

# **Severe Accidents in Fossil Energy Chains: Individual Chain Results and Aggregated Evaluations**

Peter Burgherr and Stefan Hirschberg  
Paul Scherrer Institut,  
Villigen, Switzerland

## **1 Introduction**

Severe accidents in the energy sector have been identified as one of the main contributors to man-made disasters. Based primarily on the historical experience, the Paul Scherrer Institut (PSI) carries out extensive analyses of severe accidents in the energy sector. The work presented here is focused on severe accident risks in fossil energy chains, i.e. coal, oil, natural gas and Liquefied Petroleum Gas (LPG). Additionally, selected technical aspects of severe accidents were addressed, reflecting an engineering perspective on the energy-related risk issues.

Due to the use of a variety of information sources, including databases established in various countries, PSI's database ENSAD (Energy-related Severe Accident Database) has a balanced coverage with respect to countries and regions where the accidents took place [1,2]. This eliminates some constraints encountered in many other accident databases driven by the local availability of information.

ENSAD uses seven criteria to define an energy-related severe accident [1,2]. However, analyses that are presented in this paper 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 (also compare [1,2]).

Evaluations were not limited to power plants but covered full energy chains, including exploration, extraction, processing, storage, transports and waste management since accidents can occur at any of these stages. For an adequate representation of the historical experience the time period from 1969 to 2000 was considered, because the number of energy-related accidents has exhibited a distinct increase since the late sixties due to increased activities and improved reporting [1,2]. Finally, individual results were calculated for OECD and non-OECD countries to account for differences between industrialized and developing countries.

## **2 Overview of historical experience**

For the fossil energy chains, PSI's database ENSAD comprises 1848 accidents amounting to 51'289 fatalities that are classified as severe because five or more fatalities occurred (Table 1). The coal chain accounted for two thirds of all accidents

followed distantly by oil with a share of 21%, whereas contributions of natural gas (7%) and LPG (6%) were much smaller. This dominance of coal chain accidents is fully attributable to the release of detailed accident statistics for China's coal industry that were not publicly available before [3,4]. Altogether, 819 of the 1044 accidents collected for the Chinese coal chain occurred in the years 1994-1999, demonstrating the substantial underreporting prior to the release of annual editions of the China Coal Industry Yearbook.

A similar pattern was observed when looking at fatalities, although coal (49%) had a lower contribution at the expense of oil (39%), whereas natural gas (4%) and LPG (8%) remained below 10%. This increased share observed for oil is due to few very large accidents, which were one order of magnitude greater than the largest ones for coal (compare Table 1 and Figure 1).

Energy chain	OECD			non-OECD		
	Accidents	Fatalities	Accident with max fatalities	Accidents	Fatalities	Accident with max fatalities
<b>Coal</b>	75	2259	272	102 1044 (a)	4831 18'017 (a)	434 284 (a)
<b>Oil</b>	165	3789	577	232	16'494	4375
<b>Natural Gas</b>	80	978	109	45	1000	100
<b>LPG</b>	59	1905	498	46	2016	600

Table 1: Summary of severe accidents that occurred in the fossil energy chains of OECD and non-OECD countries in the period 1969-2000 [2]. Accidents resulting in largest numbers of fatalities are also given. (a) First line: Coal non-OECD w/o China; second line: Coal China

On average, 58 severe accidents occurred each year worldwide in fossil energy chains (Figure 1a). About 60% of all accidents happened in the years 1993-2000. This dominance is primarily due to improved reporting of coal accidents in China and their publication in the China Coal Industry Yearbook (CCiy). Considering different gravity indices for fatalities, over 72% of all accidents resulted in 5-20 fatalities, whereas accidents exceeding 100 fatalities ranged from 0 to 5 per year.

The average number of fatalities amounted to about 1600 per year (Figure 1b). However, few very large accidents strongly influence the statistics of individual years. For example, two oil accidents in Afghanistan (1982; 2700 fatalities) and the Philippines (1987; 4375 fat.) made up 73% and 83% of all fatalities in these years. In contrast, fatality peaks in 1995 and 1997 were primarily caused by accidents in the size categories "5-20 fatalities" and "21-50 fatalities" in the Chinese coal chain.

### 3 Selected chain-specific analyses

Figure 2 shows the number of fatalities in severe accidents according to the different chain stages. Note that similar patterns were found for the number of severe accidents, which are not shown in the figure.

For the coal chain, the majority of fatalities occurred in the extraction stage (Figure 2a). However, the share of accidents in the exploration stage is very large in

the Chinese coal chain, compared to the almost insignificant shares in OECD and other non-OECD countries. An evaluation of severe coal accidents causes revealed that explosions of methane gas in mines were the most frequent reason, ranging from 57% for OECD countries to 80% for China (50% for other non-OECD countries). Fires, roof collapses and transport accidents generally had individual contributions below 7%. For additional information we refer to [1,2] or in the specific case of the Chinese coal chain to [3,4].

