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COMPARATIVE ASSESSMENT OF SEVERE ACCIDENT RISKS IN THE ENERGY SECTOR

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This paper addresses one of the major limitations of the current comparative studies of environmental and health impacts of energy systems, i.e. the treatment of severe accidents. The work covers technical aspects of severe accidents and thus primarily reflects an engineering perspective on the energy-related risk issues. The assessments concern full energy chains associated with fossil sources (coal, oil and gas), nuclear power and hydro power. A comprehensive severe accidents database has been established. Thanks to the variety of information sources used, it exhibits in comparison with other corresponding databases a far more extensive coverage of the energy-related accidents. For hypothetical nuclear accidents the probabilistic approach has been employed and extended to cover the economic consequences of power reactor accidents. Results of comparisons between the various energy chains are shown and discussed along with a number of current issues in comparative assessment of severe accidents. As opposed to the previous studies, the aim of the present work has been, to cover whenever possible, a relatively broad spectrum of damage categories of interest.

1 INTRODUCTION

1.1 Context of the study

In 1993 the Paul Scherrer Institute (PSI) in co-operation with the Swiss Federal Institute of Technology, Zürich (ETHZ) launched a long term project on "Comprehensive Assessment of Energy Systems" ("Ganzheitliche Betrachtung von Energiesystemen", GaBE). The ultimate goal of this project is an integrated evaluation covering risk-related, environmental and economic aspects associated with different energy systems [1]. The results of this work are intended to serve as a scientific support to the decision-making process concerning energy supply options for Switzerland.

The energy sector is one of the main contributors to man-made disasters. At the same time, major shortcomings exist in the current state-of-the-art of assessing severe accident potential, characteristic for different energy sources [2, 3].

This paper summarises the work on energy-related severe accident risks performed by PSI and reported in [4]. The approaches used and a major part of the results are of general interest and not restricted to the Swiss conditions. Parts of the work is therefore currently being used in the guidelines and state-of-the-art reports by international organisations [5, 6, 7].

1.2 SEVERE ACCIDENT ISSUE

By severe accidents we understand potential or actual accidents that represent a significant risk to people, property and the environment. A reasonably complete picture of health, environmental and economic effects can only be obtained by considering damages due to normal operation as well as due to severe accidents.

We consider accidents that might occur at fixed installations, storing and processing hazardous materials, or when transporting such materials by road, rail, pipelines, open sea and inland waterways. Examples include fires, explosions, structural collapses and uncontrolled releases of toxic substances outside of the installation boundaries.

Basing comparative assessment solely on accidents that occurred in the past provides only a partial picture of the risks since:

- Conditions (for example with respect to technology, safety principles and culture, physical and operational environment), characteristic for a specific event, may be inapplicable elsewhere, or irrelevant.
- Actual experience, if available, in most cases only reflects isolated examples from a wide spectrum of hypothetical accident scenarios.
- For some energy sources and for specific parts of energy chains the statistical evidence is very scarce, either due to unsatisfactory reporting or to high standards and reliability of safety systems.
- The effect of expected advancements in technology, including improvements of safety-specific features, are not taken into account when past events are evaluated.

Consequently, a balanced evaluation of severe accident risks associated with systems having extensive built-in safety features ideally calls for the use of predictive approaches using Probabilistic Safety Assessment (PSA) methods. Evaluations based on past experience are in any case useful as: (a) supplement to PSA; (b) source of information to support PSA and set the priorities; (c) frequently they constitute the only available option, due to the limited number of relevant PSA applications.

A number of earlier more or less comprehensive studies addressed the comparison of risks related to severe accidents in the energy sector. Fritzsche addressed the risks of energy production due to the normal operation and due to accidents [8, 9]. His results concerning health effects, including the impacts of severe accidents, were adopted within the internationally co-ordinated effort to assess these impacts [2]. When the present work was undertaken this constituted the state-of-the-art in the comparative assessment of the risks associated with power generation. In the meantime two major studies on external costs of power production were published [10, 11]. While these studies significantly improved the knowledge of environmental and health impacts of electricity generation, and advanced the methodology of the assessment, the treatment of severe accidents was not given a high priority. Some progress was achieved, but the overall state of knowledge in this context did not change much. In Switzerland, a debate on risks of energy production was intensified in connection with the publication of a Swiss study on external costs of energy production [12]. Particularly the issue of economic consequences of nuclear accidents was the subject of a discussion which also found its way to the media [13, 14].

2 SCOPE OF WORK AND IMPLEMENTATION

2.1 Project scope

The following defines the scope of the work:

1. The assessment covers coal, oil, gas, hydro and nuclear energy chains. Renewable energy sources other than hydro were not included.
2. In relative terms the efforts were primarily concentrated on the evaluation of past accidents. A comprehensive database has been established and is fully operational. PSA was only applied to nuclear power plants.
3. The results are applicable to current technologies. Analysis of the impact of prospective advancements in safety was outside of the scope.
4. The present work concentrates on technical comparative analysis of severe accidents. Being aware of the risk aspects which do affect the sociopolitical side of the matter, efforts were, however, directed towards addressing such features of energy-related severe accidents as delayed effects, the chance of large number of people being affected and the uncertainties involved in the assessment.

