Versicherungsforen Leipzig

Study

Calculating a risk-appropriate insurance premium to cover third-party liability risks that result from operation of nuclear power plants

Commissioned by the
German Renewable Energy Federation (BEE)

Leipzig, 1 April 2011

Authors:

Benjamin Günther

Torsten Karau

Eva-Maria Kastner

Dr. Walter Warmuth

Imprint:

Versicherungsforen Leipzig GmbH
Querstraße 16, 04103 Leipzig

Tel.: +49 (0) 341 / 1 24 55-0

Fax: +49 (0) 341 / 1 24 55-99

www.versicherungsforen.net

Managing directors: Markus Rosenbaum, Jens Ringel

Leipzig District Court, Commercial Register Number: HRB 25803

Summary

The nuclear accident at Japan’s Fukushima Nuclear Power Plant in March 2011 and the debate surrounding the life extension of Germany’s nuclear power plants are the two main factors that have reignited the debate over the "residual risks" associated with this form of energy production. One of the questions raised during this discussion concerns adequate financial security for the licensees[1] of these power plants in the event of a nuclear disaster. Until now the licensees have been subject to mandatory financial coverage of €2.5 billion for potential compensation payments that result from damage claims following incidents or accidents at a nuclear power plant. They are also entitled to up to €300 million in public funds from the EU.

The present study calculates the hypothetical premium for liability insurance that would cover a claim resulting from a nuclear disaster linked to an incident or accident at a nuclear power plant. It is based on previously published studies of the likelihood and the potential amount of damage of such events. In addition, the authors provide their own assumptions and resulting assessments for these two risk-determining factors in the calculations.

These calculations yield a mean total payable sum insured (limit of liability) of around €6,090 billion in the event of a nuclear disaster. Depending on the underlying probability of occurrence of such a claim, the annual premium would range between €0.01 and €305.83. However, as it would not be realistic to provide the amount insured over 1,000 years, the study presumes other payout periods. For instance, the study calculates that paying out the total amount insured over a period of 100 years would entail an annual insurance premium of €19.5 billion for every insured nuclear power plant over the entire period. Such a period cannot be considered realistic given the remaining lifespans of German nuclear power plants and the normal plant lifespan of 25 to 40 years. Shorter policies, however, lead to an exponential jump in annual premiums.

If consumers of electricity generated by nuclear power were to carry the cost of remedying the damage caused by such an event (internalisation of external costs), the apportionment of costs (based on the insurance premium) would require a net price increase for atomic energy of €0.139 to €2.36 per kWh for a duration of 100 years, based on a payout period of 100 years. With a payout period of ten years this net price increase would range from €3.96 to €67.3 per kWh.

---

[1] The law makes licensees liable for damages resulting from a nuclear incident. For this reason, the current study uses the term licensee rather than operator.

The calculations and scenarios presented, which are based on many assumptions, show that the funds currently available for protecting licensees against the risks connected with a nuclear power plant would certainly only cover a small portion of the compensation payments due in the event of a nuclear disaster. The remaining costs over and above that would be carried by the state and/or the public.

Versicherungsforen Leipzig GmbH

Versicherungsforen Leipzig is a spin-off of the University of Leipzig. For 11 years now, Versicherungsforen Leipzig has served as a bridge between insurance sciences and insurance practice, with the aim of promoting and sustainably supporting the transfer of technical knowledge, particularly within the insurance industry.

Versicherungsforen Leipzig is equally committed to both the methodology of science and the practical concerns of developing and providing knowledge that is strongly application-orientated. It focuses on topics that

- have high relevance for insurance practice,
- are forward-thinking and
- have a high market significance.

Versicherungsforen staff has academic training in insurance, with specialisations in business administration, law, computer science and mathematics. They continuously and intensively address current industry topics. Their interdisciplinary scientific perspective and practice-orientated approach provide a foundation for productive collaboration with insurance professionals. This manifests itself in Versicherungsforen Leipzig’s network of partners, for example, which comprises around 160 companies from the insurance industry.

Ongoing research and project involvement has enabled Versicherungsforen Leipzig to pool its expertise in nearly every stage of the value chain, from product design and product management to risk management, sales, customer relationship management, contract and inventory management, and loss and performance management for insurance companies. In addition, Versicherungsforen Leipzig specialises in mathematical models for finance and insurance and their application-specific implementation and simulation. An internal structure consisting of the three competence teams "Finances and Risk Management", "Processes, IT and Organisation" and "Insurance Marketing and Insurance Sales" as well as cross-team collaboration within certain thematic groups enables us to develop specialised knowledge and solutions in every subject area.

Competence teams from Versicherungsforen Leipzig also work closely with other institutions. Its associate companies, such as Energieforen Leipzig (energy) and Gesundheitsforen Leipzig (health), collaborate on selected topics to find solutions to wide-ranging issues. The Analysis and Mathematics group at Gesundheitsforen Leipzig under Dr. Walter Warmuth provides comprehensive analytics for statistics, econometrics, probability theory, actuarial science and stochastic and predictive modelling for projects that involve several different companies.

Table of contents

Table of figures

Introduction

On 11 March 2011, the Earth shook with a magnitude of 9.0 off the Pacific Coast of Japan. It was the strongest earthquake ever measured in the country. The epicentre was approximately 370 km northeast of Tokyo and 130 km east of Sendai. The quake triggered a tsunami that struck the coast of Sendai and Sanriku with waves up to 10 metres high. The flood waves that hit the Fukushima Nuclear Power Plant were only 7 m high, but the walls that protected the site had only been designed to withstand waves of up to 5.70 m. The reactor protection system shut down Units 1 to 3 immediately after the quake; Units 4 to 6 had already been shut down for maintenance. The electricity supply switched to emergency diesel-powered generators, but their fuels tanks, located directly on the seashore, had been destroyed by the tsunami. Battery-powered electricity also failed after a short time as a result of general damage to the site's electrical system. The failure of the cooling system led to a dramatic increase in temperature in the reactor cores and spent fuel pools and damaged the fuel elements. The hot coolant water underwent a fission reaction with the zirconium in the fuel rod cladding and created hydrogen, which triggered several explosions and fires. This in turn caused major damage to the buildings housing Units 1 to 4. Radioactive particles and radiation escaped.

It is already becoming clear [as of 1 April 2011] that the Japanese government and Japanese taxpayers will have to pay for a large portion of the damages that have resulted from the release of radioactivity.[2] The costs of unfolding risks stemming from the peaceful use of atomic energy, which, based on the principle of best-possible security and risk management, were considered to be practically ruled out and therefore merely hypothetical, are thus being socialised to a large extent.

In Germany, a chain of events such as those that have occurred in Japan is considered impossible. Yet a great deal of insight has been gained into existing risks and new risks since the first nuclear power plants were built in Germany, although this led only to little or no public discussion of how to deal with these developments. The attacks on the World Trade Center on 11 September 2001 are the clearest example of the risk of terrorism that had previously been dismissed as unrealistic, and one that some of Germany's nuclear power plants are insufficiently or not at all protected against.

---

[2] [Obiko Pearson/Bandel 2011]

When this study began in January 2011, no one could have predicted that the debate on nuclear energy use would take on a completely new scope following the events in Japan on 11 March 2011. The German Bundestag had just decided on 28 October 2010 to extend the life of German nuclear power plants by eight years for the seven plants put into service before 1980 and by 14 years for the remaining ten plants. Its decision was based on the argument that nuclear energy would function as a bridge technology until sustainable energy sources had become more widely available.

Several studies have already been prepared in the past on the potential damage that could result from the release of large quantities of radiation following a nuclear disaster. However, the possibility of making such damages – estimated in 1991 at up to 10 trillion German marks[3] – insurable through the private insurance sector was always ruled out.

The goal of the present study is to develop a range of possible amounts of damage on the basis of an analysis of existing publications on quantifying maximum damages. It further aims to use that range to calculate an insurance premium that would be payable for each nuclear power plant to cover the potential risks of third-party liability connected with a nuclear disaster. The primary intent is to inform the public of the order of magnitude of a hypothetical insurance premium for nuclear energy use, since information about the costs to be shouldered by society – which are not reflected in the prices for using the energy source – are an important basis for assessing alternative energy sources. A decision based on the principle of sustainability can only be made once there is sufficient transparency regarding potential external costs.

---

[3] Cf. [Ewers/Rennings 1992 b].

Subject of the study

The present study was conducted independently by Versicherungsforen Leipzig GmbH on behalf of the German Renewable Energy Federation (BEE). The information contained in the study is derived from publicly accessible sources, which have been determined to be reliable by Versicherungsforen Leipzig. However, Versicherungsforen Leipzig does not guarantee the accuracy or completeness of the information in the study. The sources were chosen exclusively by Versicherungsforen Leipzig. The views expressed by the authors of the studies used are not necessarily those of Versicherungsforen Leipzig. Versicherungsforen Leipzig is first and foremost a scientific organisation; it is independent of political parties and interest groups.

The study makes use of existing estimates of the probability of occurrence and extent of damage of a serious nuclear disaster, with the aim of calculating an adequate insurance premium to cover the damages resulting from such an event. The unit of frequency used is the number of events per unit of time and the unit of damages is the monetary value of the insurance sums to be paid. Not all types of damages, such as damage to health, can be precisely quantified, so the study draws on a number of risk parameters that are not directly associated with insurance. In the debate surrounding nuclear energy, for example, the term "external costs" has played an important role as a risk parameter in past years.

After some remarks on general aspects of actuarial science, Chapter 3 begins by explaining in general terms the applicability of the insurance concept as well as the criteria and limits of insurability, and then discusses them using the example of a nuclear disaster. Chapter 4 starts with background facts on which existing quantification approaches are based, and then reviews the literature on those approaches and explains their limitations. As a supplement to the existing approaches presented, the study makes appraisals of its own, which are described briefly at the end of the chapter.

Chapter 5 begins by presenting the range of probabilities of occurrence provided by the literature. It continues by describing scenarios that the authors see as having a significant influence on the frequency of catastrophic events as originally presumed.

Those scenarios are used to derive modifications of the probabilities of occurrence that have been presented. Chapter 6 first provides a formal description of the model used to calculate the insurance premium, and then provides the calculations themselves; the values for these calculations are taken from Chapters 3 and 5.

Chapter 7 offers a concluding interpretation of the calculated values.

Chapter 1

Definition of key terms

This chapter provides introductory definitions and explanations of the following relevant terms that are important in this study:

- Nuclear events
- International Nuclear Event Scale (INES)
- Incident and accident
- MCA and nuclear disaster

Various events can impair operations at a nuclear power plant. Operators of nuclear power plants are required to make safety provisions and plan emergency counter-measures to protect against anticipated event scenarios in accordance with legal and regulatory standards such as the German Radiation Protection Ordinance.[4]

These events can result either from the general operation of a power plant or from the use of nuclear energy. Events that occur due to the use of nuclear energy are called nuclear events. A nuclear event is defined as "any occurrence or series of occurrences having the same origin which causes nuclear damage."[5] Nuclear damages include damage to people, the environment and property.[6]

To be able to assess nuclear events, especially those that have occurred, experts from the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA) developed the "International Nuclear

---

[4] See [BMU 2008 b]

[5] See [European Commission 2003] pp. 0032 - 0040

[6] See Chapter 3.1.2

Event Scale" (INES) in 1989. INES has seven levels. According to the INES system, nuclear events can be divided into "incidents" and "accidents". The first three levels of severity are used for events that can be categorised as incidents. Levels four to seven refer to events categorised as accidents. Events of little or no safety-related significance are assigned to level zero.[7] The INES user's manual outlines the criteria for assigning an event scenario to a particular level. To help users categorise events, it includes detailed guidance for rating events based on the consequences that the radiation has on the area inside and outside the nuclear facility and impairments of safety provisions.[8]

The following diagram shows the INES categorisation of incidents and accidents.

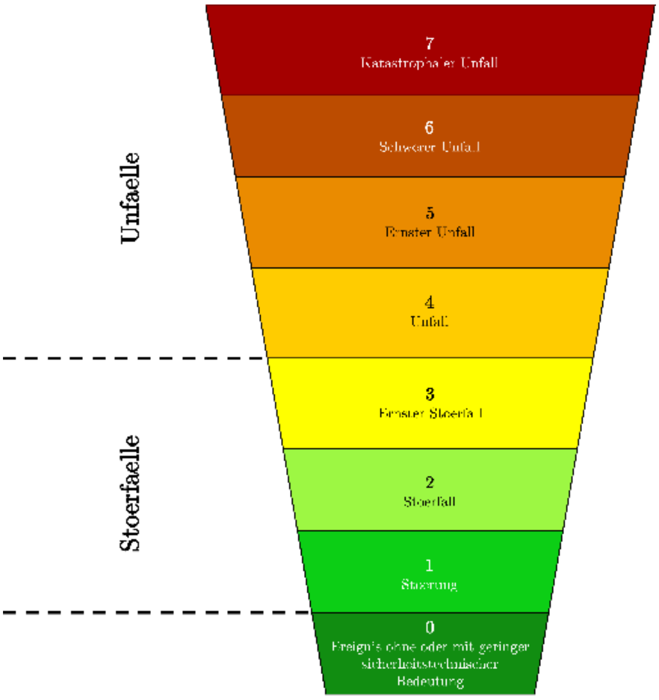


Figure 1.1: INES scale   Source: own work, adapted from [IAEA b] p. 1
Störfälle = Incidents   Unfälle: Accidents
0   Events of little or no safety significance
1   Anomaly   2   Incident   3   Serious Incident
4   Accident   5   Accident with wider consequences   6 Serious accident
7 Major accident

The German Radiation Protection Ordinance legally defines an incident as a "sequence of events the occurrence of which prevents continued operation of the installation or work activities for safety-related reasons, and for which the installation has to be designed [in terms of required

---

[7] The Gesellschaft für Reaktorsicherheit also classifies events into incidents and accidents. See [GRS].
[8] Figure A. 1 in Annex A shows the scale in greater detail.

security systems], or for which precautions have to be taken to protect the work activities concerned."[9] An incident becomes an accident when there is a release of radiation of more than 50 millisieverts[10] (effective dose).[11]

A nuclear power plant must be designed and equipped to withstand a maximum credible accident (MCA) if it is to receive an operating licence.[12] Operators must ensure that facilities have appropriate, functional security systems and measures that are capable of withstanding an MCA and preventing nuclear damage. For this reason, it is frequently also referred to as a design basis incident or a design basis accident. The current state of science and technology, laid down in safety criteria and guidelines for nuclear power plants[13], indicate the accidents that have to be brought under control.[14]

A nuclear event that triggers a nuclear disaster is a nuclear accident that exceeds the level a nuclear power plant can just about control with its security systems and emergency counter-measures. A nuclear disaster is therefore a beyond design basis accident with the realisation of residual risk. A residual risk is a risk that lies beyond the safety provisions put in place, or one that was not taken into account and consciously or unconsciously taken when those provisions were selected.[15] The German media often refers to a nuclear disaster as a "Super-GAU" (‘super MCA’) to suggest that this kind of accident has repercussions that surpass those of an MCA. In the present study, however, the term "nuclear disaster" indicates an event that corresponds to the terms "nuclear event" and "major accident" (INES level 7), which were explained above. This is also the terminology used by the German federal government.[16]

A nuclear disaster is often equated with the term "core melt accident" due to the fact that large quantities of radioactive particles can only be released when a reactor core melts.[17]

---

[9] Section 3 Par. 2 No. 28 StrlSchV

[10] A sievert (Sv) is the special unit for equivalent dose and effective dose (Joule / kg = 1 sievert). One sievert is equal to 1,000 millisieverts (mSv). Equivalent dose measures the biological effects of ionising radiation on humans. Effective dose takes into account the different sensitivities of organs and tissues to stochastic radiation effects by multiplying specified organ doses by a tissue weighting factor.

[11] See Section 3 Par. 2 No. 35 StrlSchV: "Accident: An event which may cause one or more persons to undergo an effective dose of more than 50 mSv". Compare Section 5 Sentence 2: "The limit of the effective dose per calendar year shall be 1 mSv pursuant to Section 46, Para. (1) for the protection of members of the public and up to 20 mSv pursuant to Section 55, Para. (1), first sentence for the protection of occupationally exposed
persons during the performance of their occupation."

[12] Compare Section 9 Par. 1 No. 4 and 5 StrlSchV

[13] See Figure A.2 in Annex A

[14] Cf. [Ewers/Rennings 1992 a]

[15] Cf. [Ewers/Rennings 1992 a]

[16] Cf. [Bundesregierung 2010 a] p.1

[17] Cf. [Ewers/Rennings 1992 a] and the definition and descriptions of core melt accidents in [GRS 1989].

A core melt accident, however, does not inevitably induce a nuclear disaster, as it does not necessarily result in a large release of radioactive material. An example of such an event is the accident that occurred at the Three Mile Island facility in Harrisburg, Pennsylvania in 1979.[18]

A nuclear disaster necessitates "emergency counter-measures to protect the population, including disaster control measures for preventing or reducing exposure to radiation".[19]

Another reason why the present study does not use the term core melt accident is that it would require classifying an INES level 5 accident as a nuclear disaster, since that is the first level at which a core melt can occur. However, since there are still ways of controlling such an accident with emergency counter-measures and of limiting its effects on the environment (as explained above), scientists normally reserve the term nuclear disaster for level 7 events. An event assigned to this level is a major accident; that is, one that involves a major release of radioactive material leading to serious and widespread damage to human health and the environment, and one in which this damage could not have been prevented by the available emergency counter-measures and safety provisions.[20]

The events at the nuclear power plants at Three Mile Island and Chernobyl can help clarify this distinction. The former was assigned to level 5, meaning it was not a nuclear disaster, while the latter was assigned to level 7.[21]

The following chapters on calculation of a liability insurance premium are solely devoted to the third-party liability risk of a nuclear power plant owner in the event of a nuclear disaster that triggers a maximum loss. The extent of the disaster determines the amount of damages, as does an estimate of the probability of occurrence of a maximum loss. These factors are used to determine the amount of the resulting insurance premium for the third-party liability risk.

---

[18] About one third of the reactor core melted during this event, but appropriate action by the staff helped prevent more serious damage. Radioactive gases and coolant were released into the environment. Cf. [Spiegel-Online 2009]. However, the accident at Three Mile Island was not classified as a nuclear disaster. See [Spiegelberg Planer 2010], p. 16 ff.

[19] [Bundesregierung 2010 a], p. 1.

[20] Cf. [Weil 2003], p. 35. The German federal government also assigns nuclear disasters to INES level 7. See [Bundesregierung 2010 b], p. 1.

[21] Cf. [Spiegelberg Planer 2010], p. 16 ff.

Chapter 2

Operation of a nuclear power plant and the resulting levels of liability

A nuclear power plant is a type of thermal power plant used to generate electricity by means of nuclear energy. In simplified terms, the hot water or steam required by the facility to drive the turbines in order to generate electricity is produced by controlled nuclear fission of enriched uranium or thorium. This process takes place inside a reactor and results in a high level of energy density and radioactive radiation in the reactor core.

Importance of electricity generated by nuclear power plants in Germany

Germany currently has 17 nuclear power plants with a total gross capacity of 21,517 MW_e (potential) and an output of around 140.6 billion kWh (2010, gross).[22]

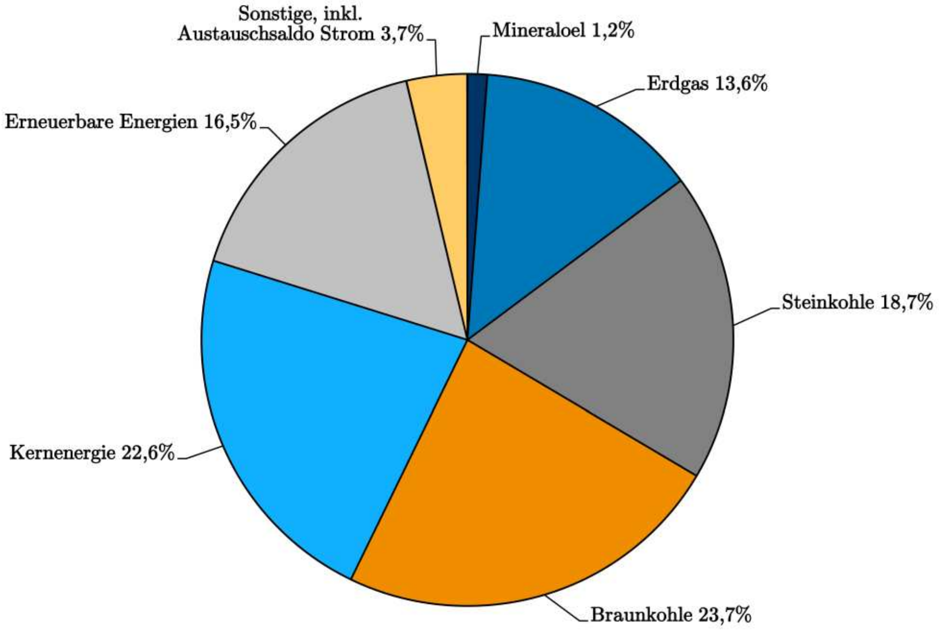
Electricity generated from nuclear power represents a considerable proportion of the total volume of primary energy consumed in Germany. In 2010, nuclear power has a share of around 22.6 per cent of total energy consumption.[23] Figure 2.1 shows the distribution of primary energy consumption according to energy source.

Distribution of nuclear power plant types according to reactor cooling system and method of electricity generation

---

[22] See also Figure 2.2. MW_e stands for megawatt electrical and denotes the nuclear power station's capacity for production of electrical energy.

[23] See also [AGEB 2011 a], p. 23.



(Clockwise from the top: Mineral oil 1.2%, Natural gas 13.6%, Bituminous coal 18.7%, Lignite 23.7%, Nuclear energy 22.6%, Renewable energy 16.5%, Others, incl. import/export balance 3.7%)

Figure 2.1: Distribution of gross electricity generation in Germany according to energy source (Source: authors' own work, based on [AGEB 2011 a] p. 24)

With regard to the cooling system employed, all of the nuclear power plants in operation in Germany are light water reactors, in which the fuel rods in the reactors are cooled by means of water. With regard to the method of electricity generation, eleven of the nuclear power plants are pressurised water reactor (PWR),[24] while the remaining plants are boiling water reactors (BWR)[25].[26]

These reactor types are distinguished as follows: in boiling water reactors, steam resulting from the evaporation of cooling water is used directly to drive the turbines, while in pressurised water reactors the water is prevented from evaporating by pressure; instead, the water remains in a liquid state, heating a separate water circulation system, with the steam from this system being used to drive the turbines.[27]

For the classification of nuclear power plants see Figure 2.2. This chart lists all the nuclear power plants in operation in Germany.[28]

---

[24] These are the Biblis A and B, Brokdorf, Emsland, Grafenrheinfeld, Grohnde, Isar 2, Neckarwestheim 1 and 2, Philippsburg 2 and Unterweser power plants.

[25] These are the Gundremmingen B and C, Isar 1, Philippsburg 1, Krümmel and Brunsbüttel power plants.

[26] Cf. [Deutsches Atomforum e.V.].

[27] Cf. [Informationskreis KernEnergie]. For a more detailed description of how a pressurized water reactor works, see [GRS 1989], p. 109 ff. Further information on how the different types of nuclear power plant work can be found in [Konstantin 2007], p. 242 ff.

[28] The list also includes the seven oldest nuclear power plants (which began operation before 1980), without taking into account the moratorium in place at the time of writing (March 2011), as a result of which these power plants have had to temporarily suspend operation.

No.	Name	Reactor type	Operator	Location	Capacity MWe	Generation output GWh, gross, 2010	Start-up year (first criticality)	Years of operation (up to and incl. 2009)
1	Neckarwestheim 1	PWR	EnBW Kernkraft GmbH (EnKK)	Neckarwestheim (BW)	840	2,208	1976	34
2	Neckarwestheim 2	PWR	EnBW Kernkraft GmbH (EnKK)	Neckarwestheim (BW)	1,400	10,874	1988	22
3	Philippsburg 1	BWR	EnBW Kernkraft GmbH (EnKK)	Philippsburg (BW)	926	6,791	1979	31
4	Philippsburg 2	PWR	EnBW Kernkraft GmbH (EnKK)	Philippsburg (BW)	1,468	11,797	1984	26
5	Grafenrheinfeld	PWR	E.ON Kernkraft GmbH	Grafenrheinfeld (BY)	1,345	7,938	1981	29
6	Gundremmingen B	BWR	Kernkraftwerk Gundremmingen GmbH	Gundremmingen (BY)	1,344	9,954	1984	26
7	Gundremmingen C	BWR	Kernkraftwerk Gundremmingen GmbH	Gundremmingen (BY)	1,344	10,936	1984	26
8	Isar 1	BWR	E.ON Kernkraft GmbH	Essenbach (BY)	912	6,543	1977	33
9	Isar 2	PWR	E.ON Kernkraft GmbH	Essenbach (BY)	1,485	12,007	1988	22
10	Biblis A	PWR	RWE Power AG	Biblis (HE)	1,225	5,042	1974	36
11	Biblis B	PWR	RWE Power AG	Biblis (HE)	1,300	10,306	1976	34
12	Emsland	PWR	Kernkraftwerk Lippe-Ems GmbH	Lingen (NI)	1,400	11,560	1988	22
13	Grohnde	PWR	E.ON Kernkraft GmbH	Grohnde (NI)	1,430	11,417	1984	26
14	Unterweser	PWR	E.ON Kernkraft GmbH	Esenshamm (NI)	1,410	11,239	1978	32
15	Brokdorf	PWR	E.ON Kernkraft GmbH	Brokdorf (SH)	1,480	11,945	1986	24
16	Brunsbuettel	BWR	Kernkraftwerk Brunsbuettel GmbH & Co. oHG	Brunsbuettel (SH)	806	0	1976	34
17	Kruemmel	BWR	Kernkraftwerk Kruemmel GmbH & Co. oHG	Kruemmel (SH)	1,402	0	1983	27
	Total				21,517	140,557		

Figure 2.2: Overview of nuclear power plants in operation in Germany (Source: authors' own work, based on [BMU 2010] and [Paulitz 2010])

Value chain stages of a nuclear power plant

The operation of a nuclear power plant, including interim storage and final disposal of fuel rods, can be divided into the following value chain stages.

- Construction of the nuclear power plant
- Prospecting and mining of uranium / thorium
- Production of fuel elements
- Intake and storage of fuel elements and facility components
- Operation of the nuclear power plant
- Interim storage and final disposal of depleted fuel elements and facility components to be disposed of inside the nuclear power plant
- Transport of fuel elements and facility components to be disposed of
- Interim storage and final disposal of depleted fuel elements and facility components to be disposed of outside the nuclear power plant
- Dismantling of the nuclear power plant

Each value chain stage entails a risk of a nuclear incident, the occurrence of which can cause damage not only to the nuclear power plant itself, but in particular to the plant's surrounding environment (in terms of people, infrastructure, flora and fauna). For the payment of financial compensation, a legal entity responsible must be identified and held liable for the damages.

The current situation in terms of liability and financial security of nuclear power plant licensees in Germany

For all "nuclear damages"[29] resulting from the operation of a nuclear power plant – that is, damage to the surrounding environment – the power plant licensee is solely liable.[30] Facility manufacturers and suppliers do not share this liability.[31] Liability generally takes the form of strict liability in tort, which means that in the event of damages, the legality thereof or culpability of the licensee is not an issue.[32] The power plant licensee bears unlimited liability, regardless of culpability, with regard to claims for compensation by third parties;[33] that is, it is obliged to pay compensation to third parties. Such compensation includes, for example, the cost of short-term evacuation or resettlement of the population in the area surrounding the affected power plant.[34] The obligation to provide compensation does not extend to damage to the nuclear facility itself, to other nuclear facilities located on the same site, or to property located on the site which is used or intended for use in connection with the nuclear power plant.[35] Nuclear power plant licensees are generally exempted from liability if the damage is a direct result of armed conflict, war or other hostilities or insurrection.[36]

In practice, however, the actual liability of the licensee is limited by the provisions of the Atomic Energy Act (*Atomgesetz*). These stipulate that the licensee of a nuclear power plant must maintain financial security to the amount of €2.5 billion per nuclear power plant in fulfilment of its legal obligations with regard to compensation.[37] For compensation payments in excess of the financial security limit, the licensee shall nonetheless be liable, but pursuant to the indemnity obligation established by Section 34 AtG, the State shall settle claims in excess of this limit if the licensee is unable to do so.[38] Provisions for the accumulation of this legally required compensation and associated measures are made in the Nuclear Financial Security Ordinance (AtDeckV). For example, the ordinance stipulates that the €2.5 billion in financial security may be assured by means of "liability insurance or some other form of financial security".[39] In addition, financial security provisions of the same or different types may be combined.[40]

The €2.5 billion in financial security is currently assured by two components: firstly, licensees of nuclear power plants in Germany hold liability insurance cover for every nuclear power plant unit, by means of the nuclear insurance pool of the German Nuclear Reactor Insurance Association up

---

[29] The concept of "nuclear damage" is defined in Art. 1 Par. a sub-paragraph (vii) of the Protocol to Amend the Paris Convention (2004). See also the information provided in Section 3.2.2.
[30] Cf. Section 31 Par. 3 AtG.
[31] Cf. Section 31 Par. 3 AtG and [Diekmann/Horn 2007], p. 49.
[32] Cf. Section 25 AtG.
[33] Cf. Section 31 AtG.
[34] Cf. [Bundesregierung 2010 a], p. 7.
[35] Cf. Art. 3 Par. A of the Protocol to Amend the Paris Convention (2004) and Section 31 AtG. Responsibility for the insurance of such damage lies with the operator of the nuclear facility. Cf. [Bundesregierung 2010 c], p. 6.
[36] Cf. Art. 9 of the Protocol to Amend the Paris Convention (2004).
[37] Cf. Section 13 Par. 3 AtG. This limitation of the financial security to 2.5 billion is regarded as a realistic amount for coverage of claims for compensation resulting from a nuclear event.
[38] Cf. Section 34 Par. 1 AtG and the related information in [Haubner 2009], p. 41.
[39] Section 1 AtDeckV.
[40] Cf. Section 1 AtDeckV.

to an amount of €255.65 million.[41] [42] Secondly, there is a supplementary solidarity agreement in place among the parent companies of nuclear power plant licensees, according to which they commit themselves, as a whole, to payment of €2,356.57 million[43] in the event of nuclear damage.[44] At the base of this solidarity agreement are audited financial securities belonging to the companies, cashable within one year.[45]

In addition to the financial security maintained by power plant licensees, funds are also available pursuant to the Brussels Supplementary Convention, which provides for up to €300 million from EU public funds. According to the Federal Ministry of Economics and Technology, this amount is sufficient to cover the maximum possible damage caused by a nuclear event involving core meltdown.[46]

Thus, the resources available to the licensee of a nuclear power plant unit in the event of liability can be summarised as follows:

€255.65 million from liability insurance
\+ €2,356.57 million from the solidarity agreement between parent companies
\+ €300.00 million from the Brussels Supplementary Convention
= €2,912.22 Million

As a result, the legal requirements for financial security to meet compensation claims are currently fulfilled.

Background of the domestic and EU legislation regulating the liability of nuclear power plant licensees

Liability for nuclear events is regulated both at an international / EU level and on the basis of German liability law.[47] Fundamentally, since 1960, according to the rules of the Paris Convention[48] and the Joint Protocol,[49] supplemented by the Atomic Energy Act, "strict liability in tort" applies.[50] The different principles of liability law are examined in greater detail below.

The international agreements – the Paris Convention, the Brussels Supplementary Convention and the Vienna Convention –were entered into in order to make the industrial use of nuclear power possible, in spite of the associated risks. The Paris Convention, in particular, which was signed in 1960, deals with liability law in the event of claims for compensation resulting from

---

[41] Until April 2002, when the Atomic Energy Act was revised, this corresponded to the legally required level of financial security.

[42] The two reactor units in Gundremmingen are jointly covered up to €255.65 million Cf. [Irrek 2008], p. 1.

[43] This amount is made up of a compulsory level of financial security in the amount of €2,244.355 million plus estimated claims settlement costs (5%) in the amount of €112.218 million.

[44] [Wuppertal Institut 2007], p. 12.

[45] Cf. [Bundesregierung 2010 c], p. 1.

[46] Cf. [Bundesministerium für Wirtschaft und Technologie 2010], p. 2

[47] For an overview of international nuclear energy law, see [BfS b]. Specifically in regard to publication of the implementation in Germany, see BGBl II, No. 24, 29 August 2008, p. 902.

[48] "Paris Convention" refers to the Convention on Third Party Liability in the Field of Nuclear Energy of 29 July 1960, as amended by the promulgation of 5 February 1976 (BGBl. II p. 310, 311) and the protocol of 16 November 1982 (BGBl. 1985 II p. 690).

[49] "Joint Protocol" refers to the Joint Protocol of 21 September 1988 relating to the Application of the Vienna Convention and the Paris Convention (BGBl. 2001 II p. 202, 203), see [IAEA 1992].

[50] Cf. Section 25 Par. 1 Sub-par. 1 AtG.

nuclear events, and provides a legal basis for strict liability in tort with regard to the use of nuclear power.

Despite a number of shortcomings that have become apparent in the international system of liability in connection with nuclear power over the intervening decades and changes in the usage and risks associated with the peaceful use of nuclear power, the underlying principles of the conventions on nuclear liability remain largely unchanged. In a process lasting several years, the Paris Convention was subjected to a major overhaul with the 2004 Protocol. The 2004 Protocol was approved by the German federal government, but so far it has not yet come into effect.[51] The Paris Convention of 1960 requires every nuclear power plant operator to keep between €6 million and €18 million available for compensation of damages. The revised 2004 protocols stipulate minimum liability of the licensee to the amount of €700 million (Paris Protocol) and €1,500 million (Protocol to Amend the Brussels Supplementary Convention).[52]

As regards EU liability law, the following trends can be observed: Since the late 1980s, Europe has sought to achieve unity with regard to community measures relating to environmental liability. The European Commission drafted a Green Paper in 1993 and a White Paper in 2000 on environmental liability, followed by a proposed directive in early 2002. In the proposed EU directive on environmental liability, environmental organisations and others demanded that liability be extended to include nuclear power plants. In the EU Directive of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage,[53] nuclear damage was excluded from environmental liability on the basis of the regulations contained in the international conventions (laid down in Art. 4, clause of Directive 2004/35/EC:

"This Directive shall not apply to such nuclear risks or environmental damage or imminent threat of such damage as may be caused by the activities covered by the Treaty establishing the European Atomic Energy Community or caused by an incident or activity in respect of which liability or compensation falls within the scope of any of the international instruments listed in Annex V, including any future amendments thereof."[54]

Annex V to Directive 2004/35/EC lists the following international conventions:

- Paris Convention of 29 July 1960 on Third Party Liability in the Field of Nuclear Energy and the Brussels Supplementary Convention of 31 January 1963.
- Vienna Convention of 21 May 1963 on Civil Liability for Nuclear Damage.

---

[51] For a more detailed examination of the Paris Convention see [Blobel 2005].

[52] [Schneider et al. 2009], p. 72.

[53] Directive 2004/24/EC of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage, Official Journal L 143/56.

[54] Art. 4 clause 4 Directive 2004/35/EC.

- Convention of 12 September 1997 on Supplementary Compensation for Nuclear Damage.
- Joint Protocol of 21 September 1988 relating to the Application of the Vienna Convention and the Paris Convention.
- Brussels Convention of 17 December 1971 relating to Civil Liability in the Field of Maritime Carriage of Nuclear Material.

The German Atomic Energy Act completes and implements the liability regulations provided by the international agreements. German legislation exceeds by far the minimum liability specified in the Paris Convention, as pursuant to Section 31 (3) AtG the licensee of a nuclear power plant bears unlimited liability. Besides Germany, this unlimited liability can be observed only in Switzerland and Japan. Strict liability in tort also applies under German law.[55]

Since the revision of the Atomic Energy Act in 2002, the amount of financial security required of nuclear power plant licensees to cover their liability with regard to compensation has increased to €2.5 billion per nuclear power plant.[56] Details of the current situation of nuclear power plant licensees with regard to liability, and of the composition of the legally required financial security were given in the preceding section.

Interim summary of the preceding paragraphs

Although the financial security currently maintained by nuclear power plant licensees meets the legal requirements, even this level of cover – much higher than called for by the regulations that preceded the review of the Atomic Energy Act in 2002 – raises doubts as to whether it is sufficient to cover obligations to third parties in terms of compensation in the event of an accident.

If a nuclear disaster were to occur, resulting in damages in excess of the legally required financial security, the licensee of the nuclear power plant would, in principle, bear unlimited liability for damages in excess of the €2.5 billion plus the €300 million from the EU Supplementary Convention. In the event of the nuclear power plant licensee being unable to meet this expense, it would ultimately fall to the state to come up with a significant share of compensation payments. Ultimately, this would constitute a considerable burden for the general public.

This study aims to answer the following crucial question: How high must the liability insurance premium be in order to cover the maximum possible damage from a nuclear disaster within a specified timeframe? The answer to this question is provided in Chapters 4 to 6 on the basis of

---

[55] Cf. Section 25 AtG.

[56] Cf. Section 13 (3) AtG. This limitation of the financial security to 2.5 billion is regarded as a realistic amount for coverage of claims for compensation resulting from a nuclear event.

various expert appraisals regarding the likely amount of damage and assumed probability of occurrence of damage, as well as methods drawing on extreme value theory.

Chapter 3

Dimensions of insurance cover for a nuclear disaster

The dimensions of insurance cover for a defined risk are calculated on the basis of the insured event (insured risks) as laid down in the insurance contract and the damages that can be claimed on the insured risks as a result, or rather the relevant benefits to be provided by the insurer as stipulated in the insurance contract.[57]

In the following Section, 3.1, important technical insurance terms are defined and the dimensions of insurance cover will be explained individually in greater detail. In the following Section, 3.2, an insurance perception will be applied to the circumstances of a nuclear disaster.

These sections fundamentally refer to liability insurance[58] as a branch of indemnity insurance[59] for coverage of damages caused by a nuclear disaster or the ensuing claims for damage by third parties. Hence, liability insurance will also be explored in greater detail in the individual sections.

