Appendices

Appendix 1: World Reactors

This appendix provides information on the world's reactors. It is divided into reactors that are operational, that are under construction and that have been permanently shut down.

Table A1.1: Operating reactors

Country/ economy	Reactor type						Total units	Total (MWe net)
	PWR	BWR	PHWR	GCR	LWGR	FBR		
United States	69	35					104	100 582
France	58					1	59	63 260
Japan	23	32					55	47 587
Russian Federation	15				15	1	31	21 743
Germany	11	6					17	20 470
Korea	16		4				20	17 451
Ukraine	15						15	13 107
Canada			18				18	12 589
United Kingdom	1			18			19	10 222
Sweden	3	7					10	9 014
China	9		2				11	8 572
Spain	6	2					8	7 450
Belgium	7						7	5 824
Chinese Taipei	2	4					6	4 921
India		2	15				17	3 782
Czech Republic	6						6	3 619
Switzerland	3	2					5	3 220
Finland	2	2					4	2 696
Slovak Republic	5						5	2 034
Bulgaria	2						2	1 906
Hungary	4						4	1 829
South Africa	2						2	1 800
Brazil	2						2	1 795
Mexico		2					2	1 360
Romania			2				2	1 300
Lithuania					1		1	1 185
Argentina			2				2	935
Slovenia	1						1	666
Netherlands	1						1	482
Pakistan	1		1				2	425
Armenia	1						1	376
Total	**265**	**94**	**44**	**18**	**16**	**2**	**439**	**372 202**

Notes for Tables A1.1, A1.2 and A1.3:
CANDU reactors are included under PHWR; **RBMK** reactors are included under LWGR.
BWR: Boiling water reactor.
GCR: Gas-cooled reactor.
LWGR: Light water-cooled graphite-moderated reactor.
PWR: Pressurised water reactor.
PHWR: Pressurised heavy water reactor.

Table A1.2: Reactors under construction

Country/ economy	Reactor type						Total units	Total (MWe net)
	PWR	BWR	PHWR	GCR	LWGR	FBR		
Korea	6						6	6 540
China	6						6	5 220
Russian Federation	5				1	1	7	4 724
India	2		3			1	6	2 910
Chinese Taipei		2					2	2 600
Japan	1	1					2	2 186
Bulgaria	2						2	1 906
Ukraine	2						2	1 900
Finland	1						1	1 600
France	1						1	1 600
United States	1						1	1 165
Iran	1						1	915
Slovak Republic	2						2	870
Argentina			1				1	692
Pakistan	1						1	300
Total	**31**	**3**	**4**	**0**	**1**	**2**	**41**	**35 128**

Note: Data for the Russian Federation include two small units of 32 MWe each.

Table A1.3: Reactors permanently shut down

Country/ economy	Reactor type							Total units	Total (MWe net)
	PWR	BWR	PHWR	GCR	LWGR	FBR	Others		
United States	12	10	1	2		1	2	28	9 764
Germany	9	5	1	2		1	1	19	5 879
France	1			8		1	1	11	3 798
Ukraine					4			4	3 515
United Kingdom				23		2	1	26	3 324
Bulgaria	4							4	1 632
Italy	1	2		1				4	1 423
Sweden		2	1					3	1 225
Lithuania					1			1	1 185
Russian Fed.	2				3			5	786
Spain	1			1				2	621
Slovak Rep.	1						1	2	501
Canada			2				1	3	478
Armenia	1							1	376
Japan		1		1			1	3	297
Netherlands		1						1	55
Kazakhstan						1		1	52
Belgium	1							1	10
Total	**33**	**21**	**5**	**38**	**8**	**6**	**8**	**119**	**34 921**

Others reactor types included above are:

Reactor type	Total units
Heavy water-moderated gas-cooled reactor	3
Heavy water-moderated boiling light water-cooled reactor	3
Organic moderated Reactor	1
Liquid metal-cooled graphite-moderated reactor	1

References for Appendix 1

IAEA (2008), Power Reactor Information System, PRISM database, International Atomic Energy Agency, www.iaea.org/programmes/a2/.

NEA (2008), *Nuclear Energy Data 2008*, Nuclear Energy Agency, OECD, Paris, France.

Appendix 2: Definition of World Regions

The regions in this book have been defined by the NEA to be consistent with the IEA's *World Energy Outlook*, with the exception that India and the Russian Federation are treated independently here and that those countries not covered by the first seven groups are categorised as the "Rest of the world". The eight regions considered by the NEA are:

OECD North America

Canada, Mexico, United States.

OECD Europe

Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom.

OECD Pacific

Australia, Japan, Korea, New Zealand.

India

China

Russian Federation

Transition economies

Armenia, Belarus, Bulgaria, Croatia, Estonia, Georgia, Kazakhstan, Latvia, Lithuania, Romania, Slovenia, Ukraine.

Rest of the world

Appendix 3: Further Details on the Assumptions and Outcomes of Selected Scenarios

As noted in Chapter 3, the likely pattern of future total primary energy supply (TPES) and global electricity demand has been modelled extensively. The models generally cover the period to 2030, and in some cases to 2050. Most produce a baseline or reference scenario for future global energy use, assuming that the existing government policies remain broadly unchanged. Baseline scenarios therefore represent "business as usual". The models then assess the impact on this baseline of potential changes to current policies, usually by developing a series of "what-if?" scenarios. These scenarios generally represent sets of different, discrete assumptions rather than a continuum of change.