2.2 Implementation and overall analysis strategy

At an early stage it was decided that building a severe accident database from scratch would not be feasible given the actual time and resource constraints. The survey of the existing sources of information, carried out at the beginning of the project, showed that:

a) Numerous sources of information exist; their availability, scope, development status and quality exhibit an enormous variation.

b) Commercial and non-commercial databases are available. They normally cover man-made accidents in a variety of sectors and in some cases also include natural disasters. Very few of the databases particularly consider energy-related accidents. If they do, the coverage concerns one specific energy carrier, for example offshore accidents. In most cases, energy-related accidents are not explicitly identified among the other accidents.

c) None of the available individual databases has a satisfactory coverage to form alone a basis for the evaluation of severe accidents within the present project.

d) The combined information assembled in the available databases would not be fully adequate for meeting the objectives of this work. It needs to be supplemented by additional sources in order to achieve a high level of completeness and quality.

As a result of these insights the following approach was applied within the project (the implementation has not been fully sequential since some of the steps were performed in parallel and also iterations were necessary):

1. **Acquisition of relevant databases**. Table 1 shows a list of major accident databases. Out of 18 databases in the table, nine were directly used as a source of information for the present work.
2. **Implementation of the acquired databases on a personal computer.**
3. **Merging of the contents of the various databases within the framework of Microsoft Access Database.**
4. **Elimination of overlapping events and/or harmonisation of non-consistent information**.
5. **Identification of energy-related accidents and among them of accidents considered as severe.**
6. **Allocation of energy-related accidents to specific energy chains and subsequently to specific stages within each energy chain**.
7. **Searches utilising supplementary sources of information and aiming at checks as well as identification of additional events; analysis of the assembled material**. This includes: annual publications, general and specialised literature, national and international newspapers, incident lists and reports, and direct contacts with responsible companies and other competent organisations or individuals.
8. **Application of Probabilistic Safety Assessment (PSA)**. This includes use of a full scope PSA to estimate external costs associated with hypothetical severe reactor accidents.
9. **Implementation of the additional evidence into the database.**
10. **Evaluations based on the "final" set of data**.

Full Database Name (Organisation)	**Country of Origin**	**Database Code Name**	**Time Period Covered**	**Geographical Area**	**Type of Accidents Covered**
Office of Foreign Disaster Assistance Database (OFDA)	USA	**OFDA**	1900-1995	World-wide	Man-made and Natural Catastrophes
Resources for the Future (RfF)	USA	**RfF**	1945-1991	World-wide	Man-made and Natural Catastrophes
Acute Hazardous Events Database (EPA)	USA	AHE	1900-1995	USA	Chemical Accidents
Minerals Management Service Accident Database (access through WOAD)	USA	MMS	1970-1995	USA	Offshore
Major Hazards Incidence Data Service (SRD)	UK	**MHIDAS**	1900-1995	World-wide	Industry
Casualties and Demolition Database (Lloyd's)	UK	LLOYD'S	1976-1995	World-wide	Offshore
MARCODE (HSE)	UK	MARCODE	1985-1995	UK	Industry
SIGMA (Schweizer Rück)	Switzerland	**SIGMA**	1969-1995	World-wide	Man-made and Natural Catastrophes
WOAD Offshore Databank (DNV)	Norway	**WOAD**	1970-1995	World-wide	Offshore
Failure and Accidents Technical Information System (TNO)	Netherlands	**FACTS**	1920-1995	World-wide	Industry
SONATA (TEMA/ENI)	Italy	SONATA	--	World-wide	Industry
Accidents Book (UB)	Germany	**HSUB**	1900-1983	World-wide	Industry
List of Failed Dams (ICOLD)	France	**ICOLD**	1850-1992	World-wide	Dam Accidents
VARO (LRIOH)	Finland	VARO	1978-1987	Finland	Man-made and Natural Catastrophes
Emergency Preparedness Canada Disaster Database	Canada	EPC	1900-1995	Canada	Man-made and Natural Catastrophes
Emergency Disaster Events Database (CRED/CUL)	Belgium	EM-DAT	1900-1995	Belgium	Man-made and Natural Catastrophes
Inventory of Belgian Catastrophes	Belgium	IBC	1889-1995	Belgium	Man-made and Natural Catastrophes
Major Accident Reporting System (JRC-ISEI)	European Community	**MARS**	1980-1991	Europe	Industry

Table 1: Major accident databases [4]; the code names of sources directly utilised in the present work are shown in boldface.

In a comprehensive analysis, accidents associated with parts of energy chains outside of the borders of the country for which the study is being performed should be included. For a specific country various energy chains usually have very different structures with respect to their geographical locations. For example, hydro power (which represents a simple chain) is completely domestic, while for most countries (including Switzerland) in the case of nuclear energy only the power plants and waste storage facilities are within the country with the other parts located abroad. In the oil fuel cycle such accident-prone activities as oil extraction and ship transportation are usually totally external but a proper share of these accidents should be allocated to the domestic power production. The analysis of domestic facilities should be based, if feasible, on PSA methods and supplemented with historical data. Whenever PSAs for other plants and/or past experience are used, the applicability/transferability of the results to the situation being analysed should be considered. The application-oriented screening of the data can lead to reduction of the risks for plants having excellent safety features. In other cases, when these features are worse than average, the plant-specific risk should be increased on the basis of careful extrapolation.

Following this strategy, a detailed analysis was performed within this project for the hydro and nuclear chains. These detailed analyses are, however, outside of the scope of the present paper.