3.1 Technical definitions of insurance cover

3.1.1 Insurance and the insured risk

A large number of different definitions of the term "risk" exist both in general economic and specialised insurance literature. All sources consistently define "risk" as the circumstances by which the decisions and corresponding economic conduct and actions of an economic entity do not lead to a certain precisely definable outcome, but rather that standard deviations from the

---

[57] Cf. [Farny 2006], p. 382 ff.

[58] Liability insurance covers against an injured third party's justified entitlement to compensation due to damage caused or brought about by a natural or legal person. Cf. [Fürstenwerth/Weiß 2001], p. 306 ff.

[59] Indemnity insurance is a type of cover "whose insurance benefits are (directly) limited to damages that actually occurred to the insured party's assets and can be concretely proved." [Fürstenwerth/Weiß 2001], p. 567.

expected outcome may occur because of environmental factors.[60] These possible outcomes each occur with different – known and unknown – probabilities, which is why a risk is also expressed in terms of the probability distribution of the possible outcomes of an action.

All in all, a risk is thus described by a probability distribution with an expected value – "the average of all possible outcomes based on probabilities"[61] – and a certain variance, which states the standard deviations from the expected outcome.[62] The standard deviations of the actual outcome from the expected value can be of a positive nature (for example, higher profits than expected during a period) or of a negative nature (for example, lower profits than expected during a period).

Related to the insurance industry, only negative deviations from the expected value of a probability distribution, measured in economic terms, are taken into account. These deviations are referred to as damages. The probability distribution (of the possible negative outcomes of an action) is therefore also referred to as damage distribution.[63] If the economic entity cannot bear these negative deviations or risks by itself, or does not wish to do so, it has the option of transferring them to insurance companies, so long as the limitations of insurability (see below) are not exceeded. Economic actors thus transfer the estimated damage distribution to the insurer; in return, the economic entities pay an insurance premium to the insurer. The insurer undertakes to pay compensation in agreed and defined cases of damages.[64] This circumstance is called insurance in the actual sense of the word, or is referred to as the risk business.[65]

From the insurer’s point of view, an insured risk is a probability distribution of insurance benefits (which the insurer must pay to the insured party in the event of damages). From the insured party’s point of view, an insured risk is a probability distribution of damages (which he transfers to the insurer).[66] [67]

In normal cases, the insurer assumes a large number of risks and their damage distributions in his portfolio (which is referred to as a pool) and in return receives premium payments for all of

---

[60] The causes of these possible outcomes or deviations of the actual from the expected outcome are natural environmental factors (such as storms, earthquakes, etc.), technical factors (such as the failure of technical systems), economic environmental factors (such as steps taken by the concern or its competitors), or social factors (for example, legislation or actions by third parties). Further uncertainties about the actual nature of the outcome arise from the fact that complete information about the relation of an action to the outcome is not available. Uncertainty exists to a certain extent, which means that an action always occurs in an unpredictable way as regards the possible nature of the outcome. Cf. [Farny 2006], p. 27.

[61] Cf. [Farny 2006], p. 27.

[62] Cf. [Farny 2006], p. 27.

[63] Cf. [Farny 2006], p. 30 ff.

[64] Cf. [Farny 2006], p. 35.

[65] The insurance cover provided by liability insurance consists of its core business, risk, and services. The latter includes advice and processing. For further information, see [Farny 2006], p. 55 ff.

[66] Cf. [Farny 2006], p. 31.

[67] Two types of risk – specific and general – should be differentiated here. Specific risk refers to the part of the total existing risk, including all of its hazards and possible damages, assumed by the insurance company. As insurers usually exclude certain hazards and damages from policies, including those such as damages resulting from war, nuclear accidents or computer viruses, the insurer’s specific and general risk are often not identical.

the insured risks in this portfolio. If the portfolio of insured risks is sufficiently large, the law of large numbers applies. Put simply, this states that while a premium will be paid for all insured risks during a period (for example, a year), damages will not be incurred for all of these risks during the period. It is thus possible for the insurer to "fund" the damages incurred to a few insured risks within the portfolio during a period by using the premium payments of all risks in this portfolio. This fundamental insurance process is known as the balance of risks in the pool. If more damage occurs than expected during a period, one speaks of an "underwriting loss"; in cases of less damage than expected, the term "underwriting profit" is used.

Insurance calculations continue to be based on underwriting profits during individual periods balancing out the underwriting losses from other periods in the long term. This principle is known as the balance of risk over time. It is possible to balance risk over the course of several periods, as most insurance policies within a pool cover periods of more than one year.[68]

By balancing risk in the pool and over time, it is possible for the insurer to assume risks in its portfolio and use the premiums received for insuring against these risks to pay compensation in the event of damage. The insurer invests its assets, which come from premium payments, in interest-generating capital investments in order to obtain returns. The insurer builds up insurance reserves for its obligations to the insured parties resulting from, for example, premiums paid in advance and insurance cover in the future, or in the event of damage that has not yet been adjusted. These reserves reflect the portion of assets tied up in capital investments (capital reserves).

Fundamentally, one distinguishes between two types of benefits paid by insurers: lump-sum and indemnity insurance. In lump-sum insurance, only a previously defined and limited amount is paid, irrespective of the actual amount of damage. This is the case, for example, in term life insurance, in which a certain limit of liability is assumed, irrespective of the "value" of the life of the insured person. By contrast, indemnity insurance is based on the amount of the actual damage incurred. In turn, this is subdivided into unlimited insurance, which does not include any restriction in the amount insured, and first-loss insurance, in which an upper limit is set for the compensation to be paid.[69] Vehicle insurance is an example of indemnity insurance.

In terms of civil or debt law, private individuals and economic entities in Germany are liable for material or financial damages that they cause to other people, economic entities or their property, and/or the environment, and they must pay compensation. As a rule, liability insurance can be acquired to fund this liability.[70] Some of these are voluntary (private liability insurance), while others are compulsory (for example, vehicle liability insurance, compulsory liability

---

[68] For information on this topic, see the description in [Farny 2006], p. 44 ff.
[69] Cf. [Fürstenwerth/Weiß 2001], p. 212 and 654.
[70] For information on this topic, see the comments in [Fürstenwerth/Weiß 2001], p. 306 ff.

insurance for medication manufacturers for harm caused to people by medication, or hunting liability insurance for hunters).[71]

As liability insurance is based on the concrete amount of actual possible or incurred damage, it should be classified as indemnity insurance. The liability insurance that nuclear power plant owners have currently taken out from the nuclear insurance pool, the German Nuclear Reactor Insurance Association, represents first-loss insurance, as the amount of compensation is limited to €255.65 million. By contrast, the hypothetical insurance premium for liability insurance calculated for this study does not assume any limitation of the amount insured. Hence, it corresponds to unlimited insurance for the actual damage incurred.

3.1.2 Insured risks and insured damage

The insurer must define or describe the insurance cover in the insurance contract. To this end, the risk to be insured is thoroughly analysed. This analysis deals both with

- the causes, which the risk can trigger (perils)
- and the possible effects (damages)

that could arise if the event occurs in the sense of the insured risk.[72] In this context, it is the duty of the insurer to include all possible perils and damages in the insurance contract, or to explicitly exclude some of them. A peril – the cause of risk – can generally be described as the harm or condition that results through forces that cannot be influenced significantly or at all. Perils exist, causing one or more real cases of damages when they occur.[73]

All of the causes/perils included in the contract are classed as insured risks and lead to an obligation on the part of the insurer to pay benefits in cases of damage.[74] Similarly, all of the effects/damages included in the contract are classed as insured damages.

Describing and configuring the insured perils and damages for an insured risk is usually a very complex and painstaking task.[75]

---

[71] Cf. [Farny], p. 149.
[72] Cf. [Farny 2006], p. 32.
[73] Cf. [Farny 2006], p. 33 ff.
[74] Cf. Section 19, Par. 1, Insurance Policies Act
[75] Cf. [Farny 2006], p. 383 ff.

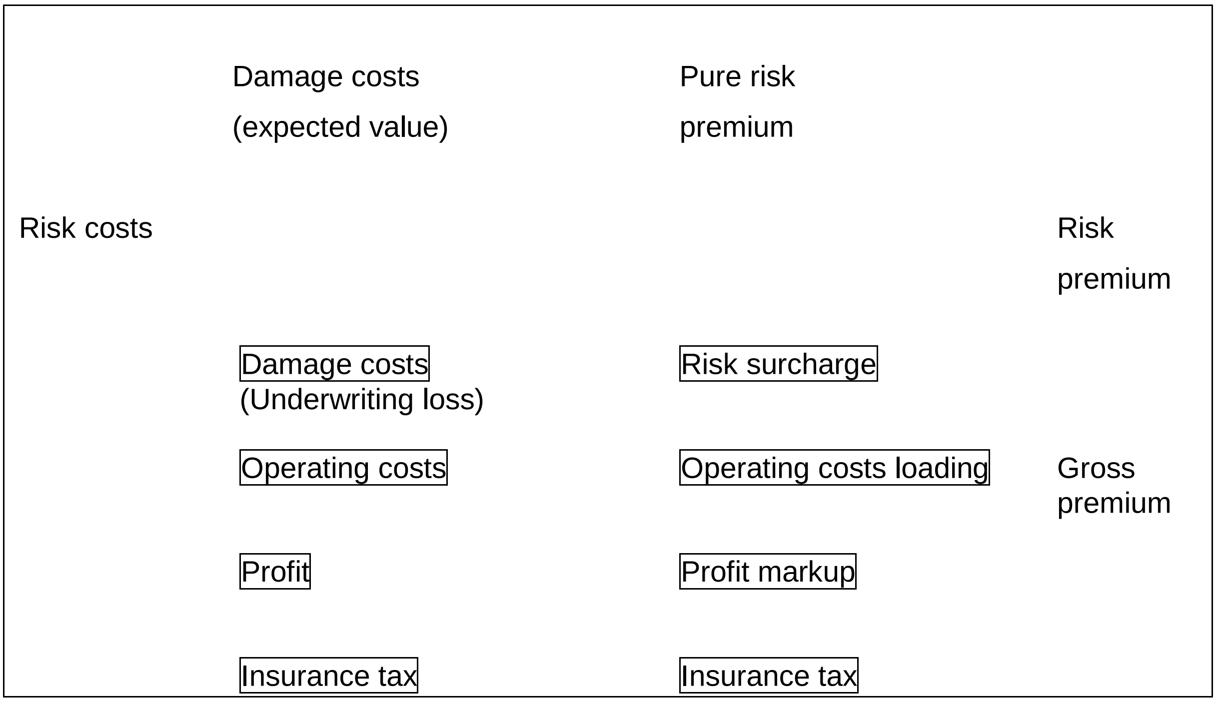
3.1.3 Insurance premium

The insurance premium essentially represents the price for the commodity of "insurance cover". With receipt of insurance premiums, the insurer funds expected compensation payments in the event of damage.

Within the scope of its premium policy, the insurer calculates the prices for the insurance cover offered with the aim of being able to use the premium income from the pool to cover the estimated expenses of claims payments arising in this pool. Empirical figures on actual expenses for similar damage events in the past and estimated expenses for future damage events[76] are included in the calculations.

Apart from the pure risk premium, other components in the insurance premium include the loading for security and operating costs, contribution margin for insurance and, in some cases, fire protection tax and a profit markup.

The pure risk premium corresponds to the amount needed to cover the expected damage costs of the risk (the expected present value of the benefits[77]).[78] The expected damage value therefore forms the basis for calculating the risk premium.



---

[76] Expenses are incurred both for the insurer's claims payments and its administration costs.
[77] Further information in Section 6.1.
[78] Cf. [Farny 2006], p. 60.

Figure 3.1: Premium/cost model. (Source: authors' own work, based on [Rosenbaum/Wagner 2006] p. 138)

The safety margin, which serves to cover possible underwriting losses due to the variance of the expected damages in the probability distribution, is another component of the insurance premium. If the variance is high (a large difference in the amounts of damage), a correspondingly high security premium must be factored into the insurance premium. The function of the security premium is thus to safeguard against fluctuations in actual claim payments as compared with the expected value. It represents an additional factor in insuring against the risk.[79]

The pure risk premium and the security premium are very closely related. They are therefore often referred to together as the risk premium.

The function of the loading for operating costs is to cover the operating costs incurred for services (for example, contract administration).[80] The contribution to insurance tax serves to cover the costs incurred for this tax.

The entire premium thus reflects the costs mentioned here: the premium is divided into individual components, which can then be interpreted as contributions to cover certain cost elements.

Figure 3.1 illustrates this type of premium/cost model.

When calculating the premium, one tries to determine the pure risk premium for every insured risk or the value of each expected claim. This is known as the principle of equivalence for individual insurance. Related to the entire pool, this also follows the principle of equivalence for the pool, which is to say that the sum of all individual risk premiums is set against the total expected value of damage costs from all insured risks.

---

[79] Cf. [Farny 2006], p. 60 and [Ngyuen 2009], p. 10.
[80] Cf. [Farny 2006], p. 60 ff.

Using the principle of equivalence for individual insurance automatically produces a premium differentiation as regards the expected individual damage values.[81] This aspect can become relevant in certain cases, taking into account different probabilities of the event occurring and the different amounts of damages (for example, depending on the state of the technology used and the available safety precautions). The background is that insured risks with a lower damage potential should be charged a lower premium that reflects this reduced risk, thus creating motivation to prevent damage.

If damages occur sooner, and/or more often, and/or at a higher value than expected within the existing insurance contract, the insurer is obliged to meet the agreed benefits even if it has not yet had the chance to cover this/these claims payment(s) completely by means of premium income. In order to be able to do so, other important elements of actuarial practice insurance technique elements are available to the insurer besides the balancing of risk in the pool / over time and the calculation of the premium. These include the interest aspect and the development of reserves previously described in Section 3.1.1 (insurance and the insured risk).[82] The interest effect occurs through the interest-generating investment of premium components, which are not urgently needed for claims payments, in various types of capital investments.

Further measures exist within the scope of the insurance risk policy of insurers (including the insurance portfolio policy or the risk-sharing policy.) However, these are of less importance for the rest of the study and will therefore not be further explained here.

3.1.4 Criteria and limitations of insurability

Many risks, including their hazards and damages, are regarded as insurable; however, in cases of other risks – including the liability risk of a nuclear disaster – the question of their "insurability" is answered in the negative by the vast majority.

There are no clearly defined limitations on whether, and in what way, a risk can be regarded as insurable. In the final analysis, this can only be decided on a case-by-case basis. Cost-benefit analysis between the insured party and the insurance company, taking into account the insurance premium to be paid, is crucial in each case. The insurability of a risk is accordingly always based on subjective and individual assessments.[83]

---

[81] Cf. [Rosenbaum/Wagner 2006], p. 137 ff.
[82] Transferring part of the risks to reinsurance companies is another option.
[83] Cf. [Farny 2006], p. 35ff. and [Goßner 2002], p. 5ff.

One way of quantifying or extrapolating the insurability of risks can to a certain extent be found in the following five criteria of insurability described in literature concerning insurance studies: calculability, randomness, autonomy and unambiguity of a risk, and the related amount of damage.[84]

The criterion of randomness is based on the occurrence of damage, and means that the occurrence of the damage event, the time that damage occurs, and the amount of damage must be uncertain. If an insurance contract is issued, these attributes must be unknown both to the insured party and the insurer.[85] Furthermore, damage should ideally also occur independently of the will or conduct of the insured party, that is, it should occur without his interference.[86] This criterion is not completely fulfilled in most insurance branches, as the insurer also pays compensation in cases of negligent or grossly negligent conduct by the insured party.[87] In such cases, the Insurance Policies Act (VVG) allows for a proportional reduction of the insurance benefits. However, if damages are the result of deliberate conduct by an insured party, the insurer does not usually pay compensation.[88]

The calculability of the damage distribution to be insured is another aspect of insurability. This concerns the possibility of estimating in advance the nature of a damage event as regards its probability of occurrence and its amount by the use of risk analyses or similar methods.[89] This aspect of insurability implies the existence of empirical figures and data histories concerning the occurrence of the damage, or that the risk can be described intuitively and/or analytically.

A further prerequisite for the insurability of a risk is the independence of a risk from other insured risks – in the sense of a lack of correlation. This means that there should be no connection implying that several insured units/objects will be affected if an event occurs. This criterion is, however, often not completely fulfilled. An example of this is when hailstones simultaneously hit a large number of an insurer’s insured vehicles. The rate of correlation should simply not be too high.[90]

In addition, a risk must be unambiguous, which is to say it must be possible to precisely define and classify the features of the insurance case – consisting of the insured risks and the damages incurred.[91]

---

[84] Cf. [Farny 2006], p. 37ff. and [Ngyuen 2009], p. 6ff.
[85] Cf. [Farny 2006], p. 38 and [Ngyuen 2009], p. 6ff.
[86] Cf. [Farny 2006], p. 38.
[87] Leaving one’s apartment for a short time while candles are lit is a classic case of grossly negligent conduct.
[88] Cf. Section 81 VVG
[89] Cf. [Farny 2006], p. 38.
[90] Cf. [Nguyen 2009], p. 8. However, the reinsurance industry has offered corresponding (re)insurance solutions for many decades for the cumulative events mentioned here, for example, as part of cumulative excess damage reinsurance.
[91] Cf. [Farny 2006], p. 38.

Unambiguity is also closely related to the final prerequisite of insurability – the size or extent of the damage. This criterion states that the maximum insurance benefit to be paid for a damage event – this value is termed PML or probable/possible maximum loss – may not exceed an insurer's risk capability.

In addition to the five prerequisites described, risk dynamics play a major role in the insurability of risks. This includes the fact that risks can change over the course of time due to technical progress among other things. Insurers must therefore constantly re-examine the question of the insurability of changed risks. The risks of terrorism, for example, were commonly included in certain insurance products in the past, but following the events of 11 September 2001 they have now been excluded from almost all insurance products.[92]

The insurability criteria are useful to the insurer in allowing risks to be classified. In addition, insurance can also be legally stipulated in the form of compulsory insurance. In this context, political intentions may also account for insurability in some cases. With regard to compulsory insurance, such as liability insurance for manufacturers of medicinal products for harm caused to people by such products, the assessment of insurability criteria is no longer decisive.

3.2 Application of the concept of insurance cover to a nuclear disaster

3.2.1 Disasters: Insurance and insured risks

Every power plant operated in Germany faces the risk of standard deviations from normal operations due to hazards (in the power plant itself and in the direct and indirect environment). This means that incidents or accidents may occur, with radioactive emissions causing damage to surrounding systems (infrastructure, health, habitats, etc.).

A power plant's risk situation is described by a combination of factors from the environment, economy, technology, legislation/politics and the power plant's individual characteristics such as:

- the power plant (type): reactor type and corresponding functionality, fuels used, age of the power plant, etc.
- the nature of regional and temporal factors: geographic location (including rivers in the region), the prevailing weather conditions and wind directions, population density in the region, etc.

---

[92] Cf. [Goßner 2002], p. 5.

Different possible characteristics and probabilities of occurrence exist for all possible factors and possible combinations of them. Some of the factors do not affect the operation of the power plant or may even have a positive impact (for example, the improvement of efficiency levels and/or safety due to the implementation of upgraded technology). Other types should be classed as hazards. They have the potential to impact negatively on the operation of a power plant; that is, to increase the probability of damage occurring. The topic of uncertainty about the occurrence of events was described in Section 3.1.1 (Insurance and the insured risk).

Each possible case of damage resulting from the occurrence of a hazard or the combination of several hazards can be described as an individual probability of damage occurring and an individual amount of damage.

An individual maximum amount of damage with an individual probability of damage occurring can arise for every power plant due to the individual characteristics of the factors. This means that the potential risk of a nuclear disaster at a power plant can be described in the form of a probability distribution of damages with an individual probability of damage occurring and an individual amount of damage. Based on the probability distribution, an expected value of damage incurred (μ) can be attributed to a nuclear disaster. This is equivalent to "the average of all possible outcomes based on the probabilities".[93] In real life, the expected value of damage is never precisely met. There is a fifty per cent probability that the real amount of damage will be lower than the expected value and a fifty per cent probability that it will be higher than this value. This corresponds to an underwriting profit and loss, respectively. The fluctuation of the expected value of damage is referred to as variance (σ). Figure 3.2 shows possible damage distribution for a nuclear disaster and illustrates the described connection between the expected value (EV) and the underwriting profit and loss.

<u>Vertical axis</u>: Probability of the amount of damage if a nuclear disaster has occurred
<u>Horizontal axis</u>: Amount of damage in a nuclear disaster EV

Underwriting profit Underwriting loss

Figure 3.2: Damage distribution of a nuclear disaster (Source: authors' own work)

The risk of a nuclear disaster is generally classified by an extremely low probability of occurrence, a lack of regularity (the calculability criterion, see Section 3.1.4, Criteria and limitations of insurability), and an extremely high damage potential. Hence, the risk of a nuclear disaster should be classed as a severe-damage or disaster risk.[94]

---

[93] [Farny 2006], p. 27ff.
[94] Cf. [Nguyen 2007], p. 6ff.

In the context of insurance, the risk of a nuclear disaster is not a "normal" or usual risk, as the above-mentioned characteristics mean that it cannot be reliably calculated using actuarial methods. It is more accurately described as representing a type of "development" risk. This means that the estimate of the probability of occurrence and of the potential maximum amount of damage must always continue to develop in line with the state of science and technology, as well as that of the surrounding systems (the development of political risks, the accumulation of value in an economy, etc.)

Among other things, a nuclear disaster in a power plant causes damage to people's lives and health, infrastructure, and to an economy's ability to act. As described in Chapter 2, the owner of a nuclear power plant is liable for all damages caused by a nuclear incident. Hence, the owner is also liable in cases of a maximum amount of damage caused by a nuclear disaster. It could transfer this risk to an insurer in the form of liability insurance – so long as an insurer (or a consortium of insurers) is willing to bear the risk involved.

The hypothetical liability insurance[95] described in this study would thus provide the owner of a power plant with compensation for all damages to third parties caused by a nuclear disaster (harm to people, property, commodities, etc.) This represents the insured risk in total.[96]

As liability insurance is based on damage to be calculated in real terms, on which the amount of the insurance benefits (limited by the amount of the agreed limit of liability) is measured, it should be classified as a type of indemnity insurance. The liability insurance currently taken out by the power plant owners from the nuclear insurance pool, the German Nuclear Reactor Insurance Association, represents first-loss insurance, as the insurance benefits are limited to a maximum of €255.65 million. The hypothetical liability insurance premium calculated in this study assumes no limitation on the amount insured. Hence, the type of liability insurance assumed here corresponds to unlimited insurance.[97]

The insurer develops risk reserves from the premiums received (annually), which it uses to pay the required insurance benefits in the event of damage.

Assuming that an insurer or an insurance pool were to include all 17 risks of a nuclear disaster (in March 2011, there were 17 power plants in Germany) in its portfolio or set up a pool, a

---

[95] This is described as "hypothetical" because no insurability of the liability risk for a nuclear disaster exists in reality.

[96] No exceptions are made in this study as regards damage caused by a nuclear disaster. This means that the insurer (theoretically) assumes all risks under the terms of a liability insurance policy without excluding certain hazards or damages from the outset. This is why the risk that actually exists and the specific risk (in the sense of the insured risk) are identical in this case.

[97] In insurance practice, this is also known as unlimited cover.

balance of risk would be possible in the (relatively small) pool,[98] as several of these similar but separate risks would be in the portfolio or form the pool.

However, if an insurer only included one of these risks in its portfolio, there could be no balance of risk in the pool.

Both of these assumptions have been taken into account separately in this study.

3.2.2 Insured risks and insured damage in a nuclear disaster

Based on the connections between risk, hazards and damage and insurability criteria, as explained above, the following section will only deal with hazards that could lead to the occurrence of the insured damage in a nuclear disaster at a power plant (as an insured risk). The damages typically incurred in a smaller incident or accident, as described by INES (levels 1 to 6 on the scale), are not covered here.

The hazards of operating a nuclear power plant, which can cause cases of damage up to the maximum case of a nuclear disaster, are very complex. In qualitative terms, they can be roughly divided into:

- accidental causes
    - technical failure (for example, flawed technology, outdated building materials, etc.)
    - human error (for example, incorrect evaluation of a situation, operating errors, tiredness, etc.)
    - (natural) disasters (for example, earthquakes, floods, accidental aeroplane crashes, etc.)

- deliberate causes
    - deliberate sabotage (internal sabotage by an employee or external sabotage by a third party)
    - acts of terrorism (for example, an aeroplane crash, an attack using guided missiles)

All possible types of hazards and damages have been included in the calculation of the insurance premium for the liability risk incurred in the operation of a power plant by its owner. No attempt is therefore made to list the individual components of both aspects in the conclusion.

---

[98] See Section 3.1.1 for a description of the balance of risk in a pool. Further comments on the balance of risk in a pool can be found in [Farny 2006], p. 46ff.

As subsequently illustrated by paradigmatic scenarios in Chapter 5, the hazards have a particular impact on the probability of damage occurring. Hazards including technical failure due to aging, human error, earthquakes or deliberate aeroplane crashes are described in this chapter, and assumptions are made about their impact on the probability of occurrence.

Equally, no limits will be set in principle as regards the quantitative, spatial and temporal characteristics of hazards that can cause a nuclear disaster, or as regards the damages incurred.

Every nuclear disaster will cause a large number of types of damage to the surrounding technical, social and ecological systems. These possible types of nuclear damage are defined in Article 1, Par. a, No. (vii) of the Protocol to amend the Convention on Third Party Liability in the Field of Nuclear Energy as follows:

1. "Loss of life or personal injury;
2. loss of or damage to property;

and each of the following to the extent determined by the law of the competent court:

3. economic loss arising from loss or damage referred to in subparagraph 1 or 2 above insofar as not included in those subparagraphs, if incurred by a person entitled to claim in respect of such loss or damage;
4. the costs of measures of reinstatement of impaired environment, unless such impairment is insignificant, if such measures are actually taken or to be taken, and insofar as not included in subparagraph 2 above;
5. loss of income deriving from a direct economic interest in any use or enjoyment of the environment, incurred as a result of a significant impairment of that environment, and insofar as not included in subparagraph 2 above;
6. the costs of preventive measures, and further loss or damage caused by such measures."[99]

The prerequisite for the recognition of damage in this sense is that it is caused by ionising radiation, which in turn is caused by a source of radiation, nuclear fuel or radioactive products inside a power plant or by a nuclear facility and its operation.[100]

In order to clarify the complexity of nuclear damage, Hahn/Sailer (1987) divided the possible types of damage into six categories, which in turn contain individual subcategories. Figure 3.3 illustrates this classification of the possible types of damage.

1. **Impact on human life and health**
   Fatalities due to exposure to the accident
   Subsequent fatalities; for example, from cancer caused by exposure to the accident
   Acutely ill people following the accident, curable
   Chronically ill people following the accident

---

[99] Protocol to amend the Convention on Third Party Liability in the Field of Nuclear Energy of 12 February 2004, Article 1, clause a.

[100] Ibid.

Genetic damage
Psychological damage

2. **Impact on other living organisms**
   Loss of organisms used for economic purposes
   Loss of common wildlife
   Loss of rare species or of those facing extinction
   Loss of biotopes
   Impact on infrastructure
   Short-term/long-term contamination of drinking water
   Soil contamination
   Removable surface contamination
   Non-removable surface contamination
   Rendering useless of neighbouring sites
   Rendering useless of other infrastructure

3. **Economic impact including disaster control measures**
   Costs of measurements and disaster control
   Costs and consequences of removal
   Costs and consequences of evacuation
   Costs of resettlement
   Production losses outside the accident site
   Secondary costs of production losses
   Loss of reputation in companies or sectors

4. **Social and political impact**
   Impact on the conduct of individuals
   Impact on the conduct of parts of society
   Changes in social conduct
   Changes in social and political benchmarks
   Changes in society and the political system
   Adverse effects on international relations
   Proliferation

5. **Ecological impact**
   Impact on the integrity of the biosphere
   Impact on ecological resources
   Changes in natural conditions

Figure 3.3 Types of damage resulting from a nuclear disaster (Source: authors' own work, based on [Hahn/Sailer 1987]).

Among other things, the quantitative calculation – the monetary valuation of individual damage – is used to calculate the total damage that may result from a nuclear disaster. The insurer factors the sum of individual damages into the calculation of the necessary liability insurance premium.[101] In this study, the insurance premium will be calculated on the basis of a single nuclear disaster or maximum damage in a power plant in Germany. The occurrence of cumulative damage[102] is excluded.

The extent of damage depends on the amount of radioactive material released. In this regard, the basic insured object (the power plant) and its characteristics have a significant impact on the extent of damage. For instance, an older power plant includes other hazards (for example, as

---

[101] For information on calculating individual damage components, see Chapter 4.

[102] Cumulative damage means that the occurrence of a hazard (for example, an earthquake) causes damages to several insured risks in an insurance company's portfolio, which are not interrelated (such as two or more power plants insured by a single insurer).

regards the causes, time and extent of possible damage) than a newer power plant built to a more recent standard of safety technology.

In general, it is very difficult to quantify the types of damage resulting from a nuclear disaster, as no quantification methods exist for many types. This is the case for types of damage such as "changes in social conduct" or "impact on the integrity of the biosphere". As far as concerns "extinction of an animal species", there is uncertainty on the one hand about how one should value this damage in monetary terms. On the other hand, the long-term secondary damages are unclear; for example, concerning the question of whether the future extinction of animal species can be classed as a direct or indirect result of a nuclear disaster.[103]

The extent of damage is influenced by a large number of further parameters. These include, in particular, weather parameters for calculating dispersion and parameters on the characteristics of the affected area, such as

- wind direction and speed,
- precipitation at the time of the accident or during the release of radioactivity,
- amount of radioactive material released,
- updraft,
- parameters affecting diffusion of the released radioactive material (for example, temperature and radiation balance),
- surface of the affected area and
- use of the contaminated area (for example, agriculture, forestry, rural and urban residential areas as well as industrial zone).[104]

Following comprehensive literature research and reading[105] for this study, various quantification approaches and defined assumed amounts of damage from earlier expert studies on quantifying the types of damage were used. The above-mentioned weather parameters were also taken into account in the estimate and calculation of the insurance premium in this study. For example, insofar as they can be statistically predicted, wind direction, wind speed, precipitation and amount of radioactive material released were included. Structured details on the factors taken into account are provided in Chapter 4.

As a general rule, cautious assumptions were made in this study when calculating the amount of damage and its probability of occurrence, as the values included from available studies, such as

---

[103] The example of the southern gastric-brooding frog (Rheobatrachus silus) will be used to explain the vast extent and impossibility of assessing the impact of extinction of an animal species. This frog became extinct in 2008. Only after this point did it become known that the species' tadpoles incubated in their mother's stomach. This was possible because of a special substance that deactivated the production of hydrochloric acid in the mother's stomach. It is possible that this substance could have been used as an ulcer treatment in earlier studies. The economic value of the extinct frog – regardless of its value as a living organism and unique species – can therefore not be defined. Cf. [Fokken 2008].

[104] Further information on meteorological parameters is available in [Strahlenschutzkommission 2003], p. 19ff.

[105] A list of the literature that goes beyond the bibliography and was taken into account in the text can be found in Annex C.

the risk coefficient for estimating the number of persons harmed by radioactive emissions, are themselves average values from epidemiological studies.

3.2.3 Relevant assumptions for the calculation of the insurance premium

The insurer uses the receipt of liability insurance premiums from one or more insured risks within the portfolio to fund expected compensation payments for an individual nuclear disaster. The damage to be insured for an individual power plant accident that counts as a nuclear disaster is calculated from the sum of the incurred damages in a power plant's surrounding systems. The results of past studies on amounts of damage[106] and the probability of damage occurring[107] as well as assumptions about scenarios affecting the probability of occ0urrence[108] were used to calculate the expected damage costs.

Risk premium

In accordance with the principle of equivalence in insurance, the pure risk premium is equivalent to the expected damage value of a nuclear disaster in a power plant.[109] Both the amount of damage and the different probabilities of occurrence are determined by means of the presented scenarios.[110]

Calculation of the pure risk premium is based on the expected value of the distribution of the entire risk of a nuclear disaster for an individual power plant. However, as specific values are only available for a few of the types of damage involved per power plant, the values only differ marginally among the 17 different power plants taken into account. The maximum expected damage for a power plant in Germany is simulated in Section 6.2 on the basis of the probability distribution of the amount of damage for the 17 power plants. Extreme value statistical methods were used in this simulation. The amount of damage calculated is combined with all probabilities of occurrence on the basis of the results of different studies (Section 5.1) and scenarios (Section 5.2). The total amount of damage is only reached at the end of the calculation period.

In symmetrical damage distribution the pure risk premium covers only 50 per cent of the damage as the equivalent of the expected damage value; as a result, the insurer factors a safety margin into the premium to be paid.

Safety margin in the risk premium

---

[106] See Chapter 4 for further information.
[107] See Section 5.1 for further information.
[108] See Section 5.2 for further information.
[109] Cf. [Farny 2006], p.60.
[110] See Chapter 5 for further information.

Section 5 of the Premium Reserve Regulation also requires the safety margin to be factored into an insurance premium: "In respect of the derivation of calculation principles that is to be made in accordance with actuarial methods, all circumstances that may cause the data gained from the underlying statistics to change and fluctuate shall be considered and weighted appropriately in accordance with actuarial principles. Derivation of calculation principles on a best-estimate basis shall not be sufficient. An estimate of future circumstances must include a negative deviation of the relevant factors from the assumptions made and derived from the statistics. This applies to the valuation that as a matter of principle relates to individual risks, and by analogy to the valuation in respect of risks, which cannot be individualized and for which no sufficient statistical data is available."[111]

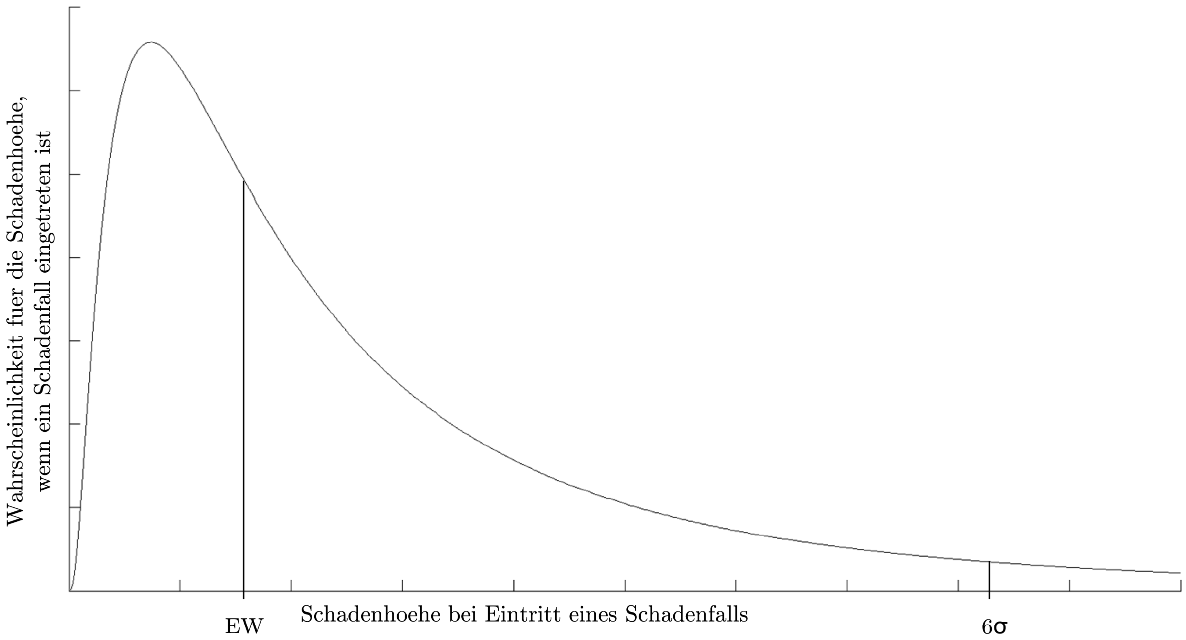
In normal symmetrical damage distribution, a safety margin equal to variance σ of the risk premium is enough to cover 68.3 per cent of damages below this normal damage distribution. A safety margin of 2σ generates cover of 95.4 per cent, while a value of 3σ provides cover of 99.7 per cent. The last-mentioned safety margin is common in property insurance.

However, normal distribution cannot be used to describe the risk of a nuclear disaster. A safety margin of 3σ does not therefore correspond to cover of 99.7 per cent when another form of distribution (for example, an asymmetrical form) appropriate to a nuclear disaster is used. Yet in order to reach cover of at least 99.5 per cent, as required by the solvency regulations for insurers, a higher safety margin of 6σ must be used. This safety margin is used (in the banking industry) to calculate the insurance premiums for risks with very high expected damage values and very low probabilities of occurrence. As this corresponds to the nature of the risk of a nuclear disaster, a safety margin of 6σ is appropriate for calculation of the insurance premium in the study. Figure 3.4 shows the probability distribution to illustrate the circumstance of a pure risk and safety margin.[112]

---

[111] Section 5 of the Premium Reserve Regulation (DeckRV).

[112] This is a random sketch of a distribution and does not equate to the maximum damage caused by a nuclear disaster.



Vertical axis: Probability of the amount of damage when a damage event has occurred

Horizontal axis: EV Amount of damage when the damage event occurs 6σ

Figure 3.4: Probability distribution to illustrate the safety margin (Source: authors' own work)

Premium components such as insurance tax, profit markup and loading for operating costs are not taken into account in this study, as they are negligible in comparison to the risk and safety margins and would not have led to any fundamental change in the methods or outcome.

Furthermore, the insurance premium was calculated on the assumption that no premium exemption would ensue; in other words, that the premium would still need to be paid after the risk had lapsed – following occurrence of the damage in a nuclear disaster – as compensation cannot be paid before the reserve sum has been completely met.

A risk of change – in the sense of a risk that changes during the term of the insurance contract– was not taken into account in the calculations conducted for this study.

