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Abstract

The framework of the present work encompassed a primarily experience-based comparison of accident risks associated with the energy sector, with special emphasis on the natural gas chain. The results of this study provide a broader perspective on the gas-specific risk, but this information is also of interest to various stakeholders beyond the gas sector.

Comparative assessment of severe accident risks was primarily based on PSI's database ENSAD (Energy-related Severe Accident Database) because it has a balanced coverage with respect to countries and regions where the accidents took place. Since its establishment in 1998, ENSAD has been continuously maintained, updated and extended using a variety of information sources, which eliminates some constraints that are encountered in many other accident databases driven by the local availability of information. The database allows to perform comprehensive analyses of accident risks, which are not limited to power plants but cover full energy chains, including exploration, extraction, processing, storage, transports and waste management. ENSAD uses seven criteria to define an energy-related severe accident (see chapter 2.1). However, analyses that are presented here focus on those accidents, which resulted in at least five fatalities because completeness and accuracy of the data concerning fatalities is superior to coverage of other types of consequences.

The study utilizes a hierarchical approach including (1) comparative analyses of different energy chains, (2) specific evaluations for the natural gas chain, and (3) a detailed overview of the German situation, based on an extensive data set provided by Deutsche Vereinigung des Gas- und Wasserfaches (DVGW). According to SVGW-expertise DVGW-data can be regarded as fully representative for Swiss conditions due to very similar technologies, management, regulations and safety culture, but has a substantially stronger statistical basis because the German gas grid is about 30 times larger compared to Switzerland. Specifically, the following tasks were carried out by PSI to accomplish the objectives of this project: (1) Consolidation of existing ENSAD data, (2) identification and evaluation of additional sources, (3) comparative assessment of accident risks, and (4) detailed evaluations of specific issues and technical aspects for severe and smaller accidents in the natural gas chain that are relevant under Swiss conditions.

The following sections give an overview of the major insights gained from the results of this study.

Energy chain comparisons: Based on comprehensive historical experience, energy-related accident risks in OECD countries are distinctly lower than in non-OECD countries. Natural gas shows lowest expected fatality rates of all fossil energy chains, both in OECD and non-OECD. Furthermore, maximum consequences for natural gas are also clearly lower than for other fossil chains; not exceeding about 100 fatalities for OECD as well as non-OECD countries, and not exceeding 27 for EU15 and 22 for Central Europe. In comparison, western hydropower and nuclear power plants have even lower expected fatality rates, but maximum credible consequences may be very large. One should be aware that damages associated with severe accidents in the whole energy sector are rather small compared to natural disasters.

Natural gas chain: Overall, the average number of fatalities over the last two decades was substantially lower in OECD than in non-OECD countries. Concerning aggregated fatality rates, they are lowest for Central Europe[a] (0.061 GW_eyr), followed by EU15 (0.077 GW_eyr) and OECD (0.080 GW_eyr), whereas non-OECD (0.110 GW_eyr) exhibits a significantly inferior performance as the other regional and country groups. Similarly, maximum consequences based on experience are also lower for Central Europe and EU15 than for OECD and non-OECD countries.

[a] In the present study "Central Europe" is defined as follows: Switzerland, Germany, The Netherlands, United Kingdom, Belgium and Denmark, depending on similar gas technology and management.

DVGW-data for Germany: Regarding fatalities and injured persons, severe accidents in gas distribution account for only about 10 to 20 percent of the respective totals, indicating that smaller accidents are the dominant contributor. Detailed evaluations of accidents at customer and company installations showed that human misconduct was clearly the primary accident cause. Normalized accident rates decreased over the period 1981 – 2002. This was evident for fatalities and even more pronounced for injured, and is thus likely to indicate a process of continuous improvement of safety in the gas industry.

Accident risk in Europe: In the context of this study it could be demonstrated that ENSAD-data for severe natural gas accidents and DVGW-data for small and severe natural gas accidents are in good agreement as supported by the respective frequency-consequence (F/N) curves. Both databases indicate the low probability of natural gas accidents consequences under European conditions, but additional accident statistics from other countries are needed to verify this accident record throughout Europe.

1 Background

1.1 Objective

The objective of this study is to present comprehensive, primarily experience-based comparisons of accident risks associated with the energy sector, with special emphasis on natural gas. Schweizerischer Verein des Gas- und Wasserfaches (SVGW) intends to use the results to provide a broader perspective on the gas-specific risks. Furthermore, this information is useful for a variety of stakeholders including the gas sector as such, relevant authorities as well as interested politicians on a national and international level.

Within Project GaBE ("Ganzheitliche Betrachtung von Energiesystemen") Paul Scherrer Institut (PSI) established a framework and the associated databases for the systematic and detailed comparative assessment of energy systems. Specifically, risk assessment elements of this approach serve as the scientific basis in the present work for the evaluation of natural gas accident risks.

1.2 Assessment scope and level of detail

The analysis of accident risks is not limited to power plants but covers full energy chains, including in applicable cases exploration, extraction, processing, storage, transports and waste management since accidents can occur at any of these stages.

The study utilizes a hierarchical approach ranging from comparative analysis of different energy carriers to specific analyses within the natural gas chain. Additionally, data are analyzed in depth for different groups of countries or regions (e.g. OECD, EU15, etc), and even for few individual countries when sufficient historical data were available.

First, comparative analyses of natural gas, other fossil energy carriers (Liquefied Petroleum Gas (LPG), coal and oil), hydropower and nuclear power were performed, using aggregated indicators and frequency-consequence (F/N) curves. Second, specific evaluations for the natural gas chain are presented including some technical aspects. Third, a detailed overview of the German situation is given, based on an extensive data set provided by Deutsche Vereinigung des Gas- und Wasserfaches (DVGW). This can also be regarded as representative for Switzerland, but has a substantially stronger statistical basis because the German gas grid is about 30 times larger compared to Switzerland and detailed statistics are available for a period of more than 20 years. Furthermore, these results may also be applicable to other Central European countries.

A relatively broad spectrum of damage categories of interest has been considered. Thus, apart from fatalities also serious injuries, evacuations, land or water contamination, and direct economic losses have been addressed on a case-by-case basis. However, the quality and completeness of the corresponding data varies strongly. The most robust indicators are energy chain specific fatality rates.

In the case of the DVGW-data for Germany also smaller accidents were taken into account because sufficient statistical evidence was available at the national level. However, the focus of the study remained on severe accidents, as these are most controversial and also most problematic in the context of risk classification of the various facilities, proposed in corresponding draft regulations in Switzerland and Europe.

2 Analysis approach

2.1 Methodology

The approach used in this study was based on the evaluation of experience with accidents in the past. Specifically for nuclear power Probabilistic Safety Assessment (PSA) was employed to obtain the relevant accident indicators.

For a detailed description of the methodology, which is beyond the scope of this report, we refer to the work performed by the GaBE group at PSI, covered in some extensive reports (Burgherr et al. to be published; Hirschberg et al. 1998).

The definition of what constitutes a "severe accident" will relate in this work to the minimum damage level for each type of consequence (fatalities, injured persons, evacuees, or economic loss), as defined in PSI's database ENSAD (Energy-related Severe Accident Database).

The PSI database ENSAD uses seven criteria to define a severe accident:

1) at least five fatalities or

2) at least ten injured or

3) at least 200 evacuees or

4) extensive ban on consumption of food or

5) releases of hydrocarbons exceeding 10'000 t or

6) enforced clean-up of land and water over an area of at least 25 km^2 or

7) economic loss of at least five million USD(2000).

Whenever any one of the above criteria is satisfied, the accident is considered to be severe. However, various types of consequences are covered to differing extents because of differences in availability and quality of information. The highest degree of completeness is available for fatalities, whereas information for injured and evacuees is often more uncertain. Therefore, evaluations in this report primarily focus on fatalities, but if applicable and meaningful additional analyses for other indicators were also performed.

Note that smaller accidents are also partially included into ENSAD but their level of completeness is much lower than it is the case for the severe accidents. Therefore, smaller accidents were only addressed in the context of specific evaluations for Germany, for which DVGW-data provided a sufficient statistical basis (compare discussion on pages 8 and 9).

Comparative evaluations for the various energy chains and within the natural gas chain were utilizing and building further on the earlier and ongoing major PSI efforts to carry out comparative assessment of severe accidents in the energy sector in industrialized and developing countries. PSI's database ENSAD, originally established in 1998 and continuously extended since then, constituted the core element for these assessments (Burgherr et al. to be published; Hirschberg et al. 2004; Hirschberg et al. 1998; Hirschberg et al. 2001).

ENSAD uses a large variety of information sources including (but not limited to) a number of commercial and non-commercial databases (Tab. 1), which to various extent address accidents of relevance for the energy sector (Burgherr et al. to be published; Hirschberg et al. 1998). Due to its broad basis ENSAD exhibits a high level of coverage of worldwide accidents, with particular attention being paid to the severe ones. Contributors from the different parts of the various fuel cycles are included. ENSAD allows quantifying a relatively broad spectrum of damage categories of interest. Applications of the ENSAD database, pursued by PSI, include comparative assessment of severe accidents in the energy sector to support energy policy, inputs to sustainability evaluations of current and future options for energy supply, as well as technology-specific externality assessment.

Tab. 1 Accident databases supporting PSI's ENSAD. Databases marked in bold are used as major information sources for the ongoing extension of ENSAD; whereas other databases are of lower importance since they contribute quite limited additional information and/or were discontinued. The time period refers to the currently available databases; the actual period considered when using them, as information sources within ENSAD may be different in some cases.

Full name of the database (contact organization or originators)	Country of origin	Database code name[a]	Time period[b]	Geographical area	Accidents covered
OFDA/CRED International Disaster Database [1]	USA	**EM-DAT**	1900-2003	World-wide	Man-made and natural catastrophes
Hazards Incidence Data Service of the UK Health and Safety Executive (HSE) [2]	UK	**MHIDAS**	1900-2003	World-wide	Industrial accidents
Library and Information Services of the UK HSE [2]	UK	**HSELINE** [3]	1900-2003	World-wide	Accidents related to health and safety at work
The Failure and Accidents Technical Information System (TNO)	Netherlands	**PC-FACTS**	1900-2003	World-wide	Industrial accidents
The "SIGMA" Publication Swiss Re Company	Switzerland	**SIGMA**	1969-2003	World-wide	Man-made and natural catastrophes
Lloyd's Casualty Week (LLP, formerly Lloyd's of London Press)	UK	**LLP** [3]	1976-2003	World-wide	Industrial accidents
The World-wide Offshore Accident Databank (DNV)	Norway	**WOAD**	1970-1998	World-wide	Offshore accidents
International Tanker Owners Pollution Federation Limited	UK	**ITOPF**	1974-2003	World-Wide	Tanker accidents
ETC Tanker Spills Database (US Department of the Interior, Minerals Management Service)	USA	**ETC**	1974-1997	World-Wide	Tanker accidents
The ICOLD Catalogues of Dam Disasters (ICOLD)	France	**ICOLD**	1850-2000	World-wide	Dam accidents
Bibliography of the History of Dam Failures	Austria	**BHDF**	2500 b.C.-2001	World-wide	Dam accidents
China Coal Industry Yearbook	China	**CCIY**	1994-2000	China	Coal chain accidents
The Fatal Hazardous Materials Accidents Database (RfF)	USA	RfF	1945-1991	World-wide	Man-made and natural catastrophes
The Accident Handbook (UBA)	Germany	Handbuch Störfälle	1900-1986	World-wide	Industrial accidents
The Major Accident Reporting System (CEC JRC-Ispra)	European Community	MARS	1980-1991	Europe	Industrial accidents
Book of the Year (Encyclopaedia Britannica)	UK	Encyclopaedia Britannica	1973-1997	World-wide	Man-made and natural catastrophes
Catalogue of Dam Disasters, Failures and Accidents (Babb and Mermel)	USA	CDDFA	1800-1968	World-wide	Dam accidents
Study on Large Losses in the Gas and Electric Utility Industry (Marsh & McLennan)	USA	MM	1965-1990	World-wide	Accidents in gas and electric utility industry
Minerals Management Service Database (access through WOAD)	USA	MMS	1970-1989	USA	Offshore accidents
Acute Hazardous Event Database (EPA)	USA	AHE	1900-1985	USA	Chemical accidents
SONATA Database (TEMA/ENI)	Italy	SONATA	1850-1998	World-wide	Industrial accidents
VARO Databank (FIOH)	Finland	VARO	1978-1998	Finland	Man-made and natural catastrophes

[1] CRED: WHO Collaborating Centre for Research on the Epidemiology of Disasters; OFDA: The US Office of Foreign Disaster Assistance Database

[2] MHIDAS and HSELINE are part of OSH-ROM (SilverPlatter Directory 2003). OSH-ROM also contains the databases NIOSHTIC and NIOSTHIC-2 (Bibliographic database published by the US National Institute of Occupational Safety and Health) and CISDOC (a product of the International Occupational Health and Safety Centre (CIS) of the International Labour Organisation (ILO).

[3] Note that the databases HSELINE and LLP are not treated as separate sources because most accidents found in LLP were also included in HSELINE. Thus, HSELINE/LLP was used as a common database code name.

Ongoing efforts, pursued by PSI primarily within and in connection with the EU research project NewExt (New Elements for the Assessment of External Costs from Energy Technologies) include:

- Review of numerous relevant external database inputs with respect to suppliers, scope, update frequency, costs etc.
- Selection of external databases of direct interest for ENSAD. Major commercial and non-commercial databases consulted as information sources and used to update and extend ENSAD are given in (Burgherr et al. to be published; Hirschberg et al. 1998). In addition to databases covering a broad spectrum of sectors also energy chain specific databases are searched.
- For normalization the continuously updated IEA database on worldwide energy production and consumption is used (IEA 2002).
- Searches for historical data on smaller accidents are carried out. Though these accidents are not in focus, they are addressed on a much lower level of detail, in order to put severe accidents into perspective. There are strong indications that small accidents are strongly underrepresented in the available databases.

In addition to the extensions of the database a methodology has been developed by PSI and University of Bath to estimate external costs from major accidents, thus advancing comparability with the results earlier obtained for beyond design basis accidents in the nuclear fuel chain. This work allows for the first time a consistent and comprehensive assessment of externalities from major accidents in non-nuclear fuel chains.

The statistical evidence for fossil systems as represented in ENSAD is very extensive and can be regarded as quite satisfactory for comparative studies of interest to SVGW. In addition the current study provides the opportunity to include data from other information sources that are potentially important for the specific evaluation of the natural gas chain. The following sections comment on these sources and their applicability for the current project.

US Office of Pipeline Safety (US OPS)

The Office of Pipeline Safety (OPS) in the US Department of Transportation (DOT) provides detailed statistics on natural gas pipeline safety for distribution and transmission incidents (US OPS 2004). Data are available for the period 1984 – 2004, and in a slightly different format also for the period 1970 – 1984.

Severe accidents from this source are included in the ENSAD database, and therefore represented in evaluations on chain comparisons (chapter 3.1) and specific evaluations for the natural gas chain (chapter 3.2). Concerning smaller accidents data were not used for a detailed analysis because US conditions were not regarded as fully comparable to those in Switzerland.

ETPS-data and EU regulations for control of major hazard pipelines

Statistics from the European Working Group on Third Party Safety (ETPS) included data for distribution, gas installations and appliances for the period 1995 – 2003 (ETPS 2004). At European Union (EU) level there are ongoing efforts to assess the requirements on safety management systems in EU regulations for the control of “Major-Accident Hazard Pipelines” (e.g., Papadakis 1999; Papadakis et al. 2004; and literature cited therein). In both cases only cumulated data were available, which were not suitable for a detailed evaluation within the framework of this study.

European Gas Pipeline Incident Data Group (EGIG)

Data from EGIG cover only a limited part of the natural gas network (design pressure ≥ 15 bar) (EGIG 2002). In contrast, the current study examines high-pressure transports and low-pressure distribution networks. Additionally, definitions of criteria for inclusion of fatalities or injured were not fully compatible with the scope of this work. Taking into account these differences lead to the decision that EGIG-data were not used within the present study.

Other data

Other information sources checked included the Office of Gas Safety (OGS) in Australia (e.g., OGS 2004) and the All Russian Scientific/Research Institute for Natural Gas and Gas Technology (Levin & Kharionovsky 1993) among others. But structural conditions and applied technologies in the natural gas sector of these countries are very different from Switzerland so that we refrained from using either of these data.