The NEA has chosen to use the outcomes of six of these sets of scenarios. Those selected are:

Assessments to 2030

- International Energy Agency (IEA) *World Energy Outlook 2006* (WEO).
- US Department of Energy, Energy Information Administration 2007 (EIA).
- International Atomic Energy Agency 2005 (IAEA).
- World Nuclear Association 2005 (WNA).

Assessments to 2050

- International Energy Agency (IEA) *Energy Technology Perspectives 2006* (ETP).
- Intergovernmental Panel on Climate Change 2000 (IPCC).

This appendix provides more information on the assumptions that underpin the scenarios and their outcomes. The scenarios are defined in Tables 3.3 and 3.4, except for EIA 3 and EIA 4 included here for comparison, which assume low (USD 34 per barrel) and high (USD 100 per barrel) oil prices respectively in 2030.

The tables of assumptions and outcomes that follow use the abbreviations listed in Table A3.1.

Table A3.1: Abbreviations and units	
Macroeconomics	
GDP	Annual global gross domestic product in trillions (10^{12}) 2000 USD, purchasing power parity
GDP AGR	Annual growth rate of GDP (% per annum)
Oil price	Crude oil import price in 2005 (USD per barrel)
Population	Global population in millions
Pop AGR	Annual growth rate of population (% per annum)
Technological innovation	
Tech progress	General speed and degree (incremental, radical) of technological progress
CCS and/or Ren	Success of carbon capture and storage technology and/or renewable energy technology
Adv nuclear	Success of advanced nuclear technology systems
AGR of EI	Annual growth rate of energy intensity (% per annum)
AGR of CI	Annual growth rate of CO_2 intensity (% per annum)
Environment	
Climate CC	Socio-political concern on climate change
CO_2 penalty	Global institution of penalty for CO_2 emissions
CO_2 EM	World energy-related CO_2 emissions (Gt)
Energy	
Energy SC	Socio-political concern on energy security
P-Energy DM	World primary energy demand (Mtoe)
Elec DM	World electricity demand (TWh)
Nuclear energy	
Nuclear track record	Success of R&D, and construction and operational experience of nuclear energy systems
PA for NPPs	Political and public acceptance for nuclear power plants
Projections for nuclear energy	
Np	Nuclear demand expressed as primary energy (Gtoe)
Ne	Nuclear electricity generation (TWh)
Nc	Nuclear capacity (GWe) for electricity generation

Table A3.2: Assumptions and projections for 2030

See Table A3.1 for units	Actual	NEA		WEO			EIA					IAEA		WNA		
	2004	Low	High	0	1	2	0	1	2	3	4	Low	High	0	1	2
GDP	55						154	136	174	155	154					
GDP AGR				3.4	3.4		4.1	3.6	4.5	4.1	4.1	▼				
Oil price	43			55			59			34	100					
Population	6 400			8 100	8 100		8 203					8 123			7 500	
Pop AGR				1.0	1.0		1.0					0.75				
Tech progress				△	▲	▲										
CCS and/or Ren					△	▲				▽	△					
Adv nuclear														△	▼	▲
AGR of EI				-1.7	-2.1		-2.2	-2.1	-2.3							
AGR of CI								-2.2								
Climate CC					△	▲							▲	△	▼	▲
CO_2 penalty					▼	▲									▼	
CO_2 EM	26.1			40.4	34.1	26.1	42.9	38.4	47.6	43.9	41.8					
Energy SC					△	▲										▲
P-Energy DM	11 204			17 095	15 405	12 897	17 691	15 978	19 496	18 147	17 196	15 774	21 534			
Elec DM	17 408			33 750	29 834	28 018	30 674	27 959	33 543	31 138	30 074	24 667	38 960	31 657	31 657	31 657
Nuclear track record					△	▲					△	▼	△		▼	▲
PA for NPPs											△	▼	△	△	▼	▲
Np	714 6.4	784	1 201	861 5.0	1 070 6.9	1 359 5.5	1 001 5.7	988 6.2	1 031 5.3	976 5.4	1 026 6.0	820 5.2	1 206 5.6			
Ne	2 740 15.7	3 008	4 607	3 304 9.8	4 106 13.8	5 203 18.6	3 619 11.8	3 561 12.7	3 716 11.1	3 518 11.3	3 698 12.3	3 115 12.6	4753 12.2	4 062 12.8	2 148 6.8	5 745 18.1
Nc	364	404	619	416	519	660	481	474	494	468	492	418	640	524	279	740

Notes: ▲ Specified high ▼ Specified low △ Implied relatively high ▽ Implied relatively low
Data in red were calculated. The figures in blue show the share (percentage) of nuclear in the total global energy demand (line Np) or electricity generation (line Ne).

Table A3.3: Assumptions and projections for 2050

See Table A3.1 for units	Actual	NEA		ETP				IPCC		
	2004	Low	High	0	1	2	3	1	2	3
GDP										
GDP AGR					2.9	2.9		▲	▲	▽
Oil price										
Population					9 100	9 100		8 704		
Pop AGR					0.9	0.9		▲	▽	▼
Tech Progress								▲	▽	▼
CCS and/or Ren		▲	▼		▽	▽	▲	▽	▽	▽
Adv nuclear					▽		▲			
AGR of EI										
AGR of CI				▽						
Climate CC			▲					▼	▼	▲
CO_2 Penalty			▲							
CO_2 EM	26.1			58.0	26.0		20.6			
Energy SC			▲							△
P-Energy DM	11 204			22 112	16 761		17 555	35 738	28 998	20 012
Elec DM	17 408			46 630	31 763	31 678	32 896	63 953	58 432	37 700
Nuclear track record		▼	▲		▽	▼	▲		▽	▽
PA for NPPs		▼	▲						▽	
Np	714 6.4	1 118	2 751	810 3.7	1 394 8.3		2 074 11.8	2 146 6.0	2 749 9.5	860 4.3
Ne	2 740 15.7	4 289 9.0	10 558 22.0	3 107 6.7	5 338 16.8	3 103 9.8	7 300 22.2	8 235 12.9	10 547 18.0	3 312 8.8
Nc	364	576	1 418	390	677	389	926	1 045	1 338	419

Notes: ▲ Specified high ▼ Specified low △ Implied relatively high ▽ Implied relatively low

Data in red were calculated. The figures in blue show the share (percentage) of nuclear in the total global energy demand (line Np) or electricity generation (line Ne).