3 THE PSI DATABASE AND ITS MERITS

The present work establishes a comprehensive database on severe accidents, with main emphasis on the ones associated with the energy sector.

ENSAD (Energy-related Severe Accident Database), which covers all stages of the analysed energy chains, has been established using a wide variety of databases and other information sources. Numerous checks and complementary analyses beyond the main sources of information were carried out. In this context, particular attention was given to the applicability and transferability of the data.

Currently, the ENSAD database covers 9845 accidents, of which 3319 (33.7%) are energy-related; 6843 (69.5%) accidents were classified as man-made and the remaining 3002 (30.5%) as natural. The percentage of energy-related accidents among the man-made ones is 48.5%. This fraction is, however, not fully representative (i.e. the share of energy-related accidents is overestimated) since at present ENSAD does not cover transportation and traffic accidents unless they belong to a specific fuel cycle or the accident resulted from an interaction with a fuel cycle.

Typically about 30 energy-related accidents with at least five fatalities per accident occur world-wide each year. Among them 1 - 5 accidents per year had consequences exceeding 100 fatalities. Nearly 90% of the energy-related accidents collected in ENSAD occurred in the time period 1945 - 1992. This dominance is mainly due to the increased level of activities; however, improved reporting coverage probably also plays an important role to this effect.

A comprehensive definition of what constitutes a severe accident was established and consequently applied to coal, oil, gas, nuclear and hydro power energy chains. Thus, an accident is considered to be severe if one or more of the following applies:

1. at least five fatalities
2. at least ten injured
3. at least 200 evacuees
4. extensive ban on consumption of food
5. releases of hydrocarbons exceeding 10 000 tonnes
6. enforced clean-up of land and water over an area of at least 25 km^2
7. economic loss of at least 5 million US$.

Various types of consequences are covered to a different extent, depending on the availability and quality of the data. These factors differ between the different energy sources. Generally, the data concerning fatalities are more complete and accurate than those concerning other types of consequences.

Fig. 1 shows the content of ENSAD in terms of the number of accidents of the different types and within specific consequence categories.

Applying the definition of a severe accident, established in the present work, 1772 energy-related accidents stored in ENSAD are severe. Accidents with at least five fatalities form the largest group (807 events). There is also in descending order a large number of energy-related accidents involving major releases of hydrocarbons, injuries, large economic losses and evacuations. This distribution is quite similar to the one which applies for man-made events in general, while for the natural accidents large pollutant releases are rarely reported.

Below follow some facts with respect to the consequences (here limited to fatalities) of the accidents represented in ENSAD:

- 48.2% of all accidents with at least five fatalities are man-made;
- 22.8% of all accidents with at least five fatalities are energy-related;
- 47.3% of man-made accidents with at least five fatalities are energy-related;
- 28.6% of all accidents with at least 100 fatalities are man-made;

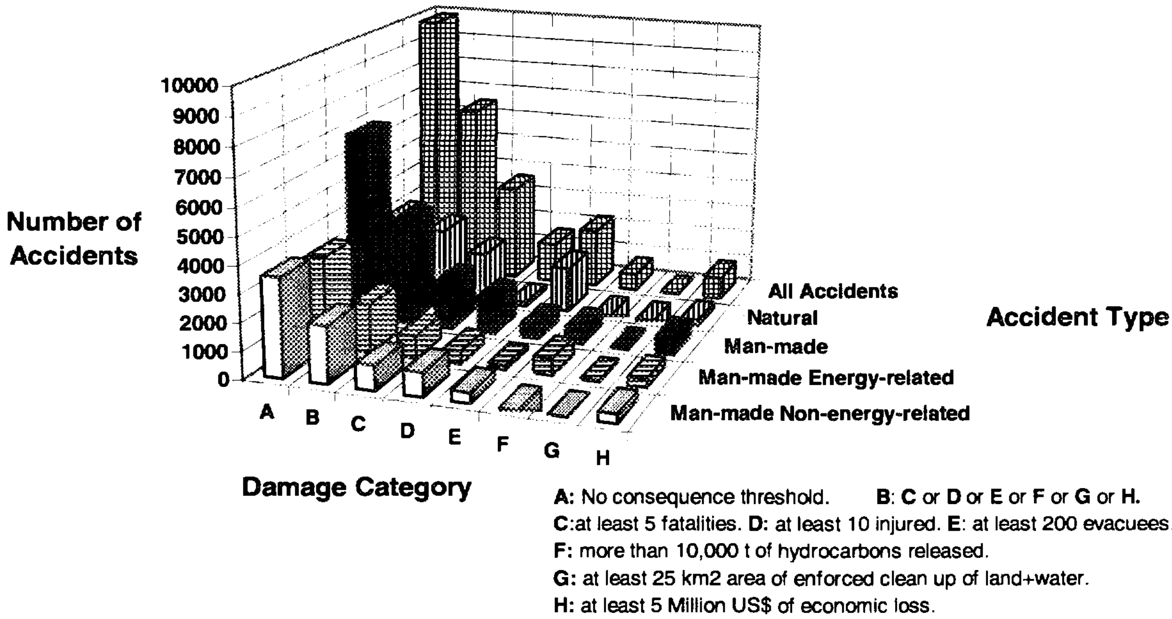


Fig. 1: Content of ENSAD - number of accidents by type and damage category [4].

- 7.2% of all accidents with at least 100 fatalities are energy-related;
- 25.2% of man-made accidents with at least 100 fatalities are energy-related.