DVGW-data for Germany

As a result of this extensive survey data from the Deutsche Vereinigung des Gas- und Wasserfaches (DVGW) for Germany were retained because they were most suitable for a number of reasons[a]:

- DVGW-data (DVGW 2004) for Germany are also representative for the situation in Switzerland according to SVGW expertise.
- The number of more than 1300 accidents in the German natural gas chain for the period 1981 to 2002 provides an excellent statistical basis for detailed evaluations including a variety of technical aspects.
- In comparison, consistent Swiss data (SVGW 2004) are only available since 1995, amounting to about 140 incidents and accidents, of which 11 events resulted in a total of 16 fatalities.

In summary, the following tasks were carried out by PSI to accomplish the objectives of this project:

- *Consolidation of existing ENSAD data* according to the lines described above; this activity partially builds upon earlier work performed within the EU project NewExt (Burgherr et al. to be published) but for the purpose of the project described here, a separate and more in-depth review of gas accident data was needed.
- *Identification and evaluation of additional sources* covering gas-specific accident data and possibly analyses of such accidents. Implementation of the relevant data into ENSAD.
- *Comparative assessment* of the various energy chains to be considered according to the scope of the project. This needs to be based on suitable pooling of the data with view to their applicability to the conditions valid for the Swiss case. The emphasis in the analysis of results will be put on the performance of natural gas.
- *Detailed evaluations of specific issues and technical aspects* (i.e., accident types and causes as well as installation types) *for severe and smaller accidents* in the natural gas chain that are relevant under Swiss conditions.

[a] Also compare chapter 3.3.1.

2.2 PSI's ENSAD database

ENSAD contains currently 18'400 accidents (Fig. 1). Man-made accidents comprise 12'943 or 70.3% of the total, whereas natural disasters amount to 5457. A total of 6404 energy-related accidents correspond to 34.8% of all accidents or 49.5% of man-made accidents. Among the energy-related accidents 3117 (48.7%) are severe, of which 2078 have 5 or more fatalities. Non-energy-related accidents and natural disasters are of second priority within ENSAD. Consequently, the corresponding data are likely to be less complete and of lower quality than the ones provided for the energy-related accidents.

About 89% of all accidents included in ENSAD occurred in the period 1969-2000. Therefore, forthcoming results and statistical evaluations that are presented in this report focus on the period 1969-2000. Additionally, the number of energy-related accidents, which are in the focus of this report, exhibited a distinct increase since the late sixties (also compare Hirschberg et al. 1998), giving additional support to this selection. Fig. 2 shows the number of fatalities worldwide in different types of accidents over this time period of more than 30 years.

Available information on severe accidents in the different energy chains is summarized in Tab. 2. Evaluations and analyses were focused on (but not limited to) fatalities because information on other indicators such as injured, evacuees or economic costs was not available at a comparable level of completeness. However, aggregated indicators could still reveal some general trends.

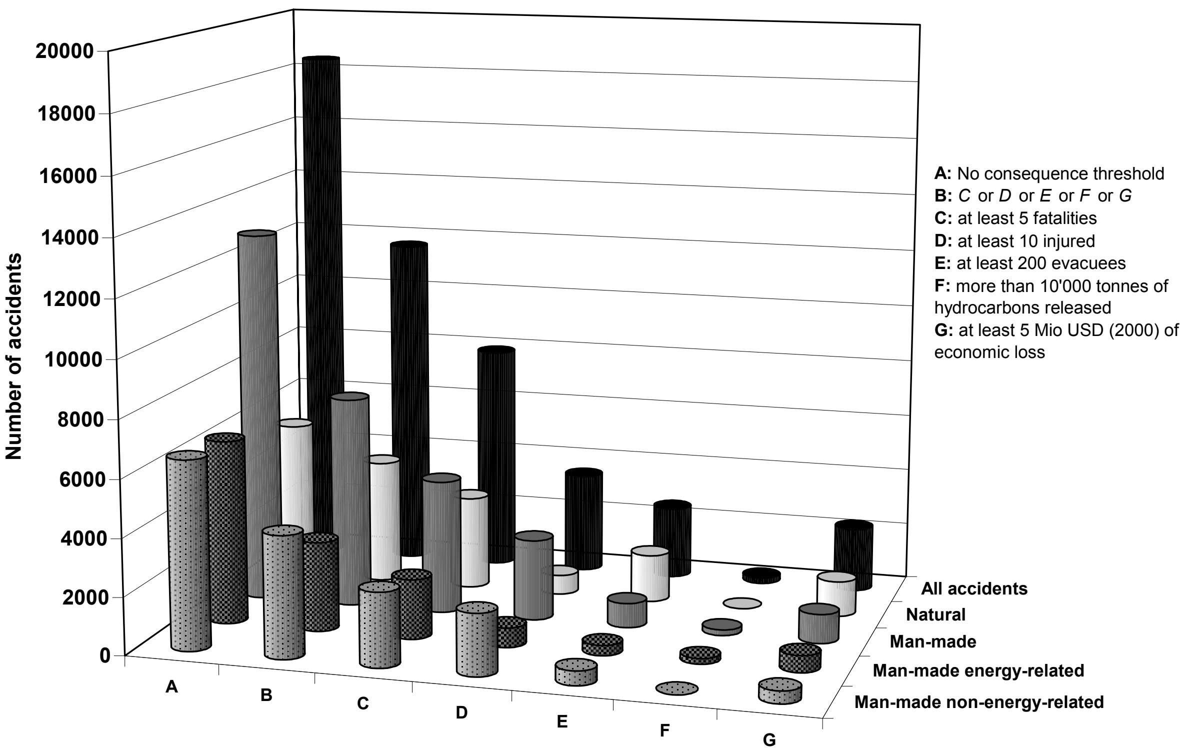

Fig. 1 Overview of the number of accidents by type (natural, man-made, man-made energy-related, man-made non-energy-related) and by different damage categories (indices A-G), as included in ENSAD. Based on data from Burgherr et al. (to be published).

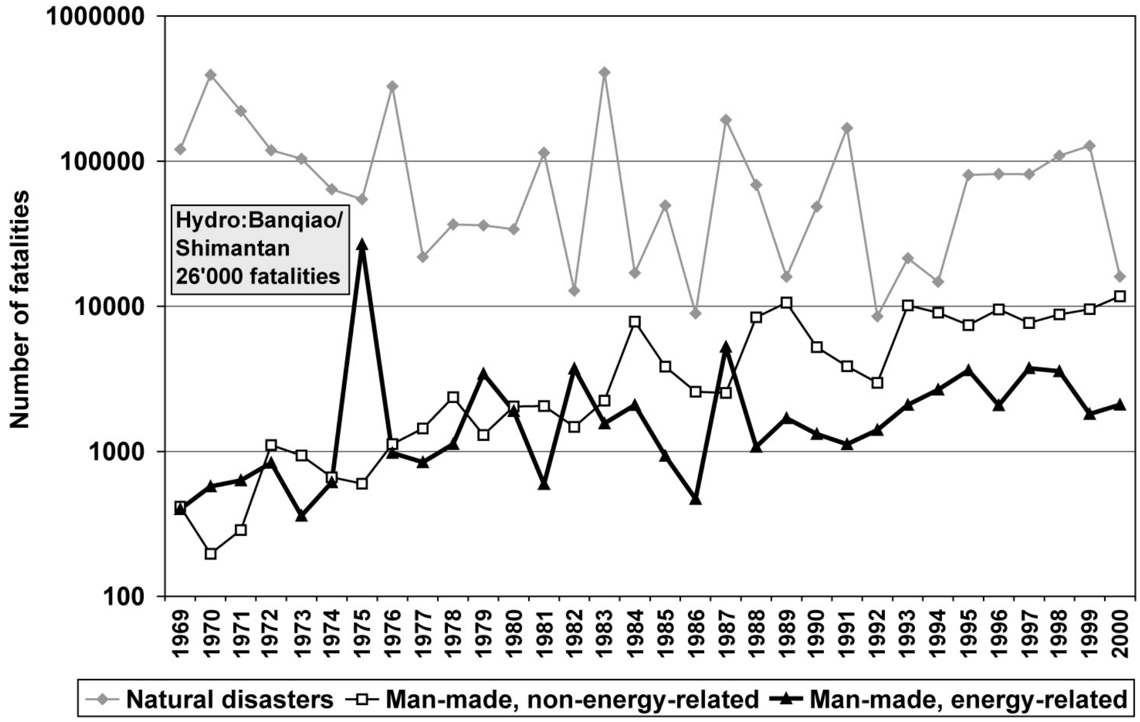

Fig. 2 **Number of fatalities in severe (≥ 5 fatalities) accidents that occurred in natural disasters and man-made accidents in the period 1969 to 2000. Based on data from Burgherr et al. (to be published).**

Tab. 2 **Summary of the severe accident database for accidents with at least five <u>immediate</u> fatalities. The time period considered is 1969 – 2000. Accident statistics are given for the categories OECD (incl. EU15), EU15 alone, and non-OECD. Based on data from Burgherr et al. (to be published).**

	OECD		EU15		non-OECD	
Energy chain	*Accidents*	*Fatalities*	*Accidents*	*Fatalities*	*Accidents*	*Fatalities*
Coal	75	2259	11	234	102 1044 [(a)]	4831 18’017 [(a)]
Oil	165	3789	58	1141	232	16’494
Natural Gas	90	1043	24	230	45	1000
LPG	59	1905	19	515	46	2016
Hydro	1	14	0	0	10	29’924 [(b)]
Nuclear	--	--	--	--	1	31 [(c)]

[(a)] First line: Coal non-OECD w/o China; second line: Coal China

[(b)] Banqiao and Shimantan dam failures together caused 26’000 fatalities

[(c)] Latent fatalities are treated separately.

3 Results

3.1 Energy chain comparisons

3.1.1 Aggregated indicators

The comparative evaluations of aggregated, normalized, energy-related damage rates shown here, are restricted to fatalities because other consequence categories differ in the completeness of data or cannot be compared over all systems (such as released amounts of hydrocarbons and chemicals, or enforced clean-up of land and water). For results concerning such categories we refer to Burgherr et al. (to be published).

For comparative purposes, the data were normalized on the basis of the unit of electricity production for the different energy sources. For nuclear and hydropower the normalization is straightforward since in both cases the generated product is electrical energy. In the case of coal, oil, natural gas and LPG the thermal energy was converted to an equivalent electrical output using a generic factor of 0.35.

The use of Gigawatt-electric-year ($GW_e yr$) was chosen because large individual plants have capacities in the neighborhood of 1 GW of electrical output (GW_e). This makes $GW_e yr$ a natural unit to use in discussions of total electricity production.

In Fig. 3 the calculated numbers of immediate fatalities per unit of energy in OECD and non-OECD countries are shown for the period 1969-2000. Among the fossil energy chains, the highest rates apply to LPG followed by coal and oil, whereas natural gas clearly exhibits the best performance. Note that with the exception for hydro relative rankings based on immediate fatalities are the same for OECD and non-OECD countries. Generally, the immediate fatality rates are for all considered energy carriers significantly higher for the non-OECD countries than for OECD countries. In the case of hydro and nuclear the difference is in fact dramatic. The recent experience with hydro in OECD countries points to very low fatality rates, comparable to the representative PSA-based results obtained for nuclear power plants in Switzerland and in USA.

Aggregated fatality rates for nuclear are very low for immediate fatalities, whereas for latent fatalities state-of-the-art PSAs for representative western plants are used as the reference values (see Hirschberg et al. 1998). PSA-based latent fatality rates for western plants are in the range $10^{-3} – 10^{-1}$ per $GW_e yr$. Delayed fatalities are likely to have occurred for the other chains with no records available; their significance per accident should, however, be incomparably smaller in comparison with the Chernobyl accident.

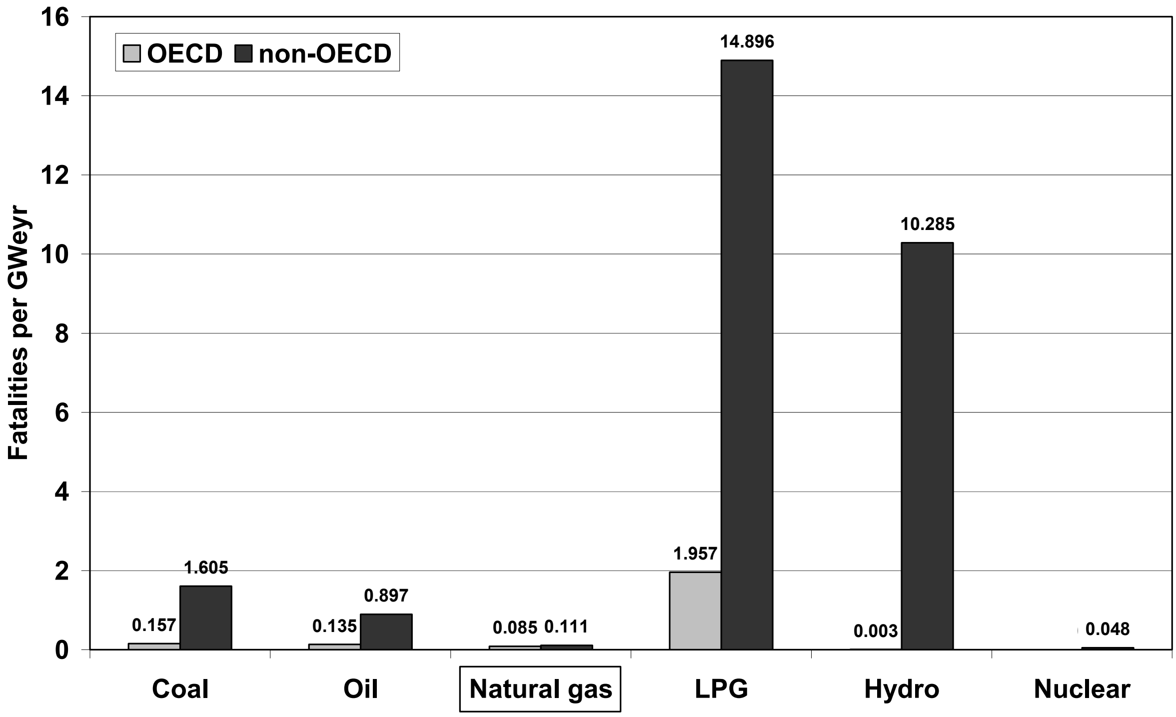

Fig. 3 **Comparison of aggregated, normalized, energy-related damage rates, based on historical experience of severe accidents that occurred in OECD and non-OECD countries for the period 1969-2000. Note that only immediate fatalities are shown, but latent fatalities, of particular relevance for the nuclear chain, have been commented in the text. Based on data from Burgherr et al. (to be published) and Hirschberg et al. (1998).**

3.1.2 Frequency-consequence curves

The comparison of results is not limited to the aggregated values obtained for specific energy chains. Also frequency-consequence (F/N) curves are provided. They reflect implicitly the above ranking but provide also such information as the observed or predicted chain specific maximum extents of damages. This perspective on severe accidents may lead to different system rankings, depending on the individual risk aversion.

Frequency-consequence curves for OECD countries are given in Fig. 4. Among the fossil chains, natural gas has the lowest frequency and LPG the highest frequency of severe accidents involving fatalities, whereas coal and oil chains are ranked inbetween. Hydro experience in OECD countries is significantly lower than for fossil chains, but with respect to fatalities there is only one severe accident for the evaluation period considered. Finally, expectation values for severe accident fatality rates associated with hypothetical nuclear accidents are lowest among the relevant energy chains.