It was assumed that the insurer uses the annually received premiums to build up a risk reserve for the case that a nuclear disaster occurs. It was further assumed that the insurer invests risk reserve assets in capital investments and transfers the financial obligations arising from this particular damage event to a tax-free reserve.

The interest-generating aspect of received premiums was taken into account in this study and an interest rate of 2 per cent was assumed.[113]

3.2.4 Assessment of the criteria and limitations of insurability relating to a nuclear disaster

The insurability of a risk is always subject to a cost-benefit calculation. This means that the insurer and the insured party weigh up their cost-benefit relationship. For the insured party, benefit results from the transfer of the damage distribution and the subsequent commitment by the insurer to cover the financial costs of damage. The disbenefit for the insured party results from the insurance premium to be paid. The cost-benefit relationship for the insurer is the exact inverse. Benefit is particularly determined by the premiums received. As shown, this is calculated on the basis of the probability of damage occurring, the expected value of damage, and the variance of the expected value. The disbenefit results from the payment of the agreed compensation in the event of damage. The insurer cannot predict with absolute certainty whether, when and to what extent the event will occur.[114]

If the insurance provides both parties with a benefit that outweighs the cost, a contract will be signed. When weighing up cost vs. benefit, the insurer refers to the criteria of insurability: randomness, calculability, unambiguity, independence and definition of the extent of damage (see Section 3.1.4, Criteria and limitations of insurability).

Randomness is limited in terms of a nuclear disaster and the maximum damage associated with it, as deliberate sabotage or acts of terrorism are also among the hazards to be insured.[115] These are planned by terrorists with the precise aim of causing maximum damage.[116] However, the criterion refers in particular to the fact that there is randomness as regards the occurrence, time and/or extent of the damage on the part of the insurer and the insured party. This implies that there must be independence from the will or conduct of the insured party (negligence), in this case the owner of a power plant.[117] This criterion can be regarded as being sufficiently met.

On the one hand, the difficulty of estimating the probability of occurrence or amount of damage of a nuclear disaster is caused by the fact that there are hardly any damage statistics, which, if compared, could allow for a sufficiently accurate estimate. Only approximately comparable incidents, such as those in Chernobyl or Harrisburg, as well as empirical studies, such as those including reports on the state of power plants, are of use in this estimate. On the other hand, the causes of risk for a nuclear disaster and its impact are very complex, which means that an

---

[113] Cf. Section 6.2.

[114] Cf. [Farny 2006], p. 35 ff.

[115] See Section 3.2.2, Insured risks and damages of a nuclear disaster, in which it was explained that no peril has been excluded from the study.

[116] For information on the randomness of terrorism risks, see [Nguyen 2009], p. 7 and [Benzin 2005], p. 723.

[117] Cf. [Farny 2006], p. 38.

estimate can only be made with great uncertainty.[118] Simulation methods and models for the disaster risks are improving in line with progress in science and technology, which could lead to better comprehension of risk (in terms of cause-and-effect analysis) and thus to a possible expansion of insurability.[119]

As implied in the previous sections, the perils that can lead to a nuclear disaster and the maximum resulting damages form a very complex system. It is therefore impossible to define all possible perils and damages precisely in advance (for example, for the purpose of premium calculation). Equally, it is not always possible to attribute an individual case of cancer or deformation with certainty to the nuclear disaster, especially when cases of long-term effects and genetic defects are involved. Hence, the criterion of unambiguous attribution of damage as a consequence of the event is not met.

Another prerequisite for the insurability of a risk is its independence from other insured risks in the same portfolio, in that there is a lack of correlation between them. The criterion of independence is met if a peril that occurs (for example, an earthquake) does not lead to a nuclear disaster in several of the power plants insured by an insurer.

Regarding the criterion of the extent of damage, the potential extent of damage is very high in risks of catastrophe – such as a nuclear disaster – and can be "infinite" as a result of different scenarios. This is the reason why limits of liability (first-loss insurance policies) have been agreed in the practice of power plant insurance to date.[120]

3.2.5 Preliminary conclusions

As a risk to be insured, a nuclear disaster represents a dynamic risk.[121] Such dynamics mean that the risk of a nuclear disaster must also be continuously re-examined in terms of its characteristics and insurability.

However, the insurer must be able to precisely define the maximum damage of a nuclear disaster in order to extrapolate a premium to cover the payments to be made in the event of loss.[122]

---

[118] Cf. [Nguyen 2009], p. 7.
[119] Cf. [Nguyen 2009], p. 8.

[120] Cf. [Nguyen 2009], p. 9.
[121] See the comments on a nuclear disaster as a development risk in Section 3.2.1.
[122] Cf. [Farny 2006], p. 39 ff. and [Nguyen 2009], p. 9.

The explanations in this section clearly show that the risk of a nuclear disaster only meets insurability criteria to a very limited extent, and that their application becomes very difficult because of the complexity of the perils to be insured and the damage in the event of a nuclear disaster.

As a result of limited fulfilment of the insurability criteria, the insurance premium calculated in this study is hypothetical. The calculation of this hypothetical premium has included the results and assumptions of a large number of existing empirical studies on the hazards and impact of nuclear radiation on surrounding systems. In particular, a large number of assumptions have been made and the difficulties regarding the insurability of a nuclear disaster have been "overlooked".

Chapter 4

Existing quantification methods for assessment of damage amounts

4.1 Bases of existing approaches

4.1.1 Bases of dose-effect relationships for nuclear radiation

Harmful effects on human health represent the most serious damage that can be caused by nuclear radiation. Assessing the number of people affected and the nature of the effects on them is therefore an essential part of all examined studies on quantifying the extent of damage after a nuclear accident. The extent of radiation-induced damage to be expected depends on the specific situation, in particular on the amount and duration of exposure.[123] Even a very small absorbed dose[124] – defined as the amount of energy deposited in a medium by ionising radiation per unit mass – can result in serious radiation damage, "since radiation deposits energy at the atomic level and can thus destroy molecules that are essential for life".[125]

The nature of the damage depends on numerous factors, in particular on the type of ionising radiation involved. To take account of their different effects on the human organism, the absorbed dose is multiplied by a radiation weighting factor that reflects the relative biological effectiveness – alpha radiation is considered about 20 times as harmful as the same amount of gamma radiation, for example – to calculate the equivalent dose, which is measured in sieverts (Sv).[126] Older studies frequently use the unit rem (an acronym for "roentgen equivalent in man"); 1 rem equals 0.01 Sv. It should be noted, however, that while the radiation weighting factor defined in 1990 by the International Committee on Radiological Protection (ICRP) in ICRP Publication 60[127] is essentially based on scientifically determined relative biological effectiveness, it is also influenced by political consensus-building processes.

A weighted average of the equivalent dose to different organs and tissues depending upon their radiosensitivity in regard to

- cancer risk and

---

[123] Cf. [GRS 2000], p. 8.

[124] Absorbed dose = absorbed radiation energy / mass; unit: Gy (gray) = 1 joule/kg.

[125] [Umweltlexikon Online a].

[126] Since 1 Sv represents a relatively large equivalent dose, values encountered in practice are usually given in millisieverts (1mSv = 0.001Sv = 10^{-3}Sv) or microsieverts (1µSv = 0. 000001Sv = 10^{-6}Sv) using an SI prefix.

[127] [ICRP 1991].

- radiation-induced genetic changes

produces the effective dose, which quantifies the risk of stochastic effects due to the exposure of individual organs and tissues or of the entire body to radiation. Stochastic effects are effects for which the probability of the effect occurring, but not the degree or severity of effect, is a function of radiation dose. The most important stochastic effects are solid tumours, leukaemia and hereditary diseases. The calculation involves multiplying the equivalent dose by radiation weighting factors for the individual organs, which are also given by the International Committee on Radiological Protection. "Uniform irradiation of the entire body and irradiation of individual organs and tissues results in the same radiation risk if the effective dose is the same."[128] Effective dose is also measured in sieverts (Sv).

In the event of an accident, the dose is limited by "emergency reference levels". These allow disaster management measures to be planned, and they set the maximum levels that make implementation of these measures imperative as part of the disaster management approach.[129] These emergency reference levels play an important role in the studies examined here as they enable the identification of areas that need to be evacuated and areas where populations need to be resettled indefinitely, for instance.

The fact that the effects of a nuclear radiation leak often emerge years or even decades after the actual event and cannot be distinguished from spontaneously occurring cancers (responsible for 20 to 25 per cent of deaths in the Western world) makes it difficult to relate the effects of nuclear radiation to particular events (such as reactor accidents).

Measure	Emergency reference level		
	Organ dose (thyroid gland)	Effective dose	Integration period and exposure pathways
Staying indoors		10 mSv	External exposure in **7 days** and committed effective dose from the radionuclides inhaled during this period
Taking iodine tablets	**50 mSv** People under 18 and pregnant women; **250 mSv** People aged 18 to 45		Committed organ dose from the radioiodine inhaled during a period of **7 days**
Evacuation		100 mSv	External exposure in **7 days** and committed effective dose from the radionuclides inhaled during this period
Long-term resettlement		100 mSv	External exposure in **1 year** from radionuclide deposits
Temporary resettlement		30 mSv	External exposure in **1 month**

Figure 4.1: Emergency reference levels for various measures (Source: [BMU 2008 a])

---

[128] [GRS 2000], p. 8.

[129] Cf. [BfS c], p. 10.

In order to keep risk levels down to much lower levels of several mSv and below, and thus to ensure better radiation protection, one are obliged to extrapolate figures from higher doses. In general practice, a simple, linear dose-effect relationship is assumed; no dose threshold has been established. This presupposes that there is no dose small enough to exclude some level of risk. A "linear" dose-effect relationship is said to exist when the effect on a patient's health increases or decreases at the same rate as the dose they are exposed to. Thus the assumption is that even the smallest dose of nuclear radiation – that is, exposure to natural radiation, too – entails some risk, albeit very slight and can theoretically cause cancers such as leukaemia. This is a purely theoretical assumption. Due to random fluctuations in spontaneous morbidity it is not possible to perform a direct epidemiological study on the risk coefficients of such low doses. Using a linear dose-effect relationship without a threshold to extrapolate lower doses that cannot be investigated by epidemiological studies from the risk levels observed for higher doses would seem to be a reliable method, supported by molecular biological, cytological and animal experiments.[130]

There is lively debate among scientists about the assumption of a linear dose-effect relationship without a threshold (a model abbreviated as LNT for linear no-threshold). Even the ICRP now states (in Recommendation 103) that an international norm has become established in the course of current scientific debate and investigations, and that there is a general attitude that in situations where many people have been exposed to very small doses it makes sense to define a limit for the individual dose under which assumptions about a collective dose cannot be the yardstick for measuring the collective risk. This "irrelevance threshold" has been set at 10 µSv per calendar year for individual members of the population. Because little is known as yet about the cancer risk at low doses and dose rates,[131] ICRP 103 recommends refraining from calculating cancer deaths in cases of exposure to small doses."[132]

The German Commission on Radiological Protection, on the other hand, has stated that there is little evidence for lower cancer risk coefficients in the case of low doses/dose rates in comparison to acute exposure to high doses of radiation, and thus does not consider it warranted to assume lower coefficients when considering radiation protection measures.[133]

Moreover, the radiation-induced cancer risk is dependent on the age of the individual when exposed to radiation. Thus risk coefficients for the induction of cancer underestimate effects on young individuals and overestimate them for older ones.

Other stochastic effects of radiation have emerged in addition to those considered so far, such as radiation-induced cataracts with no dose threshold and lower IQ scores due to foetal exposure to radiation in the third and fourth months of pregnancy. Neither of these effects is currently taken into account when calculating effective dose.[134]

---

[130] Cf. [CRP 1994], p. 5.

[131] Dose rate is equal to dose per unit of time (second, minute).

[132] [DSF 2009], p. 3.

[133] Cancer risk through several years of exposure to doses near the threshold value of the maximum professional dose according to Section 56 of the Radiation Protection Ordinance (StrlSchV) – CRP recommendation.

[134] Cf. [Krieger 2009], p. 305.

Proceeding from the assumption of a linear correlation – that is, that a small number of people receiving a high dose is equivalent to a large number of people receiving a very small one – it is possible to calculate a collective dose for a segment of the population by multiplying the average individual effective equivalent dose by the number of individuals in the group. The collective dose of a population is the sum of the collective doses of the various groups it is composed of, and is measured in "person-sieverts". However, the aggregation of very small individual doses for a large population results in a significant collective dose, obscuring the fact that the level of individual risk is extremely low.[135]

Since large numbers of people are exposed to relatively small individual doses of radiation for long periods following a nuclear accident, most of the studies considered in the present study use collective dose as a basis for estimating the expected additional cases of cancer and genetic damage. As the summary reveals, the concept of "collective dose" used by most general studies on estimating the economic impact of a serious nuclear accident is based on numerous assumptions, and it oversimplifies a number of issues and circumstances. Any precise calculation of individual effective doses must also be regarded as oversimplifying due to the many assumptions that have to be made about a potential nuclear accident (for example, the type and number of nuclides released and exposure pathways). Since more recent, more precise studies on the estimated impact of a nuclear accident in Germany are lacking, the sections below will analyse the different approaches[136] to quantification that have been published so far. The results of these approaches have also been used as a basis for deriving a mathematical distribution from the range of the amounts of damage presented in the studies.

4.1.2 Using the risk coefficient to describe the risk of cancer caused by exposure to radiation

"Radiation risk is the term used to describe the probability of an adverse effect on an individual due to radiation exposure over a certain period of time."[137]

Assuming a linear dependence between dose and mortality, leukaemia and cancer each have a straight line. The risk coefficient is equivalent to the slope of the straight lines in the dose-effect relationship. Hence, the risk (with fatalities per year as the unit) is the coefficient multiplied by the dose.

The estimate of the risk coefficient for all age groups among the exposed individuals is primarily based on epidemiological studies on the survivors of the atomic bomb explosions in Hiroshima and Nagasaki.

The International Commission on Radiological Protection (ICRP) provides estimates for the risk coefficient, each of which is based on current scientific knowledge. For example, in its 1990 recommendation, the ICRP estimated the increased individual lifespan cancer mortality risk from ionising radiation at a total of 5% per sievert in cases of whole-body exposure to a low individual dose. To illustrate this risk, if 100 people are exposed to a dose of one sievert, five of them will probably later develop cancer. The majority of the studies taken into account use this risk coefficient to extrapolate the expected stochastic number of cancer fatalities due to the collective dose.

---

[135] Cf. [OECD 2003], p. 42.

[136] The references in Annex C provide an overview of studies on this topic. They include both studies cited directly here and others that were merely read as a foundation for the present study.

[137] [Krieger 2009], p. 305.

As it has only been possible to learn about widespread and long-term exposure from the reactor accident in Chernobyl, the study by Hohmeyer,[138] which deals with the theoretical impact of a core meltdown accident in Germany, introduces another factor with the aim of taking the higher population density in Germany into account. This study argues that in a densely populated country like Germany, a significantly higher number of people would be exposed to the radiation released by a core meltdown accident than was the case in the affected area around Chernobyl. As it cannot be assumed that it would be feasible to evacuate millions of people immediately in the event of an accident, the use of this factor seems to be pertinent. It is based on the relationship between the population density in the regions affected by the Chernobyl accident and the average population density in the Federal Republic of Germany.

The following section provides an overview of the various quantification approaches, the results of which have been completely or partially included in the calculation of an insurance premium in chapter 6.

4.2. Early studies

4.2.1 Olav Hohmeyer, 1989

The first study used, which deals with the quantification of the impact of a reactor accident in the Federal Republic of Germany, was written by Olav Hohmeyer in 1989.[139] It uses a hypothetical nuclear disaster in Biblis to calculate the amount of economic damage in the form of production losses due to cancer. Other types of damage are not taken into account.

The calculations are based on the assumption that the accident has exposed the population to a radiation dose of 2.4 million person-sieverts. This assumption and the release of an assumed amount of 4% of the radioactive inventory are based on Soviet publications that were available at the time Hohmeyer’s study was prepared. According to estimates at the time, the risk coefficient for the description of the increased risk of contracting cancer due to radiation exposure fluctuated between 2% and 74% per sievert.[140] Hohmeyer based his further calculations on the value used by the International Commission on Radiological Protection at the time, namely 10% per sievert.

The concept of a collective dose is largely based on experiences from the Chernobyl disaster. Hohmeyer introduces a factor of ten in order to take into account the significant differences between the population density of a relatively sparsely populated region like the area around Chernobyl (approximately 100,000 people) and a conurbation like the region around Biblis, with over three million inhabitants in the immediate area. As previously mentioned, the aim is to take into account the fact that the number of people who would very likely be exposed to radiation following an accident is significantly higher.

By multiplying the released radioactivity by the risk coefficient and the factor used to take population density into account, the purely mathematical result is 2.4 million expected additional cancer cases. Hohmeyer uses the human capital method to calculate a monetary value for these cases at a later point in the study. He sets the production losses to the economy for one cancer fatality at 20 years of employment and DM 50,000 annually, that is, a total of

---

[138] See [Hohmeyer 1989].
[139] Idem.
[140] Cf. [Ewers/Rennings 1992 b], p. 386.

DM 1 million per cancer fatality. He equates non-fatal cancer to ten lost years of employment, that is, a total of DM 500,000. Assuming a mortality rate of 50%, this amounts to an average loss of DM 750,000 for each cancer case.

Hohmeyer calculates total economic damages as a result of production losses due to people suffering from cancer at DM 1.8 billion (equivalent to around €1.37 trillion in 2011).[141]

Shortly after publication of this study, Hohmeyer was able to draw on the results of the German Risk Study on Power Plants, Phase B. This study mentioned possible release rates of up to five times higher than the reported release rate of 4% in Chernobyl. Assuming release of 12 million person-sieverts (2.4 million x 5), the result would be 12 million cancer cases and total damage of DM 9 trillion. However, it must be noted that the exact release rate in the Chernobyl disaster is still not known today.

4.2.2 Richard Ottinger et al., Pace University, New York City, 1990

Another analysis was conducted by Richard Ottinger and colleagues at Pace University in New York City in 1990.[142] The method used to calculate the impact of a reactor accident in the United States of America is similar to that used by Hohmeyer. In addition to the monetary valuation of health damages, the study also takes asset losses due to lost agricultural production into account.

The starting point in this study is also a collective dose of 2.4 million person-sieverts, which is cited in the USSR report of 1986. Ottinger uses a value of 7.7% per sievert as the risk factor, which he bases on estimates by the American Academy of Sciences at the time. No other factors are taken in account as regards population density, which makes sense given that the population density in the USA (2010: 32 inhabitants/km²) is seven times lower than in Germany (2010: 229 inhabitants/km²).

The number of additional cancer cases resulting from these figures is 140,000 fatalities and 45,000 non-fatal cases, assuming an approximate mortality rate of 75%. Taking the review of eight empirical studies as a basis, the report uses the hedonic pricing method to calculate the monetary value. This produces a value of $4 million for a cancer fatality and $400,000 for a non-fatal cancer case. The report also takes into account figures from a report by the US Energy Department regarding expected mental disabilities (700 cases) and genetic damage in new-born babies (1,900 cases) and classes them as non-fatal cancer cases. This results in total health damages of $579 billion (equivalent to around €629 million in 2011.)

The authors use assumptions by agricultural experts to calculate agricultural production losses. These assumed a 10% loss per wheat harvest per year in the USSR as a result of the accident in Chernobyl. Ottinger calculates total values of $34 billion to $73 billion for agricultural production losses, with the variations resulting from the use of different discount rates.

4.2.3 Ewers/Rennings on the monetary damage of a nuclear disaster in Biblis, 1991

---

[141] The original amount was converted to euros with an annual inflation rate of 2% in this and all of the following conversions into euro figures for 2011.

[142] See [Ottinger et al. 1990].

The 1991[143] study by Ewers/Rennings calculates the environmental damage caused by a nuclear disaster in Biblis, using the health damages and production and asset losses resulting from the loss of workers, production locations and residential space.

The authors also use Hohmeyer’s approach as the basis for calculating health damage. They only make modifications as regards the release of radioactivity, which is assumed to be twice as high as the value stated in the Chernobyl Report (4.8 million person-sieverts). The reason given for this is a comparison of the release rates of the biologically most dangerous radioactive substances in the Chernobyl disaster with the expected rates of a similar disaster in Biblis. The risk factor of 10% per sievert and the factor of ten used to take population density into account are also taken from the study by Hohmeyer. The total health damages thus come to DM 3.6 trillion (equivalent to around €2.74 trillion in 2011.)

In addition, this study takes into account the damage resulting from the closure of areas, the resettlement of the population and the loss of agricultural production in and beyond these areas. The authors use calculations by Öko-Institut in Darmstadt on the dispersion of radioactivity. According to these calculations, some 4.3 million people would need to be evacuated, while up to ten million people could be affected by the resettlement measures. It is assumed that the exclusion zone would be closed for all use for at least five years, which was factored into the calculations via the loss of total net domestic product for the area. An amount of DM 420 billion for this loss is calculated using statistics from the Federal State of Hessen for 1987. Based on the projected population of 7.2 million and the projected value of the net domestic product, further costs of DM 670 billion are calculated for the assumed resettlement areas. Hence, the property damages caused by evacuation and resettlement come to a total of DM 1.09 trillion (equivalent to around €828 billion in 2011.)

The authors take Ottinger’s estimates of $34 billion to $73 billion as the figure for agricultural production loss. The conversion rate at the time of 1.5 US dollars to 1 German mark yields figures for damages ranging from DM 51 billion to DM 109 billion, which the authors conservatively set at DM 50 billion (equivalent to around €38 billion in 2011).

After adding up all of the individual values, the authors arrive at a figure of DM 4.74 trillion (equivalent to around €3.67 trillion in 2011) for total damages.

4.2.4 Ewers/Rennings on estimating the damage from a nuclear disaster, 1992

In a follow-up study for the PROGNOS series, "Identification and Internalisation of External Energy Supply Costs", the authors used a review of similar studies on the topic to examine the transferability of the assumptions to a nuclear disaster situation in the Federal Republic of Germany.[144]

They too apply Hohmeyer’s method in their core calculations on damage to people, and use the radiation release value of twice the assumed Chernobyl value (the previously stated figure of 4.8 million person-sieverts) from the earlier Biblis study. The ICRP’s risk coefficient is used as a further modification. According to the estimates available at the time,[145] the risk coefficient was 5% per sievert for fatal cancer cases, 1% per sievert for non-fatal cancer cases, and 1.3% per sievert for severe genetic damage.

---

[143] See [Ewers/Rennings 1991].

[144] See [Ewers/Rennings 1992 b].

[145] See [Ewers/Rennings 1992 b].

The authors make a further modification to the population density factor. They do not regard the value of ten applied by Hohmeyer to the area surrounding the power plant in Biblis as representative of the entire area of the Federal Republic of Germany. They use a factor of seven instead, their reasoning being that this reflects the ratio of population density in the most severely affected regions in Belarus after Chernobyl to population density in Germany as a whole. Furthermore, they ascertain that the population density in a 50-kilometre radius around the German power plants corresponds to the average population density in the old Länder, which also makes this factor seem appropriate.

In total, they estimate an additional 1.68 million fatal cancer cases, 336,000 non-fatal cases and 436,800 cases of severe genetic damage.

The authors apply the hedonic pricing method, which Ottinger had previously used in his study, in their monetary valuation of the fatal cases. When the study was produced, the figure of $4 million used was equivalent to DM 6 million, which amounts to a figure of DM 10.08 trillion for the total damage caused by fatal cancer cases. The authors use the previously applied human capital method for morbidity risks due to the lack of empirical studies on identifying more suitable valuation methods. This method sets non-fatal harm caused by the accident at DM 500,000. The figure was based on the assumption that there would be a loss of income of DM 50,000 per year over a ten-year period. Non-fatal cancer cases, in which the cases of severe genetic damage are also included, would thus lead to total costs of DM 386.4 billion.

Property damage is determined in relation to the values calculated for the exclusion zone in the Biblis study, as a more accurate calculation would involve calculating scenarios for all other locations. Property damage in the region around Biblis is assumed to be the maximum figure because of high population density. The authors therefore reduce this figure by 45% in order to obtain a representative figure for the entire federal territory and thus calculate a sum of DM 231 billion for expected property damage.

In total, this study calculates total damages amounting to DM 10.679 trillion (equivalent to around €8.28 trillion in 2011).

4.3 Current quantification approaches

4.3.1 Externalities of Energy (ExternE) – a research project of the European Commission, 1995

Since 1991, the European Commission has supported a research network with the aim of quantifying the external costs of energy sources using accepted methods and approaches. In this context, external costs are understood as costs that arise through potential damage to the environment and health from the use of a technology, but which are not reflected in the regular prices of these technologies. For example, the costs of damage to health from pollutants caused by normal car traffic in Germany are not included in the prices for vehicles or fuel. In order to provide state institutions in particular with a basis for deciding which technologies are genuinely sustainable, the project endeavoured to estimate these damages and valuate them in monetary units. To this end, the project team developed the impact pathway approach, which calculates the dispersion and chemical transformation of pollutant emissions, as well as their transformation, where applicable, via radiation into the air, ground and water. Based on pollutant concentrations, exposure-response relationships are used to calculate damage to human health, ecosystems, crops and materials. In a final step, these are assessed in monetary units.[146] Estimating the effects is an extremely complex task and often involves significant or insoluble uncertainties, incalculable subaspects, and a wide range of different assumptions (based on opinions).[147]

Volume 5 of the research results,[148] which analyses the external costs of the nuclear fuel cycle, is of relevance to the review undertaken here.[149] The results present the methodological approaches and applications using the nuclear fuel cycle in France as an example. Chapter 9 of the volume contains an analysis of accident scenarios resulting from a core meltdown in a nuclear power plant.

Estimates are made on

- the dose to which the population is exposed
- the risk of effects on health
- the costs of counter-measures
- the loss of land and agricultural products

At this point, the authors emphasise that comprehensive probabilistic safety assessments (PSA) would be a prerequisite for a complete investigation of possible accident scenarios, but that these are not within the scope of the project.[150] As specific data on potential source terms[151] and accident probability for French power plants was not available, four hypothetical scenarios were applied. The primary aim of doing so was to demonstrate the application of methods for risk assessment and to produce preliminary paradigmatic results. Aspects such as a factor that takes risk aversion into account were not included due to a lack of scientifically founded methods.

The method used to calculate health damage is the same as that used in the earlier studies presented above. In addition, the ICRP's 1991 risk factor of 5% per sievert for fatal cancer cases, 12% per sievert for non-fatal cases, and 1% per sievert for genetic damage is used; this was based on a collective dose of 291,200 person-sieverts, which in turn reflects the estimates made by UNSCEAR in 1988[152] following the Chernobyl disaster. However, the global effects of the contamination are not taken into account. A value of a statistical life (VSL)[153] of European Currency Unit (ECU) 2.6 million is used as a valuation method for fatal cancer cases. This is based on a willingness-to-pay approach (WTP),[154] explained in volume 2 of the ExternE study, which deals with the methods used. For non-fatal cancer cases the authors refer to a US study by Oak Ridge National Laboratory, Tennessee, published in 1993,[155] which listed the average costs of treatment for individual types of cancer. The average of these costs per cancer case, $298,000, was converted into ECU, rounded off and applied as ECU 250,000 for the valuation of non-fatal cancer cases. In total, this leads to health costs of ECU 54.1 billion (equivalent to around €74.3 billion in 2011).[156]

In terms of material costs, the costs of food bans, evacuation and resettlement received primary consideration. The basic valuation factors are listed in a table in the ExternE study. However, the values to which they were applied are

---

[146] Cf. [Friedrich 2009].
[147] Cf. [Roos 2010].
[148] See [European Commission 1995].
[149] Ibid.
[150] Cf. [European Commission 1995], p. 195.
[151] Amount and type of radionuclides released.
[152] See [UNSC 1988]
[153] The value of a statistical prevented fatality.
[154] In the WTP approach, citizens are asked how much they would be willing to pay in order to improve the environmental situation.
[155] Cf. [ORNL 1993]
[156] Cf. [European Commission 1995], p. 205.

not stated. For example, there is no information on the amounts of the various foodstuffs concerned or the number of people evacuated and resettled. Furthermore, there is no information on the duration of the measures. The calculations were carried out using a computer model called COSYMA, which was developed by the European Community Radiation Protection Programme.[157] No further information on this model is included in the study. The total costs for food bans come to ECU 27.6 billion (equivalent to around €37.9 billion in 2011) and to ECU 1.5 billion (equivalent to around €2.1 billion in 2011) for evacuation and resettlement.[158]

In total, the figure for total damages for the scenario with the highest release comes to ECU 83.252 billion (equivalent to around €114.29 billion in 2011).

4.3.2 Response by the German federal government to a minor interpellation on "Nuclear disaster – disaster control and evacuation", 2011

Weather situation	Approximate area for long-term resettlement [km²]
Strong wind from changing directions, dry	80
Strong wind from a constant direction, dry	400
Moderate wind from changing directions, dry	160
Moderate wind from a constant direction, dry	1,200
Light wind from changing directions, dry	350
Light wind from a constant direction, dry	700
Strong wind from changing directions, precipitation of 1 mm/h	22,900
Strong wind from a constant direction, precipitation of 1 mm/h	9,900
Moderate wind from changing directions, precipitation of 1 mm/h	15,600
Moderate wind from a constant direction, precipitation of 1 mm/h	6,200
Light wind from changing directions, precipitation of 1 mm/h	10,100
Light wind from a constant direction, precipitation of 1 mm/h	2,700

Figure 4.2: Possible sizes of resettlement areas following a nuclear disaster. (Source: [Bundesregierung 2010 a])

The response by the German federal government to a minor interpellation on the topic, "Nuclear disaster – disaster control and evacuation" provides an approach for quantifying the costs resulting from resettlement of the population.[159] The question posed was:

---

[157] See [European Commission 1991].

[158] As no precise information was given on these figures and linear dependence on the total amount of damage is not assumed, they are used as fixed values in the calculation of the insurance premium.

[159] Cf. [Bundesregierung 2010 a].

"For what maximum area (expressed in square kilometres) could evacuation be necessary following a nuclear event and given various meteorological dispersion conditions, if a dose of 100 mSv by external exposure over the course of a year is used as a criterion for assessing the need to evacuate?"[160]

The response was presented as a table containing the possible sizes of evacuation and resettlement zones. It was assumed that release was similar to that in Chernobyl. A decision support system known as Real-time Online Decision Support system for off-site emergency management (RODOS), which is available to nuclear power plant operators for such cases, was used to calculate the theoretically affected areas for the different weather situations shown in figure 4.2. The probability of the individual weather situations was not stated.

4.3.3 The analysis by Öko-Institut Darmstadt of the threat potential of a "deliberate aeroplane crash" using Biblis A as an example, 2007

The study by Öko-Institut Darmstadt[161] examines the safety and construction of core reactors in terms of an aeroplane crash. The details of this investigation are further explained in the scenarios in section 5.2 of the present study. The presentation of possible effects, which the authors of the Öko-Institut study thoroughly undertake in chapter 4 of their report, is of relevance to the quantification of the results of an accident. These include the realistic estimate of a source term and calculations of generic dispersion in order to examine the measures that would probably need to be carried out, bearing in mind the emergency reference level for disaster control.

The action level in the Radiological Basis for Decisions on Measures to Protect the Population in Cases of Accidental Release of Radionuclides calls for evacuation when there is external exposure and an effective secondary dose via inhaled radionuclides of 100 mSv in seven days. Long-term resettlement is indicated if external exposure of 100 mSv over the course of a year is expected.[162]
The calculations conducted in the study are based on the ICRP's guidelines and use a Gaussian plume model[163] to describe dispersion in a constant direction. Different diffusion categories, wind directions and precipitation scenarios are taken into account.

The calculation scenario for "an area to be resettled for the long term in cases of neutral to light stable air turbulence and wind from the south-west (large dispersion)" indicates a resettlement area in the shape of an ellipse measuring some 350 km in length and around 60 km in width. If one also includes the radius of 25 km around the power plant in the exclusion zone, which seems realistic given the 30-km exclusion zone around Chernobyl, the result is that a total area of 18,000 km² would be affected by long-term resettlement. This falls within the range of the results of sample calculations conducted using the RODOS decision support system.

4.3.4 The Other Report on Chernobyl (TORCH), 2006

The Other Report on Chernobyl, or TORCH, is a report on the health impact of the Chernobyl disaster that was written by two British scientists and published in 2006.[164] The report is an independent scientific study of the available data on the release of radioactivity into the environment and the ensuing health risks following the accident in

---

[160] [Bundesregierung 2010 a], p. 6.
[161] Cf. [Küppers/Pistner 2007].
[162] Cf. [BMU 2008 a], p. 28 ff.
[163] This is a model used to predict emissions in an atmospheric dispersion calculation.
[164] See [Fairlie/Sumner 2006].

Chernobyl. According to TORCH, previous reports by the IAEA, UNSCEAR and the Chernobyl Forum significantly underestimated the actual damage to health. For instance, the official reports did not take contamination outside the most severely affected areas sufficiently into account, although this constituted a large part of the collective dose. The authors mention the impact of very low doses and the resulting discussion about a threshold as well as the estimates of internal doses from nuclides that are inhaled or ingested via food as further uncertain factors in existing studies.

If all of the contamination is sufficiently taken into account, the authors state that the collective dose was 600,000 person-sieverts. The population of Belarus, Ukraine and Russia accounted for 36% of this group; 53% came from the rest of Europe and 11% from the rest of the global population. Using risk factors ranging from 5% to 10% per sievert, the two authors calculate a total of 30,000 to 60,000 additional fatalities from cancer worldwide as a result of the Chernobyl disaster in a period of up to 70 years following the disaster.

4.3.5 The Federal Environment Agency's methodological convention for the economic assessment of environmental damage

A document published by the Federal Environment Agency[165] in 2007 presents methodological conventions for estimating external environmental costs. These conventions are based on extensive discussions in the Federal Environment Agency and with political decision makers and scientists. The conventions are "aimed at developing a standard for an expert assessment of environmental costs and at improving the transparency of estimates."[166] The report presents the state of research in the field of economic assessment of external costs in great detail and describes a standardised approach for calculating these costs. The recommendations for assessing health risks are therefore regarded as particularly relevant to the current study.

According to the report, health risks consist of three components:

1. The first component, resource costs, includes "medical costs covered by the health system or insurances, and any other personal out-of-pocket-expenses incurred by an individual or a family."[167] With respect to the subject-matter examined by this study, these would be the costs of treating non-fatal cancer cases and genetic defects. A treatment period is always implied in fatal cancer cases as well.

2. Opportunity costs, which make up the second component, refer to the loss of productivity and income due to disability or reduced performance. The human capital method, which Hohmeyer used in his 1989 study due to a lack of alternatives, takes these components, above all, into account. It becomes clear, however, that they may only represent a small portion of the actual costs, as the resource costs usually account for the largest percentage of the costs.

3. The third component is individual disbenefit, which can manifest itself as limitations on or reduced enjoyment of leisure activities, or as pain and suffering.

The assessment of fatal health risks is often made in the form of the value of a statistically prevented death, which is often referred to as the value of a statistical life (VSL) in specialised literature. The Federal Environment Agency reviewed various studies on calculating this value for its report. However, the agency does not make any direct recommendation for the use of a specific VSL for fatal risks, as "[i]n its current version, the methodological convention

---

[165] See [UBA 2007].
[166] Ibid, p. 13.
[167] Ibid, p. 67.

concentrates on the non-fatal health risks relevant in environmental terms".[168] The report does, however, indicate a meaningful range of between €1 million and €3 million per fatality for sensitivity calculations.

In conclusion, the research by the Federal Environment Agency is particularly suited to a current hypothetical study on estimates of the impact of a nuclear disaster in Germany because of the Agency's comprehensive approach and the fact that the research was conducted recently.

4.3.6 Extrapolated quantification approaches

This text uses approaches from some of the reviewed studies to conduct further quantifications of damage costs. These will now be introduced in brief, as they are included as additional valuations in the insurance premium calculations (see chapter 6).

Weather situation	Approximate area for long-term resettlement (km²)	Number of inhabitants affected	Loss of GDP for five years (in billions of euros)
Strong wind from changing directions, dry	80	18,320	2.68
Strong wind from a constant direction, dry	400	91,600	13.42
Moderate wind from changing directions, dry	160	36,640	5.37
Moderate wind from a constant direction, dry	1,200	274,800	40.26
Light wind from changing directions, dry	350	80,150	11.74
Light wind from a constant direction, dry	700	160,300	23.49
Strong wind from changing directions, precipitation of 1 mm/h	22,900	5,244,100	768.31
Strong wind from a constant direction, precipitation of 1 mm/h	9,900	2,267,100	332.15
Moderate wind from changing directions, precipitation of 1 mm/h	15,600	3,572,400	523.39
Moderate wind from a constant direction, precipitation of 1 mm/h	6,200	1,419,800	208.02
Light wind from changing directions, precipitation of 1 mm/h	10,100	2,312,900	338.86
Light wind from a constant direction, precipitation of 1 mm/h	2,700	618,300	90.59

Figure 4.3. Possible amounts of loss incurred for resettlement measures due to a nuclear disaster. (Source: [Bundesregierung 2010 a], authors' own calculations).

The response by the German federal government to a minor interpellation, which was described in section 4.3.2, provides an initial approach for moving the discussion forward. The possible resettlement zones forecast by the RODOS decision support system are used as a basis for calculating the costs of damage that would arise from the loss of these zones' total economic income. The gross domestic product for the individual affected zones is calculated by using the population density and data on the average gross domestic product in the Federal Republic of Germany. This is then multiplied by the factor five in order to take into account the rather conservative assumption that production will not be possible in these zones for five years. However, it can be presumed that the resettled population would contribute to gross domestic product in another part of Germany during this period, so the assumption appears to be justified.

---

[168] [UBA 2007], p. 71.

With an average population density of 229 inhabitants/km²[169] in the Federal Republic of Germany and an average gross domestic product of $40,873.27 per capita,[170] this leads to the costs shown in figure 4.3, assuming five years of complete loss of production in this exclusion zone.

