost directly. 100 further persons contacted severe burns requiring lengthy hospital treatment, in some cases up to two years of time.

4 Conclusion

Global population growth and economic development will continue, during the coming decades, to result in an increased energy demand. This increasing demand will be partly coincident with the need to renew a significant part of current electricity generating installations.

As exemplified in the present paper, be it somewhat pessimistic and provocative, the "pure" society with total protection and no risks is unfortunately an utopian ideal. This is especially true for the different energy sources available and required for the development of any healthy society.

Illustrated by the jogger's dilemma, the society must develop an integrated view on risks connected to its main activities as energy supply, chemical industry, transportation, food production, etc.

As a part of this integrated view and with due consideration taken from the experience gained so far, comparative health and environmental risk assessment studies for different energy sources should be strongly promoted.
RISK ANALYSIS AND NUCLEAR REGULATION METHODOLOGY
APPLIED TO NON-NUCLEAR ENERGY PRODUCTION

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Abstract

The paper gives an account of energy options and effects on man and the environment of various energy systems including hydropower, nuclear power, coal, oil, natural gas and peat. A comparison of risk figures from different energy systems is given on a qualitative scale with the components "favorable, relatively favorable, unfavorable". Calculations have been made relating concentration in peat ash to the critical group for two processes, burning and bleaching from raw ash deposit. Based on maximum permissible doses in the whole peat fuel cycle, maximum permissible concentrations for the seven radionuclides are derived as a basis for a tentative regulation for peat energy production.

1. Introduction

Energy is intimately related to questions concerning our health and our environment. The problems related to our need of energy circulates to the same extent around the problems of the supply of (energy) raw materials and environmental and safety issues from energy production. Sometimes it seems that the environmental concern overrides the concern of getting enough supply of raw materials for the world's energy production.

There are several methods of transforming "latent" energy into a form that is useful for man and the society. Some of these methods, or processes, are summarised in Table 1. All energy transformation methods have one thing in common; they will have a potential to affect our health and environment both positively and negatively. In this paper we will only be concerned with negative effects. Some methods may result in a large impact on our environment and also give rise to acute as well as delayed health effects, e.g. cancer. Other methods may be relatively harmless to man but may result in large changes in the landscape. Figure 1 gives an indication on atmospheric releases from a 1000 MWe coal, oil, natural gas and peat fueled power plant (ref. 1).

The number of injuries and deaths caused by accidents at different steps in the fuel cycles is relatively easy to estimate. However, when it comes direct or indirect health effects, especially late ones such as cancer, the situation is much more complicated and challenging. Table 2 gives an indication of the effects various pollutants may give rise to (ref 2).

In this paper the authors try to compare the effects or risks from six different energy systems - hydropower, nuclear power, coal, oil, natural gas and peat. As an example on how regulations from the nuclear field can be applied to alternative energy production, the authors also discuss suggested regulatory aspects in relation to energy extraction from peat and releases of radioactive substances.
Table 1. Examples on energy transformations

<table>
<thead>
<tr>
<th>Transformation from</th>
<th>Transformation to</th>
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<tbody>
<tr>
<td></td>
<td>Radiation energy</td>
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<tr>
<td>Radiation energy</td>
<td>In solar cells</td>
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<tr>
<td>Potential energy</td>
<td>In hydro power stations</td>
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<td>Kinetic energy</td>
<td>In generators</td>
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<td>Electric energy</td>
<td>In lamps</td>
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<td>Chemical energy</td>
<td>In muscles</td>
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<td>High temperature heat</td>
<td>In steam power turbines</td>
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<td>Nuclear energy</td>
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<td>Low temperature heat</td>
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</table>

**FIGURE 1.** Release of pollutants per GWe and year to the atmosphere (ref. 1)

Table 2. Known effects from some chemical substances

<table>
<thead>
<tr>
<th></th>
<th>Nerve damage</th>
<th>Tumour</th>
<th>Damage on respiratory system</th>
<th>Damage on liver or kidney</th>
<th>Blood disease</th>
<th>Heart and vascular disease</th>
<th>Damage to the skin</th>
<th>reduced fertility</th>
<th>miscarriage</th>
<th>Damage on the foetus</th>
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<tr>
<td>Benzene</td>
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<td>Toluene</td>
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<td>CS₂</td>
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</tbody>
</table>
2. **Effect on man and the environment**

Once contaminants are generated there is a potential risk that they, at least to some extent, are released to the environment and give rise to unwanted effects. Even if a very high ambition level for protection is adopted, e.g. for some substances one has internationally agreed to maintain "zero emission standards", the risk can never fully be eliminated.

As an example, for the spent nuclear fuel generated at the Swedish nuclear power stations, the plans are to encapsulate the waste in copper canisters and to dispose of these canisters at a large depth in the granitic bedrock. For further protection, the canisters will be surrounded by bentonite clay. Despite this high ambition to protect man from undue exposure from the waste, there is no way to fully guarantee that the toxic substances not will escape to the biosphere and give rise to enhanced exposure levels in a remote future.

For radioactive waste and nonradioactive waste that undergo transmutation, the toxicity will change with time. Radioactive elements ultimately lose their radiotoxicity when they decompose to stable elements, although along a decay chain radioactive elements of different radiotoxicity will appear and disappear. An analogous situation may also apply to chemicals, i.e. for some chemicals the transmutation may lead to intermediate products of enhanced toxicity. Some heavy metals, on the other hand, never lose their toxicity and they may therefore constitute a risk to man and the environment for, in principle, all times.

In all cases, the effect on man and the environment may be divided into two main categories: deterministic effects that are directly observable if the exposure exceeds a given value and stochastic effects that occur randomly with enhanced frequency as the exposure increases.

For deterministic effects, the effect is always observable if the exposure to an agent exceeds a given level, i.e. the threshold level. The exposure often results in death of the exposed cells or that the exposed cells lose their ability to replicate and produce new cells. The exposure time is generally of short duration and sensitive organs can be seriously damaged. Stochastic effects are often a result of exposure to low-level doses of an agent and there is a probability that cells with erroneous genetic information may survive. The effect of low-dose exposure may remain invisible for relatively long periods and may give rise to cancer or hereditary effects.

It is very doubtful if today's knowledge is sufficient to express risk to humans for late effects in a quantitative manner. This can be understood if one takes into account, i) traditional difficulties for toxicologists to extrapolate results from high doses to low doses from a test organism (mammals or humans), ii) the difficulty to use epidemiological results to, e.g. detect the enhanced mortality in cancers for a population exposed to low doses and iii) the fact that the waste might be composed of a complex mixture of harmful substances.

Nonetheless, it is important to identify any lack of knowledge as well as the safety ambition that form the basis for the legal framework.

3. **Protection criteria**

Protection criteria may be set differently depending on if the agent studied exhibits a threshold or no threshold value. It is generally believed that there is no threshold value for carcinogens. This view is based on the fact that most agents that cause cancer also cause irreversible damages on DNA. An absence of a threshold implies that even if the exposure level approaches
zero there still is a risk that the exposure leads to unwanted effects, i.e. only zero exposure results in zero risk. For agents exhibiting a threshold behaviour, the situation is quite different. For these agents one usually has adopted a "black and white" perspective. Above a certain level, the agent cause a detectable damage while below this level no damage is observed. This level is sometimes called NOEL (No Observed Effect Level). In order to be on the safe side, the NOEL is reduced by one or more safety factors.

**Source and individual related protection**

The sources of the agents are linked to individuals through a network of environmental pathways. Assessment of the protection can either be related to the source giving rise to exposure to individuals (source related) or to the total individual exposure from all relevant sources (individual related).

The protection against deterministic effects on human beings must be individually related since it is the sum of the contributions from all sources that must be kept below a specified limit or threshold value.

The protection against stochastic effects, however, does not necessarily need to be individually related. If one assumes, as ICRP does for ionising radiation, that the probability for developing cancer or hereditary effects increases linearly with the exposure level, a small increase of exposure leads to the same contribution to the risk regardless of the initial exposure level. Thus, the risk due to releases from a nuclear power plant is not affected by variations in natural background, and consequently regulatory bodies can set release limits for this particular source. As an analogy, the risk of a traffic accident on a particular motorway is not affected by the fact that you drove along another road yesterday, and speed limits may be set for that particular motorway. However, this is only true if the initial exposure level is reasonably low which is usually the case under normal conditions. The source related protection will account for the magnitude and probability of exposure of individuals related to a given source.

