Project No 213744

SECURE
Security of Energy Considering its Uncertainty, Risk and Economic implications

SP1 – Cooperation
Collaborative project
Small or medium-scale focused research project

DELIVERABLE No 5.7.2a
[Final Report on Severe Accident Risks including Key Indicators]

Due date of deliverable: March 2010
Actual submission date: January 2011

Start date of project: 1/1/2008

Duration: 36 months

Organization name of lead contractor for this deliverable: PSI

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Revision:

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Final report on Severe Accident Risks including Key Indicators

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Executive Summary

The energy sector is both a key resource and a critical infrastructure for the economy that forms the backbone of today's society, its goods and services. Therefore, the comparative assessment of accident risks is a pivotal aspect in a comprehensive evaluation of energy security concerns.

Historically, only consequences of severe accidents caused by technological or natural hazards have been focused on; however in the past decade the potentially disastrous consequences of purposed malicious actions, ranging from vandalism to sabotage and terrorist attacks, emerged as additional topics calling for attention.

Effects of severe accidents and terrorist attacks are interrelated to a variety of other energy security facets including vulnerability to transient or long-term physical disruptions to import supplies, geopolitical dependencies due to imported resources, price fluctuations as a result of single events with extremely large consequences, increased likelihood for accidents due to infrastructure ageing and underinvestment, and enhanced awareness of so-called Natech (natural disaster-triggered technological) disasters because of global climate change.

Work package 5.7 of the EU project SECURE (Security of Energy Considering Its Uncertainty, Risk and Economic Implications) analyzes the risks of severe accidents and terrorism in the production and use of energy, which are presented in two separate deliverables, i.e. D5.7.2a (public) for the former and D5.7.2b (confidential) for the latter, as agreed upon with European Commission.

This report presents an analysis of the accident risks in fossil (coal, oil, natural gas) as well as renewable and nuclear energy chains and develops and calculates three risk indicators that capture the available information on frequency and severity.

The numbers and associated consequences of man-made accidents appear to have increased in the past decades. Furthermore, accidents in the energy sector have been shown to form the second largest category (after transportation) of man-made accidents. Economic consequences include not only the direct damages but also rising prices e.g. for products after refinery accidents. While economic consequences are certainly significant, this report investigates primarily consequences to human life and the environment, with fatalities as the main focus.

The present report investigates the average frequency and average severity (e.g. average number of fatalities per accident). It is, however, also crucial to quantify the potential for very rare but catastrophic accidents, mainly for hydropower, fossil fuels and nuclear power, as these accidents contribute significantly to the aggregate damage. The probability for such accidents can be extracted only from data accumulated over longer time periods and inherently has a high uncertainty.

The analysis of accidents in the fossil and hydro chains is based on historical data available from the database ENSAD (Energy-related Severe Accident Database); while for nuclear energy a simplified Probabilistic Safety Assessment (PSA) was used to assess site-specific consequences of hypothetical accidents. Among new renewable energy technologies, levels of maturity and penetration are different, which is why for some technologies limited (compared to fossil chains) accident data was available (e.g.

Wind, Photovoltaics (PV)), whereas for others estimates were based on approximations and combined with literature studies and expert judgment due to missing historical experience (e.g. geothermal energy from Hot Dry Rock (HDR)).

For fossil energy and hydro power, our analysis is based on historical data from 1970-2008 extracted from database ENSAD, which allows carrying out comprehensive analyses of accident risks that are not limited to power plants but cover full energy chains. Such a broader perspective is essential because for the fossil chains accidents at power plants play a minor role compared to the other chain stages, i.e. analyses based on power plants only would radically underestimate the real situation. Within the project SECURE, ENSAD was updated to cover accidents up to the year 2008. The large number of accidents in the fossil energy chains allows also investigating trends in accident frequency.

For this report, the two components of risk, i.e the frequency measuring the number of accidents per year and the severity of the consequences of each accident were first separately analyzed because they do not follow the same patterns. The frequency of accidents was tested for trends over time to achieve an up-to-date quantification of accident risk. From the resulting frequency - consequence model, risk indicators were calculated that allow the direct comparison between different energy chains and can directly be used as input into decision making tools. As a measure of consequences this report focuses on the number of fatalities. The distribution of the severity of the consequences are modeled with a joint probability distribution of a generalized Pareto distribution for the high severity tail of the distribution over a threshold and an empirical distribution for accidents with lower severity. In the final step, the results from both analyses can then be aggregated to obtain the full risk.

Among centralized large-scale technologies in industrialized countries estimated expected accident risks are by far lowest for hydro and nuclear while fossil fuel chains exhibit the highest risks. On the other hand the maximum credible consequences of low frequency hypothetical severe accidents, which can be viewed as a measure of risk aversion, are by far highest for nuclear and hydro (given high population density down-stream from the dam), in the middle range for fossil chains and very small for solar and wind. For nuclear, the maximum consequences are expected to be strongly reduced for the chosen reference GEN IV designs (Sodium Cooled Fast Breeder reactor (FBR) and High Temperature Gas Cooled reactor (HTR)) compared with the GEN III design (European Pressurized Reactor (EPR)).

Severe accidents affecting energy infrastructure can be costly and can affect other critical infrastructures due to dependencies on energy supply. In most cases, the effects of severe accidents on security of supply are of short-term character due to redundancies. Severe nuclear accidents could cause a long-term problem in electricity supply primarily due to potential secondary effects of such accidents, negatively affecting nuclear energy in general. There are also concerns for hydro, particularly in small countries with relatively few large dams and high dependence on their output.

Decentralized energy systems are less sensitive to the issue of severe accidents than large centralized ones. Finally, allocating appropriate resources for assuring high safety standards of nuclear power plants and hydro dams is of central importance also for security of supply.

1 Introduction

1.1 Scope and objectives of SECURE project

The primary purpose of the project SECURE (Security of Energy Considering its Uncertainty, Risk and Economic implications) is the establishment of a comprehensive framework for the assessment of energy security relevant for European Union (EU 27). SECURE addresses energy security not only under the narrow definition of supply security, but from the broader perspective of sustainable energy supply. To provide a holistic basis for decision making and subsequent policy formulation, an overarching goal of SECURE is the development of an extensive set of energy security indicators for all major energy technologies (oil, natural gas, coal, nuclear and renewables), covering technical, economic/regulatory, geopolitical, environmental/climate change and social (e.g. severe accidents and terrorist threat) aspects as well as their short- versus long-term impacts.

The SECURE project is divided into a number of work packages: WP1 includes conceptual and general methodological developments. WPs 2 to 6 provide the core scientific activities including valuation of energy security (WP2), development of qualitative story lines (WP3) and quantitative global models (WP4), technology specific evaluations (WP5.x), and review and integration of results as well as the formulation of policy recommendations (WP6). Finally, WP7 is designated to stakeholder consultations and dissemination.

Work Package 5.7 contains the development and application of a methodology for assessing impacts of severe accidents and terrorist threat on energy security. The specific objectives of WP 5.7 are:

- State-of-the-art comparative assessment of severe accidents in major energy chains, the topic addressed by this report (Deliverable D5.7.2a; public).
- Development and applications of a methodology for the assessment of the terrorist threat to major energy infrastructures, addressed in a separate report (Deliverable D5.7.2b; confidential).
- Risk aversion in accident risk assessment (Deliverable D.5.7.3; public).

1.2 Severe accident risks in the context of energy security

Historically, energy security has been primarily viewed in terms of oil supply disruptions (WEF, 2006), whereas in recent years a variety of new and interrelated threats have made it a major concern on the political agenda. Man-made accidents and natural disasters affect people's health and property, the supply of economic goods and services, and degrade ecosystems and their functions (Burgherr and Hirschberg, 2008a; Burgherr et al., 2008; Dilley, 2006; Hirschberg et al., 1998; Lerner-Lam, 2007; Munich Re, 2005; Swiss Re, 2004). In recent years, a number of single major catastrophes and regularly recurring loss events further increased the awareness of a large proportion of the populace due to broad media coverage and public debate, including:

- The unprecedented impact of hurricanes Katrina and Rita in 2005 on offshore oil and gas structures in the Gulf of Mexico (Kaiser et al., 2009).
- The recent blowout and subsequent spill on the drilling rig Deepwater Horizon in the Gulf of Mexico (20 April 2010) resulting in a release of up to 4’900’000 bbl of oil (669'340 t) according to, of which approximately 800’000 bbl were captured prior to the capping of the well (RestoretheGulf.gov 2010). A more recent estimate published on 23 September 2010 in Science estimates that some 4’400’000 bbl of oil were released into the water, using an optical technique known as flow velocimetry (Crone and Tolstoy, 2010).
- Despite a substantial reduction in the numbers and volumes of tanker spills since the 1970s, even comparatively smaller oil spills like the ones of the Exxon Valdez in Prince Williams Sound, Alaska (1989; 38500 t released) or the Prestige off the Galician coast (2002; 63000 t) can result in disastrous consequences for the local environment and economy (Burgherr, 2007)
- Accidental rupture of gasoline pipelines or puncture by thieves for looting in Nigeria often attracts large numbers of scavengers in the neighborhood. Subsequent explosions and fires can kill up to several hundred persons (Burgherr et al., 2008; Giroux, 2008).
- Frequent attacks on Iraqi oil pipelines, installations and personnel (IAGS, 2009) Most of the about 7000 km of crude and product pipelines in Iraq (CIA, 2008) are above ground and therefore very difficult to protect, which makes them easy and attractive targets for sabotage or other malicious actions.
- Coal mine accidents in China claim thousand of fatalities every year (Burgherr and Hirschberg, 2007).
- Although non-OECD countries are more prone to severe, energy-related accidents, they also occur in the highly developed countries of OECD (Organisation for Economic Co-operation and Development) or EU (European Union): the explosion of a natural gas transmission pipeline in Ghislenghien (Belgium; 2004; 23 fatalities; 200 injuries), the explosion of the Buncefield fuel depot (UK, 2005; 43 injuries; 2000 evacuees), explosion on the tanker “Friendship Gas” that was undergoing repair in the port of Perama (Greece; 2008; 8 fatalities; 4 injuries) or the explosion at a natural gas power plant due to a gas leak (USA; 2009; 5 fatalities; 12 injuries). (Burgherr et al., 2008).

Thus, the protection of critical infrastructure facilities in the energy sector is of paramount importance because a sufficient and continuous energy supply forms the backbone of today’s society and many of its products, which are relying on interrelated and interdependent information and communication technologies (Burgherr and Hirschberg, 2009). As a consequence, the interest and demand for more and better data on the assessment of severe accidents has considerably risen because they are the basis for improved risk management and informed decision-making concerning the diverse safety, health and environmental problems (Burgherr and Hirschberg, 2009; Dilley, 2006; Dilley et al., 2005; Flynn et al., 2001).

Mankind's vulnerability towards accident and catastrophe hazards has been increased in the past decades by a variety of factors such as the steady growth of industrialization, continuing rapid urbanization, the disproportionately high development of coastal and other risk-prone areas, and strong dependency on complex, inter-related infrastructures (Burgherr and Hirschberg, 2008a; Dilley et al., 2005; Rinaldi et al., 2001). In combination with the potential for future changes in the intensity and frequency of some hazards these factors constitute a serious challenge to society and its sustainable development because they can affect a wide range of social and ecological systems; in both the industrialized and developing countries (Dilley et al., 2005; Thomalla et al., 2006).

Reporting of industrial accidents is often regulated by national and supra-national frameworks. For example, companies are obliged to report accidental events from industrial activities falling under the SEVESO II Directive of the European Union allowing in-depth analysis of accident frequencies and consequences (Nivolianitou et al., 2006; Papadakis, 2000). Although accidents in the energy sector have been shown to form the second largest group of man-made accidents (after transportation), their level of coverage and completeness was not satisfactory because they were commonly not surveyed and analyzed separately, but just as a part of technological accidents (Hirschberg et al., 1998). The Paul Scherrer Institut (PSI) started a long-term research activity in the 1990s to close this gap and to enable a factual and appropriate treatment of accident risks in the energy sector. Severe accidents are most controversial in public perception and energy politics. Therefore they are the main focus of investigations, even when the total sum of the many small accidents with minor consequences is substantial (Burgherr and Hirschberg, 2008a; Burgherr and Hirschberg, 2008b).

The aim and content of this deliverable are the following:

- To provide an analysis of severe accidents in the context of energy security performed within the SECURE project as part of Work Package (WP) 5.7 "Impacts of severe accidents and terrorist threat on energy security".
- An overview of the achievements accomplished in the update of PSI's accident database ENSAD (Energy-related Severe Accident Database), which has been performed within SECURE.

This report denotes Deliverable D5.7.2a of the SECURE project, which builds upon D5.7.1 that includes a detailed introduction to ENSAD and the general methodology for the analysis of severe accident risks in the energy sector. The present report comprises a concise methodological description (1) of the analysis of historical accident data in fossil energy chains and hydropower that is based on ENSAD, (2) the simplified Probabilistic Safety Assessment (PSA) applied to the nuclear chain, and (3) the treatment of new renewables for which empirical experience is limited, and thus needs to be partially complemented by expert judgment. The results of comparative risk assessment for the various energy technologies including the calculation of specific risk indicators to be used in Multi-Criteria Decision Analysis (MCDA) – that is conducted in WP 6 – are also discussed.

Note that the assessment of energy infrastructures with regard to the terrorist threat and aspects of risk aversion are addressed in separate deliverables (D5.7.2b, D5.7.3).

2 Methodological approach and analysis framework

2.1 Scope and extent of analysis

The aim of this analysis is to compare the accident risks of different energy chains on the basis of objective and quantitative information. Fatalities were chosen as the main indicator as they are more reliable than other measures such as injuries or financial losses, both in terms of coverage and accuracy. The fatality indicator is also independent of time, whereas financial losses need to be adjusted for inflation and converted into the same currency to obtain comparable values. The focus is on severe accidents according to the severe accident definition used in the database ENSAD (compare chapter 2.2.2), i.e. accidents with five or more fatalities are included in the analysis. This threshold selection ensures a high degree of completeness, even in areas of the world where the regulatory environment and/or its implementation are less rigorous.

The wide range of technologies used in energy production and conversion makes the direct comparison of accident risks a challenging task because the various energy chains show very different risk profiles (Burgherr and Hirschberg, 2008a; Burgherr et al., 2008). For example, fossil energy chains show highest accident frequencies, whereas hydropower or nuclear accidents are very rare events. At the same time, maximum consequences of fossil accidents are typically one to two orders of magnitude lower than for hydropower and nuclear. Finally, risk in specific chain stages can substantially differ among energy chains.

Furthermore, the number of historically recorded accidents determines if a certain energy chain can be analyzed based on empirical experience. In the case of fossil energy chains (coal, oil, natural gas) there exist extensive and detailed accident statistics for several decades, which are contained in ENSAD. For hydropower, evidence of actual accidents is already much less comprehensive, while for nuclear there has occurred only one severe accident with at least five immediate fatalities (Chernobyl, 1986), which makes the application of Probabilistic Safety Assessment (PSA) mandatory. New renewable technologies such as electricity generation from geothermal energy are still emerging and expected to further develop in the coming years and decades, thus their accident statistics are rather limited. Additionally, individual chains may pose distinct challenges such as Hot Dry Rock (HDR) geothermal for which it is still under discussion if there is a risk to potentially trigger a severe earthquake when applying hydraulic fracturing techniques to enhance or create rock permeability. Until now the largest induced seismic events at geothermal sites had a maximum magnitude between 2.9 and 3.7 (Bromley and Mongillo, 2008). Consequently, such risks can only be discussed on a qualitative level until further research produces more conclusive results.

To include results of comparative risk assessment into formal decision making frameworks such as Multi Criteria Decision Analysis (MCDA), it is important to develop and calculate risk indicators that can capture the different facets of technology-specific risk profiles. Within SECURE, three such risk indicators were defined and quantitatively evaluated (see chapter 2.5).

2.2 Severe accident database ENSAD

2.2.1 Origin, development and structure of ENSAD

The unsatisfactory treatment or complete non-consideration of severe accident risks and their human health, environmental, economic and social impacts has already been recognized as a major limitation of the comparative assessment of energy systems in the beginning of the 1990s (Fritzsche, 1992). In response to this gap, the Paul Scherrer Institut (PSI) started a dedicated activity dealing with accident risks and their associated consequences of the major energy chains (fossil, hydro and nuclear). The database ENSAD forms the core of this analytical framework. ENSAD builds upon a wide range of existing information sources (commercial and freely available) that are combined using the MS Access environment, which makes it a fully relational database. The complete process of database building and implementation has been streamlined and standardized to the extent possible (Burgherr et al., 2009, chapter 3.1).

This includes the following steps:

1. The survey of primary information sources.
2. The collection, merging, harmonization and verification of raw information.
3. The use of a defined input template to assure consistent data records with a minimum of redundant information.

Finally, ENSAD has been continuously upgraded to support a multitude of flexible queries to generate tailored database extracts that can be exported for subsequent analysis. Besides these more technical and process-related developments, numerous extensions concerning the scope and analysis options have been accomplished in the course of specific research projects and related activities:

– Use of several new primary information sources to enhance completeness, consistency and geographic coverage of the data. During the China Energy Technology Program (CETP) access to detailed statistics on Chinese coal mine accidents could be established (Hirschberg et al., 2003a; Hirschberg et al., 2003b).

– External cost calculations of accident risks for non-nuclear chains in the EU project NewExt (Burgherr et al., 2004).

– Estimation of uncertainties for results of standard methods; i.e. aggregated indicators and frequency consequence curves. (EU projects NewExt (Burgherr et al., 2004) and NEEDS(Burgherr et al., 2008)).

– Implementation of a simplified Probabilistic Safety Assessment (PSA) for the nuclear chain. (CETP (Hirschberg et al., 2003b), NewExt (Burgherr et al., 2004), NEEDS (Burgherr et al., 2008)).

– Calculation of specific risk indicators to be used within Multi-criteria Decision Analysis (MCDA). (CETP (Hirschberg et al., 2003b), NEEDS (Burgherr et al., 2008), projects for Swiss utility Axpo (Roth et al., 2009) and the International Committee on Nuclear Technology (Hirschberg et al., 2004b)).

– Trend extrapolation of risk indicators to the future. (Axpo (Roth et al., 2009), NEEDS (Burgherr et al., 2008))

– Coupling of ENSAD with Geographic Information Systems (GIS) and multivariate statistical analyses to assign accident risks to specific geographical areas, and to produce illustrative maps and contour plots showing spatial patterns (Burgherr, 2008; Burgherr et al., 2008).

– Consideration of intentional human action, such as vandalism, sabotage and terrorist attacks within the broader context of critical infrastructure protection (CIP). (Burgherr et al., 2008; this deliverable)

Figure 1 and Figure 2 show a graphical overview of the overarching methodological framework of ENSAD and how the relational database model has been implemented. Figure 3 gives an overview over the historical updates of ENSAD in different projects.

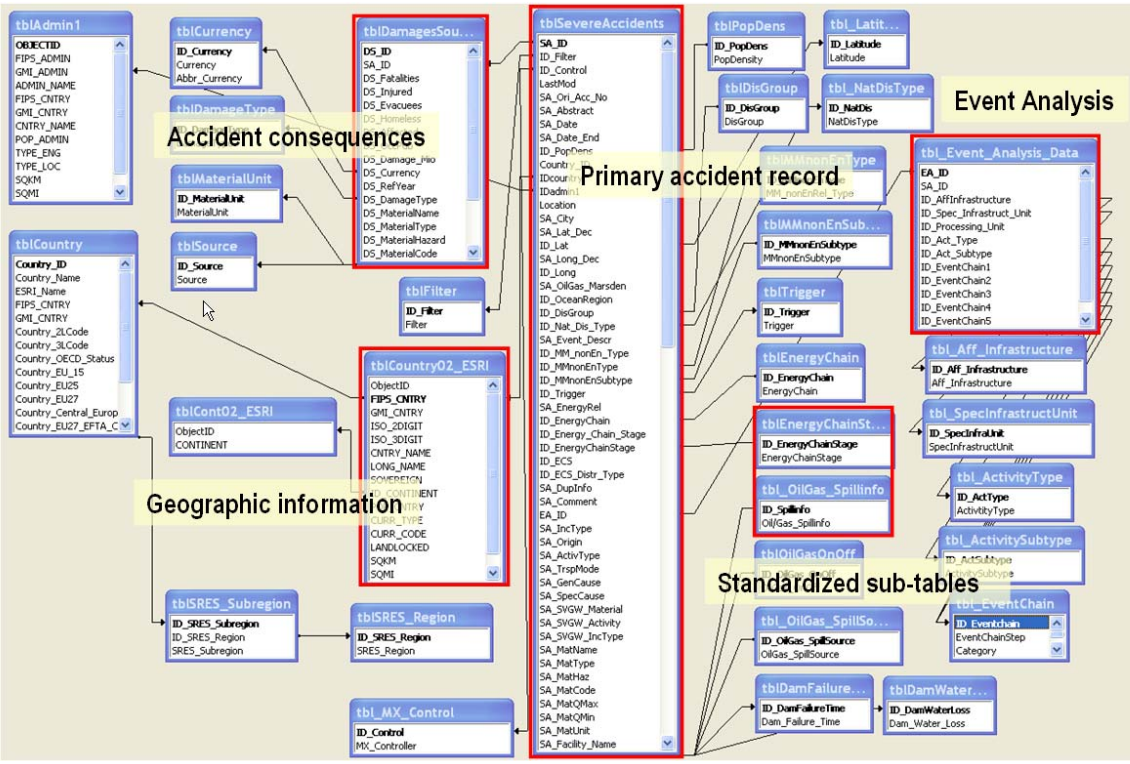

Figure 1: Representation of the relational database structure of ENSAD. Red boxes and accompanied titles indicate examples of specific sets of tables.