Clearly the share of man-made accidents and energy-related ones in particular decreases when the very large accidents are considered. This is because natural disasters frequently have extremely severe consequences and dominate this category. Summing all fatalities due to accidents in the period 1969 - 1992 as covered by ENSAD amplifies this picture. Thus, the energy-related accident fatalities constitute only 1.1% of the total in this period. This does not include the latent fatalities associated with the Chernobyl accident, which may be manifested over a 70 year period. Inclusion of the estimated latent fatalities and its allocation to this period of time would increase the contribution from the energy-related fatalities to between 1.4 and 2.3% (depending on whether a radiation dose cut-off is used or not). This is still a relatively small share which would be further reduced by inclusion of all transport and traffic accidents.

Sixty five percent of all reported severe accidents with at least 5 fatalities occurred in the Western World. Similar to the registered increase (in relation to the past) of the number of energy-related accidents during the last 20 years, this is primarily caused by the higher level of activity but some influence of underreporting from the developing countries is evident.

By using a variety of information sources from various countries, ENSAD has a balanced coverage with respect to countries and regions where the accidents took place. This eliminates a problem encountered in many other accident databases where local circumstances limit the availability and quality of information.

Access to and implementation of the highly diverse input resulted also in a much more extensive coverage of man-made accidents in ENSAD in comparison with other databases. In particular, while there are 807 energy-related accidents with at least five fatalities in ENSAD, MHIDAS [15] contains 222 such events and SIGMA [16] 170 such accidents. It has been shown that even when higher damage categories are considered, ENSAD provides superior coverage of energy-related accidents.

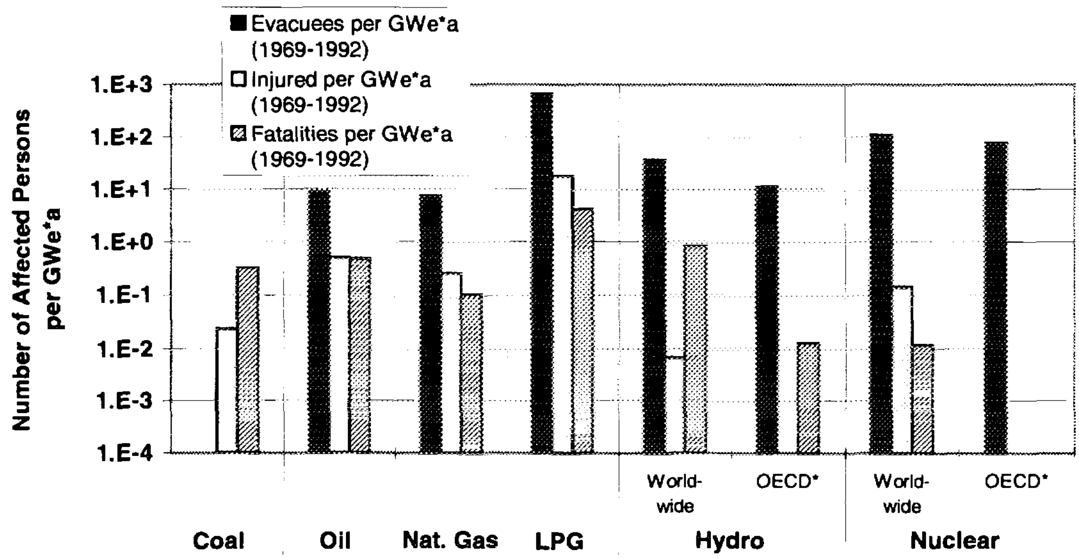
4 COMPARATIVE ASSESSMENT

This paper presents some examples of comparisons between the results obtained for the various energy chains. Detailed energy chain-specific results may be found elsewhere. For the full account we refer to [4], but some highlights, e.g. estimated failure rates for different types of hydro dams and offshore oil spills, may be found in [17]. Similarly, for the account of the PSA-based analyses, including external costs associated with hypothetical severe nuclear power plant accidents, we refer to [4, 5, 18, 19].

4.1 Energy chain comparisons

Comparisons between the different energy sources, based on the statistical evidence, were carried out for the period 1969 - 1992.

The lower limit for the evaluations has been chosen with view to temporal changes in technology, safety regulations, efficiency of emergency services, degree of underreporting etc.



* Includes all OECD countries except Japan and the Republic of Korea. This exclusion enhances the consistency of the comparison since our records on Japanese dam accidents are incomplete.

Fig. 2: Comparison of aggregated, normalised energy-related severe accident records for the period 1969 - 1992; **immediate** fatalities, injured and evacuated persons per unit of energy [4].

Fig. 2 shows the estimated number of **immediate** fatalities, injured and evacuated persons per unit of energy for six energy chains. Only accidents with at least 5 fatalities, 10 injured and 200 evacuated, respectively, have been included. With the exception of Liquefied Petroleum Gas (LPG) all other energy chains represent different means for electricity production. The results are based on world-wide accident statistics assembled within the present work. In the case of hydro and nuclear, the results based on past accidents in OECD countries (with the exception of Japan and Republic of Korea) are provided separately. For normalisation, data on energy production by different means were used, expressed in terms of equivalent electrical output; these data originate primarily from the International Energy Agency [20].