If the agent does not have a proven threshold value and a linear approach is adopted, one has the possibility to quantitatively estimate the total exposure or dose to a population, i.e. the collective exposure or dose, from different relevant sources. The collective "dose" is assumed to be proportional to the number of casualties, e.g. lethal cancers. By using the concept of collective "dose", it is also possible to estimate to what extent it is possible and reasonable to improve the protection at the source, e.g. through the reduction of emitted pollutants. Protection at a given source, especially during the construction phase, is to be preferred and is often more effective than protection close to the exposed individuals.

If the agent is ionising radiation, an internationally accepted method exists to quantify the effect by estimating the number of cancers a given radiological activity might give rise to and judging if it is reasonable to further improve the protection. This is usually not a procedure adopted if the acting agent is something else than ionising radiation.

**Risk limits**

For agents exhibiting no threshold values as for carcinogens and mutagens of which ionising radiation is a subgroup, there is no possibility to define an exposure level where there is zero risk to man and the environment. One has therefore, in addition to optimise the protection as mentioned above, to establish a maximum permissible exposure level or risk limit.

The maximum permissible risk limit related to individuals, i.e. individual exposure to agents from all relevant sources, is often regarded as $10^{-5}$ per year. This is to say that the annual
probability of a fatality occurring is 10 in a million. On the other hand, the risk level coupled to
agents from a source, the source related protection, could be defined, say, as one tenth of the
individual related risk, that is $10^{-6}$ per year. The limit could also be of an expression which is
indirectly related to the individual (derived limit) such as thickness of walls for shielding,
maximum permissible stay in a contaminated area or a release limit. This will provide a more
offensive protection than an approach based on direct individual exposure only. A negligible
risk limit, however, could be defined as 1% of the maximum permissible source and individual
related risk limits.

If an activity involves ionising radiation, methods exist for estimating the associated risk, e.g.
through the collective dose concept. For other agents than ionising radiation, however, this is
generally not the case.

For agents exhibiting threshold values detrimental effects only become apparent above these
values. A wide range of effects can be observed varying from headaches to impaired organs
and malformations. Exposure below threshold values does not result in such pathological
effects. Substances known to have threshold values may be restricted on the basis of No
Observed Effect Level (NOEL), with the application of suitable safety factors.

The definition of a protection criterion for the environment could be based on the principle that
the biological diversity shall be preserved. This means that populations are to be protected but
not necessarily individuals. A protection criterion could be defined such that 95% of a
population in a region shall be unaffected from all relevant practices that can cause harm to the
environment.

The major problem in protecting man and the environment is not to define various risk limits,
but rather to couple the concentrations of various agents in man and the environment to their
associated risks or to derive maximum permissible concentrations from a given risk limit.

This difficulty might, at least under some circumstances, be avoided if one could compare
agents released to and remobilised in the environment due to human activities with naturally
existing agents. These natural agents could either be identical to man made ones or behave and
act in an analogous manner to man made agents. In this case, the maximum permissible level
could be defined as a fraction of the natural level of the identical or analogous agent. For
agents amenable to this criterion, i.e. heavy metals, man and the environment would
automatically be protected as long as the criterion is fulfilled.

4. Effects from various energy sources

In this chapter the authors have tried to compile some of the effects from a number of energy
sources. Data presented are taken from the literature, however, the authors are aware of that the
presentation is far from complete. In Table 3 we have compiled the effects from the energy
sources discussed in this paper. The number of fatalities is given in Figure 2.

4.1 Hydropower

Hydropower is a renewable energy source where the sun constitutes the driving source. The
electric power is created by means of water in its natural cycle: evaporation, precipitation and
run-off. Because of this no pollutants and waste will in principle be generated.
Table 3. Comparison of effects from various energy sources

<table>
<thead>
<tr>
<th>Effects</th>
<th>Hydro power</th>
<th>Nuclear Power</th>
<th>Coal</th>
<th>Oil</th>
<th>Gas</th>
<th>Peat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health effects</td>
<td>Social problems in relation to changes in the landscape, dry up, etc.</td>
<td>Genotoxic effects due to emissions from nuclear installations, waste repositories, etc.</td>
<td>Sickness in the respiratory system. Genotoxic effects. Effects due to releases of metals (e.g. Hg) from ash piles.</td>
<td>Sickness in the respiratory system.</td>
<td>Sickness in the respiratory system? Genotoxic effects</td>
<td>Dams in the landscape.</td>
</tr>
<tr>
<td>Occupational effects</td>
<td>Risks due to construction works. Exposure to radon.</td>
<td>Radiation effects. Risks coupled to mining, transportation, fuel fabrication, reprocessing, waste treatment, etc.</td>
<td>Risks coupled to mining, transportation, fuel and waste treatment.</td>
<td>Risks coupled to oil extraction and transportation.</td>
<td>Risks coupled to gas extraction and transportation.</td>
<td>Risks coupled to excavation, drying and transportation.</td>
</tr>
<tr>
<td>Environmental effects</td>
<td>Need of large areas, e.g. damming, dry up. Damages on plant and animal life. Changes in plant and animal life.</td>
<td>Need of large areas, e.g. excavation of uranium. Releases of coolant water and radioactive substances. Releases of radioactive substances from waste repositories.</td>
<td>Need of large areas, e.g. mines, storage of coal and ash heaps. Emission of SO$_2$ and NO$_X$ metals, etc. Acidification of land and water.</td>
<td>Need of land or sea areas when extracting oil. Emission of SO$_2$, NO$_X$, metals, etc. Acidification of land and water.</td>
<td>Need of land or sea areas when extracting gas. Emission of NO$_X$, CO$_2$, etc.</td>
<td>Need of large land areas, e.g. excavation, storage of peat and disposal of ash. Emission of SO$_2$, NO$_X$, CO$_2$, etc. Changes in the landscape. Releases of radioactive substances.</td>
</tr>
<tr>
<td>Climatological changes</td>
<td>&quot;Greenhouse effect&quot;</td>
<td>&quot;Greenhouse effect&quot;</td>
<td>&quot;Greenhouse effect&quot;</td>
<td>&quot;Greenhouse effect&quot;</td>
<td>&quot;Greenhouse effect&quot;</td>
<td></td>
</tr>
<tr>
<td>Large accidents</td>
<td>Dam failure</td>
<td>Reactor accidents</td>
<td>Gas explosions and collapsing mines</td>
<td>Explosions in refineries and damages on tank vessels</td>
<td>Explosions and fire.</td>
<td>Explosions and fire.</td>
</tr>
</tbody>
</table>
In order to get access to the energy, man must make large interferences in the nature, such as building of dams and creation of water stores. Once built, hydropower stations only need small amounts of maintenance and the working environment is usually very safe.

Break through of dams may lead to the release of large amounts of energy within a relatively short period of time. The released amount of energy may be comparable to energy released by burning hundreds of thousands tonnes of oil.

During the latest decades there have been a number of large accidents at hydropower stations throughout the world. In some accidents hundreded of people have been killed and large material costs have occurred. In Vaiont in Italy 1963, about 2000 persons were killed because of an accident at a hydropower station.

It is in principle concrete dams between rock walls that have suffered from large accidents and this type of dams is not used in Sweden. It is therefore difficult to extrapolate the risks of break through of dams based on foreign data to Swedish conditions.

Breakthrough of hydropower dams in Sweden may in principle only be possible during war and the consequences of a break through may differ from river to river, among other things depending on if there are lakes and/or flat land down stream that can act as "buffers" for released water masses.

4.2 Nuclear power

The operation of nuclear power stations generates waste that is radioactive as well as non-radioactive. The radioactive waste in Sweden will be disposed of in rock caverns at various depths depending on the type of waste. Low and intermediate level radioactive reactor waste is disposed of in rock caverns about 50 metres down in the bedrock while spent nuclear fuel will, in the future, be disposed of in rock cavern at about 500 metres depth. Some of the very low level radioactive waste is disposed of at shallow land burial sites located at the nuclear facilities.
The release of radioactive substances may give rise to consequences in the short time as well as in the long time perspective.

**Health effects**

In contrast to other energy sources, e.g. oil and coal, nuclear power is not expected to give any detectable health effects on man during normal operation in Sweden. Human beings living in the vicinity to a nuclear power plant are only allowed to receive 0.1 mSv per year at most. This limit is considerably below levels that constitute a significant risk for damages on, e.g. foetuses.

The operation of nuclear power plants, however, gives rise to waste that may constitute a risk to future generations. Because of this, it is of utmost importance that the waste generated is taken care of in a safe way. In principle, it is usually agreed that the waste should not at any time give rise to damages that are larger than damages from normal operation of nuclear power plants.

**Occupational effects**

For existing power plants one should only consider risks associated to management and maintenance. Risks associated with construction of nuclear power plants are not relevant in Sweden because of earlier political decisions. However, in relation to decommissioning occupational effects must be considered. There may also be some risk associated with handling of irradiated fuel. In Sweden this kind of waste is transported by ship to a wet storage (CLAB) were it will be stored for several decades before it finally will be disposed off.