Appendix 4: Comparative Analysis of Severe Accidents Risks in the Energy Sector

Keeping in mind that no human activity can be carried out with zero risk, policy makers and other stakeholder groups very often request comparisons of the risks associated with different sources of energy. This is a very difficult question, especially since data regarding catastrophic events and their effects remain heterogeneous, and there is little or no historical experience of severe accidents in some energy sectors such as hydro or nuclear in OECD countries.

One of the most comprehensive approaches to this question was developed by the Paul Scherrer Institut (PSI) in Switzerland since the early 1990s built on the database ENSAD (Energy-related Severe Accident Database). This Appendix provides a brief overview of the PSI analysis of severe accident risks in the energy sector. The scope of this analysis is not restricted just to accidents occurring in power and heating plants, but covers the complete energy chains because accidents can take place in every stage from exploration to extraction, refining, storage, distribution, and finally waste disposal. Such a broader perspective is essential because for the fossil chains, accidents at power plants play a minor role compared to the other chain stages, i.e. analyses based on power plants only would radically underestimate the real situation.

In the literature no commonly accepted definition can be found of what constitutes a severe accident. In the ENSAD database, an accident is considered severe if it is characterised by one or more of the following consequences: 5 or more fatalities, 10 or more injured persons, 200 or more evacuees, release of more than 10 000 tonnes of hydrocarbons, enforced clean-up of land and water area greater than 25 km^2, extensive ban on consumption of food, or economic losses over USD 5 million (at 2000 values). The number of fatalities is generally considered as the most reliable indicator and results presented below focus on this indicator.

In the case of nuclear power, application of probabilistic safety assessment (PSA) was necessary because of lack of statistically relevant historical records. In OECD countries there was not a single accident in the severe category, and in non-OECD countries, only one (Chernobyl). Consequences of hypothetical nuclear accidents were analysed using PSA techniques (see box).

Nuclear regulators generally consider PSA as a powerful tool to assess the impact on safety of changes in a given design; however they give little consideration to the absolute values themselves resulting from PSA techniques.

Probabilistic Safety Assessments

Probabilistic safety assessment (PSA) is a systematic and comprehensive technique used to evaluate risks associated with complex systems such as nuclear power plants. It is also used in other industries that use complex technologies like the chemical industry, commercial airline operation and aeroplane construction. PSA is used during both the design and the operating stages of a nuclear plant to identify and analyse conceivable faults and sequences of events that might result in severe core damage and releases of radioactivity. PSA looks at three questions:

- What are the initiating faults and sequences of events that could lead to core damage?
- What are the consequences of core damage and potential radioactivity release?
- How likely are these events to occur?

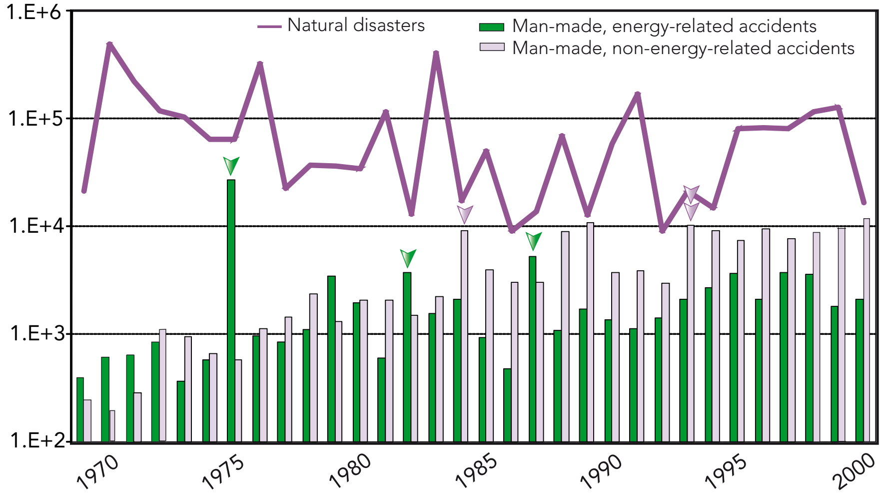
A PSA numerically assesses the probability and consequence of all foreseeable faults, and determines risk for each. Analysis of potential system faults includes assessment of human reliability and common mode failure (which looks at effects that could cause simultaneous failures across several systems). PSA considers both internal and external events, in both operational and shutdown conditions. Internal events include component failure and human error; external events include natural hazards like seismic events and man-made events like aircraft crash. Given that the output relies on input reliability data and the comprehensiveness of the faults considered, the results should not be considered as an exact prediction of the event probabilities.

A4.1 Contents of ENSAD

The ENSAD database currently contains 18 706 accident records of all kinds, of which 88.4% occurred in the years 1969-2000. Within this period, 6 995 accidents resulted in five or more fatalities, of which 39.5% were natural disasters and the other 4 233 (60.5%) were man-made accidents. The latter can be further divided into 1 870 energy-related accidents (44.2%) and 2 363 other man-made accidents (55.8%).