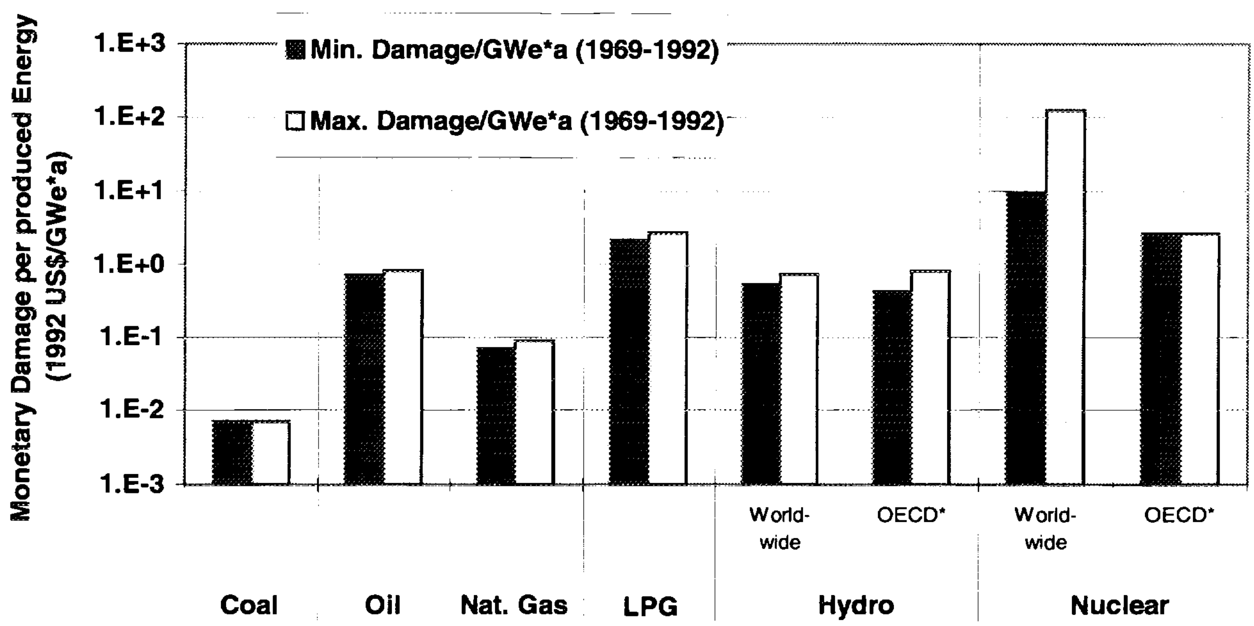
The **delayed** fatalities, particularly relevant for the Chernobyl accident, must to be treated separately. The current best estimate of the Chernobyl-specific delayed fatalities, primarily based on the assessed doses received by the emergency workers and by the public, is in the range 2.9 to 10.4 fatalities per GWe*a produced by the nuclear energy; the upper bound was obtained using no exposure threshold, an approach not recommended by the Health Physics Society [21].

The statistical evidence available for nuclear accidents resulting in fatalities is limited to one accident. In the case of hydro power the statistical basis is significantly better but still not very extensive. On the other hand, the number of records for the fossil energy chains is relatively high.

In the nuclear case, contrasting the Chernobyl-specific results with probabilistic estimates typically obtained for western reactors demonstrates that naive uses of the historical data may be crude and sometimes evidently unsuitable. In the hydro case, as demonstrated in Fig. 2, using the records for the OECD countries only, the normalised fatality rate decreases by a factor of more than 50 in comparison with the generic world average. This result is comparable with the corresponding PSA-based estimate of $2.0 \cdot 10^{-2}$ **latent** fatalities per GWe*a, obtained for the Swiss nuclear power plant Mühleberg. Both estimates illustrate one of the pitfalls of the uncritical use of the generic experience.

The regional dependence applies also to coal, oil and LPG chains, and less so to natural gas. However, here the generic data may be much more applicable also for developed countries, particularly those which are importers of coal, oil and/or gas (applies fully to Switzerland) and where the impacts of external parts of various energy chains are to be accounted for. The reason for this is that for these chains the extraction and/or long transport steps exhibit high, frequently dominant relative risk importance.

The comparison of economic damages is limited by incompleteness and some serious inconsistencies. First, the estimates of monetary losses are not available for a major part of non-nuclear accidents. Second, the cost elements covered, i.e. the boundaries of the calculation, are normally not documented and may vary widely from case to case. Third, the nature of the reported costs may be different - there is normally a large discrepancy between the compensation paid by insurance companies, claimed damages, real damages, direct costs and indirect costs. In the nuclear case the costs of two accidents have been included, namely TMI and Chernobyl. They are domi-



* Includes all OECD countries except Japan and the Republic of Korea. This exclusion enhances the consistency of the comparison since our records on Japanese dam accidents are incomplete.

Fig. 3: Comparison of aggregated, normalised economic losses due to energy-related severe accidents in the period 1969 - 1992 [4].

nated by the latter accident which exhibits more than one order of magnitude difference between the lower and higher bound of the cost estimate.

Fig. 3 shows the monetary damages for each of the energy chains, normalised by the energy produced and based on the currently available information. The results and their interpretation are subject to the serious reservations mentioned above.

Due to the devastating damages associated with the Chernobyl accident, the normalised monetary damages are clearly highest for the nuclear chain, followed by LPG, oil, hydro, natural gas and coal. Consideration of the regional distribution of accidents leads to a somewhat different ranking for the developed countries.