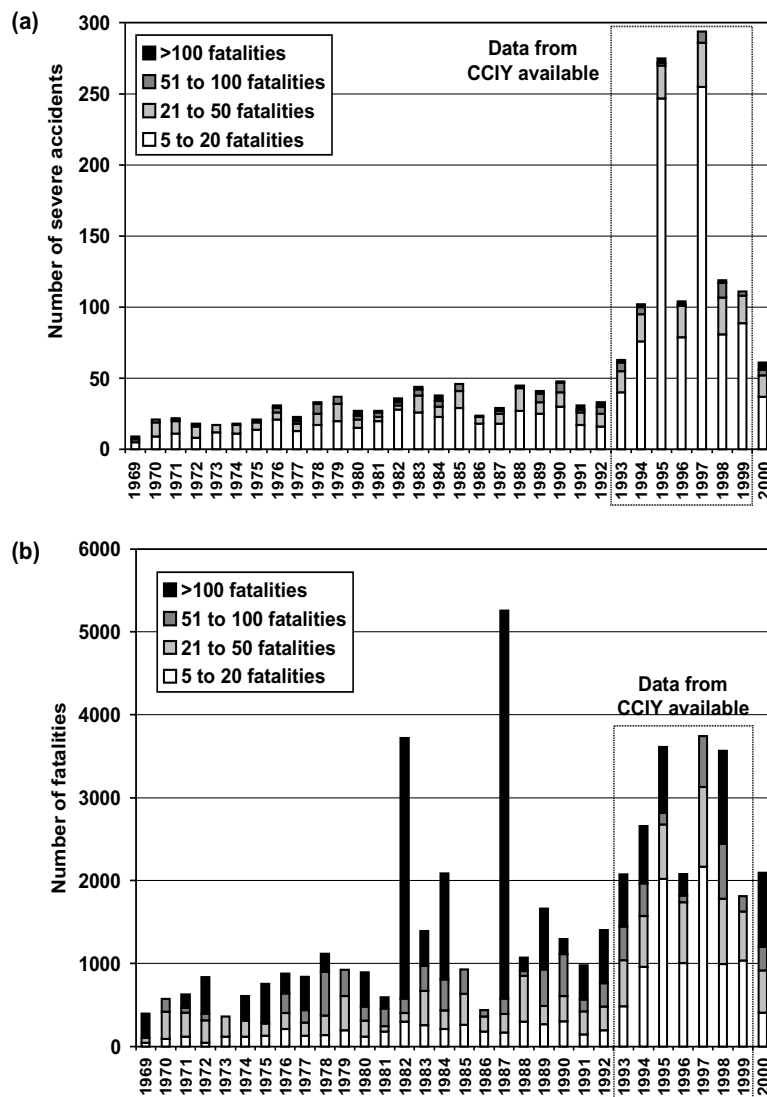


Figure 1: Worldwide numbers of (a) severe accidents and (b) fatalities in fossil energy chains according to different gravity indices for the period 1969-2000 [2]. The dashed box indicates the period for which data of the China Coal Industry Yearbook (CCIY) were available.

Transportation stages (i.e., regional distribution and transport to refinery) were the most accident-prone oil chain stages (Figure 2b), accounting for 72.9% of fatalities in OECD and 89.9% in non-OECD countries. Refinery, extraction and exploration stages followed distantly. Contributions of Heating and Power Plant are practically negligible. Analysis of transportation modes for the oil chain revealed that maritime accidents dominated within the “Transport to Refinery” stage. This is primarily due to tankers that exploded, caught fire or were involved in a collision. Concerning the “Regional Distribution” stage road accidents were most common, caused mainly by collisions of road tankers with other vehicles and overturning of road tankers.

For the natural gas chain, the majority of fatalities also occurred during transportation stages (OECD: 78.0%, non-OECD: 50.2%), followed by heating (16.6% vs. 27.8%) (Figure 2c). Nearly 57% of all accidents occurred during transport by pipelines, distantly followed by activities such as process (10.4%), storage (8.8%) and incidents that originated in domestic or commercial premises (Dom/com; 17.6%). The majority of accidents involving pipelines were caused by impact failures (46%) and mechanical failures (30%).