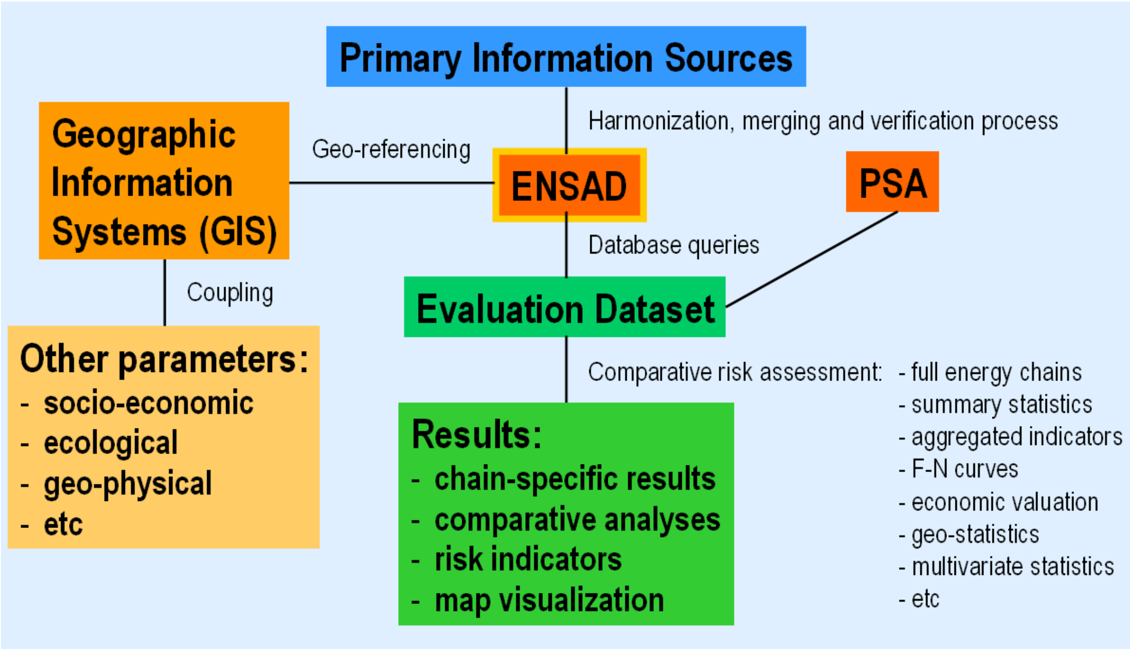

Figure 2: Overview of the methodological framework for severe accident analysis based on the ENSAD database.

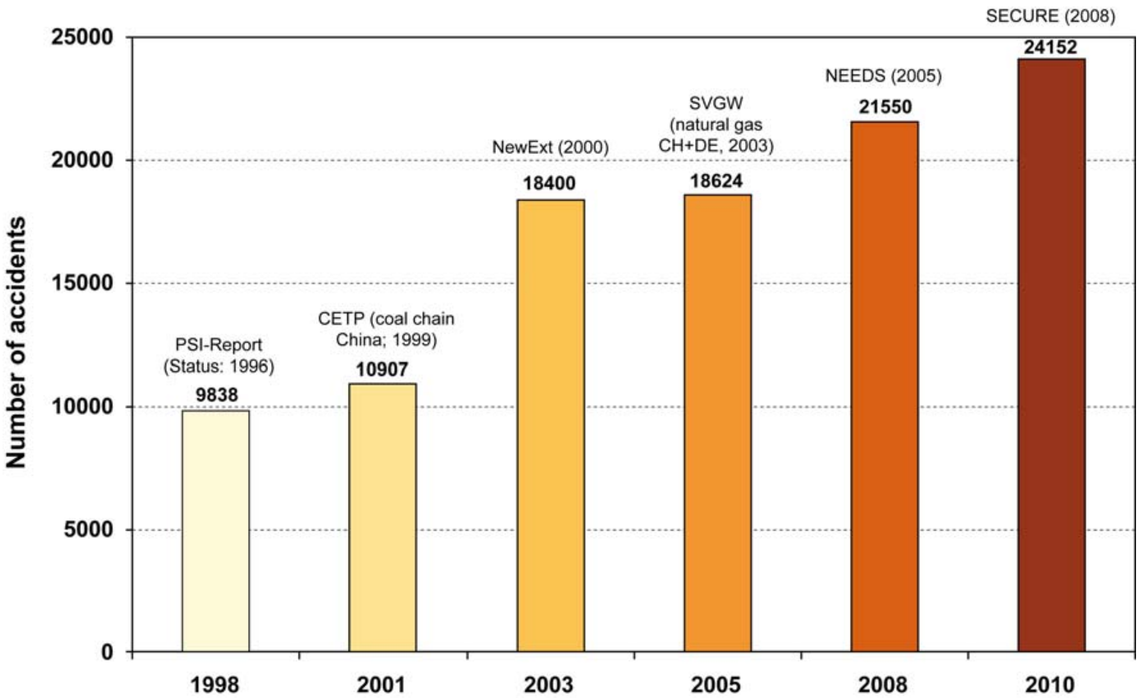

Figure 3: Major steps in the development, extension and update in contents of the ENSAD database. See text for Abbreviations.

2.2.2 Severe accident definitions and criteria

In the literature no commonly accepted definition can be found of what constitutes a severe accident. Differences concern the actual damage types considered (e.g. fatalities, injured persons, evacuees or economic costs), use of loose categories such as "people affected", and differences in damage thresholds to distinguish severe from smaller accidents. Table 1 illustrates the different consequence indicators and their thresholds as used within ENSAD along with some other well established disaster databases.

Table 1: Comparison of severe accident definitions based on consequence indicators and their thresholds as used in ENSAD and selected other disaster databases (Burgherr et al., 2004; Hirschberg et al., 1998). An accident is considered severe if it is characterized by one or several of the listed consequences. Sources: [1]: Burgherr et al. (2008); [2]: Swiss Re (2009); [3] EM-DAT (2009); [4] Munich Re (2008); [5] DNV (1999)

Consequence indicator	ENSAD [1]	Sigma [2]	EM-DAT [3] [4]	NatCat [4] [6]	WOAD [5] [7]
Fatalities	≥ 5	≥ 20 (dead or missing)	≥ 10	> 20	≥ 1
Injured persons	≥ 10	≥ 50	[5]	-	-
Evacuees	≥ 200	[2]	[5]	-	-
Extensive ban on consumption of food	yes	-	-	-	-
Release of hydrocarbons	≥ 10000 t	-	-	-	≥ 1000 t
Enforced clean up of land and water area	≥ 25 km^2	-	-	-	-
Economic loss	≥ 5 million USD(2000) [1]	≥ 85.4 million USD(2008) [3]	-	> 50 million USD (2007)	-

[1] USD values were extrapolated using the US Consumer Price Index (CPI) to obtain year 2000 values.

[2] Sigma considers the indicator "Homeless" with a threshold of 2000 persons.

[3] For economic loss Sigma uses four different indicators, namely three for insured losses (≥ 17.2 for maritime disasters, ≥ 34.4 for aviation, ≥ 42.7 for other losses) and 85.4 for total losses; all in million USD(2008).

[4] EM-DAT uses two additional criteria that are not considered in ENSAD, namely "declaration of a state of emergency" and "call for international assistance".

[5] EM-DAT uses a composite indicator called "Affected", which includes people affected, injured and homeless.

[6] Munich Re distinguishes six categories (Cat) for natural catastrophes, ranging from Cat 1 (1-9 fatalities) through Cat 3 (severe catastrophe; values in table) to Cat 6 (great natural catastrophe, i.e. when a region's ability to help itself is clearly overstretched).

[7] The WOAD database distinguishes five release sizes, namely "small" (0 – 9 t), "moderate" (10 – 100 t), "significant" (100 – 1000 t), "large" (1000 – 10000 t) and "very large" (>10000 t).

Generally, fatality data is most reliable, accurate and complete, whereas for injured or evacuated persons details on the severity of an injury or the duration of an evacuation are frequently not clearly indicated. The estimation of precise values for economic loss is often difficult because different sources of information report various types of economic damages (e.g., insured vs. total loss), depending on their specific scope (e.g., insurance company vs. disaster recovery organizations). The other consequence indicators are either only relevant for specific energy chains or ENSAD contains very few entries with sufficiently detailed information. Therefore, ENSAD-based results presented here are focused on the number of fatalities.

For a more detailed discussion consult SECURE Deliverable D5.7.1, chapter 3.2 (Burgherr et al., 2009).

2.2.3 Information sources

PSI's highly comprehensive database ENSAD utilizes merged and harmonized historical data from a large variety of information sources. Therefore, ENSAD can be considered superior compared to single database approaches that are also often limited concerning geographic area, time period, and energy chains included.

For the assessment of severe, energy-related accident risks within the SECURE project, external database inputs relevant for ENSAD were reviewed with respect to suppliers, scope, update frequency, acquirement costs etc. Table 2 provides an overview of the main information sources that have been considered for the ENSAD update within the SECURE project, covering the years 2006-2008. The table reports only the most important information sources surveyed, but a more comprehensive list is given in SECURE Deliverable 5.7.1 (Burgherr et al., 2009).

The year 2009 was only partially covered because a complete consideration was not possible due to the fact that accident reporting and in particular consolidated information and final reports are only available with a certain delay after an event occurred. This time lag generally can be in the range of 6-12 months for severe accidents, which is why 2009 was not included in the severe accident analysis of SECURE.

One should note that both freely available sources and commercial databases were taken into account because the latter may contain proprietary information not available at all or documented in a less detailed manner in non-commercial sources. Furthermore, several sources already surveyed earlier but with limited relevance for the SECURE update or such that have not been updated or continued recently, are not listed in Table 2. Nevertheless, a total of about 30 primary information sources were surveyed within the SECURE update of ENSAD. For some countries, energy chains or chain stages it was necessary to survey very specific information sources. For example, a variety of local sources for Newly Independent States (NIS) (Belyaeva, 2009), and specialized databases for oil spills. Additionally, up to 50 secondary information sources were considered for purposes of cross-checking and complementing retrieved data.

Table 2: Selection of main information sources used to update the ENSAD database within the SECURE project. Abbreviations: C = commercial database, F = freely available database.

Database	Geographic area	Accident types
Hint (C)	Worldwide	Industry
OSH Update (C)	Worldwide	Industry
Swiss Re (C/F)	Worldwide	Natural & Man-made disasters
EM-DAT (F)	Worldwide	Natural & Man-made disasters
Industrial Fireworld Log (F)	Worldwide	Industry
FACTS/Friends (C) (tbd)	Worldwide	Industry
Centre de Documentation, de Recherche et d'Expérimentations sur les Pollutions Accidentelles des Eaux Cedre (CEDRE) (F)	Atlantic, Mediterranean	Oil spills
International Tanker Owners Pollution Federation Ltd. (ITOPF) (C/F)	Worldwide	Oil spills
The Center for Tankship Excellence (CTX) (F)	Worldwide	Oil spills
Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC) (F)	Mediterranean	Oil spills
National Oceanic and Atmospheric Administration (NOAA), NOAA Incident News (F)	Mainly USA	Oil spills
Cargolaw (F)	Worldwide	Oil spills
TankTerminals.com owned and operated by PortStorage Group B.V. nl (F)	Worldwide	Industry
Tank Use Mishaps (F)	Worldwide	Industry
Port World News (F; registration required)	Worldwide	Industry
Longdown Associates (F; registration required)	Worldwide	Industry
Windpower databases (F)	Germany, Europe	Wind
Local non-English information sources (F)	Newly Independent States (NIS)	Oil & Gas energy chains
Other sources (C/F)	Worldwide	Various

2.2.4 Full chain approach

The risks to the public and the environment, associated with various energy systems, arise not only at the power plant stage but at all stages of energy chains (Burgherr and Hirschberg, 2008b; Hirschberg et al., 1998). In general, an energy chain may comprise the following stages: exploration, extraction, transport, storage, power and/or heat generation, transmission, local distribution, waste treatment, and disposal. However, one should be aware that not all these stages are applicable to every energy chain. Figure 4 gives an overview of distinct stages for the major fossil (coal, oil, natural gas and liquefied petroleum gas (LPG)), hydro and nuclear chains.

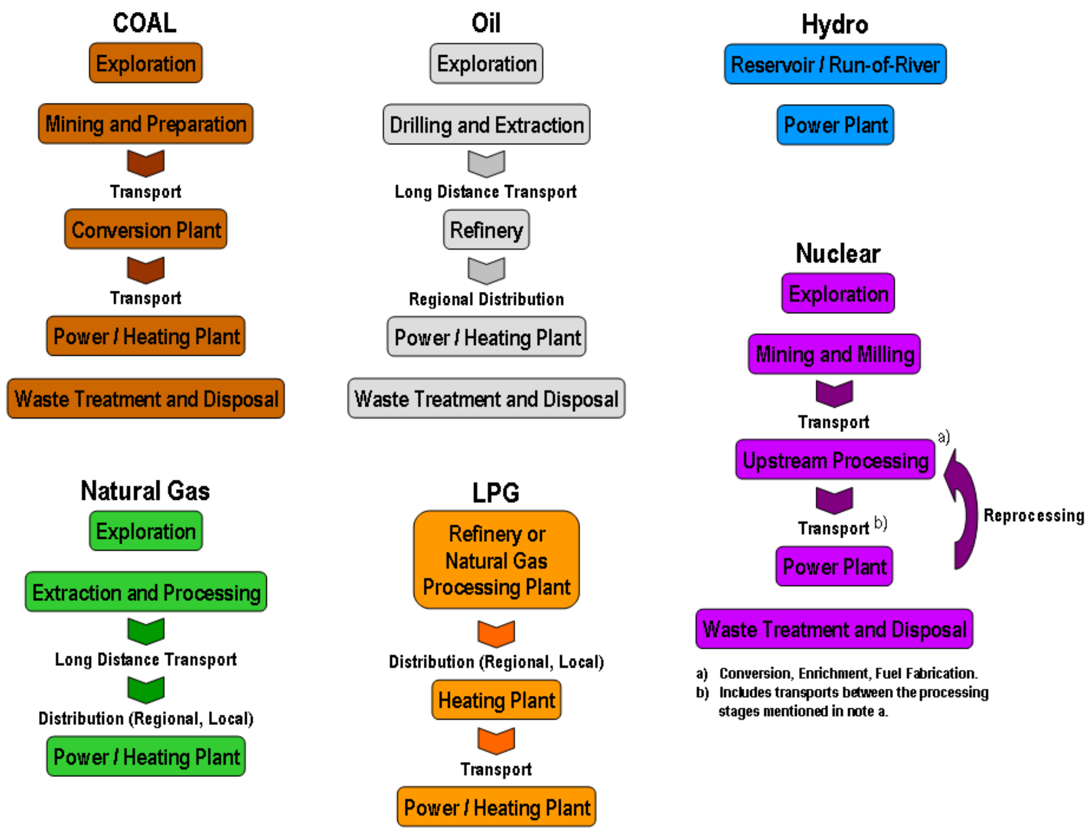

Figure 4: Main stages of different energy chains (modified from Hirschberg et al., 1998).

Table 3 lists the energy chains and technologies that were considered in the various WP 5.x within SECURE and how their corresponding severe accident risks were analyzed in terms of available data sources, assumptions and methodological treatment. Note that the choice of renewable energy sources is based on the analysis of WP 5.5, investigating the role of renewable energies in energy security.

For fossil energy chains (**coal**, **oil**, **natural gas**) and **hydropower** the historical experience of severe accidents as contained in the ENSAD database has been used for risk assessment. A simplified Probabilistic Safety Assessment (PSI) was applied to the evaluation of **nuclear** technologies. New renewables are comparatively at much earlier stages in their technological development and market penetration, and thus available statistical data with regard to accidental events, and even such with severe consequences, is rather limited, and largely varies for different renewables. Therefore, specific assumptions and approximations as well as expert judgment had to be included in their analysis.

Concerning risks of solar **photovoltaic** (PV) there have occurred accidental events, and some of them have even led to fatalities; but so far none with five or more victims. Therefore, in the case of PV a number of hazardous substances and their potential to cause fatal accidents were analyzed, both for their actual use at a PV manufacturing site and their transport to a site.

For **wind** power specific accident databases have been established in the past decade, however they only include small accidents according to the ENSAD definition, i.e. no accidents with more than two fatalities seem to have happened until now. Furthermore, experience with offshore wind farms is even more limited. Therefore, available accident data are only of indicative value, but had to be combined with expert judgment and a survey of relevant literature.

Under the heading **biomass** a broad range of technologies can be summarized and assessed, which has also been done in recent projects (e.g., Burgherr et al., 2008; Roth et al., 2009). In this report, Combined Heat and Power (CHP) **biogas** was considered, for which the natural gas chain from the local distribution stage was used as a proxy for the biogas accident risk because the biogas can be injected into local distribution natural gas networks if it has pipeline quality. However, upstream stages were not included in the biogas chain because due to the decentralized nature of its production, the potential for severe accidents appears to be limited (Burgherr et al., 2008).Solid biomass and biowaste as described in deliverable D5.5.1 (Held et al., 2009) are not included in this study.

Biofuels are a diverse array of fuels that are in some way derived from biomass. They are considered to contribute to increased energy security and to reduced greenhouse gas emissions when substituting fossil fuels, but key issues for biofuels also include potential competition with food production and use of water resources (Koh and Ghazoul, 2008). The ENSAD database currently contains 30 accidents involving biofuels, however none of them with five or more fatalities (23 with no fatalities and 7 with less than 5 fatalities). In this study we did not include biofuels because in contrast to the other technologies evaluated their use prevails in the transportation sector.

Risk estimation of **geothermal** generation was restricted to hot dry rock (HDR) enhanced geothermal systems (EGS). The actual geothermal drilling uses the same type of equipment as for oil exploration and thus accident risks can roughly be approximated from the corresponding risks in the oil chain. A broader discussion on the risks associated with geothermal is provided in chapter 3.1.3. Another important factor pertains to seismic risks, which were only qualitatively addressed in this Deliverable.

Concerning **wave and tidal power** only a few pilot and demonstration plants are in operation, using different technologies. No risk evaluation was performed for them in this study because of a general lack of data that prevented the establishment of a sufficient appraisal with at least knowing the order of magnitude of its uncertainties.

Table 3: Overview of energy chains and technologies, and the data sources and assumptions used for the comparative analysis performed within WP 5.7 of SECURE.

Coal – ENSAD Database @ PSI; severe (≥5 fatalities) accidents. Fatality rates are normalized to the unit of energy production in the corresponding country aggregate. Maximum consequences correspond to the most deadly accident that occurred in the observation period. – Furthermore three risk indicators R1, R2 and R3 were calculated (see chapter 3.3). – OECD: 1970-2008; 86 accidents; 2239 fatalities. EU 27: 1970-2008; 45 accidents; 989 fatalities. Non-OECD w/o China: 1970-2008; 163 accidents; 5808 fatalities. (this study) Previous studies: Burgherr et al., 2008; Burgherr et al., 2004; Hirschberg et al., 1998. – China (1994-1999): 818 accidents; 11302 fatalities. Analysis within the China Energy Technology Program (CETP). Sources: Burgherr and Hirschberg, 2007; Hirschberg et al., 2003a; Hirschberg et al., 2003b. – China (2000-2009): for comparison, the fatality rate in the period 2000-2009 was calculated based on data reported by the State Administration of Work Safety (SATW)[1] of China (available in English: http://en.wikipedia.org/wiki/Coal_power_in_China). Annual values given by SATW correspond to total fatalities (i.e. severe and minor accidents). Thus for the fatality rate calculation it was assumed that fatalities from severe accidents comprise 30% of total fatalities, as has been found in the CETP (Burgherr and Hirschberg, 2007; Hirschberg et al., 2003a; Hirschberg et al., 2003b). Chinese fatality rate (2000-2009) = 3.14E+0 fatalities / GW_eyr.
Oil – ENSAD Database @ PSI; severe (≥5 fatalities) accidents. Fatality rates are normalized to the unit of energy production in the corresponding country aggregate. Maximum consequences correspond to the most deadly accident that occurred in the observation period. – Furthermore three risk indicators R1, R2 and R3 were calculated (see chapter 3.3). – OECD: 1970-2008; 179 accidents; 3383 fatalities. EU 27: 1970-2008; 64 accidents; 1236 fatalities. Non-OECD: 1970-2008; 351 accidents; 19376 fatalities. (this study) Previous studies: Burgherr et al., 2008; Burgherr et al., 2004; Hirschberg et al., 1998.
Natural Gas – ENSAD Database @ PSI; severe (≥5 fatalities) accidents. Fatality rates are normalized to the unit of energy production in the corresponding country aggregate. Maximum consequences correspond to the most deadly accident that occurred in the observation period. – Furthermore three risk indicators R1, R2 and R3 were calculated (see chapter 3.3). – OECD: 1970-2008; 109 accidents; 1257 fatalities. EU 27: 1970-2008; 37 accidents; 366 fatalities. Non-OECD: 1970-2008; 77 accidents; 1549 fatalities. (this study) Previous studies: Burgherr and Hirschberg, 2005; Burgherr et al., 2008; Burgherr et al., 2004; Hirschberg et al., 1998.
Nuclear – The analysis for nuclear energy performed within SECURE is based on the approach described in chapter 2.6. – Previous studies undertaken by PSI analyzed Generation II (Pressurized Water Reactor, PWR), Generation III (European Pressurized Reactor, EPR) and Generation IV (European Fast Reactor, EFR) (Burgherr et al., 2008; Roth et al., 2009). – The two core-melt events that have occurred at Three Mile Island 2 (TMI-2, USA, 1979) and Chernobyl (Ukraine, 1986) have also been described in detail previously by Hirschberg et al. (1998).
Hydro – ENSAD Database @ PSI; severe (≥5 fatalities) accidents. Fatality rates are normalized to the unit of energy production in the corresponding country aggregate. Maximum consequences correspond to the most deadly accident that occurred in the observation period. – OECD: 1970-2008; 1 accident; 14 fatalities (Teton dam failure, USA, 1976). EU 27: 1970-2008; 1 accident; 116 fatalities (Belci dam failure, Romania, 1991). (this study) – Based on a theoretical model, maximum consequences for the total failure of a large Swiss dam range between 7125 – 11050 fatalities without pre-warning, but can be reduced to 2 – 27 fatalities with 2 hours pre-warning time. (Burgherr and Hirschberg, 2005 and references therein) – Non-OECD: 1970-2008; 12 accidents; 30007 fatalities. Non-OECD w/o Banqiao/Shimantan 1970-2008; 11 accidents; 4007 fatalities; largest accident in China (Banqiao/Shimantan dam failure, China, 1975) excluded. (this study) – Previous studies: Burgherr et al., 2008; Burgherr et al., 2004; Hirschberg et al., 1998.