Figure A4.1 shows fatalities in all categories of severe (≥ 5 fatalities) man-made accidents and natural disasters from 1969 to 2000, amounting to about 3.4 million fatalities. Of these, more than 90% were victims of natural catastrophes and about 10% of severe man-made accidents; 37% of the latter were killed in energy-related accidents.

Figure A4.1: Number of fatalities for severe (≥ 5 fatalities) natural disasters and man-made accidents, 1969 to 2000



Note: Arrows indicate the three most deadly accidents per category, which are also described in the text.
Source: based on slightly updated data from Burgherr *et al.* (2004).

The largest non accident disasters were a storm and flood catastrophe in Bangladesh in 1970 (300 000 fatalities), the Tangshan earthquake in China in 1976 (290 000), and a drought and civil war in Sudan in 1983 (250 000). In contrast, the largest man-made accidents resulted in fatalities one to two orders of magnitude lower. The top-ranked energy-related accidents include the Banqiao/Shimantan dam failures in China in 1975 (26 000 fatalities), the collision of the tanker “Victor” with the Ferry “Doña Paz” off the Philippines in 1987 (4 386), and a tank truck collision with another vehicle in the Salang tunnel in Afghanistan's Parvan province in 1982 (2 700). Large non-energy-related severe accidents include the accident at a pesticide plant in Bhopal in India in 1984 (5 000 fatalities), the sinking of the ferry "Neptune" near the coast of Haiti in 1993 (1 800) and the failure of the Gouhou dam (the primary purpose of which was irrigation and water supply) in China in 1993 (1 250).

The ENSAD database includes 1 870 severe accidents for the various energy chains in the period 1969-2000, amounting to 81 258 immediate fatalities (Table A4.1). The coal chain accounted for 65.3% of all accidents, with oil a distant second at 21.2%. Contributions by the natural gas (7.2%) and liquefied petroleum gas (LPG) (5.6%) chains were much smaller, while both hydro and nuclear account for less than 1% each. This dominance of coal-chain accidents is fully attributable to the release of detailed accident statistics by China's coal industry, data that were not previously publicly available. Altogether, 819 of the 1 044 accidents collected for the Chinese coal chain occurred in the years 1994-1999, implying substantial under-reporting before the release of the annual editions of the *China Coal Industry Yearbook*.

Table A4.1: Summary of severe (≥ 5 fatalities) accidents that occurred in fossil, hydro and nuclear energy chains in the period 1969-2000

Energy chain	OECD		Non-OECD		World total	
	Accidents	Fatalities	Accidents	Fatalities	Accidents	Fatalities
Coal	75	2 259	102 1 044 (819)[a]	4 831 18 017 (11 334)[a]	1 221	25 107
Oil	165	3 713	232	16 505	397	20 218
Natural gas	90	1 043	45	1 000	135	2 043
LPG	59	1 905	46	2016	105	3 921
Hydro	1	14	10	29 924	11	29 938
Nuclear	0	0	1	31[b]	1	31
Total	**390**	**8 934**	**1 480**	**72 324**	**1 870**	**81 258**

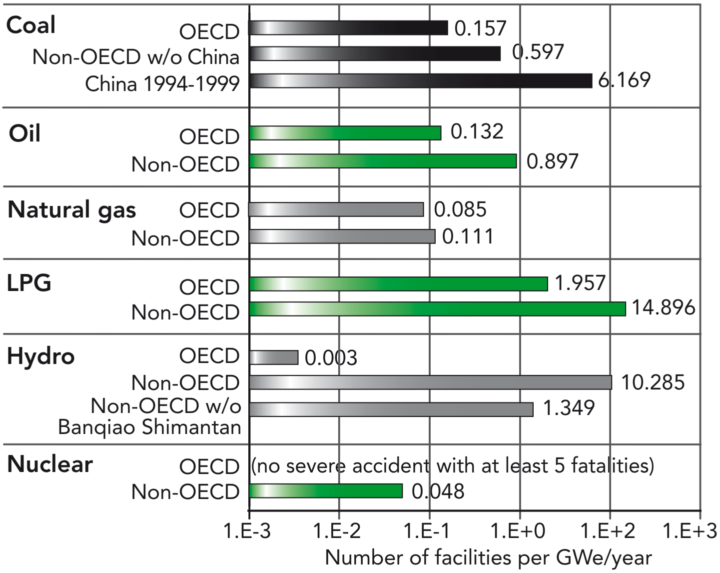
a. First line: Coal non-OECD w/o China; second and third line: Coal China 1969-2000, and in parentheses 1994-1999. Note that only data for 1994-1999 are representative because of substantial under-reporting in earlier years.
b. Only immediate fatalities.
Source: based on slightly updated data from Burgherr *et al.*, 2004.

Fatalities were clearly dominated by the Banqiao/Shimantan dam failures, which together resulted in 26 000 deaths. As a consequence, the hydro chain accounts for 36.8% of all fatalities. Among the fossil chains, coal accounted for most fatalities, followed by oil, LPG and natural gas.