The Öko-Institut study, "Analysis of the Threat Potential of a 'Deliberate Aeroplane Crash' Using Biblis-A as an Example" provides another approach. Using the calculations made by the Öko-Institut, the present study will attempt to take into account the probability of conurbations being affected by long-term resettlement, as this would have a significant impact on the economic costs of a nuclear disaster. However, only material costs in the form of loss of gross domestic product for an assumed closure of these areas for five years is assumed, as the calculation of personal damage is made according to the available collective dose principle and independently of the affected areas.

The calculations make use of wind roses provided by Germany's National Meteorological Service for locations close to the nuclear power plants operated in Germany. The virtually ellipse-shaped dispersion pattern of the above-mentioned scenario is spread over the individual locations for eight wind directions (N, NE, E, SE, S, SW, W, NW). The highest damage scenario is also always considered for each direction. The average population density in the Federal Republic of Germany of 229 inhabitants/km² forms the basis for estimating the amount of people affected. The number of inhabitants of towns with over 100,000 inhabitants is added to this figure so that particularly densely populated areas such as the Ruhr region are sufficiently taken into account. Areas with a lower population density and dispersion, such as along the North Sea, are reduced accordingly. The figure for amounts of damage produced by multiplying the affected number of inhabitants to be resettled by German per-capita gross domestic product is calculated for a period of five years and then multiplied by the frequency of the various wind directions (see Annex *B*). The resulting expected amounts of material damage costs for the 12 power plant locations examined are shown in figure 4.4.

Power plant location	Meteorological measurement plant location	Loss of GDP for five years in billions of euros (2011 figures)
Biblis	Lindenfels	707.19
Brunsbuettel	Brunsbuettel	575.32
Brokdorf	Brunsbuettel	393.80
Kruemmel	Ahrensburg-Wulfsdorf	573.50
Emsland	Lingen	688.85
Grohnde	Hameln	993.94
Grafenrheinfeld	Bad Kissingen	732.98
Philippsburg	Karlsruhe	713.59
Neckarswestheim	Stuttgart-Schnarrenberg	774.40
Isar	Muenchen Flughafen FSJ	690.28
Unterweser	Bremerhaven	747.86
Gundremmingen	Ulm	626.89

Figure 4.4. Property damage taking into account wind direction scenarios for the twelve power plant locations in Germany (Source: author's own work)

---

[169] [SÄBL 2011].

[170] [SBD 2010].

By taking into account the frequencies of the wind directions, the resulting values do not generally display great variance. One reason for this is that most scenarios are based on average population density. Another reason is that events of maximum damage, such as the resettlement of almost the entire Ruhr region, are levelled out by the infrequency of the wind directions for this scenario.

4.4 An overview of the quantification approaches used

The approaches shown in figure 4.5 are used to calculate damage distributions that form the basis for the calculation of an insurance premium.

These values should now be applied by multiplying them with one another for each form of damage in order to produce a total for all possible combinations. For example, a figure of around €80.5 billion for fatal cancer cases is calculated by multiplying the lowest value for released radioactivity with the risk coefficient, the population density factor and the lowest valuation factor.

Approach	Value	Source
Collective dose	291,200 person-Sv	ExternE, Vol. 5, 1995 [EC 1995]
	600,000 person-Sv	The Other Report on Chernobyl, 2006 [FS 2006]
	2,400,000 person-Sv	USSR Chernobyl Report, 1986 [Ewers/Rennings, 1992a]
	4,800,000 person-Sv	Ewers/Rennings, 1992 [Ewers/Rennings, 1992a]
Risk factor for fatal cancer cases	5% per sievert	ICRP 60, 1991 [ICRP 1991]
Risk factor for non-fatal cancer cases	12% per sievert	ICRP 60, 1991 [ICRP 1991]
Risk factor for genetic damage	1% per sievert	ICRP 60, 1991 [ICRP 1991]
German population density factor	7	Ewers/Rennings, 1992 [Ewers/Rennings, 1992a]
Valuation approaches for fatal cases of cancer per case	€790,446.85 (2011) per case	DM 1,000,000 (1989) Hohmeyer, 1989 [Hohmeyer 1989]
	€1,000,000 (2011) per case	Lowest level in the range provided by the Federal Environment Agency, 2007 [UBA 2007]
	€2,600,000 (1995) per case	Value of a Statistical Life ExternE, Vol. 5, 1995 [EC 1995]
	€3,000,000 (2011) per case	Maximum level in the range provided by the Federal Environment Agency, 2007 [UBA 2007]
	€4,469,134.35 (2011) per case	DM 6,000,000 (1992) Ewers/Rennings, 1992 [Ewers/Rennings, 1992a]
Valuation approaches for non-fatal cancer cases per case	€305,125.10 (2011) per case	$298,000 (1993) Oak Ridge National Laboratory, 1993 [ORNL 1993]
Valuation approaches for severe genetic damage per case	€406,344.57 (2011) per case	ECU 296,000 (1995) ExternE Vol. 5, 1995, 3% discount rate [EC 1995]
	€53,538.64 (2011) per case	ECU 39,000 (1995) ExternE Vol. 5, 1995, 10% discount rate [EC 1995]
Food bans	€37,935,011,060.19 (2011)	ECU 27,633,600,000 (1995) ExternE Vol. 5, 1995 [EC 1995]
Costs of evacuation and resettlement	€2,080,044,900.35 (2011)	ECU 1,515,200,000 (1995) ExternE Vol. 5, 1995 [EC 1995]

Figure 4.5: Valuation bases used to calculate the insurance premium (Source: authors’ own work)

Example:

	291,200 person-sieverts
X	5% per sievert for fatal cancer cases
X	7 population density factor
X	€790,000
=	€80.5 billion

The following tables show the combinations of all of the valuation bases for personal damage used to calculate the amount of damage in the insurance premium in euros. Personal damage is divided into genetic damage, fatal cancer cases and non-fatal cancer cases.

Release in person-sieverts	Risk coefficient in % per Sv	Population density factor	Number of genetic damage cases	Valuation	Total in euros
291,200	1%	7	20,384	406,344	8,282,916,096
291,200	1%	7	20,384	53,538	1,091,318,592
600,000	1%	7	42,000	406,344	17,066,448,000
600,000	1%	7	42,000	53,538	2,248,596,000
2,400,000	1%	7	168,000	406,344	68,265,792,000
2,400,000	1%	7	168,000	53,538	8,994,384,000
4,800,000	1%	7	336,000	406,344	136,531,584,000
4,800,000	1%	7	336,000	53,538	17,988,768,000

Figure 4.6. Amounts for genetic damage (calculated by the authors)

Release in person-sieverts	Risk coefficient in % per Sv	Population density factor	Number of non-fatal cancer cases	Valuation	Total in euros
291,200	12%	7	244,608	305,125.00	74,636,016,000
600,000	12%	7	504,000	305,125.00	153,783,000,000
2,400,000	12%	7	2,016,000	305,125.00	615,132,000,000
4,800,000	12%	7	4,032,000	305,125.00	1,230,264,000,000

Figure 4.7. Amounts of damage for non-fatal cancer cases (calculated by the authors)

Release in person-sieverts	Risk coefficient in % per Sv	Population density factor	Number of fatal cancer cases	Valuation	Total in euros
291,200	5%	7	101,920	790,446.85	80,562,342,952
291,200	5%	7	101,920	1,000,000.00	101,920,000,000
291,200	5%	7	101,920	2,600,000.00	264,992,000,000
291,200	5%	7	101,920	3,000,000.00	305,760,000,000
291,200	5%	7	101,920	4,469,134.35	455,494,172,952

600,000	5%	7	210,000	790,446.85	165,993,838,500
600,000	5%	7	210,000	1,000,000.00	210,000,000,000
600,000	5%	7	210,000	2,600,000.00	546,000,000,000
600,000	5%	7	210,000	3,000,000.00	630,000,000,000
600,000	5%	7	210,000	4,469,134.35	938,518,213,500
2,400,000	5%	7	840,000	790,446.85	663,975,354,000
2,400,000	5%	7	840,000	1,000,000.00	840,000,000,000
2,400,000	5%	7	840,000	2,600,000.00	2,184,000,000,000
2,400,000	5%	7	840,000	3,000,000.00	2,520,000,000,000
2,400,000	5%	7	840,000	4,469,134.35	3,754,072,854,000
4,800,000	5%	7	1,680,000	790,446.85	1,327,950,708,000
4,800,000	5%	7	1,680,000	1,000,000.00	1,680,000,000,000
4,800,000	5%	7	1,680,000	2,600,000.00	4,368,000,000,000
4,800,000	5%	7	1,680,000	3,000,000.00	5,040,000,000,000
4,800,000	5%	7	1,680,000	4,469,134.35	7,508,145,708,000

Figure 4.8 Amounts of damage for fatal cancer cases (calculated by the authors)

Section 6.2 uses these results, the economic costs calculated in figures 4.3 and 4.4, the costs for food bans amounting to some €38 billion, and the costs of evacuation and resettlement amounting to around €2.1 billion to estimate the expected maximum damage. A complete list of all results for each power plant can be found in Annex *B*.

4.5 Other types of damage

The studies reviewed here only deal with a limited selection of possible damage that could arise due to a nuclear disaster. They almost exclusively valuate personal and property damages. The ExternE Study also calculates the costs of food bans, evacuation and resettlement.

A large number of other types of damage could be included in a study, such as the costs for decontamination and permanent disposal of contaminated material or the loss of biotopes and endangered species. The reason that these types of damage are not included in most calculations is that the quantification methods available for them are often inadequate. For example, the Federal Environment Agency comments as follows on the monetary assessment of irreversible damage: "If the consequences of a damage are unknown or knowledge is very uncertain (for example, loss of a species), the ranges of possible damage should be described and assessed in monetary terms (analyses of scenarios). If no analysis on possible damage is available, the possible consequences can be described in qualitative terms only."[171] The numbers presented in the studies reviewed here thus tend to underestimate the actual possible total damage. However, it should be noted that the health costs due to radiation exposure are assumed to account for the largest share of the total costs.

---

[171] [UBA 2007], p. 73.

Chapter 5

Probability of occurrence: Current methods of quantification and impact of scenarios on a nuclear disaster

5.1 Current methods for quantifying the probability of occurrence of a nuclear disaster

One of the most informative statements for Germany on the probability of occurrence of accidents that exceed the limits of security design comes from the study *Deutsche Risikostudie Kernkraftwerke Phase B* (German risk study on nuclear power plants – phase B), published by the Gesellschaft für Reaktorsicherheit (GRS) in June 1989.[172] The study involved comprehensive investigations of how nuclear power plants react to incidents, using Biblis B as a reference plant. Detailed analyses focused on how incidents develop over time, on the strain they place on the plant, and on the intervention of security systems for incident control. They also took into account plant-internal accident-management measures, which are designed to function as backup security if security systems do not intervene as planned.

The *DRS Phase B* study calculated that for a reactor of the Biblis B type, the probability of occurrence of a category AF-SBV scenario (large-scale containment failure, which releases almost all the radioactive material of a power plant into the atmosphere), without accident-management measures, is 3×10^{-5} per year. This equates to an event of this scale occurring at the reactor approximately every 33,300 years per operating year. Taking accident-control measures into account and assuming that they are fully effective, a probability of the pressurised water reactor Biblis B suffering an accident involving core meltdown is 3.6×10^{-6} per year. This roughly corresponds to one accident every 280,000 operating years.

In 2001, GRS assessed the accident risk for advanced pressurised water reactors in Germany.[173] It used the Neckarwestheim 2 (GKN 2) nuclear plant as its reference plant. Other plants of this design are the Konvoi-type Isar Block 2 and Emsland plants. The probability of occurrence of a

---

[172] See [GRS 1989].
[173] See [GRS 2001].

category AF-SBV damage event at these reactors is assumed to be 10^{-8} per year, which corresponds to an event every 100 million years.

ExternE[174] bases its calculations of the financial consequences of accidents on a core-meltdown frequency of 5×10^{-5} per operating year. It also assumes that only 19 per cent of these cases will result in a release of radioactive material, with the containment holding for the remaining 81 per cent. This results in a probability of occurrence of one event every 105,000 operating years.

Based on a source from 1997, the German Federal Environment Agency's *Methodological Convention* puts the estimated probability of occurrence of core meltdown in Germany at 1:10,000,000 operating years.[175]

None of these figures take into account deliberate damage brought about by war, civil war, air strikes, terrorism or sabotage. Over time, however, such events can become dominant risk factors. For example, the involvement of the Bundeswehr in operations abroad could increase the risk of terrorism in Germany, since terrorists might see attacking the country as a way to gain political leverage. The following section presents scenarios that could increase the probability of occurrence.

5.2 Incorporating other scenarios that directly affect the probability of occurrence of a nuclear disaster

This section presents scenarios that affect, or significantly increase the probability of occurrence of a nuclear disaster. These scenarios supplement the figures available on the probability of occurrence of a nuclear disaster given in Section 5.1. They are mainly intended to improve understanding of the potential threat concerning probabilities of occurrence, and of what causes the probabilities to change.

The theoretical evaluation bases used here are merely stress assumptions taken from incidents and accidents that have actually occurred. They were not developed or validated using a model.

With the exception of the terrorism risk (for which we estimate a direct value), all the scenarios affect the probabilities of occurrence given in Section 5.1, which are backed up by sources. This affect is demonstrated using modification factors. A factor of two doubles the originally assumed probabilities of occurrence. After this section has looked at each of the scenarios in turn, Section 5.3 will summarise all the probabilities in table format.

5.2.1 Scenario: Ageing nuclear power plants

Germany's 17 pressurised water reactors and boiling water reactors

---

[174] [European Commission 1995].
[175] [UBA 2007], p.29.

[176] were built at different times and therefore belong to different generations, or construction types.[177] Each of the reactors was built according to different construction methods, techniques and basic safety concepts.[178]

Measured against state-of-the-art science and technology, none of the power plants fully conform to today's legal requirements and none would receive an (initial) operating permit. This means that not even the latest generation of nuclear plants in Germany corresponds to state-of-the-art technology, since these reactors are now over 20 years old.[179]

The results of a variety of analyses indicate that considerably more reportable events have occurred in older nuclear plants (second-generation, or Type-69 reactors) since they went into operation than in the "newer" reactors. Furthermore, irrespective of the generation or type, longer lifetimes increase the frequency of events that lead to disruptions in plant operation.[180]

There are two ways that ageing in nuclear plants results in incidents or accidents: on the one hand, they occur when the technology in use ages in comparison to the state-of-the-art; on the other they are caused by the length of operating time and associated wear and tear. Therefore, extending plant lifetimes of nuclear power plants in Germany, including transferring residual electricity volumes to old reactors would result in a disproportionate increase in the risk of incidents and accidents.[181]

These connections are highlighted in the results, shown in Figure 5.1, of the 2010 study of incidents and accidents at nuclear power plants in Germany.

Generation / type	Nuclear power plant	Year of startup (first criticality)	Years of operation (up to and including 2009)	No. of incidents and accidents
Pressurised water reactors (PWR)				
Second-generation PWR	Biblis A	1974	36	12
	Biblis B	1976	34	12
	Neckarwestheim 1	1976	34	12
	Unterweser	1978	32	10
Third-generation PWR	Grafenrheinfeld	1981	29	7
	Grohnde	1984	26	8
	Philippsburg 2	1984	26	7
	Brokdorf	1986	24	9
Fourth-generation PWR	Isar 2	1988	22	3
	Emsland	1988	22	5
	Neckarwestheim 2	1988	22	4
Boiling water reactors (BWR)				
Type-69 BWR	Philippsburg 1	1979	31	11

---

[176] See also Figure 2.2.

[177] See also Figure 5.1.

[178] Cf. [Becker 2009], p.2.

[179] Cf. [Büro für Atomsicherheit 2010], p.1 and [Becker 2009], p.2. This means that the nuclear power plants must upgrade their current security standards by 2012. But underlying conceptual disadvantages in security mean that even the option of upgrading is considered limited. See also [Büro für Atomsicherheit 2010], p.22 ff.

[180] Cf. [Büro für Atomsicherheit 2010], p.11 and [Kotting-Uhl 2010].

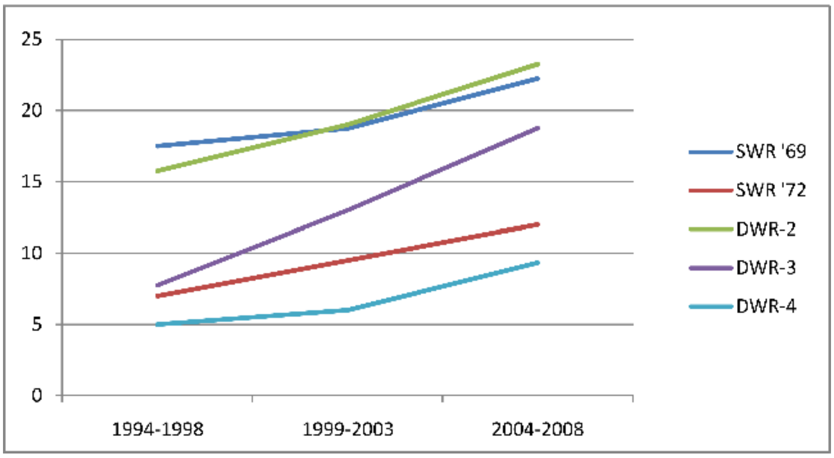
[181] Cf. [Büro für Atomsicherheit 2010], p.6 and [Paulitz 2010], p.1.

	Isar 1	1977	33	8
	Brunsbuettel	1976	34	14
	Kruemmel	1983	27	12
Type-72 BWR	Gundremmingen B Gundremmingen C	1984 1984	26 26	4 4

Figure 5.1: Nuclear power plants in operation in Germany and approximate number of reportable events (Source: authors' own work, adapted from [Paulitz 2010], p.7.)

Figure 5.2 also shows how defects in structural components caused by increasing age and operating time in German nuclear power plants can result in a disproportionate increase in events.[182]

Baulinien-Ø	SWR '69	SWR '72	DWR-2	DWR-3	DWR-4
1994-1998	17,5	7	15,75	7,75	5
1999-2003	18,75	9,5	19	13	6
2004-2008	22,25	12	23,25	18,75	9,33



Types *Type-69 BWR, Type-72 BWR, 2nd gen. PWR, 3rd gen. PWR, 4th gen. PWR*

Figure 5.2: Trend in the number of defects in structural components in nuclear power plants in Germany (Source: [Kotting-Uhl 2010]):

Ageing occurs in the following areas:

- Ageing of materials
- Ageing of safety documentation

---

[182] The value per generation or type is the result of the quotient of the absolute number of events and the number of reactors belonging to a given type (e.g. Type-69 BWR = Brunsbüttel, Isar 1, Philippsburg 1, Krümmel). Cf. [Kotting-Uhl 2010].

- Ageing of staff
- Ageing of concepts (plants based on safety concepts that have aged).[183]

The following explanations relate to the ageing of concepts. For example a Type-69 boiling water reactor differs from a Type-72 in that it is particularly susceptible to rapid containment failure caused by melting, has relatively thin walls in the reactor building, and has less capacity for emergency core cooling. Comparing two generations (second generation and newer generations) also reveals failings in safety concepts and therefore factors that increase risk. Second-generation PWRs have thinner walls, lower pressure and temperature resistance in the containment building, and a lack of full automation when shutting down the secondary side during emergency core cooling.[184]

These deficits in safety technology at older nuclear power plants increase the probability that incidents or accidents will occur. At the same time, they decrease the probability of controlling such events, since the plants have less structural and technical safety reserves. The effects of an event can therefore be much more serious for an older nuclear plant than for one of a more recent generation.[185]

The Biblis plant, for example, does not spatially separate its power-supply and control cables. This means that the same scenario that actually took place on 22 March 1975 at the US Browns Ferry plant could also happen at Biblis. A controller at Browns Ferry used a candle to look for an air leak. The cables were covered in a foam coating, which the candle flame ignited. This only became apparent when the foam was already on fire and had caused considerable damage to the power-supply and control cables. This caused a power cut, which meant that almost all the emergency cooling systems in both blocks of the plant were incapable of functioning properly. Just one system, in Block 2, remained operational. Without sufficient cooling, a plant risks core meltdown, for even after the reactors have been shut down, the radioactive decay they contain continues to generate so much heat that the reactor vessels may not being able to withstand it. Core meltdown was avoided at Browns Ferry by connecting two condensate pumps, which were actually intended for the normal operating system.

As a result of this event in the US, spatial separation of cables became a basic safety feature for new nuclear power plants. While Biblis has applied fire-retardant coating to the cables and has partially separated the cable harnesses, its original structural design means that it cannot implement retrofitting measures to fully separate its power supply and control. Thus, Biblis remains a higher risk plant than those belonging to more recent generations or types.

---

[183] Cf. [Büro für Atomsicherheit 2010], p.16 ff.
[184] Cf. [Becker 2009], p.3 ff.
[185] Cf. [Becker 2009], p.5.

[186]

Probabilistic safety assessments (Level 1) calculate the probability of serious accidents occurring at nuclear power plants. The relatively low safety level of older plants and inadequacies of retrofitting measures affect the outcome. For older Type-69 boiling water reactors, the probability per plant of serious accidents occurring was two to six times higher than in newer BWRs. Second-generation pressurised water reactors are between ten and 18 times more likely than newer-generation plants to suffer serious accidents.[187] These values were taken into account as modification factors of the probabilities of occurrence.

These changes that nuclear-plant ageing makes to the probability of occurrence of serious accidents were incorporated into the calculation of the liability insurance premium in Section 6.2.

5.2.2 Scenario: Terrorist act

The attacks on the World Trade Center changed how the world saw the risk of terrorist attacks. Acts of terrorism can be defined as "any action that is carried out by individuals or groups to achieve political, religious, ethnic or ideological goals, and that is capable of spreading fear or terror throughout the population or parts thereof and therefore of influencing a government or state institutions."[188] Terrorists can carry out their attacks in a number of different ways – such as from the air, the ground or the water.

We can assume that terrorists will aim to cause the greatest possible damage – also to human life – to achieve their goals. It is therefore conceivable that they would target nuclear power plants, as a successful attack that releases radioactive material into the atmosphere would result in a disaster with widespread, long-term effects.[189]

The threat of a terrorist attack on a nuclear power plant is very real. Proof is available in reports detailing attempts to break into plants, attack them or threaten them. The reports concern Argentina, Russia, Lithuania, South Africa, South Korea, the US and France and show that nuclear power plants have often been the focus of terrorist or criminal activities.[190]

Assuming that a terrorist group intends to cause maximum damage with its attack, it must attack a nuclear plant during the plant's lifetime. Older, particularly vulnerable plants will be shut down sooner than newer ones, which means that the risk of these newer plants becoming terrorist targets should be considered as especially high.

---

[186] Cf. [Büro für Atomsicherheit 2010], p.16 ff.
[187] Cf. [Becker 2009], p.17.
[188] [Haubner 2009], p.41.
[189] Cf. [Bundesregierung 2006], p. 4 and 6.
[190] Cf. [Kelle/Schaper 2001], p.35.

A number of possible scenarios exist for the threat of a terrorist attack. The following sections will present the scenarios of an air attack, a ground attack and insider sabotage.

Terror risks are a special kind of disaster risk, since they do not occur by chance but rather as a result of deliberate human action. This means that it is impossible to use data and processes to model the probability of occurrence of damage or associated perils brought about by terror risks.[191] Nevertheless, it is safe to assume that the probability of a terrorist attack is very high if a terrorist group decides to carry one out.[192]

Rather than taking the terrorist risk into account with a modification factor, this study estimates it at 1:1,000 per operating year.

5.2.2.1 Scenario: Targeted aeroplane crash

Several analyses have assessed how German nuclear power plants would stand up to an attack from the air.[193] The results showed that, even after introducing additional safety measures (following the September 11 attacks), Germany's plants could not withstand a targeted airplane crash because the walls of the reactor buildings are too thin. There is therefore a risk of nuclear disaster if this scenario occurs. The older plants are particularly vulnerable to terrorist attacks, since the walls of their reactor buildings are even thinner than those of newer types.[194] The Biblis and Brunsbüttel plants are therefore under particular threat; even if a comparatively small aircraft, such as an Airbus A320, crashed into them it could lead to a nuclear disaster.[195] These two plants, as well as Isar 1 and Philippsburg 1, do not feature the safety measures necessary to protect them against an airplane crash.[196]

The report that the US Congress' investigative commission published on the events of 11 September 2001 shows that the attackers, or the group they belonged to, had also considered crashing a plane into a nuclear power plant on US soil.[197] Since the September 11 attacks at least 20 other planes have been hijacked. Therefore, it is entirely conceivable that terrorists could hijack a plane and deliberately crash it into a nuclear power plant somewhere in the world. An attack of this kind that targets German nuclear plants[198] is, according to German authorities and courts, a very real risk for the country.[199] Heavy air traffic makes German airspace very difficult to monitor. Every day, over 8,600 planes take off from and land at the country's airports, and 3,000 aircraft fly through its airspace.[200] The scenario could unfold as follows:

A terrorist manages to get into the cockpit of a passenger aircraft. The cockpit door is armoured and can only be accessed using a code, but the terrorist forces his way in when the crew are serving the

---

[191] Cf. [Haubner 2009], p.41 and [Becker 2010 a], p.2.
[192] Cf. [Becker 2010 a], p.2.
[193] See, e.g. [Dietzel 2002], [Hirsch et al. 2004] and [Becker 2010 a].
[194] Cf. [Becker 2010 a], p.1. The reinforced-concrete walls of the Biblis A reactor building are just 60 centimetres thick. Cf. [Becker/Hirsch 2005], p.14.
[195] Cf. [Hirsch 2001], p.7 ff. and [Hirsch et al. 2004], p.3.
[196] Cf. [Küppers/Pistner 2007], p.9 ff.
[197] Cf. [9-11 Commission 2004].
[198] Cf. [Dietzel 2002].
[199] Cf. [Becker 2010 a], introduction (page 2 of this document).
[200] Cf. [Becker 2010 a], p.3 ff.

pilots drinks.[201] *The cabin crew are insufficiently trained in how to handle a hijacking, and two other terrorists easily overpower them. The terrorists force the pilot to fly into a nuclear power plant.*[202] *The plane hits the reactor building,*[203] *damaging the wall. Fuel from the plane leaks into the building and a fire breaks out.*[204] *The plane's impact causes damage to the inside of the plant (heavy vibrations rupture the cooling water piping, for example).*[205] *A number of redundancies are affected, and the kerosene fire and primary-cooling failure trigger a series of events that can no longer be controlled. Because the necessary emergency measures (emergency cooling) are no longer operational, these events lead to a core melt accident*.[206]

5.2.2.2 Scenario: Anti-tank guided missile attack

It is not unrealistic to think that terrorists might attack a nuclear power plant with a rocket launcher. In 1982, for example, the unfinished Creys-Malville plant in France was targeted with several missiles fired from an RPG-7 portable rocket launcher. The plant was not seriously damaged. Another example of this scenario is the threat that the war posed to Slovenia's Krsko power plant in the early 1990s.[207]

The past 20 years have seen continual developments in anti-tank guided missiles.[208] This is because on the battlefield armed conflicts are often waged between tanks and armour-piercing weapons – a situation that has resulted in an "arms race" involving both technologies.[209] The Lebanese organisation Hezbollah, for example, has been stocking up on anti-tank guided missiles since 1993, and has already used them in attacks on Israel.[210]

In recent decades, significant improvements have been made to anti-tank guided missiles in terms of penetrating power, accuracy, range, secondary effects, and scope of use.[211] Modern anti-tank guided missile systems have such a high level of accuracy that even at long range they have an 80% chance of hitting the same target several times in a row.[212] In addition to shaped charge warheads, the systems can also fire thermobaric warheads. These contain flammable substances, which means that they are capable of causing greater destruction.[213]

Anti-tank guided missiles and warheads were developed to destroy tanks. If a shaped charge warhead, comprising a "hollow metal cone coated in explosives",[214] hits a tank's armour, the impact ignites the explosives. The speed of the incoming warhead will destroy the armour and transfer some of the

---

[201] Cf. [Becker 2010 a], p.6.
[202] There is also the possibility that the terrorists themselves know how to fly a plane. See [Becker 2010 a], p.26.
[203] Even if the plant is concealed by a smokescreen (which is triggered by a system set up to activate when an aircraft gets to within 15 to 20 km of the plant and is designed to reduce the probability of a plane hitting a specific target), there is still a chance that the plane could hit the reactor building, especially if the plant is old. Evaluations of this smokescreen technology found it to be insufficient, particularly with regard to the most prominent sections of a plant such as the reactor building. Cf. [Becker 2010 a], p.17.
[204] Cf. [Küppers/Pistner 2007], p.13 ff.
[205] Cf. [Küppers/Pistner 2007], p.6.
[206] Cf. [Küppers/Pistner 2007], p.13 ff. and [Kelle/Schaper 2001], p.35.
[207] Cf. [Stritar et al. 1993], p.70.
[208] Cf. [Becker 2010 b], p.2.
[209] Cf. [Becker 2010 b], p.1.
[210] See [Global Security 2006], p.1 and [Marcus 2006].
[211] Cf. [Becker 2010 b], p.1 ff.
[212] Cf. [Bundesministerium der Verteidigung 2010], p.1.
[213] Cf. [Becker 2010 b], p.1.
[214] [Becker 2010 b], p.2.

energy of the explosion into the tank. The warhead and the fragments of the destroyed armour devastate the vehicle interior. This scenario could also arise if a reactor building were attacked with this kind of warhead.[215]

The walls of reactor buildings are made of reinforced concrete. No information could be found on tests of anti-tank guided missiles and reinforced-concrete walls with a thickness of between 1.2 and 2 m, as is common in German nuclear power plants.[216] However, information is available on the penetrating power of other anti-tank missiles, which can penetrate a two-metre-thick concrete target from a distance of 1.3 kilometres provided there is no fence protecting the wall.[217] If a protective fence does exist, the reactor building could only be destroyed if several missiles were fired in succession.[218]

The Milan 3 (Missile d’infanterie l´eger antichar 3) anti-tank missile, which Germany and France jointly developed, can penetrate reinforced concrete walls that are three metres thick.[219] Russia’s Kornet anti-tank missile is rumoured to have even greater penetrating power.

With regard to the penetrating power of anti-tank guided missiles, it does not make much difference whether a single or tandem shaped charge warhead is used. The weight of the warhead is the decisive factor.

Assuming that an attack using these kinds of weapons causes primary and emergency cooling systems to fail during plant operation, this scenario could also lead to a nuclear disaster.

---

[215] Cf. [Becker 2010 b], p.2.
[216] The walls at Germany’s oldest nuclear power plants are even thinner. Some are just 60 centimetres thick. See [Becker/Hirsch 2005], p.14.
[217] Cf. [Bundesministerium der Verteidigung 2010], p.2.
[218] Cf. [Bundesministerium der Verteidigung 2010], p.1.
[219] Cf. [army-technology].

5.2.2.3 Scenario: Insider sabotage

Experts from the US Environmental Protection Agency say that "insiders" can pose a threat to nuclear power plants. Insiders could be plant employees. In addition to information from publicly accessible sources, employees also have extensive knowledge of "their" plant's safeguards and of how the components involved in plant safety function. They can use this knowledge to sabotage the systems. Insiders can also be non-employees who gain access to the plant.

[220]

Recent years have seen a rise in the threat of terrorist attacks and therefore of insider sabotage. Two factors have created more opportunities for terrorists to gain access to plants today: the increasing amount of maintenance work and testing that have to be carried out on nuclear plants, particularly during plant operation; and the fact that this work requires the involvement of external companies.[221]

The risk of a nuclear plant and its functions sustaining serious damage increases further if one takes into account the possibility of an insider suicide attack, since this generally involves relatively large explosions. However, factors such as more rigorous security checks for prospective employees and employees from external companies do help to reduce the risk of serious damage being done to the plant.[222] Existing security gaps are of particular importance for older nuclear plants because the low level of their safety standards compared to current technology and practice (design reserves) means that these plants are less likely to be able to cope with an accident. However, the threat also depends on the safety culture at the individual plant.[223]

In March 2006, an employee performing checks at the Philippsburg 1 plant was given a set of keys so that he could do work on an emergency generator. A few hours later, twelve of the keys had gone missing, three of which unlocked doors to areas involved in plant security. Work on changing the locks did not begin until a few days later. Over 100 had to be changed.[224] On 15 February 2007 an external company informed the nuclear authority responsible for the plant that no adequate checks were carried out on the company's own tools and devices when they were brought into the plant. This allegation was confirmed. It turned out that plant staff were unsure as to how thorough the checks should be. The problem was resolved by making the necessary additions to the instructions for the site's security services.[225]

---

[220] Cf. [Honnellio/Rydell 2005].
[221] Cf. [Becker 2009], p.37.
[222] See [Honnellio/Rydell 2005].
[223] Cf. [Becker 2009], p.37 ff.
[224] Cf. [Stuttgarter Zeitung 2006].
[225] Cf. [LTBW 2009], p.5

Another case involving sabotage happened at the Koeberg nuclear plant near Cape Town. An eight-centimetre-long bolt was discovered inside a generator. It should have been on the outside. The reactor malfunctioned, which meant that the second reactor ran longer than the maintenance interval planned.[226]

Between 2002 and 2008, a suspected member of al-Qaeda worked at a nuclear power plant in New Jersey. The US authorities did not classify him as a "high-risk individual". He is alleged to have worked in other plants as well. The Yemen Ministry of Defence believes that the man has been involved in a number of terrorist attacks.[227]

On 22 June 2009, a large group of Greenpeace activists drew attention to the possibility of sabotaging a nuclear plant. Their campaign aimed to raise awareness of the dangers of nuclear energy and involved them forcing their way into the grounds of the Unterweser plant and occupying the dome of the reactor.[228]

The examples provided above are intended to highlight the very real threat of sabotage at nuclear power plants.

5.2.3 Scenario: Computer virus

In 2010, the Stuxnet computer worm attacked the Bushehr nuclear power plant in Iran. It damaged several computers at the plant, which had only recently gone online. The attack aimed to slow down Iran’s nuclear programme by overriding the control system for large-scale industrial plants.[229] The same worm is suspected of being responsible for the destruction of over 1,000 centrifuges at Iran’s Natanz uranium enrichment facility.[230] A computer expert who decoded Stuxnet called it the biggest malware operation in history. The worm is alleged to have been programmed by experts who had access to insider knowledge about the plant and to information from the secret services. Government organisations were therefore suspected of being behind the attack.[231]

Opinions vary greatly on the subject of cyber attacks on nuclear power plants. Some organisations believe that they are the biggest threat facing plants today, while other institutions claim that they pose almost no serious threat at all. The German Federal Government also rules out the possibility of

---

[226] Cf. [DPA 2006].
[227] Cf. [Welt Online 2010]
[228] Cf. [Becker 2009], p.37.
[229] Cf. [Pick 2010].
[230] Cf. [Albright/Brannan/Walrond 2010], p.1 ff.
[231] Cf. [Ladurner/Pham 2010].

outside influences controlling computer systems to the extent that they cause damage with far-reaching consequences for the plant and its surroundings.[232]

IT security experts are of the opinion that while a computer worm like Stuxnet can cause major damage to a nuclear power plant, it would not be able to actually put one out of action. For example, a plant could be indirectly affected if a virus attack caused air-conditioning systems to fail, but this it itself is a relatively non-critical situation. More problematic however, is the fact that knowledge is already circulating on how to attack industrial control software and infect and effectively disrupt programmable logic controllers. This could potentially escalate to a situation with catastrophic consequences.[233]

Even if the occurrence of cyber attacks is currently rated as improbable, developments in malware mean that the probability could rise in future and threaten plant safety by causing computer and control systems to malfunction. Based on this assumption, we estimate an increase of 10% to 50% in the probability of occurrence of a nuclear disaster, which is reflected in a modification factor of between 1.1 and 1.5.

5.2.4 Scenario: Human error

Chernobyl provides an example of a scenario where human error in the form of negligence can be partly responsible for causing a nuclear disaster. On 25 April 1986 a systems test was carried out on reactor number four to see whether energy from the turbines could be used during a power failure to generate electricity until the emergency diesel generators started up. These generators take between 40 and 50 seconds to start up. An operating crew carried out the test without the authorisation of the responsible authorities. But it was not the first time that the test had been performed; reactor three had been tested the previous year, although not during reactor operation. The 1986 crew violated operational guidelines by testing reactor four while it was operating at half power. In addition, as planned in the test design, the crew isolated the emergency cooling system to prevent emergency signals causing water to be fed in for cooling during the test. Operating errors and unfortunate links between safety features and the reactor’s physical properties caused the test to go out of control. The next morning the reactor exploded, and the hall and the turbine building were damaged. Core meltdown ensued, releasing a large cloud of radioactive material.[234]

The accident on 28 March 1979 at the Three Mile Island plant in Harrisburg, Pennsylvania, which also released a cloud of radioactive material, was also partly caused by human error. The accident began with a failure at Unit 2. Small technical defects went unnoticed, and a valve that should have

---

[232] Cf. [Bundesregierung 2006], p.11.
[233] Cf. [DPA 2010]
[234] Cf. [Czakainski et al. 1996], p.4 ff. For a detailed description of the causes and course of the Chernobyl disaster, see [Czakainski et al. 1996].

closed remained open, causing cooling water to pour out. The operating crew implemented a series of measures that exacerbated the situation and ultimately led to core meltdown and the release of radioactive material.[235]

Both these accidents prove that the risk of human error causing nuclear events absolutely exists. The long hours security staff work are one reason human error might occur. Security staff sometimes work 72 hours over six days. The authorities and the public were already aware of this problem, but it was highlighted again in 2007 when an employee of the Peach Bottom plant in Pennsylvania sent an anonymous letter to the US Nuclear Regulatory Commission, complaining about security staff sleeping while on duty.[236]

Discussions in connection with the risk of human error also focus on the steady loss of expertise as a result of experienced staff leaving plants, advisory companies and supervisory authorities. The situation is complicated by the fact that it is becoming increasingly difficult for nuclear power plants to find sufficiently qualified personnel because of the continuing decline in students opting for subjects in the natural sciences, particularly with regard to nuclear technology.[237] This also has the potential to increase the risk of human error.