[1] Data from SATW for the years 2000-2005 have been reported in the China Labour NewsFlash No. 60 (2006-01-06) available at http://www.china-labour.org.hk/en/node/19312 (accessed December 2010). SATW data for the years 2006-2009 have been published by Reuters, available at http://www.reuters.com/article/idUSPEK206148, http://uk.reuters.com/article/idUKPEK32921920080112, http://uk.reuters.com/article/idUKTOE61D00V20100214, http://uk.reuters.com/article/idUKTOE61D00V20100214 (all accessed December 2010)

Photovoltaic (PV)
- Current estimates include only Si technologies, weighted by their 2008 market shares, i.e. 86% for c-SI and 5.1% for a-Si/u-Si.
- The analysis covers risks of selected hazardous substances (Chlorine (Cl) Hydrochloric acid (HCl), Silane (SiH4) and Trichlorosilane (HSiCl3)) relevant in the Si PV life cycle.
- Accident data were collected for USA (for which a good coverage exists), and for the years 2000-2008, to ensure that estimates are representative of currently operating technologies.
- Database sources: ERNS, RMP, MHIDAS, MARS, ARIA, OSH.
- Since collected accidents were not only from the PV sector, the actual PV fatality share was estimated, based on the above substances amounts in the PV sector as a share of the total USA production, as well as data from the ecoinvent database.
- Cumulated fatalities for the four above substances were then normalized to the unit of energy production using a generic load factor of 10% (Burgherr et al., 2008).
- Assumption that 1 out of 100 accidents is severe (e.g. for natural gas in Germany it is about 1 out of 10 (Burgherr and Hirschberg, 2005), and for coal in China even about 1 out of 3 (Hirschberg et al., 2003a; Hirschberg et al., 2003b)).
- Current estimate for fatality rate: based on data as described above (this study).
- Maximum consequences represent an expert judgment due to limited historical experience (Burgherr et al., 2008).
- Previous studies: Burgherr et al., 2008; Burgherr et al., 2004; Roth et al., 2009.
- Other studies: Fthenakis et al., 2006; Ungers et al., 1982.

Wind
Onshore:
- Data sources: Windpower Death Database (Gipe, 2010) & Wind Turbine Accident Compilation (Caithness Windfarm Information Forum, 2010).
- Fatal accidents in Germany in the period 1975-2010; 10 accidents; 10 fatalities. 3 car accidents, where driver distraction from wind farm is given as reason, were excluded from the analysis.
- Assumption that 1 out of 100 accidents is severe (e.g. for natural gas in Germany it is about 1 out of 10 (Burgherr and Hirschberg, 2005), and for coal in China even about 1 out of 3 (Hirschberg et al., 2003a; Hirschberg et al., 2003b)).
- Current estimate for fatality rate: based on German data as described above. (this study)
- Maximum consequences represent an expert judgment due to limited historical experience (Roth et al., 2009).
- Previous study: Hirschberg et al., 2004b.

Offshore:
- Data sources: see onshore above.
- Up to now there were 2 fatal accidents in UK (2009 & 2010) with 2 fatalities, and 2 fatal accidents in USA (2008) with 2 fatalities.
- For the current estimate only UK accidents were used, assuming a generic load factor of 0.43 (Roth et al., 2009) for the currently installed capacity of 1340 MW (Renewable UK, 2010).
- Assumption that 1 out of 100 accidents is severe (see onshore above).
- Current estimate for fatality rate: based on UK data as described above. (this study)
- Maximum consequences: see onshore above.

Biomass: Combined Heat & Power (CHP) Biogas
- ENSAD Database @ PSI; severe (≥5 fatalities) accidents. Due to limited historical experience, the CHP Biogas fatality rate was approximated using natural gas accident data from the local distribution chain stage.
- OECD: 1970-2008; 24 accidents; 260 fatalities. (this study)
- Maximum consequences represent an expert judgment due to limited historical experience. (this study)
- Previous studies: (Roth et al., 2009)

Enhanced Geothermal System (EGS)
- For the fatality rate calculations only well drilling accidents were considered. Due to limited historical experience, exploration accidents in the oil chain were used as a rough approximation because of similar drilling equipment.
- ENSAD Database @ PSI; severe (≥5 fatalities) accidents.
- OECD: 1970-2008; oil exploration, 7 accidents; 63 fatalities. (this study)
- For maximum consequences an induced seismic event was considered to be potentially most severe. Due to limited historical experience, the upper fatality boundary from the seismic risk assessment of the EGS-project in Basel (Switzerland) was taken as an approximation. (Dannwolf and Ulmer, 2009)
- Previous studies: (Roth et al., 2009)

2.2.5 Evaluation period

The ENSAD database allows carrying out comprehensive analyses of accident risks that are not limited to power plants but cover full energy chains. Such a broader perspective is essential because for the fossil chains accidents at power plants play a minor role compared to the other chain stages, i.e. analyses based on power plants only would radically underestimate the real situation (Hirschberg et al., 1998). Furthermore, identification of weak links in an energy chain, potential improvements and effective measures on the technical or regulatory levels require deep knowledge of events, their possible causes, dimensions and relationships (Burgherr and Hirschberg, 2008a; Hirschberg et al., 1998). Severe accidents in the energy sector are analyzed for the years 1970-2008. The starting year was chosen because energy-related severe accidents distinctively increased at the end of the 1960s, which is primarily due to the increase in the volume of activities (Hirschberg et al., 1998). Therefore, the selected period of observation covers more than three decades of historical experience, which allows evaluating temporal trends. Accidents further back in time were not taken into account because they may confound results since they are not comparable due to (1) less comprehensive coverage in past years; (2) improved reporting and documentation, particularly in the last five to ten years; and (3) changes over time (i.e., technological advancements, more strict safety regulations, etc.).

2.3 Comparative analyses

The integration of severe accident risks into the context of energy security builds upon comparative risk assessment that provides the overarching methodological approach to establish a diverse set of results with a common basis, which allow direct comparisons of different risk aspects as well as the calculation of specific risk indicators to be used in Multi-Criteria Decision Analysis (MCDA) of WP 6, Task 2.

Comparative evaluations of different energy chains need to be performed in a consistent manner, calling for a number of decisions and definitions that determine the extent and area of validity of such evaluations. For the purpose of the SECURE project, the ENSAD database has been queried using the following boundary conditions:

- Only so-called severe accidents according to the ENSAD definition (compare Table 1) were considered.
- The years 1970-2008 have been chosen as the period of observation (see chapter 2.2.5) for fossil energy chains and hydropower. In the case of nuclear a simplified PSA approach, and for new renewables partially different assumptions were considered (Table 3).
- Evaluations focused on fatalities as the main consequence indicator (compare Table 1) because their reporting coverage and completeness is generally superior and more complete compared to other consequence indicators.

In a second step the geographic resolution of the analysis has to be decided upon. Within SECURE, results for EU 27[2] are of primary interest; however calculations for OECD[3] and non-OECD countries are also valuable because of the substantial

[2] The European Union currently comprises 27 member states, which includes the former EU 15 countries Belgium, Germany, France, Italy, Luxembourg, The Netherlands, Denmark, United Kingdom, Ireland, Greece, Portugal, Spain, Austria, Finland, Sweden as well as Czech Republic, Estonia, Cyprus, Latvia, Lithuania, Hungary, Malta, Poland, Slovenia, Slovak Republic that joined 2004; and finally Bulgaria and Romania became member states as of 2007.

[3] The Organisation for Economic Co-operation and Development (OECD) was established in 1961 and currently consists of 30 member countries, which are: Australia, Austria, Belgium, Canada, Czech Republic, Denmark,

differences in management, regulatory frameworks and general safety culture between these two groups of countries (Burgherr et al., 2008; Burgherr et al., 2004; Hirschberg et al., 2004a). Furthermore, it can be shown that variation is much larger within the group of non-OECD countries than within the group of OECD countries. Concerning the coal chain, a separate treatment of China is necessary because it has been shown to significantly differ from other non-OECD countries, both in its accident frequency (number of accidents per year) and severity (number of victims per accident) (Burgherr and Hirschberg, 2007; Hirschberg et al., 2003a).

Lastly, comparisons of different energy chains need to be based on data normalized to the unit of electricity production[4] because raw data do not account for significant differences in the statistical basis among them. For fossil energy chains the thermal energy was converted to an equivalent electrical output using a generic efficiency factor of 0.35. For nuclear and hydro power the normalization is straightforward since in both cases the generated product is electrical energy. The 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 the $GW_e yr$ a natural unit to use when presenting normalized indicators generated within technology assessment.

2.4 Statistical analyses of fossil and hydro accident data

The approach described in this chapter is consistently applicable to severe accidents in the various fossil energy chains (coil, oil, natural gas) as well as to hydropower because for these energy chains extensive historical experience is available for the previously defined observation period (1970-2008) used within the SECURE project. For nuclear power a simplified Probabilistic Safety Assessment (PSA) was used (see chapter 2.6) because results are very dependent on the actual plant design (e.g. type, installed power) and location (e.g. country, coast vs. inland), which in turn affect the source term inventory and subsequent off-site consequences. In the case of renewables, historical experience is much more limited, and with few exceptions no severe accidents have occurred, which often impedes a straightforward application of the above-described approach. Therefore, the assessment of renewables needs to be complemented by approximate estimates, literature studies and expert judgment.

2.4.1 Overview and description of approach

Risk can be expressed as the product of the frequency of an event and the severity of the resulting consequences. Measures for the severity of consequences of accidents are for example the number of fatalities, the amount of financial losses (e.g. insured loss, business interruption, total loss) or the size of oil spills in metric tonnes released.

For a full characterization of the risk, thus, the total frequency of accidents needs to be known together with the relative probability of possible consequences. Frequency and

Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, The Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, and United States. The most recent extension in 2010 with Chile, Estonia and Israel becoming members was not considered in this analysis.

[4] Electricity production is the sum of domestic production, imports and exports.

consequences are analyzed independently as shown in the following flow diagram (Figure 5):

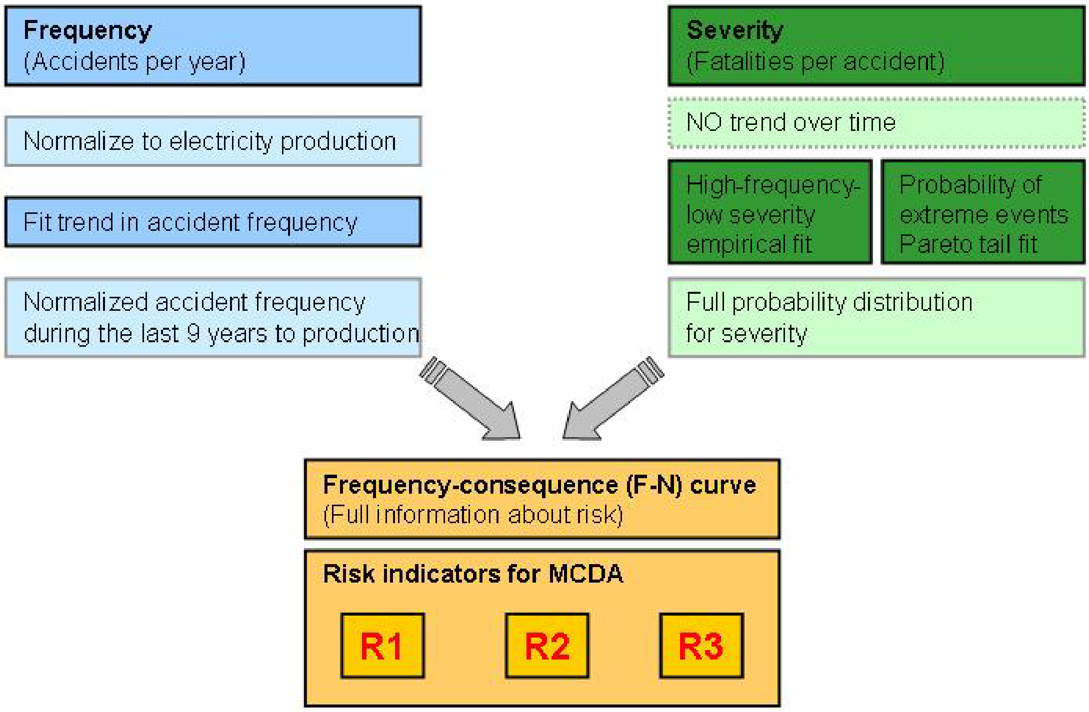

Figure 5: Schematic overview of data analysis steps in comparative risk assessment.

The frequency of accidents, i.e. the number of accidents per year shows little statistical variation. As accidents can be considered independent events, the frequency follows typically distributions like Poisson. The main parameter is the average number of accidents per year; the accident frequency is thus a good measure to identify trends over time or for detailed geographical comparisons.

The possible consequences of accidents typically span a large range from accidents with very limited consequences but relatively high frequencies to very rare events with disastrous consequences. Generally, the available data basis for smaller accidents is more extensive, however simultaneously the completeness in reporting of smaller accidents is likely to decrease, particularly in non-OECD countries. Therefore, the severe accident definition of the ENSAD database was applied prior to data analysis, i.e. only accidents with at least five fatalities were considered, ensuring a high degree of completeness and comparability among different country aggregates. In addition to the substantially greater likelihood of severe accidents being reported, they generally are also documented in much more detail.

Figure 6 shows two examples for the distribution p(N) of accident severity for severe accidents (≥5 fatalities). N is the number of fatalities and p(N) gives the probability that a given severe accident results in N fatalities. The area under this distribution is one. It can then be scaled with accident frequency to get the full information about risk.

In general the severity of accidents follows a Gamma or lognormal distribution for accidents with low and medium severity. The framework of extreme value theory shows that the probability of extreme events with high severity follows a power law distribution and can thus be fitted with for example a generalized Pareto function (GPD) (Pickands III, 1975). The GPD function is used to model extreme events in widespread areas such as financial markets, insurance claims or severity of natural catastrophes (Coles and Casson, 1998; Embrechts et al., 1997). To model the severity distribution, the data is split into a low severity part that is fitted in our case with an empirical distribution as enough data points are available and a Pareto tail fit for high severities (Lambert et al., 1994). The threshold where high frequency distribution and Pareto tail are joined needs to be chosen for every dataset separately by increasing the threshold parameter until the tail function is stable. This allows achieving a reliable characterization of the high severity end of the distribution. The threshold was chosen to be as low as possible while still ensuring that the risk indicators R2 and R3 described in chapter 3.3 are not strongly dependent on the threshold.

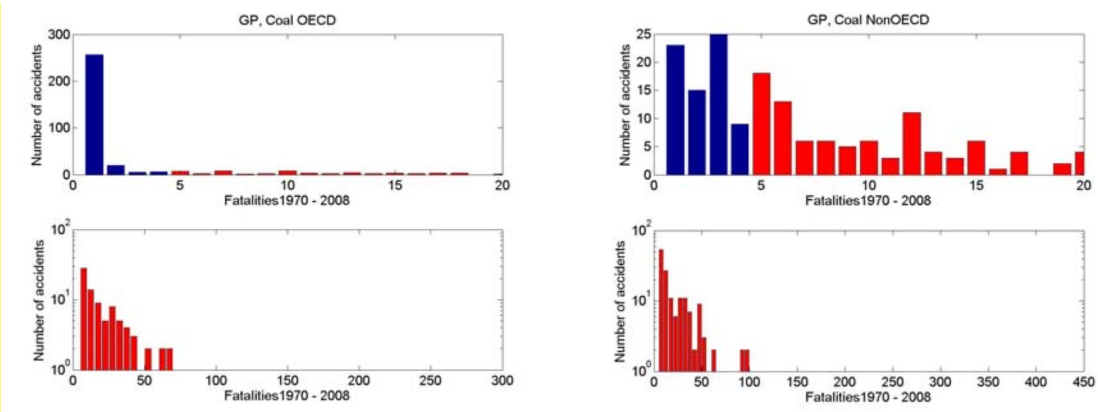

Figure 6: Relative frequencies of accidents depending on their severity for the coal chain in the OCED (left) and in non-OECD (right) countries. Severe accidents (≥ 5 fatalities) are shown in red, non-severe accidents are in blue. The distribution function for the severe accidents can again be split into a high frequency part and a low frequency-high severity tail, where the frequency drops less than exponentially.

2.4.2 Accident frequency: development in time

To assess how the accident frequency changes over time, the data was normalized to consumed energy and fitted with an exponential trend. Figure 7 shows the respective fits for EU 27, OECD countries and non-OECD countries. Over the period 1970-2008, severe accidents show a clear trend towards lower frequencies in OECD countries and EU 27 for all analyzed fossil energy chains. The opposite trend is visible in non-OECD countries, where the number of severe accidents continues to rise.

This clear trend implies that for an assessment of current risks in the fossil energy chains the frequencies should not be averaged over the entire period from 1970-2008. Instead for the comparison of risks in the different energy chains, the accident frequency is calculated on the basis of accidents from 2000 to 2008 only, to better account for the current situation.

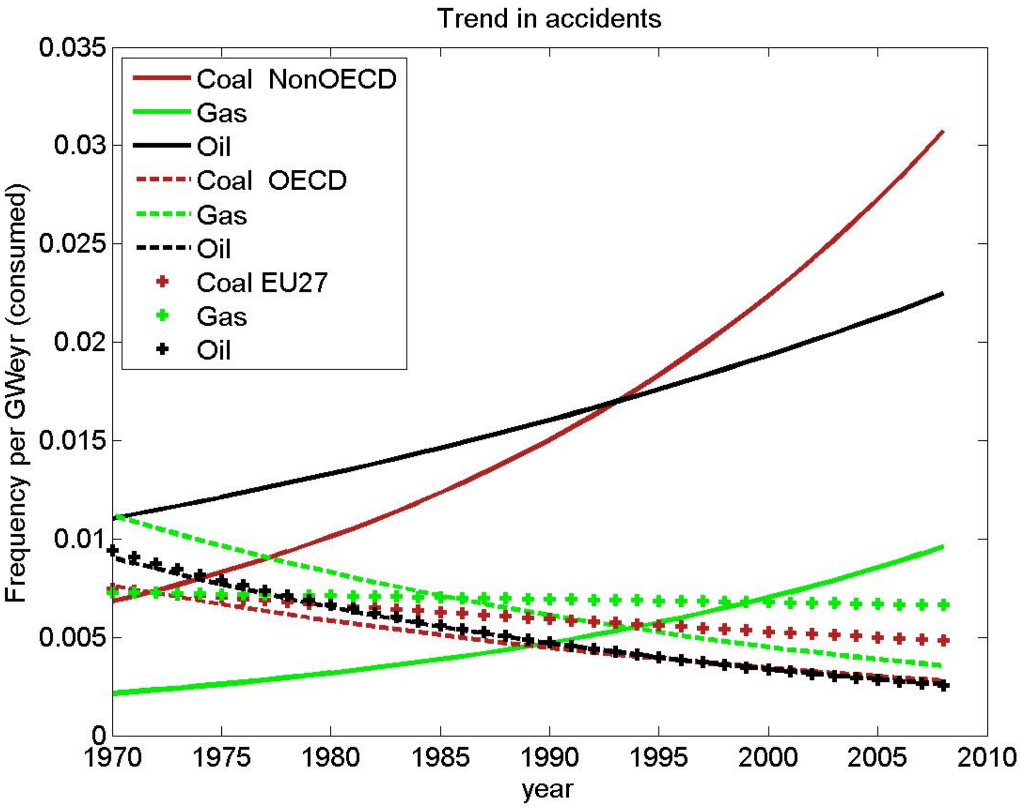

Figure 7: Trends in accident frequency 1970-2008. Exponential fit normalized to consumption in GW_eyr (see chapter 2.4.4).

In principle both the accident frequency and the severity distribution can change over time. However, as extreme events are very rare, the basis of data is not sufficient to detect statistically significant trends in the severity distributions and the distribution is thus fitted to data over the entire time span of the evaluation.

2.4.3 Frequency consequence curves

Figure 8 shows a frequency-consequence (FN) curve for severe coal accidents in non-OECD countries. Symbols represent actual data and the solid red line is calculated from the Pareto tail fit discussed in chapter 2.4.1. The curve gives the frequency of accidents with at most N fatalities per year. FN-curves are calculated by integrating the probability/relative frequency distribution p(N) over the high severity tail for each number of fatalities, and multiplied with the average number of accidents per year, n. If N is the number of fatalities, F(N) is calculated as follows:

$$F(N) = n\int_{N}^{\infty} p(N')dN'$$

The same procedure, i.e. calculating the number of accidents that exceed a given number of fatalities can be directly performed with the data. FN-curves are a common way to present risk with severity and consequences, spanning several orders of magnitude and thus are mostly given as double logarithmic plots.

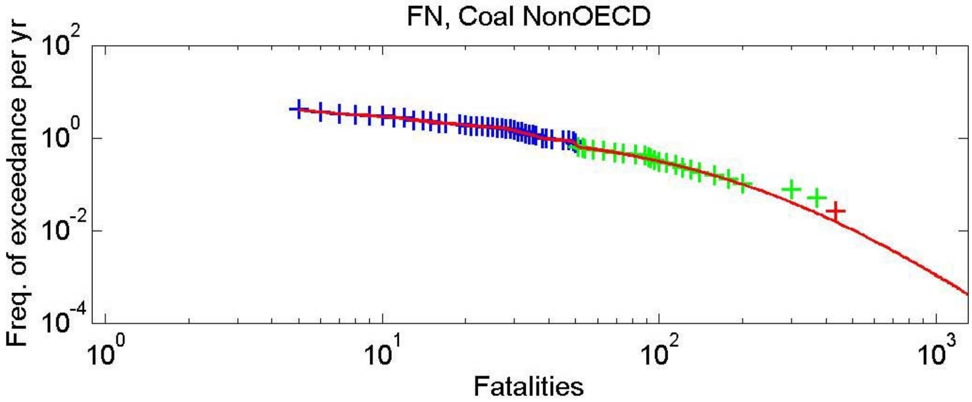

Figure 8: Frequency consequence curve of severe coal accidents in non-OECD countries (excluding China). The red solid line is calculated from the fitted probability distribution, The red cross marks the most severe accident, blue crosses are data points forming the empirical distribution of the low severity part, green crosses are data that were used in the Pareto tail fit.

2.4.4 Normalization of data to unit electricity consumption

To be able to compare between the different energy chains, the accident frequency is normalized to the unit of electricity consumption. For fossil energy chains thermal output in Mtoe (million tonnes oil equivalent) was converted to electricity production in $GW_e yr$ (Gigawatt-electric-year) as explained in chapter 2.3. For hydro, nuclear and new renewables the conversion is straightforward because the generated product is electricity. Consumption data was taken from the freely available statistical review of world energy 2009 by BP[5]. Figure 9 shows the average consumption from 2000-2008 in the different energy chains:

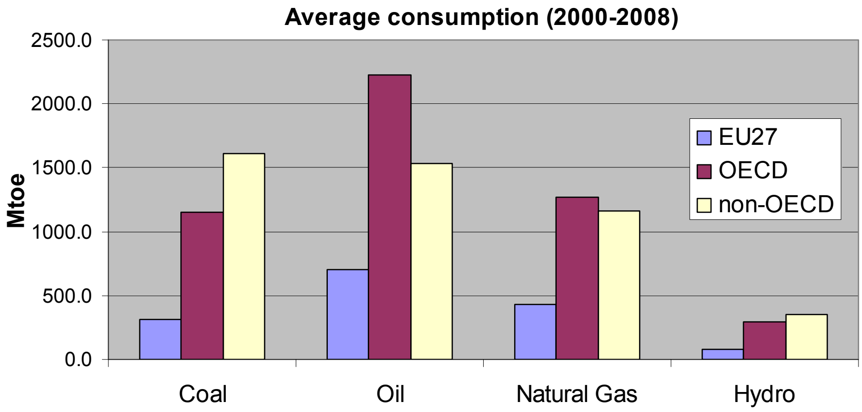

Figure 9: Average energy consumption for the years 2000-2008 in the different energy chains and regions[5].