Sweden has one fuel fabrication plant which produces all the fuel for the Swedish nuclear power program. Only one accident which led to the death of one worker has occurred at this plant. In this case an explosion took place when zircalloy chips were burned.

All the uranium used for fuel fabrication in Sweden is imported and hence there will be no risk for Swedish workers with uranium mining. However, Sweden indeed contributes to the overall occupational effects associated with this practice. According to the literature, the risk associated with uranium mining may vary between 0.005 and 1.5 deaths per GW(e)a (ref. 4, 7).

**Environmental effects**

The environmental effects will be coupled to normal releases of radioactive releases from the plant and potential releases from generated waste. The normal releases are usually very small and in Sweden no effects on the environment have been observed. Radioactive elements in the vicinity of the power plants are of course detectable.

The low and intermediate level waste will mainly be disposed of in SFR-1, an underground repository situated about 50 metres down in the granitic bedrock. Some low level waste will also be disposed of in shallow land disposals at the nuclear power plants. The activity of this type of waste is mainly dominated by cobalt and caesium, with half-lifes of 5 and 30 years respectively, and will thus only constitute a risk for some hundred years. The environmental consequences from these facilities are judged to be small and estimated radiation doses to future generations are small and well below today's permissible limits. Scenarios such as intrusion might, however, cause higher radiation doses.

High level and long lived waste, on the other hand, will constitute a risk not only today and in a relatively near future, but also in the far future. The time scale considered might extend over several million years or more and environmental effects can hardly be quantitatively evaluated for these time periods (ref. 8).
All nuclear power plants must be cooled. In Sweden, where the power plants are located at the coast, sea water is used for cooling. A light water reactor of 1000 MW(e) may use about 50 m$^3$ coolant water per second. When this coolant water is released to environment there will be a temperature rise over a relatively large area and within this area changes in animal and plant life can take place.

**Climatological changes**

Since energy production by means of fission does not produce any significant amounts of "greenhouse" gases such as carbon dioxide and methane as in the case of combustion of fossil fuels, the contribution to climatological changes is negligible.

**Large accidents**

Large accidents in relation to fuel fabrication may be releases of uranium hexafluoride and criticality accidents. The dominating risk from releases of UF$_6$ is, however, from the chemical toxicity. Accidental releases of ammonia and nitrous gases can also take place.

The consequences from transportation of uranium has been evaluated by SSI (ref. 9). Depending on the situation, the radiation doses to rescue personnel and the public vary substantially depending on the situation.

The probability of large reactor accidents is judged to be very small, of the order of $10^{-5}$ per year. The consequences depend on several factors such as plant construction and weather conditions. In Sweden the power plants are equipped with a passive filter or a scrubber system that prevent atmospheric releases of of radioactive materials that give rise to ground contamination, especially cesium, iodine and tellurium. The main demand these systems has to fulfil is that 99.9% of the materials that could give rise to ground contamination shall be contained. This means, in the case of a severe accident at a Swedish nuclear power plant, that the environmental contamination is strongly reduced and hence the effects on man and the environment might be small.

So far there has only been one accident that has caused significant international contamination of the environment. This accident took place in Chernobyl 1986 and large amounts of radioactive materials were released and spread globally. No health effects are expected to be detected in Sweden but the contamination of land and water has indeed affected some people's living conditions, especially lapps who are dependent on reindeer breeding. However, some additional cancers are expected, but these cases constitute only a very small fraction of the normal cancer frequency and will therefore not be detected as an enhancement of the cancer frequency.

### 4.3 Coal

A coal fired power plant generates large amounts of waste that is either released immediately to the environment or trapped within the plant. How much waste that immediately is released depends on the effectiveness of the plant's cleaning system. The cleaning system does not necessarily affect the total amount of waste produced, it only redistributes the waste and gives the possibility to a safe waste management, i.e. to protect man and the environment.

**Health effects**

It is well known that when burning coal as well as other fossil fuels and peat, a large number of substances such as polyaromatic hydrocarbons (PAH), benzo(a)pyren, ethene, benzene, heavy
metals, etc are produced and become mobilized. These substances will have a potential to directly or indirectly harm man and the environment. The organic substances will, analogously to radioactive decay, transform into less harmful substances, either via intermediates that may be more or less harmful, or directly. It is because of this that a good waste management philosophy must be achieved.

The heavy metals will, however, enter into the environment sooner or later regardless of which protective measures man take. Hopefully we are able to affect the rate by which the heavy metals enter into the environment. This also apply to long-lived radionuclides.

The release of PAH, benzo(a)pyrene, ethene, benzene, etc may give rise to genotoxic effects and hence cancers.

In the literature, figures on public health effects as a consequence from energy generation from coal vary between a few deaths to several hundreds of deaths per GW(e)a (ref. 3, 4, 10). The total number of deaths from fossil fuel in Sweden has been estimated to vary between 50 to 500 per GWa.

Coal also contains radioactive isotopes of uranium and thorium as well as their daughter products. From a coal fired power plant, radioactive elements will thus be released into the environment and give rise to exposure to man. The radiation doses to the public are very small (of the order of microsievert per year) and comparable with those radiation doses man receives from releases from nuclear power plants under normal operation conditions (cf. e.g. ref. 11).

**Occupational effects**

Among the risks related to the coal fuel cycle one can mention collapsing mines, explosions, air pollution, transportation, generation of energy and waste management.

In Sweden, the occupational effects will be linked to the generation of energy, management of waste as well as construction and decommissioning of the power plants. As indicated in Figure 2 the number of deaths in the coal fuel cycle seems to be of the order of 10 per GWa or less for workers. Only a fraction of these deaths are due to energy generation and waste management. For the public, the number of deaths per GWa seems to be considerably higher.

**Environmental effects**

The environmental effects will be dependent on the normal releases from the plant and immediate as well as potential releases from disposed waste.

Acidification of the environment is one of the most manifested effects from burning coal. One consequence from acidification is that metals will be mobilized and enter into various pathways in the environment. Several of the heavy metals are strongly poisonous for plants and animals. The most critical elements might be mercury, aluminium and cadmium. As an example, several thousands of lakes in Sweden have cadmium concentrations significantly above the background level.

At present, there are no possibilities to estimate the health effects caused by the mobilization of these metals.

Other environmental effects may be coupled to the large areas needed for mining activities, construction of facilities and deposition of generated waste.
Similar to a nuclear power plant, a coal fired plant must be cooled. The release of coolant water to the environment may effect living conditions for plants and animals.

**Climatological changes**

All energy production alternatives based on combustion of fossil fuels will lead to an accumulation of gases such as CO$_2$ and NO$_x$. The relative importance of some "green house" gases is indicated in Figure 3. Data on the carbon dioxide concentration shows a very large increase during the last century (ref. 12). The consequences, however, cannot easily be predicted, not even with the best prognosis models but the general opinion is that there will be a temperature increase.

![Comparison of the importance of various "greenhouse" gases.](image)

**FIGURE 3.** Comparison of the importance of various "greenhouse" gases.

Other gases that affect the earth's radiation balance, e.g. methane, will also contribute to this temperature change. Some gases may also affect the ultraviolet radiation.

**Large accidents**

Large accidents for the coal fuel cycle are related to mining activities. Several hundreds of people have been killed in coal mines during the latest decades.

**4.4 Oil**

Oil is a complex mixture of various hydrocarbons such as normal paraffins, isoparaffins, naphtenes and aromatic compounds. These carbon compounds also contain sulphur, nitrogen and small amounts of metals of which nickel and vanadium may dominate.

**Health effects**

The health effects are similar as those from using coal in energy production. The amount of ash produced is, however, much less than produced in a coal fueled power plant expressed per GWA. The concentration of environmentally hazardous substances, however, is much higher in oil ash than in coal ash. Even if the production of oil ash is considerably smaller than the production of coal ash, the total environmental impact and resulting health effects from oil ash can be expected to be similar and of the same order as from coal ash.
The genotoxic substances emitted from an oil fueled power plant are of the same type as those emitted when burning coal.

The total number of fatalities in the public vary from a few cases to about a hundred cases per GWa (ref. 3).

Oil fueled power plants also emit small amounts of radioactive substances, mainly Ra-226 and Ra-228 and the resulting radiation doses are expected to be very small.

Environmental effects
Oil fueled power plants also contribute to the acidification of the environment and hence to the mobilization of various metals. The emission of SO$_2$ will also affect the growth of plants. It has been reported (ref. 13) that a long term average air concentration of 30 µg/m$^3$ SO$_2$ may cause damages on pine and the double concentration may affect the growth. Short time average values of 800 µg/m$^3$ or more may also affect pine. Also vanadium that has deposited is expected to affect the growth of plants. Both nickel and vanadium may also give rise to biological effects.