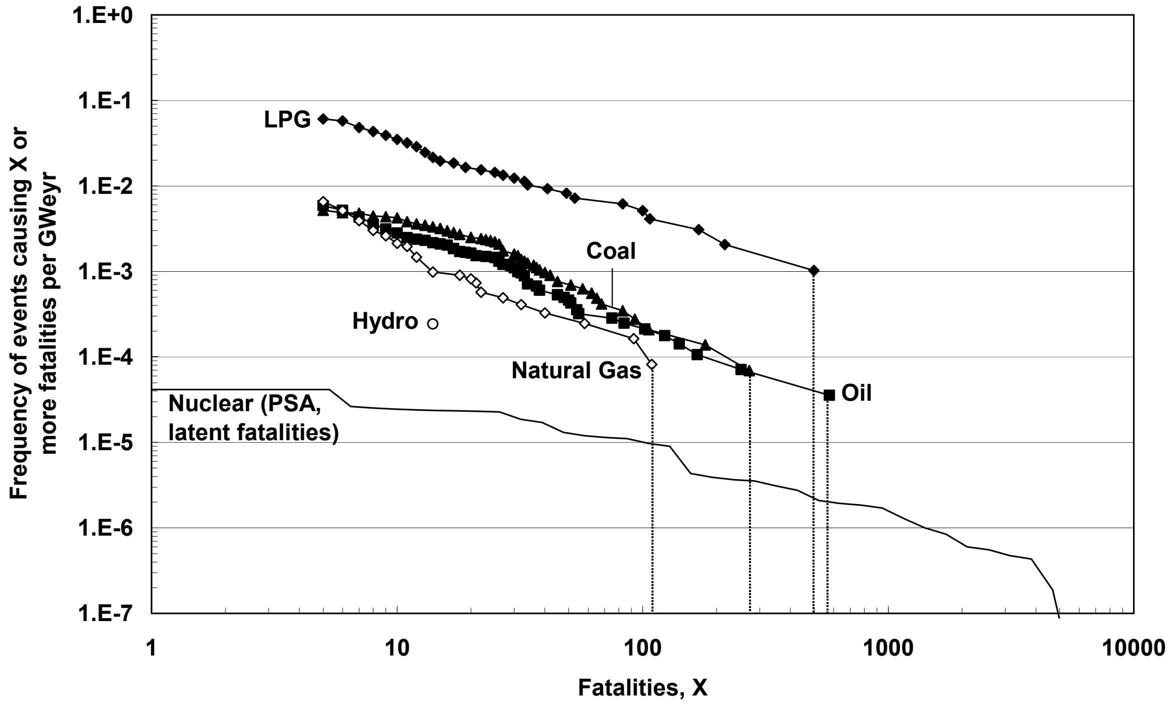

Fig. 4 **Comparison of frequency-consequence curves for full energy chains in OECD countries for the period 1969-2000. The curves for coal, oil, natural gas, LPG and hydro are based on historical accidents and show immediate fatalities. For the nuclear chain, the results originate from the plant-specific Probabilistic Safety Assessment (PSA) for the Swiss nuclear power plant Mühleberg and reflect latent fatalities. Dashed vertical lines represent maximum numbers of fatalities in fossil energy chains. Based on data from Burgherr et al. (to be published).**

In Fig. 5 frequency-consequence curves for non-OECD countries are compared. Fossil energy chains in non-OECD countries display a similar ranking as for OECD countries. Natural gas shows a performance that is about two orders of magnitude better than for LPG, and maximum numbers of fatalities are also six times lower. The Chinese coal chain exhibits significantly higher accident frequencies than in other non-OECD countries[a]. However, the vast majority of severe coal accidents in China result in less than 100 fatalities.

Accident frequencies of the oil and hydro chains are also much lower than for the (Chinese) coal chain, but maximum numbers of fatalities within the oil and hydro chains are one respectively two orders of magnitude higher than for coal and natural gas chains.

Finally, expectation values for severe accident fatality rates associated with the nuclear chain (Chernobyl) are relatively low, but the maximum credible consequences may be very large, i.e. comparable to the Banqiao and Shimantan dam accident that occurred in China in 1975. However, the large differences between Chernobyl-based estimates (Fig. 5) and probabilistic plant-specific estimates for Mühleberg (Fig. 4) illustrate the limitations in applicability of past accident data to cases which are radically different in terms of technology and operational environment.

[a] For a detailed discussion of the Chinese coal chain we refer to Hirschberg et al. 2003a and Hirschberg et al. 2003b.

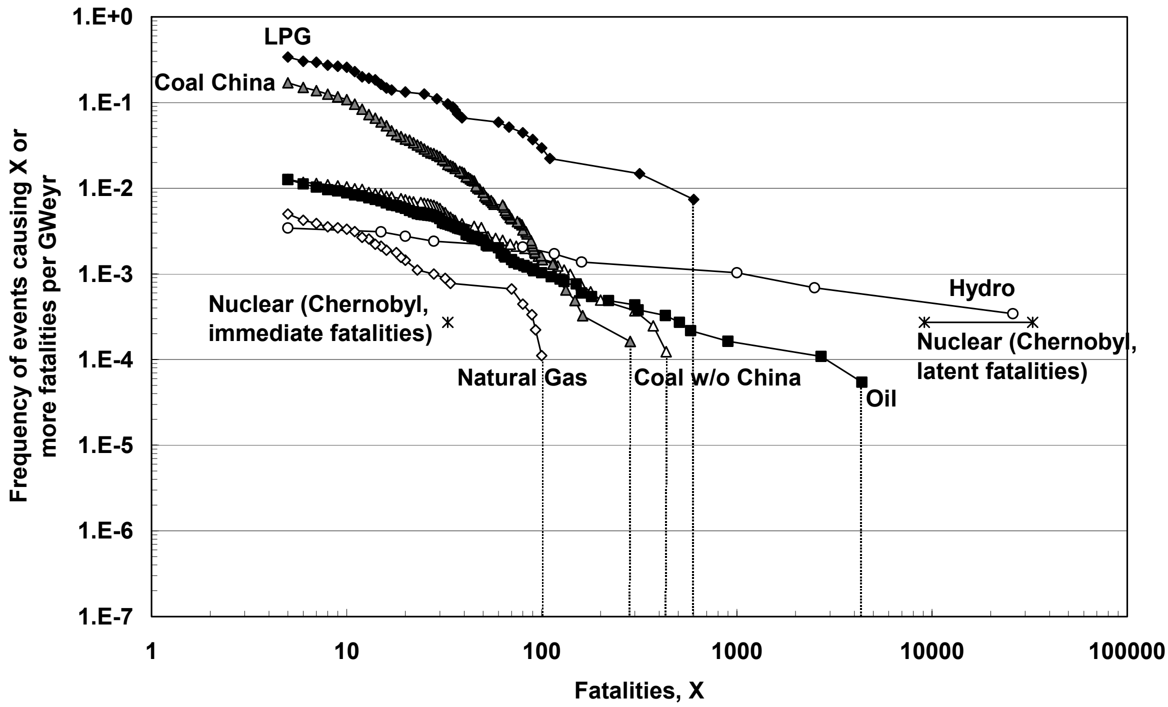

Fig. 5 **Comparison of frequency-consequence curves for full energy chains in non-OECD countries for the period 1969-2000. The curves for coal w/o China, coal China, oil, natural gas, LPG and Hydro are based on historical accidents and show <u>immediate</u> fatalities. For the nuclear chain, the <u>immediate</u> fatalities are represented by one point (Chernobyl); for the estimated Chernobyl-specific <u>latent</u> fatalities lower and upper bound are given. Dashed vertical lines represent maximum numbers of fatalities in fossil energy chains. Based on data from Burgherr et al. (to be published).**

At this point, it should be stated that the worst consequences of accidents in chains other than nuclear, as shown in these F/N-curves, are based on historical experience only. Given lack of statistical data, results of state-of-the-art Probabilistic Safety Assessments (PSAs) for representative western nuclear power plants are used as the reference values (for details see Hirschberg et al. 1998). Concerning hydropower, development of a concept for experience-based dam risk assessment with stronger consideration of design- and location-specific factors would be desirable. An outline of such an approach will be provided in Burgherr et al. (to be published).

3.1.3 Maximum credible consequences

With the exception of nuclear maximum credible consequences are defined as the accident with the largest number of fatalities that ever occurred worldwide for a specific energy chain. This definition is dictated by practical reasons that are discussed in detail by Hirschberg (e.g. Hirschberg et al. 2003b; Hirschberg et al. 1998).

Based on historical experience, maximum numbers of immediate fatalities for fossil energy chains are shown in Fig. 6. Natural gas clearly exhibits lowest maximum consequences with about 100 fatalities for OECD as well as for non-OECD countries. In comparison, largest potential accidents for coal, LPG and oil resulted in about 3 – 6 times more fatalities for OECD countries. Performance of non-OECD countries is even much worse, although the same relative ranking is obtained.

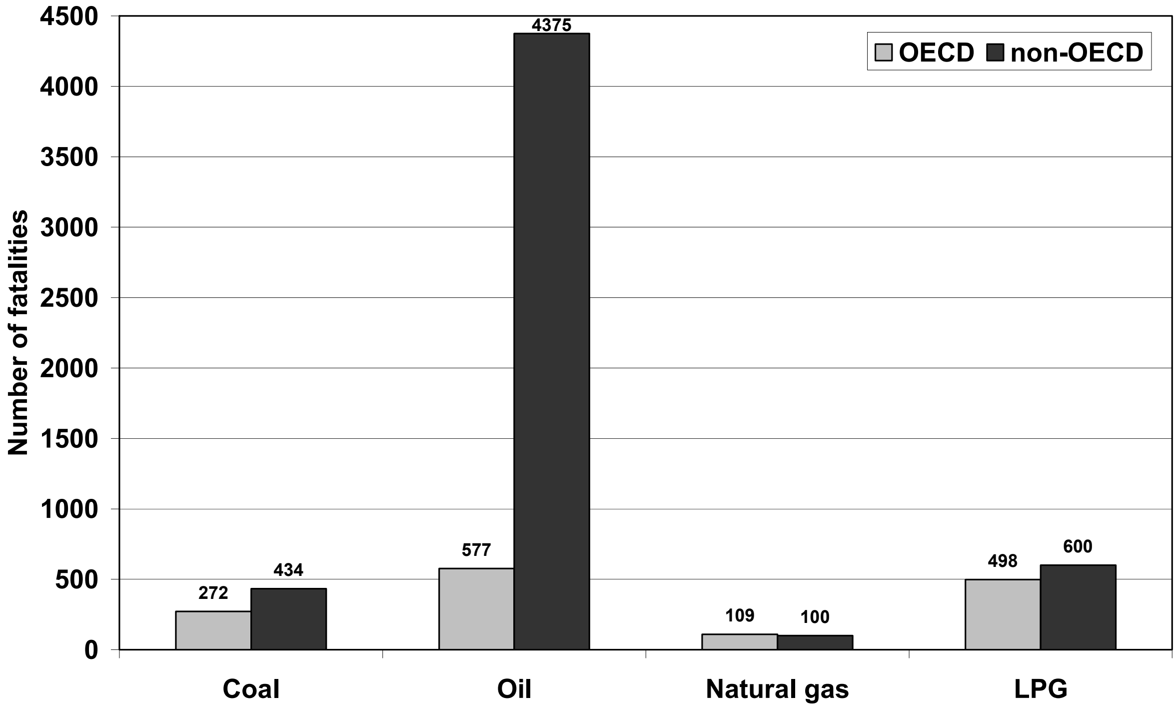

Fig. 6 **Maximum credible consequences expressed as number of immediate fatalities for fossil energy chains. Note that results are based on historical experience for the period 1969-2000. Based on data from Burgherr et al. (to be published).**

In the following sections hydropower and nuclear chains are presented and some reservations are made as far as direct comparisons of absolute numbers of maximum fatalities are concerned.

When looking at dam incidents and accidents in Switzerland it becomes evident that the most serious accidents in terms of fatalities occurred not after the bursting of dams but during construction, which is attributable to the difficult working conditions in the Alps (for details see Hirschberg et al. 1998). The most severe accident during construction was that of Mattmark dam (Saas Almagell, Valais) in 1965 when an ice-avalanche catastrophe caused the death of 88 workers (Fig. 7.). However, it has to be mentioned that Swiss construction accidents have in practice no impact on the final results of the comparative evaluations since their occurrence was almost exclusively prior to the chosen evaluation period of 1969 – 2000 or resulted in less than 5 fatalities. For this reason, historical experience in OECD countries could be used as a representative proxy for Switzerland; which for the years 1969 – 2000 is limited to the failure of Teton dam (Idaho, USA). Additionally, analyses based on an empirical study and on a theoretical model are presented (Hirschberg et al. 1998; Rüst 1997). However, results of such a hypothetical dam failure are dependent on the model chosen and the pre-warning time among various other factors. Additionally, potential consequences have to be viewed under consideration of the frequency of occurrence of such an event, which for Swiss dams is in the range 10^{-5} to 10^{-4} events per dam year (Hirschberg et al. 1998). Finally, it has to be acknowledged that Swiss dams exhibit a number of favorable safety-related features. Of particular importance is the relatively low capacity of earth dams, which is a positive factor for the mitigation of accidents and for the limitation of the extent of potential damages.

For the nuclear chain, immediate fatalities are negligible, whereas latent fatalities are of utmost importance as shown in Fig. 7. Due to the radical differences in the plant design and operational environment the Chernobyl accident is essentially irrelevant for the evaluation of the safety level of the representative western nuclear power plants. This also applies to a large extent to most nuclear power plants in non-OECD countries. The range of 1500 – 6000 latent fatalities for the nuclear power plant Mühleberg has an estimated frequency of about 10^{-6} to 10^{-8} per year for the end-points (see Burgherr et al. to be published; Hirschberg et al. 1998).

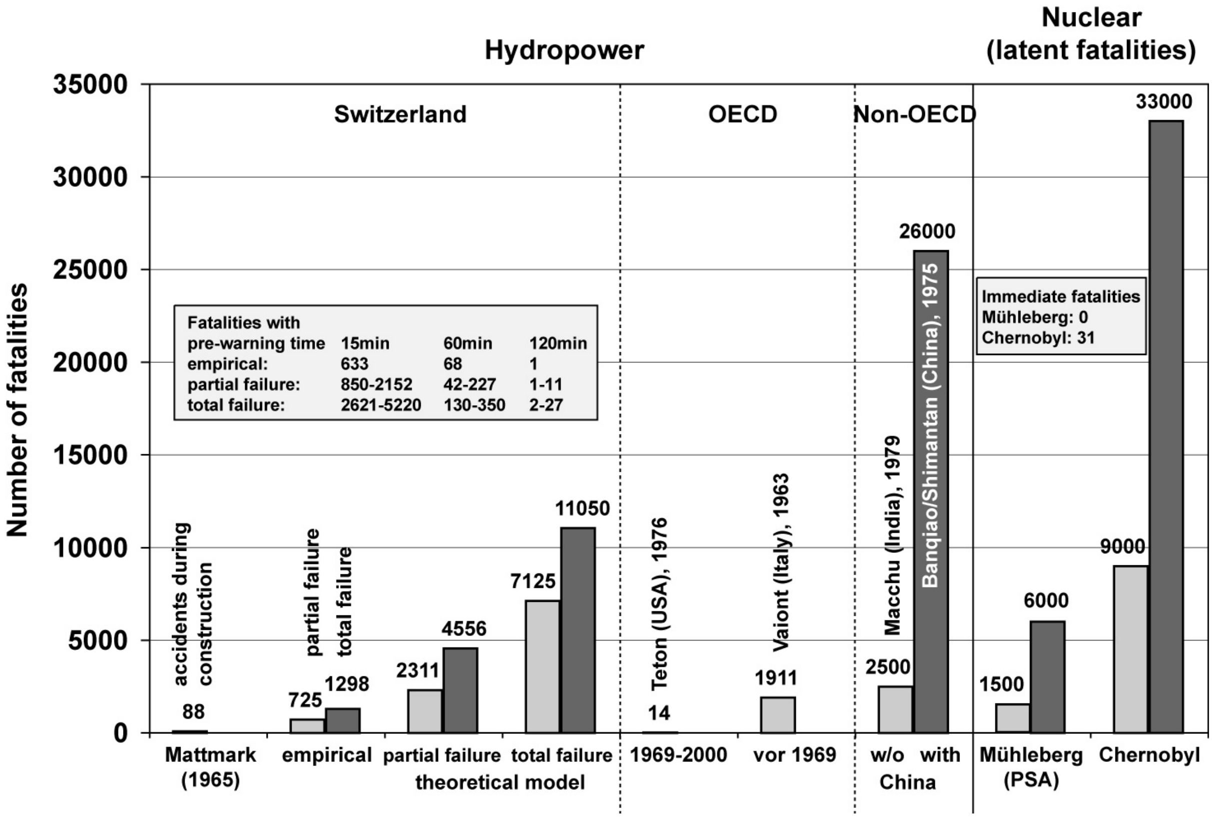

Fig. 7 **Maximum credible consequences are shown for hydropower and nuclear. Historical experience of hydropower for OECD and non-OECD countries is based on immediate fatalities. Additionally, various hypothetical dam failure scenarios for Switzerland are presented using minimum and maximum values. For nuclear minimum and maximum numbers of latent fatalities are considered, which represent values from a plant-specific PSA for the Swiss power plant Mühleberg, and for Chernobyl-specific estimates, respectively. Based on data from Burgherr et al. (to be published), Hirschberg et al. (1998) and Rüst (1997).**

In summary, the natural gas chain historically exhibits the lowest consequences among all energy chains. Regarding hydropower, historical experience suggests that very large accidents in the period 1969-2000 have been restricted to non-OECD countries (Burgherr et al. to be published; Hirschberg et al. 1998). Also for hydro an implementation of a probabilistic approach would be desirable, but only specific elements such as scenario-based consequences shown in the figure are available. For the nuclear chain the use of a probabilistic approach is mandatory, as the relevant statistical experience to support the evaluation of severe accidents fortunately does not exist.