Human error is one of the threats that receives the most attention in risk-reduction efforts. The authors therefore estimate that this scenario will have a relatively minimal effect on changing the probability of occurrence in the present study. We consider it to increase the probability of occurrence from Section 5.1 by 10%.

5.2.5 Scenario: Earthquake

Recent events in Fukushima have drawn attention to the fact that a "residual risk" that seems extremely unlikely can actually occur.

On 11 March 2011 a magnitude 9[238] earthquake was first measured off Japan’s northeast coast. The quake triggered a tsunami. Among other things, these natural disasters caused the cooling system and the external power supply to fail at the Daiichi nuclear plant in Fukushima, which comprises six boiling water reactors. Because of the tsunami, it was not possible to keep the emergency diesel generators operational for long enough. It is likely[239] that at least one of the units suffered core meltdown, and a fire in the spent fuel pool for the fuel rods caused a large cloud of

---

[235] Cf. [USNRC 2009], p.1.ff.

[236] Cf. [Harwood 2007].

[237] Cf. [Büro für Atomsicherheit 2010], p.15 ff.

[238] Cf. [Schweizer Erdbebendienst 2011], p.14 ff. The magnitude describes the force of an earthquake.

[239] This study was compiled in March 2011. At that time the exact course of events and their consequences were still unclear.

radioactive material to be released. During compilation of the present study in March 2011, the accident had already been given an INES level of 6 (serious accident).[240]

Given its geographic location, an identical scenario involving an earthquake and tsunami could not happen in Germany. That said, some German plants are located in areas where lower-magnitude earthquakes do occur, such as the region around the Rhine Rift Valley and those close to the Alps. These areas have even been known to suffer earthquakes of magnitudes between 6 and 8.[241] Figure 5.3 shows earthquakes of these higher magnitudes using earthquake data from the year 800 to 2010.

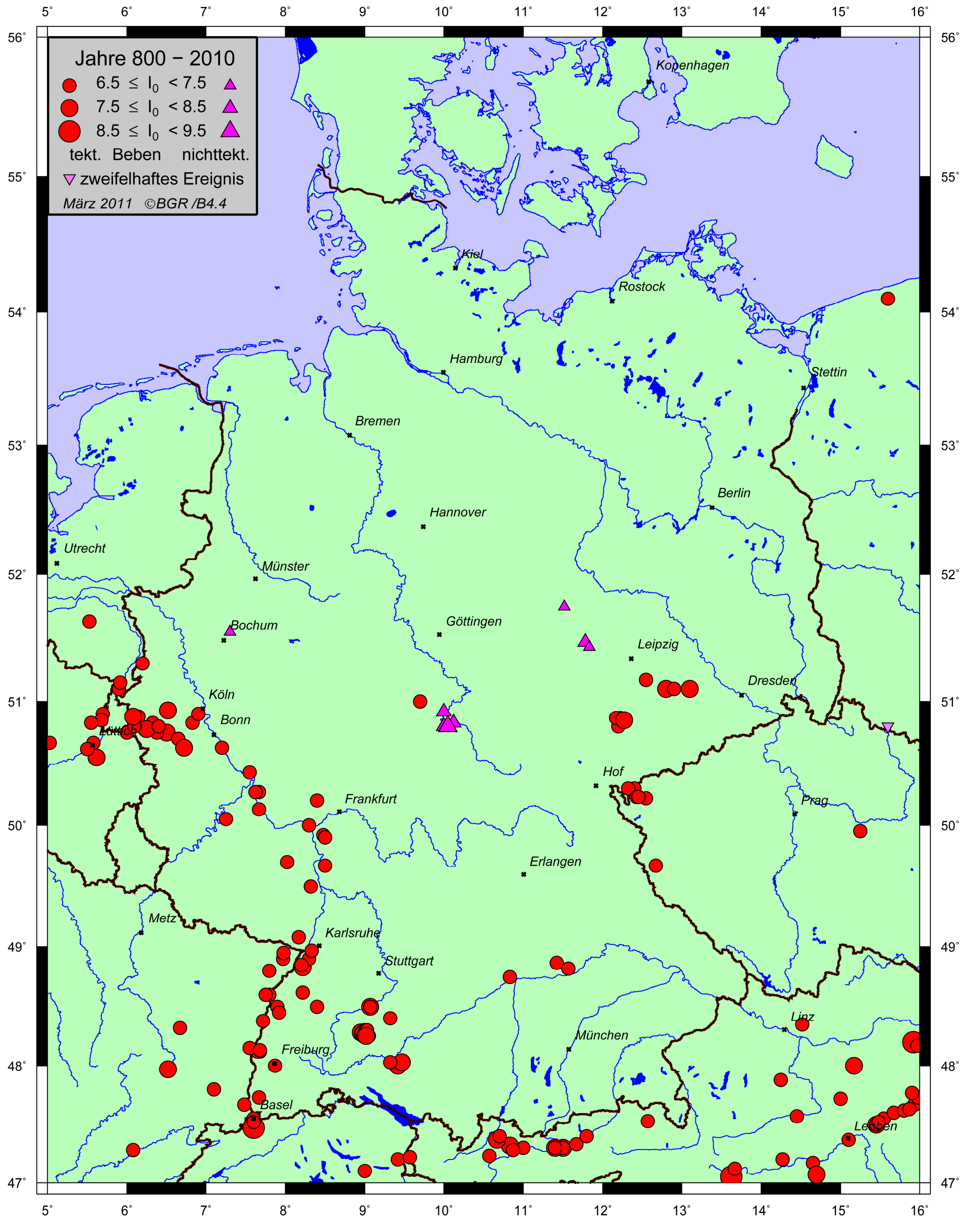
Up until the end of the 1990s it was assumed that the strongest earthquake that could hit Germany would measure 7.75 on the Richter scale. This assumption provided the basis for constructing nuclear plants in Germany and for setting up safety precautions.[242] Biblis B, for example, is designed to withstand earthquakes up to a magnitude of eight; that is, the structure, building fabric and safety precautions should all be able to survive an earthquake of this magnitude.[243] But current knowledge shows that Germany could potentially suffer stronger earthquakes.[244] Geoscientist Eckhard Grimmel from the Institute of Geography at the University of Hamburg says that we largely underestimate earthquake activity in Germany.[245] Hessen’s nuclear supervisory authority has an expert report on earthquakes that says Germany could suffer earthquakes up to a magnitude of ten.[246]

Therefore, one cannot rule out the possibility of Germany suffering a powerful earthquake. An earthquake poses the risk of triggering a nuclear disaster, which is why the present study includes the scenario of an earthquake as a potential threat to a nuclear power plant.[247]

Nuclear power plants are also at risk if, despite being designed to withstand earthquakes, the construction work was not carried out properly. This is what led to the unscheduled shut-down

---

[240] Cf. [Focus Online 2011].
[241] Cf. figure from the [Bundesanstalt für Geowissenschaft und Rohstoffe 2011].
[242] Cf. [Becker 2005], p.14 ff.
[243] Cf. [Paulitz 2008], p.2.
[244] Cf. [Becker 2005], p.14 ff.
[245] Cf. [Steeb 2011].
[246] Cf. [Paulitz 2008], p.2
[247] The effect of an earthquake was taken into account in previous studies – presented in Section 5.1. It is mentioned here purely because of current events. However, it has not been incorporated it into the following calculations because there was no change in the earthquake risk.



Years 800 to 2010
Tectonic Non-tectonic
▼Disputed event
March 2011

Figure 5.3 Earthquakes in Germany between the years 800 and 2010
(Source: [Federal Institute for Geosciences and Natural Resources 2011])

of the Biblis B unit in 2006, after random checks during a general overhaul of Unit A showed a number of incorrectly installed dowels. The plant operator said that staff had to check between 3,500 and 4,000 heavy dowels used to install pipelines and secure them against earthquakes.
[248]

Nonetheless, current events in Japan do not affect the probability of occurrence of this kind of scenario. It is only because of the change in public perception of this risk that it has come to the foreground in recent weeks. This means that the threat of an earthquake does not influence the assumed probability of occurrence of a nuclear disaster.

5.3 Summary of estimates of probabilities of occurrence

The following table shows all probabilities of occurrence addressed in Section 5.1 along with the scenario-modified probabilities.

	Modification factor	Scenario: Terrorist act (Section 5.2.2)	Externalities of Energy (ExternE) Vol. 5	Modification factor	Scenario: Terrorist act (Section 5.2.2)	Externalities of Energy (ExternE) Vol. 5
Probability of occurrence per operating year		l:1,000/Ra	l:100,000/Ra	1:33,333/Ra	1:280,000/Ra	l:10,000,000/Ra
Scenario: Ageing nuclear power plants (Section 5.2.1)	2		1:50,000/Ra	l:16,666/Ra	l:140,000/Ra	1:5,000,000/Ra
Scenario: Ageing	6		l:16,666/Ra	1:5,555/Ra	1:46,666/Ra	l:1,666,666/Ra

---

[248] Cf. [Spiegel Online 2006].

nuclear power plants (Section 5.2.1)		No modification				
Scenario: Ageing nuclear power plants (Section 5.2.1)	10		l:10,000/Ra	1:3,333/Ra	1:28,000/Ra	l:1,000,000/Ra
Scenario: Ageing nuclear power plants (Section 5.2.1)	18		1:5,555/Ra	l:1,850/Ra	l:15,555/Ra	1:555,555/Ra
Scenario: Computer virus (low approach) (Section 5.2.3) Scenario: Human error (Section 5.2.4)	1,1		1:90,909/Ra	1:30,300/Ra	1:254,545/Ra	1:9,090,909/Ra
Scenario: Computer virus (high approach) (Section 5.2.3)	1,5		1:66,666/Ra	1:22,222/Ra	l:186,666/Ra	1:6,666,666/Ra

Figure 5.4: Overview of all probabilities of occurrence given in Chapter 5 (Source: authors' own work)

Chapter 6

Calculation of the liability insurance premium for the risk of a nuclear disaster

6.1 Methodology used / Description of the model

6.1.1 Tasks and objectives

The following model is intended to calculate the incidental anticipated present value of benefits necessary to privately insure against damages and the costs of abating damages suffered by third parties as a result of a nuclear disaster at a nuclear power plant. To do this, the effects of a nuclear disaster at a nuclear power plant are simulated and the underlying risk quantified. There are already various studies for estimating the damage amounts and probabilities of occurrence. These were presented in Chapter 4 and 5, and will be used as the basis for calculation.

Damage events in a nuclear disaster at a nuclear power plant are distinguished in particular by extremely high damages and very low probabilities of occurrence. The probability of occurrence of a single amount of damage of the entire probability function is of the order of 500 femto (10^{-15}). Therefore the calculation of the present value of benefits is performed using extreme value statistics. For this the distribution function[249] *F* is estimated for each damage type *X* for the occurrence of damage amounts based on the studies available. Section 6.1.3 explains how this estimate takes place. The distribution of the order statistics[250] can be determined from this distribution function. For large *n*, the "normalized"[251] order statistics converge to an extreme value distribution.

The following section will explain the main features of extreme value theory for better understanding of matters. Then the distribution function that is used for the occurrence of damage amounts will be explained together with how the worst case damage and loss forecast are determined.

6.1.2 Introduction to extreme value theory

Extreme value theory[252] is concerned with the minimum and/or maximum values of random samples. The question arises whether a limiting distribution exists for the extreme values for independent, identically distributed random variables $X_1, X_2, \ldots, X_n$ with the distribution function *F* and how the latter can be determined clearly.

Here it is enough if only the distribution of maximum values is considered, which due to the independence of the random variables is given by

$$\mathbb{P}(\max(X_1, X_2, \ldots, X_n) \leq x) = \mathbb{P}(X_1 \leq x, X_2 \leq x, \ldots, X_n \leq x) = F^n(x)$$

This equation states that the probability that the largest value of the random variables is smaller than *x* is the same as the probability that all random variables are smaller than *x*.

Only the behaviour of the maximum extents of damage[253] is relevant for quantifying the risk of a nuclear disaster. However, for the sake of completeness for extreme value theory, note that corresponding statements can also be made regarding the distribution of minimum values. The determination of the limiting distribution for the minimum value then occurs analogously, because based on the property

$$\min(X_1, X_2, \ldots, X_n) = -\max(-X_1, -X_2, \ldots, -X_n)$$

and with

---

[249] A distribution function *F* describes the probability distribution of a random variable *X*. The value *F(x)* of the distribution function *F* at position *x* indicates the probability that the random variable assumes values smaller than or equal to *x*, i.e. *F(x)* indicates how probable the event $X \leq x$ is..

[250] A random sample $X_1, \ldots, X_n$ of random variables is referred to as statistics. The associated order statistics orders the random variables by magnitude.

[251] A random variable is referred to as normalized if its expected value is equal to 0 and its variance is equal to 1. If *X* is a random variable, then the normalization of the random variable *X* is given by

$$Y = \frac{X - \mathbb{E}X}{\sqrt{Var(X)}}$$

[252] See [Leadbetter et al. 1983] and [Reiss/Thomas 2007].

[253] The maximum extents of damage in relation to nuclear disasters are the simulated worst case losses.

$$\bar{F}(x) = 1 - F(x)$$

it follows that

$$\mathbb{P}(\min(X_1, X_2, \ldots, X_n) > x) = (1 - F(x))^n = \bar{F}^n(x)$$

Consequently for the distribution function of the minimum values it is true that

$$\mathbb{P}(\min(X_1, X_2, \ldots, X_n) \leq x) = 1 - \bar{F}^n(x)$$

and using the extreme value distribution for maximum values the extreme value distribution of minimum values can be deduced.

The following main statements represent the central results of extreme value theory. The first result states that, with appropriate "normalization"[254], the distribution of the maximum values of a random sample approaches a limiting distribution *G*:

Theorem 6.1.1 X_1, X_2,..., X_n are independent, identically distributed random variables.

Then there are two number sequences $(a_n)_{n\in N}$ and $(b_n)_{n\in N}$ with a_n, $b_n \in \mathbb{R}$ and $a_n > 0$, such

that:

$$\frac{\max(X_1, X_2, \ldots, X_n) - b_n}{a_n} \xrightarrow{\mathcal{D}} G\ .$$

G is a non-degenerate limiting distribution.

The second main result of extreme value theory states that the limiting distribution *G* of the maximum values of a random sample assumes one of three distribution function types:

Theorem 6.1.2 *X_1,X_2,..., X_n are independent, identically distributed random variables. The limiting distribution of the "normalized" maxima is defined by one of the following three distribution function types:*

Type 1 (Gumbel type):

$$G_0(x) = \exp(-e^{-x}) \qquad -\infty < x < \infty;$$

Type 2 (Fréchet type):

$$G_{1,\alpha}(x) = \begin{cases} 0, & x \leq 0, \\ \exp(-x^{-\alpha}), \quad \alpha > 0, & x > 0; \end{cases}$$

Type 3 (Weibull type):

$$G_{2,\alpha}(x) = \begin{cases} \exp(-(-x)^{\alpha}), \quad \alpha > 0, & x \leq 0, \\ 1, & x > 0. \end{cases}$$

6.1.3 Selecting the distribution function for the occurrence of damage amounts

The risk of financial obligation from the liability of a nuclear power plant licensee after a nuclear disaster is to be insured. In other words, the insurer is only obligated to pay if a nuclear disaster has taken place. Other losses and accidents associated with operation of the nuclear power plant aside from the case of a nuclear disaster, such as individual illnesses of the personnel due to excessive radiation exposure in the nuclear power plant, are not covered by this insurance. Therefore the probability of particular extreme damage amounts of loss type *X* are of interest under the assumption that a nuclear disaster occurred. This distribution function is designated by *F*.

Since a nuclear disaster is always associated with very high claims expenditures and has at least a particular extent of damage, the distribution function *F* is obviously a left-skewed distribution. Furthermore it is assumed that the extent of damage of an individual nuclear disaster has an upper limit. Therefore the distribution function of loss amounts is limited on the high side. Given that a nuclear disaster has occurred, the relation between the loss amount and the associated probability for it assumes the form shown in Figure 6.1.

---

[254] It is not a normalization of the random variable in the actual sense, because a_n and b_n are not necessarily the deviation and the expected value as described in footnote 251.

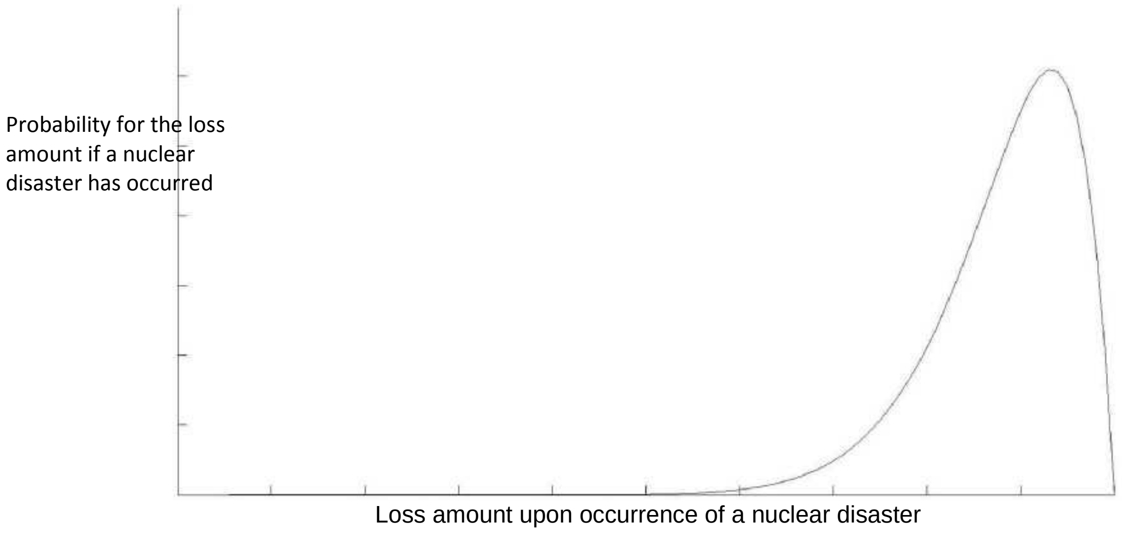


Figure 6.1: Probabilities for loss amounts if a nuclear disaster has occurred (Source: authors' own work)

The two-parameter beta distribution with the parameters α > 0 and β > 0 satisfies this characteristic with the corresponding choice of parameters[255]. Therefore the assumption that the loss amounts with the occurrence of a nuclear disaster have a beta distribution is taken as a basis. First the mathematical plan constituting the basis for this chapter will be illustrated. Then the beta distribution will be described. However, since the conventional beta distribution is limited to the interval [0,1] it will then be generalized for an arbitrary interval [*a,b*]. There then follows an explanation of how the parameters α and β must be selected so the damage of a nuclear disaster can be described.

The applied mathematical concept is based on uniquely describing the beta distribution by its moments[256]. Considering this fact, the distribution function can be derived from the moments. Using the studies examined the expected value and the variance – that is, the first moment and the second central moment[257] – are assumed to be known for a loss from a nuclear disaster. Since the moments of the beta distribution depend only on the parameters α and β, under the assumption that the losses have a beta distribution and that the expected value and variance of the losses are known, these parameters can be calculated.

In the interval [0,1] the beta distribution has the density[258]

$$f_{Beta}(x) = \frac{1}{B(\alpha,\beta)} x^{\alpha-1}(1-x)^{\beta-1}\,, \qquad 0 \le x \le 1 \quad \text{und} \quad \alpha,\beta > 0\,,$$

in which

$$B(\alpha,\beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)} = \int\limits_0^1 y^{\alpha-1}(1-y)^{\beta-1}dy$$

designates the beta function.

Taking the first derivative enables the calculation that the density of the beta distribution reaches its extreme[259] at the point

$$x_e = \frac{\alpha-1}{\alpha+\beta-2}$$

Correspondingly, the characteristics of a beta-distributed random variable *X* with the parameters α and β can also be demonstrated using the beta function. It applies to the

expected value

$$\mathbb{E}X = \frac{\alpha}{\alpha+\beta}\,.$$

---

[255] The parameters α and β describe the form of the beta distribution; moreover, they determine the expected value and the variance.

[256] The *k*-th moment m_k of a random variable *X* is given by the expected value of the *k*-th power *X*, i.e.

$$m_k = \mathbb{E}\left[X^k\right].$$

The first moment of a random variable is consequently its expected value.

[257] The central moments of a random variable take into account the distribution of the probability measures around the expected value, i.e.

$$\mu_k = \mathbb{E}\left[(X-\mathbb{E}X)^k\right].$$

The second central moment is the variance.

[258] The probability density function, referred to as the density for short, enables statements regarding the frequency of occurrence for events. The maximum of a density function describes the most probable value of a distribution function. If the density exists, it uniquely describes the associated distribution function.

[259] If it is a maximum, it is the most probable value of the distribution. A minimum is the least probable value.

The variance is given by

$$Var(X) = \frac{\alpha\beta}{(\alpha+\beta+1)(\alpha+\beta)^2}$$

Correspondingly, the coefficient of variation is found by

$$VarK(X) = \frac{\sqrt{Var(X)}}{\mathbb{E}X} = \frac{\sqrt{\alpha\beta}}{\alpha\sqrt{\alpha+\beta+1}} \,.$$

By determining the third central moment, the skewness[260] can be specified by

$$\nu(X) = \frac{\mu_3(X)}{\sigma^3(X)} = \frac{2(\beta-\alpha)\sqrt{\alpha+\beta+1}}{(\alpha+\beta+2)\sqrt{\alpha\beta}}$$

If the parameters of the beta distribution satisfy the characteristic

$$\beta < \alpha$$

then the distribution is left-skewed.

The loss amount of a nuclear disaster is not limited to the interval [0,1]. Therefore the general beta distribution for the arbitrary interval [*a,b*] is considered. The density of this distribution function is given by

$$f_{Beta,[a,b]}(x) = \frac{1}{B(a,b,\alpha,\beta)}(x-a)^{\alpha-1}(b-x)^{\beta-1} \,, \qquad a \le x \le b \text{ und } \alpha,\beta > 0 \,,$$

in which the general beta function is represented by

$$B(a,b,\alpha,\beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)}(b-a)^{\alpha+\beta-1} = \int\limits_a^b (y-a)^{\alpha-1}(b-y)^{\beta-1}dy$$

As an illustration, Figure 6.2 shows the density of a general beta distribution in the interval [0; 5 x·10^{12}].

The most probable value of the general beta distribution is achieved at the point

$$x_e = \frac{(\alpha-1)b-(\beta-1)a}{\alpha+\beta-2}$$

The expected value of a random variable *X* with the parameters α > 0 and β > 0, which is beta-distributed in the interval [*a, b*], is given by

$$\mathbb{E}X = \frac{\alpha}{\alpha+\beta}(b-a)+a \,. \qquad (6.1)$$

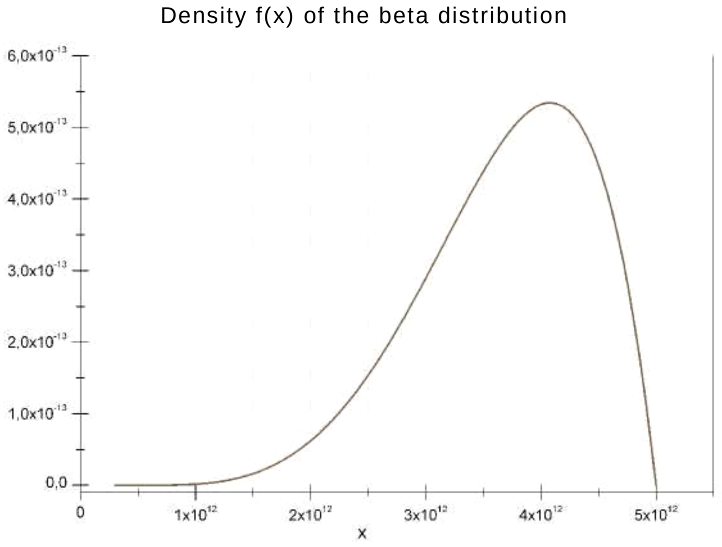


Figure 6.2: Graph of the density of a general beta distribution (Source: authors' own work)

By calculating the second moment, the variance can be specified by

$$Var(X) = \frac{\alpha\beta}{(\alpha+\beta+1)(\alpha+\beta)^2}(b-a)^2 \qquad (6.2)$$

Thus the following applies for the coefficients of variation:

$$VarK(X) = \frac{\sqrt{Var(X)}}{\mathbb{E}X} = \frac{\sqrt{\alpha\beta}(b-a)}{(\alpha(b-a)+a(\alpha+\beta))\sqrt{\alpha+\beta+1}} \,.$$

---

[260] The skew indicates how strongly a distribution is biased to the right (*v(X)* > 0) or left (*v(X)* < 0). Figure 6.1 is correspondingly *v(X)* < 0.

As mentioned previously, the beta distribution can be uniquely described by its moments. Thus the associated general beta distribution can be determined with knowledge of the expected value and the variance. The use of equations (6.1) and (6.2) enables determination of the parameters of the beta distribution describing the extent of damage from a nuclear disaster. By rearranging (6.1) according to β and substituting in (6.2), the following equations are obtained:

$$\alpha = \frac{\mathbb{E}X - a}{b-a}\left(\frac{(b-\mathbb{E}X)(\mathbb{E}X-a)}{Var(X)} - 1\right) \qquad (6.3)$$

$$\beta = \frac{b-\mathbb{E}X}{b-a}\left(\frac{(b-\mathbb{E}X)(\mathbb{E}X-a)}{Var(X)} - 1\right) \qquad (6.4)$$

6.1.4 Determination of worst case damage and its expected value

After the distribution function F has been determined, the distribution function of the greatest extreme loss occurring is to be considered. For this a random sample is taken of the random variables $X_1, X_2, \dots, X_n$, which represent extreme losses independently and identically distributed according to F. Then these extreme losses are sorted according to magnitude. Thus one obtains the order statistics $X_{(1)}, X_{(2)}, \dots, X_{(n)}$, i.e. $X_{(i)}$, $i = 1, 2, \dots, n$, corresponding to the i-th smallest value of the random sample $X_1, X_2, \dots, X_n$. Therefore

$$X_{(1)} = \min(X_1, X_2, \dots, X_n)$$

and

$$X_{(n)} = \max(X_1, X_2, \dots, X_n). \qquad (6.5)$$

For the distribution functions $F_{X(i)}$, $i = 1,2,\dots,n$, for the order statistics it is known[261] that:

$$F_{X_{(i)}} = \mathbb{P}(X_{(i)} \leq x) = \sum_{j=i}^{n} \binom{n}{j} [F(x)]^j [1-F(x)]^{n-j}$$

$$= \frac{n!}{(i-1)!(n-i)!} \int_0^{F(x)} t^{i-1}(1-t)^{n-i} dt.$$

The expected value is thus obtained as

$$\mathbb{E}X_{(i)} = \int_0^{\infty} \sum_{j=0}^{i-1} \binom{n}{j} [F(x)]^j [1-F(x)]^{n-j} dx.$$

As mentioned, equation (6.5) is true, and based on the independence of the random variables, it follows as described in Section 6.1.2 that

$$F_{X_{(n)}} = \mathbb{P}(X_{(n)} \leq x) = \mathbb{P}(X_1 \leq x, X_2 \leq x, \dots, X_n \leq x) = F^n(x).$$

With increasing n the expected value of the worst case damage does not decrease and the variance does not increase. As an illustration, Figure 6.3 shows various n-th powers using the example of a general beta distribution.

If it is assumed that $F(x) < 1$ for all $x < \infty$, then

$$\lim_{n\to\infty} F^n(x) = 0$$

is true for all

$$x < \infty.$$

The extreme value theory from Section 6.1.2 is applied below, particularly the sentence

from Fisher-Tippett: "For large values of n, the ‘normalized’ random variable $\frac{X_{(n)}-\nu_n}{\varsigma_n}$ of the order statistics X(n) converges to an extreme value distribution." The variables vn are candidates[262] for the expected value for extreme loss and the variables ςn are candidates for the standard deviation.

The modelling is based on the fact that worst case losses in a nuclear power plant disaster are fundamentally associated with very large values and very low probabilities (evaluation of the extreme case in the light of its rare occurrence).

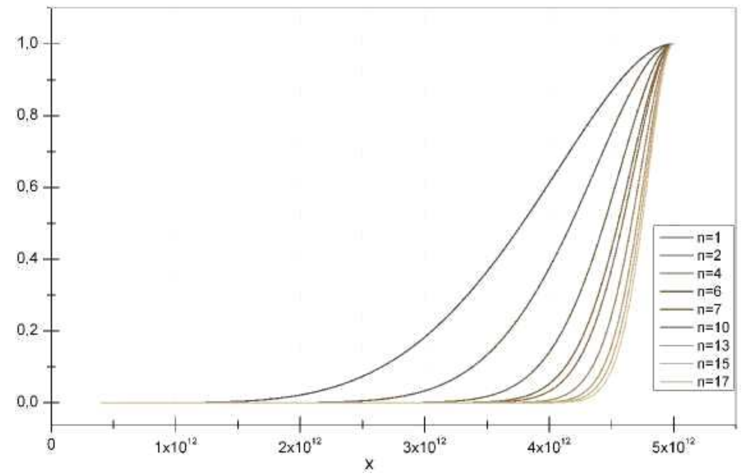
A risk premium is determined for the liability limit $v_n + 3ς_n$ (usual consideration of random variations in property insurance) or $v_n + 6ς_n$ (consideration of extreme losses) for the probability of a nuclear disaster occurring.[263] Due to the nature of extreme loss, $v_n+6ς_n$ is selected. Here the pure risk premium can be determined from v_n and the security premium from 6ς. Furthermore, various scenarios are taken into account in which 99.5 per cent of the coverage amount must be available at an earlier stage rather than at the end of the term.

---

[261] See [Buning/Trenkler 1994].

[262] These are approximations of the respective variables, so-called estimators.

[263] See Section 3.1.3.



n-th power of the beta distribution function *F(x)*

Figure 6.3: Various *n*-th powers of the general beta distribution (Source: authors' own work)

With the knowledge of the extreme value distribution, which is defined by Section 6.1.2, and of the amount of the worst case loss – that is, the order statistics $X_{(n)}$ – the probability of extreme loss can be determined.

But before the probability of extreme loss can be determined, the worst case damage of a nuclear disaster must be simulated. As known, the random samples of the extreme loss amounts $X_1, \ldots, X_n$, which are independently and identically distributed according to *F*, and the associated order statistics are considered. Now these order statistics must be arranged in a matrix so they increase monotonically by both rows and columns. For sufficiently large *n,* the worst case damage thus converges on the value in the *n*-th line and *n*-th column.

For this *n* different random samples of size *n* are simulated, i.e. an *n* × *n* matrix of random variable results for the extent of damage:

$$\begin{pmatrix} X_{1,1} & X_{2,1} & \ldots & X_{n,1} \\ X_{1,2} & X_{2,2} & \ldots & X_{n,2} \\ \vdots & \vdots & \ddots & \vdots \\ X_{1,n} & X_{2,n} & \ldots & X_{n,n} \end{pmatrix}$$

For *i* = 1, 2,..., *n* the following random vectors

$$X^{(i)} = \begin{pmatrix} \max\limits_{j=1,\ldots,i} X_{j,1} \\ \max\limits_{j=1,\ldots,i} X_{j,2} \\ \vdots \\ \max\limits_{j=1,\ldots,i} X_{j,n} \end{pmatrix}$$

are introduced, i.e. the vector of the line maxima up to the *i*-th column. The associated "normalized" order statistics of these vectors thus yield the following matrix:

$$\begin{pmatrix} \frac{X^{(1)}_{(1)}-\nu_{1,1}}{\varsigma_{1,1}} & \frac{X^{(2)}_{(1)}-\nu_{2,1}}{\varsigma_{2,1}} & \ldots & \frac{X^{(n)}_{(1)}-\nu_{n,1}}{\varsigma_{n,1}} \\ \frac{X^{(1)}_{(2)}-\nu_{1,2}}{\varsigma_{1,2}} & \frac{X^{(2)}_{(2)}-\nu_{2,2}}{\varsigma_{2,2}} & \ldots & \frac{X^{(n)}_{(2)}-\nu_{n,2}}{\varsigma_{n,2}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{X^{(1)}_{(n)}-\nu_{1,n}}{\varsigma_{1,n}} & \frac{X^{(2)}_{(n)}-\nu_{2,n}}{\varsigma_{2,n}} & \ldots & \frac{X^{(n)}_{(n)}-\nu_{n,n}}{\varsigma_{n,n}} \end{pmatrix}$$

The order statistics

$$X^{(i)}_{(j)}, i = 1, \ldots, n$$

and *j* = 1, ..., *n* increase monotonically both by rows and by columns, i.e. the worst case damage is represented by

$$X^{(n)}_{(n)}$$

The variables $v_{n,n}$ and $\varsigma_{n,n}$ are thus candidates for the expected value of extreme loss and for the standard deviation of the extreme loss.

6.1.5 Mathematical principles for the calculation of an insurance premium

In the previous chapter it was explained how the probability of extreme loss $v_{n,n}$ and the standard deviation of the extreme loss $\varsigma_{n,n}$ are determined. In accordance with the consideration of extreme losses already mentioned, the coverage amount is determined as $v_{n,n} + 6\varsigma_{n,n}$. This is the expected present value of benefits for liability insurance for the event of a nuclear disaster at a nuclear power plant. This quantifies the underlying risk accordingly.

The funds required to assume the risk must essentially be provided by all the payments; that is, they must be covered by the insurance premium.[264] This situation is taken into account using the mathematical insurance benefits principle.[265] The (net) risk premium[266] is calculated based on the benefits principle. Actuarial interest of 2 per cent is used as a basis here. This actuarial interest rate was chosen because the current maximum actuarial interest for the life insurance is 2.25 per cent and will be reduced to 1.75 per cent as of 2012.

According to the benefits principle, the expected present value of benefits corresponds to the expected present value of the premiums,[267] i.e.

expected present value of benefits = expected present value of premiums.

The time period in which the premium is to be paid influences the values of the annual risk premium. If, for example, the risk premium to be paid over a period of 1000 years is compared with a risk premium that ensures that 99.5 per cent of the coverage amount is saved within the next 30 years, then the former risk premium is lower due to the effect of compound interest.[268] However, this would also mean that the loss can only be compensated after 1000 years even if a nuclear disaster takes place after just 20 years. Furthermore, the licensee of the nuclear power plant and future generations of nuclear power plant licensees are obligated to continue paying the risk premium even if the nuclear power plant is not in operation for the entire period.

Therefore various scenarios are considered which are involved with the systematics of the period and the funding of the amount covered.

6.2 Application of the methodology

6.2.1 Estimation of the distribution of damage amounts

Various studies for estimating loss amounts were referred to for quantifying the risk of "nuclear disaster". These were considered in detail in Chapter 4 and shown in an overview of the values used. An exact list of the individual loss amounts used can be found in Annex *B*.

Where there is no location-specific data available that enables an individual calculation of all loss types for each individual nuclear power plant in Germany, the same values are assumed for all power plants. If detailed values determined with a particular methodology are available for individual locations, then that same methodology is used to apply them to the other locations. Thus, for example, self-created estimates for wind direction scenarios, which impact the number in the population affected by resettlement measures, enable the specification of a loss amount differentiated by location.

All data that affects the loss amounts are generally average estimates. Rare events of particularly great magnitude are already included in this expected value with their low probability. These values do not permit a serious orientation toward worst case loss. Thus here, too, the practice is conservative and not overestimating.

Modelling of various distribution functions from one value in each case, which also does not differ much from nuclear power plant to nuclear power plant, would have led to a general increase in the standard deviation of the other variables to estimate as a result of the necessary assumptions regarding the standard deviation at each power plant. The expected value of the distribution of the maximum would not be affected by this. However, this procedure would effectively increase the selection of a candidate for the expected value of the extreme loss according to 6.1.4.

With the modelling of a distribution function that is uniform for all nuclear power plants, a conservative approach is chosen which does not "unnecessarily" contribute to increasing the expected value or the standard deviation (which would also increase the safety margin).

---

[264] As explained in Section 3.1.1.

[265] Briefly designated as the "benefits principle" below

[266] This was defined in Section 3.1.3 and is designated briefly below as the "risk premium".

[267] See [Adelmeyer/Warmuth 2003] p. 27 ff.

[268] Even without interest, the first risk premium would be lower, because the amount of coverage remains constant and in the second case can be divided over a lesser period.

In the first step, the calculated results from Chapter 4 are used to derive weighted loss amounts for each nuclear power plant. For this the values[269] for each loss type, obtained by evaluating all the results of the investigated studies, were totalled. For all loss types, except the costs of relocation, half the total weighting is allocated to the highest values in each case, and the other values are given the same weight in each case in the remaining 50 per cent. This weighting is performed so that the character of a premium appropriately reflects a worst case loss event.

For example, for the loss type fatal cancers there are 20 loss amounts available. The highest value is included with a weighting of 50 per cent in loss amount determination. The remaining 50 per cent is divided equally among the remaining 19 values. The calculation is thus performed as follows:

0.5 × 7.50812 trillion euros + 0.5(1/19 × 80.6 billion euros + ... + 1/19 × 5.040 trillion euros)

For relocation costs, the self-calculated values for different wind direction scenarios are weighted with 50 per cent and all other values weighted the same to take greater account of the influence of wider dispersions of radioactivity. Costs for food bans, evacuation and resettlement were taken into full account in each case. The weighted loss amounts for each nuclear power plant are shown in Figure 6.4. The assumed expected loss is the expected value of the results for all 17 nuclear power plants, amounting to 5.756 trillion euros. The standard deviation is a value indicating how far the results of the random variables differ on average from the expected value. As the evaluated studies are predominantly unspecific with respect to location, it amounts to only 60.7 billion euros. The loss amounts[270] are shown in Figure 6.4.