The environmental effects due to cooling are comparable as those from nuclear power and other fossil fuel plants.

Accidental releases of oil will often cause large local damages on plant and animal life. On land can these oil spills lead to contamination of groundwaters for long times.

Climatological changes
The climatological effects from burning oil are the same as from other fossil fuels.

Large accidents
Large accident with catastrophic effects on man and the environment can take place e.g. when drilling for oil and during oil transportation and refinement.

During drilling at sea or land, oil as well as gas may be released in an uncontrolled way. Such a release is called "blow out" and is usually more severe at sea than on land. The risk for an explosion when a blow out occurs is imminent and many people may be at risk.

Transportation of oil at sea can lead to large releases, e.g. the summer 1989 occurred an accident in Alaska where large amounts of oil were released. Blow out has also led to large releases of oil to the environment, e.g. Ixtoc, Mexico 1979/80, Western Offshore 3, Iran 1971 and Ekofisk B, Norway 1977.

4.5 Natural Gas

Natural gas is mainly composed of methane and smaller fractions of ethane and other components such as nitrogen, carbon dioxide and sulphur compounds. Gases from oil sources may also contain smaller amounts of propane and butane. Combustion of natural gas gives considerably smaller amounts of waste than other fossil fuels.
Health effects
Health effects, as well as environmental effects, from natural gas are small (ref. 16) and hence natural gas is an advantageous energy source. No detectable effects are expected following emission of dust, \( \text{SO}_2 \), \( \text{NO}_x \) or metals (ref. 14).

The emission of polyaromatic substances is comparable to that from oil or coal, however, the emission of metals, such as arsenic, cadmium and chromium which are believed to give rise to cancer, is considerably lower (ref. 14).

Natural gas also contains certain radioactive trace elements, usually Rn-222. The release of radon from natural gas is of no significance.

Occupational effects
Transportation of gas is usually of very low risk, especially if the transportation takes place by means of pipelines. The risk associated with the operation of a power plant is comparable with the risk of an oil fueled plant. However, the risk from explosions following gas leakages is larger.

Environmental effects
Compared to oil, natural gas only gives rise to negligible amounts of waste. If the comparison is made with coal, the difference is even more obvious. This is one of the most valuable properties of natural gas.

A gas fueled power plant uses coolant water and the environmental effects due to release of coolant water is similar as for coal and oil fueled plants.

Climatological changes
Combustion of natural gas give rise to emission of gases that affect the earth's radiation balance. This may, as for all fossil fuels, lead to an enhanced temperature on Earth.

Large accidents
Natural gas is transported in pipelines or special ships. Transport in pipelines is relatively safe, especially if one avoids, as far as possible, populated areas. Transport of gas by ship may result in large releases followed by fire if gas tanks are damaged, e.g. via collisions.

4.6 Peat

Before peat extraction can take place one must first drain the area, remove trees, etc. All these works as well as the following peat extraction strongly affect the region. Only peat bogs larger than about 50 hectare are found to be useful for peat extraction in Sweden. In Sweden there are about 5.4 million hectares of peat bogs but only about 350,000 hectares are judged to be useful for peat production. The total energy content corresponds to about 2000 TWh.

Health effects
The health effects are strongly dependent on the cleaning system of the plant. Small plants usually have very simple cleaning systems while the larger facilities have sophisticated systems. The gases emitted contain the same substances as from fossil fuels, although the relative composition may be different.
In Sweden peat contains considerable amounts of radioactive substances which have been accumulated in the peat as a result of infiltrating water from the surroundings which may have rocks containing e.g. uranium. The radiation doses to the public from burning peat may be higher than those the public receive from a nuclear power station.

*Occupational effects*
In contrast to other fuels such as oil, coal, natural gas and uranium, the occupational effects in Sweden will be linked to the whole peat fuel cycle, i.e. production of peat fuel, transportation and energy generation. The number of deaths has been estimated to about one per GWe a (ref. 5, 6).

*Environmental effects*
Release of organic and inorganic pollutants may give rise to similar effects on the environment as observed from fossil fuels.

For the production of peat as fuel large areas are needed and large changes in the landscape occurs. The drainage of land and removal of peat largely affect the life in the region. However, many of the environmental effects related to the activity may only be temporary.

*Large accidents*
Large accidents may be related to fires and dust explosions.

5. **Comparison between various energy sources**

It is very difficult to compare the total risks from different energy sources. What is quite obvious, however, is that the occupational and health effects are about the same for the natural gas and uranium fuel cycle if one not considers the effects from nuclear accidents. Hydropower seems to be slightly less favourable than nuclear power. Except for natural gas, the fossil fuels cause the largest health effects to man. The health effects from peat are, however, very uncertain.

The emissions per GWe that may cause harm to man is about similar for fossil fuels and peat. However, this depends strongly on the effectiveness of the energy plants' cleaning system which in many cases can and should be improved. Natural gas emits substantially smaller amounts of SO₂, metals and dust.

The waste produced from the discussed energy production alternatives vary over several orders of magnitude. Coal produces most solid waste, of the order of megatonnes per year and GWe.

The waste from oil is about 1000 times smaller (ref. 14). Compared to this, natural gas only result in negligible amounts of waste.

Metals and other hazardous compounds may leach from waste repositories and despite the much lower amounts of oil waste, the concentration of elements in leaching water may exceed the concentrations of elements in leaching water from coal ash by several orders of magnitude (ref. 15).

In Table 4 we have tried to tentatively divide the risks associated with the energy options discussed in four groups.
Table 4. Comparison of risk between different energy systems

<table>
<thead>
<tr>
<th>Option</th>
<th>Favourable</th>
<th>Relatively favourable</th>
<th>Relatively unfavourable</th>
<th>Unfavourable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>Occupational risks</td>
<td>Need of land</td>
<td>Large accidents</td>
<td>Climatological changes</td>
</tr>
<tr>
<td></td>
<td>Health effects</td>
<td>Changes in landscape</td>
<td></td>
<td>Genotoxic effects</td>
</tr>
<tr>
<td></td>
<td>Leaching from waste</td>
<td>Acidification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear power</td>
<td>Occupational risks</td>
<td>Genotoxic effects</td>
<td>Large accidents?</td>
<td>Large accidents?</td>
</tr>
<tr>
<td></td>
<td>Health effects</td>
<td>Leaching from waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acidification</td>
<td>Need of land</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Changes in landscape</td>
<td>Acidification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydropower</td>
<td>Occupational risks</td>
<td>Large accidents?</td>
<td>Large accident?</td>
<td>Large Accidents?</td>
</tr>
<tr>
<td></td>
<td>Health effects</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Genotoxic effects</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Leaching from waste</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Acidification</td>
<td></td>
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<tr>
<td></td>
<td>Changes in landscape</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>Occupational risks</td>
<td>Need of land</td>
<td>Large accidents?</td>
<td>Occupational risks</td>
</tr>
<tr>
<td></td>
<td>Health effects</td>
<td>Changes in landscape</td>
<td></td>
<td>Health effects</td>
</tr>
<tr>
<td></td>
<td>Genotoxic effects</td>
<td></td>
<td></td>
<td>Genotoxic effects</td>
</tr>
<tr>
<td></td>
<td>Leaching from waste</td>
<td></td>
<td></td>
<td>Acidification</td>
</tr>
<tr>
<td></td>
<td>Acidification</td>
<td></td>
<td></td>
<td>Large accidents?</td>
</tr>
<tr>
<td></td>
<td>Changes in landscape</td>
<td></td>
<td></td>
<td>Climatological changes</td>
</tr>
<tr>
<td>Oil</td>
<td>Occupational risks</td>
<td>Large accidents?</td>
<td></td>
<td>Health effects</td>
</tr>
<tr>
<td></td>
<td>Need of land</td>
<td></td>
<td></td>
<td>Genotoxic effects</td>
</tr>
<tr>
<td></td>
<td>Changes in landscape</td>
<td></td>
<td></td>
<td>Acidification</td>
</tr>
<tr>
<td></td>
<td>Leaching from waste</td>
<td></td>
<td></td>
<td>Large accidents?</td>
</tr>
<tr>
<td></td>
<td>Acidification</td>
<td></td>
<td></td>
<td>Climatological changes</td>
</tr>
<tr>
<td>Peat</td>
<td>Occupational risks?</td>
<td>Large accidents</td>
<td>Leaching from waste</td>
<td>Changes in landscape</td>
</tr>
<tr>
<td></td>
<td>Genotoxic effects (large plants)</td>
<td></td>
<td>Acidification</td>
<td>Genotoxic effects (small plants)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Changes in landscape</td>
<td></td>
</tr>
</tbody>
</table>

6. Regulatory aspects - Peat

In this chapter it is demonstrated how radiation protection principles can be used to regulate peat extraction, burning and waste handling, using the same limits as those which apply to other practices involving the use of radiation such as nuclear power. As a step towards regulating peat production, calculations have been done by the Swedish radiation protection institute to present tentative maximum concentrations of radioactive substances in peat (ref. 17).