3.1.4 Risk dominant energy chains

Tab. 3 and Tab. 4 show the overview of the risk dominant energy chains based on historical accidents for OECD and non-OECD countries in the period 1969-2000. Only accidents with at least 5 fatalities, or 10 injured, or 200 evacuees, or 5 million USD(2000) economic damage were considered.

The following evaluation categories are used in the tables:

I Largest aggregated number of fatalities, injured, evacuees, or highest aggregated economic losses.

II Largest number of fatalities, injured, evacuees, or highest economic loss in a single accident.

III Largest aggregated number of fatalities, injured, evacuees, or highest aggregated economic losses, averaged per accident.

IV Largest aggregated number of fatalities, injured, evacuees, or highest aggregated economic losses, per unit of energy produced.

Tab. 3 Risk-dominant energy chains based on historical experience of severe accidents within <u>OECD</u> countries in the period 1969-2000. Latent health impacts are here equivalent to latent fatal and non-fatal cancers. No severe accidents (in terms of latent fatalities) occurred in OECD. Based on data from Burgherr et al. (to be published).

Evaluation category	Immediate fatalities	Latent health impacts	Injured	Evacuees	Economic Loss
I	Oil	---	LPG	LPG	Oil
II	Oil	---	LPG	LPG	Nuclear
III	LPG	---	Hydro	Nuclear	Nuclear
IV	LPG	---	LPG	LPG	LPG

Tab. 4 Risk-dominant energy chains based on historical experience of severe accidents within <u>non-OECD</u> countries in the period 1969-2000. For immediate fatalities, rankings are additionally given for non-OECD without China because of the dominant influence of the Chinese coal chain. Latent health impacts are here equivalent to latent fatal and non-fatal cancers. Based on data from Burgherr et al. (to be published).

Evaluation category	Immediate fatalities		Latent health impacts	Injured	Evacuees	Economic Loss
	non-OECD with China	*non-OECD w/o China*	*non-OECD with China*	*non-OECD with China*	*non-OECD with China*	*non-OECD with China*
I	Hydro (Coal) (a)	Oil	Nuclear	Oil	Oil	Nuclear
II	Hydro (Oil) (a)	Oil	Nuclear	Oil	Hydro/LPG (b)	Nuclear
III	Hydro	Hydro	Nuclear	Nuclear	Nuclear	Nuclear
IV	LPG	LPG	Nuclear	LPG	Nuclear	Nuclear

(a) Ranking is changing if the Chinese dam failures of Banqiao and Shimantan with a total of 26'000 fatalities are excluded from the analysis.
(b) 150'000 evacuees were reported for both energy chains.

It is interesting to note that natural gas is the only energy carrier among the analyzed ones not represented in the above tables. The presence of nuclear in these tables is primarily due to the Chernobyl accident, with a contribution from the Three Mile Island (TMI) accident to the economic losses and evacuation. Estimates of latent fatalities and latent cancers are only available for the nuclear chain for which they are of particular relevance. Delayed fatalities are likely to have occurred for the other chains with no records available; their significance per accident should, however, be incomparably smaller in comparison with the Chernobyl accident.

3.2 Specific evaluations for natural gas chain

3.2.1 Structure of natural gas chain

Natural gas, also known as methane, is a colorless fossil gas lighter than air. After extraction, it passes through several steps before it can be transported by pipeline. The treatment (deposition of elemental sulphur, introduction of corrosion inhibitors, separation of liquids, mercury or nitrogen removal, etc.) can take place at the well or in centralized processing plants.

A complex transportation system lies between the extraction of the natural gas deposits and the consumer. The natural gas is pumped in long distance pipelines and is transported under an average pressure of 70 – 100 bar to the take-over stations of the regional distributors. From there the gas is transported at different pressures to power plants or to the control stations of the local distribution system. At pressures ranging from 20 mbar to 5 bar the natural gas finally reaches industrial, commercial or domestic consumers. In the context of energy-related applications the natural gas chain can be roughly characterized as shown in Fig. 8.

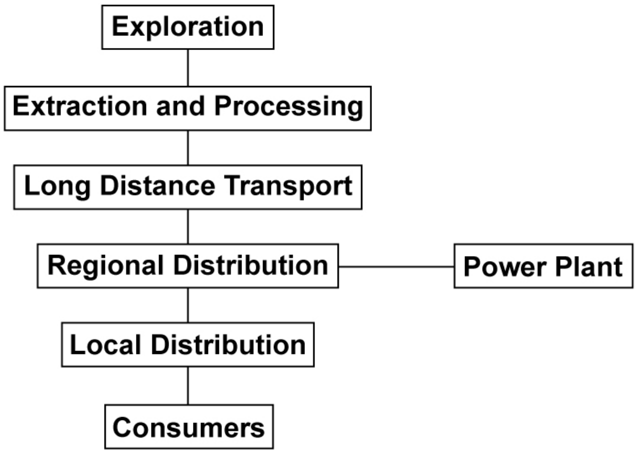

Fig. 8 Rough breakdown of the natural gas chain into different stages.

3.2.2 Distribution of severe accidents in the natural gas chain

For the period 1969-2000 a total of 129 severe (≥ 5 fatalities) accidents with 1971 fatalities were recorded worldwide[a]. Annual totals for the number of severe accidents (Fig. 9) and fatalities (Fig. 10) are shown separately for OECD and non-OECD countries. Both figures give a good indication of the distribution and interannual variation of numbers of accidents and fatalities.

Concerning fatalities, accidents with more than 50 fatalities rarely occurred in OECD (3 events) and non-OECD countries (6 events). Fatalities in OECD countries remained at low levels since the 1980s. The peak in the year 1995 is clearly attributable to one large accident in Taegu (Korea) with 109 fatalities. This single accident also accounted for about 30% of all OECD-fatalities in the 1990s. Generally, total fatalities in non-OECD countries were higher in the last two decades than in OECD.

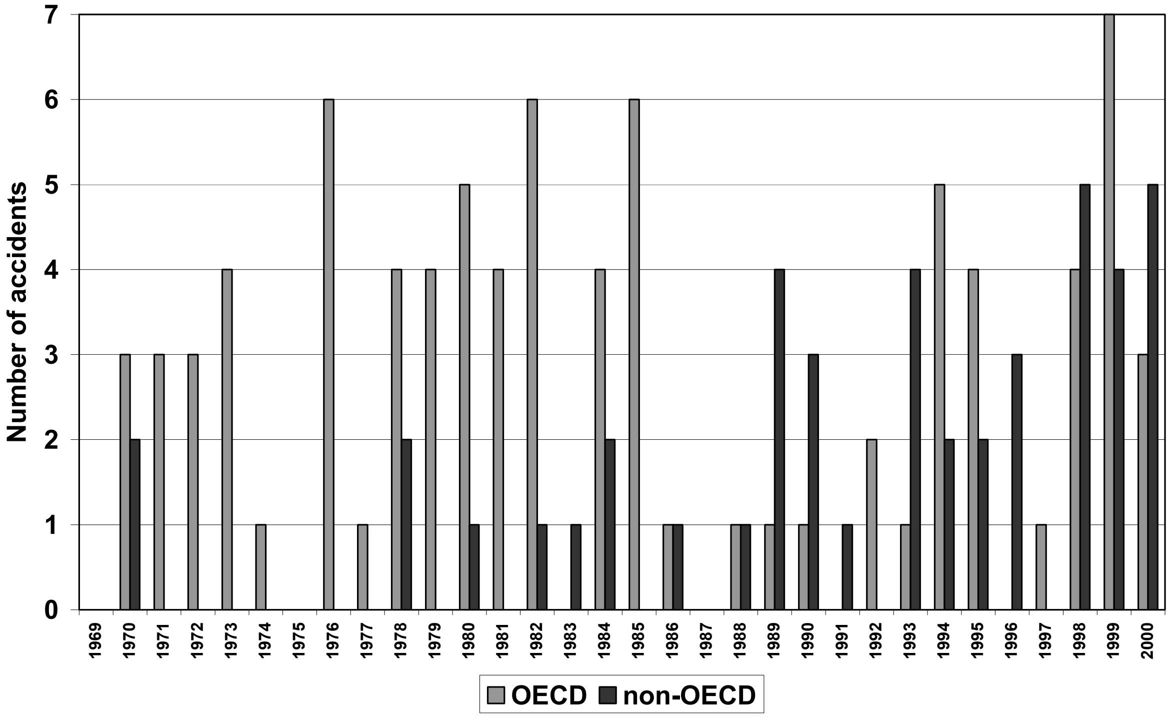

Fig. 9 Number of severe (≥ 5 fatalities) accidents in the natural gas chain in OECD and non-OECD countries for the period 1969-2000. Based on data from Burgherr et al. (to be published).

[a] Note that for analyses within the natural gas chain, accidents with Liquefied Natural Gas were excluded, as the latter are of less interest in this study. In total 5 accidents that occurred in OECD and 1 that occurred in non-OECD were excluded.

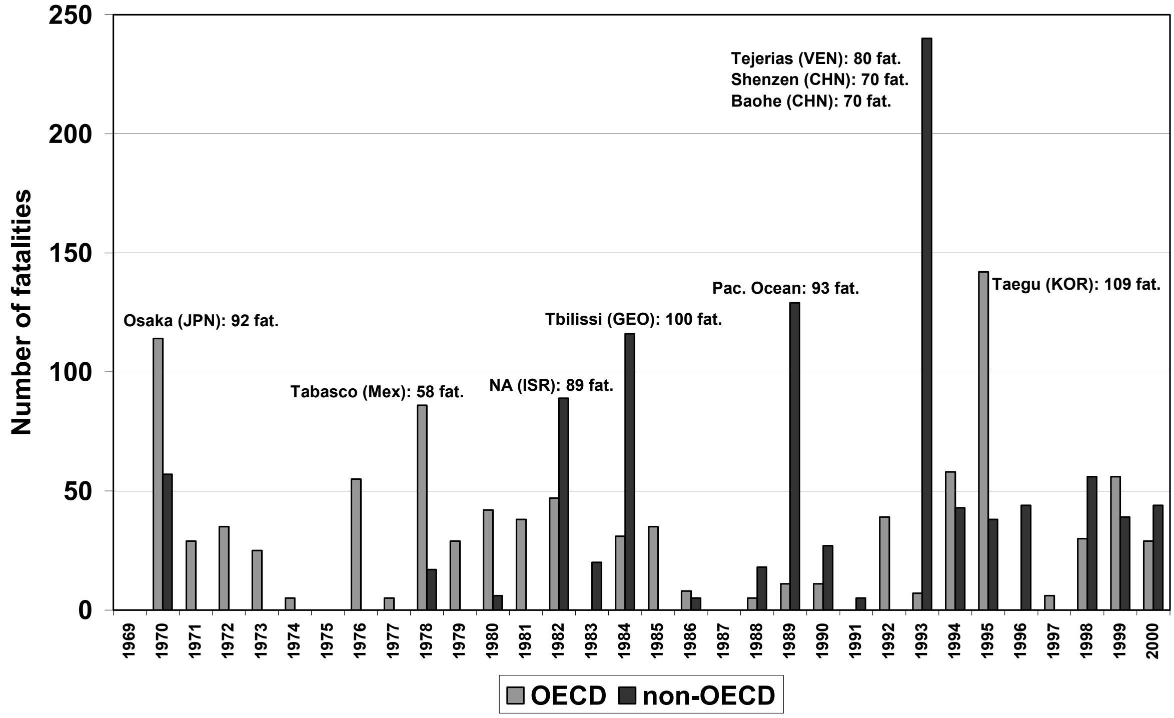

Fig. 10 **Number of fatalities in severe (≥ 5 fatalities) accidents in the natural gas chain in OECD and non-OECD countries for the period 1969-2000. Based on data from Burgherr et al. (to be published).**

3.2.3 Aggregated indicators

Severe accident indicators (≥ 5 fatalities) were not only calculated for OECD and non-OECD countries, but also for EU15 and Central Europe[a], as the latter two subdivisions are of particular interest due to the scope of this study. Although the number of reported accidents in OECD countries is higher than in non-OECD countries (Fig. 11a), the total number of fatalities is lower (Fig. 11b).

These findings indicate that the presentation of absolute numbers should be complemented by weighted indicators. Therefore aggregated fatality rates of severe (≥ 5 fatalities) accidents were computed. Normalization of data was done as already described in chapter 3.1.1; based on immediate fatalities and the same time period from 1969 – 2000.

[a] In agreement with SVGW "Central Europe" is defined in this study as follows: Switzerland, Germany, The Netherlands, United Kingdom, Belgium and Denmark, depending on similar gas technology and management.

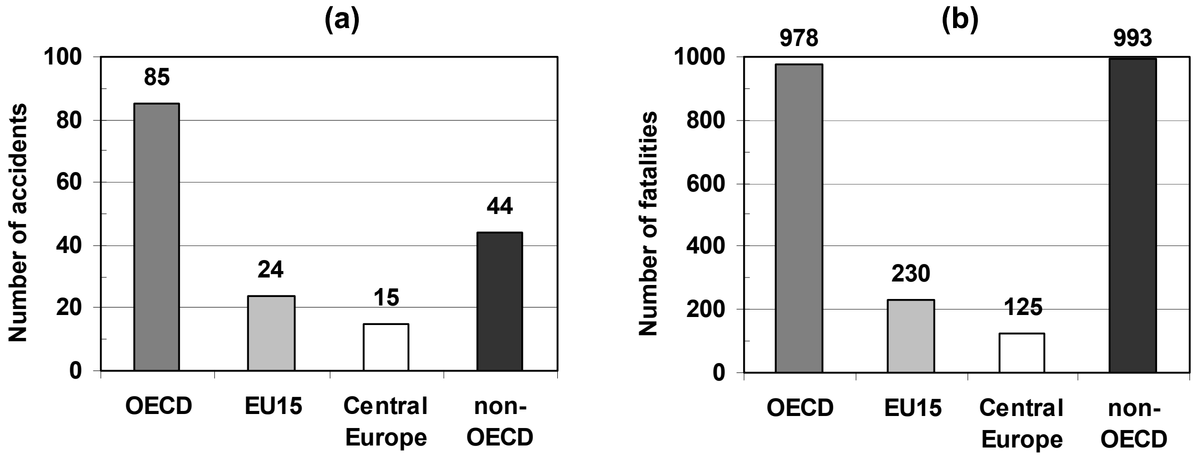

Fig. 11 **Number of accidents and fatalities for the natural gas chain, based on historical experience of severe accidents that occurred in the period 1969-2000. Results are given for OECD, EU15, Central Europe (CH, DE, NL, GB, BE, DK) and non-OECD. Based on data from Burgherr et al. (to be published).**

Fatalities per accident were almost twice as high in non-OECD countries compared to OECD countries (Fig. 12a). EU15 and particularly Central Europe showed an even better performance than the whole OECD. Concerning fatalities per GW_eyr a similar pattern was observed (Fig. 12b). Non-OECD exhibited the highest failure rate followed distantly by OECD and EU15. As before, Central Europe performed best with a fatality rate of 0.061 per GW_eyr.