Nuclear power plant	Weighted damage total (€)	Average value (€)	Standard deviation (€)
Biblis A	5,765,028,543,594	5,756,466,403,899	60,718,280,095
Biblis B	5,765,028,543,594		
Brokdorf	5,608,337,868,136		
Brunsbuettel	5,699,096,453,230		
Emsland	5,755,911,013,272		
Grafenrheinfeld	5,777,925,424,626		
Grohnde	5,908,407,122,808		
Gundremmingen B	5,724,878,931,293		
Gundremmingen C	5,724,878,931,293		
Isar 1	5,756,577,040,625		
Isar 2	5,756,577,040,625		
Kruemmel	5,698,184,067,681		
Neckarwestheim 1	5,798,633,202,876		
Neckarwestheim 2	5,798,633,202,876		
Philippsburg 1	5,768,232,334,353		
Philippsburg 2	5,768,232,334,353		
Unterweser	5,785,366,811,054		

Figure 6.4: Loss amounts, expected value and standard deviation (Source: authors' own work)

The distribution function of the loss amounts is determined below according to the model from Section 6.1.3. The distribution function is determined by four parameters: the location parameter, the form parameter, the minimum loss amount and the maximum loss amount.

---

[269] See Figures *B*.3 and *B*.4 in Annex B

[270] Please note explicitly that the amounts documented exactly to the euro suggest an accuracy that cannot be taken seriously. In fact, the results are shown here just as they are obtained from calculations, taking into account all assumptions.

Since a nuclear disaster is always associated with high costs, the lower limit for the loss amount cannot be assumed to be zero. For the interval boundary a calculation of the smallest loss amount is therefore performed, which is derived from the lowest assumptions for the loss amount and calculated as follows:

Fatal cancers

291,200 person-sieverts
x 5 per cent per sievert for fatal cancers
x 7 as a factor for the population density
x €790,446.85 per case
= €80.6 billion

Non-fatal cancers

291,200 person-sieverts
x 12 per cent per sievert for fatal cancers
x 7 as a factor for the population density
x €305,125.10 per case
= €74.6 billion

Genetic damage

291,200 person-sieverts
x 1 per cent per sievert for fatal cancers
x 7 as a factor for the population density
x €53,538.64 per case
= €1.09 billion

GDP losses due to resettlement

Lowest value at 80 km^2 resettlement area = €2.68 billion

Food bans

Value from the ExternE study in 1995 = €37.9 billion

Costs for evacuation and resettlement

Value from the ExternE study in 1995 = €2.1 billion

Altogether, the smallest loss amount is found to be €198.97 billion. Since this value already represents an expected value, standard deviations on the low side can also occur in this case. Since no statements were made in the underlying studies regarding standard deviations from these values, rounding this value to €150 billion is appropriate from conservative perspectives in order to obtain an actual lowest loss value as a lower limit of the interval.

The upper limit is taken as the sum of the expected value in the amount of 5.756 trillion euros and ten times the standard deviation of the values at 60.7 billion. This surcharge on the expected value is intended to model the upper limit of possible variations of the worst case loss; the amount is 6.363 trillion euros.

For determining the location parameter and form parameter, the expected value of the losses and the standard deviation[271] are used in equations (6.3) and (6.4).

The result is

$$\alpha = 832$$
$$\beta = 90.$$

Thus a distribution with the following density is obtained:

$$f_{loss}(x) = \frac{1}{B_{loss}}(x - 150\,\text{billion})^{832-1}(6.363\,\text{trillion} - x)^{90-1}\,, \tag{6.6}$$

where 150 billion ≤ x ≤ 6.363 trillion and B_{loss} is given by

$$B_{loss} = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)}(\,\text{Upper Limit - Lower Limit}\,)^{\alpha+\beta-1}.$$

---

[271] Variance Var(X) = $(\text{deviation})^2$

Neither modelling as a general beta distribution nor the choice of the lower and upper limit influences the expected value of the worst case loss and its variance according to Section 6.2.2.

6.2.2 Estimation of the expected worst case loss and its standard deviation

The uniform general beta distribution from 6.2.1 is applied for all 17 nuclear power plants. Following a conservative approach, the losses for the 17 nuclear power plants are considered to be independent. According to the distribution derived in (6.6), the losses for the 17 nuclear power plants are generated as random numbers and ordered by size. These sorted random numbers are then "normalized" as described in Section 6.1.4. These normalized variables converge to an extreme value distribution as described in Section 6.1.2. This limiting distribution is used as a starting point for simulating a worst case loss. By minimizing the amount of the expected value of the normalized random numbers, so-called candidates, or approximations of the respective sizes, are determined for the expected worst case loss $v_{n,n}$ and its deviation $\varsigma_{n,n}$. With increasing *n*, the worst case loss either remains the same or increases but it never decreases, and the more values are added, the lower the deviation of the worst case loss becomes. Thus the expected value of the worst case loss does not decrease with an increasing number of nuclear power plants involved. The determination of candidates always takes place in pairs. In choosing candidates, attention must be given to keeping the candidate for the expected value of the worst case loss as low as possible. The fact that the variance of the worst case loss nonetheless remains rather small is due to the rather narrow distribution form of the uniform loss amount distribution.

The values for this are found in Figure 6.5. The risk of a nuclear disaster is thus quantified by an expected value for the amount (net risk) and a security premium can ensue using the variance. According to this, the coverage amount (gross risk = net risk + security premium) that must be provided for a nuclear disaster is 6.09 trillion euros.

Estimate	Values (€)
Expected worst case loss ($v_{n,n}$)	5,900,000,000,000.00
Variance ($\varsigma_{n,n}$)2	(31,666,666,667.00)^2
6*standard deviation (6*$\varsigma_{n,n}$)	190,000,000,000.00
Coverage amount ($V_{n,n}$+6* $\varsigma_{n,n}$)	6,090,000,000,000.00

Figure 6.5: Candidates for expected worst case loss and its standard deviation (Source: authors' own work)

6.2.3 Premium scenarios

This coverage amount was recalculated using the insurance benefits principle[272] to yield an annual premium for each nuclear power plant assuming various availability scenarios. Actuarial interest of two per cent was used as a basis here, with the crediting of interest occurring at the end of a year in each case. Due to the low probability of occurrence for a nuclear disaster, a long period for liability insurance is assumed.

Depending on the expected occurrence of a nuclear disaster, there are different premium amounts. For the scenario of a terrorist act, for which the probability of occurrence was estimated at 1:1,000, an annual premium of 305.83 euros per nuclear power plant must be paid to cover the risk under the condition that the coverage amount is payable only at the end of the calculation period of 1,000 years. For events which occur with less frequency than about once in 1,500 years the annual premium per nuclear power plant is only a cent and less, due to the effect of compound interest. The following table shows the premium amount per year and nuclear power plant with specification of the underlying probability of occurrence with availability of the coverage amount at the end of the calculation period.

However, this is not an adequate evaluation for the risk of a nuclear disaster. If the risk premium is determined by this method the losses from a nuclear disaster could also only be compensated at the end of the calculation period. Based on the values considered in Section 5.1, insurance periods of up to 10 million years are also conceivable. Since the event can occur at any time within this period, an occurrence on the first day is just as likely as an occurrence at the end of these 1,000 years or even 10 million years. With an accumulation phase extending over such long periods, losses from a nuclear disaster could not be covered if they occur at the beginning of this period. It must likewise be made clear that with a distribution of premiums over the entire calculation period, the payment of premiums must also be ensured over the course of this same period, even if the service life of today's nuclear power plants usually does not exceed 60 years.

---

[272] See Section 6.1.5.

Source of the estimate	Probability of occurrence per year of reactor operation	Premium amount per year and nuclear power plant
Scenario for a terrorist act	1:1,000	€305.83
Externalities of Energy (ExternE) Vol. 5	1:100,000	less than €0.01
Ageing scenario (x2)	1:50,000	less than €0.01
Ageing scenario (x6)	1:16,666	less than €0.01
Ageing scenario (x10)	1:10,000	less than €0.01
Ageing scenario (x18)	1:5,555	€33.95
Scenario for a computer virus (x1.1) Scenario for human error (x1.1)	1:90,909	less than €0.01
Scenario for a computer virus (x1.5)	1:66,666	less than €0.01
DRS Phase B without accident management	1:33,333	less than €0.01
Ageing scenario (x2)	1:16,666	less than €0.01
Ageing scenario (x6)	1:5,555	less than €0.01
Ageing scenario (x10)	1:3,333	less than €0.01
Ageing scenario (x18)	1:1,850	less than €0.01
Scenario for a computer virus (x1.1) Scenario for human error (x1.1)	1:30,300	less than €0.01
Scenario for a computer virus (x1.5)	1:22,222	less than €0.01
DRS Phase B with accident management	1:280,000	less than €0.01
Ageing scenario (x2)	1:140,000	less than €0.01
Ageing scenario (x6)	1:46,666	less than €0.01
Ageing scenario (x10)	1:28,000	less than €0.01
Ageing scenario (x18)	1:15,555	less than €0.01
Scenario for a computer virus (x1.1) Scenario for human error (x1.1)	1:254,545	less than €0.01
Scenario for a computer virus (x1.5)	1:186,666	less than €0.01
Method convention of the German Federal Environmental Agency	1:10,000,000	less than €0.01
Ageing scenario (x2)	1:5,000,000	less than €0.01
Ageing scenario (x6)	1:1,666,666	less than €0.01
Ageing scenario (x10)	1:1,000,000	less than €0.01
Ageing scenario (x18)	1:555,555	less than €0.01
Scenario for a computer virus (x1.1) Scenario for human error (x1.1)	1:9,090,909	less than €0.01
Scenario for a computer virus (x1.5)	1:6,666,666	less than €0.01

Figure 6.6: Premiums to be paid per nuclear power plant and year with availability of the coverage amount at the end of the calculation period (Source: authors' own work)

Scenarios must therefore be considered, in which the coverage amount must already be available before the end of the calculation period. In the accumulation phase, these scenarios are consequently independent of the probability of a nuclear disaster occurring, since the availability of the required funds must occur significantly earlier. As much shorter timeframes must now be assumed for the accumulation periods ("availability periods") of the coverage amount, this also has a corresponding effect on the amount of the risk premium. Thus, for example, for each nuclear power plant operated an annual premium of 19.5 billion euros must be paid throughout the entire time period if the coverage amount is to be available after 100 years.

Availability periods	Annual premium for each nuclear power plant
Availability in 500 years	€6,103,559.32
Availability in 100 years	€19,504,708,144.15
Availability in 90 years	€24,640,242,714.04
Availability in 80 years	€31,428,696,231.34
Availability in 70 years	€40,605,979,598.00
Availability in 60 years	€53,396,911,879.16
Availability in 50 years	€72,003,347,095.51
Availability in 40 years	€100,824,504,085.85
Availability in 30 years	€150,118,026,766.82
Availability in 20 years	€250,644,413,383.02
Availability in 10 years	€556,178,554,699.78

Figure 6.7: Annual premiums as a function of various availability periods for the entire sum insured (Source: authors' own work)

The assumptions made previously are that each nuclear power plant operated in Germany would be covered by a separate insurance company so no collective compensation would take place. If an actual insurance for liability risks resulting from the operation of nuclear power plants is assumed, this would sooner be done via an insurance pool covering multiple nuclear power plants[273] in Germany or all of them. As the periods for availability of the coverage amount are very short compared to the entire span of possible occurrence probabilities, with the assumption of complete independence of the loss events it can be assumed that the probability for two or more nuclear disasters during this period is extremely low. As the number of nuclear power plants in the insurance pool increases, however, the probability of occurrence for a nuclear disaster also increases due to the independence of the loss events. The following example is intended to illustrate this. In the present study, the probability of occurrence for a terrorist act is assumed to be 1:1,000 per year of reactor operation. Assume that a special insurer covers all 17 nuclear power plants in Germany in a single portfolio. Then with 17 reactors insured, the probability of occurrence increases to 17:1,000; that is, every 58,824 years this case is to be expected for the collective. As a consequence, availability periods of 59 years or more are no longer adequate to cover the risk for this case. Thus an availability period must always be chosen that is shorter than the probability of occurrence of an insurance case in the collective. Taking into account this limitation, insuring two or more nuclear power plants would therefore not lead to multiplication of the entire annual premium to be paid. In the most favourable case, all nuclear power plants in the pool would pay only the simple annual premium. Exceptions only apply if it is assumed that locations with multiple reactors have an increased risk of loss events involving all reactors at the same time. This could be the case with an earthquake, flooding or simultaneous terrorist attacks. With separate insurance of the reactors with different insurance companies, no change would result, as in this case a dedicated coverage amount is accumulated for each reactor. This cumulative risk would only need to be considered with the formation of a pool in which one or more locations with two reactors were insured. Then within the pool, locations with two reactors would have to pay premiums between the single premium and twice that amount. There is no need to assume a linear progression of the premium amount and the number of reactors at a location, based on the fact that in a case of loss the same weather conditions prevail for both reactors at the location. These scenarios are not explicitly considered below, however, since on the one hand the number of locations with two reactors in operation will be reduced following the German federal government's nuclear moratorium, and on the other hand these assumptions can be covered by the range of premiums for separate insurance and complete formation of a pool. Therefore these different scenarios are considered for the following calculations.

Scenario 1a

All 17 nuclear power plants operated prior to the March 2011 nuclear moratorium are each insured by separate insurance companies. Consequently, the full coverage amount will be accumulated for each individual nuclear power plant, corresponding to a grand total of 103.53 trillion euros.

Scenario 1b

Only the nine nuclear power plants still running as of March 31, 2011 will continue operation, each being covered by separate insurance companies.

Scenario 2

There are four power utilities operating nuclear power plants in Germany. Each company insures its nuclear power plants in a pool, so altogether four pools handle the insurance for the nuclear power plants.

For this scenario it is assumed that the number of nuclear power plants in the individual pools does not matter, because a premium payment is made for each pool.

Scenario 3

All nuclear power plants operated in Germany are insured in a single pool. The exact number here is irrelevant just as in Scenario 2.

Assuming that the risk premiums to be paid for unlimited coverage of the liability risks are passed on via the price of electricity, the following costs in euros per kilowatt hour for a 100 year availability period result based on the total nuclear power of 140.5 billion kWh[274] produced domestically in 2010:

Scenario 1a: €19.5 billion × 17 nuclear power plants = €331.5 billion

---

[273] It is conceivable in principle that a specialized insurance provider might cover more nuclear power plants than just those in Germany. This can occur in particular through the application of the principle of "atomization"; that is spreading risks via reinsurance solutions or capital market instruments.

[274] See [BDEW 2011].

€331.5 billion /140.5 billion kWh = €2.36 / kWh

Scenario 1b: €19.5 billion × 9 nuclear power plants = €175.5 billion

€175.5 billion / 140.5 billion kWh = €1.25 / kWh

Scenario 2: €19.5 billion × 4 power utility companies = €78 billion

€78 billion / 140.5 billion kWh = €0.56 / kWh

Scenario 3 €19.5 billion / 140.5 billion kWh = €0.14 / kWh

The costs for all availability periods are shown in Figure 6.8.

From the overview of costs per kWh for the individual scenarios it is clear that with regard to the situation in Germany there is no possibility to ensure coverage of the entire risk resulting from the operation of nuclear power plants. Only after an accumulation phase of 100 years with full pool participation for all nuclear power plant risks is the surcharge to the cost of electricity of an order which at first glance appears affordable. However, in view of the remaining service life of German nuclear power plants and normal periods of 25 to 40 years, much shorter periods would need to be applied for the accumulation of funds in order to ensure availability prior to the complete elimination of risk in the form of an exit from nuclear power. The actual ability to finance this scenario is not given. This clearly shows the problem of having a risk that is present from the moment of start-up while not having accumulated sufficient funds to provide compensation for claims that can result if that risk occurs. If the various scenarios for collective formation are considered a liability risk premium results which would increase the kWh cost in a range from €0.14 to €67.30. This surcharge to the regular price of electricity would have to be paid over the entire period of accumulation for the coverage amount. The subsequent pure risk premium to be paid would depend primarily on the assumed probability of occurrence, the remaining service life and the number of insured risks in the pool. Taking into account the effect of interest, theoretically considerable annual return flows of funds would be expected.

Scenario	Availability period	Cost per kWh (€)
1a	500 years	0.00074
1b		0.00039
2		0.00017
3		0.00004
1a	100 years	2.36000
1b		1.24941
2		0.55529
3		0.13882
1a	50 years	8.71215
1b		4.61231
2		2.04992
3		0.51248
1a	10 years	67.29563
1b		35.62710
2		15.83426
3		3.95857

Figure 6.8: Net surcharges to the cost of electricity for nuclear power taking into account various scenarios (Source: authors' own work)

Chapter 7

Interpretation of results and conclusions

The insurance premium calculated in this study merely represents a hypothetical insurance premium, intended as a measurement of the total risk connected with a nuclear disaster. The overall risk-commensurate liability insurance premium established corresponds to the limit of liability for all damage, including partial damage, incurred in the event of a nuclear disaster. The results of the calculations show that both the required limit of liability in the amount of €6.09 trillion, based on an estimate of the average maximum damage and corresponding variance, and the resulting insurance premium for different assumed payment periods, are significantly higher than the financial resources legally required of nuclear power plant operators to date.

The calculations show that the amount of the premium depends in particular on the duration of the contribution period, that is, the length of time in which contributions are paid towards the reserve, and on the type of insurance pools that could be formed. The need for a relatively short contribution period arises from the fact that no institution would be in a position to pay compensation in an amount of this magnitude in the event of damage. Distribution of the insurance premium over the entire period of the assumed probability of occurrence is rejected on the grounds of the practicality issues discussed in Chapter 6. The premium for different scenarios with distinct contribution periods is dominated above all by the effect of compound interest. The further into the future the date by which the full reserve sum must be met, the lower the annual premium to be paid. Conversely, due to the effect of exponential distribution, shorter durations result in sharply rising premiums. In the event of damage during the contribution period, an early withdrawal of the reserve accumulated thus far cannot occur, as the full coverage amount based on present value assessment will only be reached if it remains available until the end of the calculated contribution period, with ongoing premium payments. The choice of too long a contribution period defeats the purpose of ensuring cover for possible damage as expediently as possible. As a result, contribution periods in excess of the remaining lifespan of existing German nuclear power plants are not considered viable.

The results must be qualified insofar as the lack of studies providing quantitative damage assessments meant that certain types of damage could not be included in the calculations. In addition, no reassessment of the individual amounts of damage was performed for this study. Instead, the appraisal of the expected extent of damage relied for the most part on existing studies. However, as only published works were included, scientific results in this field might erroneously be perceived as being more consistent than they in fact are. In extreme cases, non-existent distinctions or relationships may have been observed merely by chance, while studies in which nothing of the sort was observed might have never been published. Furthermore, the topic of nuclear energy tends to strongly polarise people, including scientists. This explains why assumptions made in regard to amount of damage and probability of occurrence in the studies consulted display significant discrepancies (discrepancies at the macro level[275]). As no evaluation was made of the studies available, the entire range of assumptions made in the studies was taken into account. It should furthermore be noted that regardless of the assumptions made in relation to the expected values, discrepancies can also occur at the micro level.[276] It is therefore possible for individual incidents to occur that far exceed the assumed expected value. An example of this would be the extinction of animal species.

---

[275] The macro level, in this context, should be taken to include assumptions which have a direct effect on the expected value.

[276] The micro level, in this context, should be taken to include discrepancies on the level of individual occurrences, which involve a significant departure from the expected value, but have no direct effect on it as a result of their low probability.

The risk of a nuclear disaster is a "development risk"; that is, one that changes over time. Advances in science and technology, or observation of the circumstances behind real-world incidents (11 September 2001 in New York or the earthquake and tsunami in Japan) and consequent reassessment of the risk situation are primary factors in this regard. These factors should be taken as an opportunity to conduct regular political and social debates on how to handle the changed risk situation. The availability of transparent and realistic information about these risks and the decisions taken with regard to risk management and risk-bearing measures is a fundamental prerequisite for this to occur. For the provision of such information in the domain of nuclear power, an extensive investigation into accident probability and the possible effects of major accidents for each power plant assumes particular urgency if reliable information is to be obtained about the overall risk. To this effect, a survey of the German public's willingness to pay for the prevention of the major risks associated with nuclear power should be conducted.

The amounts of damage and the liability insurance costs estimated in this study exceed the financial resources that nuclear power plant licensees are currently required to maintain by several orders of magnitude. The occurrence of a nuclear disaster would result in external effects involving the destruction of the surrounding environment, the costs of which would ultimately be transferred to the general public. In this event, electricity generated from nuclear power, contrary to what has so far been widely affirmed, would cease to be economical in comparison to other sources of energy. According to the calculations in this study, depending on the scenario, with respect to contribution periods of 10 to 100 years and the number of power plants insured, either individually or within a pool, the net price of electricity generated from nuclear power would rise anywhere from €0.139 per kWh to €67.3 kWh over the entire duration of the savings period.

In practice, nuclear disasters are not insurable, due in particular to a combination of

- insufficient size of the (required) risk pool
- extreme amount of the expected maximum damage and
- difficulty of estimating the probability of occurrence of damage (due to the assumed infrequency of the damage event)

Nonetheless, the results presented in this study can serve as a starting point for further considerations.

One possibility for an insurance provider would be a state-owned insurance company in the form of a public institution or corporation, which would also have to work in accordance with the insurance principles presented herein, in order to relieve the state from ultimately having to bear the costs as is currently the case.

A more practicable solution – in the context of these theoretical considerations – would be the establishment of a privately organised insurer along the lines of a "captive company", whereby nuclear power plant licensees would form their own insurance company with which to cover the liability risks resulting from the operation of nuclear power plants. The advantage of this solution for the nuclear power plant licensees would be that in the event of no claim, the accumulated reserve sum paid in would, after all risks have lapsed, revert to the proprietors. However, the above-mentioned problems of uninsurability would remain unsolved; in particular, short-term accumulation of a reserve of this size is an unrealistic goal.

A further (hypothetical) alternative is the use of the international capital markets as a risk carrier. In this process, the required capital would be gathered from the capital markets by issuing catastrophe bonds on which, in the event of no incident, appropriate interest would be paid. However, it would seem impossible for capital to be collected in the required order of magnitude. Even if it were possible, the commensurate interest demanded by the providers of capital would lead to unsustainable financial commitments.

The concept of insurance is essentially based on balance of risk in the pool and over time – that is, random risk decreases as portfolio size increases – and the contemplation of multiple single-period balances of risk. The considerations made in this study deal with the German nuclear power market; that is, the model calculations were limited to a maximum risk pool of 17 insurable units. A larger risk pool would benefit from the advantage of lower deviation of the overall damage distribution in the long term and a higher number of enterprises contributing to the reserve. A conceivable solution might be to include other countries that use nuclear power in the EU, all of Europe or even the entire world. The differing interests of the individual nations involved in such an undertaking would have to be taken into account.

The insurance premium calculated, which is based on the estimated costs of a nuclear disaster, is ultimately intended as a contribution to the current debate about the "residual risk" of a nuclear disaster, and to provide an estimate of the extent of the financial resources that would need to be made available. The premium should therefore be viewed as a measurement, which should be factored into the calculation of the overall external costs of the nuclear fuel cycle if the costs of a nuclear disaster are to be taken into account. At various points in the study, the low degree of insurability or financability of this risk was noted. Accordingly, the use of nuclear power and the associated risks are not so much an economic issue, but rather one of the willingness of society and the economy to bear the risks quantified herein. This is an issue that can only be resolved by means of public debate.

Annex A

Additional figures for Chapter 1

Figure A.1 describes the individual INES levels in more detail. The pyramid of laws depicted in Figure A.2 shows the regulatory standards for nuclear power plants. These are classified according to their binding force, starting with laws such as German Basic Law and the German Atomic Energy Act which are generally binding up to operating manuals and technical specifications that are stipulated by the industry.

Level / Short description	Aspects		
	First aspect: Radioactive off-site effects	Second aspect: Radioactive on-site effects	Third aspect: Defence-in-depth degradation
7 Major accident	Major release: Widespread health and environmental effects		
6 Serious accident	Significant release: Full implementation of disaster countermeasures		
5 Accident with wider consequences	Limited release: Implementation of some disaster counter-measures	Serious damage to reactors / radiological barriers	
4 Accident with local consequences	Minor release: Exposure for population at the level of natural radiation exposure	Limited damage to reactors / radiological barriers Radiation exposure on workers including deaths	
3 Serious incident	Very minor release: Exposure for population a fraction of natural radiation exposure	Severe contamination Acute health effect on workers	Near accident Extensive failure of tiered safety provisions
2 Incident		Significant contamination Exposure of workers in excess of statutory limits	Incident Limited failure of tiered safety provisions
1 Anomaly			Standard deviations from the permissible levels for the secure operation of the facility
0			No or little safety significance

Figure A.1: Description of the INES levels (authors' own work, adapted from [IAEA a])

Federal legislator	Basic Law	Generally binding
	Atomic Energy Act	
Federal government, Bundesrat	Ordinances	
	General administrative regulations	Binding for authorities
Federal government, federal state authorities	Safety criteria for nuclear power plants Regulatory guidelines by the Federal Ministry of the Environment (BMU) • Incident guidelines • Guidelines and recommendations	Binding once included in the license or, in individual cases, through measures of the supervisory body
Federal bodies	RSK (Reactor Safety Commission) guidelines, RSK and SSK (Commission on Radiological Protection) proposals	
KTA (German Nuclear Safety Standards Commission)	KTA safety standards	
Industry	Technical specifications for components and systems Organisation manuals and operating manuals (such as DIN, IEC)	

Figure A.2: Regulatory pyramid: Hierarchy of national sources, authorities and institutions that lay down the regulations, and their binding force (Source: authors' own work, adapted from [BMU 2009])

Annex B

Additional figures for Chapter 4

The following figure shows the wind frequency for each main wind direction at the different selected locations in Germany.

Location of nuclear power plant and measuring station Frequency in % Wind direction	Isarl&2 Munich airport FJS	Kruemmel Ahrensburg-Wulfsdorf	Brokdorf Brunsbuettel	Brunsbuettel Brunsbuettel	Emsland Lingen	Grafenrheinfeld Bad Kissingen
N	4.03	5.69	5.53	5.53	8.04	11.16
NE	10.58	7.52	7.11	7.11	8.04	26.18
E	22.17	8.13	16.21	16.21	10.72	4.29
SE	5.79	12.20	10.47	10.47	9.65	3.43
S	7.05	15.85	11.86	11.86	18.23	16.31
SW	19.14	16.06	18.38	18.38	23.06	27.90
W	24.69	21.95	17.39	17.39	11.80	6.87
NW	6.55	12.60	13.04	13.04	10.46	3.86

Location of nuclear power station and measuring station Frequency in % Wind direction	Grohnde Hameln	Gundremmingen B&C Ulm	Biblis A&B Lindenfels	Neckarwestheim 1&2 Stuttgart-Schnarrenberg	Philippsburg Karlsruhe	Unterweser Bremerhaven
N	3.16	9.14	3.79	6.64	8.82	8.32
NE	5.00	11.60	17.89	8.71	20.96	7.92
E	24.21	7.73	18.97	9.13	10.29	13.07
SE	15.00	4.22	6.78	16.60	3.68	11.49
S	4.74	10.54	3.79	14.52	5.88	13.07
SW	8.68	29.00	20.05	11.62	37.87	19.21
W	21.05	11.60	22.76	16.60	8.82	15.64
NW	18.16	16.17	5.96	16.18	3.68	11.29

Figure B.l: Wind frequency for each main wind direction (authors' own calculations, using the National Meteorological Service's wind roses)

Figure B.2 shows the calculation of the amounts of damage specified in Chapter 4.3.6 through resettlement measures following a nuclear disaster.

Weather situation	Approximate area for long-term resettlement [km²]	Number of inhabitants per km²	Number of inhabitants affected	GDP per inhabitant in US dollars	GDP per year in US dollars	GDP for 5 years in US dollars	GDP for 5 years in euros
Strong wind from changing directions, dry	80	229	18,320	40,873.27	748,798,306	3,743,991,532	2,684,067,529
Strong wind from a constant direction, dry	400	229	91,600	40,873.27	3,743,991,532	18,719,957,660	13,420,337,646
Moderate wind from changing directions, dry	160	229	36,640	40,873.27	1,497,596,613	7,487,983,064	5,368,135,059
Moderate wind from a constant direction, dry	1,200	229	274,800	40,873.27	11,231,974,596	56,159,872,980	40,261,012,939
Light wind from changing directions, dry	350	229	80,150	40,873.27	3,275,992,591	16,379,962,953	11,742,795,441
Light wind from a constant direction, dry	700	229	160,300	40,873.27	6,551,985,181	32,759,925,905	23,485,590,881
Strong wind from changing directions, precipitation of 1 mm/h	22,900	229	5,244,100	40,873.27	214,343,515,207	1,071,717,576,035	768,314,330,259
Strong wind from a constant direction, precipitation of 1 mm/h	9,900	229	2,267,100	40,873.27	92,663,790,417	463,318,952,085	332,153,356,750
Moderate wind from changing directions, precipitation of 1 mm/h	15,600	229	3,572,400	40,873.27	146,015,669,748	730,078,348,740	523,393,168,212
Moderate wind from a constant direction, precipitation of 1 mm/h	6,200	229	1,419,800	40,873.27	58,031,868,746	290,159,343,730	208,015,233,520
Light wind from changing directions, precipitation of 1 mm/h	10,100	229	2,312,900	40,873.27	94,535,786,183	472,678,930,915	338,863,525,573
Light wind from a constant direction, precipitation of 1 mm/h	2,700	229	618,300	40,873.27	25,271,942,841	126,359,714,205	90,587,279,114

Figure B.2: Amounts of damage through resettlement measures (authors' own calculations)

The following figures *B.3* and *B.4* depict all the amounts of damage (in millions of euros) included in the calculations of this study for the different nuclear power plants in Germany. Most of the amounts of damage that were calculated on the basis of results from previous studies do not differentiate between the individual nuclear power plants. Only the amounts of damage based on the authors' own quantification approaches detailed in Chapter 4.3.6 to calculate the loss of GDP in the resettlement areas vary for each nuclear power plant.

Type of damage	Biblis A	Biblis B	Brokdorf	Brunsbuettel	Emsland	Grafenrheinfeld	Grohnde	Gundremmingen B	Gundremmingen C
	Amounts of damage in millions of euros								
Fatal cancer cases	80.56	80.56	80.56	80.56	80.56	80.56	80.56	80.56	80.56
	101.92	101.92	101.92	101.92	101.92	101.92	101.92	101.92	101.92
	165.99	165.99	165.99	165.99	165.99	165.99	165.99	165.99	165.99
	210.00	210.00	210.00	210.00	210.00	210.00	210.00	210.00	210.00
	264.99	264.99	264.99	264.99	264.99	264.99	264.99	264.99	264.99
	305.76	305.76	305.76	305.76	305.76	305.76	305.76	305.76	305.76
	455.49	455.49	455.49	455.49	455.49	455.49	455.49	455.49	455.49
	546.00	546.00	546.00	546.00	546.00	546.00	546.00	546.00	546.00
	630.00	630.00	630.00	630.00	630.00	630.00	630.00	630.00	630.00
	663.98	663.98	663.98	663.98	663.98	663.98	663.98	663.98	663.98
	840.00	840.00	840.00	840.00	840.00	840.00	840.00	840.00	840.00
	938.52	938.52	938.52	938.52	938.52	938.52	938.52	938.52	938.52
	1,327.95	1,327.95	1,327.95	1,327.95	1,327.95	1,327.95	1,327.95	1,327.95	1,327.95
	1,680.00	1,680.00	1,680.00	1,680.00	1,680.00	1,680.00	1,680.00	1,680.00	1,680.00
	2,184.00	2,184.00	2,184.00	2,184.00	2,184.00	2,184.00	2,184.00	2,184.00	2,184.00
	2,520.00	2,520.00	2,520.00	2,520.00	2,520.00	2,520.00	2,520.00	2,520.00	2,520.00
	3,754.07	3,754.07	3,754.07	3,754.07	3,754.07	3,754.07	3,754.07	3,754.07	3,754.07
	4,368.00	4,368.00	4,368.00	4,368.00	4,368.00	4,368.00	4,368.00	4,368.00	4,368.00
	5,040.00	5,040.00	5,040.00	5,040.00	5,040.00	5,040.00	5,040.00	5,040.00	5,040.00
	7,508.15	7,508.15	7,508.15	7,508.15	7,508.15	7,508.15	7,508.15	7,508.15	7,508.15
Non-fatal cancer cases	74.64	74.64	74.64	74.64	74.64	74.64	74.64	74.64	74.64
	153.78	153.78	153.78	153.78	153.78	153.78	153.78	153.78	153.78
	615.13	615.13	615.13	615.13	615.13	615.13	615.13	615.13	615.13
	1,230.26	1,230.26	1,230.26	1,230.26	1,230.26	1,230.26	1,230.26	1,230.26	1,230.26
Genetic Damage	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09
	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
	8.28	8.28	8.28	8.28	8.28	8.28	8.28	8.28	8.28
	8.99	8.99	8.99	8.99	8.99	8.99	8.99	8.99	8.99
	17.07	17.07	17.07	17.07	17.07	17.07	17.07	17.07	17.07
	17.99	17.99	17.99	17.99	17.99	17.99	17.99	17.99	17.99
	68.27	68.27	68.27	68.27	68.27	68.27	68.27	68.27	68.27
	136.53	136.53	136.53	136.53	136.53	136.53	136.53	136.53	136.53
	2.68	2.68	2.68	2.68	2.68	2.68	2.68	2.68	2.68
	5.37	5.37	5.37	5.37	5.37	5.37	5.37	5.37	5.37

Loss of GDP in resettlement Area	11.74	11.74	11.74	11.74	11.74	11.74	11.74	11.74	11.74
	13.42	13.42	13.42	13.42	13.42	13.42	13.42	13.42	13.42
	23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49
	40.26	40.26	40.26	40.26	40.26	40.26	40.26	40.26	40.26
	90.59	90.59	90.59	90.59	90.59	90.59	90.59	90.59	90.59
	208.02	208.02	208.02	208.02	208.02	208.02	208.02	208.02	208.02
	332.15	332.15	332.15	332.15	332.15	332.15	332.15	332.15	332.15
	338.86	338.86	338.86	338.86	338.86	338.86	338.86	338.86	338.86
	523.39	523.39	523.39	523.39	523.39	523.39	523.39	523.39	523.39
	768.31	768.31	768.31	768.31	768.31	768.31	768.31	768.31	768.31
	707.19	707.19	393.80	575.32	688.95	732.98	993.94	626.89	626.89
Food bans	37.94	37.94	37.94	37.94	37.94	37.94	37.94	37.94	37.94
Evacuation and resettlement	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08

Figure B.3: Total damage amounts per nuclear power plant, part 1 (authors' own calculations) x

Type of damage	Isar 1	Isar 2	Kruemmel	Neckarwestheim 1	Neckarwestheim 2	Philippsburg 1	Philippsburg 2	Unterweser
	Amounts of damage in millions of euros							
Fatal cancer cases	80.56	80.56	80.56	80.56	80.56	80.56	80.56	80.56
	101.92	101.92	101.92	101.92	101.92	101.92	101.92	101.92
	165.99	165.99	165.99	165.99	165.99	165.99	165.99	165.99
	210.00	210.00	210.00	210.00	210.00	210.00	210.00	210.00
	264.99	264.99	264.99	264.99	264.99	264.99	264.99	264.99
	305.76	305.76	305.76	305.76	305.76	305.76	305.76	305.76
	455.49	455.49	455.49	455.49	455.49	455.49	455.49	455.49
	546.00	546.00	546.00	546.00	546.00	546.00	546.00	546.00
	630.00	630.00	630.00	630.00	630.00	630.00	630.00	630.00
	663.98	663.98	663.98	663.98	663.98	663.98	663.98	663.98
	840.00	840.00	840.00	840.00	840.00	840.00	840.00	840.00
	938.52	938.52	938.52	938.52	938.52	938.52	938.52	938.52
	1,327.95	1,327.95	1,327.95	1,327.95	1,327.95	1,327.95	1,327.95	1,327.95
	1,680.00	1,680.00	1,680.00	1,680.00	1,680.00	1,680.00	1,680.00	1,680.00
	2,184.00	2,184.00	2,184.00	2,184.00	2,184.00	2,184.00	2,184.00	2,184.00
	2,520.00	2,520.00	2,520.00	2,520.00	2,520.00	2,520.00	2,520.00	2,520.00
	3,754.07	3,754.07	3,754.07	3,754.07	3,754.07	3,754.07	3,754.07	3,754.07
	4,368.00	4,368.00	4,368.00	4,368.00	4,368.00	4,368.00	4,368.00	4,368.00
	5,040.00	5,040.00	5,040.00	5,040.00	5,040.00	5,040.00	5,040.00	5,040.00
	7,508.15	7,508.15	7,508.15	7,508.15	7,508.15	7,508.15	7,508.15	7,508.15
Non-fatal cancer cases	74.64	74.64	74.64	74.64	74.64	74.64	74.64	74.64
	153.78	153.78	153.78	153.78	153.78	153.78	153.78	153.78
	615.13	615.13	615.13	615.13	615.13	615.13	615.13	615.13
	1,230.26	1,230.26	1,230.26	1,230.26	1,230.26	1,230.26	1,230.26	1,230.26
Genetic Damage	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09
	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
	8.28	8.28	8.28	8.28	8.28	8.28	8.28	8.28
	8.99	8.99	8.99	8.99	8.99	8.99	8.99	8.99
	17.07	17.07	17.07	17.07	17.07	17.07	17.07	17.07
	17.99	17.99	17.99	17.99	17.99	17.99	17.99	17.99
	68.27	68.27	68.27	68.27	68.27	68.27	68.27	68.27
	136.53	136.53	136.53	136.53	136.53	136.53	136.53	136.53
	2.68	2.68	2.68	2.68	2.68	2.68	2.68	2.68
	5.37	5.37	5.37	5.37	5.37	5.37	5.37	5.37
	11.74	**11**.74	**11**.74	11.74	11.74	11.74	**11**.74	**11**.74

Loss of GDP in resettlement Area	13.42	13.42	13.42	13.42	13.42	13.42	13.42	13.42
	23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49
	40.26	40.26	40.26	40.26	40.26	40.26	40.26	40.26
	90.59	90.59	90.59	90.59	90.59	90.59	90.59	90.59
	208.02	208.02	208.02	208.02	208.02	208.02	208.02	208.02
	332.15	332.15	332.15	332.15	332.15	332.15	332.15	332.15
	338.86	338.86	338.86	338.86	338.86	338.86	338.86	338.86
	523.39	523.39	523.39	523.39	523.39	523.39	523.39	523.39
	768.31	768.31	768.31	768.31	768.31	768.31	768.31	768.31
	690.28	690.28	573.50	774.40	774.40	713.59	713.59	747.86
Food bans	37.94	37.94	37.94	37.94	37.94	37.94	37.94	37.94
Evacuation and resettlement	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08

Figure B.xi: Total damage amounts per nuclear power plant, part 2 (authors' own calculations)

Annex C

Literature reviewed

[1] Bartsch, Matthias; Brandt, Andrea; Fröhlingsdorf, Michael; Höflinger, Laura; Kaiser, Simone; Latsch, Günther; Meyer, Cordula; Rosenbach, Marcel; Stark, Holger; Traufetter, Gerald: Atomkraft - Landkarte des Schreckens. In: Der Spiegel 12/2011.