A4.2 Comparative analysis of major energy chains

Aggregated indicators were calculated as fatalities per GWyr, differentiating between OECD and non-OECD countries. It should be noted that the statistical basis for the indicators for individual energy chains may differ radically. For example, there are 1 221 severe accidents with at least five fatalities in the coal chain and only one in the nuclear chain (Chernobyl). Figure A4.2 shows the significant differences between the aggregated, normalised fatality rates assessed for the various energy chains. Generally, OECD countries exhibit significantly lower fatality rates than non-OECD countries. Among the fossil chains, LPG is most accident-prone per GWyr, followed by oil and coal, whereas natural gas performs best. Western style nuclear and hydropower plants have the lowest fatality rates. The recent experience with hydro in OECD countries points to very low fatality rates, comparable to the representative PSA-based results obtained for nuclear power plants in Switzerland, whereas in non-OECD countries, dam failures can pose a much higher risk. The figure also shows that the Chinese coal chain should be treated separately as its accident fatality rates are about ten times higher than in other non-OECD countries and about forty times higher than in OECD countries.

Figure A4.2: Comparison of aggregated, normalised, energy-related fatality rates for OECD and non-OECD countries, 1969 to 2000



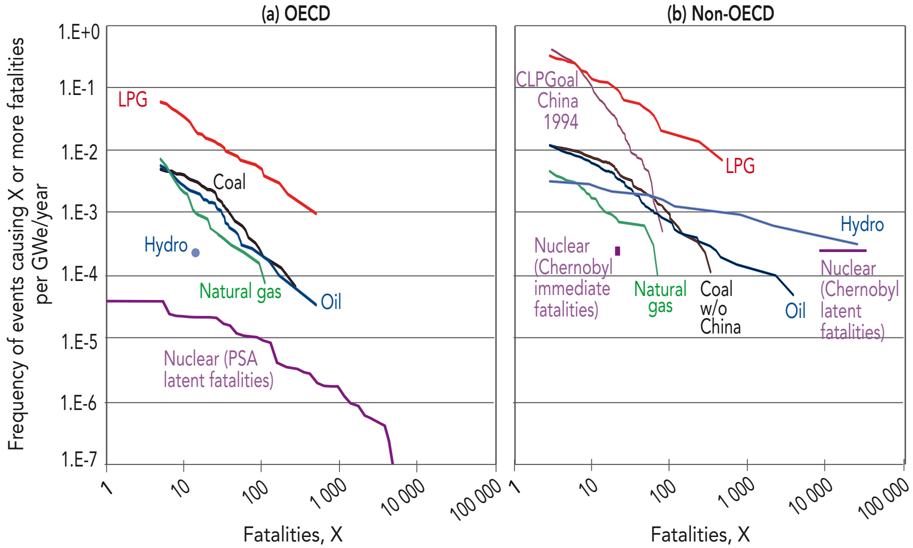
Note: based on historical experience of severe (≥ 5 fatalities) accidents that occurred in OECD and non-OECD countries in the period 1969-2000, except for coal China where complete data from the *China Coal Industry Yearbook* were only available for the years 1994-1999. Note that only immediate fatalities were considered.

Source: based on slightly updated data from Burgherr *et al.* (2004).

The above discussion was restricted to immediate fatalities; however, in the case of the nuclear chain, latent fatalities dominate total fatalities. For the only severe (≥ 5 fatalities) nuclear accident with an impact on human health (Chernobyl), then estimates of latent fatalities would range from 13.9 to 51.2 deaths per GWyr (for non-OECD countries). However, applying these estimates for nuclear energy in OECD countries is not appropriate, because current OECD plants use other, safer technologies which are operated under a strict regulatory regime. This is also predominantly true for the current situation in non-OECD countries. In the OECD, latent fatality rates based on PSA are therefore generally significantly lower, around 0.02 fatalities per GWyr.

Frequency-consequence (F-N) curves shown in Figure A4.3 retain the ranking of energy chains derived from aggregated indicators, but provide additional insight on chain-specific maximum damages and on the probability of an accident exceeding a specified consequence threshold.

Figure A4.3: Comparison of frequency-consequence curves for full energy chains



Based on historical experience of severe accidents in OECD and non-OECD countries for the period 1969-2000, except for China 1994-1999.
Source: based on slightly updated data from Burgherr *et al.* (2004).

For OECD countries, fossil energy chains clearly exhibited higher frequencies of severe accidents than hydro and nuclear (Figure A4.3a). Among fossil chains, LPG exhibits the worst performance and natural gas the best, whereas coal and oil chains are ranked in between. When comparing maximum consequences, there is only one data point for hydro, followed by natural gas (109 fatalities), and other fossil chains having 2.5 to 4.5 times higher values compared to natural gas.

For non-OECD countries (Figure A4.3b) the ranking of F-N curves was comparable to that for OECD countries, except for the Chinese coal chain that showed a significantly worse performance than other non-OECD countries. Furthermore, frequencies at corresponding numbers of fatalities were generally higher for non-OECD compared to OECD; for LPG and coal China (1994-1999) chain frequencies at lower death tolls were even greater than 10-1. Regarding chain-specific maxima, non-OECD values of coal (without China), oil and LPG were substantially higher than the corresponding OECD values. In addition, the range in observed maximum fatalities among individual chains was larger in non-OECD, particularly because the oil chain historically shows maximum numbers up to one order of magnitude higher than other fossil chains.

For nuclear energy, immediate fatalities play a minor role, whereas latent fatalities clearly dominate. Expectation values for severe accident fatality rates associated with the nuclear chain in OECD countries are very low, but the maximum credible consequences may be large because of the dominance of expected latent fatalities, i.e. for large events, comparable to the Banqiao/Shimantan dam accident that occurred in China in 1975. Results concerning Chernobyl were published in Hirschberg et al., (1998). Earlier studies by EC/IAEA/WHO and UNSCEAR formed the main basis for the numerical estimates of total latent fatalities associated with Chernobyl, supported by numerous sources including Russian ones. Estimated latent fatalities range from 9 000 (based on dose cut-off) to 33 000 (entire northern hemisphere with no dose cut-off) over the next 70 years, indicating that the upper range in estimates used here is conservative (as intended) because it was not limited to the most contaminated areas.