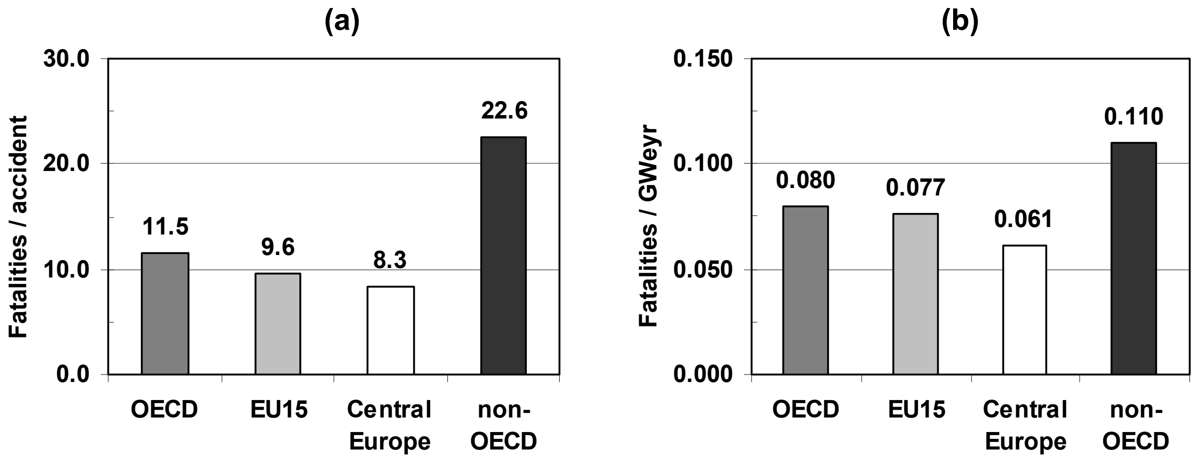

Fig. 12 **Aggregated indicators for the natural gas chain, based on historical experience of severe accidents that occurred in the period 1969-2000. Results are given for OECD, EU15, Central Europe (CH, DE, NL, GB, BE, DK) and non-OECD. Based on data from Burgherr et al. (to be published).**

3.2.4 Frequency-consequence curves

Frequency-consequence curves were constructed for OECD and non-OECD countries, but also for EU15 and Central Europe (Fig. 13). When looking at accident frequencies, non-OECD has a substantially worse performance than the other regions and country groups. For severe accidents with less than 10 fatalities the non-OECD curve is not fully representative because reporting of smaller-sized accidents is much less complete and reliable than in OECD countries. Differences among OECD, EU15 and Central Europe are rather small in terms of accident frequencies, indicating that maximum consequences are the discriminating criterion between them.

OECD and non-OECD showed significantly larger maximum damage extents compared to EU15 and Central Europe. However, the Figure also indicates that the largest OECD-accident is an exception in the sense that no other accident with 40 or more fatalities occurred after 1978. In contrast, there were 4 accidents with 70 to about 90 fatalities in non-OECD in the 1980s and 1990s. For EU15 and Central Europe maximum damages are 27 and 22 fatalities, respectively, which is about 4 – 5 times lower than for OECD.

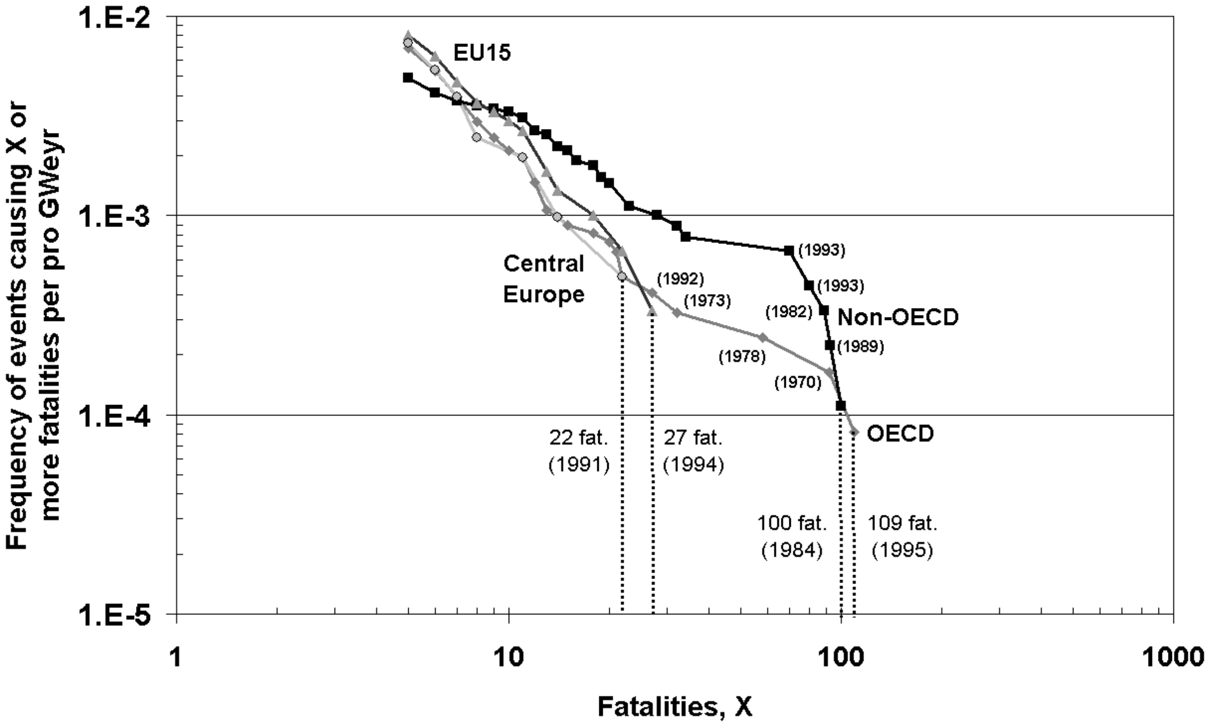

Fig. 13 **Comparison of frequency-consequence curves for natural gas in OECD and non-OECD countries, EU15 and Central Europe for the period 1969-2000. Numbers in parentheses indicate years, in which accidents happened; but see text for explanations. Based on data from Burgherr et al. (to be published).**

3.3 Analyses of DVGW-data for Germany

3.3.1 Overview of German natural gas statistics from DVGW

Analyses in previous chapters 3.1 and 3.2 focused on severe accidents using worldwide data. However, smaller accidents could not be analyzed in detail because a survey performed indicated that the completeness of reporting is correlated to the severity of accidents, i.e. the lower the damage the higher the likelihood that the accident will not be found in the commercial and non-commercial databases considered (compare Tab. 1) because its consequences are below the damage thresholds used for inclusion. The findings were also indicative that indicators other than fatalities were even much more incomplete than in the case of severe accidents. For a detailed discussion of this topic we refer to Burgherr et al. (to be published).

Therefore, a major effort was made in the context of this study to close this gap. Potential data had to fulfill several criteria to be useful for this study:

- Sufficiently large amount of accident records, which enable a valid and coherent analysis.
- From a regional point of view only data from Central Europe, or EU15 as a second priority, came into question because otherwise data could not be regarded as representative for Swiss conditions.
- Adequate coverage of severe and smaller accidents with regard to completeness of records.
- Different damage indicators should be covered to the same level of detail, if possible. In our case this requirement considered fatalities and injured persons.
- Supplementary data on length of the pipeline network, number of customers, etc are needed for chain-specific normalization of accident data.
- Additional information provided for individual accident records should allow detailed evaluations for chain-specific technical aspects (e.g., accident types or causes).

The above criteria were best met by data at national level from Germany, which were provided by DVGW (DVGW 2004) for the period 1981 to 2002[a]. Other data sets that also covered smaller accidents, but were not equally suitable in the context of this study, are described in chapter 2.1. Evaluations based on DVGW-data are especially meaningful in the sense that the natural gas sector in Germany is also representative for conditions in Switzerland.

Available gas accident data from DVGW for the period 1981 – 2002 were assigned to the two categories customer installations (Kundenanlagen, UK) and company installations (Eigenanlagen, UE). In a preliminary step, the following categories of accidents were excluded:

- Accidents with town gas (Stadtgas), which apply to the period before the changeover to natural gas and are not any more relevant today.
- Accidents with Liquefied Petroleum Gas (LPG) that are also listed in DVGW-statistics.
- Accidents of unspecified gas types were excluded from the data set as there were no indications that natural gas was involved.

As a result 837 natural gas accidents at customer installations and 500 at company installations were retained for subsequent analyses.

[a] Statistics include newly formed German states as of 1991.

The distribution of natural gas accidents is shown in Fig. 14 according to their severity in terms of fatalities. The majority of accidents result in no fatalities with corresponding shares of 73.8% at customer installations and 90.4% at company installations. On the other hand, severe (≥ 5 fatalities) accidents contribute less than 1% (0.7% at UK and 0.4% at UE) to total number of accidents. Despite their small share severe accidents make up 11.8% of total fatalities at customer installations and 23.3% at company installations. Nevertheless, smaller accidents are the major contributor to total fatalities, whereof accidents with one fatality and to a lesser extent with two fatalities account for most fatalities.

The severity of accidents according to injured persons is given in Fig. 15. Most accidents result in no more than 2 injured amounting to 88.3% of all accidents at customer installations and 86.8% at company installations. Accordingly, severe (≥ 10 injured) accidents contribute very little to total number of accidents (0.8% for UK and 1.0% for UE), which is similar to the findings for fatalities. With regard to number of injured persons, severe accidents account for 9.1% of total injured at customer installations and 13.0% at company installations, confirming that smaller accidents are also the dominant source for injured persons. Finally, it is also interesting to note that accidents classified as severe have either at least 5 fatalities or at least 10 injured, except for one severe accident that fulfills both criteria.

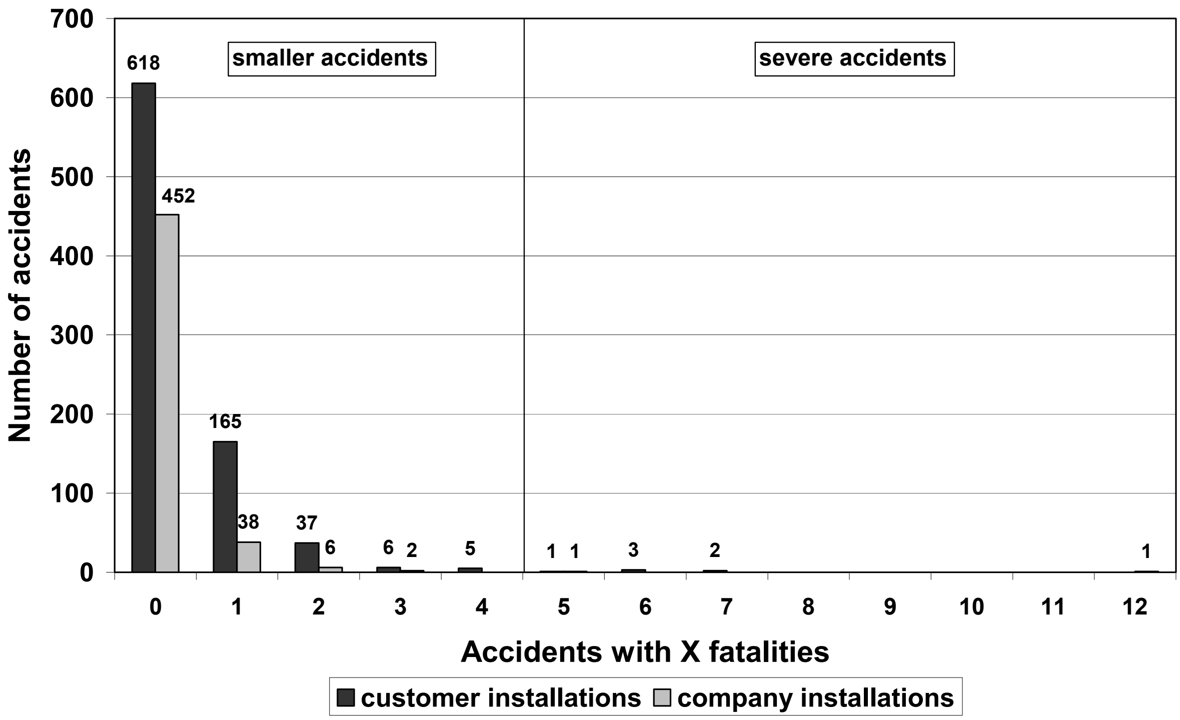

Fig. 14 **The distribution of natural gas accidents is shown according to their severity in terms of fatalities for the period 1981-2002. Based on data from DVGW (2004).**

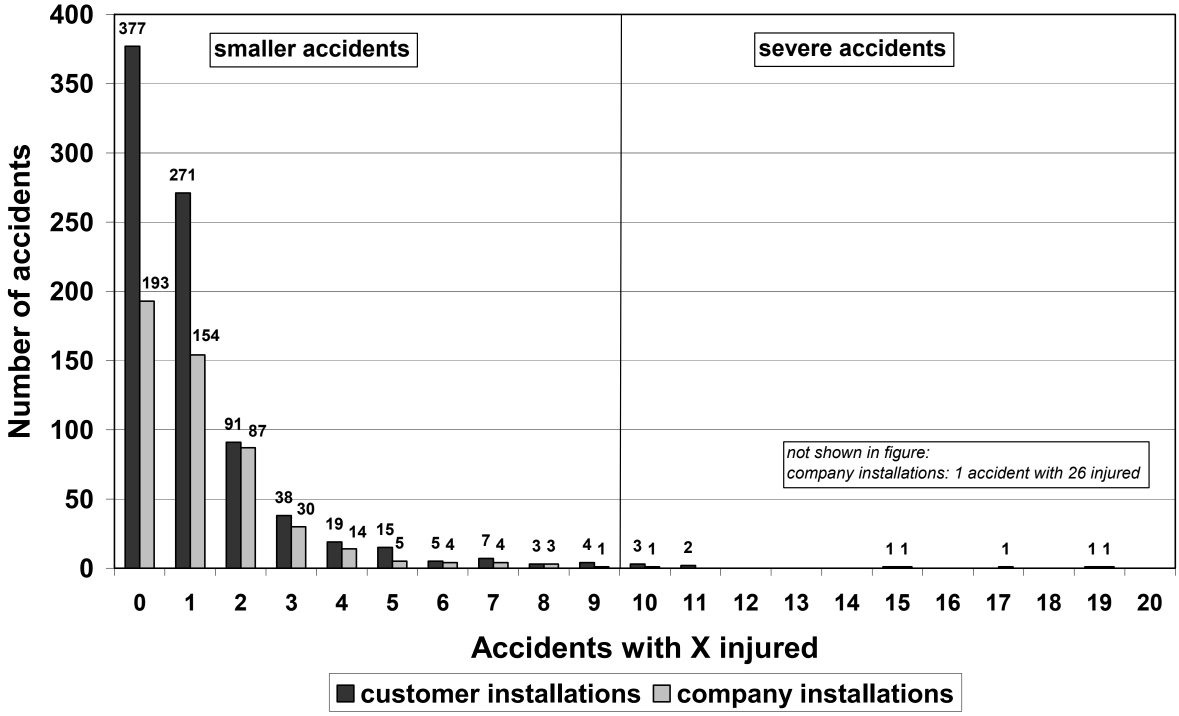

Fig. 15 **The distribution of natural gas accidents is shown according to their severity in terms of injured persons for the period 1981-2002. The largest accident with 26 injured is not shown in the figure for reasons of graphical representation. Based on data from DVGW (2004).**

3.3.2 Weak-point analysis of accidents

The following evaluations are based on accident types, accident causes and installation types. Note, that tables also include in parentheses the German terms that are used in the DVGW form sheets for damage and accident statistics in the natural gas sector.

Customer installations

In Tab. 5 results are summarized for customer installations with regard to number of accidents, fatalities and injured persons for the period 1981 – 2002. The majority of accidents were attributable to the types explosion (27%), deflagration (31%) and exhaust fumes poisoning (29%). Similarly, numbers of fatalities and injured were highest for the types explosion and exhaust fumes poisoning. In contrast, deflagration only showed high numbers of injured whereas number of fatalities were rather small. When looking at trends of these three accident types over time different patterns could be observed (Fig. 16)[a]. Cumulated numbers for fatalities from explosions and deflagrations showed less interannual variability than exhaust fumes poisoning, but no clear trend was observed. In contrast, exhaust fumes poisoning exhibited a continuously decreasing tendency since the 1990s, which could be indicative of technological advancements and implemented safety measures.

With respect to accident causes, the categories technical defects, manipulation failures and intentional interventions at gas installations[b] were most accident-prone. These categories were also dominant contributors to total fatalities and injured, with the only exception that installation failures caused more injured than manipulation failures. Overall, it became clearly evident that human misconduct is by far the

[a] Since patterns for number of accidents, fatalities and injured showed no major differences, only figures for fatalities are shown.

[b] In contrast, Swiss data suggest that intentional interventions are less common than observed for Germany.

most common accident cause. However, Fig. 17 demonstrates that constant improvements were achieved for manipulation failures as well as for technical defects + installation failures, and to a lesser extent also for illegal changes of installation conditions + inappropriate interventions. In contrast, intentional interventions scattered in a wider range but could be somewhat reduced in the last few years.