It is also worthwhile to note that the somewhat arbitrary limitation of the evaluation period strongly influences the results. For example, some of the hydro accidents that occurred further back in time resulted in extremely high damages.

Fig. 4 shows **immediate** fatalities for various energy chains as normalised frequency-consequence curves. Coal and oil chains exhibit the highest frequency of accidents up to the level of about 70 fatalities per GWe*a while hydro has the lowest. The reverse applies at higher levels of consequence. Fatalities in the coal chain are predominantly occupational in contrast with the other energy carriers.

The results for the Swiss nuclear power plant Mühleberg, shown in Fig. 5, originate from the plant-specific Probabilistic Safety Assessment (PSA) and represent **latent** fatalities; the different curves illustrate the outcome of uncertainty propagation. The range of values for predicted Chernobyl-specific latent fatalities reflects the impact of using a dose cut-off. The large difference between the PSA-based results obtained for Mühleberg and the experience-based Chernobyl results illustrates once again the limitations in applicability of past accident data to cases that are radically different in terms of technology and operational environment.

4.2 Issues in comparative assessment of energy-related severe accidents

In spite of significant progress made, some issues in the comparative assessments of severe accidents remain open. They are difficult to handle or may be subject to inherent limitations. The following summary is not exhaustive:

- **Non-uniform level of knowledge and limited scope of applications of risk analysis**. Few comprehensive PSAs have been performed for energy chains other than nuclear although there is a steadily growing number of applications for offshore, fuel transport, refineries, gas storage etc. Regrettably few of such studies are published and available for potential users.

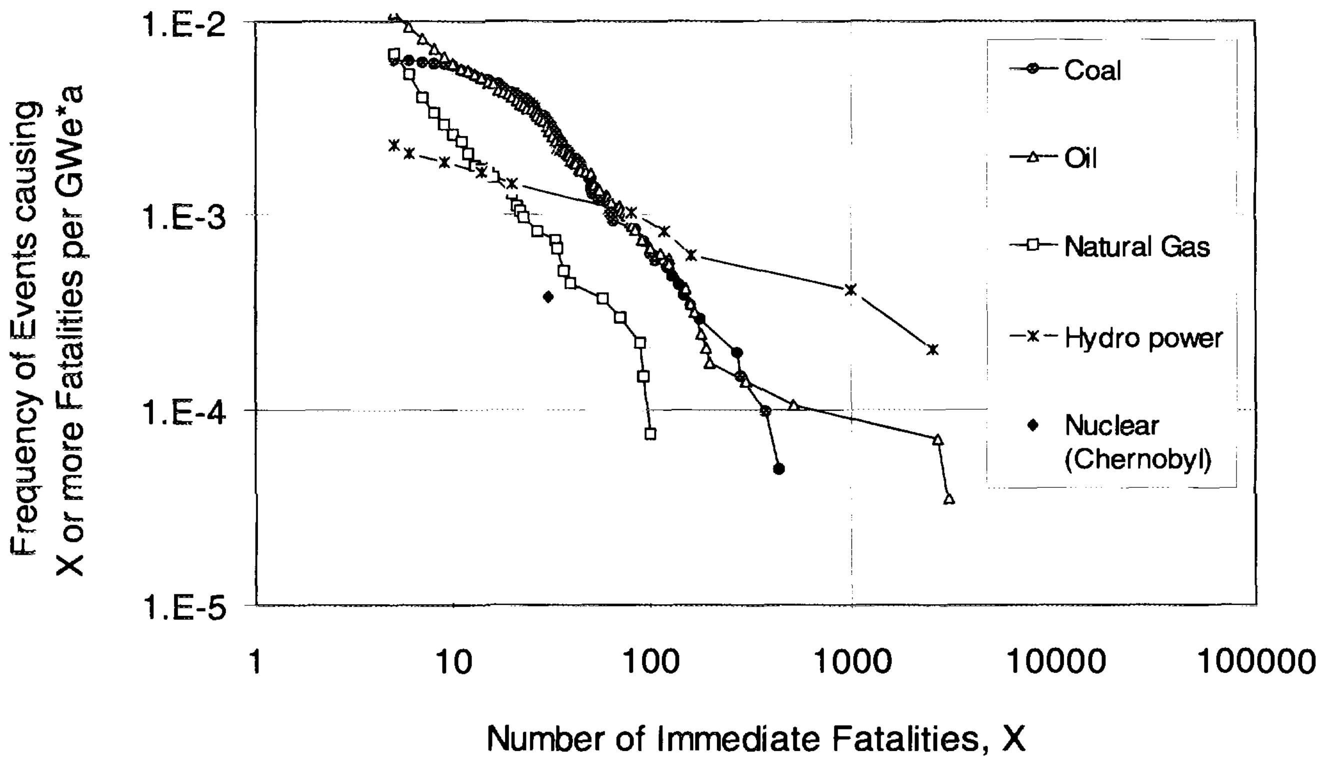


Fig 4: Frequency-consequence (**immediate** fatalities) curves for different energy chains, based on historical accidents world-wide in the period 1969 - 1992 [4].