6.1 Radioactive substances in peat

Radiation protection regulation in some form or another may be necessary for other energy production systems than nuclear power. In the following example of peat energy production, an investigation is carried out of the need for limitation of radioactive substances in peat, covering both extraction, burning and waste handling.

Sweden has large deposits of peat, corresponding to a heat energy production of about 2000 TWh. Recent decisions about long term strategies for releases to the atmosphere of sulphur, NO\(_X\), and carbon dioxide may limit competitively of peat energy production.
The contents of most radioactive substances in peat in Sweden stem from U-235, U-238, Th-232 and their daughters in Swedish rock. After the Chernobyl accident, caesium may present problems for some potential sites.

The concentrations of radioactive substances in peat is related to their concentrations in the surrounding rock, but the relation is not simple. Uranium is relatively mobile and often found bound and enhanced in peat by its humus substances. Radium can be transported by ground water but is often adsorbed by clay in the ground before it reaches the peat. In some cases, ground water enriched in radium has infiltrated the peat land directly with resulting high levels of radium. In some cases surprisingly high concentrations of uranium can be found where the surrounding rock contains only modest concentrations of uranium. Although it would, in principle, be possible to describe radioactive concentrations in peat using geological and hydrological data and the quality and type of the peat, there exists at present no simple "rule of thumbs" to give even a rough idea of the radioactive content in peat judging from the content of the surrounding rock.

As a maximum Swedish peat was in one case found having 90 000 Bq/kg ash of uranium (approximate 4 500 Bq/kg peat or 7 500 ppm). Radium has been found in concentrations of 300 000 Bq/kg in peat ash (approximate 15 000 Bq/kg peat).

About 4 PBq caesium-137 was deposited in Sweden 1986 attributable to the Chernobyl accident. The Swedish Radiation Protection Institute initiated a study of caesium in peat from areas with high caesium deposition and found a mean value of 10 000 Bq/kg in ash, corresponding to about 500 Bq/kg in peat.

After consideration, the Swedish Radiation Protection Institute has suggested the following nuclides to be subject to radiation protection regulation in Swedish peat energy production: uranium-238, uranium-235, radium-226, thorium-232, lead-210, polonium-210 and caesium-137.

6.2 Peat extraction

In the peat fuel cycle, individual doses to tractor drivers caused by inhalation of radioactive dust during peat extraction seems to be the most obvious concern in radiation protection. Measurements have shown that dust concentrations usually are in the range 0.1 - 3 mg per cubic meter. In some cases with poor cabin ventilation higher concentrations have been measured, including a maximum value of 100 mg per cubic metre.

Swedish regulations give a limit of 5 mg per cubic meter for organic dust concentration in a workplace. This concentration was used to calculate lung doses to tractor drivers. It was assumed that peat extraction is carried out in campaigns of 2.5 months' duration in 12 hour shifts. Dust inhalation is calculated using an inhalation volume of 29 liter per minute relevant for light work according to ref. 18. Table 5 gives concentration in dry peat for seven nuclides which each would give an effective dose of 15 mSv.

If peat with the most extreme radium content measured is used in peat production, tractor drivers would receive a dose of about 4 mSv from radium alone. The external radiation level on such a peat bog can be as high as 10 μSv/h. The concentrations for peat bogs in use for peat extraction today are lower and are not expected to come near the reference values.
Table 5. Concentrations of radionuclides in dry peat which may lead to a dose of 15 mSv to a tractor driver

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Activity Bq/kg d.w.</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238</td>
<td>80,000</td>
</tr>
<tr>
<td>U-235</td>
<td>80,000</td>
</tr>
<tr>
<td>Ra-226</td>
<td>1,200,000</td>
</tr>
<tr>
<td>Th-232</td>
<td>6,000</td>
</tr>
<tr>
<td>Pb-210</td>
<td>800,000</td>
</tr>
<tr>
<td>Po-210</td>
<td>1,200,000</td>
</tr>
<tr>
<td>Cs-137</td>
<td>300,000,000</td>
</tr>
</tbody>
</table>

Individual doses to the public may result from inhalation of dust which drifts to surrounding areas. Measurements at nearby dwellings have showed dust concentrations of about 10 microgram per cubic metre air as a 24 hour average.

6.3 Peat Burning

The ash content of peat varies normally between 2 - 8%. The ash consists of fly ash which in the absence of filters follows the chimney gases, and bottom ash. The distribution between fly and bottom ash depends on the fuel's quality, its water content and burning technique. It may vary between 10 and 90% of the total ash mass. In the model calculation it has been assumed that 95 % of lead-210 and polonium-210 and 75% of the other radionuclides studied escapes through the chimney. Calculations have been made for 2 cases: 1) a 10 MW plant with no gas filters and 2) a 100 MW plant with 94 % gas filtration.

Concentrations in ash which would result in a dose of 0.1 mSv to individuals in the critical group were calculated for seven nuclides. The critical group is defined by ICRP as "a group of persons who as a result of their customs, age or place of residence receive higher radiation dose contributions than other persons as a result of the releases". Also collective doses have been calculated. In Sweden, the collective dose from nuclear power production is to be kept lower than 5 manSv/GW installed electric effect. This limit is introduced to ensure that nuclear energy if introduced globally does not give a dose to the public exceeding 0.1 mSv per year, as a global average at any time during or after the use of nuclear power. The calculations are made as an illustrative example. It is not expected that peat energy production would be used on a global scale.
In Table 6 are the concentrations of the studied nuclides that would result in a dose of 0.1 mSv to individuals in the critical group, and to the collective dose of 5 manSv per installed GW and year given. The collective dose is calculated as lifetime doses to man for a release in one year. Calculations were made for both a 10 and 100 MW plant.

Table 6. Reference values for different radionuclides at 0.1 mSv for individual dose to the critical group and a collective dose of 5 manSv per installed GW and year. Concentration in ash, approximate 20 times the concentration in dry peat

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Individual dose, 0.1 mSv/a</th>
<th>Collective dose, 5 manSv/(GWa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 MW</td>
<td>100 MW</td>
</tr>
<tr>
<td>U-238</td>
<td>40,000</td>
<td>300,000</td>
</tr>
<tr>
<td>U-235</td>
<td>40,000</td>
<td>300,000</td>
</tr>
<tr>
<td>Ra-226</td>
<td>60,000</td>
<td>500,000</td>
</tr>
<tr>
<td>Th-232</td>
<td>3,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Pb-210</td>
<td>30,000</td>
<td>2,000,000</td>
</tr>
<tr>
<td>Po-210</td>
<td>100,000</td>
<td>900,000</td>
</tr>
<tr>
<td>Cs-137</td>
<td>4,000,000</td>
<td>40,000,000</td>
</tr>
</tbody>
</table>

The values in this table indicate that limitations may be needed for peat with very high levels of uranium-238 and radium-226.

When peat is produced it may not be decided where or how it is burned and it may therefore be reasonable for regulatory purposes to assume conservatively that all peat is burned in 10 MW plants.

6.4 Peat Waste

Peat waste with high levels of radionuclides needs to be regulated from a radiation protection standpoint for various reasons: 1) a waste deposit may release radioactive substances including radon to the environment and 2) workers may receive external doses from peat ash as well as doses from dust inhalation. Which effect will dominate depends wholly on the design of the deposit and working methods. International transport rules for radioactive substances may be involved for ash with high concentration and even rules regulating handling fissionable material relating to safeguards may collide with waste from peat.

Leaching water has been deemed to be the limiting pathway in the proposed regulation. The calculation of doses from peat ash deposits has many degrees of freedom and comparatively little work has been made on peat ash leaching. The uncertainty is therefore largest in this part of the peat fuel cycle.