Among installation types, gas appliances with exhaust fumes system caused most accidents (37%) and also resulted in most fatalities (33%) and injured (28%). Damages to pipes and pipe joints were also responsible for a substantial amount of fatalities and injured. Regarding performance of gas appliances with exhaust fumes system + exhaust fumes systems noticeable improvements were made, so that total fatalities per year were only once over 10 fatalities after 1986 and since 1994 no more than 5 fatalities per year were recorded (Fig. 18). Gas appliances w/o exhaust fumes system were at very low fatality levels over the whole observation period, but still a slight decreasing tendency was recorded.

Tab. 5 Number of accidents, fatalities and injured for accident types, accident causes and installation types at customer installations for the period 1981 – 2002. Based on data from DVGW (2004).

Accident type (Unfallart)	# accidents	# fatalities	# injured
Explosion (Explosion)	224	104	487
Fire (Brand)	88	10	40
Deflagration (Verpuffung)	257	18	158
Asphyxiation (Gasvergiftung)	16	3	20
Exhaust fumes poisoning (Abgasvergiftung)	240	179	233
Not specified (Keine Angaben)	12	0	5
Total	*837*	*314*	*943*
Accident cause (Unfallursache)	**# accidents**	**# fatalities**	**# injured**
Technical defects (Technische Mängel)	220	44	152
Installation failures (Installationsfehler)	123	39	173
Manipulation failures (Bedienungsfehler)	175	84	143
Illegal changes of installation conditions of gas appliances (Unzulässige Veränderung der Aufstellbedingungen von Gasgeräten)	34	19	18
Inappropriate interventions at gas installations (Unsachgemässe Eingriffe in die Gasanlage)	64	24	64
Intentional interventions at gas installations (Vorsätzliche Eingriffe in die Gasanlage)	202	101	386
Not specified (Keine Angaben)	19	3	7
Total	*837*	*314*	*943*
Installation type (Anlagenart)	**# accidents**	**# fatalities**	**# injured**
Pipes (Rohrleitungen)	144	45	187
Pipe joints (Rohrverbindungen)	90	55	195
Valves (Armaturen)	28	4	41
Gas appliances w/o exhaust fumes system (Gasgeräte ohne Abgasanlage)	136	40	122
Gas appliances with exhaust fumes system (Gasgeräte mit Abgasanlage)	311	104	267
Exhaust fumes system (Abgasanlage)	55	35	63
Combustion air supply (Verbrennungsluftzufuhr)	3	0	1
Not specified (Keine Angabe)	70	31	67
Total	*837*	*314*	*943*

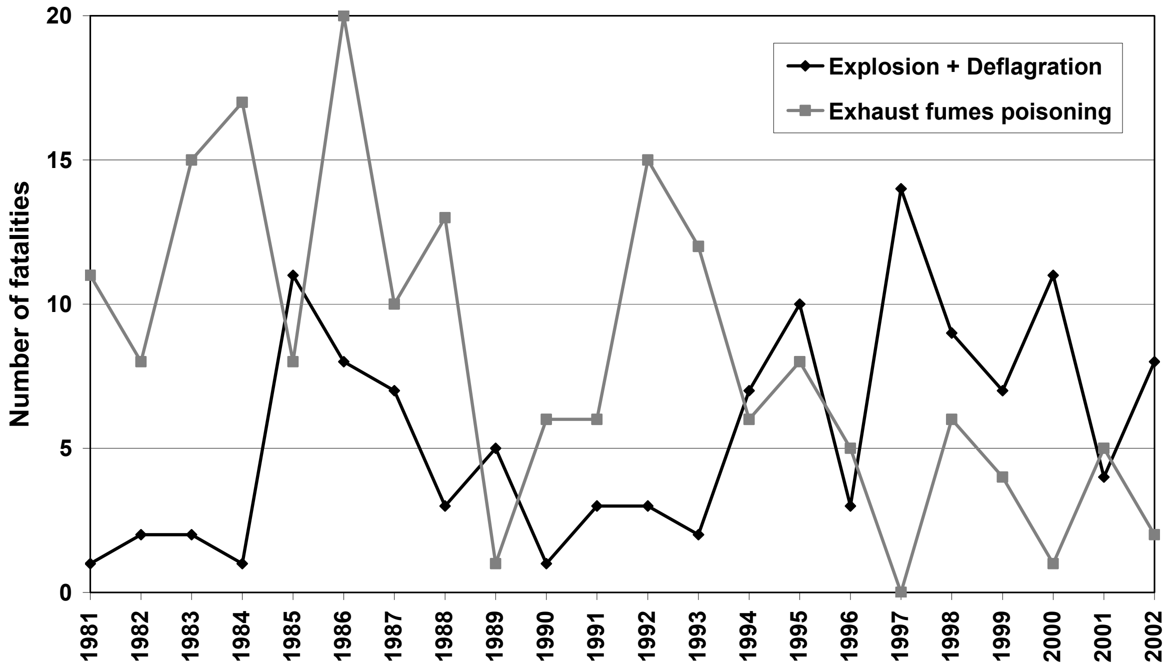

Fig. 16 **Annual number of fatalities for selected categories of accident types at customer installations for the period 1981 – 2002. Based on data from DVGW (2004).**

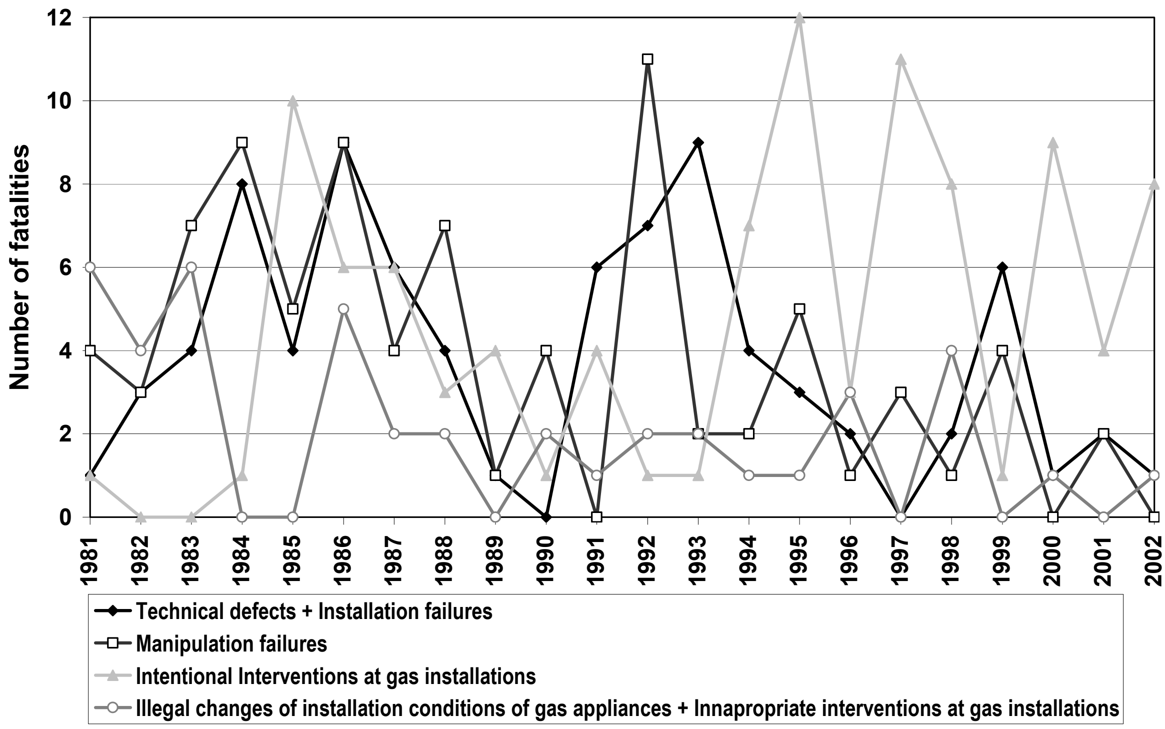

Fig. 17 **Annual number of fatalities for selected categories of accident causes at customer installations for the period 1981 – 2002. Based on data from DVGW (2004).**

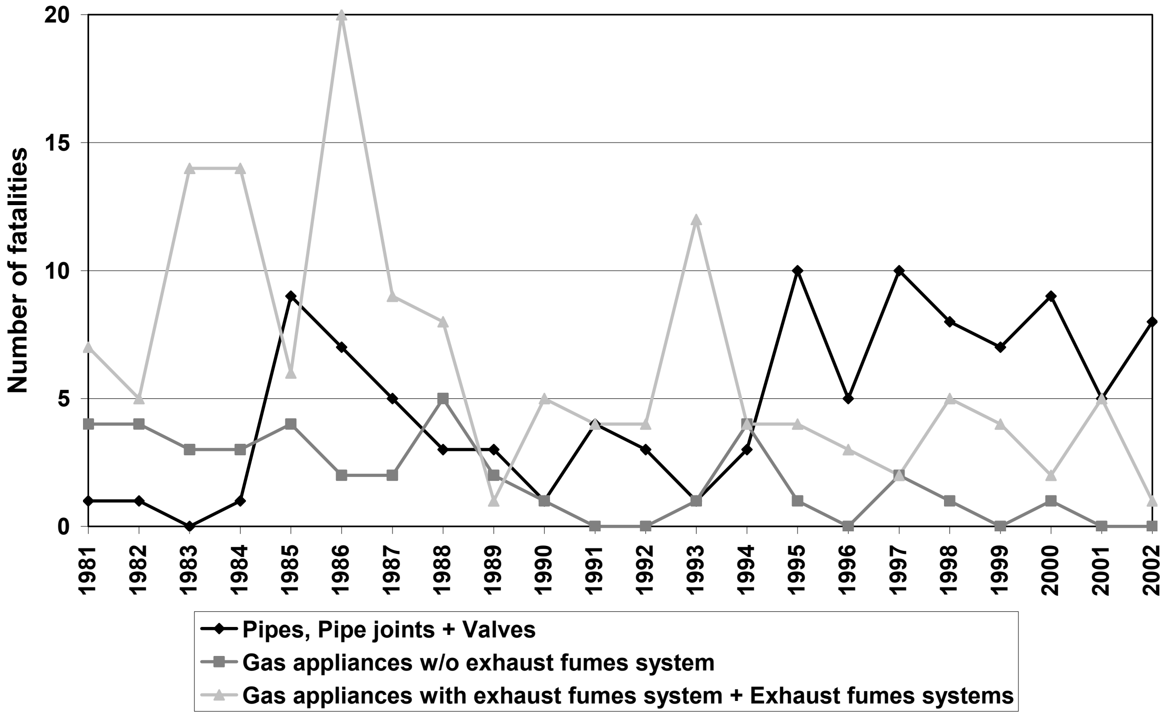

Fig. 18 **Annual number of fatalities for selected categories of installation types at customer installations for the period 1981 – 2002. Based on data from DVGW (2004).**

Company installations

In Tab. 6 results are summarized for company installations in regard to number of accidents, fatalities and injured persons for the period 1981 – 2002. The majority of accidents were attributable to the types explosion (18%), deflagration (52%) and fire (24%). However, fatalities were dominated by explosion followed distantly by deflagration, whereas fatalities from fire were negligible. Explosion and deflagration were also dominant for injured but fire also contributed a considerable share. Fig. 19 looks at trends over time of accident types explosion + deflagration versus other. Annual fatalities from explosions + deflagration remained at similar levels since the mid 1980s, except for the years 2000 and 2001, in which statistics were strongly driven by two severe accidents with 12 and 5 fatalities, respectively. Fatalities from other accident types contributed only marginally, accounting for only 5 fatalities over the whole period of observation.

The major accident causes were inappropriate working, mechanical external factors and ground motion, which were also the dominant contributors to numbers of fatalities and injured (Fig. 20). Besides the distinct peak in the curve for mechanical external factors, which is again due to the severe accident in year 2000 that caused 12 fatalities, all three categories of accident causes had low annual numbers of fatalities since the mid 1980s.

Among installation types, main and service lines collectively accounted for more than 80% of all accidents, and similarly for most fatalities and injured. There were also no clear temporal trends as fatalities remained at rather low levels for the whole period of observation, except for the one severe accident already mentioned before (Fig. 21).

Tab. 6 Number of accidents, fatalities and injured for accident types, accident causes and installation types at company installations for the period 1981 – 2002. Based on data from DVGW (2004).

Accident type (Unfallart)	# accidents	# fatalities	# injured
Explosion (Explosion)	91	44	240
Fire (Brand)	118	1	95
Deflagration (Verpuffung)	260	21	286
Asphyxiation (Gasvergiftung)	5	4	8
Not specified (Keine Angaben)	26	3	42
Total	*500*	*73*	*671*
Accident cause (Unfallursache)	**# accidents**	**# fatalities**	**# injured**
Mechanical external factors (Mechanische Fremdeinwirkung)	128	26	183
Thermal external factors (Thermische Fremdeinwirkung)	22	10	30
Ground motion (Bodenbewegung)	75	18	90
Corrosion (Korrosion)	25	4	42
Damaged pipe joints (Defekte Rohrverbindungen)	19	1	20
Defects at pipes and fittings (Mängel an Leitungen u. Zubehör)	12	2	24
Technical failure of control and measuring systems (Technisches Versagen von Regel- u. Messanlagen)	11	0	1
Inappropriate working (Unsachgemässes Arbeiten)	201	12	280
Not specified (Keine Angaben)	7	0	1
Total	*500*	*73*	*671*
Installation type (Anlagenart)	**# accidents**	**# fatalities**	**# injured**
Main lines up to PN 4 (Versorgungsleitungen bis PN 4)	188	30	248
Service lines up to PN 4 (Anschlussleitungen bis PN 4)	227	35	330
High-pressure pipelines > PN 4 up to PN 16 (Hochdruckleitungen > PN 4 bis PN 16)	12	2	37
High-pressure pipelines > PN 16 (Hochdruckleitungen > PN 16)	16	2	11
Other components (Sonstige Bauteile)	10	1	9
Control station in customer installations (GVU-eigene Regel- u. Messanlagen)	9	0	3
Control station in the distribution grid (Regel- u. Messanlagen)	15	1	8
Not specified (Keine Angabe)	23	2	25
Total	*500*	*73*	*671*

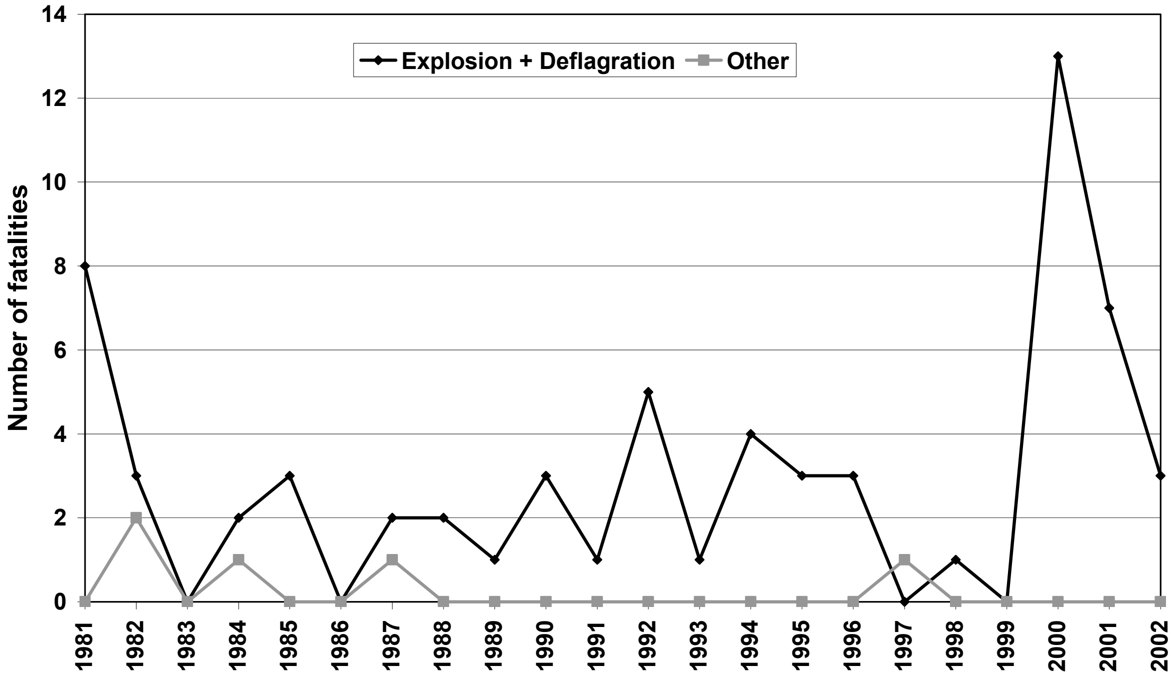

Fig. 19 **Annual number of fatalities for selected categories of accident types at company installations for the period 1981 – 2002. Based on data from DVGW (2004).**