As explained in 2.4.3, the accident frequencies were calculated on the basis of data from 2000-2008 as we could show a clear trend over time in the accident frequencies so that averaging over the last 39 years would distort the current risk estimates. This means that also the normalization is done on the basis of consumption data from 2000-2008.

[5] available from http://www.bp.com

2.5 Risk Indicators

FN-curves give the full information about the relation between frequency and consequences. To integrate risk information into decision making frameworks such as Multi-Criteria Decision Analysis (MCDA), risk indicators need to be generated that capture the main characteristics of the structure of the risk.

Within SECURE, three indicators were chosen to characterize the risk of severe accidents, which in the remainder of this report are called R1, R2 and R3 (Figure 10):

R1 denotes the fatality rate of severe (≥5 fatalities) accidents, i.e. it gives the expected number of fatalities per GW_eyr, thus representing the mean severe accident. R1 measures essentially the high frequency part of the accident risk distribution as shown in 2.4.3. R1 is calculated by multiplying the expected number of fatalities in an accident calculated from the fit with the average number of accidents per year in the period from 2000-2008 divided by the average yearly consumption in GW_eyr for the period 2000-2008.

R2 provides a consistently calculated value for low frequency accidents with very large consequences. A straightforward approach is to define R2 as the most deadly accident that occurred in the observed period of time; however this based on historical experience only and disregards the specific distribution properties. R2 gives the number of fatalities at a risk level of 5e-5 per GW_eyr. This level was chosen to be in the region of the maximum historical accident. So for every produced GW_eyr the probability that the corresponding number of fatalities R2 is exceeded is 5e-5. R2 is in principle a quantile measure and is very similar to “Value at Risk” (VaR), an indicator that is used to measure the loss risk in financial portfolios for low frequency extreme events. To allow a comparison between the different energy chains however instead of a quantile measure, such as VaR, the fixed risk level was chosen to account for the different amounts of energy produced as well as the different accident frequencies in the different energy chains.

R3 is calculated in the same way as R1, i.e. the expected number of fatalities over a given minimum, only with R2 as minimum instead of 5 fatalities. R3 is then the expected number of fatalities for an accident exceeding R2 level, thus measuring the risk in the low frequency but high severity tail of the distribution p(N) (see 2.4.2).

These risk measures can replace indicators that are solely based on actual data from historical experience such as the number of fatalities in the largest historical accident because they are calculated in a consistent and more objective manner, taking advantage of the entire available information that is contained in the fitted distribution.

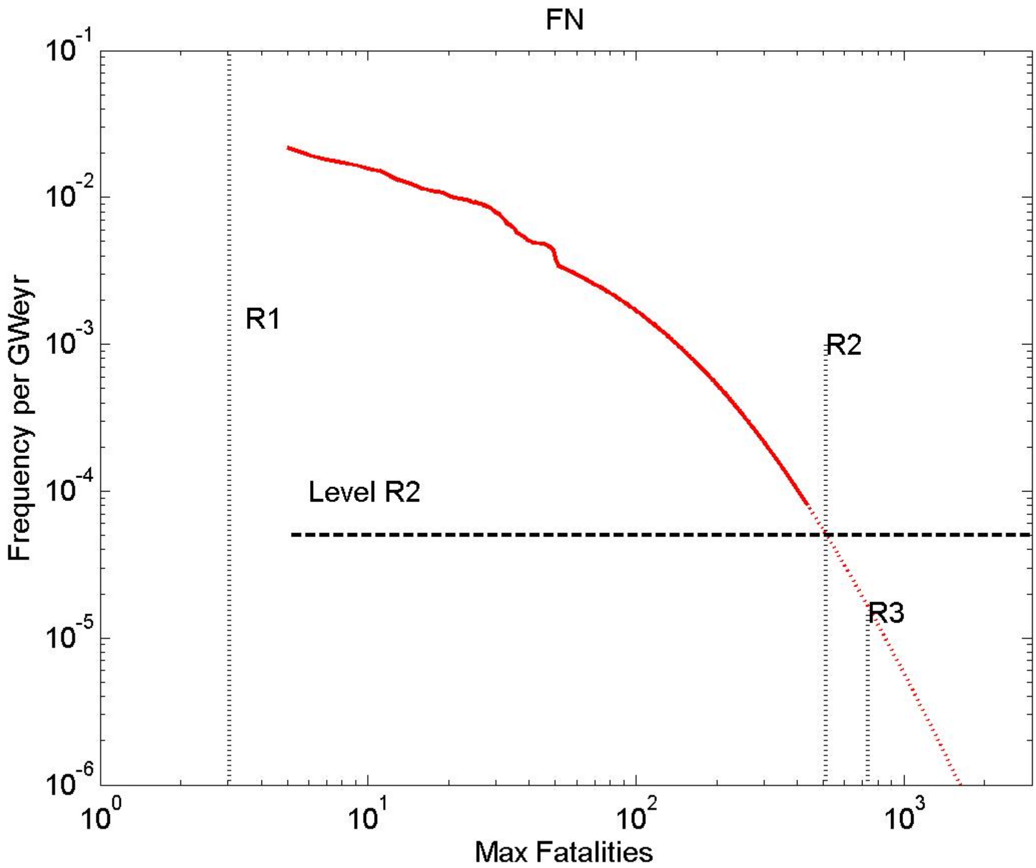

Figure 10: Visualization of the risk indicators R1, R2 and R3.

2.6 Simplified PSA-approach for nuclear

2.6.1 Advanced nuclear power plant designs

Within SECURE, three advanced nuclear power plant (NPP) designs are considered among the numerous planned NPPs (Gen III) and proposed future designs (Gen IV), namely the European Pressurized Reactor (EPR), a fast breeder reactor (LMFBR) and a high temperature, gas cooled reactor (HTR).

The generation III light water reactor plant of the EPR (AREVA) design is based on the current U235 technology. The behavior of this plant is sufficiently understood, since AREVA has been conducting and reporting partial results from the PSA for the Olkiluoto 3 (OL3, 1600 MW) plant that is currently under construction in Finland. Core inventories, strength and weaknesses, response to abnormal conditions and a variety of accident initiators are well known and data have been used in previous projects such as NEEDS (Burgherr et al., 2008). The EPR is extremely resistant to external solicitations, and its layers of protection would make it almost impossible to organize an attack with serious consequences (see Deliverable D5.7.2b).

The generation IV fast breeder reactor (LMFBR) is based on a uranium-plutonium-minor-actinide-zirconium metal alloy fuel cycle (mostly U-238). The behavior of this type of plant has not yet been completely ascertained, especially depending on the type of coolant used (either Na or Pb). Core inventories however are known, and consequences from severe accidents have also been previously estimated (Burgherr et al., 2008). This plant is hardened to external solicitations, and the layers of protection would make it difficult to organize an attack with serious consequences (see Deliverable D5.7.2b).

Finally, a generation IV high temperature gas cooled plant (HTR, pebble bed type) was chosen. Other types of high temperature reactors have been considered, however, like the liquid Molten Salt Reactor (MSR) type, they were found to be less practical concepts. For example, in the MSR fissile, fertile and fission isotopes are dissolved in a high temperature molten fluoride salt with a very high boiling point (1400° C) that is both the reactor fuel and the coolant. This means that there cannot be any incident that would be described as a design basis accident in an LWR, and any problem arising in the system, such as a small leak, would essentially result in permanent shutdown, as it happened to the original prototype after 3 years of operations. Estimates of core inventories have been published (Fassbender and Kröger, 1981). The behavior under severe accident conditions is largely unknown, and large uncertainties appear present depending on design type. However the essential facts for this project are that these plants, regardless of the design, would very likely be built with a confinement and not containment, making the plant extremely vulnerable to any concerted and organized terrorist attack that employed some semi-sophisticated type of technology (e.g., a plane attack) (see Deliverable D5.7.2b).

2.6.2 Source Terms

For the three reactor types (EPR, LMFBR and HTR) the following accident scenarios with their corresponding releases are considered:

- RC1: no containment failure (limited core damage – recovered)
- RC4: early containment failure (containment failure following a highly energetic event)
- RC6: containment bypass (containment completely bypassed)

2.6.2.1 Source terms for an EPR plant

A detailed discussion of the plant design and source term calculations resulting from severe accidents can be found in the Appendix. The assessment is based on a simplified methodology that uses results from MELCOR (Gauntt, 2005) calculations for other operating Pressurized Water Reactors (PWR). Details of this methodology have been described in previous projects such as NEEDS (Burgherr et al., 2008). When considering a terrorist attack on this plant type, only three types of possible outcomes resulting in offsite consequences should be expected, depending on the hypothetical scenario (see also Deliverable D5.7.2b).

Within NEEDS (Burgherr et al., 2008), six hypothetical accidental releases were defined, which are:

- RC1: accidents where the containment function is preserved and radioactivity is dispersed to the environment via a small assumed leak (a design basis leak of less than 0.05 containment volume per day%, as specified by FANP, and a small leak from the secondary isolated containment).

- RC2: accidents where the containment is vented by the operators at least 12 hours after accident initiation (it is assumed that the Swiss authorities would require this system, as was done for all other Swiss plants; alternatively, the containment may fail in these accidents after at least 24 hours, with very similar offsite consequences).
- RC3: accidents where the containment fails within 12 hours from the start, resulting in a leak through the primary containment, the filtered ventilation system of the secondary containment, to the environment.
- RC4: accidents where containment isolation fails from the beginning and a small leak occurs via pipings directly to the environment.
- RC5: accidents initiated by an un-isolated SGTR or small IS-LOCAs (Interfacing Systems Loss of Coolant Accident).
- RC6: accidents involving large IS-LOCAs.

Note that, for the last two release types, very little mitigation, if any, is possible or can be assumed by design. In addition, accidents with late failure of the containment are not included, because failure by hydrogen combustion is almost precluded, due to the presence of Passive Autocatalytic Recombiners (PARs), or because the core debris is very likely cooled by the combination of passive core catcher systems.

Table 4 summarizes releases of relevant radionuclides for the three release classes RC1, RC4 and RC6.

Table 4: Radionuclide releases of RC1, RC4 and RC6 for the EPR.

Release class	Xe	CsI	CsOH	Te	Sr	Ru	La	Ce	Ba
RC1	7,0E-05	4,8E-09	4,2E-09	9,1E-10	7,8E-10	1,2E-11	1,2E-11	1,2E-11	7,8E-10
RC4	9,0E-01	3,2E-03	3,1E-03	8,1E-04	7,7E-04	1,1E-05	1,1E-05	1,1E-05	7,7E-04
RC6	9,9E-01	6,0E-01	6,0E-01	1,3E-01	1,0E-01	1,6E-03	1,6E-03	1,6E-03	1,0E-01

The corresponding source terms for RC1 are given in Table 5.

Table 5: Accidents without containment failure (RC1), fractions of initial inventories, mean, EPR.

Radionuclide Group	In-Vessel [1]	To Containment [2]	To Secondary Containment [3, 5]	To Environment [4]
Xe	0.72	0.72	1.4E-4	7.0E-5
I	0.72	0.58	1.2E-8	4.8E-9
Cs	0.72	0.54	1.1E-8	4.2E-9
Te	0.22	0.14	2.8E-9	9.1E-10
Sr-Ba	0.22	0.13	2.6E-9	7.8E-10
Ru	3E-3	2E-3	4.0E-11	1.2E-11
La	3E-3	2E-3	4.0E-11	1.2E-11
Ce	3E-3	2E-3	4.0E-11	1.2E-11

1 Assume that one third of the accidents results in only 30% core damage (TMI-2), as for Siemens PWR makeup of in-vessel arrest versus ex-vessel recovery. Assume no ex-vessel release.
2 Assume low primary pressure retention.

3 Assume leak << 1E-3 per day for two days (pressure dependent, see TMI-2 analyses), assume average retention (deposition) of aerosol over two days of one order of magnitude every 12 hours, i.e. a total AVERAGE reduction of two orders of magnitude for a total aerosol transport outside containment equal to 2E-6.
4 Assume secondary containment is not isolated. Releases through the ventilation system (retention factor of two in secondary containment) and deposition in ventilation system as in-vessel retention.
5 Assume IRWST (In-containment Refueling Water Storage Tank) not saturated, retention factor of 100 (Dana Powers).

Given the EPR core inventories, the RC4 accident would be classified as INES4 on the IAEA INES scale resulting in a release of at most 100 Bqs of I131 and equivalent (Table 6).

Table 6: Accidents with early containment failure (RC4), fractions of initial inventories, mean, EPR.

Radionuclide Group	In-Vessel	To Containment [1]	To Environment [2]
Xe	0.90	0.90	0.90
I	0.90	7.2E-3	3.2E-3
Cs	0.90	6.8E-3	3.1E-3
Te	0.28	1.8E-3	8.1E-4
Sr-Ba	0.28	1.7E-3	7.7E-4
Ru	4E-3	2.4E-5	1.1E-5
La	4E-3	2.4E-5	1.1E-5
Ce	4E-3	2.4E-5	1.1E-5

1 Assume low primary pressure retention, IRWST not saturated, DF equal 100 for aerosol.
2 Assume failure around the time of vessel breach. Retention of aerosol in containment is 0.1 (transmission 0.9). Large containment breach, all radioactive material released to secondary containment. The secondary containment leaks, retention in secondary is 0.5.

We suggest that RC6 should be used for the most catastrophic type of accident because no retention mechanism is credited (Table 7). Given the EPR core inventories, this accident would be classified as INES7 in the IAEA INES scale with a release of several tens of thousands Bqs of I131 and equivalent.

Table 7: Accidents with containment bypassed (RC6) (SGTR (Steam Generator Tube Rupture) and others), fractions of initial inventories, mean, EPR.

Radionuclide Group	In-Vessel	SGTR To Environment [1]	AREVA Bypass
Xe	0.90	0.90	9.9E-1 **
I	0.90	0.18	6.0E-1
Cs	0.90	0.14	0.50 - 0.60
Te	0.28	3.3E-2	1.3E-1
Sr-Ba	0.28	2.5E-2	1.0E-1
Ru	4E-3	3.6E-4	1.6E-3
La	4E-3	3.6E-4	1.6E-3
Ce	4E-3	3.6E-4	1.6E-3

1 Assume retention in secondary side piping as low pressure primary retention, in addition to MELCOR calculated retention in primary side and secondary side of SG. No ex-vessel releases (either core catcher works, or no path to environment from containment).
** All releases calibrated on Cs CCDF shown by AREVA, using Siemens PWR results for in-vessel releases.

2.6.2.2 Assessment of source terms for LMFBR type reactors.

Sodium cooled fast breeder reactors had been extensively investigated in the period 1970-1984, and several prototypes of different designs had been operating, (current total operating experience is about 300 reactor years). But the largest model (Super Phenix) was shut down due to safety concerns. In addition, at least one severe accident has occurred in an experimental breeder reactor (the EBR-II in Idaho), where parts of the fuel melted, no one was injured[6].

The interest for these reactors has been revived during the push for Generation IV plants, due to expected smaller consequences from severe accidents than for LWRs, and some studies have been conducted including attempts to Level 2 PSA by INEEL (Idaho National Engineering and Environmental Laboratory), ORNL (Oak Ridge National Laboratory), and the Japanese CRIEPI (Central Research Institute of Electric Power Industry). A large amount of information can be found on the Internet. However, it must be cautioned that the safety analyses efforts so far have been very primitive and limited; hence the information found in open sources must be interpreted very conservatively.

A summary of a joint effort by ORNL and CRIEPI (Toshiba-Hitachi, 2005) is the most interesting document, and the present estimates are extracted from that publication. CRIEPI shows the preliminary results for a Level 2 PSA conducted for a Small Breeder Reactor (SBR) which appears to be in operation. The reactor power can be extended to 1500 MW_{Th} (500-600 MW electric output, depending on turbine efficiency, not yet specified), and the fuel can be exchanged to conventional LWR MOX fuel. A commercial power plant may likely operate with MOX fuel like an LWR.

Therefore, for the remainder of the discussion, it is assumed that the plant would be MOX-fuelled, making it easier for comparisons to LWRs. It should be noted that, if non-MOX fuel were to be used, the main differences would be a longer time for progression to core damage, but a possibly much higher inventory of long-lived elements such as Cs-137, hence in the end safety concerns balance each other out.

The CRIEPI analysis is very incomplete, and takes into consideration ONLY internal initiating events, and moreover it would appear that not all accident sequences have been analyzed. In particular, results (very abbreviated) are shown for three sequences, Protected Loss of Heat Sink (PLOHS), Unprotected Loss of Heat Sink (ULOHS), and Transient Over Power (TOP). The first two presumably refer to loss of heat exchangers, and/or steam generators capabilities, the last to transients with power increase, which would include ATWSs (Anticipated Transient without Scram). Primary system LOCAs and Loss of Power events appear not to be considered and ATWS may thus not be completely covered in TOP.

For these scenarios, frequencies and source terms are provided for what appear to be six release categories, for one radionuclide group only (presumably I-Cs). Table 8 shows the data which can be extracted from the information given by CRIEPI. Release classes are not specified but from the magnitude of releases it can be guessed that they correspond to the following LWR classes:

[6] https://netfiles.uiuc.edu/mragheb/www/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Fast%20Breeder%20Reactors.pdf

RC1: Intact containment

RC2, RC3: Two different scenarios with late containment failure

RC4, RC5: Two different scenarios with early containment failure

RC6: Containment function impaired from the start of the accident

Accident frequencies have been modified/corrected from the above-mentioned CRIEPI data, assuming that the analysis is incomplete (i.e., assuming conservatively that all missing scenarios behave as the worst scenario ULOHS), and further assuming that the frequency of external and area events contributes about one third of the total CDF for states at power (as for most LWRs), and that shutdown states also contribute an additional 50% of the total CDF at power (as is the case for the EPR plant). Source terms for groups other than I and Cs are extrapolated from typical LWR analyses, which is reasonable for a MOX core.

Table 8 Releases of relevant radionuclides for the three release classes

HTGR:

Release class	Xe	CsI	CsOH	Te	Sr	Ru	La	Ce	Ba
RC6	5.0E-01	1.5E-03	9.0E-03	2.5E-03	3.0E-03	1.0E-04	5.0E-05	3.0E-04	3.0E-03

LMFBR:

Release class	Xe	CsI	CsOH	Te	Sr	Ru	La	Ce	Ba
RC1	1.0E-01	1.0E-04	1.0E-04	5.0E-05	2.0E-05	2.0E-06	5.0E-06	1.0E-07	2.0E-05
RC4	9.8E-01	1.0E-02	1.0E-02	6.0E-03	4.0E-03	3.0E-04	5.0E-04	1.0E-05	4.0E-03
RC6	1.0E+00	1.0E-01	1.0E-01	5.0E-02	3.0E-02	3.0E-03	7.0E-03	3.0E-04	3.0E-02

Table 9 shows the estimated source terms and frequencies, reconstructed from CRIEPI (Toshiba) on the S4 project in Japan (2005).

Table 9: Estimated source terms and frequencies, reconstructed from CRIEPI (Toshiba) preliminary work on S4 project in Japan (2005), corrected for external and area events and shutdown states.

Release class	Frequency (/Ry)	Xe	I	Cs	Te	Sr	Ru	La	Ce	Ba
RC1/FBR	5.9e-7	0.1	1E-4	1E-4	5E-5	2E-5	2E-6	5E-6	1E-7	2E-5
RC2/FBR	2.7e-7	0.98	9E-4	9E-4	4E-4	2E-4	2E-5	6E-5	2E-8	2E-4
RC3/FBR	1.6e-7	0.98	8E-3	8E-3	6E-3	3E-3	3E-4	6E-4	3E-6	3E-3
RC4/FBR	7.0E-8	0.98	0.01	0.01	6E-3	4E-3	3E-4	5E-4	1E-5	4E-3
RC5/FBR	1.4E-9	0.98	0.07	0.07	0.04	0.02	2E-3	4E-3	2E-4	0.02
RC6/FBR	2.5E-12	1.00	0.10	0.10	0.05	0.03	3E-3	7E-3	3E-4	0.03

For the present work, it is assumed that the containment of these plants would be constructed with the EPR standards. Hence the conditional probabilities and releases, given the same scenarios, would be the same. The only releases to be considered would be RC1 (limited core damage, recovered), RC4 (containment fails following a highly energetic event), and RC6 (containment is completely bypassed).

2.6.2.3 Assessment of source terms for High Temperature Reactors (HTR)

Gas cooled reactors have been operating mostly in the UK, where about 50 units at one time were producing electricity, and now are being rapidly phased out. Two models were represented in the fleet, the GCR (Gas Cooled Reactor) and the AGR (Advanced Gas Cooled Reactor). Operating history is very poor: there were two events at Windscale (England)[7] and one at Transfynydd (Wales)[8] power stations, which resulted in fairly large releases of radiation, needing some limited offsite long term intervention but no immediate intervention, and several other incidents involving smaller releases of radiation, in less than a total of 1500 years of operation.

Few HTGRs (High Temperature Gas Cooled Reactor) have been in operation; hence their historical evidence is not very relevant. Most were or are prototypes or research plants, and only one safety analysis is still available, dating back to 1986, for a modular HTGR designed by GA Technologies (currently General Atomics), with a power of 250 MW_{Th}.

None of the PSAs was complete, but included at best only internal and some external events during operations at power. Findings for these five PSAs are summarized in Table 10. Large late releases are defined as releases which would trigger immediate offsite interventions, i.e., evacuation or sheltering. Due to inherent design and physical behavior, there cannot be any so-called large early release. In the face of the operating history, the PSAs for GCRs and AGRs strike as being optimistic, at least as far as the total CDF is concerned, while the GA PSA seems to reflect actual operating histories. The frequency of large releases seems to be for the most part consistent among the PSAs and reflecting design improvements.

Table 10: Summary of PSAs and findings for gas cooled reactors.