A deposit of 1 m thickness has been assumed. The infiltration though the ash layer has been taken as 50 mm/a. One percent of the radionuclide content has been assumed to leach to an aquifer connected to a drinking well. The maximum yearly dose then occurs after 10 years. Table 7 gives individual doses from uranium-238, radium-226 and caesium-137 together with individual doses from air emission from peat burning. Since a licence to extract peat may be applied for without knowledge of which plant will be used, a choice has been made to assume conservatively a 10 MW plant with no filtration. Also included for illustration is the concentration which would give a collective dose of 0.05 Sv/year. For a 10 MW plant this corresponds to a collective dose of 5 GW/y which applies to the nuclear industry.
Table 7. Reference values for concentrations of radioactive substances in peat ash (Bq/kg)

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Individual dose</th>
<th>Collective dose (5 manSv/(GWa))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emission to air (combustion)</td>
<td>Ash deposit (leaching)</td>
</tr>
<tr>
<td>U-238</td>
<td>40,000*</td>
<td>60,000</td>
</tr>
<tr>
<td>U-235</td>
<td>40,000*</td>
<td>60,000</td>
</tr>
<tr>
<td>Ra-226</td>
<td>60,000</td>
<td>300*</td>
</tr>
<tr>
<td>Th-232</td>
<td>3,000*</td>
<td></td>
</tr>
<tr>
<td>Pb-210</td>
<td>30,000*</td>
<td></td>
</tr>
<tr>
<td>Po-210</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td>Cs-137</td>
<td>4,000,000</td>
<td>8,000*</td>
</tr>
</tbody>
</table>

* Limiting concentration (Collective dose not included)

As can be seen the relatively low level of radium-226 in table 8 may create problems. Even ash from wood in Sweden may exceed this value.

### 6.5 The Caesium problem; Accident intervention versus planning and design

It has been argued that for the caesium from Chernobyl normal regulation pertaining to planning and design of an acceptable radiation environment should not be used. Rather, along with recommendations in ICRP 60, the possible net benefit of an intervention should be considered. Such a view would lead to different rules for old and new peat extraction companies, since for the potential new companies, caesium represents a known problem.

However, for various reasons including political decisions regulating peat production this may not constitute a serious problem.

### 6.6 The proposed regulation

Some research may be needed before limiting concentrations of radioactive substances are used for licensing peat extraction. The present, tentative, proposition employs values taken from table 8 to give a simple formula for the weighted sum of concentrations of the seven chosen nuclides in kBq/kg ash:

\[
\frac{C_{U-238}}{40} + \frac{C_{U-235}}{40} + \frac{C_{Ra-226}}{0.3} + \frac{C_{Th-232}}{3} + \frac{C_{Pb-210}}{30} + \frac{C_{Po-210}}{100} + \frac{C_{Cs-137}}{8} < 1
\]

The suggested regulations are complemented with other assumptions, for example that filters are used for plants with higher effects than 50 MW.
References

5. M. Kangas and H.P. Niininen, ibid., p. 73.
12. "Trends '90, A compendium of Data on Global Change", The Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, USA.
ASSESSMENT OF ENVIRONMENTAL AND HEALTH IMPACTS OF ENERGY SYSTEMS AND OTHER SOURCES IN FINLAND

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Espoo, Finland

Abstract

At the Technical Research Centre of Finland environmental and health impacts of energy systems and other sources have been studied for many years and from many aspects. In the early 1980s a comparison of the risks of electricity production by coal, peat and nuclear energy was assessed. The whole fuel cycle from mining to waste management was considered. The environmental impacts were assessed qualitatively and the health impacts quantitatively for the alternative ways of producing electricity. In the quantitative analysis both occupational and public health risks for normal and accidental conditions were estimated. The quantitative assessment contained a relatively large uncertainty although based on the best international knowledge at that time. In the mid 1980s the Technical Research Centre took part in the United Nations Environment Programme on the environmental impacts of production and use of energy. Methods for comparative assessment of the environmental impacts of energy sources and cost-benefit analysis and its use in emission control were reviewed and estimated. In the co-ordinated research programmes the methodologies for risk assessment and cost-effectiveness analyses of radiological impacts from different stages of the nuclear fuel cycle were developed and applied in actual situations in Finland. It has been concluded that the direct health effects caused by atmospheric releases from different types of power plants do not differ decisively from each other provided that expectation values are employed for accidental impacts. Consequently during the last years increasingly higher emphasis has been paid on the environmental impacts. An integrated acidification model (HAKOMA) has been developed to study the effects of various energy uses and traffic scenarios and emission reduction strategies on the different phases of the chain leading to acidification. The phases are emissions, deposition and impacts on forest soils and lakes. The model has been developed in close collaboration with several Finnish Research institutes and IIASA (International Institute of Applied Systems Analysis). The model covers acidifying emissions from energy systems, industry, transportation and agriculture. The objectives of the model arc to obtain quantitative relationships between acidifying emissions (SO\(_2\), NO\(_x\) and NH\(_3\)) and processes relevant to acidification of forest soils and lakes. The HAKOMA model system can also be used to estimate costs of emission reduction alternatives. The existing model systems for full scope probabilistic safety assessments (PSA) of nuclear power plants continue to be developed. One important application has been the comparative analysis of alternative engineered features to prevent/mitigate the off-site consequences of severe accidents. Similarly a comprehensive modelling system has been developed for the analysis of long-term radiological safety of nuclear waste repositories.

1 INTRODUCTION

At the Technical Research Centre of Finland (VTT) environmental and health impacts of energy systems have been studied for many years and from many aspects. The emphasis has been on impacts of nuclear energy. During the last years much research has also been done on the environmental impacts of conventional energy systems. Most of the research has been limited to assessing the impacts of certain energy systems or estimating the importance and relationships of different factors and processes that are relevant to certain impacts. Only a few comparative risk assessment studies have been performed.

There are many difficulties in comparative risk assessment of different energy systems. The nature, extent and time scale of the health and the environmental impacts differ significantly for the different energy systems. This makes a direct comparison of the impacts difficult. The information and knowledge on environmental and health impacts
of energy systems and other sources is insufficient and contains many uncertainties. The impacts are also very much site specific which increases the uncertainties in generalizing the data.

The objective of comparative risk assessments of different energy systems is to provide information to decision-makers concerned with the energy planning. It is essential that this information is comprehensive and credible so that it helps the decision-makers to make the right conclusions. It is important that the decision-makers are provided with enough background information on the data, assumptions and judgements the comparison is based upon. All significant uncertainties and their relevance to the conclusions should be indicated. Subjective evaluations cannot be avoided when dealing with environmental problems. All choices based on subjective judgements should be indicated and justified.

In this paper some of the studies performed at VTT on health and environmental impacts of energy and also other systems are reviewed with the objective that some of the results and conclusions can be used in comparative risk assessment of energy systems.

2 THE INTEGRATED ACIDIFICATION MODEL (HAKOMA)

2.1 Objectives and coverage of the model

The Finnish integrated acidification model is developed to assess factors and processes influencing the acidification of forest and lakes. The model system is developed at Technical Research Centre of Finland in co-operation with the International Institute of Applied System Analysis (IIASA) and several institutes in Finland (Johansson, M. et al. 1990). The model covers sulphur dioxide, nitrogen oxide and ammonia emissions from energy use, industry, transportation and agriculture, abatement measures, atmospheric dispersion and transformation, deposition and impacts on forests and lakes (see fig. 1).

The objectives of the integrated model are:

- to obtain quantitative relationships between different factors and processes relevant to acidification; to identify the most important factors and greatest contributors to uncertainties
- to obtain estimates on the future development of emissions, deposition and impacts on forest soils and lakes; eg. for the planning of emission criteria and emission abatement strategies; and
- to collect and present the data relevant to acidification in a form which is informative and easy to use.

2.2 Acidifying emissions and deposition in Finland

Acidifying emissions from both Finnish and foreign sources are considered in the model. Sulphur dioxide (SO\(_2\)), nitrogen oxide (NO\(_x\)) and ammonia (NH\(_3\)) emissions are the main contributors to acidification of forest soils and lakes. Sulphur dioxide and nitrogen oxide emissions originate mainly from energy use, industry and transportation. Ammonia emissions originate mainly from agriculture.

Sulphur dioxide emissions are due to the sulphur content in the fuel. In conventional burning processes the sulphur is released to a large extent to the atmosphere. A smaller
fraction of the sulphur dioxide emissions originates from raw materials of industrial processes and from the ore in basic metal industry. The nitrogen oxide emissions are caused by combustion processes mainly, and the origin of nitrogen can be both the nitrogen in the fuel and nitrogen in the inlet air in the burning process. Energy production by boilers, and especially road traffic, are the most important sources of nitrogen oxide emissions. The ammonia emissions originate from agriculture, that is livestock manure and use and production of artificial fertilizers. The origin for the emissions is the nitrogen content in the animal feed and in the fertilizers.