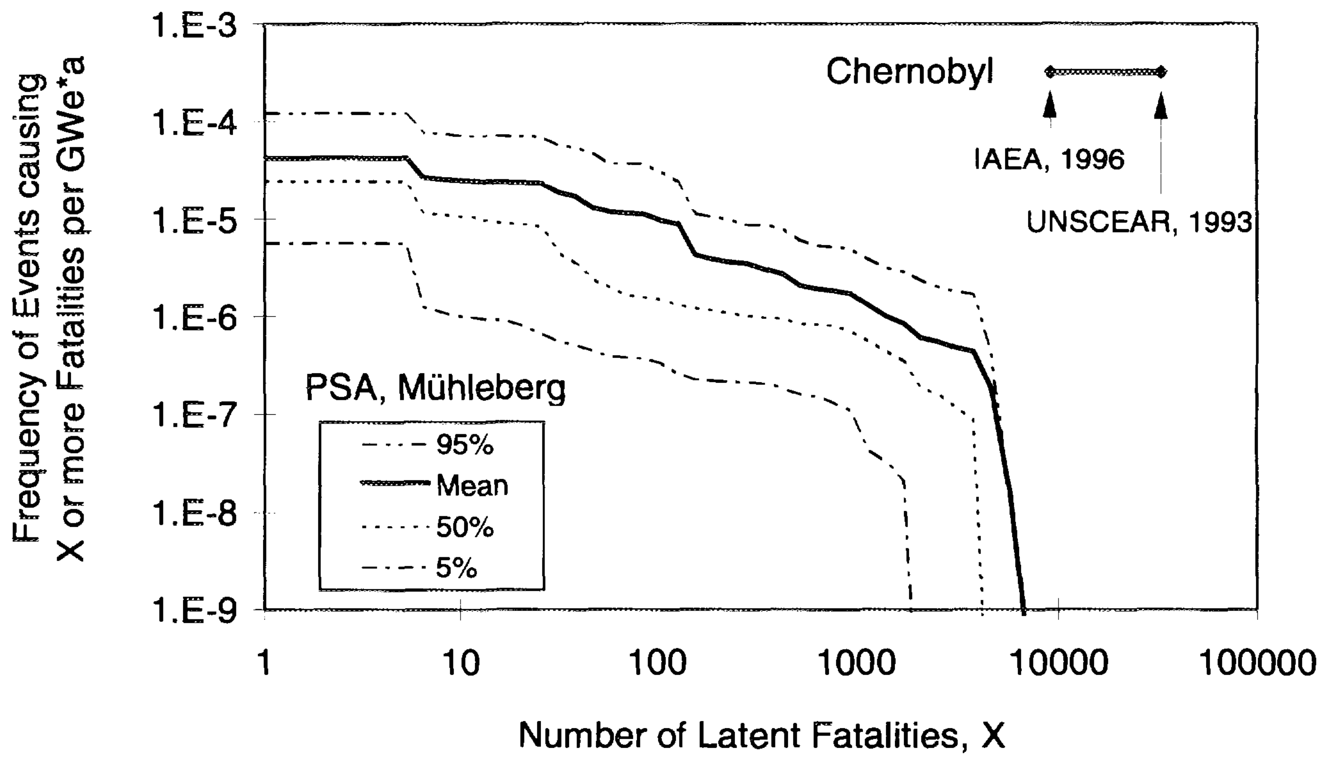


Fig. 5: Frequency-consequence (**latent** fatalities) curves for different energy chains, based on PSA for the Swiss nuclear power plant Mühleberg [22] and on the Chernobyl-specific potential latent fatalities with and without dose cut-off [4].

- **Uncertainties in PSA**. While uncertainties are implicitly represented in all analyses, including the deterministic ones, PSA makes them visible. The most significant limitations of nuclear PSA, which affect the uncertainties, concern the treatment of human interactions, common cause failures, external events, phenomenological aspects of accident progression and source term issues. Some of these limitations (such as the treatment of human interactions) also apply to non-nuclear PSAs; however, due to the multitude of processes involved, generalisations are not possible.
- **Difficulties to cover a wide range of consequences in a consistent manner**. There is a discrepancy between the wide range of consequence categories covered by the definition of severe accidents and the current possibilities to consistently quantify their extent and the associated likelihood for different energy technologies. For this reason, reasonably consistent comparisons of quantitative indicators are usually by necessity limited to only a few categories.
- **Treatment of the distribution of impacts in time and space**. Given the increased uncertainty of the long range assessments there is a need to agree on reasonable analysis boundaries that reflect the priorities of decision makers. This issue is open also in the context of impacts of normal operation.
- **Applicability and transferability of severe accident data**. Due to technological, operational, cultural and environmental differences, when analysing a specific object any use of generic data or data specific for a plant other than the one being examined must take into account these differences. This inevitably involves use of engineering judgement.
- **Treatment of risk aversion and non-quantifiable social detriments associated with extreme accidents**. No consensus exists with respect to the appropriate methods and data to be used to quantify risk aversion. Further research will help to improve and balance the current situation but is not expected to fully resolve this issue in the near future.

In [4] recommendations for future work are provided. These include: (a) Database maintenance and basic extensions; (b) Coverage of renewable energy sources other than hydro power; (c) Consideration of technological advancements and associated safety improvements; (d) Further applications of probabilistic techniques; (e) Estimation of external costs associated with energy-related severe accidents (beyond the nuclear energy chain); (f) Swiss-specific allocation of accidents in external stages of energy chains; (g) Development of site-specific consequence analysis for hydro power; (h) Refinements and broadening of comparative assessment; (i) Explicit consideration of risk perception/aversion.