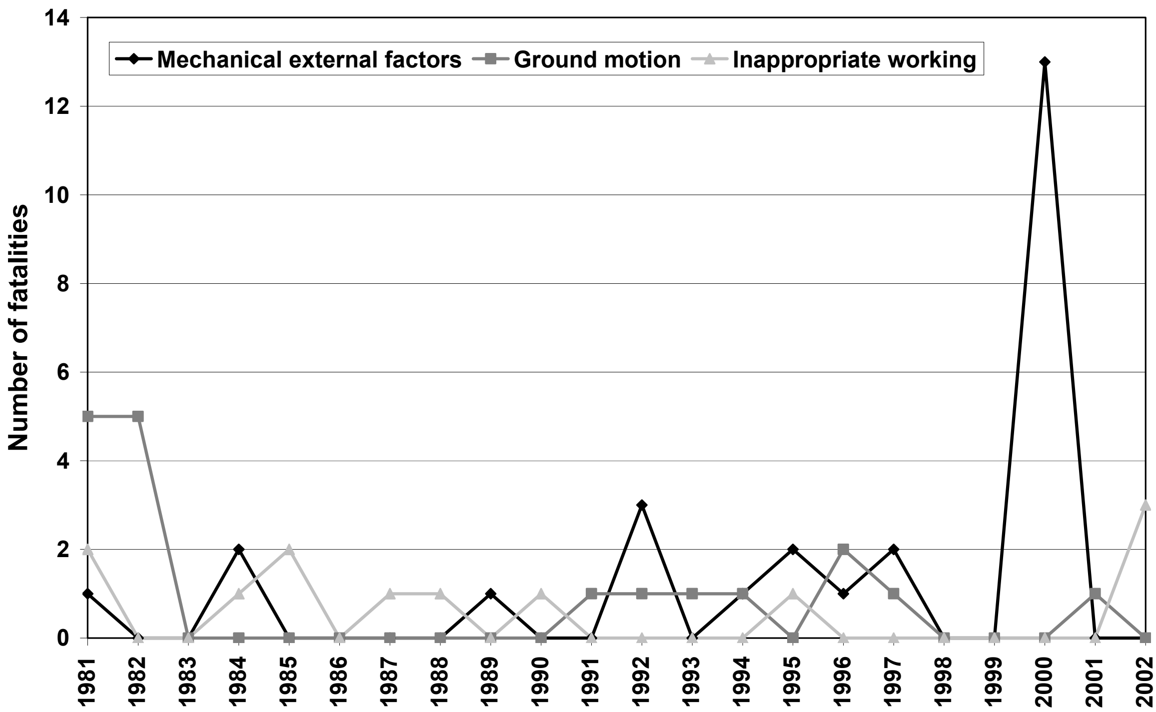

Fig. 20 **Annual number of fatalities for selected categories of accident causes at company installations for the period 1981 – 2002. Based on data from DVGW (2004).**

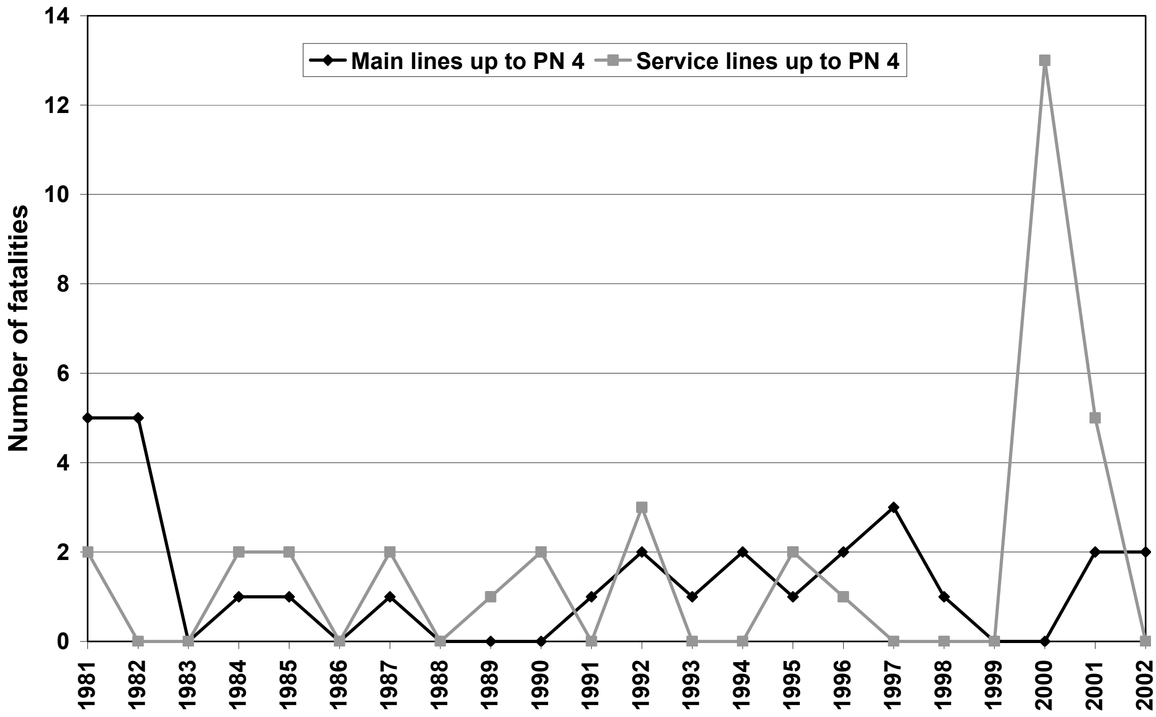

Fig. 21 **Annual number of fatalities for selected categories of installation types at company installations for the period 1981 – 2002. Based on data from DVGW (2004).**

3.3.3 Structural changes in the natural gas sector

Number of accidents, fatalities and injured persons are shown in the course of structural changes over time for the natural gas sector at customer installations (Fig. 22) and company installations (Fig. 23). As indicators for structural changes, number of customers and gas sales are considered at customer installations, and length of pipeline network and number of gas supply companies at company installations.

Despite some interannual variability, numbers of accidents and fatalities at customer installations (Fig. 22) showed a downward trend over time; for injured such a trend was less obvious from the figure. Similarly no clear trend was found for numbers of accidents, fatalities and injured at company installations (Fig. 23). To achieve a complete picture the other curves in these two figures have to be taken into account. For example, the number of customers and the length of the gas grid have been doubled between 1981 and 2002. Another factor affecting the results presented in these figures was the accession of newly formed German states and their inclusion in the statistics as of 1991. In general, their consideration resulted in a short-term increase in number of accidents as well as fatalities and injured persons. However, it did not significantly confound or even reverse long-term trends. Finally, one should consider that during the period of observation the clear increase in number of customer installations, grid length and gas sales have a distinct effect on normalized accident rates, which is presented and discussed in detail in chapter 3.3.4.

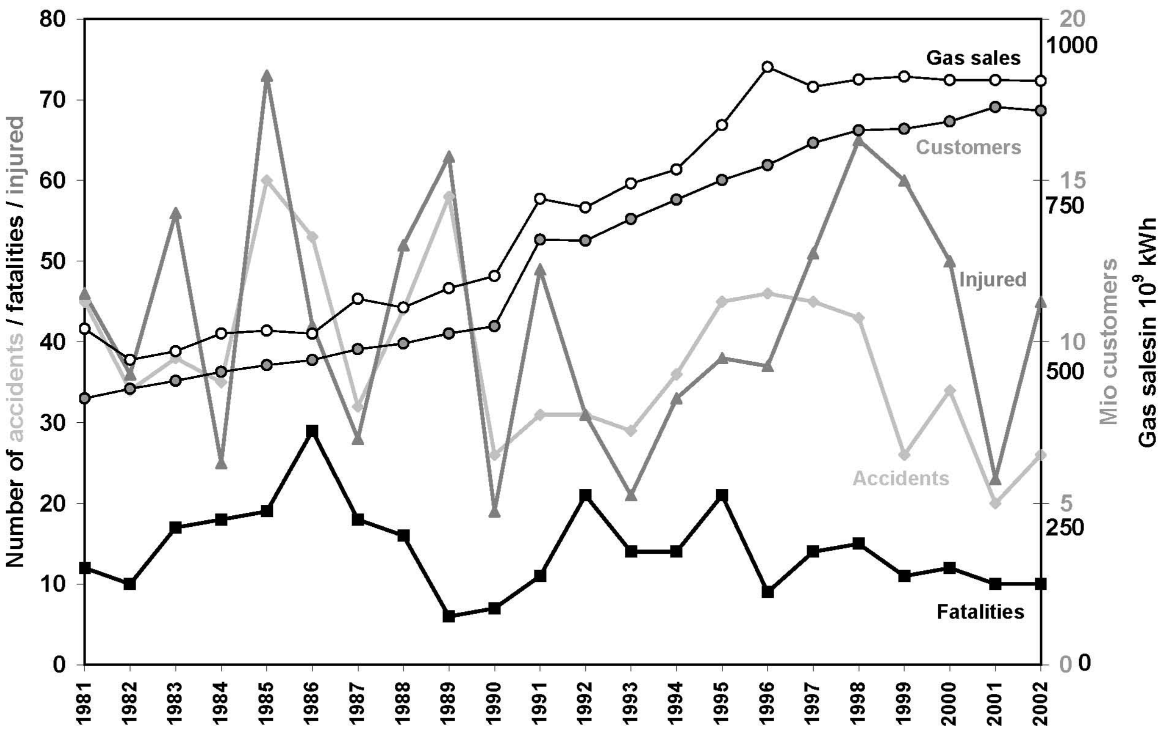

Fig. 22 Annual numbers of accidents, fatalities and injured at customer installations for the period 1981 – 2002. Additionally, indicators for structural changes in the natural gas sector were expressed as gas sales and number of customers. Based on data from DVGW (2004).

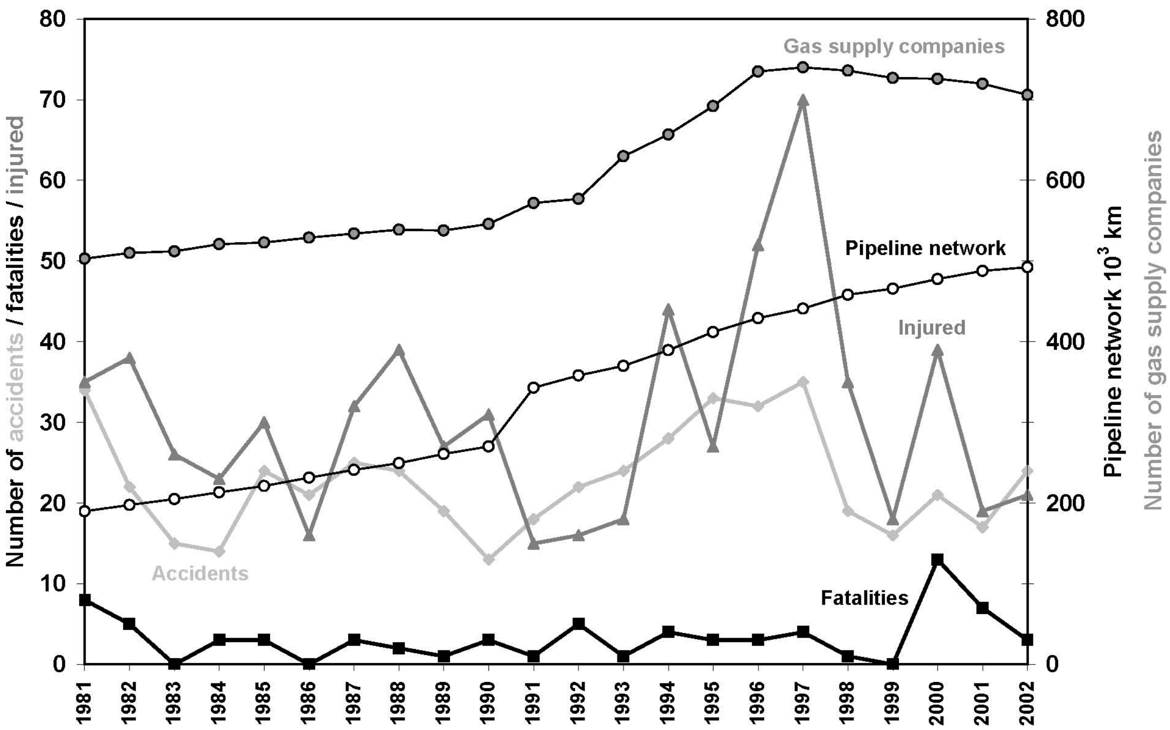

Fig. 23 Annual numbers of accidents, fatalities and injured at company installations for the period 1981 – 2002. Additionally, indicators for structural changes in the natural gas sector were expressed as total length of pipeline network and number of gas supply companies. Based on data from DVGW (2004).

3.3.4 Development of overall failure rates

An overview of the development of overall failure rates for the total period 1981 – 2002 is given for customer installations (Fig. 24 and Fig. 25) and company installations (Fig. 26). The figures show the gradual reduction in overall failure rates in each year, which is the cumulative total from 1981 onwards. In order to see the results over the last period, without the influence of the past, a moving average was calculated only over the past 5 years (1981 – 1985, 1982 – 1986, 1983 – 1987 etc). These additional curves are also included in the same figures.

Generally, data for fatalities and injured that were normalized to different indicators showed similar trends indicating that failure rates decreased over the period of observation. However, on the one hand achieved reductions for injured were higher, but on the other hand fatality risks were at significantly lower levels compared to injured risks.

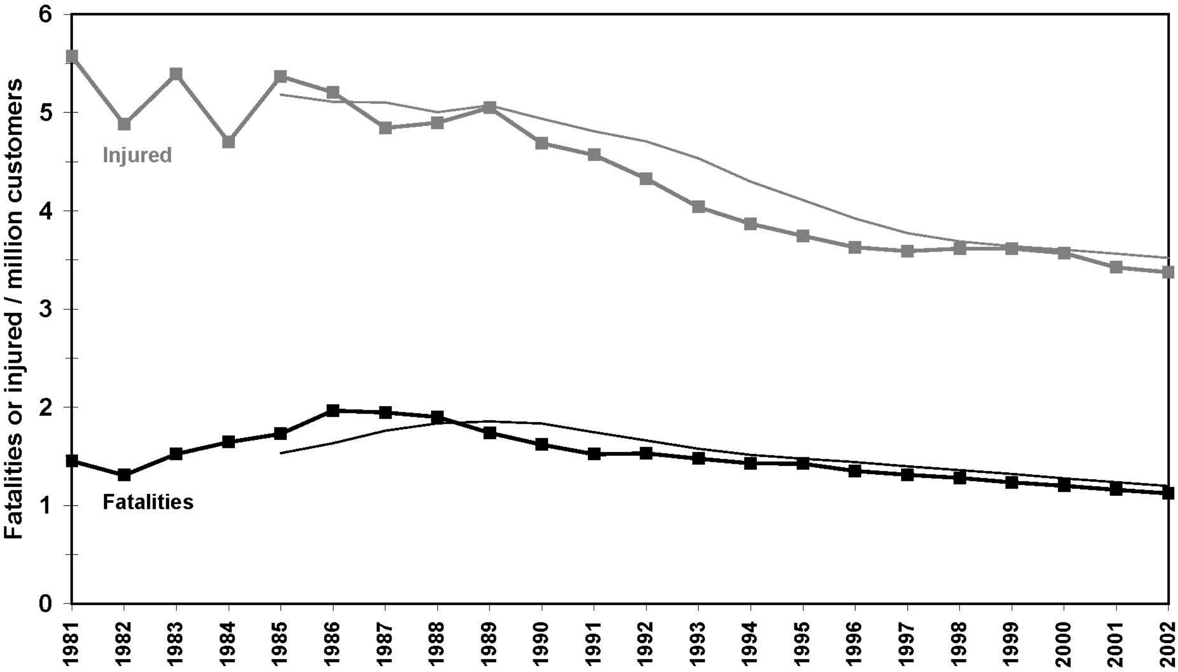

Fig. 24 **Development of overall failure rates normalized to number of customers for fatalities and injured at customer installations for the period 1981 – 2002. Thin solid lines represent moving average (past 5 years). Based on data from DVGW (2004).**