In the integrated model system the emissions in Finland are estimated on the basis of energy use, transport performance and agricultural forecast scenarios, and on the basis of alternative emissions control and energy production strategies. The main objective on the emission model in the HAKOMA system is to produce future emission estimates to be used as source terms to the atmospheric dispersion model and further in the forest soil and lake impact studies. It is possible to study how various energy production and use and traffic scenarios and control strategies affect the development of the emissions, deposition and acidification of forest soils and lakes.

In the calculation of the acidifying deposition in Finland both Finnish and European emissions are considered. The emissions data and scenarios for the other European countries are obtained from IIASA and EMEP (European co-operative programme for Monitoring and Evaluation on the long-range transmission of air Pollutants in Europe).
The acidifying compounds contribute as follows to the acidification: sulphur 50 %, nitrate oxides 30 % and ammonia 20 %. As the deposition of sulphur is decreasing because of strict reduction measures the significance of the nitrogen emissions is increasing (Kauppi et al. 1990). The acidifying emissions and deposition are given in table 1 and the geographical distribution of the deposition in figures 2 - 4.
2.3 Impacts on forests and lakes

The sulphur and nitrogen deposition have direct impacts on the environment. These impacts are significant near the sources. The deposition affects the environment also indirectly. The deposition of acidifying sulphur and nitrogen compounds decreases the amount of basic cations in the forest soils and lowers the pH. When the amount of cations is below a certain limit aluminium begins to dissolve in the soil solution. Aluminium is harmful for the plants. The acidifying effect is more significant for the growth and health of the forests than the direct effect when larger areas are considered.
The impacts of the nitrogen deposition are more complicated than those of the sulphur deposition. Nitrogen is an essential nutrient for the plants. The Nordic forests are nitrogen poor regions and the nitrogen deposition stimulates the growth of the forests. This leads to eutrophication of the forests and many plant species characteristic to the original conditions are endangered. The stimulated growth also increases the biological acidification of the forests.

The impacts of the acidifying depositions can be assessed using different indicators (base saturation, pH) that describe the impacts. By comparing the values obtained for these indicators with certain criteria the significance of the impact can be assessed. In the Finnish integrated acidification model many criteria have been used for the acidifying impacts. As an example two criteria for critical loads of the total acidifying deposition have been used: (1) no acidification is allowed and (2) acidification is allowed to the limit where the concentration of dissolved aluminium does not yet affect the growth of the plants. The acidifying deposition exceeds the more stringent critical load in the whole of Finland and also the less stringent value in large parts of Finland.

2.4 Cost-effectiveness of abatement measures

The costs of the abatement of the acidifying emissions are large and it is therefore important to know where the measures should be directed to achieve the most effective results. With the HAKOMA model it is possible make cost-effectiveness analyses of abatement measures. One way to perform a cost-effectiveness analysis is to set a target value for the deposition in a certain region and to calculate how this target is reached at lowest cost.
The approach in the HAKOMA model system is effect oriented whereas in comparative risk assessment of different energy sources the approach is source oriented. The model system could although be used in comparative risk assessment of energy systems. The effects on acidification of different energy polices, building of new power plants, replacement or technical improvements in old ones, choice of fuel etc. can be assessed by the model system both on local and regional scale.
3 PROBABILISTIC SAFETY ASSESSMENT (PSA) OF NUCLEAR POWER PLANTS

The development of probabilistic safety assessment tools was commenced at VTT already in the 1970's. In the beginning the main emphasis was paid on development of tools for level 1 PSA-studies. Nowadays these tools are in extensive use also in non-nuclear applications. The area of probabilistic studies was subsequently expanded to cover also the probabilistic off-site consequence assessment of reactor accidents and the computer code ARANO was developed. In the beginning of 1980's the development of computerized methodology was initiated to analyze the physical/chemical behaviour of reactors during severe accidents. Consequently there is now capabilities at VTT to perform fullscope PSA-studies (levels 1 to 3) of nuclear power plants. During the recent years the most important applications have been the comparative analysis of alternative engineered safety features to prevent and mitigate the potential off-site consequences of severe accidents. The applications have dealt both with backfitting of the existing nuclear power plants and with the design analysis of reactor alternatives for new nuclear power stations.

4 SAFETY OF NUCLEAR WASTE REPOSITORIES

A comprehensive safety assessment of nuclear waste disposal includes the survey of possible release scenarios, prediction of probabilities for these scenarios, estimation of environmental consequences and finally the combination of probabilities and consequences as well as the overall assessment of the risk estimates in view of performance criteria.

The radiological impact evaluation is based on conditions where the release of radionuclides from the repository is possible only via gradual dissolution into and transport along with groundwater. The dose assessment consists of the analyses of the following items:

- groundwater movements including main pathways, travel times, fluxes and spatial distribution of flows,
- the radionuclide releases out of the repository into the surrounding rock,
- the radionuclide migration in the rock,
- the radionuclide behaviour in the biosphere,
- the doses via different internal and external exposure pathways.

Models presently in active use at Nuclear Engineering Laboratory of Technical Research Centre of Finland in performance assessments are presented in table 2.

The performance assessment/safety analysis tools have been applied extensively in various situations already during the 1980's. The applications have covered generic safety assessment of spent nuclear fuel repository concepts, comparison of alternative concepts for reactor and decommissioning waste repositories and preliminary & final safety analyses of the Olkiluoto repository for low and intermediate level operational wastes. In addition the methodology has been applied in cost-effectiveness analyses of nuclear waste management options. These studies are summarized in section 5.3.
Table 2. Performance analysis models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Own development</th>
<th>Field of applications, capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORIGEN-2</td>
<td></td>
<td>Activity inventory, heat power etc.</td>
</tr>
<tr>
<td>ANISN</td>
<td></td>
<td>Radiation shielding</td>
</tr>
<tr>
<td>QAD</td>
<td></td>
<td>- &quot; -</td>
</tr>
<tr>
<td>REPTEM</td>
<td>X</td>
<td>Thermal responses in a repository for spent fuel</td>
</tr>
<tr>
<td>FEFLOW</td>
<td>X</td>
<td>3-d groundwater flow model</td>
</tr>
<tr>
<td>PAAWI</td>
<td>X</td>
<td>Algorithms for inserting of 2-d fracture zone elements in an already existing 3-d element mesh</td>
</tr>
<tr>
<td>ELMO</td>
<td>X</td>
<td>Pre- and postprocessing of element meshes</td>
</tr>
<tr>
<td>PATRAN</td>
<td></td>
<td>Fracture network models developed within the Stripa project</td>
</tr>
<tr>
<td>FracMan/MAFIC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAPSAC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>REPCOM</td>
<td>X</td>
<td>A compartment model for near-field analysis of repositories for low and medium level waste</td>
</tr>
<tr>
<td>REFREP</td>
<td>X</td>
<td>A near-field mass flow model for a repository for spent fuel</td>
</tr>
<tr>
<td>FTRANS</td>
<td></td>
<td>Modelling of groundwater flow and tracer migration</td>
</tr>
<tr>
<td>TRUCHN</td>
<td></td>
<td>Modelling of tracer migration</td>
</tr>
<tr>
<td>MATDIF</td>
<td>X</td>
<td>- &quot; - (only advection and matrix diffusion, no decay chains)</td>
</tr>
<tr>
<td>MIGCONV</td>
<td>X</td>
<td>- &quot; - (matrix diffusion taken into account by means of effective retardation coefficient, no decay chains)</td>
</tr>
<tr>
<td>DETRA</td>
<td>X</td>
<td>Biospheric transport and dose evaluation model</td>
</tr>
<tr>
<td>SYVAC/FI</td>
<td>(X)</td>
<td>An integrated probabilistic model</td>
</tr>
<tr>
<td>GRESS</td>
<td></td>
<td>Sensitivity analysis</td>
</tr>
</tbody>
</table>

5 COMPARATIVE RISK ASSESSMENTS

5.1 Comparison of risks of electricity production by coal, peat and nuclear energy

In 1980 a comparison of the risks of electricity production by coal, peat or nuclear energy was made by Lautkaski et al. (1980). The whole fuel cycle from mining to waste management was considered.

The nature of the environmental impacts is different for the alternative ways of producing electricity. Electricity production by coal and peat affects the environment mostly through the continuing atmospheric emissions during normal operation whereas the most significant impacts on the environment of nuclear energy are caused by radioactive emissions during potential severe accidents. The time scale of the impacts is also different. Injuries and fatalities during accidents are examples of short term effects. Long term effects are caused for instance by heavy metals in the environment.
and from long lived radioactive material in nuclear waste. The environmental impacts can occur on local (for instance warming of sea water caused by cooling water), regional (acidifying emissions) or global (CO₂-emissions from fossil fuels) scale. Because of the differences in the environmental impacts only a qualitative analysis was made with no attempt to quantify the impacts or to put them in an order of significance.