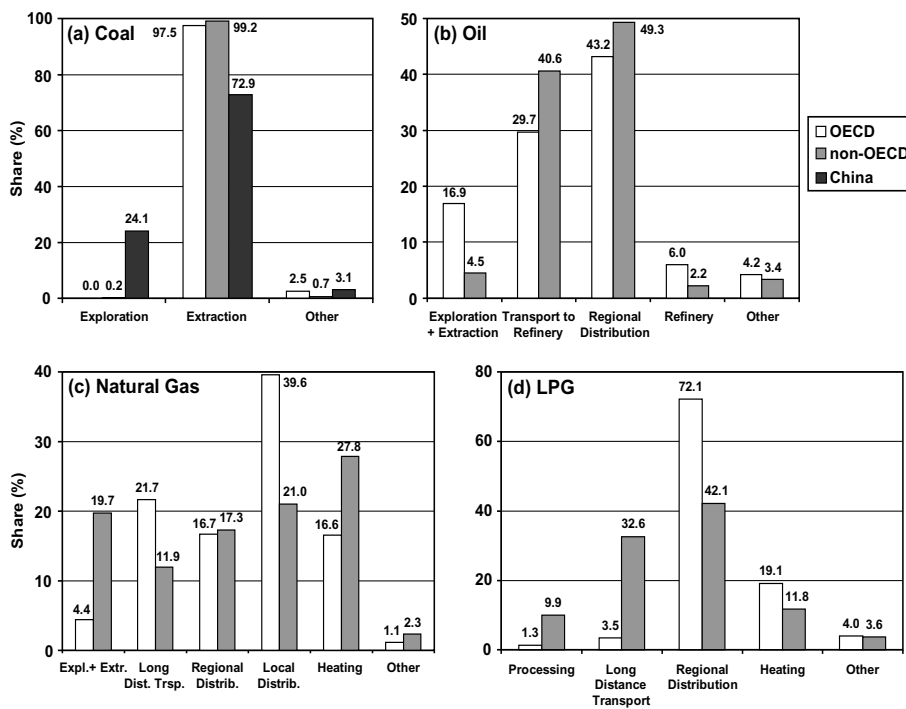


Figure 2: Shares of fatalities in severe accidents according to chain stages. Data are shown for OECD and non-OECD countries [2]. For the coal chain, results for China and other non-OECD countries are shown separately.

Concerning the LPG chain, regional distribution accounted for 72.1% of fatalities in OECD countries, whereas the share of the stage long distance transport was minimal (Figure 2d). In non-OECD countries, regional distribution (42.1%) and long

distance transport (32.6%) made up about three quarters of all fatalities. The distinctly higher percent contribution of the stage long distance transport in non-OECD countries is due to the largest LPG accident with 600 fatalities (Asha-Ufa, Russia) that alone amounts to 29.8% of all fatalities in non-OECD countries. Concerning accident causes related to the different activities, no detailed evaluation was possible because most accident descriptions did not contain such information. Therefore, only some broad tendencies could be identified, which appear to be in accordance with the results found in earlier analyses (compare [1]). Impact failures were the most important cause for accidents during transport, whereas mechanical failures were the most frequent cause for accidents during process, transfer and storage activities.

## 4 Aggregated indicators

For comparative purposes, aggregated fatality rates were used, normalized on the basis of the unit of electricity production for the different energy chains. Note that only immediate fatalities are covered here, based on historical experience of severe accidents. Aggregated fatality rates differed substantially among the various energy chains (Table 2). Generally, fatality rates for all considered energy chains were substantially higher for non-OECD countries than for OECD countries.

Energy Chain	Number of immediate fatalities per GWeyr		
	Worldwide	OECD	Non-OECD
Coal	0.876	0.157	0.597(a) 6.169 (b)
Oil	0.436	0.135	0.897
Natural Gas	0.093	0.080	0.111
LPG	3.536	1.957	14.896

Table 2: Experience-based fatality rates associated with severe accidents within full energy chains, using no reallocation of damages between OECD and non-OECD countries [2]. (a) non-OECD countries w/o China; (b) China 1994-1999; CCIY were available; no allocation

## 5 Conclusions

### Coal chain

- The overall number of severe accidents in the coal chain decreased slightly in OECD countries in the last two decades as opposed to non-OECD countries.
- The Chinese coal chain is a special case with more than 6000 fatalities (about one third due to severe accidents) every year, and a fatality rate about ten times higher than in other non-OECD countries, and even about 40 times higher than in OECD countries (no allocation of damages).
- The coal chain stage with by far most fatalities is “Extraction”, whereas the other stages have relatively small contributions to severe accidents.

- Methane gas explosions in underground mining were the most frequent cause of severe coal accidents worldwide.

#### **Oil chain**

- Along with higher oil consumption there has been a trend of increasing number of severe accidents and resulting fatalities in non-OECD countries, but not in OECD countries.
- The most risk prone stages in the oil chain are “Regional Distribution” and “Transport to Refinery”.
- Maritime accidents are the most frequent accidents during the stage “Transport to Refinery” while road accidents are the most frequent accidents during the stage “Regional Distribution”.

#### **Natural gas and LPG chains**

- The yearly number of LPG and natural gas severe accidents significantly increased after 1970 in non-OECD countries, whereas OECD countries exhibited an opposite trend. At the same time, there is a large scatter in the number of accidents from year to year.
- The majority of severe accidents occurred in the stages “Long Distance Transport”, “Regional Distribution”, “Local Distribution” and “Heating” for natural gas and “Regional Distribution” for LPG.
- Nearly 60% of all severe natural gas accidents occurred during transport by pipelines.
- Almost half of all severe LPG accidents occurred during transport, particularly by road tankers. The dominant accident cause was impact failure.

#### **Aggregated indicators**

- Aggregated fatality rates worldwide are highest for LPG followed by coal, oil and natural gas. However, for non-OECD countries the corresponding rate is higher for oil than for coal (when China is excluded).
- Natural gas accidents generally resulted at most in about 100 fatalities, whereas maximum number of fatalities for oil and to a lesser extent also for LPG and coal were substantially higher in some cases.

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