While the risk to individuals receiving very small doses is equivalently very small, a huge number of people in space and time are affected. When the large collective dose (resulting from summing millions of very small doses) is combined with a linear dose response function with no threshold (i.e. the probability of a fatal cancer in the long term is directly related to the dose received, even down to infinitesimal doses) for the individual exposure, the thus estimated health effects may become dominant. To put this in perspective, the global effective dose of 600 000 person-Sieverts from the Chernobyl accident is equivalent to only 5% of some 13 000 000 person-Sieverts estimated to be annually delivered to the world population from natural sources. For the 70 years over which the above fatality figures were calculated for the accident, the collective dose from natural sources would be 910 000 000 person-Sieverts (assuming a constant population), some 1 500 times larger, therefore theoretically causing 1 500 times as many fatalities due to exposure to natural background radiation.

Some further perspective can also be gained by considering the latent health effects of fossil fuel burning, the main alternative for baseload electricity production, as discussed in Chapter 4. The *OECD Environmental*

Outlook (OECD, 2008) reports that outdoor air pollution due to fine particulates (≤ 10 microns) is estimated to have caused approximately 960 000 premature deaths in 2000 and 9 600 000 years of life lost worldwide. The OECD Environmental Outlook baseline estimate is that, by 2030, this will rise to 3 100 000 deaths per annum and 25 400 000 years of life lost. While not all of this can be attributed to electricity generation, the same source reports the European Environment Agency estimate of 30% due to energy production in Europe, where emission standards will be more demanding than in many other countries of the world.

In September 2005, a new report on the consequences of the Chernobyl accident was released by the Chernobyl Forum (2005) consisting of a number of professional organisations of the United Nations (IAEA, WHO, UNDP, FAO, UNEP, UN-OCHA and UNSCEAR) as well as the World Bank and the governments of the Russian Federation, Belarus and Ukraine. This report reflects the findings of a large team of natural scientists, economists and health specialists. One of the conclusions of the report is that in the areas with high contamination, up to 4 000 people could eventually die from radiation doses from the Chernobyl accident, most of them among the so-called "liquidators". This is significantly lower than the previously mentioned values because of the more limited area considered. Nevertheless, the report emphasises the large scale of economic and social consequences, which manifest the catastrophic dimension of the Chernobyl accident beyond what is expressed by fatality rates only.

Finally, the large differences between Chernobyl-based estimates and probabilistic plant-specific estimates for a Swiss nuclear power plant (Figure A4.3a,b) illustrate the limitations in applying past accident data to cases that are radically different in terms of technology and operating environment.

A4.3 Conclusions

The ENSAD database provides a well-founded basis for technical comparisons of severe accident risks in the energy sector. However, analyses should be complemented by a PSA approach when full chain risks are dominated by the power plant stage or when availability and applicability of historical experience is strongly limited, as is the case for OECD hydro and nuclear power plants.

Comparative analyses confirmed substantial numerical differences between the different energy chains as well as country groups. Hydropower in non-OECD countries and upstream stages within fossil energy chains are most accident-prone, whereas the natural gas chain exhibits the lowest risks among the fossil chains. When comparing country groups, energy-related accident risks are distinctly lower in the OECD countries than in other countries.

Consideration of regional differences is particularly important for the nuclear and hydro chains, where expected values for fatality rates due to severe accidents are lowest for OECD power plants.

The choice of technology for electricity production is affected by many factors, one of which may be the perceived level of associated risk. The analysis presented here indicates that, contrary to that which many people would expect, nuclear power is a very safe technology because of the exacting standards to which it is designed, operated and regulated (see Chapter 7).

References for Appendix 4

Burgherr, P., S. Hirschberg, A. Hunt and R.A. Ortiz (2004), "Severe accidents in the energy sector". *Final Report to the European Commission of the EU 5th Framework Programme "New Elements for the Assessment of External Costs from Energy Technologies" (NewExt)*, DG Research, Technological Development and Demonstration (RTD), Brussels, Belgium.

Chernobyl Forum (IAEA, UNDP, FAO, UNEP, UN-OCHA, UNSCEAR, World Bank, governments of Belarus, the Russian Federation and Ukraine) (2005), "Chernobyl's legacy: health, environmental and socio-economic impacts and recommendations to the governments of Belarus, the Russian Federation and Ukraine". *The Chernobyl Forum: 2003-2005*. Second revised version, International Atomic Energy Agency, Vienna, Austria.

Hirschberg, S., G. Spiekerman and R. Dones (1998), "Severe accidents in the energy sector – first edition". *PSI Report No. 98-16*, Paul Scherrer Institut, Villigen, Switzerland.

OECD (2008), *OECD Environmental Outlook to 2030*, OECD, Paris, France.

Appendix 5: Reactor Types and Technologies

A5.1 Reactor types

This appendix presents an overview of the main reactor types and technologies currently used around the world to generate nuclear electricity. These are primarily Generation II reactors built in the 1970s and 1980s as commercial power plants. Very few Generation I reactors, the prototypes and early commercial plants developed in the 1950s and 1960s, are still operating. A small number of Generation III/III+ plants are already operational and more are currently being built; these are described in Section 13.3.

Nuclear reactors that operate by fission are classified by neutron energy (thermal or fast), by coolant fluid (water, gas or liquid metal), by moderator type (light water, heavy water, graphite, or none in fast reactors) and by reactor generation. Reactor generations are described in Section 13.2.