Table 3. Estimated mean values for health risks from electricity production by coal, peat and nuclear energy for one power plant year (1 GW(e)). The values for health risk outside Finland are given in brackets. The other values apply for Finland (Lautkaski et al. 1980).

<table>
<thead>
<tr>
<th></th>
<th>Coal</th>
<th>Peat</th>
<th>Nuclear energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal operation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupational health hazards - fatalities</td>
<td>(2)¹</td>
<td>not estimated</td>
<td>0.15² (0.23)³</td>
</tr>
<tr>
<td>Public health hazards</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- fatalities</td>
<td>0.6 - 2.2⁴</td>
<td>0.2 - 2.2⁵</td>
<td></td>
</tr>
<tr>
<td>- delayed effects of radiation</td>
<td>0.02⁶,⁹</td>
<td>not estimated</td>
<td>0.004⁷,⁹ (0.3)⁸,⁹</td>
</tr>
<tr>
<td>Accidents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupational fatal accidents</td>
<td>0.13¹⁰ (1.6)¹</td>
<td>0.05²</td>
<td>0.01² (0.2)¹</td>
</tr>
<tr>
<td>Public risk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- fatalities</td>
<td>0.01¹¹</td>
<td>0.9 - 1.9¹²</td>
<td>0.002¹³</td>
</tr>
<tr>
<td>- delayed effects of radiation</td>
<td></td>
<td>0.02⁹,¹⁴</td>
<td></td>
</tr>
<tr>
<td>Wastes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- delayed effects of radiation</td>
<td></td>
<td>0.006⁹,¹⁵ (0.2)⁹,¹⁶</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.7 - 2.3 (3.6)</td>
<td>1.2 - 4.2</td>
<td>0.2 (0.9)</td>
</tr>
</tbody>
</table>

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The environmental impacts were described in words for the different ways of producing electricity for:
- mining, extraction and refining
- transportation
- production of energy at the power plant
  - atmospheric emissions during normal operation
  - pollution by effluents during normal operation
  - changes in water temperature and the effects on marine life by cooling water releases
- occupational health hazards
- accidents
- waste treatment and disposal.

Global impacts were also described. The health impacts (deaths and severe genetical changes) were also quantified. The harmful emissions (SO₂, particulates, PAH-compounds and radioactive materials) were estimated. Only Finnish emissions were considered. The concentration profiles were obtained from dispersion models for air pollutants. The dispersion calculations were made at the Finnish Meteorological Institute. The Statistical Centre of Finland provided data on population densities with made it possible to calculate mean doses for the population. The health risks were estimated for impacts that occur in Finland and abroad using simple linear and nonlinear dose-effect-relationships. The results are shown in table 3.
The largest risk components were atmospheric emissions from peat and coal power plants. Significant risk was also estimated to be caused by transportation of peat and from the coal mining. The mean public risk for nuclear energy was estimated to be small. This may not be a good way the describe the risk because the consequences of a potential accident can be very severe although the probabilities for these accidents are small. The total health risk estimates did not differ decisively for the alternatives. The estimates contain many uncertainties, especially the public health risk estimates. The risk ranges in table 3 depend only on the correlations used in the calculation of the health risk and they do not contain an estimate of the uncertainty.

Large areas are temporarily or permanently committed to the energy systems and the associated infrastructure. This may have a significant impact on the land use and the landscape. These impacts, however, are characteristic of most major industrial projects, and were thus outside the scope of the study. The impacts of the construction of power plants were also omitted.

5.2 United Nations Environmental Programme on environmental impacts of production and use of energy

The Technical Research Centre of Finland took part in the United Nations Environmental Programme on the environmental impacts of production and use of energy. Cost-benefit analysis and its use in emission control and methods for comparative assessment of the environmental impacts of production and use of energy were reviewed and estimated.

5.2.1 Cost-benefit analysis

In the cost-benefit study (Lautkaski et al. 1985) the objective was to provide a state-of-the-art review of the application of cost-benefit analysis to the control of airborne emissions from commercial energy systems and to give the decision-maker an idea of the type of decisions in which a cost-benefit analysis is helpful. Cost-benefit analysis attempts to quantify the social advantages and disadvantages of alternative courses of action in terms of a common monetary unit. Cost-benefit analysis is a tool to support decision-making. It can be applied to (1) to find out the justification of a single project, (2) to choose among candidates the project which shows the largest benefits over costs or (3) to determine an optimal level of activity.

In cost-benefit analysis environmental and health impacts have to be valued in monetary units. It is obvious that objective and scientific valuations are not obtainable for those effects. The valuation of costs and benefits is subject to uncertainties which relate to
- identification and quantification of the impacts
- monetary evaluation of impacts
- performance of the technology used
- price forecasts.

Some uncertainties are methodological and some due to the scarcity of data. The uncertainties should be quantified or if a quantification is difficult a subjective assessment of the uncertainty should be made. The uncertainty should be propagated to final results, so that the sensitivity of the conclusions to the uncertainty can be tested.
5.2.2 Comparative assessment of the environmental impacts of energy systems

The purpose of the study (Pirilä et al. 1986) was to describe the present situation in the field of incorporating the environmental impacts in the energy system planning process and to give some guidance in how to proceed with planning of electric power systems in the absence of applicable well developed systems.

The basic difficulties in the attempt to include the environmental factor in the energy planning process were considered to be the lacking of quantitative information on the environmental impacts and to the difficulties in comparing the environmental impacts of very different natures and not due to lacking of methodology.

The first step in the environmental assessment is to collect the available data on all significant environmental consequences of the alternatives being considered. The selection of the environmental impacts should be based on their significance, not on the quality of the data available in order that the conclusions and results based on this data will be meaningful. The importance of the data should always dominate over the accuracy and ease by which the data is obtained.

Proceeding beyond collecting data and reporting a description of the various environmental consequences of a project, the alternatives can be ranked with the help of a comparative assessment. The assessment can be made with no attempt produce a single value of merit in monetary or other units or the ranking can be done further by using cost-effectiveness and cost-benefit analyses.

5.3 Cost-effectiveness of nuclear power station waste management options

There has been an obvious need to consider the achievable level of safety of waste management in view of the costs involved. The feasibility of the cost-effectiveness approach for this purpose has been studied in the framework of practical case studies. The analysis indicates that such an approach has had clear benefits, but it has also revealed several issues and ambiguities in its application. The waste management alternatives considered have included various concepts for the disposal of low- and intermediate-level reactor and decommissioning wastes as well as of the unreprocessed spent fuel versus disposal of high-level waste from reprocessing. A summary of our studies performed in the context of the IAEA coordinated research programme on application of cost-effectiveness analyses is included in our final report (Vuori et al.)

The employed impact indicators describe both the individual and collective risks. In addition, indicators simultaneously giving a perspective into other risks in the society and a means to make a rank ordering of the alternative options should be considered. The cost-effectiveness ratios for collective risks vary in the range of ten to hundreds of millions US$ per man-Sv. The examples considered also indicate that increased costs do not necessarily improve safety.

Especially in the case of spent fuel and/or high-level waste disposal the extremely long time ranges bring about large uncertainties and ambiguities in applying the conventional concept of total collective dose commitment. However, the application of cost-effectiveness approach is not fixed to any specific impact indicator and consequently other indicators, like the maximum individual risk or inflow rate to the biosphere can be used as a basis for decision-making.
Furthermore, results from the practical case studies on different repository concepts demonstrate the importance of realistic models and data to reduce the uncertainties and to facilitate the intercomparison of alternative solutions.

6 CONCLUSIONS

Comparative assessment of environmental and health impacts of energy systems is a very demanding task. The impacts are very ambiguous: they can have local, regional or global consequences, the effects can be immediate or be shown only after a long time has elapsed from the process leading to the impact. The relationships linking the cause and the effect can be complicated and often insufficiently known.

The methods used in comparative risk assessment of different energy systems should be transparent, that is the user of the assessment should be able to understand precisely the connection between the important starting points and the results of the analysis. The analysis should also be comprehensive. No important factors should be neglected. All uncertainties and subjective evaluations should be expressed openly. Although objectivity is aimed, it is seldom possible to avoid subjectivity when dealing with environmental problems. All significant subjective choices should be indicated and justified. Commonly presented alternative views should also be presented together with arguments for and against these views.

Assessments of environmental and health impacts have been done for many specified systems and actual projects. The studies have accentuated the importance of the environmental impacts above direct health effects. Especially pollution of large areas (acidification, heavy metals in the environment, consequences of severe nuclear accidents) and global impacts are of great concern. The results of the studies provide data for comparative assessment, but it should be noted that the impacts are often very site specific and generalizing the data increases the uncertainties of the analysis.

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