[2] Becker, Oda: Risiko Restlaufzeit - Die Probleme und Schwachstellen der vier ältesten deutschen Atomkraftwerke Schwerpunkt Biblis B. 2005.

[3] Becker, Oda: Risiko Restlaufzeit - Die Probleme und Schwachstellen der vier ältesten deutschen Atomkraftwerke Schwerpunkt Brunsbüttel. 2005.

[4] Becker, Oda: Risiko Restlaufzeit - Die Probleme und Schwachstellen der vier ältesten deutschen Atomkraftwerke Schwerpunkt Neckarwestheim-1. 2005.

[5] Becker, Oda: Auswirkungen eines schweren Unfalls im Atomkraftwerk Biblis - Betroffenheit eines Klägers. Hanover, August 2008.

[6] Becker, Oda: Auswirkungen eines schweren Unfalls im Atomkraftwerk Brunsbüttel - Betroffenheit der Kläger und Klägerinnen. Hanover, January 2009.

[7] Becker, Oda: Auswirkungen eines schweren Unfalls im Atomkraftwerk Philipsburg - Betroffenheit der Kläger. 2009.

[8] Becker, Oda: Auswirkungen eines schweren Unfalls im Atomkraftwerk Isar 1 - Betroffenheit der Kläger. 2009.

[9] Becker, Oda; Hirsch, Helmut: Schwere Unfälle im AKW Esenshamm und ihre Folgen - Schwerpunkt Terrorgefahr. 2006.

[10] Büro für Atomsicherheit: Risiken alter Atomkraftwerke. Study, Bonn, June 2010.

[11] Bundesamt für Strahlenschutz (ed.): Epidemiologische Qualitätsprüfung der KiKK Studien. 2008.

[12] Bundesamt für Strahlenschutz: Grundsätze für die weitere Entwicklung des Strahlenschutzes. September 2009.

[13] Blank, Ingo: Rückschau Energie und Umwelt - Diskussion um Kernkraftwerke. Information zum Beitrag im Ersten, 13 July 2010. URL: http://www.daserste.de/plusminus/beitrag_ dyn~uid, qqgk3x97by97ml82~cm. asp (accessed on 25 March 2011).

[14] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit: Antwort auf Fragen 7/117 vom 16. Juli 2008 zur Haftungsverteilung im Falle eines Atomunglücks. 21 July 2008.

[15] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit: Rahmenempfehlungen für den Katastrophenschutz in der Umgebung kerntechnischer Anlagen - Stand 21.09.2008, Nichtamtliche Fassung, 2008. URL: http://www.bmu.de/files/pdfs/allgemein/application/ pdf/rahmenempfehlung_katastrophenschutz.pdf (accessed on 26 March 2011).

[16] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit: Antwort auf Fragen 11/156 vom 23. November 2009 zur Kündigung des "Beherrschungsvertrages" und 11/159 vom 24. November 2009 zur Verlustübernahme von Konzernmüttern. 27 November 2009.

[17] Bundesministerium der Verteidigung: Antwort auf die mündliche Frage vom 19. Februar 2010 zum Schutz eigener Kräfte gegen die Wirkung von Doppelhohlladungssprengköpfen, die aus tragbaren Infanteriewaffen abgefeuert werden. 24 February 2010.

[18] Bund für Umwelt und Naturschutz Deutschland (BUND): Atomkraftwerke und die Terrorgefahr - Nichts gelernt aus dem 11. September 2001. Berlin, 8 September 2006.

[19] Bund für Umwelt und Naturschutz Deutschland (BUND): Kurzexpertise Sicherheit der vier Atomkraftwerke in Baden-Württemberg. Hanover, March 2011.

[20] Carroll, Simon; Foggatt, Antony: The Future of Nuclear Energy in A Carbon Constrained World - Nuclear Third Party Insurance - The Nuclear Sector’s "Silent" Subsidy - State of Play and Opportunities in Europe. Discussion paper, New York, 5 November 2007.

[21] CE Solutions for environment, economy and technology (ed.): Environmentally harmful support measures in EU Member States. Delft, January 2003.

[22] CIO: Stuxnet dringt nicht in Kernsysteme eines Kraftwerks vor, report of 27 September 2010.

[23] Deutscher Bundestag: Endbericht der Enquete-Kommission "Nachhaltige Energieversorgung unter den Bedingungen der Globalisierung und der Liberalisierung". Printed paper 14/9400 of July 2002.

[24] Deutscher Bundestag: Kleine Anfrage der Abgeordneten Sylvia Kotting-Uhl, Hans-Josef Fell, Bärbel Höhn, weiterer Abgeordneter und der Fraktion BÜNDNIS 90/DIE GRÜNEN - Nuklearer Katastrophenfall - "Liquidatoren" und Dekontamination im Falle eines "Super GAUs". Printed paper 17/2387 of 2 July 2010.

[25] Droste-Franke, Bert: Quantifizierung von Umweltschäden als Beitrag zu umweltökonomischen Gesamtrechnungen. Dissertation 2005.

[26] European Commission (ed.): Externalities of Energy "ExterE" Project - Volume 2 - Methodology: Method for Estimation of Physical Impacts and Monetary Valuation for Priority Impact Pathways, URL: http://www.externe.info/reportex/vol2.pdf (accessed on 25 March 2011).

[27] European Commission (ed.): ExternE National Implementation Germany. November 1997.

[28] European Commission (ed.): ExternE Methodology Update 2005. Luxemburg, 2005. ISBN: 92-79-00423-9.

[29] Eidgenössische Kommission für AC-Schutz: Atmosphärische Ausbreitungsrechnungen bei Unfällen in Kernanlagen. 7 March 2002.

[30] European Spatial Planning Observation Network (ed.): Technological hazards - Nuclear power plants. URL: http://www.gsf.fi/projects/espon/Nuclear.htm (accessed on 5 March 2011).

[31] Forum Ökologisch-Soziale Marktwirtschaft: Staatliche Förderungen der Atomenergie - Der Zeitraum 1950-2008. Study commissioned by Greenpeace, Berlin, 2 September 2009.

[32] Freudenreich, Daniel: Bund ohne Notfallplan für Reaktor-Gau. Beitrag in: Der Westen, 1. August 2010. URL: http://www.derwesten.de/nachrichten/politik/Bund-ohne-Notfall plan-fuer-Reaktor-Gau-id3356203 .html (accessed on 25 March 2011).

[33] Froggatt, Antony: Nuclear Industry Status, Prospects and 3rd Party Liability. Seminar document, Vienna, 15 February 2010.

[34] Gesellschaft für Strahlenschutz e.V.: Gesundheitliche Folgen von Tschernobyl - 20 Jahre nach der Reaktorkatastrophe. April 2006.

[35] Greenpeace e.V.: The Chernobyl Catastrophe - Consequences on Human Health. Greenpeace, Amsterdam. April, 2006. ISBN 5-94442-013-8.

[36] Greenpeace: Terrorangriffe aus der Luft auf ältere deutsche Atomkraftwerke. September 2010.

[37] Grawe, Joachim: Sind die deutschen Kernkraftwerke ausreichend versichert? 5 April 2001.

[38] Gesellschaft für Anlagen- und Reaktorsicherheit; Physikerbüro Bremen; Öko-Institut e.V.: Sicherheitstechnische Überprüfung von Anlagen zu ausgewählten Anforderungen und Ereignissen im Rahmen von Anträgen zur Reststrommengenübertragung - Teil 1 KWB-A/KKE Bewertungsgegenstand 1 "Auswertung der Betriebserfahrung hinsichtlich Trends meldepflichtiger Ereignisse und Transienten". May 2007.

[39] Gesellschaft für Anlagen- und Reaktorsicherheit; Physikerbüro Bremen; Öko-Institut e.V.: Sicherheitstechnische Überprüfung von Anlagen zu ausgewählten Anforderungen und Ereignissen im Rahmen von Anträgen zur Reststrommengenübertragung - Teil 1 KWB-A/KKE Bewertungsgegenstand 13 "Großes Leck innerhalb des Sicherheitsbehälters". May 2007.

[40] Gesellschaft für Anlagen- und Reaktorsicherheit; Physikerbüro Bremen; Öko-Institut e.V.: Sicherheitstechnische Überprüfung von Anlagen zu ausgewählten Anforderungen und Ereignissen im Rahmen von Anträgen zur Reststrommengenübertragung - Teil 2 GKN-1/GKN-2 Bewertungsgegenstand 1 "Auswertung der Betriebserfahrung hinsichtlich Trends meldepflichtiger Ereignisse und Transienten". February 2008.

[41] Gesellschaft für Anlagen- und Reaktorsicherheit; Physikerbüro Bremen; Öko-Institut e.V.: Sicherheitstechnische Überprüfung von Anlagen zu ausgewählten Anforderungen und Ereignissen im Rahmen von Anträgen zur Reststrommengenübertragung - Teil 2 GKN-1/GKN-2 Bewertungsgegenstand 13 "Großes Leck innerhalb des Sicherheitsbehälters". February 2008.

[42] Harbrücker, Dirk: Versicherung gegen nukleare Schäden durch terroristische Angriffe. In: Pelzer, Norbert (ed.): Die Internationalisierung des Atomrechts, p. 187-195. 2005.

[43] Hirsch, Helmut; Becker, Oda: Risiko Restlaufzeit - Schwerpunkt Biblis A. Hanover, July 2005.

[44] Hirsch, Helmut; Becker, Oda: Risiko Restlaufzeit - Schwerpunkt Biblis B. Hanover, July 2005.

[45] Hirsch, Helmut; Becker, Oda: Risiko Restlaufzeit - Schwerpunkt Brunsbüttel. Hanover, July 2005.

[46] Hirsch, Helmut; Becker, Oda: Risiko Restlaufzeit - Schwerpunkt Neckarwestheim-1. Hanover, July 2005.

[47] Hohmeyer, Olav: Adäquate Berücksichtigung der Erschöpfbarkeit nicht erneuerbarer Ressourcen. In: Prognos AG (ed.): Externe Effekte der Energieversorgung - Versuch einer Identifizierung, p. 178-195, Baden-Baden, Nomos Verlagsgesellschaft, 1991.

[48] Hohmeyer, Olav: Ausarbeitung zum aktuellen Sachstand der wissenschaftlichen Debatte um externe Kosten. Flensburg, February 2002.

[49] Hohmeyer, Olav: Die Abschätzung der Kosten des anthropogenen Treibhauseffekts. Vierteljahreshefte zur Wirtschaftsforschung 74 (2005), 2, p. 164-168, 2005.

[50] International Center for Technology Assessment: Gasoline Cost Externalities - Security and Protection Services. 25 January 2005.

[51] Informationskreis KernEnergie: Der Reaktorunfall in Tschernobyl. 4th edition, June 2007

[52] Internationale Länderkommission Kerntechnik: Untersuchungen zum gezielten Absturz eines großen Verkehrsflugzeuges auf Kernkraftwerke - Ergebnisse aus dem Gutachten. November 2002.

[53] International Physicians for the Prevention of Nuclear War (IPPNW): AKW-Störfallauswertung der IPPNW. Berlin, 2 June 2010.

[54] Jakat, Lena: Versicherungsrisiko AKW - Katastrophe mit beschränkter Haftung. Article in the Süddeutsche Zeitung, 18 March 2011. URL: http://www.sueddeutsche.de/wirtschaft/ 2. 220/versicherung-der-kernkraft-mal-die-betreiber-zahlen-lassen- 1. 1074008 (accessed on 25 March 2011).

[55] Jilek, Wolfgang; Karner, Karin; Rass Andrea: Externe Kosten im Energiebereich. 2. Zwischenbericht - Literaturrecherche. URL: http://www.wind-energie.de/fileadmin/dokumente/ Themen_A-Z/Externe%20Kosten/Studie_ExterneKosten_Uebersicht.pdf (accessed on 25 March 2011).

[56] Kastchiev, Georgui; Lyman, Ed; Kromp, Wolfgang; Sailer, Michael; Kurth, Stephan; Lochbaum, David; Schneider, Mycle: Residual Risk - An Account of Events in Nuclear Power Plants since the Chernobyl Accident in 1986. May 2007. URL: http: //www. greens-efa. org/cms/topics/dokbin/181/181995 .residual_risk@en.pdf (accessed on 25 March 2011).

[57] Kelle, Alexander; Schaper, Annette: Bio- und Nuklearterrorismus - Eine kritische Analyse der Risiken nach dem 11. September 2001. Hessische Stiftung Friedens- und Konfliktforschung (ed.), October 2001. ISBN: 3-933293-55-3.

[58] Kraus, Gerald: Fachberater Strahlenschutz - Nuklearer Katastrophenschutz Symposium Biblis 08. 15 November 2008

[59] Krewitt, Wolfram; Schlomann, Barbara: Externe Kosten der Stromerzeugung aus erneuerbaren Energien im Vergleich zur Stromerzeugung aus fossilen Energieträgern. 6 April 2006.

[60] Küchler, Swantje; Meyer, Bettina: Billiger Strom aus Atom und Kohle? Staatliche Förderungen 1970-2008. October 2010. URL: http://www.kernenergiedebatte.de/pdfs/101015_ FOES_Studie.pdf (accessed on 25 March 2011).

[61] Large and Associates: Chernobyl - A Nuclear Catastrophe 20 Years On. 22 April 2006.

[62] Masuhr, Klaus P.; Wolff, Heimfrid; Keppler, Jan: Identifizierung und Internationalisierung Externer Kosten der Energieversorgung. Basel, June 1992.

[63] Matthes, Felix Chr.: Nuklearhaftung - Subvention eines Energieträgers. Seminarunterlage Wien, 15 February 2010.

[64] Mayer, Leopold: Versicherungswirtschaftslehre II. Teil. Lecture script, October 2008.

[65] Meyer, Bettina: Hintergrundpapier Externe Kosten der Energieversorgung. Kiel, 8 November 2009.

[66] Michel, Rolf: Sinn und Unsinn beim Gebrauch der effektiven Dosis und der Kollektivdosis. Conference document, 2006.

[67] Michel, Rolf: Sinn und Unsinn beim Gebrauch der effektiven Dosis und der Kollektivdosis. Conference document, 2010.

[68] Nell, Martin: Staatshaftung für Terrorrisiken?.Working Papers on Risk and Insurance Hamburg University No.4, Hamburg, December 2001.

[69] Nitsch, Joachim: Leitstudie 2007 "Ausbaustrategie Erneuerbare Energien - Aktualisierung und Neubewertung bis zu den Jahren 2020 und 2030 mit Ausblick bis 2050". 2007. URL: http://www.bmu.de/erneuerbare_energien/downloads/doc/38787.php (accessed on 25 March 2011).

[70] Inc.: Russland: Stuxnet hätte zweites Tschernobyl auslösen können, article on heise online, 28 January 2011. URL: http://www.heise.de/newsticker/meldung/Russland-Stuxnethaette-zweites-Tschernobyl-ausloesen-koennen-1179402.html (accessed on 25 March 2011).

[71] Öko-Institut e.V. (ed.): Folgen schwerer Unfälle im KKW Krümmel für das Gebiet der Freien und Hansestadt Hamburg und Auswirkungen von Katastrophenschutzmaßnahmen. Darmstadt, April 1992.

[72] Öko-Institut e.V. (ed.): Analyse der Emissions- und Immissionsdaten des Kernkraftwerkes Krümmel im Zusammenhang mit den Leukämiefällen in der Elbmarsch. 1994.

[73] Öko-Institut e.V.(ed.): Analyse des Bedrohungspotenzials "gezielter Flugzeugabsturz" am Beispiel der Anlage Biblis-A. Darmstadt, 20 November 2007.

[74] Öko-Institut e.V. (ed.): Klärung technischer und rechtlicher Fragestellungen bei der Beseitigung radioaktiv kontaminierter Abfälle landwirtschaftlicher Produkte nach Ereignissen mit nicht unerheblichenradiologischen Konsequenzen. Darmstadt, 26 Februar 2010.

[75] Patalong, Frank: Stuxnet - Angst vor einem zweiten Tschernobyl. Article on Spiegel online, 18 January 2011. URL: http://www.spiegel.de/netzwelt/netzpolitik/0,1518,739950, 00.html (accessed 25 March 2011).

[76] Rechsteiner, Rudolf: Grün gewinnt. Zürich, Orell Füssli Verlag, 2003. ISBN: 3-280-05054-5.

[77] Rieger, Frank: Der digitale Erstschlag ist erfolgt. Article in the Frankfurter Allgemeine Zeitung, 22 September 2010.

[78] Sander, Lalon: Was uns die Atomkraft kostet. 2010. URL: http://www.taz.de/1/zukunft/ schwerpunkt-anti-akw/artikel/1/was-uns-die-atomkraft-kostet/ (accessed on 25 March 2011).

[79] Sauer, Gustav W.: Haftung, Deckungs- und Stillegungsvorsorge bei kerntechnischen Anlagen. In: Recht Technik Wirtschaft Schriftenreihe Band 64, S. 177-202. Carl Heymanns Verlag, Cologne/Berlin/Bonn/Munich, 1991. ISBN: 3-452-22221-7.

[80] Sinwel, Manuel: Atomenergie - Vorteile, Risiken und Nachhaltigkeit. 2006.

[81] Strahlenschutzkommission: Bewertung von Messungen der ARGE PhAM zur Radioaktivität in der Elbmarsch. 14 February 2003.

[82] Umweltbundesamt Österreich (ed.): Grenzüberschreitende UVP gemäß Art. 7 UVP-RL zum Standortzwischenlager Biblis. Vienna, February 2002.

[83] Umweltbundesamt Österreich (ed.): Grenzüberschreitende UVP gemäß Art. 7 UVP-RL zum Standortzwischenlager Grundremmingen. 2002.

[84] Umweltbundesamt Österreich (ed.): Grenzüberschreitende UVP gemäß Art. 7 UVP-RL zum Standortlager Philippsburg. 2002.

[85] Umweltbundesamt Österreich: Atomare Risiken - Wirtschaftliche und rechtliche Aspekte - Schloss Wilhelminenberg, Wien, 10. Dezember 1996. Conference Reports, Vol. 23, Vienna, 1997. URL: http://www.umweltbundesamt.at/fileadmin/site/publikationen/CP023.pdf (accessed on 26 March 2011).

[86] Umweltforschungsplan des Bundesumweltministeriums: Reaktorsicherheit und Strahlenschutz - Epidemiologische Studie zu Kinderkrebs in der Umgebung von Kernkraftwerken (KiKK Study). 2006.

[87] Welfens, Paul J.J.: Atomstrom ist extrem teuer. Article in Handelsblatt of 24 March 2011.

[88] Wolff, Verena: Atomkatastrophe in Japan - Die Kosten. Article of 16 March 2011 on sueddeutsche.de. URL: http://www.sueddeutsche.de/wirtschaft/atomkatastrophe-in-japanwer-soll-das-alles-zahlen-1.1072821 (accessed on 25 March 2011).

[89] Ziesing, Hans-Joachim (ed.): Externe Kosten in der Stromerzeugung. VWEW Energieverlag GmbH, Frankfurt/Berlin/Heidelberg, 2004. ISBN 3-8022-0794-7.

[90] Zentrum für Klinische Studien Essen: Epidemiologische Qualitätsprüfung der KiKK-Studien im Auftrag des Bundesamts für Strahlenschutz. 19 March 2008.

[91] Zweifel, P.; Umbricht, R.: Verbesserte Deckung des Nuklearrisikos zu welchen Bedingungen? May 2002.

Bibliography

[9-11 Commission 2004] National Commission On Terrorist Attacks Upon The United States (ed.): *The 9/11 Commission Report*. 22 July 2004. URL: http://www. 9-11commission.gov/report/911Report.pdf (accessed on 1 April 2011).

[Adelmeyer/Warmuth 2003] Adelmeyer, Moritz; Warmuth, Elke: *Finanzmathematik für Einsteiger*. Vieweg Verlag, Braunschweig Wiesbaden, 2003. ISBN 3-528-03185-9.

[AGEB 2011 a] Arbeitsgemeinschaft Energiebilanzen e.V. (ed.): *Energieverbrauch hat sich 2010 kräftig erholt, Arbeitsgemeinschaft Energiebilanzen*. pressedienst No. 1/2011, 23 February 2011, p. 51. URL: http://www.ag-energiebilanzen.de/componenten/ download.php?filedata=1298451813 .pdf&filename=AGEB_Pressedienst_01_2011.pdf (accessed on 28 February 2011).

[AGEB 2011 b] Arbeitsgemeinschaft Energiebilanzen e.V. (ed.) : *Energieverbrauch in Deutschland im Jahr 2010*. February 2011. URL: http: //www. ag-energiebilanzen. de/componenten/download.php?filedata=1298302717 .pdf&filename=AGEB_ Jahresbericht2010_20110221 .pdf&mimetype=application/pdf (accessed on 25 March 2011).

[Albright/Brannan/Walrond 2010] Albright, David; Brannan, Paul; Walrond, Christina: *Did Stuxnet Take Out 1,000 Centrifuges at the Natanz Enrichment Plant?* Preliminary Assessment, Institute for Science and International Security (ISIS), 22 December 2010. URL: http://isis-online.org/uploads/isis-reports/documents/ stuxnet_FEP_22Dec2010.pdf (accessed on 23 March 2011).

[army-technology] army-technology.com (ed.): *Milan Anti- Tank Missile System.* URL: http: //www.army-technology.com/projects/milan/ (accessed on 1 April 2011).

[BDEW 2011] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. (ed.): *Entwicklung der Energie Versorgung 2010*. 23 February 2011. URL: http://www.vewsaar.de/fileadmin/dokumente/Energie/pdf/energie_info_ entwicklung_energieversorgung_23022011.pdf (accessed on 28 March 2011).

[Becker 2005] Becker, Oda: *Risiko Restlaufzeit - Die Probleme und Schwachstellen der vier ältesten deutschen Atomkraftwerke - Schwerpunkt Biblis A*. Greenpeace Deutschland e.V. (ed.), Juli 2005. URL: http://www.greenpeace.de/fileadmin/gpd/user_ upload/themen/atomkraft/greenpeace_studie_restrisiko_biblisa . pdf (accessed on 23 March 2011).

[Becker 2009] Becker, Oda: *Studie zu den Gefahren von Laufzeitverlängerungen.* Bund für Umwelt und Naturschutz Deutschland, August 2009. URL: http: //www . bund. net/fileadmin/bundnet/publikationen/atomkraft/20090806_ atomkraft_studie_laufzeitverlaengerungen.pdf (accessed on 21 March 2011).

[Becker 2010 a] Becker, Oda: *Terrorangriffe aus der Luft auf (ältere) deutsche Atomkraftwerke - Bericht und Bewertung von Schwachstellen in der Luftsicherheit.* Greenpeace e.V. (ed.), September 2010. URL: http://www.greenpeace.de/ fileadmin/gpd/user_upload/themen/atomkraft/Bericht_und_Bewertung_von_ Schwachstellen_in_der_Luftsicherheit_05092010.pdf (accessed on 21 March 2011).

[Becker 2010 b] Becker, Oda: *Terrorangriff mit einer panzerbrechenden Waffe (AT-14 Kornet-E) auf (ältere) deutsche Atomkraftwerke*. Greenpeace e.V. (ed.), September 2010. URL: http://www.greenpeace.de/fileadmin/gpd/user_upload/themen/ atomkraft/KURZ_Panzerbrechende_Waffen_14092010.pdf (accessed on 21 March 2011).

[Becker/Hirsch 2005] Becker, Oda; Hirsch, Helmut: *Risiko Restlaufzeit - Die Probleme und Schwachstellen der vier ältesten deutschen Atomkraftwerke - Schwerpunkt Biblis A.* Greenpeace e.V. (ed.), Hanover, August 2005. URL:' http://www.greenpeace.de/fileadmin/gpd/user_upload/themen/atomkraft/greenpeace_studie_ restrisiko_biblisa.pdf (accessed on 21 March 2011).

[Benzin 2005] Benzin, Arne: *Versicherbarkeit von Terrorismusrisiken*. Zeitschrift für die gesamte Versicherungswissenschaft, Vol. 94, 2005, p. 709ff.

[BfS a] Bundesamt für Strahlenschutz (BfS) (ed.): *Systematik der internationalen Bewertungsskala (INES)*. URL: http://www.bfs.de/de/kerntechnik/ereignisse/ines.html (accessed on 22 February 2011).

[BfS b] Bundesamt für Strahlenschutz (BfS) (ed.): *Multilaterale Vereinbarungen über nukleare Sicherheit und Strahlenschutz mit nationalen Ausführungsvorschriften*. URL: http://www.bfs.de/de/bfs/recht/rsh/rechtsvorschriften_E35.html (accessed on 3 March 2011).

[BfS c] Bundesamt für Strahlenschutz (BfS) (ed.): *Positionsbestimmung des BfS zu Grundsatzfragen des Strahlenschutzes ("Leitlinien Strahlenschutz")*. URL: http://www.bitkom.org/files/documents/Entwurf_Leitlinien_Strahlenschutz.pdf (accessed on: 25 March 2011).

[Blobel 2005] Blobel, Felix: *Das Protokoll von 2004 zum Pariser Übereinkommen - wesentliche Verbesserungen im internationalen Atomhaftungsrecht*. Zeitschrift Natur und Recht, Vol. 27, No. 3, March 2005, p. 137-143.

[BMU 2008 a] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (ed.): *Empfehlung der Strahlenschutzkommission: Radiologische Grundlagen für Entscheidungen über Maßnahmen zum Schutz der Bevölkerung bei unfallbedingten Freisetzungen von Radionukliden*. 21 September 2008. URL: http: //www.bmu. de/files/pdfs/allgemein/application/pdf/radiologische_grundlagen.pdf (accessed on 25 March 2011).

[BMU 2008 b] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (ed.): *Sicherheitsanforderungen für Kernkraftwerke.* 2008. URL: http://www.bmu.de/atomenergie_sicherheit/sicherheitsprinzipien/ sicherheitsanforderungen/doc/42288 .php (accessed on 22 February 2011).

[BMU 2009] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (ed.): *Rechtsvorschriften / Technische Regeln und Regelungen*. 2009. URL: http://www.bmu.de/atomenergie_sicherheit/rechtsvorschriften_ technische_regeln/doc/40327.php (accessed on 23 February 2011).

[BMU 2010] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (ed.): *Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global - Leitstudie 2010*. December 2010. URL: http://www.bmu.de/files/pdfs/allgemein/ application/pdf/leitstudie2010_bf.pdf (accessed on 17.03.2011).

[Bundesanstalt für Geowissenschaft und Rohstoffe 2011] Bundesanstalt für Geowissenschaftund Rohstoffe (ed.): *Karte der Epizentren der Schadenbeben (ab Intensität VI-VII) in der Bundesrepublik Deutschland Jahre 800 bis 2010*. Bundesanstalt für Geowissenschaft und Rohstoffe, 14 March 2011. URL: http: //www.bgr.bund. de/cln_169/nn_331926/DE/Themen/Seismologie/Downloads/ karte-epizentren-schadenbeben-800-2010, templateId=raw, property= publicationFile .pdf/karte-epizentren-schadenbeben-800-2010 .pdf (accessed on 23 March 2011).

[Bundesministerium der Verteidigung 2010] Bundesministerium der Verteidigung (ed.): *Lenkflugkörpersysteme zur Panzerabwehr und deren Durchschlagsleistungen*. 15 March 2010.

[Bundesministerium für Wirtschaft und Technologie 2010] Bundesministerium für Wirtschaft und Technologie (ed.): *Beantwortung der schriftlichen Fragen an die Bundesregierung im Monat Mai 2010 - Fragen Nr. 381 und 382*. 7 June 2010.

[Bundesregierung 2006] Bundesregierung (ed.): *Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Hans Josef Fell, Dr. Reinhard Loske, Sylvia Kotting-Uhl, weiterer Abgeordneter und der Fraktion BÜNDNIS 90/DIE GRÜNEN - Gefahren der Atomenergie*. 19. April 2006. URL: http://dipbt.bundestag.de/dip21/btd/ 16/012/1601249.pdf (accessed on 22 March 2011). [Bundesregierung 2010 a] Bundesregierung (ed.): *Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Sylvia Kotting- Uhl, Hans-Josef Fell, Bärbel Höhn, weiterer Abgeordneter und der Fraktion BÜNDNIS 90/DIE GRÜNEN - Drucksache 1 7/2403 - Nuklearer Katastrophenfall - Katastrophenschutz und Evakuierung*. 3 September 2010. URL: http://dip21.bundestag.de/dip21/btd/17/028/ 1702871.pdf (accessed on 22 February 2011).

[Bundesregierung 2010 b] Bundesregierung (ed.): *Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Sylvia Kotting-Uhl, Hans-Josef Fell, Bärbel Höhn, weiterer Abgeordneter und der Fraktion BÜNDNIS 90/DIE GRÜNEN - Drucksache 17/3156 - Nuklearer Katastrophenfall - Internationales Haftungsrecht bei Atomkraftwerken*. 20 October 2010. URL: http://dipbt.bundestag.de/dip21/btd/ 17/033/1703371.pdf (accessed on 22 February 2011).

[Bundesregierung 2010 c] Bundesregierung (ed.): *Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Sylvia Kotting- Uhl, Hans-Josef Fell, Bärbel Höhn, weiterer Abgeordneter und der Fraktion BÜNDNIS 90/DIE GR ÜNEN - Drucksache 17/2547 - Nuklearer Katastrophenfall - Ökonomische Folgen*. 27 July 2010. URL: http://dipbt.bundestag.de/dip21/btd/17/026/1702682.pdf (accessed on 22 February 2011).

[Büning/Trenkler 1994] Büning, Herbert; Trenkler, Götz: *Nichtparametrische statistische Methoden*. 2nd edition, De Gruyter, Berlin and New York, 1994. ISBN 3-11-014105-1.

[Büro für Atomsicherheit 2010] Büro für Atomsicherheit (ed.): *Risiken alter Atomkraftwerke, im Auftrag für die Bundestagsfraktion Bündnis 90 / Die Grünen, Bonn. Juni 2010*. URL: http://www.atomsicherheit.de/app/download/4497095464/ Risiken+alter+AKW+final+2010+06+22 .pdf?t=1285189068 (accessed on 18 March 2011).

[Czakainski et al. 1996] Czakainski, Martin; Butz, Heinz-Peter; Haug, Peter; Knapp, Sabine; Koelzer, Winfried; Pfrommer, Axel: *Tschernobyl - Der Reaktorunfall - Unfallhergang, Mittel- und langfristige Folgen, Perspektiven für die Stillegung.* Informationskreis Kernenergie (ed.), Bonn, 1996. URL: http://www.blaulicht24.com/de/ software/download/tschernobyl .pdf (accessed on 22 March 2011).

[Deutsches Atomforum e.V.] Deutsches Atomforum e.V. (ed.): Deutsche Kernkraftwerke in Betrieb. URL: http://www.atomforum.de/kernenergie/Themen/Kernkraftwerke/ Kernkraftwerke_in_Deutschland/index .php (accessed on: 23 February 2011).

[Diekmann/Horn 2007] Diekmann, Jochen; Horn, Manfred: *Abschlussbericht zum Vorhaben "Fachgespräch zur Bestandsaufnahme und methodischen Bewertung vorliegender Ansätze zur Quantifizierung der Förderung erneuerbarer Energien im Vergleich zur Förderung der Atomenergie in Deutschland"*. Deutsches Institut für Wirtschaftsforschung Berlin (DIW), Berlin, 2007. URL: http: //www. erneuerbare-energien.de/files/pdfs/allgemein/application/pdf/diw_abschlussbericht .pdf (accessed on 3 March 2011).

[Dietzel 2002] Dietzel, Wilhelm: *Untersuchungen zum gezielten Absturz eines großen Verkehrsflugzeuges auf Kernkraftwerke - Ergebnisse aus den Gutachten.* Internationale Länderkommission Kerntechnik, 29 November 2002. URL: http://www.greenpeace.de/fileadmin/gpd/user_upload/themen/atomkraft/ ilk_frontal_21.pdf (accessed on 23 March 2011).

[DPA 2006] Deutsche Presseagentur (ed.): *Regierung in Südafrika: Sabotage in Atomkraftwerk.* Deutsche Presseagentur, 28 February 2006.

[DPA 2010] Deutsche Presse Agentur (ed.): *Experte: Stuxnet dringt nicht in Kernsysteme eines Kraftwerks vor - Interview: Christoph Dernbach*. Deutsche Presse Agentur, 27 September 2010. URL: http://www.greenpeace-magazin.de/index.php? id=55&tx_ttnews%5Btt_news%5D=88778&tx_ttnews%5BbackPid%5D=23&cHash=31e346e4d6 (accessed on 22 March 2011).

[DSF 2009] Deutsche Strahlenschutz-Fachgesellschaften (ed.): *Konsequenzen aus den Empfehlungen der ICRP 103 für den Strahlenschutz in Deutschland - Gemeinsames Positionspapier der mit dem Strahlenschutz befassten deutschen Fachgesellschaften zu wesentlichen Schwerpunkten von ICRP 103*. October 2009. URL: http://osiris22.pi-consult.de/userdata/l_20/p_105/library/data/ icrp103_positionspapier_ger.pdf (accessed on 28.03.2011).

[European Commission 1991] European Commission (ed.): *COSYMA Report EUR 13028 EN*. Brussels, 1991.

[European Commission 1995] European Commission (ed.): *ExternE: Externalities of Energy, Vol. 5: Nuclear (Report EUR 16520 EN of the JOULE programme)*. Brussels/Luxemburg, 1995. ISBN: 92-827-5214-3.

[European Commission 2003] European Commission (ed.): *Protocol to amend the Convention on Third Party Liability in the Field of Nuclear Energy of 29 July 1960, as amended by the Additional Protocol of 28 January 1964 and by the Protocol of 16 November 1982*. Official Journal L 338 of 23 December 2003. URL: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:22003A1223(02):EN:HTML.

[Ewers/Rennings 1991] Ewers, Hans-Jürgen; Rennings, Klaus: *Die volkswirtschaftlichen Kosten eines Super-Gau's in Biblis*. Zeitschrift für Umweltpolitik und Umweltrecht (ZfU) No. 4, p. 379-396, 1991.

[Ewers/Rennings 1992 a] Ewers, Hans-Jürgen; Rennings, Klaus: *Die Kosten möglicher Schäden durch einen sogenannten Super-Gau – monetäre Bewertung und umweltpolitische Implikationen*. Zeitschrift für angewandte Umweltforschung (ZAU) Special Issue 3 (1992), p. 155-167.

[Ewers/Rennings 1992 b] Ewers, Hans-Jürgen; Rennings, Klaus: *Abschätzung der Schäden durch einen sogenannten "Super-GAU"*. April 1992. URL: http: //www. zukunftslobby. de/Tacheles/prognstu.html (accessed on 25.03.2011).

[Fairlie/Sumner 2006] Fairlie, Ian; Sumner, David: *The other Report on Chernobyl (TORCH)*. Berlin/Brussels/Kiev, 6 April 2006.

[Farny 2006] Farny, Dieter: *Versicherungsbetriebslehre*. 4th edition, Verlag Versicherungswirtschaft, Karsruhe, 2006.

[Focus Online 2011] Focus Online (ed.): *Japan - Atom-Katastrophe in Fukushima 1 bedroht Tokio - Evakuierung unmöglich*. Focus Online, 15 March 2011. URL: http://www.focus.de/panorama/welt/tsunami-in-japan/japan-atom-katastrophe-in-fukushima-1-bedroht-tokio-evakuierung-unmoeglich_ aid_608895.html (accessed on 23 March 2011).

[Fokken 2008] Fokken, Ulrike: *Ein Wert an sich.* Die Tageszeitung, 23 May 2008. URL: http://www.taz.de/1/debatte/kommentar/artikel/1/ein-wert-an-sich/ (accessed on 18 March 2010).

[Friedrich 2009] Friedrich, Reiner: *Wie hoch sind die "externen Kosten" der verschiedenen Energie-Techniken bei der Stromerzeugung?* 2009. URL: http: //www. energie-fakten.de/pdf/externe-kosten.pdf (accessed on 25 March 2011).

[Fürstenwerth/Weiß 2001] Fürstenwerth, Frank von; Weiß, Alfons: *Versicherungs-Alphabet (VA) - Begriffserläuterungen der Versicherung aus Theorie und Praxis*. 10. Auflage, Verlag Versicherungswirtschaft, Karlsruhe, 2001.

[Global Security 2006] Global Security (ed.): *Hizballah rockets*. Global Security.org, 30 July 2006. URL: http://www.globalsecurity.org/military/world/para/ hizballah-rockets.htm (accessed on 22 February 2011).

[Goßner 2002] Goßner, Alfred: *Gibt es neue unversicherbare Risiken?* In: Der Umgang mit den Risiken im Grenzbereich der Versicherbarkeit, Verlag Versicherungswirtschaft, Karlsruhe, 2002.