Plant Type	CDF or equivalent / year	Details
GCR	10^{-4}	(Slaper et al. 1994): CDF=10-4 / year, conditional probability of large late release = 0.1; therefore LRF=10-5 / year (Wenisch 1998): LRF=10^{-3} /year
AGR	10^{-4}	(Slaper et al. 1994): CDF=10-4/ year, conditional probability of large late release = 0.01; therefore LRF=10-6 / year (Wenisch 1998): LRF=10^{-4} /year
HTGR	10^{-2}	(General Atomics 1986): Total CDF > 10^{-1} / year, frequency of releases involving substantial amount of radioactivity (> 10^{11} Bq of Iodines) is ~10^{-2} / year, frequency of LRF ~10^{-6} / year

As mentioned, High Temperature Gas Cooled Reactors (HTGR) prototypes have been in operation since the 1970s-1980s, but the IAEA databases, which should provide the best source of data, do not contain much relevant information on safety and PSAs for these plant types, hence the best source of information is the GA PSA available from the US DOE databases. Currently, designs are revised and "improved" exploring HTGR designs and modular Pebble Bed Reactors (PBRs). The safety studies for these plant types are still in their infancy therefore it is not easy to assess either core damage frequencies or releases. By necessity, this work must take into consideration the

[7] Decalssified investigation report available from http://news.bbc.co.uk/2/shared/bsp/hi/pdfs/05_10_07_ukaea.pdf
[8] http://www.nuclearfiles.org/menu/key-issues/nuclear-weapons/issues/accidents/accidents-1980%27s-06.htm

existing old GCR/AGR and GA data and conservatively extrapolate to new designs which may improve on the older ones only with a limited background of "lessons learned". Table 11 shows the current status of HTGR works.

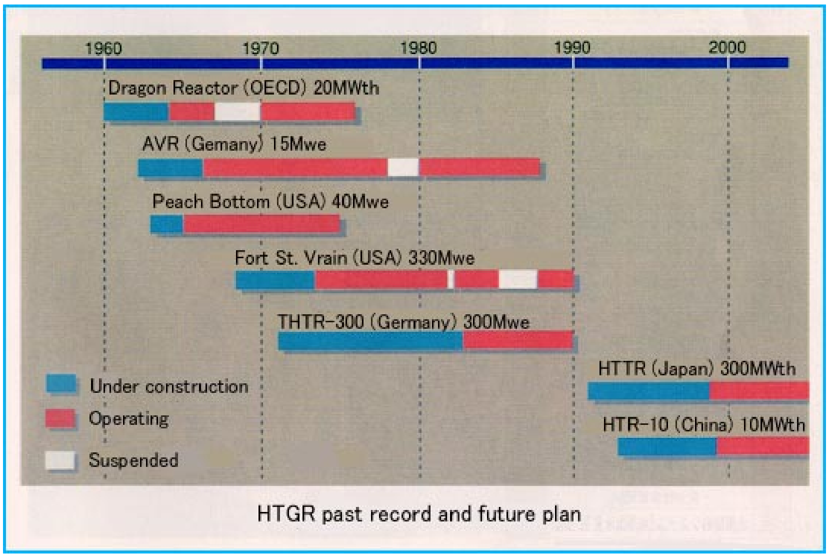

Figure 11: HTGR past record and future plan. [9]

Before trying to provide data for the current models, some comments must be made to justify some of the assumptions. Firstly, there is the issue of radioactive core inventories, definition of core damage, and releases. Gas cooled reactors do not use conventional LWR fuels, but can use spent or non-irradiated fuel. For this reason, if core cooling is lost or the fuel heats up, progression to core damage is much slower, and is estimated to go from 0.1-1 day for LWRs, and to 4.5 days for GCRs, respectively. Moreover, the GCR practitioners, for semantic reasons, prefer to identify core damage as simply core heat-up resulting in radioactive releases, small or large; in other words, the core cannot melt but slower release mechanisms are not precluded. This has implications for possible operator's interventions to stop an accident before large amounts of radioactivity are released. With regard to release mechanisms severe HTGR-accidents can be grouped into two groups:

- Water ingress events with fission product release due to hydrolysis of defective coated particles and desorption of plate out activity (minor releases).
- Core heat-up events with fission product release after coated particle failure due to excessive temperatures.

For these reasons core heat-up accidents are the counterpart to core melt-down accidents for LWR, but because of different generic and genetic features of an HTGR, fission product release is reduced or at least drastically delayed. Nevertheless, on a scale of several days, the GA analyses show substantial releases from the fuel matrix to the confinement/containment.

A second consideration is what has just been mentioned, i.e., the containment building of these plants may be large comparatively to power, but the building's design leak is very large, hence the practitioners prefer to talk about a confinement. Obviously this

[9] http://www.jaea.go.jp/jaeri/english/ff/ff43/randd01.html

has implications on environmental releases, since any accident or incident at an HTGR can be considered similar to a containment bypass sequence in an LWR.

Thirdly, thermal power for these reactors would be small, hence radioactive decay coupled with much smaller inventories of Iodine would make this design “inherently safe” with respect to the need for immediate offsite countermeasures in case of an accident. However, inventories of long-lived radionuclides may be much larger, as shown in the following example:

Estimates of core inventories for an 1100 MWTh Pebble Bed HTGR have been performed in South Africa: Decay heat as was calculated with ORIGEN-JUel[10]; a comparison of the fraction of total activity compared to a reference PWR’s core inventories (3412 MWTh plant), as used in the current models, showed that inventories of Cs radionuclides would be a factor of approximately 3 times larger than in LWR plants, while inventories of I radionuclides may be a factor of two smaller . Therefore, the argument about an “inherently safe” design is a-priori not true, since long term interventions are not precluded. This conclusion is supported by the historical evidence of the GCRs and AGRs in the UK.

After having terminated the preliminary discussions and comments on definitions and status of HTGR safety assessment, we can pass to estimates of accident releases and frequencies.

The basis for the assessment is the GA complete PRA from 1986. This PSA can be summarized as a perfect work based on imperfect understanding of safety issues and significance of events, especially in relation to long term effects of releases of radiation.

After considerable effort on trying to relate the results of the GA PRA to current LWR PSAs, the following conclusions were reached:

– The cumulative frequency of all accident at power leading to releases from the fuel is > 10-1 / year.
– The cumulative frequency of accidents with releases comparable to a core melt accident in LWRs is >> 10-4 / year.
– The cumulative frequency of accidents needing immediate offsite countermeasures is about 10-6 / year.

Shutdown events would not contribute except for unplanned shutdown states and maintenance time. Refuelling shutdown periods may be of the order of 20 years.

Releases from SGTRs are the limiting events for thyroid doses (iodine releases). Estimated frequency is about 5 x 10-6 / year. The estimated dose beyond the site exclusion zone would be equivalent to a release of about 2400 Ci or > 8 x 1013 Bq of Iodine131. In terms of core inventories, this is equivalent to about 0.001 of the total inventory for a 250 MWTh reactor.

Releases from LLOCAs are the limiting events for doses from other radionuclides and for the need of long term countermeasures. The frequency of such events is about

[10] http://sacre.web.psi.ch/ISAMM2009/ISAMM09/papers/Session%206%2840,3,7,30,34%29/Paper%206.3%287%29Viatzkova.pdf

10-6 / year. The estimated dose would be equivalent to the release of 0.003 of the total inventory of Cs. This is consistent with the inventory estimates given for the modular PBR, assuming that I and Cs are released with the same rates.

Therefore, giving credit to lessons learned, and extrapolating frequencies also to unplanned shutdown states, the results of the GA PRA have been scaled down in frequency to a total CDF of about 5 x 10-5 / year. Six release classes have been defined, not necessarily corresponding to any of the more than 33 accident types given in the GA PRA, except for the last two classes, which correspond to SGTRs and LLOCAs, respectively.

Table 11 shows the reconstructed matrix of releases and frequencies, with release fractions as a function of the HTGR actual core inventories. Xe releases may be over-estimated, but they are provided to be consistent with LWR estimates, and are not important to risk.

Table 12 shows the same data, scaled to LWR core inventories, following the results of the South African study for modular PBRs. For this study, it is also assumed that an 1100 MWTh plant of this type may be constructed and operated.

Table 11: HTGR source terms as fractions of HTGR core inventories (independent of power).

Release class	Frequency (/Ry)	Xe	I	Cs	Te	Sr	Ru	La	Ce	Ba
RC1	4.00E-05	0.1	1.00E-09	1.00E-09	1.00E-09	1.00E-09	1.00E-10	1.00E-10	1.00E-11	1.00E-09
RC2	6.00E-06	0.5	1.00E-08	1.00E-08	1.00E-08	1.00E-08	1.00E-09	1.00E-09	1.00E-10	1.00E-08
RC3	3.00E-06	0.7	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-07	1.00E-08	1.00E-08	1.00E-06
RC4	1.00E-08	0.9	2.00E-05	2.00E-05	1.00E-05	1.00E-05	1.00E-06	1.00E-06	1.00E-07	1.00E-05
RC5	5.00E-07	1	3.00E-04	3.00E-04	4.00E-04	1.00E-04	1.00E-05	1.00E-05	1.00E-06	1.00E-04
RC6	2.00E-07	1	3.00E-03	3.00E-03	5.00E-03	1.00E-03	1.00E-04	1.00E-04	1.00E-04	1.00E-03

Table 12: HTGR 110 MW_{Th} Source Terms as a fraction of 1100 MW_{Th} PWR core inventories.

Release class	Frequency (/Ry)	Xe	I	Cs	Te	Sr	Ru	La	Ce	Ba
RC1	4.00E-05	0.05	5.00E-10	3.00E-09	5.00E-10	3.00E-09	1.00E-10	5.00E-11	3.00E-11	3.00E-09
RC2	6.00E-06	0.25	5.00E-09	5.00E-09	5.00E-09	3.00E-08	1.00E-09	5.00E-10	3.00E-10	3.00E-08
RC3	3.00E-06	0.35	5.00E-07	5.00E-07	5.00E-07	3.00E-06	1.00E-07	5.00E-09	3.00E-08	3.00E-06
RC4	1.00E-08	0.45	1.00E-05	1.00E-05	5.00E-06	3.00E-05	1.00E-06	5.00E-07	3.00E-07	3.00E-05
RC5	5.00E-07	0.5	1.50E-04	9.00E-04	2.00E-04	3.00E-04	1.00E-05	5.00E-06	3.00E-06	3.00E-04
RC6	2.00E-07	0.5	1.50E-03	9.00E-03	2.50E-03	3.00E-03	1.00E-04	5.00E-05	3.00E-04	3.00E-03

More recently, some estimate on source terms related to HTRs has been published. The data shown for the limiting scenario (LLOCA with fast depressurization, corresponding to RC6 in the table) is at least two orders of magnitude lower than the GA assessed releases. However, the article states that a large uncertainty is connected with the dust borne activity carried by the coolant during normal operations, with the comment that this would require a conservative treatment. For this assessment therefore the GA results are used as bounding data. In particular, since another point in serious doubt is the performance of the containment (in reality a confinement: due to the potentially large and fast blow down in case of an incident, the confinement would require some type of pressure relief system, such as windows equipped with blowout panels), it is almost assured that any type of serious terrorist attack would result in destruction of the confinement, a large LOCA, and therefore only the source terms for RC6 are used in this study. Acceptance conditions for HTRs without conventional containment are given in the USNRC NUREG 1338[11], but the cited article states that post September 11 attacks are not currently considered.

2.6.3 Simplified methodology to assess offsite consequences

The MACCS2 version of the USNRC consequence code system MELCOR/MACCS has been released to the PSI in late 2004 (Chanin and Young, 1998). The simplified methodology employed for this work makes use of risk coefficients, which directly relate activity of releases (i.e., amount of radioactive materials dispersed into the environment) to three risk measures: acute (immediate) fatalities, chronic (delayed) fatalities, and severe land contamination (i.e., land that may be lost for very protracted lengths of time).

Risk coefficients are calculated using a reference site and plant (Three Mile Island, TMI-2), for each radionuclide specie of importance in the evaluation of risks from a nuclear power generating facility (the importance is specified in MACCS input requirements, and has been assessed by the USNRC and its contractors). Risk coefficients are calculated for best estimate and extreme weather conditions (assumed to be represented by the 95th percentile of risk distributions).

For this work, a coastal US site was used, with Eastern US weather. The site data file was developed for the PSI to study releases from the TMI-2 accident of 1978. The population density can be characterized as medium (about 100 persons per km^2) in the relevant areas around the plant (i.e., to a distance of 80 km), and the area occupied by usable land is reduced, with respect to that of a continental site. Since the calculations performed by MACCS are probabilistic, the influence of weather types and other site specific data on the risk results are of less importance (for instance, all weathers types are fairly homogeneously represented in all MACCS calculations, irrespectively of site specific weather variations).

In order to verify the appropriateness of the simplified methodology, with respect to full MACCS calculations, a comparison has been performed for the risks of six hypothetical accidents (source terms), using both MACCS and the simplified methodology.

The six source terms correspond to the six accident classes identified for the EPR reactor in NEEDS (Burgherr et al., 2008), and the MACCS calculations have been performed for the TMI-2 site discussed above. The following table and figures show the results of the comparisons. In Table 13, PM stands for "Present Model". Assessment of costs provided by MACCS includes only actuarial costs of deaths, decontamination and loss of land, but not the long term costs attached to evacuation, relocation, and the costs of plant loss and replacement. The present model for costs includes all of the above. Figure 12, Figure 13 and Figure 14 show a comparison of

[11] USNRC, NUREG-1338. Draft pre-application safety evaluation report for the modular high-temperature gas-cooled reactor, March 1989.

results between the MACCS and the simplified model (PM), for early and late fatalities and land contamination, respectively.

Table 13: Consequences for EPR at TMI-2 site. PM = Present Model.

Release class	*Consequences*							
	Early Cancer Fatalities		*Late Cancer Fatalities*		*Land Contamination (km2)*		*Costs (USD)*	
	MACCS	PM	MACCS	PM	MACCS	PM	MACCS	PM
RC1	0	2.4E-05	0	3.71E-03	0	1.6E-04	0	1.54E+10
RC2	0	2.6E-01	3	4.11E+01	0	4.0E-03	2	1.56E+10
RC3	1.0E-02	2.7E-01	51	3.23E+01	1.5E+01	1.3E+01	1.2E+07	1.56E+10
RC4	0	2.1E+00	3.57E+02	1.35E+02	2.0E+02	1.2E+02	1.4E+08	1.66E+10
RC5	0	2.0E+01	1.24E+03	4.36E+02	9.4E+02	5.8E+02	5.4E+08	1.99E+10
RC6	1.41E+02	1.1E+03	1.94E+04	1.62E+04	1.81E+04	2.2E+04	2.4E+10	1.95E+11

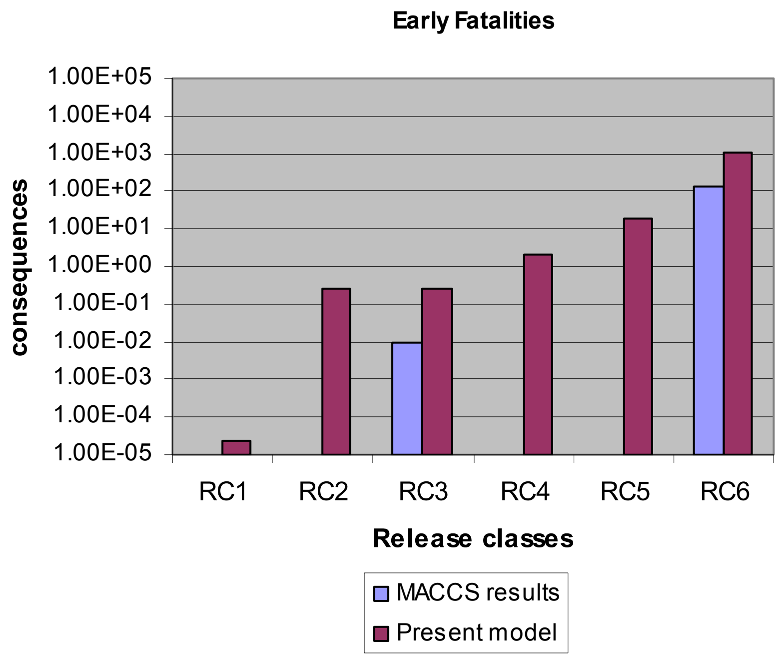

Figure 12: Comparison of MACCS2 results and Present Model Results, Early Fatalities.

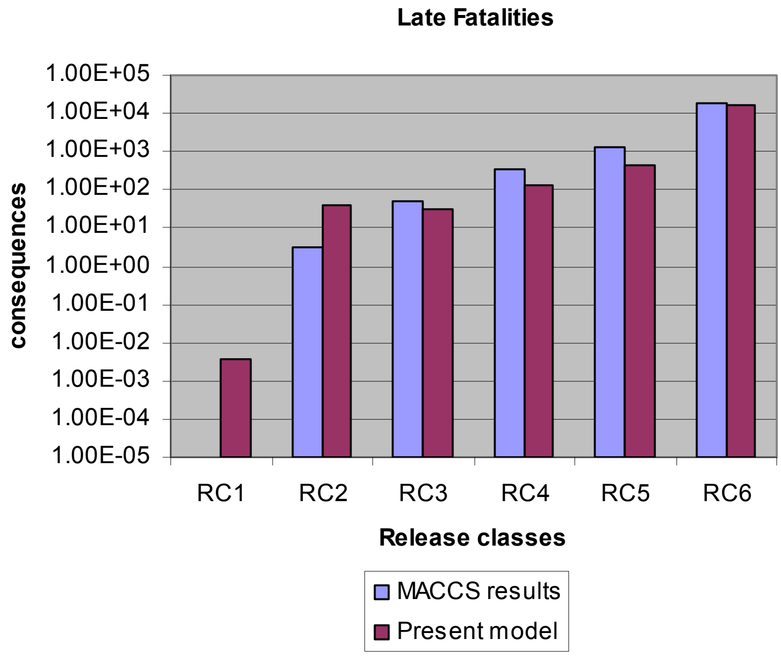

Figure 13: Comparison of MACCS2 results and Present Model Results, Late Fatalities.

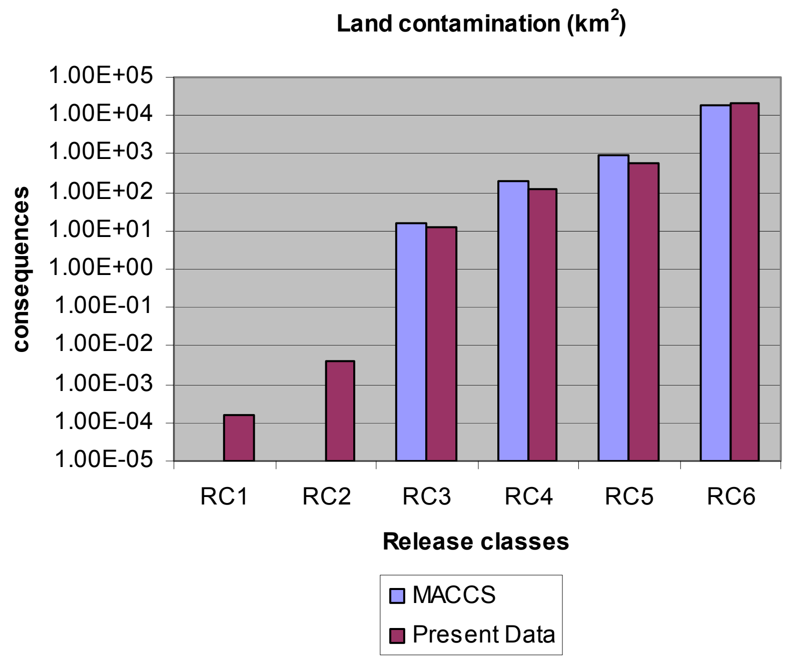

Figure 14: Comparison Comparison of MACCS2 results and Present Model Results, Land Contamination.

Results show that the simplified methodology provides conservative results for immediate health effects (see Figure 12). The reason is that the calculations performed with MACCS of “immediate” fatalities consider a threshold of 5 Gy absorbed dose for lethality, while the simplified model assumes no threshold, and hence the probability of death is assumed to be non-zero even below 5 Gy. Fairly good agreement is achieved for the other risk measures, i.e. late fatalities due to cancer and land contamination as shown in Figure 13 and Figure 14, respectively. This proves that once the data is developed for one site, it can be used for all assessments pertaining to accidents in that site, without the need to rerun MACCS, or to develop new detailed inputs. However, extrapolation to other sites with different characteristics is not proven in this work, and is still an assumption of the simplified methodology.

2.6.4 Calculations of consequences

2.6.4.1 Choice of sites

The choice of sites for this work has been largely left to our discretion. From previous experiences with assessments of risks, including NEEDS (Burgherr et al., 2008), the sites should be selected to represent a good mix of conditions. Since the models for calculation of consequences depends on population and land fractions (compared to sea) at the sites, results can be easily extrapolated from one site to any other „unknown“ site, once the specific data is collected, and without repeating the calculations. The sites analyzed here are the same as in the assessment for terrorist attacks (Deliverable D5.7.2b).

Table 14 shows the sites used for the assessment, and the specific conditions that apply to each site.

Table 14: Site data base; all population current.

Site	population/scaling factors				area	
	to 8 km		to 80 km		land fraction	scaling factor
USA Surry – TMI-2	28’000	1.0	2’230’000	1.0	0.75	1.0
Finnland TVO	3’600	0.13	830’000	0.37	0.52	0.69
China Quingdao	70’000	2.5	7’750’000	3.47	0.67	0.89

2.6.4.2 Assessment of consequences

The following power scaling factors have been used for the three types of power plants:

Reference plant:	PWR (MACCS)	3142 MW_{Th}	
Calculated plants			Scaling factor
	EPR	- 4500 MW_{Th}	1.32
	HTGR	- 1100 MW_{Th}	0.32
	LMFBR	- 3000 MW_{Th}	0.95

3 Results

In this chapter, the results of the comparative risk assessment are presented. For the fossil energy chains and hydro power results were calculated on the basis of the database ENSAD, and for nuclear energy a simplified PSA approach was applied. For new renewable technologies estimates of risk indicators were derived from available data (that in some cases are rather limited, a literature survey, and expert judgment.

Table 15 gives an overview over historical accidents in the different energy chains and regions.

Table 15: Summary of severe accidents with at least 5 immediate fatalities that occurred in fossil, hydro and nuclear energy chains, as well as for selected renewables in the period 1970-2008. Accident statistics are given for the categories OECD, EU 27, and non-OECD. For the coal chain, non-OECD w/o China and China alone are given separately.