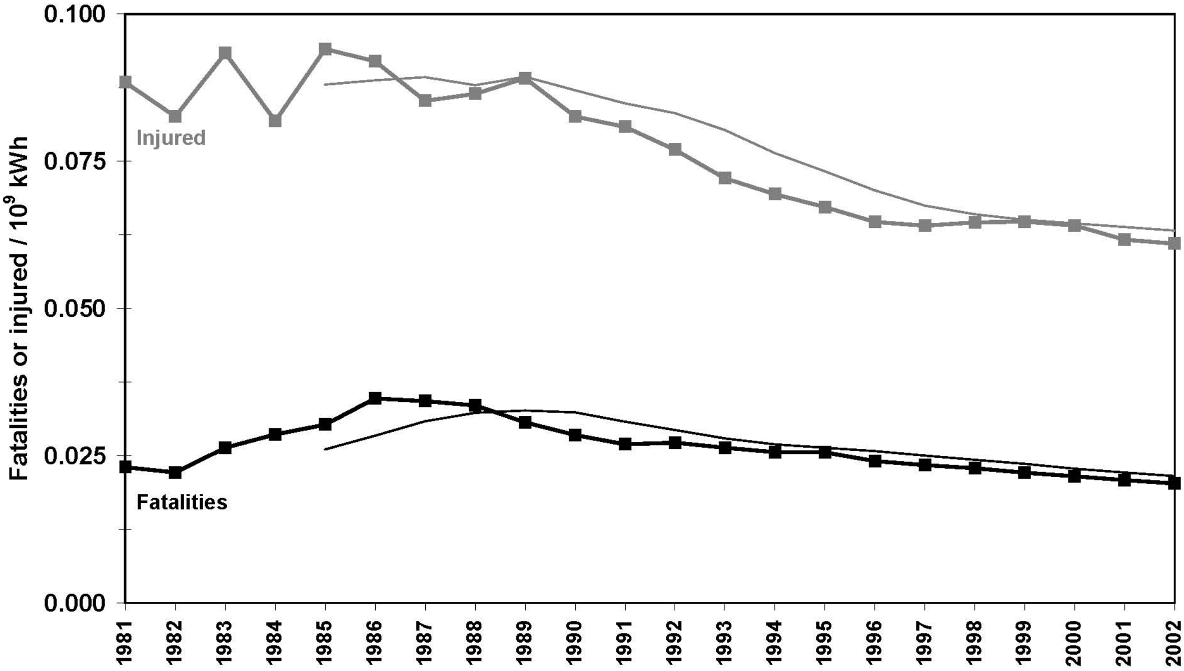

Fig. 25 **Development of overall failure rates normalized to gas sales in 10^9 kWh for fatalities and injured at customer installations for the period 1981 – 2002. Thin solid lines represent moving average (past 5 years). Based on data from DVGW (2004).**

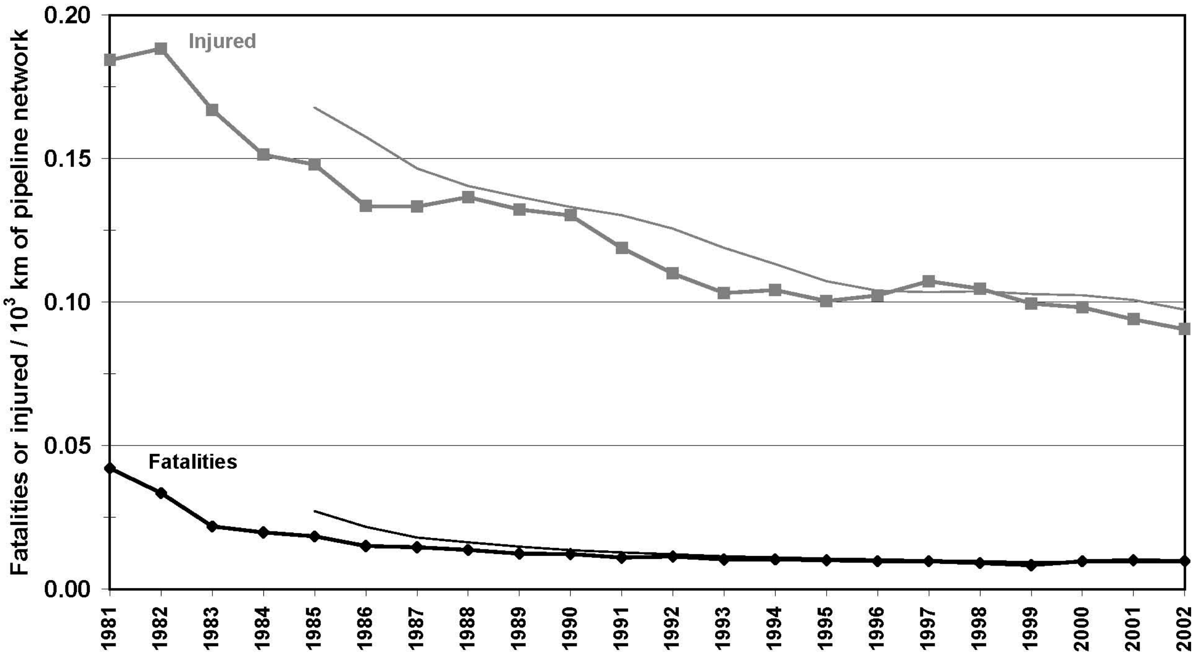

Fig. 26 **Development of overall failure rates normalized to length of pipeline network in 10^3 km for fatalities and injured at company installations for the period 1981 – 2002. Thin solid lines represent moving average (past 5 years). Based on data from DVGW (2004).**

3.4 Comparison between Germany and Switzerland

With regard to the extent of available data there are significant differences between Germany and Switzerland. For Germany data on more than 1300 incidents and accidents for the period 1981 – 2002 are documented in the statistics (DVGW 2004), whereas for Switzerland this amounts to about 140 incidents and accidents since 1995, out of which 11 events resulted in a total of 16 fatalities (SVGW 2004). This difference in database content is clearly reflecting the large difference in grid size and number of customers in the natural gas sector of the two countries. However, very similar technologies, management, regulations and safety culture are indicative that conditions in the natural gas sector of both countries are highly comparable. Therefore, evaluations based on German data can be regarded as fully representative for Switzerland, but have the advantage that they are statistically more robust due to the much larger amount of accident records.

3.5 Accident risk in Europe

In Fig. 27 a comparison of frequency-consequence (F/N) is shown for natural gas accident risks based on data from ENSAD and DVGW, respectively. Curves for EU15 and Central Europe are using ENSAD-data of severe accidents (≥ 5 fatalities). In contrast, the curve for Germany could be extended to accidents with a minimum of one fatality because DVGW-statistics also include extensive coverage of smaller accidents. It has been verified that there is complete agreement between data from ENSAD and DVGW for severe accidents that occurred in Germany. Although time periods covered differed between ENSAD (1969 – 2000) and DVGW (1981 – 2002) this is not a major problem because data were normalized per GW_eyr. Altogether, the figure indicates that German data could serve as an acceptable approximation to extend F/N-curves for EU15 and Central Europe towards smaller accidents.

This is an important finding because it demonstrates the possibility of combining severe accident data from ENSAD with suitable national or regional data sources that allow the generation of F/N-curves, which include coverage of smaller accidents. Therefore, future efforts should aim to incorporate additional data at a European level. In this context, cooperations with organizations such as ETPS or Marcogaz could have a great potential.

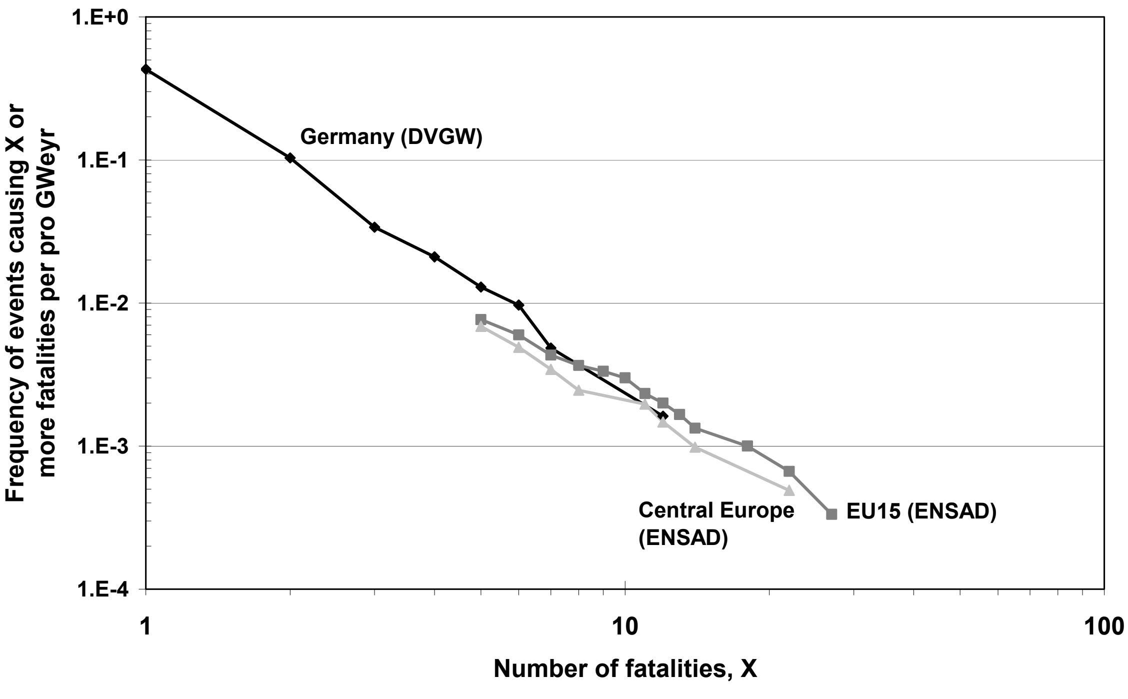

Fig. 27 Comparison of frequency-consequence curves for natural gas for EU15 and Central Europe (ENSAD-data; severe accidents only; 1969-2000) and Germany (DVGW-data; severe and smaller accidents; 1981-2002). Based on data from Burgherr et al. (to be published) and DVGW (2004).

4 Summary of insights

Energy chain comparisons

- Comparison of the different energy chains based on the comprehensive historical experience of energy-related severe accidents in PSI's database ENSAD.
- Energy-related accident risks in OECD countries are distinctly lower than in non-OECD countries.
- Natural gas shows lowest expected fatality rates of all fossil energy chains, both in OECD and non-OECD. For OECD natural gas has a fatality rate of 0.085 fatalities per GW_eyr. Corresponding OECD-values for oil, coal and LPG are 0.135, 0.157 and 1.957 fatalities per GW_eyr, respectively.
- Based on historical experience, maximum consequences for natural gas are clearly lowest among fossil energy chains; not exceeding about 100 fatalities for OECD as well as non-OECD countries, and not exceeding 27 for EU15 and 22 for Central Europe.
- Among the different energy chains analyzed, natural gas was the only one not classified as “risk dominant” in any of the defined categories.
- Western hydropower and nuclear power plants have even lower rates, but maximum credible consequences may be very large.
- Damages associated with severe accidents in the whole energy sector are rather small compared to natural disasters.

Natural gas chain

- The average number of fatalities over the last two decades was substantially lower in OECD than in non-OECD countries.
- Aggregated fatality rates are lowest for Central Europe (0.061 GW_eyr), followed by EU15 (0.077 GW_eyr) and OECD (0.080 GW_eyr), whereas non-OECD (0.110 GW_eyr) exhibits a significantly inferior performance as the other regional and country groups.
- Maximum credible consequences are also lower for Central Europe and EU15 than for OECD and non-OECD countries.

DVGW-data for Germany

- The DVGW-data on gas accidents allow detailed evaluations of smaller accidents and of chain-specific technical aspects (e.g., accident types or causes).
- Although, severe natural gas accidents attract a great deal of public and media attention, they are rather rare events (around 1% of all accidents) when compared to smaller accidents that constitute the large majority.
- Regarding fatalities and injured persons, severe accidents in gas distribution account for only about 10 to 20 percent of the respective totals, indicating that smaller accidents are again the dominant contributor.
- Evaluations of accidents at customer and company installations showed that human misconduct was clearly the primary accident cause. This evidence calls for further efforts to increase manipulation security and training of staff.
- Normalized accident rates decreased over the period 1981 – 2002. This was evident for fatalities and even more pronounced for injured, and is thus likely to indicate a process of continuous improvement of safety in the gas industry.

Comparison between Germany and Switzerland

- Extensive statistical experience on natural gas incidents and accidents for Germany is available from DVGW-Statistics, which can also be regarded as fully representative for Swiss conditions due to very similar technologies, management, regulations and safety culture.
- The most severe consequences of a single accident in Germany (12 fatalities) and Switzerland (5 fatalities) are clearly below corresponding numbers for Central Europe and EU15 mentioned before.

Accident risk in Europe

- ENSAD-data for severe natural gas accidents and DVGW-data for small and severe natural gas accidents are in good agreement as supported by the respective frequency-consequence (F/N) curves.
- Both databases indicate the low probability of natural gas accidents consequences under European conditions, but additional accident statistics from other countries are needed to verify this accident record throughout Europe.

5 Glossary

BHDF	Bibliography of the History of Dam Failures, edited by A. Vogel, Risk Assessment International, Austria.
Central Europe	In this study the definition of the term Central Europe comprises the following countries: Switzerland, Germany, The Netherlands, United Kingdom, Belgium and Denmark.
CCIY	China Coal Industry Yearbook
CISDOC	International Occupational Health and Safety Centre Bibliographic Database
company installations	Eigenanlagen, UE. Installations under the ownership and/or responsibility of the gas supply companies.
CRED	See EM-DAT
customer installations	Kundenanlagen, UK. Installations or parts of installations at gas customers behind the service valve.
DNV	Det Norske Veritas. See WOAD
DOT	US Department of Transportation
DVGW	Deutsche Vereinigung des Gas- und Wasserfaches
EGIG	European Gas Pipeline Incident Data Group
EM-DAT	Since 1988 the WHO Collaborating Centre for Research on the Epidemiology of Disasters (CRED) has been maintaining an Emergency Events Database - EM-DAT. EM-DAT was created with the initial support of the WHO and the Belgian Government.
ENSAD	Energy-related Severe Accident Database
ETC	The Environmental Technology Centre maintains a worldwide tanker spill database where accidental spills of over 1000 barrels of petroleum products were released. Incidents can be searched for by date and/or vessel name.
ETPS	European Working Group on Third Party Safety
EU	European Union
F/N curve	Frequency-consequence curve
GaBE	Ganzheitliche Betrachtung von Energiesystemen (Comprehensive Assessment of Energy Systems)
HSE	Health and Safety Executive (UK).
HSELINE	Library and Information Services of HSE
ICOLD	International Commission on Large Dams
IEA	International Energy Agency
ILO	International Labour Organisation
ITOPF	International Tanker Owners Pollution Federation Ltd.
LLP	Lloyd’s Casualty Week; formerly Lloyd’s of London Press
LPG	Liquefied Petroleum Gas
Marcogaz	Technical Association of the European Natural Gas Industry
MARS	The Major Accident Reporting System is a distributed information network of the European Union
MHIDAS	Major Hazards Incidence Data Service
NewExt	New Elements for the Assessment of External Costs from Energy Technologies

NIOSHTIC	National Institute of Occupational Safety and Health (USA)
OECD	Organisation for economic cooperation and development
OFDA	See EM-DAT
OGS	Office of Gas Safety, Victoria, Australia
OPS	Office of Pipeline Safety in the US Department of Transportation (DOT)
OSH	Occupational Health and Safety
PC-FACTS	Failure and Accidents Technical Information System; TNO Department of Industrial Safety, The Netherlands.
PSA	Probabilistic Safety Assessment
SIGMA	Sigma is published approximately eight times a year by Swiss Re's Economic Research & Consulting Team based in Zurich, New York and Hong Kong
SVGW	Schweizerischer Verein des Gas- und Wasserfaches
TMI	Three Mile Island
VNIIGAS	All Russian Scientific/Research Institute for Natural Gas and Gas Technology, Moscow
WOAD	Worldwide Offshore Accident Databank; Det Norske Veritas, Norway

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