[GRS 1989] Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS) (ed.): *Deutsche Risikostudie Kernkraftwerke Phase B. Eine Untersuchung im Auftrag des Bundesministers für Forschung und Technologie*. 1989. URL: http://www.grs.de/content/ deutsche-risikostudie-kernkraftwerke-phase-b (accessed on 23 February 2011).

[GRS 2000] Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS) (ed.): *Tschernobyl: Gesundheitliche Folgen - BMU-Sachstandsbericht Nr. 1. Eine Untersuchung im Auftrag des Bundesministers Umwelt, Naturschutz und Reaktorsicherheit* 2000. URL: http://www.grs.de/sites/default/files/pdf/GRS-S-47.pdf (accessed on 24 March 2011).

[GRS 2001] Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS) (ed.): *Bewertung des Unfallrisikos fortschrittlicher Druckwasserreaktoren in Deutschland*. GRS-175, October 2001. URL: http://www.grs.de/content/ grs- 175-bewertung-des-unfallrisikos-fortschrittlicher-druckwasserreaktoren-deutschland (accessed on 25 March 2011).

[GRS] Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS) (ed.): *IN-ES - International Nuclear Event Scale*. URL: http://www.grs.de/content/ ines-information-auf-einen-blick (accessed on 22 February 2011).

[Hahn/Sailer 1987] Hahn, Lothar; Sailer, Michael: *Charakterisierung von Sicherheitsphilosophien in der Kerntechnik*. Öko-Insitut Darmstadt, 1987.

[Harwood 2007] Matthew Harwood: *Sleeping on the Job, Security Management*. 10 December 2007. URL: http://www.securitymanagement.com/news/sleeping-job (accessed on 22 March 2011).

[Haubner 2009] Haubner, David: *Grenzen der Versicherbarkeit*. Anmerkungen zum Katastrophenrecht – Documentation of the working group Disasters and Law, 2nd Academic Kolleg of the Studienstiftung des deutschen Volkes, 2009. URL: http://fzk.rewi.hu-berlin.de/Sammelband_Katastrophenrecht. pdf (accessed on 17 March 2011).

[Hirsch 2001] Hirsch, Helmut: *Gefährdung deutscher Atomkraftwerke durch den Absturz von Verkehrsflugzeugen*. Greenpeace e.V., November 2001. URL: http://www.greenpeace.de/fileadmin/gpd/user_upload/themen/atomkraft/ greenpeace_studie_gefaehrdung_akw_durch_verkehrsflugzeuge . pdf (accessed on 21 March 2011).

[Hirsch et al. 2004] Hirsch, Helmut; Becker, Oda; Neumann, Wolfgang: *Terrorangriffe auf deutsche Atomkraftwerke - Bewertung der Gegenmaßnahmen - Unter besonderer Berücksichtigung der Gegebenheiten an den Standorten Biblis und Brunsbüttel*. Greenpeace e.V., Hanover, April 2004. URL: http://www.greenpeace.de/fileadmin/gpd/user_upload/themen/ atomkraft/greenpeace_studie_terrorangriffe_auf_deutsche_akw . pdf (accessed on 21 March 2011).

[Hohmeyer 1989] Hohmeyer, Olav: *Soziale Kosten des Energieverbrauchs.* 2nd edition, Berlin/Heidelberg, 1989.

[Honnellio/Rydell 2005] Honnellio, Antonio.; Rydell, Stan: *Sabotage vulnerability of nuclear power plants.* Int. J Nuclear Governance, Economy and Ecology, Vol 1, No. 3, 2007. URL: http://inderscience.metapress.com/app/home/content.asp?referrer=contribution&format=2&page=1&pagecount=0 (accessed on 22 March 2011).

[IAEA 1992] International Atomic Energy Agency (IAEA) (ed.): *Joint protocol relating to the application of the Vienna convention and the Paris Convention*. May 1992. URL: http://www.iaea.org/Publications/Documents/Infcircs/Others/ infcirc402.pdf (accessed on 15 March 2011).

[IAEA a] International Atomic Energy Agency (IAEA) (ed.): *INES*. URL: http://www-ns.iaea.org/tech-areas/emergency/ines.asp (accessed on: 22 March 2011).

[IAEA b] International Atomic Energy Agency (IAEA) (ed.): *User's Manual 2008 Edition.*URL: http://www-pub.iaea.org/MTCD/publications/PDF/INES-2009_web. pdf (accessed on 22 February 2011).

[ICRP 1991] International Commission on Radiological Protection: *Recommendations of the International Commission on Radiological Protection*. Annals of the ICRP, Vol. 21, No. 1-3, Pergamon Press, Oxford/New York/Seoul/Tokyo, 1991.

[Informationskreis KernEnergie] Informationskreis KernEnergie (ed.): *Reaktortypen - Worum geht es?* URL: http://www.kernfragen.de/kernfragen/technik/ 04-Reaktortypen/4-01-Worum-geht-es .php (accessed on 23 February 2011).

[Irrek 2008] Irrek, Wolfgang: *Kernenergie - Haftung und Versicherung in Deutschland.* Wuppertal Institut, 2008.

[Kelle/Schaper 2001] Kelle, Alexander; Schaper, Annette: *Bio- und Nuklearterrorismus - Eine kritische Analyse der Risiken nach dem 11. September 2001*. Hessische Stiftung Friedens- und Konfliktforschung, October 2001.URL: http://www.google.de/url?sa=t&source=web&cd=1&ved=0CBkQFjAA&url=http%3A%2F%2Fse2. isn. ch%2Fserviceengine%2FFiles%2FESDP%2F29709%2Fipubli cat iondocument_singledocument% 2F964D5B25-35F0-4023-8991-2E964178D980%2Fde%2Frep1001 .pdf&ei= 7n6HTdOoKs3XsgaD_JGwAw&usg=AFQj CNESDDj TOZFXcqhG3mNWK5DwhUwCHQ (accessed on 21 March 2011).

[Konstantin 2007] Konstantin, Panos: *Praxisbuch Energiewirtschaft - Energieumwandlung, - transport und -beschaffung im liberalisierten Markt*. Springer Verlag, Berlin Heidelberg, 2007.

[Kotting-Uhl 2010] Kotting-Uhl, Sylvia: *Entwicklung der Anzahl an Bauteildefekten in den 17 AKWs, die heute noch eine Betriebsgenehmigung haben*. Büro Kotting-Uhl, Deutscher Bundestag, 29 April 2010.

[Krieger 2009] Krieger, Hanno: *Grundlagen der Strahlungsphysik und des Strahlenschutzes*. 6th edition, Vieweg+Teubner GWV Fachverlage GmbH, Wiesbaden, 2009.

[Küppers/Pistner 2007] Küppers, Christian; Pistner, Christoph: *Analyse des Bedrohungspotenzials "gezielter Flugzeugabsturz" am Beispiel der Anlage Biblis-A*. Öko-Institut e.V. Darmstadt, 20 November

2007. URL: http://www.oeko.de/oekodoc/623/ 2007-163-de.pdf (accessed on 21 March 2011).

[Ladurner/Pham 2010] Ladurner, Ulrich; Pham, Khuê: *Stuxnet - Iran im Krieg 2.0*. Die Zeit Online, 30 September 2010. URL: http://www.zeit.de/2010/40/ Stuxnet-Computerwurm (accessed on 23 March 2011).

[Leadbetter et al. 1983] Leadbetter, Malcolm R.; Lindgren, Georg; Rootz´en, Holger: *Extremes and Related Properties of Random Sequences and Processes*. Springer-Verlag, New York Heidelberg Berlin, 1983. ISBN: 3-540-90731-9.

[LTBW 2009] Landtag Baden-Württemberg (ed.): *Antrag der Abg. Franz Untersteller u. a. GRÜNE und Stellungnahme des Umweltminsteriums - Vertuschung eines Korruptionsfalls im Atomkraftwerk Philippsburg, Drucksache 14 / 4334*. 8 April 2009. URL: http://www.landtag-bw.de/wp14/drucksachen/4000/14_4334_d. pdf (accessed on 22 March 2011).

[Marcus 2006] Marcus, Jonathan: *Tough lessons for Israeli armour*. BBC News, 15. August 2006. URL: http://news.bbc.co.uk/2/hi/middle_east/4794829.stm (accessed on 22 March 2011).

[Nguyen 2007] Nguyen, Tristan: *Grenzen der Versicherbarkeit von Katastrophenrisiken - Erweiterungsmöglichkeiten durch Rückversicherung, Katastrophenanleihen und Versicherungsderivate*. Post-doctoral thesis, FernUniversität Hagen, 1st edition, Deutscher Universitäts-Verlag, Wiesbaden, June 2007.

[Nguyen 2009] Nguyen, Tristan: *Versicherbarkeit von Katastrophenrisiken und staatliche Risikoübernahme*. WHL Wissenschaftliche Hochschule Lahr, Lahr, February 2009. URL: http://www.akad.de/fileadmin/akad.de/assets/PDF/WHL_ Diskussionspapiere/WHL_Diskussionspapier_Nr_21.pdf (accessed on 25.03.2011).

[Obiko Pearson/Bandel 2011] Obiko Pearson, Natalie; Bandel, Carolyn: *Atomic Cleanup Cost goes to Japan's Taxpayers, May Spur Liability Shift*. Article on Bloomberg.com, 23 March 2011. URL: http://www.bloomberg.com/news/2011-03-23/nuclear-cleanup-cost-goes-to-japan-s-taxpayers-may-spur-liability-shift. html?utm_source=newsletter&utm_medium=email&utm_campaign= sendNuclearHeadlines (accessed on 25 March 2011).

[OECD 2003] Organisation for Economic Co-operation and Development: *Nuclear Electricity Generation: What are the External Costs?* 2003. ISBN 92-64-02153-1.

[ORNL 1993] Oak Ridge National Laboratory ORNL/RFF: *Draft Report: Damages and benefits of the Fuel Cycle: Estimation Methods, Impacts and Values*. Oak Ridge, 1993.

[Ottinger et al. 1990] Ottinger, Richard L.; Wooley, David R.; Robinson, Nicholas A.; Hodas, David R.; Babb, Susan E.; Buchanan, Shepard C.; Chernick, Paul L.; Caverhill, Emily; Krupnick, Alan; Harrington, Winston; Radin, Seri; Fritsche, Uwe: *Environmental Costs of Electricity*. Oceana Publications Inc., New York, 1990.

[Paulitz 2008] Paulitz, Henrik: *Das Atomkraftwerk Biblis B ist nicht für die am Standort möglichen Erdbeben ausgelegt - Eine "bestmögliche Gefahrenabwehr und Risikovorsorge" nach dem Stand von Wissenschaft und Technik ist nicht gewährleistet, Anlage B der Klagebegrändung zur Stilllegung des Atomkraftwerkblocks Biblis B in dem Verwaltungsstreitverfahren vor dem Hessischen Verwaltungsgerichtshof Lauerwald u.a. ./. Land Hessen beigeladen: RWE Power AG - 6 C 164/08.T*. Deutsche Sektion der Internationalen Ärzte für die Verhütung des Atomkrieges Ärzte in sozialer Verantwortung e.V. (IPPNW), August 2008. URL: http://www.ippnw.de/commonFiles/pdfs/Atomenergie/Anlage_B_-_Biblis_B_ist_unzureichend_gegen_Erdbeben_ausgel....pdf (accessed on 23 March 2011).

[Paulitz 2010] Henrik Paulitz: AKW-Störfallauswertung der IPPNW. International Physicians for the Prevention of Nuclear War (IPPNW), 2 June 2010. URL: http://www.ippnw.de/commonFiles/pdfs/Atomenergie/2010-06-02_AKW-Stoerfallauswertung_der_IPPNW.pdf (accessed on 21 March 2011).

[Pick 2010] Pick, Ulrich: *"Stuxnet" schlich sich auch ins Atomkraftwerk Buschehr*. Tagesschau.de, News of the ARD, 26 September 2010. URL: http://www. tagesschau.de/ausland/stuxnet108.html (accessed on 23 March 2011).

[Posser/Schmans/Müller-Dehn 2002] Posser, Herbert; Schmans, Malte; Müller-Dehn, Christian: *Atomgesetz - Kommentar zur Novelle 2002*. Heymanns Taschenkommentare, Cologne et al., 2002. ISBN: 978-3-452-25274-6.

[Reiss/Thomas 2007] Reiss, Rolf-Dieter; Thomas, Michael: *Statistical analysis of extreme values*. Birkhäuser, Basel Berlin, 2007. ISBN 3-7643-7230-3.

[Roos 2010] Roos, Joachim : *ExternE - Introduction*. 5 October 2010. URL: http: //www. externe.info/ (accessed on 25 March 2011).

[Rosenbaum/Wagner 2006] Rosenbaum, Markus; Wagner, Fred: *Versicherungsbetriebslehre*. 3nd edition, Verlag Versicherungswirtschaft GmbH, Karlsruhe, 2006. ISBN: 3-89952- 238-9.

[SÄBL 2011] Statistische Ämter des Bundes und der Länder (ed.): *Gebiet und Bevölkerung - Fläche und Bevölkerung*. 14 February 2011. URL: http : //www. statistik-portal. de/Statistik-Portal/de_jb01_jahrtab1 . asp (accessed on 25 March 2011).

[SBD 2010] Statistisches Bundesamt Deutschland (ed.): *Basisdaten Bruttoinlandsprodukt je Einwohner*. 19 October 2010. URL: http://www.destatis.de/jetspeed/portal/cms/Sites/destatis/Internet/DE/Content/Statistiken/Internationales/InternationaleStatistik/Thema/Tabellen/Basistabelle__BIPproKopf, templateId=renderPrint .psml (accessed on: 25 March 2011).

[Schneider et al. 2009] Schneider, Mycle; Thomas, Steve; Groggatt, Antony; Koplow, Doug: *Der Welt-Statusreport Atomindustrie 2009 - Unter besonderer Berücksichtigung wirtschaftlicher Fragen.* Commissioned by the Federal Minister for the Environment, Nature Conservation and Reactor Safety, Paris, Berlin, August 2009. URL: http://www.bmu.de/files/pdfs/allgemein/application/pdf/welt_statusbericht_atomindustrie_0908_de .pdf (accessed on 17 March 2011).

[Schweizerischer Erdbebendienst 2011] Schweizerischer Erdbebendienst (ed.): *Seismologische Analyse der jüngsten Erdbebenkatastrophen in Neuseeland und Japan: 10 Rückschlüsse für die Schweiz*. 17 March 2011. URL: http://www.seismo.ethz.ch/ Earthquake_Talk_2011_03_17_de (accessed on 23 March 2011).

[Spiegelberg Planer 2010] Spiegelberg Planer, Rejane: *Public Communications: Communicating the safety significance of events - INES - Part 1*. International Atomic Energy Agency (IAEA), 24 November 2010. URL: https://iaea.org/inisnkm/nkm/pages/2010/NEM_Trieste_Italy_2010/topics/docs/Nov_24/3a_Spiegelberg_Public_Communications_INES .pdf (accessed on 15 March 2011).

[Spiegel-Online 2006] Spiegel-Online (ed.): *Dübel legen AKW Biblis lahm*. Spiegel Online Politik, 17 October 2006. URL: http://www.spiegel.de/politik/deutschland/0, 1518,443082, 00.html (accessed on 01 April 2011).

[Spiegel-Online 2009] Spiegel-Online (ed.): *Das amerikanische Tschernobyl. einestages - Zeitgeschichten* on Spiegel Online, 25 March 2009. URL: http://einestages.spiegel.de/static/topicalbumbackground/3849/das_ amerikanische_tschernobyl .html (accessed on: 23 February 2011).

[Steeb 2011] Niko Steeb: *Die vergessenen Erdbeben - Deutsche Atomkraftwerke in der Gefahrenzone*. Augsburger Allgemeine, 17 March 2011. URL: http://www.augsburger-allgemeine.de/politik/Deutsche-Atomkraftwerke-in-der-Gefahrenzone-id14315666 .html (accessed on 23 March 2011).

[Strahlenschutzkommission 1994] Strahlenschutzkommission (SSK): *Ionisierende Strahlung und Leukämieerkrankungen von Kindern und Jugendlichen, Stellungnahme der Strahlenschutzkommission, Verabschiedet in der 124. Sitzung der Strahlenschutzkommission*. 21 April 1994. URL: http://www.ssk.de/de/werke/1994/volltext/ssk9401.pdf (accessed on 25 March 2011).

[Strahlenschutzkommission 2003] Strahlenschutzkommission (SSK) des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit: *Leitfaden für den Fachberater Strahlenschutz der Katastrophenschutzleitung bei kerntechnischen Notfällen*. Reports of the Commission on Radiological Protection (SSK) of the Federal Ministry for Environment, Nature Conservation and Reactor Security, Issue 37, Bonn, September 2003.

[Stritar et al. 1993] Stritar, A.;Mavko, B.; Susnik, J.; Sarler, B.: *Some Aspects of Nuclear Power, Plant Safety under War Conditions*. Nuclear Technology, Vol. 101, February 1993, p. 193-201.

[Stuttgarter Zeitung 2006] Stuttgarter Zeitung (ed.): *Schlüssel im Kernkraftwerk Philippsburg verschwunden*. Stuttgarter Zeitung, 29 March 2006.

[UBA 2007] Umweltbundesamt (ed.): *Ökonomische Bewertung von Umweltschäden – Methodenkonvention zur Schätzung externer Umweltkosten*. Dessau, 2007.

[Umweltlexikon Online a] KATALYSE Institut für angewandte Umweltforschung e.V. (ed.): Umweltlexikon Online. URL: http: //www.umweltlexikon-online. de/RUBradioaktivitaet/Radioakt ivitaetundStrahlung.php (accessed on 25 March 2011).

[UNSC 1988] United Nations Scientific Committee (ed.): *United Nations Scientific Committee on the Effects of Atomic Radiation Sources, Effects and Risks of Ionizing Radiation 1988 Report*. New York, 1988.

[USNRC 2009] United States Nuclear Regulatory Commission (ed.): *Three Mile Accident, Backrounder, United States Nuclear Regulatory Commission, Office of Public Affairs*. August 2009. URL: http://www.nrc.gov/reading-rm/doc-collections/ fact-sheets/3mile-isle.pdf (accessed on 22 March 2011).

[Weil 2003] Weil, Leopold : *Charakterisierung der Risiken der Kernenergienutzung*. Faculty of Mechanical Engineering, RWTH Aachen University, field of study: decommissioning of nuclear facilities, post-doctoral thesis, Aachen, 2003. URL: http://www.uni-saarland.de/fak7/fze/AKE_Archiv/AKE2004H/AKE2004H_Vortraege/AKE2004H_05Weil_Charakteri sierung_derKernenergieRisiken/AKE2004H_05aWeil_habil2002_Risiken-derKernenergienutzung.pdf (accessed on 15 March 2011).

[Welt Online 2010] Welt Online (ed.): *Al-Qaida- Terrorist arbeitete in US-Atomkraftwerk*. 13 March 2010. URL: http://www.welt.de/politik/ausland/article6754850/ Al-Qaida-Terrorist-arbeitete-in-US-Atomkraftwerk.html (accessed on 01 April 2011).

[Wuppertal Institut 2007] Wuppertal Institut (ed.): *Kernenergie im energiepolitischen Zieldreieck von Klimaschutz, Versorgungssicherheit und Wirtschaftlichkeit*. Wuppertal, March 2007. URL: http://www.wupperinst.org/uploads/tx_wibeitrag/ Kernenergie-FactSheet .pdf (accessed on 17 March 2011).

List of abbreviations

a	year
Art.	article
AtDeckV	Verordnung über die Deckungsvorsorge nach dem Atomgesetz (Nuclear Financial Security Ordinance)
AtG	Gesetz über die friedliche Verwendung der Kernenergie und den Schutz gegen ihre Gefahren (Atomic Energy Act)
BGBl.	Federal Law Gazette
BWR	boiling water reactor
cf.	confer
DeckRV	Verordnung über Rechnungsgrundlagen für die Deckungsrückstellungen (Premium Reserve Regulation)
DM	German mark
e.V.	eingetragener Verein (type of association)
ECU	European Currency Unit
ed.	editor
et al.	et alia (and others)
etc.	et cetera
EU	European Union
ExternE	Externalities of Energy
ff.	and the following
Fig.	figure
GbR	Gesellschaft bürgerlichen Rechts (type of partnership)
GDP	gross domestic product
GKN	Neckarwestheim nuclear power plant
Gy	gray
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
INES	International Nuclear Event Scale
IQ	intelligence quotient
IT	information technology
kg	kilogramme
km	kilometre
kWh	kilowatt hour
LNT	linear no-threshold
MCA	Maximum credible incident
mSv	millisievert
MWe	MegaWatt electrical
No.	number
OECD/NEA	Nuclear Energy Agency of the Organization for Economic Cooperation and Development

p.	page
Par.	paragraph
PJ	PetaJoule
PWR	pressurised water reactor
rem	roentgen equivalent in man
RODOS	Real-time On-line Decision Support system for off-site emergency management
RPG	rocket-propelled grenade
StrlSchV	Verordnung über den Schutz vor Schäden durch ionisierende Strahlen (Radiation Protection Ordinance)
Sv	sievert
TORCH	The Other Report on Chernobyl
USSR	Union of Soviet Socialist Republics
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
URL	Uniform Resource Locator
USA	United States of America
US dollars	US dollars
vs.	Versus
VSL	value of a statistical life
VVG	Gesetz über den Versicherungsvertrag (Insurance Policies Act)

List of symbols

€	euro
μSv	microsievert
P	probability measure
X	type of loss (understood as a random variable)
X_i, Y	random variables, where $i = 1, \ldots, n$
$X_{(i)}$	order statistics in relation to random variable X_i
n	natural number
$\min(X_1, \ldots, X_n)$	lowest value from X_1 to X_n
$\max(X_1, \ldots, X_n)$	highest value from X_1 to X_n
$P(X)$	probability of X
F	distribution function
f	probability density function of F
m_n	n-th moment
μ_n	n-th central moment
EX	expected value of random variable X
$\sigma(X)$	standard deviation of random variable X
$Var(X)$	variance of random variable X, corresponds to σ^2
$VarK(X)$	coefficient of variation of random variable X
$v(X)$	skew of random variable X
f_{Beta}	density of the beta distribution on the interval [0,1]
$B(\alpha, \beta)$	beta function in the interval [0,1] with regard to parameters α and β
$f_{Beta, [a, b]}$	density of the beta distribution on the interval $[a, b]$
$B(a, b, \alpha, \beta)$	general beta distribution in the interval [a, b] with regard to parameters α and β
$\Gamma(\alpha)$	gamma function of α
v_n	probability of extreme loss
ς_n	standard deviation of extreme loss

Glossary

Absorbed dose

This dose states the amount of radiation energy absorbed per unit mass. It is measured as Joules per Kg and represented by the unit Gy (gray).

Accident

Accident refers to the sequence of events that can result in an effective dose of over 50mSv to one or more persons.

Activity / radioactivity

Activity is the number of nuclear transformations that occur in a radioactive material per unit of time. The unit for activity used to indicate the number of nuclear transformations per second is the becquerel (symbol Bq). Since radionuclides can be contained in substances that are in different states of matter, activity is often stated with the unit for the state of matter, as in becquerels per gram (Bq/g) for solids, becquerels per litre (Bq/l) for liquids and becquerels per cubic metre (Bq/m3) for air. Nothing can be said about radiation exposure by just stating the activity; the radionuclide must also be known.

Actuarial interest rate

The proportional benefit obligations are calculated annually for insurance companies' balance sheets. An imputed interest rate, the actuarial interest rate, is used in this calculation. This rate is set in accordance with the Premium Reserve Regulation when the insurance is taken out. The highest legally stipulated actuarial interest rate is currently set at 2.25%. It will be reduced to 1.75% from 2012.

Actuarial principle of equivalence

In accordance with the actuarial principle of equivalence, the insurance premium is calculated on the basis of the type and size of the risk or the relevant risk group.

Alpha, beta and gamma rays

Some chemical elements have an unstable atomic nucleus that decays. These elements are called radioactive. The decay processes can vary. The radiation that decaying elements release is divided into three types: alpha and beta radiation consists of particles, while gamma radiation is made up of electromagnetic waves similar to x-ray radiation. However, it has a much shorter wavelength, which makes it extremely energetic. Alpha radiation consists of positively charged helium nuclei that have two protons and two neutrons. Beta rays consist of electrons. They are created when a neutron transforms into a proton and an electron that is emitted from the nucleus.

Availability period

The availability period is the agreed amount of time by the end of which insurance will cover the effects of a loss event.

Becquerel

The standard unit for activity. Substances are radioactive if they release radiation as they decay. Activity (A) is used to indicate how intense that radiation is. It is measured in becquerels (Bq) and specifies how much radiation a decaying substance generates during a certain period of time. One becquerel is defined as one decay per second. Thus, the faster a sample decays, the more intense its radiation.

Beta distribution

The beta distribution is a continuous probability distribution defined on the interval [0, 1]. The general beta distribution is a continuous probability distribution defined on the random interval [a, b].

Boiling water reactor

In boiling water reactors, the steam produced by the evaporation of the cooling water is used directly to power the turbines.

Calculation period

The estimated interval of time during which a loss event will theoretically occur once.

Candidates

Candidate is the term used for approximations to a certain value, so-called estimators.

Capital investments

Insurers, particularly life insurance companies, must invest their aggregate assets safely, profitably and in liquid funds under the terms of the Law on the Supervision of Insurance Companies (VAG). They are obliged to hold an appropriate mix and spread of investments.

Collective dose

The collective dose is the measurement used for the total exposure of segments of the population to radioactivity (collective). Assuming a linear relation, by which it is the same if a small number of people are exposed to a high dose or a large number of people are exposed to a very low dose, the collective dose of a population segment can be calculated from the sum of the individual doses by multiplying the average of the effective equivalent dose in this population segment by the number of people in the segment. The collective dose in a population is the sum of the collective doses of the individual population segments and is measured in person-sieverts.

Composite insurers

Composite insurers are insurance companies that offer various types of indemnity insurance (including accident insurance). The opposite is a life, health, legal costs or credit insurance company.

Compulsory insurance

Compulsory insurance is the obligation to take out insurance that is stipulated by law or a statute. For example, every vehicle owner must take out vehicle liability insurance (Section 1 of the Law on Compulsory Insurance for Vehicle Owners).

Credit insurance

Credit insurance protects the insured party from the loss of insured outstanding payments for deliveries of goods or the provision of services due to the insolvency of its clients. Bond insurance and employee dishonesty (fidelity) insurance also form part of the wider field of credit insurance.

Coverage amount

The coverage amount is also called the amount insured. It refers to the capital value (calculated using actuarial principles) of existing obligations to pay insurance benefits and premium refunds for life, health, liability and accident insurance.

Cumulative damage

Cumulative damage refers to several risks that are insured or reinsured by the same insurance company, which can be jointly affected by a damage event. Examples: 1. Fire insurance – fires that spread to neighbouring buildings or the joint applicability of fire insurance and business interruption insurance (due to fire). 2. Storm insurance and other storm and tempest insurance types – cumulative damage can occur over a wider area along the path of a storm, in an earthquake region or along a river.

Damage

Damage is harm arising from the reduction or loss of goods and is therefore the opposite of benefit or also negative benefit. Damage can be material or immaterial and actual or expected.

Design basis accident

A design basis accident is an accident that a nuclear power plant’s security systems must be designed to withstand. In the event of a design basis accident, radiation levels outside the facility must not exceed the limits set by the German Radiation Protection Ordinance.

Direct insurance

Direct insurance is insurance between companies and natural persons on the one side and insurers on the other. It is also referred to as insurance that one takes out oneself or "direct insurance".

Disaster

In insurance terms, a disaster is a damage situation that lasts for a longer period, mainly affects a large area, cannot be properly tackled by the usual emergency services (fire brigade, ambulance service, police), and can only be brought under control by national (or international) aid and additional resources (the military and non-organised members of the population).

Effective dose

This dose takes into account the different sensitivities of organs and tissues to stochastic radiation effects by multiplying specified organ doses by a tissue weighting factor. "Effective dose is determined by adding up all of the weighted organ doses of all specified organs and tissues, where the sum of the tissue weighting factors is 1. The tissue weighting factors are derived from the relative contributions of the individual organs and tissues to the entire stochastic radiation injury (detriment) to a person exposed to homogenous full-body radiation. The unit of effective dose is J/Kg; it is called the sievert (Sv)."

Electricity production

Electricity production is understood in general terms as the production of electrical energy. In physics, it always refers to the conversion of energy from different energy sources into electrical energy. This electrical energy is then mostly transmitted via a power grid to the connected machines to meet their electricity needs. Most electricity production is carried out on an industrial scale in power plants.

The term net electricity production more precisely describes the difference between the total amount of energy produced (gross electricity production) and the electricity needed by the different types of power plants. For example, coal power plants themselves need about 10% of the energy that they generate, while nuclear power plants require around 5% for their own use.

Emergency reference level

Emergency reference levels define dose limits during an accident. They help with planning disaster control measures and specify the points at which the principles of disaster control mandate that those measures be taken.

Equivalent dose

Equivalent dose is a measure of the biological impact of ionising radiation on humans. It is measured in Joules/Kg or sieverts.

Expected present value of benefits

Expected present value is the amount of cover for the expected costs of damage arising from a risk; that is, the expected amount of insurance benefits.

Expected value / Expected value of damages

The expected value is the average of all possible outcomes weighted by the probabilities. The expected value of damages is the expected value of all possible damages.

Extreme value theory / Extreme value statistics

Extreme value theory deals with the maximum and minimum values of random samples.

Fuel element

Arrangement of a number of fuel rods in a unit. Used to insert nuclear fuel into a nuclear reactor.

Fuel rod

Geometric shape in which nuclear fuel surrounded by cladding material is inserted into a reactor. Several fuel rods are normally compiled into a fuel element. The Krümmel nuclear power plant has a boiling water reactor with a fuel element consisting of 72 fuel rods. The pressurised water reactor at the Emsland nuclear power plant has a fuel element that contains 300 fuel rods.

Gray

Unit for absorbed dose. Even if the intensity of emission of a radioactive substance is known, that does not say anything about the effect of the radiation on the body. For that, it is important to determine how much energy is absorbed by a certain mass unit of the body. The absorbed dose (D) is specified in grays (Gy), with one gray defined as the absorption of one Joule of energy by one kilogram of matter.

Incident

Incident is the term used for a sequence of events, the occurrence of which prevents the continued operation of the power plant or work activities for safety reasons and which the power plant has to be designed to manage or for which precautions have to be taken to protect the work activities concerned.

Indemnity insurance

In indemnity insurance, the insurer is obliged to replace the damage to property arising in the insured event in accordance with the terms of the insurance contract (Section 1, Para. 1, Sentence 1 of the former version of Law on Insurance Contracts). The amount of compensation depends on the concrete amount of damages to be calculated, which is limited by the amount insured.

INES

The International Nuclear Event Scale (INES) ranks security-related events, incidents and accidents at nuclear facilities, especially those that affect the safety of nuclear power plants. The INES is divided into 8 levels (Level 0 to Level 7).

Insurance

Insurance is the pledge to pay compensation in case of damage or in case of death and survival in life insurance. The insurance companies assume risks on behalf of their personal and commercial clients and make it possible for them to plan their economic activities. In return, insured parties pay an appropriate insurance premium.

Insurance pool

An insurance pool is established by insurers as a type of reinsurance to cover large or not easily calculable risks; for example, for nuclear or terrorist disasters. The insurers undertake to designate all of the risks listed in the pool contract in line with a previously stipulated ratio. Pools are usually set up to cover large or not easily calculable risks. When the pool is first set up, the individual risks are not yet clear. Insurers each insure an insured party and cede the risk to the pool. Each pool member covers a ratio of each risk in the pool.

Insurance premium

An insurance premium, which is often simply referred to as "a premium", is the price for insurance cover. In general, it has to be paid per year. Apart from the pure risk premium, the components of an insurance premium include the security premium, the operating costs premium, the insurance tax contribution and the profit premium.

Insured hazard

Insured hazard describes the type of hazard (for example, natural hazards, fire, explosion, theft) covered by insurance. Insured hazards are those included and covered under the terms of the insurance contract. In concrete terms, an insured hazard is the event that brings about the insured event should it arise. Insured hazards are described in the insurance premium.

Insured risk

Insured risk is the term used to describe the insured object in the insurance contract. In life insurance, it thus refers to the insured person.

Liability and absolute liability

Liability in the narrow sense is when a legal entity is subject to the enforcement powers of the state (governmental authority).

In its wider sense, liability is when one party assumes the damages directly caused to another party, that is, the legal obligation to provide compensation (civil liability). Absolute liability is liability for damages resulting from an authorised hazard (such as operating dangerous equipment or keeping a pet). Absolute liability differs from liability resulting from intolerable action in that it does not involve an illegal action or a misdeed on the part of the liable party.

Liability insurance

Liability insurance is a form of insurance that requires the insurer to settle property losses resulting from damage claims made against the insured party. A claim can be made for insurance benefits if the insured party is guilty of violating a duty of care (tort liability) or acted in a way that exacerbated the danger (absolute liability), thereby causing damage to a third party. Liability insurance can be taken out as unlimited insurance, which places no constraints on the limit of liability, or as lump-sum insurance, which places an upper limit on compensation payments. Liability insurance is also prescribed for nuclear power plants, nuclear fuels and other radioactive materials as well as for aeroplanes and certain occupations (accountants, tax advisors, notaries public, carnival operators, hunters). Professional liability insurance is required for doctors, dentists, veterinarians, pharmacists and others.

Liability limit

The person who causes an accident bears unlimited liability. Certain liability limits apply in cases of absolute liability, that is, in the absence of fault.

Lump-sum insurance

Lump-sum insurance is the counterpart to indemnity insurance. In the former, the insurance provider undertakes to pay exactly the agreed amount in the insured event.

MCA

Maximum credible accident (MCA) is a postulated scenario that a nuclear power plant must be able to withstand.

Negligence

Section 276, Par. 2 of the German Civil Code defines negligence as failing to provide "the care required" for a task. Negligence differs from intent insofar as its consequences are not anticipated. Negligence can only be said to exist where the action is in violation of the law or other duties and the ensuing negative result could have been foreseen and avoided. There must also be a realistic possibility of alternative conduct in the situation. Negligence is measured relatively to objectively necessary care, not customary care.

Civil law distinguishes between two types of negligence. Gross negligence occurs in instances of serious carelessness. Simple negligence is when it was not possible to provide due care or when due care was not provided with intentional carelessness.

Nuclear event

A nuclear event refers to every event that causes damage, where the event or the damage it causes arise from radioactive properties or the combination of radioactive properties with poisonous, explosive or otherwise hazardous nuclear fuels or radioactive products or waste, or from ionising radiation produced by another source of radiation within the nuclear facility.

Nuclear disaster

A nuclear disaster is a beyond design basis accident and is thus so to speak realization of the remaining residual risk. A residual risk is a risk that lies beyond the safety provisions put in place or one which was not taken into account and consciously or unconsciously taken on when those provisions were selected. The German media often refer to a nuclear disaster as a "Super-GAU" – "GAU" is the German for MCA, the maximum credible accident. "Super" implies that this accident will have an impact that goes beyond that of an MCA.

Nuclear fission

Nuclear fission is a nuclear reaction in which the nucleus of a heavy atom is split into smaller parts by neutrons, releasing large amounts of energy. When a nucleus is split, two medium-sized nuclei are produced each time. These are called the radioactive fission products. In addition, free neutrons are produced, which can trigger further nuclear fission. Nuclear fission can also occur spontaneously, that is, without outside interference. However, the nuclear fission that takes place in nuclear power plants is controlled.

Nuclear insurance pool

The German Nuclear Reactor Insurance Association (DKVG) offers pooled liability insurance and property insurance for risks connected with the construction and operation of nuclear reactors and similar facilities.

Nuclear power plants

Nuclear power plants are also known as atomic plants. A nuclear power plant is a thermal power plant mainly used to generate electricity, in which the nuclear binding energy released by nuclear fission in a reactor is converted into heat and subsequently into electrical energy via a water/steam cycle by a turbine and generator.

Person-sievert

Person-sievert is the unit for the collective dose in a population.

Pressurised water reactor (PWR)

Pressure keeps the water in this type of reactor from boiling into steam. This enables it to remain in a liquid state and transfer its heat to a secondary water system, which in turn generates steam to drive the turbines.

Probability distribution

In probability theory, the probability distribution indicates how the probabilities are distributed over the possible random events, particularly the possible values of a random variable.

Pure risk premium

The pure risk premium is the reserve amount for the expected damage costs of the risk.

Reinsurance

Reinsurance relieves the primary insurer of some of the risk assumed on behalf of the client, which is transferred to a reinsurer in return for payment of a reinsurance premium. Put simply, this is "insurance for the insurer".

Rem

Rem is the unit formerly used for sievert. 1 rem = 0.01 sievert.

Risk

Risk is the qualitative and/or quantitative description of damage as regards the possibility that it will occur (probability of occurrence) and the size of its damage impact (extent of damage).

Security premium

The security premium serves as a reserve amount for possible underwriting losses due to variance in the expected damages.

Sievert

Sievert is the unit of equivalent dose for people. As one sievert represents a relatively large equivalent dose, values that occur in real life are mostly expressed with an SI prefix in millisievert or microsievert. 1 sievert (Sv) equals 1000 millisievert (mSv). 1 millisievert equals 1000 microsievert (μSv).

Sievert per time unit

Sievert per time unit is a unit used for exposure to radiation. In order to be able to assess the effects of radiation on the body more precisely, it is important to know how long a particular dose affects the body. Exposure to radiation is therefore mostly measured in sievert per time unit, for example, millisievert per year or microsievert per hour. The average natural exposure to radiation in Germany is 2.1 millisievert per year, that is, 0.24 microsievert per hour. On average, two millisievert per year caused by artificial sources of radioactivity can be added to this. Most of this is caused by medical procedures.

Specific risk

The part of the total existing risk assumed by an insurance company with all of its hazards and possible damages is referred to as specific risk. As insurers usually exclude certain hazards and damages from policies, including those such as damages resulting from war, nuclear accidents or computer viruses, specific and general risk are often not identical.

Standard deviation

Standard deviation describes the spread of a probability distribution around a location parameter.