	OECD		EU 27		Non-OECD	
Energy Chain	*Accidents*	*Fatalities*	*Accidents*	*Fatalities*	*Accidents*	*Fatalities*
Coal	86	2239	45	989	163 1437 818	5808 (a) 25772 11302
Oil	179	3383	64	1236	351	19376
Natural Gas	109	1257	37	366	77	1549
LPG	60	1880	22	571	70	2801
Hydro	1	14	1	116 (b)	12	30007 (c)
Nuclear	--	--	--	--	1	31 (d)
Biogas	--	--	--	--	2	18 (e)
Biofuel (f)	6	8	--	--	1	3
Wind (g)	54	60	24	24	6	6
Geothermal	--	--	--	--	1	21 (h)

(a) First line: Coal non-OECD w/o China; second and third line: Coal China 1970-2008 and 1994-1999, respectively. Note that only data for 1994-1999 are representative because of substantial underreporting in earlier years (Burgherr and Hirschberg, 2007; Hirschberg et al., 2003a; Hirschberg et al., 2003b).

(b) Belci dam failure (Romania, 1991).

(c) Banqiao/Shimantan dam failures (China, 1975) together caused 26'000 fatalities.

(d) Only immediate fatalities. In the case of Chernobyl estimates for latent fatalities range from about 9000 for Ukraine, Russia and Belarus to about 33'000 for the whole northern hemisphere in the next 70 years (Hirschberg et al., 1998). According to a recent study (Chernobyl Forum, 2005) by numerous United Nations organizations (IAEA, WHO, UNDP, FAO, UNEP, UN-OCHA and UNSCEAR) up to 4000 persons could die due to radiation exposurein the most contaminated areas. This estimate is substantially lower than the upper limit of the PSI interval, which, however, was not restricted to the most contaminated areas.

(e) Waste gas (13 fat., China, 2004), wastewater (5 fat., Pakistan, 2008).

(f) Only small accidents.

(g) Only small accidents.

(h) Guatemala (1991).

For the fossil chains, hydro power and nuclear energy, the ENSAD database at PSI includes 435 severe accidents in OECD countries, 169 in EU 27, and 2111 in the non-OECD for the period 1970-2008, amounting to 8773, 3278, and 85344 fatalities, respectively (Table 15).

3.1 Fossil and hydro energy chains

3.1.1 Frequency-consequence curves

As explained in chapter 2.4.3, risk is commonly displayed using frequency-consequence (F-N) curves that give the full information about the risk.

The severity distributions are based on the entire dataset from 1970 to 2008, as the severity distribution cannot be shown to have changed over this time period. This curve is then scaled along the frequency axis with the number of accidents per year divided by the produced amount energy over the period from 2000-2008.

As it was shown in chapter 2.4.2 the accident frequency per produced $GW_e yr$ changes significantly over time, while no significant trend can be found for the severity distributions (except for coal). The severity curves are therefore fitted to all data from 1970-2008. For the F-N curves and also for the risk indicators these severity distributions are multiplied with the average frequency per $GW_e yr$ over the period from 2000 until 2008. This approach allows on the one hand calculating an accurate severity distribution based on a large dataset as well as a relevant frequency for today.

Figure 15 shows the FN curves for the fossil energy chains (coal, oil natural gas), hydro power and nuclear energy. Hydro power caused only one severe accident in the OECD over the period from 1970 until 2008, causing 14 fatalities (Teton dam, USA, 1976). To estimate the risk from hydro power this one accident was used for the frequency (i.e. 1/39 years). To estimate the severity distribution, accidents from non OECD countries were used (excluding the Banqiao/Shimantan dam failure (China, 1975) that alone caused 26000 fatalities). This dataset contains eleven severe accidents with up to 2500 fatalities. This is a very small dataset for an estimate of the risk and results in high uncertainties in the risk estimate. In the future this data should be supported with probabilistic safety assessment similar to the risk estimates used for nuclear power.

The FN curve for nuclear power is based on a risk assessment of an EPR reactor in France. The location of the reactor affects the consequences via the population density. The fatality curve comprises both early and late fatalities, with late fatalities dominating. In chapter 3.2 results for the nuclear chain are presented for the different countries and locations that were also analyzed in Deliverable D5.7.2b.

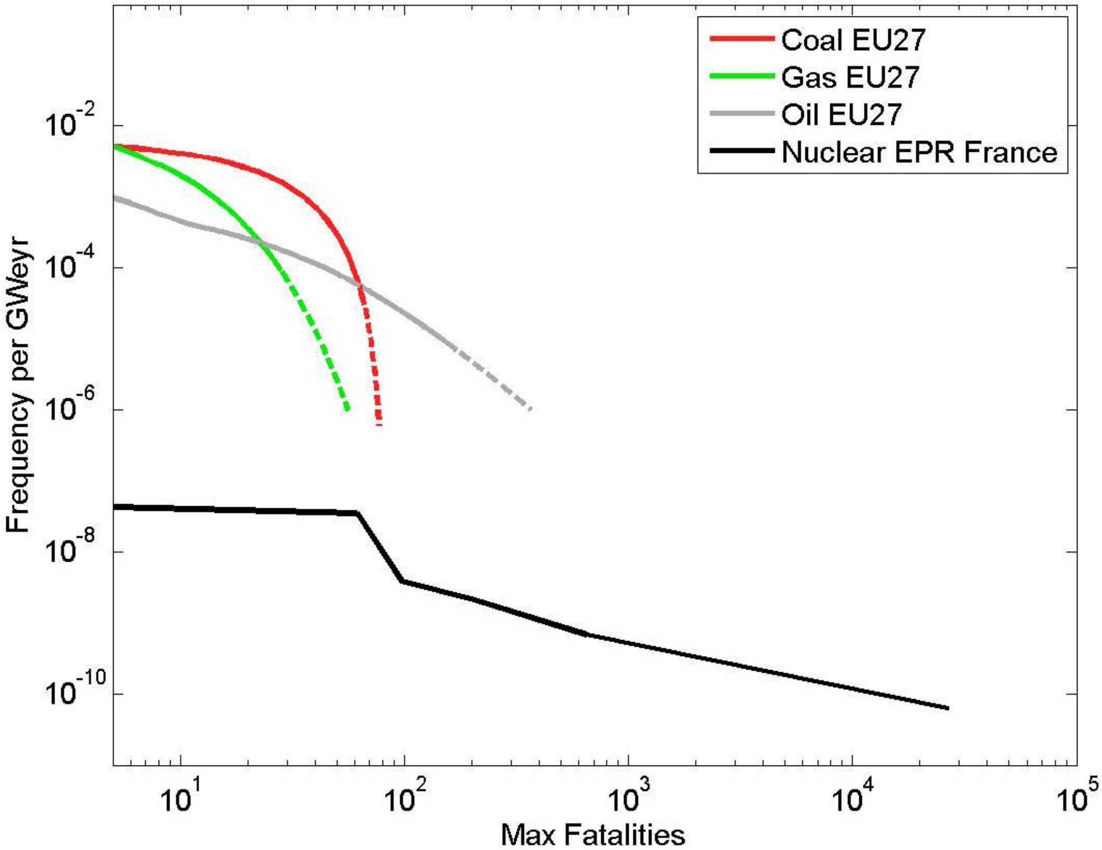

Figure 15: Comparison of F-N for full energy chains, based on historical experience (1970-2008) of severe accidents in fossil chains in EU 27, and a simplified PSA for nuclear energy (EPR, France). The solid lines of the F-N curves represent the part of the distribution for which historical data are available, whereas the dashed lines go beyond the most severe accident that occurred in the observation period. F-N curves for fossil chains have been truncated at 1E-6.

3.1.2 Risk indicators

In this chapter risk indicators are given for the fossil energy chains and hydro power in OECD, EU 27 and non-OECD countries. The selected risk indicators are defined as follows (for details see 2.5):

– R1: Expected number of fatalities per $GW_e yr$ (for severe accidents, at least 5 fatalities)
– R2: Number of fatalities at a risk level of 5E-5 per $GW_e yr$, which is in the region of the maximum historical accident
– R3: Expected number of fatalities exceeding this level (low frequency tail of distribution)

Figure 16, Figure 17 und Figure 18 show results for the risk indicators R1 to R3 and the different country groups.

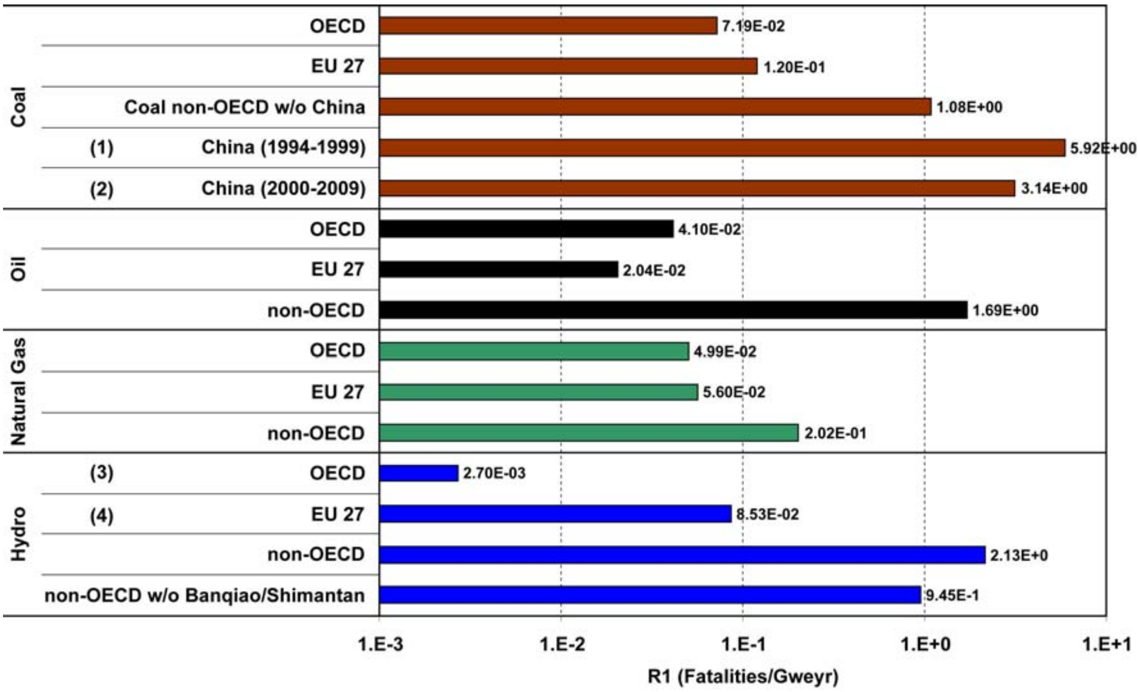

Figure 16: Risk indicator R1 for the fossil and hydro chains in OECD, EU 27 and non-OECD countries. Notes: (1) Coal China (1994-1999) is based on data from the China Energy Technology Program (CETP); (2) Coal China (2000-2009) is based on data from the China Coal Industry Yearbook (CCYI) (compare Table 3); (3) Teton dam failure (1976, USA); (4) Belci dam failure (1991, Romania).

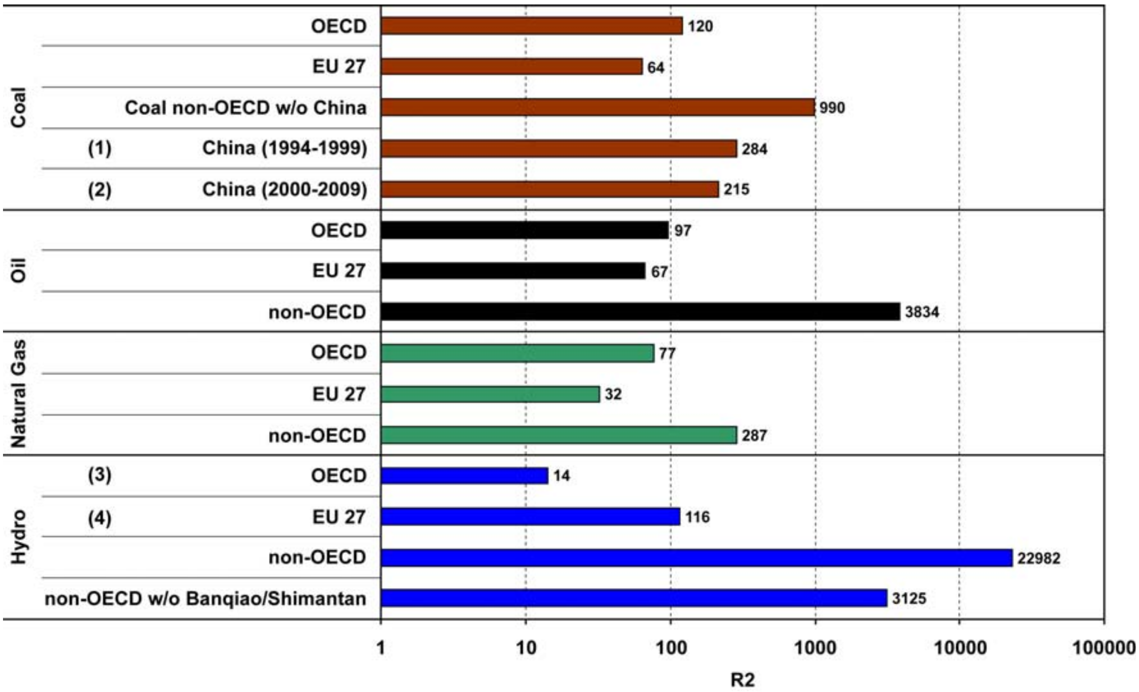

Figure 17: Risk indicator R2 for the fossil and hydro chains in OECD, EU 27 and non-OECD countries. Notes: (1), (2), (3) and (4) see Figure 16 above.

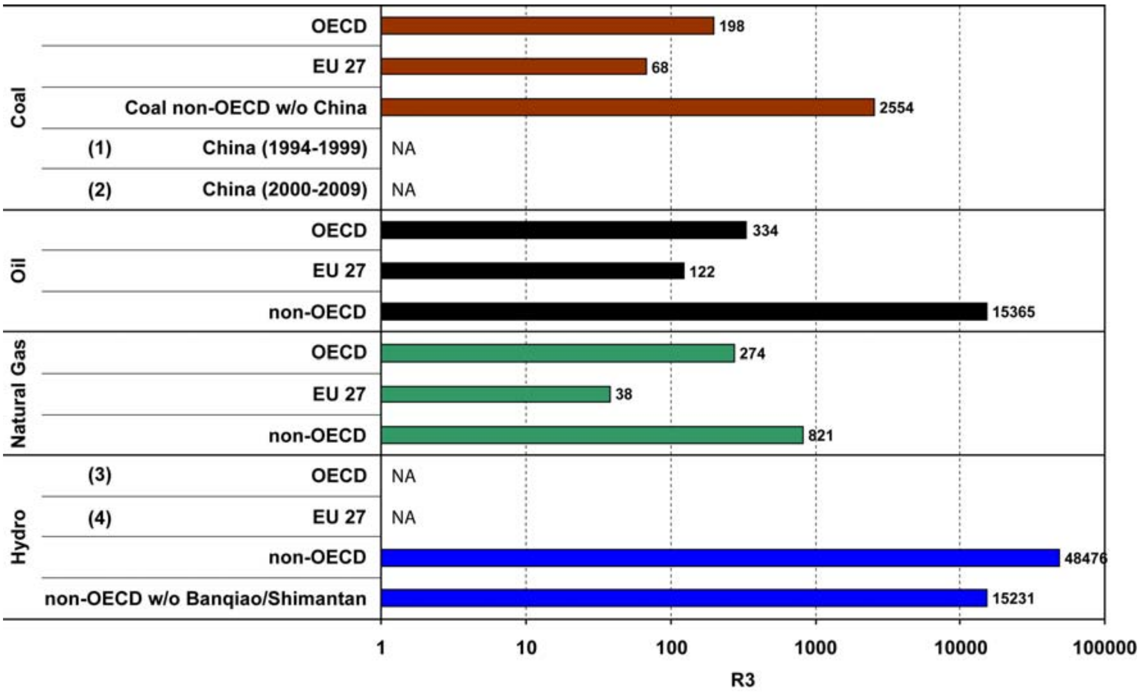

Figure 18: Risk indicator R3 for the fossil and hydro chains in OECD, EU 27 and non-OECD countries. Notes: (1), (2), (3) and (4) see Figure 16 above.

Risk indicators R1 to R3 were calculated based on the approach described in chapter 2.5. However, for specific energy chain and country group combinations this approach was not applicable due to insufficient historical data.

For coal China, data contained in the database ENSAD prior to 1994 were subject to substantial underreporting (Burgherr and Hirschberg, 2007; Hirschberg et al., 2003a; Hirschberg et al., 2003b), which is why results for the period coal China (1994-1999) were based on data from the China Energy Technology Program (CETP), and Coal China (2000-2009) was based on data from the China Coal Industry Yearbook (CCIY). Therefore, values for R2 denote the most deadly accident that occurred in the respective observation period (historical maximum consequences), while calculation of R3 was not possible.

For hydropower in OECD and EU 27 historical experience in the period 1970-2008 is very limited with only 1 severe accident in each of these country groups (see Figure 16). Therefore, values for R1 and R2 were just based on the data from these accidents, and calculation of R3 was not possible.

The proposed approach for the risk indicators R1 to R3 allows a consistent and transparent methodological calculation (with exception of the previously described cases). Nevertheless, results should be carefully reviewed and interpreted, as exemplified for the following instances.

In the case of “coal non-OECD w/o China” R2 and R3 amount to 990 and 2554 fatalities, respectively, whereas the observed maximum consequences in the years 1970-2008 correspond to 434 fatalities (1972, Zimbabwe). When looking back much further in time, there occurred few coal chain accidents with significantly larger death tolls. On 26 April 1942 a gas explosion in the Honkeiko (Benxihu) colliery resulted in

1549 fatalities in a coal mine at Benxi (Liaoning, China).[12] In 1906 a coal mine accident in Northern France at the Courrières mine killed 1099 workers, for which a coal dust explosion was supposed to be the primary cause.[13] However, these accidents cannot be considered relevant for today's situation because of widely different technologies utilized in coal mining as well as totally different safety regulation and management frameworks. Furthermore, modern underground mines generally have much less workers below surface due to substantially higher levels of mechanization than in past times. For example the average number of workers in underground mines in the USA is nowadays around 100 persons[14], although there are of course mines with more employees. Particularly in other countries including China productivity in terms of coal produced per number of employees is substantially lower (Hirschberg et al., 2003b). In contrast, open pit mines may have significantly larger numbers of employees, such as the Cerrejon mine in Colombia with about 5300 workers[15], but there the conditions are totally different, which rules out some accident scenarios typical for underground mines. Another possibility for a very large accident in the coal chain could be the collapse of large coal waste piles. In 1982 an accident in China killed 284 workers, but the number of victims is strongly depending on the number of persons located close to such a waste pile.

For oil in non-OECD countries the value of R2 is in the order of the most severe accident (4386 fatalities), whereas R3 is about 3.5 times higher. In the case of hydropower in non-OECD R2 accounts for about 88% of the total fatalities that occurred in the most deadly accident, if the Banqiao/Shimantan dam failure (1975, 26000 fatalities) is included (Figure 18), whereas R2 without this accident is about 25% larger than the observed maximum, which is then an accident in India (1979, 2500 fatalities). Both values for R3 are substantially higher than the respective historical maxima; however such a catastrophic event may not be excluded per se because the actual warning time (and evacuation scheme) and the population living downstream of large reservoir may strongly influence the death toll (Burgherr and Hirschberg, 2005).

3.1.3 Carbon Capture and Storage (CCS)

This chapter provides an overview of accident risks in for Carbon Capture and Storage (CCS) technologies in various fossil energy chains. For a more detailed presentation see the report by Pieber (2010).

In recent years numerous studies on Carbon Capture and Storage technologies and their potential to mitigate CO_2-emissions have been conducted, basic regulations have been set up, as well as several pilot and demonstration activities have been initiated. Several of these studies address the great number of e.g. economical and ecological risks surrounding CCS. However, further risks of various types of accidents with possibly severe adverse effects on humans and/or ecosystems, are not very well understood yet; both in terms of their potential frequency of occurrence and consequences. Only few studies address these risks primarily. However, accident risks

[12] http://www.britannica.com/EBchecked/topic/1503377/Honkeiko-colliery-mining-disaster
[13] http://en.wikipedia.org/wiki/Courri%C3%A8res_mine_disaster
[14] http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html
[15] http://en.wikipedia.org/wiki/Cerrej%C3%B3n

are an essential factor in decision making processes and can also strongly impact public perception and opinion. Therefore, objective and accurate facts are needed to avoid emotional or subjective decisions on a potential CO_2 mitigation technology.

One of the main issues related to CCS is the uncontrolled leakage and release of CO_2 to surrounding environments, the surface and the atmosphere. CO_2 is gaseous, colorless and odorless at normal ambient conditions and is normally present with about 0.03 vol% in the atmosphere. Apart from its global climate effects, it does have local effects on humans and ecosystems as well, particularly if it occurs at elevated (toxic) concentrations. In addition, it displaces oxygen and acts as asphyxiate therefore, especially if it appears as cold vapor (e.g. sublimating from dry ice) that stays close to the ground due to its density which is greater compared to that of air.

The effect a certain released amount of CO_2 has, depends largely on the atmospheric and topographical surrounding conditions, the type of release and the dispersion behavior of CO_2 (e.g., Bachu, 2008; Hepple, 2005): CO_2 tends to accumulate on the ground especially in depression areas and at low wind velocity. A low release rate of small leaks (that are hardly detectable in addition) will favour the accumulation, whereas high release rates of even great amounts can result in mixing with the surroundings. Examples for the adverse effect that a leakage and accumulation of CO_2 in a topographically favoring area can have are severe accidents at meromictic lakes in Cameroon (Nyos, 1986, ca. 1746 fatalities and Monoun, 1984, 37 fatalities (e.g., Hepple, 2005)). In addition to the effects on human safety, animals are similarly affected and vegetation and ecosystems are disturbed by acidified soil leading potentially to tree kills (e.g., Patil et al., 2010). Finally the release of CO_2 diminishes the positive effect of the storage on the atmospheric CO_2 concentrations and the subsequent climate change.

Hazardous situations with CO_2 can occur in every step of the CCS process chain, i.e. the capture, transport (by e.g. pipeline), injection into the subsurface and (long-term) storage in geological media of various types onshore and offshore.