5 REFERENCES

[1] S.Hirschberg, *Framework for and Current Issues in Comprehensive Comparative Assessment of Electricity Generating Systems.* Invited paper presented at the International Symposium on *Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making*, organised by EC, ESCAP, IAEA, IBRD, IIASA, OECD/NEA, OPEC, UNIDO, WMO, 16 - 19 October 1995, Vienna, Austria. IAEA Proceedings Series, Vienna (1996) 245 - 278.

[2] M.J. Chadwick, ed., Key Issue Paper No. 3 by International Expert Group 3: *Comparative Environmental and Health Effects of Different Energy Systems for Electricity Generation.* Proceedings of Senior Expert Symposium on Electricity and the Environment, 13 - 17 May 1991, Helsinki, Finland. IAEA, Vienna (1991) 91 - 141.

[3] A.F. Fritzsche, *Severe Accidents: Can They Occur Only in the Nuclear Production of Electricity?* Editorial, Risk Analysis, **12** (1992) 327 - 329.

[4] S. Hirschberg, G. Spiekerman, R. Dones, *Severe Accidents in the Energy Sector.* PSI Report, First Edition, Paul Scherrer Institut, Würenlingen and Villigen, CH (to be published 1997).

[5] S. Hirschberg, *External Costs of Nuclear Reactor Accidents*, 28 pp., November 1995. Contribution to the OECD/NEA Report on Methodologies for Assessing the Economic Consequences of Nuclear Reactor Accidents (to be published 1997).

[6] S. Hirschberg, *Severe Accidents*, 12 pp., November 1995. Contribution to the IAEA/World Bank Reference Book on Enhanced Electricity System Analysis for Decision Making (to be published 1997).

[7] S. Hirschberg, *Key Methodological Issues*, 33 pp., March 1996. Contribution to the IAEA Guidelines for the Comparative Assessment of Health and Environmental Impacts of Electrical Energy Systems (to be published 1997).

[8] A.F. Fritzsche, *Gesundheitsrisiken von Energieversorgungssystemen; Von der Kohle bis zu Energien der Zukunft und den Rohstoffen bis zu Entsorgung*, Verlag TÜV Rheinland, Köln (1988).

[9] A.F. Fritzsche, *The Health Risks of Energy Production*. Risk Analysis, **9** (1989) 565 - 577.

[10] European Commission, *Externalities of Energy.* Volumes 1 - 6, published by the European Commission Directorate General XII, Luxemburg (1996).

[11] ORNL&RfF, *U.S. - EC Fuel Cycle Study.* Reports 1 - 8, prepared by Oak Ridge National Laboratory and Resources for the Future. McGraw-Hill/Utility Data Institute, Washington D.C. (1992 - 1995).

[12] W. Ott et al., *Externe Kosten und kalkulatorische Energiepreiszuschläge für den Strom und Wärmebereich.* Bericht 724.270 D, Bundesamt für Konjunkturfragen, Bern, CH (1994).

[13] S. Hirschberg, G. Erdmann, *Wie hoch sind die Kosten der Stromproduktion? Die Bewertung externer Kosten als heikle Aufgabe.* Neue Zürcher Zeitung, No. 192, 6 October 1994.

[14] P. Zweifel, S. Nocera, *Was kostet die Vermeidung von Atomrisiken? Fundierte Grundlagen zur Bewertung externer Kosten.* Neue Zürcher Zeitung, No. 274, 23 November 1994.

[15] SRD, *The Major Hazards Incidence Data Service.* AEA Technology, Consultancy Services (SRD), Cheshire, UK (1993).

[16] Schweizer Rück, *Naturkatastrophen und Grossschäden.* Nr. 1, January 1970 - 1993, Swiss Reinsurance Company, Zürich, CH (1970 - 1993).

[17] S. Hirschberg, G. Spiekerman, *Comparative Evaluation of Severe Accident Risks Associated with Electricity Generation Systems.* Proceedings of ESREL'96/PSAM-III International Conference on Probabilistic Safety Assessment and Management, 24 - 28 June 1996, Crete, Greece, ed. P.C. Cacciabue, I.A. Papazoglou, Springer-Verlag, London (1996) 39 - 45.

[18] S. Hirschberg, E. Cazzoli, *Contribution of Severe Accidents to External Costs of Nuclear Power.* Proceedings of ENS Topical Meeting on PSA/PRA and Severe Accidents '94, 17 - 20 April 1994, Ljubljana, Slovenia (1994) 242 - 249.

[19] S. Hirschberg, *External Costs of Electric Power Generation - Are Accidents Adequately Treated?* Schweizer Ingenieur und Architekt, **20** (1995) 469 - 473.

[20] IEA, *Energy Statistics and Balances, OECD (1960 - 1991), Non-OECD (1971 - 1991).* International Energy Agency, Diskette Service, OECD, Paris (1993).

[21] K.L. Moosman, M. Goldman, F. Massé, W.A. Mills, K.J. Schiager, R.J. Vetter, *Health Physics Society Position Statement: Radiation Risk in Perspective.* HPS Newsletter **XXIV** 3, March 1996.

[22] E. Cazzoli et al., *A Regulatory Evaluation of the Mühleberg Probabilistic Safety Assessment, Volume II: Level 2.* ERI/HSK Report 93-304, HSK 11/356 (Limited Distribution), Villigen, CH (1993).