Of the Generation II plants in operation today, around 80% use ordinary (light) water as both moderator and coolant. These are light water reactors (LWRs). There are two types of LWRs: pressurised water reactors (PWRs) and boiling water reactors (BWRs). Other reactors use heavy water as moderator and coolant, primarily in Canada and India; these are pressurised heavy water reactors (PHWRs). There are two types of graphite-moderated reactors, cooled either by light water (LWGRs or RMBKs) or by carbon dioxide gas (GCRs). Fast breeder reactors (FBRs) have no moderator and those operating today use liquid sodium as coolant. Table A5.1 shows the numbers and global power outputs of these reactor types (IAEA, 2008). Further details of operational reactors by country, and of reactors shutdown and under construction, are given in Appendix 1.

Table A5.1: Numbers of reactor types worldwide

Type	Number of units	Total MWe	Neutron energy	Coolant fluid	Moderator
PWR	265	243 429	Thermal	Light water	Light water
BWR	94	85 287	Thermal	Light water	Light water
PHWR	44	22 358	Thermal	Heavy water	Heavy water
LWGR	16	11 404	Thermal	Light water	Graphite
GCR	18	9 034	Thermal	CO_2	Graphite
FBR	2	690	Fast	Sodium	None
Total	**439**	**372 202**			

Source: IAEA (2008).

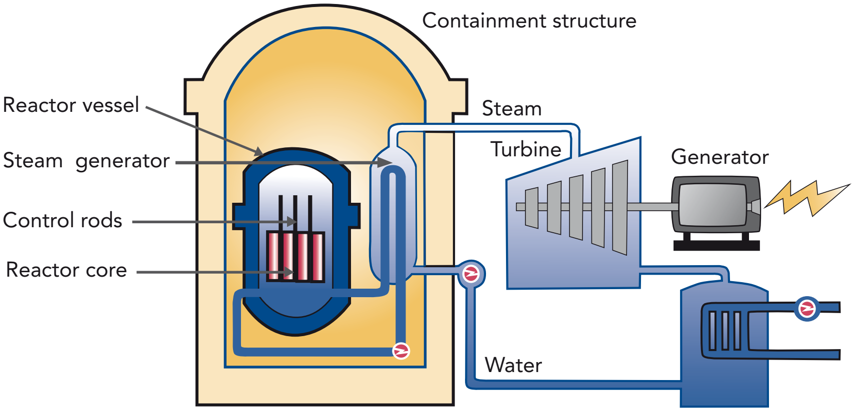
Each of the main types of commercial reactor is briefly described below. Within each basic type, there are different designs resulting from different national, manufacturer and operator requirements.

A5.2 Reactor technologies

A5.2.1 Pressurised water reactors (PWRs)

There are 265 PWRs operating worldwide, of which 150 are in France, Japan and the United States (see Appendix 1). Ordinary ("light") water is used as both coolant and moderator in these plants. The technology was originally developed for submarine propulsion. The coolant is kept at high pressure (about 15.5 MPa) to keep it liquid during operation, and is retained within a pressure boundary comprised of the reactor pressure vessel and the primary cooling system piping. The coolant is circulated using powerful pumps so that the heat is transferred from the core to boil water in a separate, secondary loop in steam generators. The steam thus produced drives the electricity-producing turbine generators. A schematic of the process is shown in Figure A5.1 (NEA, 2005).

Figure A5.1: Pressurised water reactor system



Source: NEA (2005).

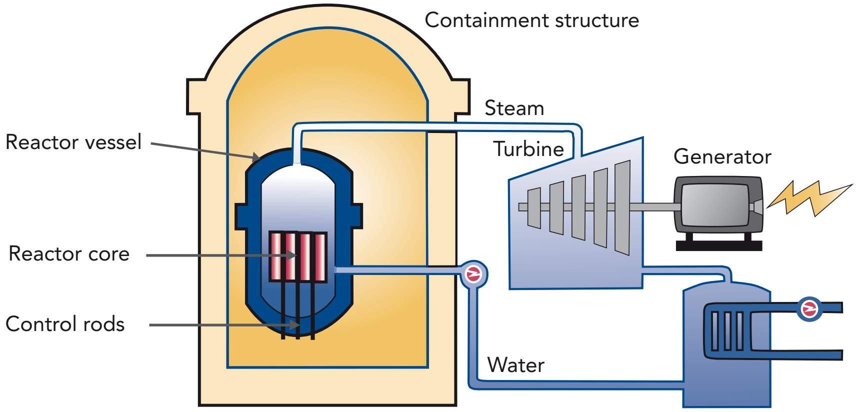
PWRs require enriched fuel, usually ceramic uranium dioxide with a melting point around 2 800°C. Fuel pellets (typically 1 cm diameter and 1.5 cm long) are placed in an alloy tube, usually made of zirconium, to make a fuel rod. A fuel assembly consists of a square array of 179 to 264 fuel rods, and 121 to 193 fuel assemblies 3.5 to 4.0 metres long are loaded into an individual reactor (Mitsubishi, 2006). The fuel assemblies form the reactor core contained within the thick steel pressure vessel. Surrounding the pressure vessel, steam generators and other primary circuit components is the containment structure, designed to protect the reactor (for example from an aircraft crash) and to prevent escape of radioactivity to the outside environment in the event of any major malfunction inside. It is a concrete and steel structure, about one metre thick.

VVERs are the pressurised water reactors developed initially by the former Soviet Union. They are currently used in the Russian Federation and other countries including Bulgaria, the Czech Republic, Finland, Hungary, the Slovak Republic and Ukraine. VVER is an abbreviation of the Russian for water-cooled, water-moderated energy reactor. Like their Western counterparts, the VVERs have been developed from early prototypes, but only the latest version – the VVER 1000 – has the massive containment structure typical of a LWR designed in the OECD countries.