The risks the CO_2-capture and separation, liquefaction and compression add to a given power plant have not been widely addressed so far. Generally it can be assumed, that the risks of a given power plant are increased due to the additional steps added to the process. Furthermore are additional emissions caused due to the use of chemicals etc. and their production in a life cycle prospective which are assumed to increase the risks of the given power plant. In addition, the loss in efficiency needs to be taken into account when analyzing the risk of a power plant with carbon capture.

Hazardous situations related to CO_2 pipelines result mainly from a slow or sudden release of CO_2 and contained impurities. A number of studies address the risks related to pipeline-transport of CO_2 in different approaches. Often (e.g., Gale and Davison, 2004) it is assumed that the risks of these pipeline are similar, or even lower, compared to that of natural gas pipelines. However, further studies (e.g., Eldevik et al., 2009) that demonstrate that CO_2 pipelines can not be evaluated accurately on basis of the risk of natural gas pipelines due to its different properties: Concerning the frequency of hazardous events, it must be noted that the corrosion-behavior is different due to the dissolution of CO_2 and impurities (e.g. H_2S, NO_x, SO_x) in the wet gas stream, forming acids. However, dehydration lowers corrosion rates. Furthermore, poor lubricant properties of dry CO_2 and different material compatibility as well as other operating conditions (dense supercritical conditions, dense liquid conditions, two phase flow, cooling in decompression, etc.) make the approximation by natural gas pipelines difficult. Concerning the severity of an accident, it needs to be considered that CO_2 is non-flammable and does not explode but has toxic and asphyxiating properties, posing different risks compared e.g. to natural gas. Furthermore can harmful or even toxic impurities be contained in the transported CO_2-stream (e.g. CO, H_2S), resulting in severe accident consequences.

The frequency and consequences of failure and (severe) accidents posed by the injection, sequestration and especially the (long-term) storage of CO_2 are less well understood and greater uncertainties exist. According to Damen et al. (2006), possible hazards include not only the CO_2 migration and leakage, but dependent on the addressed on- and offshore storage option (depleted oil-fields and enhanced oil recovery, depleted gas-fields and enhanced gas recovery, unmineable coal seams and enhanced coal bed methane recovery, saline aquifers) also methane leakage, induced seismicity, induced ground movement, brine displacement, groundwater acidification and its contamination with brine or by acidification dissolved heavy metals.

The injection of any fluid in the subsurface has geomechanical and hydrodynamic effects as well as geochemical effects in the long-term. It needs to be noted that the different storage options addressed show major geological differences and therefore processes will vary from storage type to storage type and also from storage site to storage site depending on the given ambient conditions. In general, it can be stated that with increased storage duration, geochemical processes can take place and add to the security of the storage (e.g., Bachu, 2008). Consequently migration and leakage from the injection and sequestration is much more likely than from a long-term stored reservoir, as e.g. adsorption, stratographical and hydrodynamic mechanisms are much more reversible compared to the geochemical processes, especially mineral trapping.

Slow (upward) leakage of CO_2 can result from reservoir fractures and faults or any wells in the storage area (e.g. injection wells in saline aquifers, injection or production wells in EOR, monitoring wells, etc.). “Positive” buoyancy due to the lower density of CO_2 compared to water and possibly brine pushes CO_2 upwards in saline aquifers. Contrary forces “negative” buoyancy the saturated water (1-2% CO_2 in water) that is heavier compared to non-saturated water and CO_2 towards the bottom of the storage aquifer. However, in ECBM other mechanisms act (e.g. adsorption instead of dissolution) and CO_2 adsorbed onto the coal surfaces will be immobile as long as the pressure does not drop (Bachu, 2008). Sudden rapid (upward) leakage of CO_2 can result from reservoir fractures, faults and wells and especially well-failure or well blow-outs (Holloway et al., 2007), induced by changes in pressure and temperature.

In general, industry records can be used as a first approximate for frequencies of leakage and migration, as well as experience with analogues for underground CO_2 storage (e.g. EOR, Acid Gas Injection, etc.). However, even here data are very limited or not available for research and limitations have to be taken into account, as in Vendrig et al. (2003) and Mazzoldi et al. (2009) who focused their quantitative risk assessment on data from the oil- and gas-industry. Therefore, a strong focus should be laid on the establishment of a database that includes hazardous situations and accidents that occur in relation to existing CCS-components (existing capture-, injection- and storage-projects as well as pipelines for which a database at least in the USA already exists) and their consequences, to make an accurate quantification of CCS-risks possible.

Overall, the CCS risk accident risks as assessed for the SECURE project can be summarized as follows, based on the study by Pieber (2010):

– Overall, the survey questionnaire showed that an objective and unbiased discussion of the various risk aspects of CCS is very important to achieve a sufficient level of information among decision-makers and the general public, which is a necessary prerequisite for a broad acceptance. The survey was also able to identify topical areas that are already well understood, but also where more research is needed. Finally, an often stated comment among survey participants was that careful site selection and appropriate monitoring are essential to reduce risks and ensure high safety standards.
– Hazardous situations with CO_2 can occur in every step of the CCS process chain. While the accident risk at the plant itself (capture) and the subsequent transport (by e.g. pipeline) could be approximated using data from PSI's accident database ENSAD and other published data, the accident risks from injection into the subsurface and (long-term) storage in geological media of various types onshore and offshore are yet much less understood; only few published data are available, and thus further research is needed.
– The release of CO_2 from a direct source as approximation of a pipeline puncture, rupture or the release from an injection plant or storage site was modeled in a generic way using the ALOHA (Areal Locations of Hazardous Atmospheres) software from the Environmental Protection Agency (EPA). However, ALOHA as well as other modeling tools are at the moment not capable to model CO_2 releases and dispersion accurately if for example a release from high pressurized pipelines is considered, and furthermore results are strongly dependent topographical and demographical conditions, which greatly influence the consequences of a hazardous event. Thus, the first approximations for one specific site (Germany), indicating that about 30 injuries and up to 18 fatalities could occur, should be taken with great caution because neither the actual magnitude nor the uncertainty of the results could be established within these preliminary analyses.

3.2 Nuclear energy

The work has focused on the assessment of radioactive releases and associated frequencies for the three reference advanced designs, namely EPR, FBR and HTGR located in Finland, USA and China.

Figure 19, Figure 20 and Figure 21 show F-N curves for early (immediate) fatalities, late fatalities and land contamination for the three advanced designs in the three countries.

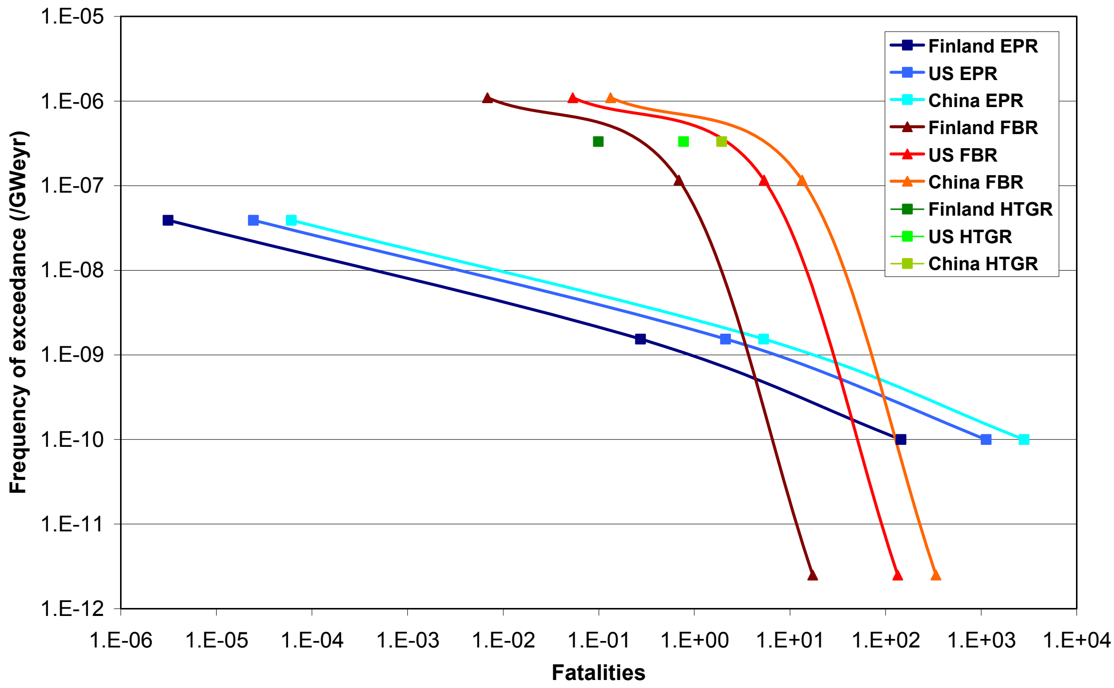

Figure 19: F-N curves for early fatalities of the EPR, FBR and HTGR advanced designs in Finland, USA and China.

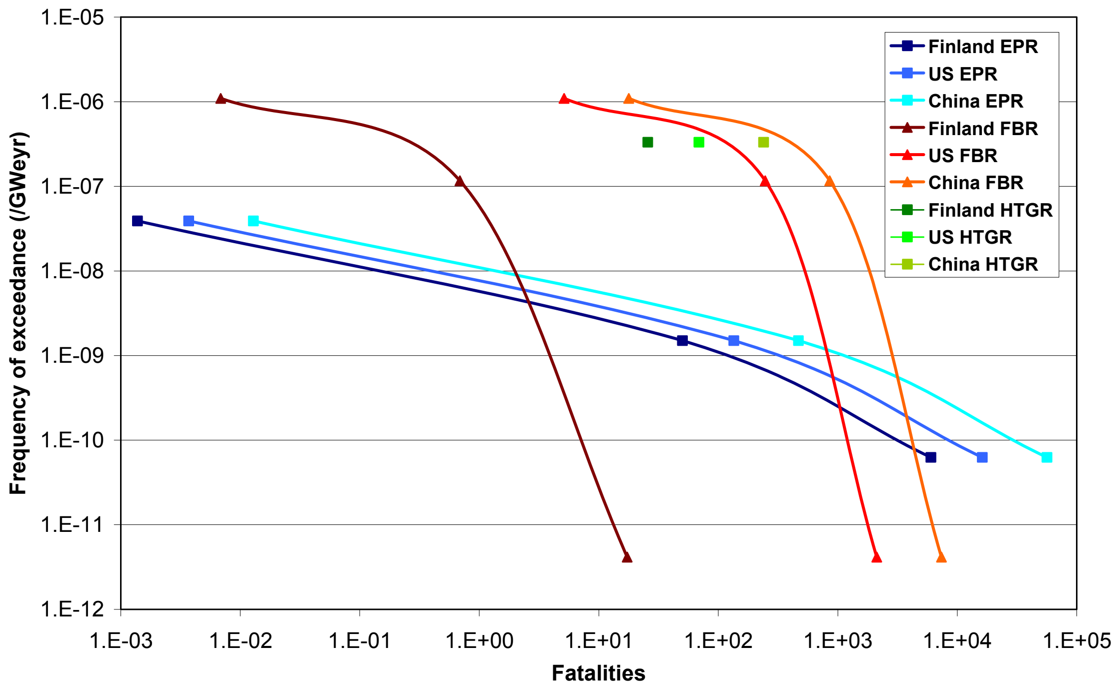

Figure 20: F-N curves for late fatalities of the EPR, FBR and HTGR advanced designs in Finland, USA and China.

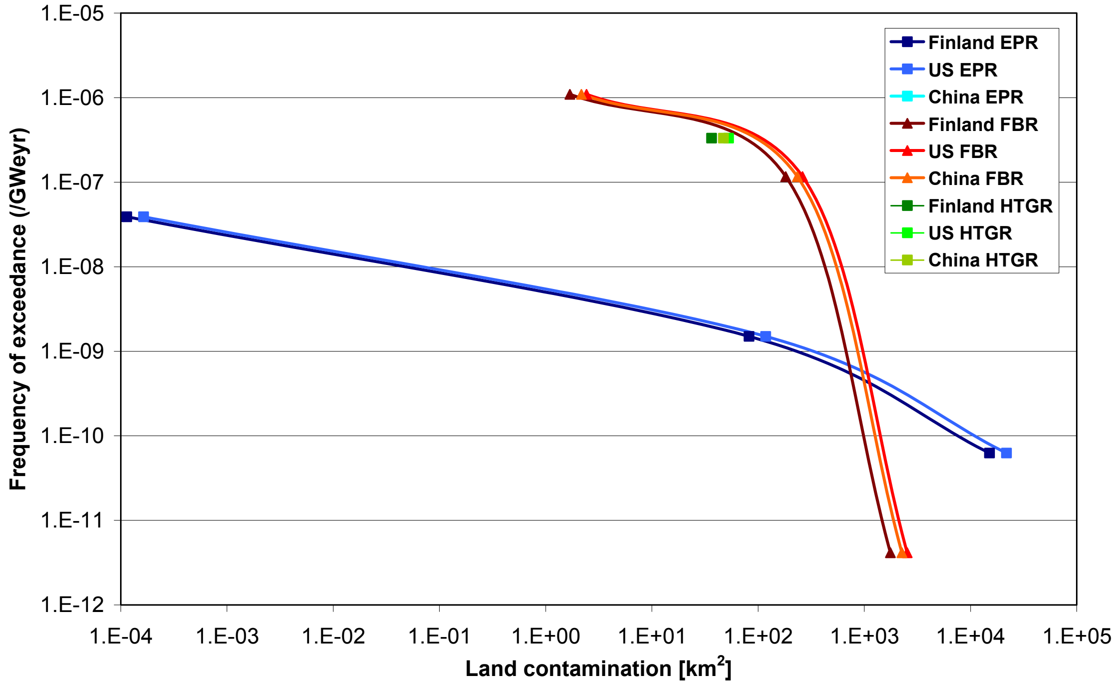

Figure 21: F-N curves for land contamination of the EPR, FBR and HTGR advanced designs in Finland, USA and China.

3.3 Renewable energy technologies

3.3.1 Wind power

For onshore wind power there exist specific accident databases such as the Windpower Death Database (Gipe, 2010) and the Wind Turbine Accident Compilation (Caithness Windfarm Information Forum, 2010). Fatal accidents with onshore wind power have resulted in one or two fatalities only so far, i.e. no severe accident has been recorded according to the severe accident definition used for the database ENSAD. In previous studies by PSI, fatality rates for onshore wind power were estimated for currently operating and future technologies (Hirschberg et al., 2004b; Roth et al., 2009). For the current study fatal accidents in Germany in the period 1975-2010 were considered to provide a fatality risk estimate (see chapter 2.2.4)

Furthermore, generic risk contours for wind turbines are given in Braam et al. (2005)[16], depending on the size of the turbine for different risk groups such as persons (p16.), high voltage cables, transport and transport of hazardous substances.

For offshore wind generation the same accident databases already mentioned above can be used. However, up to now there were only two fatal accidents during construction of offshore wind farms in the UK, whereas two fatal accidents in the USA occurred during research activities. Therefore, the current fatality rate estimate for offshore wind power is based on the rather limited UK experience only (see chapter 2.2.4).

[16] Only available in Dutch

Several research projects investigate risks related to offshore wind parks, dealing with structural resistance of wind turbines to strong wind and collisions. Environmental impact assessments investigate danger to birds and bats, consequences to human life however are not explicitly considered.

Possible risks include the collision of ships with turbines. Recent studies called “safeship” and “safety at sea” co-financed by the European Community investigated this risk and possible mitigation measures. These studies give collision frequencies and analyze consequences, for an actual wind farm and a model wind park respectively. Frequencies are found to be strongly site dependent. Investigated are measures to reduce the collision risk by rerouting shipways, electronic signaling through ship to ship collision warning system AIS or improved optical signaling as well as mitigation measures by fendering, i.e. cushioning turbines.

With the accelerating expansion of offshore wind parks, the risk analysis of ship collisions with offshore wind turbines and the subsequent implementation of risk reducing measures becomes an import aspect; although the frequency of occurrence is low, the consequences could be large (Biehl and Lehmann, 2006; Christensen et al., 2001).

3.3.2 Photovoltaics

The photovoltaic (PV) industry experienced strong annual growth rates in the past decade, and it is generally viewed as a clean and low-risk technology. Recent studies have mainly addressed the areas of Life Cycle Assessment (LCA) of PV electricity generation, health and environmental hazards of PV production, and various risk assessment aspects in the fabrication of PV modules. For example several studies were conducted concerning the health and environmental impacts of the PV fabrication (e.g., Ladwig and ten Hope, 2003; Mulvaney, 2009). Furthermore, risks associated with the use of hazardous materials in the PV manufacture have been addressed (Fthenakis and Kim, 2010; Fthenakis et al., 2006). As a consequence, the concern about the risk associated with the production of PV modules is slowly coming into public focus. However, there is still a need to further improve the methodological framework for PV risk estimation to enable a consistent comparison between PV and other energy sectors.

Therefore, within WP 5.7 of the SECURE project a dedicated assessment of PV accident risks was performed, which is described in detail in the report by Zapata (2010).

The estimated fatality rate obtained within the SECURE project is reported in chapter 4, whereas the reminder of this chapter provides a summary of the overall PV assessment undertaken.

In order to investigate deeply the accident risks associated with PV cell manufacturing particularly for the public, the different steps involved in the fabrication of the most commercial photovoltaic technologies were analyzed. The technologies involved in the study were: monocrystalline silicon, polycrystalline silicon, a-Si, CdTe and CIGS.

Several hazardous materials used during the production process were identified. Some of these hazardous materials, such as silane and trichlorosilane (TCS), are highly explosive. Others such as chlorine, hydrogen selenide and hydrogen fluoride are extremely toxic. Silane is responsible for most of the historical accidents that have occurred so far in photovoltaic facilities (Biello, 2010; Cheyney, 2008), while chlorine has been investigated intensively and it is recognized to be very hazardous to the society (Bernatik et al., 2008; Brown et al., 2000; Scenna and Santa Cruz, 2005).

Furthermore, scenario analysis was used to estimate site-specific consequences for the release of selected hazardous materials, which were based on the worst case scenario as defined by RMP (US EPA, 2010). First, the consequences of the worst case scenario were estimated for several facilities reporting the use of the studied chemicals. The calculations are done using the software RMP comp (US EPA, 2009), which is especially developed for this purpose by the United States Environmental Protection Agency (US EPA). Second, several scenarios were simulated to analyze potential off-site consequences of an accidental release from selected RMP facilities involving the most hazardous materials, namely hydrogen selenide, diborane and trichlorosilane. The simulations were performed utilizing ALOHA (Areal Locations of Hazardous Atmospheres), which is a software designed to be used as a guide during a chemical emergency (US EPA, 2007).

These results suggest that the risk associated with the PV industry is by far lower than those associated with the other industries that handle these hazardous chemicals. The majority of the studied chemicals are widely used in other applications and the PV industry represents only a small share in the demand of these substances. Other chemicals that are fabricated almost specifically for the use in the PV and electronics industry report only a few accidents with localized effects that do not affect the surrounding community. Nevertheless, these results can change in the future, depending on the evolution of the PV market and the influence of new PV technologies.

Nevertheless, these results can change in the future, depending on the evolution of the PV market. In fact it is expected that by 2020 the market share of silicon solar cell will reduce to nearly 50 %. At the same time it is estimated that the CIGS solar cells will become the leader among the thin film technologies accounting for approximately 15 % of the total PV market. Consequently the risk due to the use of hydrogen selenide could gain more importance. Furthermore new concepts to manufacture PV cells that make use of nanotechnology could bring along new hazards that cannot be assessed at the moment.

To be able to compare the risk inherent in the production of a solar cell with the risk in other energy technologies, it would be necessary to know the precise amount of the hazardous chemicals used per produced cell. The risk from the different chemicals could then be aggregated and normalized to the energy the cell will produce over a lifetime. Unfortunately it was not possible to obtain the necessary data on the precise amounts as processes are not published. Also databases designed for lifecycle assessment are of limited use as process chemicals that are recycled and not used up in production are not represented.

Therefore it is necessary to make the PV industry aware of the importance to cooperate in a risk assessment study. This kind of study could help to enhance the credibility of this industry and to maintain the good public opinion, which has been one of the most important elements that influenced the ever-growing PV market.

3.3.3 Biomass

Previous studies by PSI have estimated fatality rates and maximum consequences of severe accidents for several biomass technologies (Burgherr et al., 2008; Roth et al., 2009). Within SECURE only Combined Heat & Power (CHP) biogas was considered, using the approach described in chapter 2.2.4, and reported in chapter 4.

3.3.4 Geothermal

Almost everywhere geothermal energy can be used directly for heating by exploiting small temperature differences of a few degrees between the surface temperature and the ground by cycling water through the ground and extracting the energy with heat pumps.

To efficiently generate electricity, however, larger temperature gradients are needed. Traditionally, geothermal energy has been exploited in active geological regions where hot water or steam can be found close to the surface and directly extracted and used as heat source or to produce electricity. Examples are Iceland, the Philippines, Chile, Italy, New Zealand, and the United States. Geographically this resource is limited.

More recently, efforts are under way to extract geothermal energy from dry rock, a resource that is in principle available is essentially available worldwide, and the necessary depths vary from 3 to 10 km so that more areas become available with advancing techniques to drill deeper. To extract the heat, water is forced through cracks in rock and subsequently used for heat and power generation.

Current larger projects designed for more than 1 MW include Soultz-sous-Forêts (France), Landau and Unterhaching (Germany), Basel (Switzerland) that has been abandoned (see below), and Cooper Basin (Australia).

Risks of such Enhanced Geothermal Systems (EGS) include occupational hazards due to geothermal gases and heat, as well as induced seismicity. Induced seismicity has already been the cause of delays, and two major EGS projects in the USA (California) and Switzerland (Basel) were even permanently abandoned (Dannwolf and Ulmer, 2009; Majer et al., 2007; Oppenheimer, 2010).

So called micro seismicity occurs during the drilling phase as well as during production. In the drilling phase it is used to map the way of the water pressed into the ground through the cracks that then determines the location of the second hole to recover the steam water.

One of the fist commercial projects for deep geothermal heat extraction was approved in 2003 Basel, Switzerland. This demonstration project was designed to deliver 6 MW power and 17 MW heat by heating up water to 200 degrees in a depths of 5000m. The project was stopped in 2006 after it provoked and earth quake with magnitude 3.4, creating damage of around 40 million CHF (insured).

The project was finally abandoned in 2009 as the financial risk of damages in the densely populated Basel area is too high. Table 16 gives an overview of triggered earth quakes by geothermal drilling.

Table 16: Induced seismicity in geothermal drillings: largest events world wide (Bromley and Mongillo, 2008).

Site	Maximum magnitude
Cooper Basin, Australia	3.7
Basel, Switzerland	3.4
Rosemanowes, UK	3.1
Soultz-sous-Forêts, France	2.9

4 Risk indicators

This chapter provides a summary and discussion of the risk indicators calculated as detailed in previous chapters of this report. Table 17 shows results of risk indicators R1 to R3 for the various fossil chains, hydro power, nuclear energy, and new renewable energy technologies in OECD, EU 27 and non-OECD countries.

Table 17 Comparison of risk indicators R1 to R3 for fossil chains, hydro power, nuclear energy, and new renewables in OECD, EU 27 and non-OECD countries. Values in [x]are discussed in the text.

	Severe accident risk indicators		
Energy chain	R1	R2	R3
Coal, OECD (1970-2008)	7.19E-2	120	198
Coal, EU 27 (1970-2008)	1.20E-1	64	68
Coal, non-OECD w/o China (1970-2008)	1.08E+0	[990]	[2554]
Coal, China (1994-1999)	5.92E+0	284	--
Coal, China (2000-2009)	3.14E+0	215	--
Oil, OECD (1970-2008)	4.10E-2	97	334
Oil, EU 27 (1970-2008)	2.04E-2	67	122
Oil, non-OECD (1970-2008)	1.69E+0	3834	[15365]
Natural Gas, OECD (1970-2008)	4.99E-2	77	274
Natural Gas, EU 27 (1970-2008)	5.60E-2	32	38
Natural Gas, non-OECD (1970-2008)	2.02E-1	287	821
Hydro, OECD (1970-2008)	2.70E-3	14	--
Hydro, EU 27 (1970-2008)	8.53E-2	116	--
Hydro non-OECD (1970-2008)	2.13E+0	22982	[48476]
Hydro non-OECD w/o Banqiao/Shimantan (1970-2008)	9.45E-1	3125	[15231]
Nuclear, Gen. II (PWR, Switzerland)	7.26E-3	10240	--
Nuclear, Gen III (EPR, Switzerland)	1.07E-5	48800	--
Nuclear, non-OECD (Chernobyl)	3.02E-2	33000	--
PV (crystalline Silicon)	2.45E-4	5	--
Wind Onshore (Germany)	1.89E-3	5	--
Wind Offshore (UK)	6.41E-3	10	--
Biomass: CHP Biogas	1.49E-2	10	--
Geothermal: EGS	1.74E-3	7	--

Color code:

R1, R2 and R3 were calculated according to the approach described in chapter 2.4.

Coal China was based on data from the China Energy Technology Program (CETP) for the period 1994-1999, and data from the China Coal Industry Yearbook (CCYI) for the years 2000-2009 (compare Table 3, chapter 2.2.4).

For hydropower in OECD and EU 27 the available data were too scarce to calculate R1 to R3 according to chapter 2.5, and thus were directly estimated from the available data.

For nuclear R1 and R2 are PSA-based. R3 is not estimated since based on PSA R2 already corresponds to consequences of highest credible release of radioactivity.

For new renewable technologies R1 and R2 were calculated according to Table 3 (see chapter 2.2.4). Estimating R3 is not feasible since the necessary statistical basis is not available. Substantially higher consequences than those provided for R2 cannot be excluded, particularly for PV and geothermal.

As already discussed in chapter 3.1.2 the values of R2 and R3 for "coal non-OECD w/o China" are rather high, and thus using the historical maximum of 434 fatalities of the most severe accident that occurred in the period 1970-2008 would be a more conservative estimate. Similarly the estimated R3 for "oil non-OECD" is much higher than the most deadly accident in the years 1970-2008, which resulted in 4386 fatalities (1987, Philippines). Similarly, for hydropower in non-OECD countries, the remarks made on the estimate of R3 in chapter 3.1.2 should be taken into account.

Concerning hydropower in OECD and EU 27 the limited historical experience points towards low maximum credible consequences. However, analyses of a hypothetical dam failure based on an empirical study and on a theoretical model indicate that results are dependent on the model chosen and the pre-warning time among various other factors (Hirschberg et al., 1998; Rüst, 1997). For the total failure of the chosen large Swiss dam the estimated death toll with 0 min warning time would be between 7125 and 11050 fatalities, but would be strongly reduced to 2-27 fatalities if pre-warning time is 2 hours. Additionally, potential consequences have to be viewed under consideration of the frequency of occurrence of such an event, which for the example of Swiss dams is in the range 10^{-5} to 10^{-4} events per dam year (Hirschberg et al., 1998).

For nuclear energy a PSA-based approach is mandatory because results are strongly dependent on the chosen reference reactor design and the actual location and operating environment of the plant, which has been shown by the results of previous projects for PWR and EPR plants located in different countries (Burgherr et al., 2008; Roth et al., 2009).

For fossil energy chains and hydropower, OECD and EU 27 countries generally show lower fatality rates and maximum consequences than in non-OECD. Among fossil chains, natural gas performs best with respect to all three indicators. The fatality rate for coal China (1994-1999) is distinctly higher than for the rest of non-OECD (Burgherr and Hirschberg, 2007; Hirschberg et al., 2003a; Hirschberg et al., 2003b), however, data for 2000-2009 suggest that China slowly approaches the rest of non-OECD. Among large centralized technologies, western style nuclear and hydro power plants have the lowest fatality rates, but at the same time the consequences of extreme accidents can be very large. Experience with hydro in OECD countries points to very low fatality rates, comparable to the representative PSA-based results obtained for nuclear power plants, whereas in non-OECD dam failures can claim large numbers of victims. For nuclear energy, new Generation III reactors are expected to have significantly lower fatality rates than currently operating power plants, but maximum consequences could increase. Finally, the Chernobyl accident is neither representative for operating plants in OECD using other and safer technologies, nor today's situation in non-OECD countries (Hirschberg et al., 2004; Burgherr and Hirschberg, 2008). In contrast, decentralized renewable technologies exhibit distinctly lower fatality rates than fossil chains, and are fully comparable to hydro and nuclear in highly developed countries. Concerning maximum consequences, new renewables clearly outperform all other technologies because their decentralized nature strongly limits their catastrophic potential. However, it is important to assess additional risk factors of renewables that are currently difficult to fully quantify, but could potentially impede their large scale deployment.

The calculated risk indicators provide valuable insights and conclusions by themselves, but furthermore they provided essential input to the Multi-Criteria Decision Analysis (MCDA) performed within WP6, Task 2, which analyzed and compared the various policy scenarios developed by the POLES model (WP 4). For the SECURE MCDA three indicators from WP 5.7 were used, i.e. from this report (D5.7.2a) the fatality rate (R1) and maximum consequences (R2) indicators, and from D5.7.2b a terrorist risk indicator.

Risk indicators can on the one hand contribute to decisions on / formulation of energy policies at different spatial scales (local/regional, national, supranational) and for different technology portfolios, and on the other provide essential inputs into MCDA, the results of which can support stakeholders to assess and better understand the sustainability performance of current and future energy technologies or scenarios.

5 Conclusions and policy recommendations

The energy sector is both a key resource and a critical infrastructure for the economy that forms the backbone of today's society, its goods and services. Therefore, the comparative assessment of accident risks is a pivotal aspect in a comprehensive evaluation of energy security concerns.

Historically, only consequences of severe accidents caused by technological or natural hazards have been focused on; however in the past decade the potentially disastrous consequences of purposed malicious actions, ranging from vandalism to sabotage and terrorist attacks, emerged as additional topics calling for attention.

Effects of severe accidents and terrorist attacks are interrelated to a variety of other energy security facets including vulnerability to transient or long-term physical disruptions to import supplies, geopolitical dependencies due to imported resources, price fluctuations as a result of single events with extremely large consequences, increased likelihood for accidents due to infrastructure ageing and underinvestment, and enhanced awareness of so-called Natech disasters because of global climate change.

The primary objectives of Work Package 5.7 were threefold: (1) state-of-the-art comparative assessment of severe accidents in major energy chains (Deliverable D5.7.2a, public), (2) development and application of a methodology for the assessment of the terrorist threat to major energy infrastructures (Deliverable D5.7.2b, confidential), and (3) evaluation of risk aversion aspects of severe accidents (Deliverable D5.7.3, public).

The PSI database ENSAD (Energy-related Severe Accident Database) provides the quantitative basis for the objective and comparative risk assessment of currently operating technologies as well as for trend extrapolation for future technologies. For nuclear power the application of Probabilistic Safety Assessment is mandatory to account for decisive and plant- and location-specific differences, whereas for new renewables limited experience needs to be complemented by expert judgment.

Among centralized large-scale technologies in industrialized countries estimated expected accident risks are by far lowest for hydro and nuclear while fossil fuel chains exhibit the highest risks. On the other hand the maximum credible consequences of low frequency hypothetical severe accidents, which can be viewed as a measure of risk aversion, are by far highest for nuclear and hydro (given high population density down-stream from the dam), in the middle range for fossil chains and very small for solar and wind. For nuclear, the maximum consequences are expected strongly reduced for the GEN IV plant designs (FBR, HTR) compared with GEN III (EPR).

Severe accidents affecting energy infrastructure can be costly and can affect other critical infrastructures due to dependencies on energy supply. In most cases, the effects of severe accidents on security of supply are of short-term character due to redundancies. Severe nuclear accidents could cause a long-term problem in electricity supply primarily due to potential secondary effects of such accidents, negatively affecting nuclear energy in general. There are also concerns for hydro, particularly in small countries with relatively few large dams and high dependence on their output.

Decentralized energy systems are less sensitive to the issue of severe accidents than the centralized ones.

Allocating appropriate resources for maintaining high safety standards of nuclear power plants and hydro dams is of central importance also for security of supply.

6 Acknowledgements

This study was performed as part of the Project SECURE (Security of Energy Considering its Uncertainty, Risk and Economic Implications, Project No. 213744) of the 7th Framework Programme of European Community.

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Appendix 1 – EPR, LMFBR and HTR source terms

Tables A1 to A3 provide detailed results for the consequences from radionuclides released in the different release classes depending on the nuclear power plant type (NPP) and country location. The numbers marked in green and red show the largest absolute consequences that are to be expected.

Table A1: Early fatalities for EPR, LMFBR and HTGR in Finland (TVO), USA (TMI) and China (Chingdao).

Site	NPP type	Release class	Radionuclide groups									ECF Total
			Xe	CsI	CsOH	Te	Sr	Ru	La	Ce	Ba	
Chingdao	EPR	RC1	5.66E-05	2.65E-06	1.18E-08	3.97E-07	7.32E-07	2.93E-08	5.19E-08	5.44E-08	3.70E-07	6.09E-05
		RC4	7.28E-01	3.00E+00	8.72E-03	3.53E-01	7.23E-01	2.68E-02	4.76E-02	4.99E-02	3.66E-01	5.31E+00
		RC6	8.01E-01	2.60E+03	1.69E+00	5.67E+01	9.39E+01	3.91E+00	6.92E+00	7.26E+00	4.75E+01	2.81E+03
	HTGR	RC6	9.27E-02	1.90E-01	5.80E-03	2.50E-01	6.46E-01	5.59E-02	4.96E-02	3.12E-01	3.26E-01	1.93E+00
	LMFBR	RC1	5.06E-02	3.45E-02	1.76E-04	1.36E-02	1.17E-02	3.05E-03	1.35E-02	2.84E-04	5.93E-03	1.33E-01
		RC4	4.95E-01	5.87E+00	1.76E-02	1.64E+00	2.35E+00	4.58E-01	1.35E+00	2.84E-02	1.19E+00	1.34E+01
		RC6	5.06E-01	2.70E+02	1.76E-01	1.36E+01	1.76E+01	4.58E+00	1.89E+01	8.51E-01	8.90E+00	3.36E+02
TVO	EPR	RC1	2.91E-06	1.36E-07	6.08E-10	2.04E-08	3.77E-08	1.51E-09	2.67E-09	2.80E-09	1.90E-08	3.13E-06
		RC4	0.037441	1.55E-01	4.49E-04	1.82E-02	3.72E-02	1.38E-03	2.45E-03	2.57E-03	1.88E-02	2.73E-01
		RC6	0.041185	1.33E+02	8.68E-02	2.92E+00	4.83E+00	2.01E-01	3.56E-01	3.73E-01	2.44E+00	1.45E+02
	HTGR	RC6	4.77E-03	9.76E-03	2.98E-04	1.28E-02	3.32E-02	2.88E-03	2.55E-03	1.60E-02	1.68E-02	9.91E-02
	LMFBR	RC1	2.60E-03	1.77E-03	9.04E-06	7.01E-04	6.04E-04	1.57E-04	6.95E-04	1.46E-05	3.05E-04	6.86E-03
		RC4	2.55E-02	3.02E-01	9.04E-04	8.41E-02	1.21E-01	2.35E-02	6.95E-02	1.46E-03	6.10E-02	6.89E-01
		RC6	2.60E-02	1.39E+01	9.04E-03	7.01E-01	9.06E-01	2.35E-01	9.73E-01	4.37E-02	4.58E-01	1.73E+01
TMI	EPR	RC1	2,26E-05	1,06E-06	4,73E-09	1,59E-07	2,93E-07	1,17E-08	2,08E-08	2,18E-08	1,48E-07	2,44E-05
		RC4	2,91E-01	1,20E+00	3,49E-03	1,41E-01	2,89E-01	1,07E-02	1,90E-02	2,00E-02	1,46E-01	2,12E+00
		RC6	3,20E-01	1,04E+03	6,75E-01	2,27E+01	3,76E+01	1,56E+00	2,77E+00	2,90E+00	1,90E+01	1,13E+03
	HTGR	RC6	3,71E-02	7,59E-02	2,32E-03	9,99E-02	2,58E-01	2,24E-02	1,98E-02	1,25E-01	1,31E-01	7,71E-01
	LMFBR	RC1	2,02E-02	1,38E-02	7,03E-05	5,45E-03	4,70E-03	1,22E-03	5,41E-03	1,13E-04	2,37E-03	5,34E-02
		RC4	1,98E-01	2,35E+00	7,03E-03	6,54E-01	9,39E-01	1,83E-01	5,41E-01	1,13E-02	4,75E-01	5,36E+00
		RC6	2,02E-01	1,08E+02	7,03E-02	5,45E+00	7,04E+00	1,83E+00	7,57E+00	3,40E-01	3,56E+00	1,34E+02

Table A2: Late fatalities for EPR, LMFBR and HTGR in Finland (TVO), USA (TMI) and China (Chingdao).

Site	NPP type	Release class	Radionuclide groups									LCF Total
			Xe	CsI	CsOH	Te	Sr	Ru	La	Ce	Ba	
Chingdao	EPR	RC1	1,25E-02	3,94E-05	3,03E-04	1,11E-05	1,73E-05	1,04E-06	1,63E-06	3,30E-06	2,62E-05	1,29E-02
		RC4	1,61E+02	2,63E+01	2,23E+02	9,84E+00	1,71E+01	9,55E-01	1,50E+00	3,02E+00	2,59E+01	4,69E+02
		RC6	1,77E+02	4,92E+03	4,33E+04	1,58E+03	2,21E+03	1,39E+02	2,18E+02	4,39E+02	3,36E+03	5,63E+04
	HTGR	RC6	2,04E+01	2,82E+00	1,49E+02	6,96E+00	1,52E+01	1,99E+00	1,56E+00	1,89E+01	2,31E+01	2,40E+02
	LMFBR	RC1	1,12E+01	5,13E-01	4,51E+00	3,80E-01	2,77E-01	1,09E-01	4,26E-01	1,72E-02	4,20E-01	1,78E+01
		RC4	1,09E+02	5,13E+01	4,51E+02	4,56E+01	5,54E+01	1,63E+01	4,26E+01	1,72E+00	8,40E+01	8,57E+02
		RC6	1,12E+02	5,13E+02	4,51E+03	3,80E+02	4,15E+02	1,63E+02	5,96E+02	5,15E+01	6,30E+02	7,37E+03
TVO	EPR	RC1	1,34E-03	4,22E-06	3,24E-05	1,18E-06	1,85E-06	1,12E-07	1,75E-07	3,53E-07	2,81E-06	1,38E-03
		RC4	1,72E+01	2,81E+00	2,39E+01	1,05E+00	1,83E+00	1,02E-01	1,61E-01	3,24E-01	2,77E+00	5,02E+01
		RC6	1,89E+01	5,27E+02	4,63E+03	1,69E+02	2,37E+02	1,49E+01	2,33E+01	4,71E+01	3,60E+02	6,03E+03
	HTGR	RC6	2,19E+00	3,02E-01	1,59E+01	7,45E-01	1,63E+00	2,13E-01	1,67E-01	2,02E+00	2,47E+00	2,57E+01
	LMFBR	RC1	2,60E-03	1,77E-03	9,04E-06	7,01E-04	6,04E-04	1,57E-04	6,95E-04	1,46E-05	3,05E-04	6,86E-03
		RC4	2,55E-02	3,02E-01	9,04E-04	8,41E-02	1,21E-01	2,35E-02	6,95E-02	1,46E-03	6,10E-02	6,89E-01
		RC6	2,60E-02	1,39E+01	9,04E-03	7,01E-01	9,06E-01	2,35E-01	9,73E-01	4,37E-02	4,58E-01	1,73E+01
TMI	EPR	RC1	3,59E-03	1,13E-05	8,71E-05	3,18E-06	4,97E-06	3,00E-07	4,70E-07	9,48E-07	7,54E-06	3,71E-03
		RC4	4,62E+01	7,56E+00	6,43E+01	2,83E+00	4,91E+00	2,75E-01	4,31E-01	8,69E-01	7,44E+00	1,35E+02
		RC6	5,08E+01	1,42E+03	1,24E+04	4,54E+02	6,37E+02	4,00E+01	6,27E+01	1,26E+02	9,66E+02	1,62E+04
	HTGR	RC6	5,88E+00	8,12E-01	4,28E+01	2,00E+00	4,38E+00	5,73E-01	4,49E-01	5,43E+00	6,64E+00	6,90E+01
	LMFBR	RC1	3,21E+00	1,48E-01	1,30E+00	1,09E-01	7,97E-02	3,12E-02	1,23E-01	4,94E-03	1,21E-01	5,12E+00
		RC4	3,15E+01	1,48E+01	1,30E+02	1,31E+01	1,59E+01	4,68E+00	1,23E+01	4,94E-01	2,42E+01	2,47E+02
		RC6	3,21E+01	1,48E+02	1,30E+03	1,09E+02	1,19E+02	4,68E+01	1,72E+02	1,48E+01	1,81E+02	2,12E+03

Table A3: Land contamination for EPR, LMFBR and HTGR in Finland (TVO), USA (TMI) and China (Chingdao).

Site	NPP type	Release class	Radionuclide groups									km² Total
			Xe	CsI	CsOH	Te	Sr	Ru	La	Ce	Ba	
Chingdao	EPR	RC1	0,00E+00	7,06E-05	6,28E-05	3,92E-06	3,92E-06	6,94E-08	1,49E-07	1,38E-07	4,72E-06	1,46E-04
		RC4	0,00E+00	4,71E+01	4,64E+01	3,49E+00	3,87E+00	6,36E-02	1,37E-01	1,26E-01	4,66E+00	1,06E+02
		RC6	0,00E+00	8,82E+03	8,97E+03	5,60E+02	5,03E+02	9,25E+00	1,99E+01	1,84E+01	6,06E+02	1,95E+04
	HTGR	RC6	0,00E+00	5,05E+00	3,08E+01	2,47E+00	3,46E+00	1,32E-01	1,43E-01	7,90E-01	4,16E+00	4,71E+01
	LMFBR	RC1	0,00E+00	9,19E-01	9,35E-01	1,35E-01	6,28E-02	7,23E-03	3,89E-02	7,18E-04	7,57E-02	2,17E+00
		RC4	0,00E+00	9,19E+01	9,35E+01	1,62E+01	1,26E+01	1,08E+00	3,89E+00	7,18E-02	1,51E+01	2,34E+02
		RC6	0,00E+00	9,19E+02	9,35E+02	1,35E+02	9,43E+01	1,08E+01	5,44E+01	2,15E+00	1,14E+02	2,26E+03
TVO	EPR	RC1	0,00E+00	5,48E-05	4,87E-05	3,04E-06	3,04E-06	5,38E-08	1,16E-07	1,07E-07	3,67E-06	1,14E-04
		RC4	0,00E+00	3,65E+01	3,60E+01	2,71E+00	3,00E+00	4,94E-02	1,06E-01	9,81E-02	3,62E+00	8,21E+01
		RC6	0,00E+00	6,85E+03	6,96E+03	4,35E+02	3,90E+02	7,18E+00	1,55E+01	1,43E+01	4,70E+02	1,51E+04
	HTGR	RC6	0,00E+00	3,92E+00	2,39E+01	1,92E+00	2,68E+00	1,03E-01	1,11E-01	6,13E-01	3,23E+00	3,65E+01
	LMFBR	RC1	0,00E+00	7,13E-01	7,25E-01	1,05E-01	4,88E-02	5,61E-03	3,02E-02	5,57E-04	5,88E-02	1,69E+00
		RC4	0,00E+00	7,13E+01	7,25E+01	1,25E+01	9,75E+00	8,41E-01	3,02E+00	5,57E-02	1,18E+01	1,82E+02
		RC6	0,00E+00	7,13E+02	7,25E+02	1,05E+02	7,32E+01	8,41E+00	4,22E+01	1,67E+00	8,82E+01	1,76E+03
TMI	EPR	RC1	0,00E+00	7,90E-05	7,03E-05	4,39E-06	4,39E-06	7,77E-08	1,67E-07	1,54E-07	5,29E-06	1,64E-04
		RC4	0,00E+00	5,27E+01	5,19E+01	3,91E+00	4,33E+00	7,12E-02	1,53E-01	1,41E-01	5,22E+00	1,18E+02
		RC6	0,00E+00	9,88E+03	1,00E+04	6,27E+02	5,63E+02	1,04E+01	2,23E+01	2,06E+01	6,78E+02	2,18E+04
	HTGR	RC6	0,00E+00	5,66E+00	3,45E+01	2,76E+00	3,87E+00	1,48E-01	1,60E-01	8,84E-01	4,66E+00	5,27E+01
	LMFBR	RC1	0,00E+00	1,03E+00	1,05E+00	1,51E-01	7,03E-02	8,09E-03	4,35E-02	8,04E-04	8,48E-02	2,43E+00
		RC4	0,00E+00	1,03E+02	1,05E+02	1,81E+01	1,41E+01	1,21E+00	4,35E+00	8,04E-02	1,70E+01	2,62E+02
		RC6	0,00E+00	1,03E+03	1,05E+03	1,51E+02	1,06E+02	1,21E+01	6,09E+01	2,41E+00	1,27E+02	2,53E+03