A5.2.2 Boiling water reactors (BWRs)

There are 94 BWRs operating in nine countries, mostly in Japan and the United States (see Appendix 1). In a BWR, ordinary water again acts as both coolant and moderator. The coolant is kept at a lower pressure than in a PWR (about 7 MPa) allowing the coolant to boil as it transfers heat from the reactor core. The resultant steam is passed directly to the turbine generators to produce electricity without an intermediate steam generator. While the absence of a steam generator simplifies the design, as compared with PWRs, the electricity-generating turbine becomes contaminated, to a low level, with radioactivity. A schematic of the process is shown in Figure A5.2 (NEA, 2005). Like PWRs, BWRs use enriched fuel and have a thick steel pressure vessel and massive containment structure.

Figure A5.2: Boiling water reactor system



Source: NEA (2005).

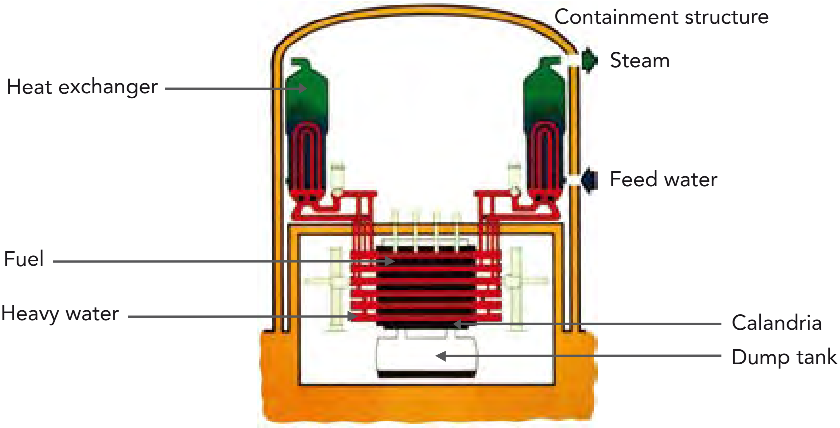
Both PWRs and BWRs have to be shut down to refuel, because the pressure vessel has to be opened. Refuelling is done every one or two years, when between a quarter and a third of the fuel assemblies are replaced with new ones.

A5.2.3 Pressurised heavy water reactors (PHWRs)

There are 44 PHWRs operating worldwide in seven countries, of which 18 are in Canada, and 15 in India (see Appendix 1). CANDU (short for Canadian deuterium uranium) reactors are PHWR designs. Generation II PHWRs use heavy water (D_2O, water formed with deuterium, a heavy isotope of hydrogen), as both coolant and moderator. The heavy water moderator allows natural uranium to be used as the fuel, thereby eliminating the need for, and the cost of, enriching the uranium. On the other hand, the production of heavy water requires a dedicated plant to separate the D_2O from ordinary water, raising the concentration of D_2O from its natural concentration of less than 0.1% to the 99% used in a PHWR.

Figure A5.3 shows a schematic of a PHWR (British Energy, 2006). This type of reactor does not have a large pressure vessel like a PWR or BWR. Instead, pressurised heavy water is pumped through a large number of horizontal fuel tubes (the calandria) and heated by the nuclear reaction before being passed on to a steam generator. As in a PWR, the coolant is passed through a steam generator to boil ordinary water in a secondary loop. An advantage of the PHWR design is that the fuel is contained in a series of pressure tubes rather than in a single pressure vessel, which allows refuelling to take place during operation, whereas PWRs and BWRs must be shut down to refuel. This feature allows high availability but also increases the complexity of the design.

Figure A5.3: Pressurised heavy water reactor system



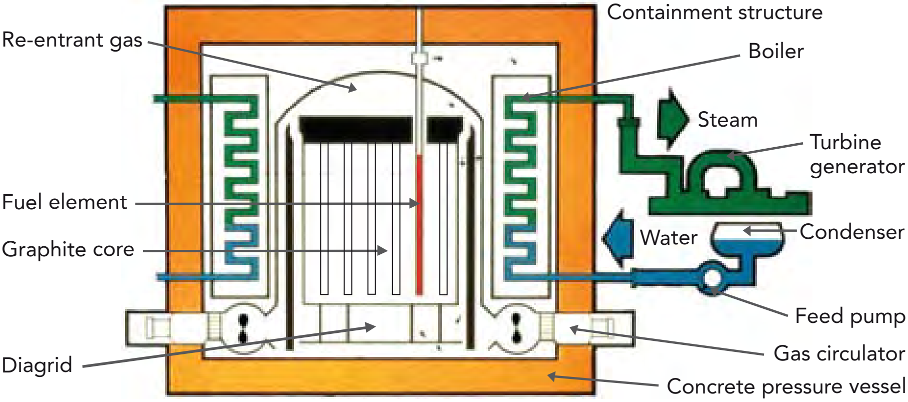
Source: British Energy (2006).

A5.2.4 Gas-cooled reactors (GCRs)

There are 18 gas-cooled reactors in operation, all in the United Kingdom. There are two types, Magnox reactors (named after the magnesium alloy used to clad the natural uranium metal fuel elements), of which only four of the original fleet of 26 remain operational, and advanced gas-cooled reactors (AGRs). The AGRs have a gas outlet temperature of around 600°C, which allows thermal efficiencies of about 42% compared with typically 33-36% available from a water reactor. Both use carbon dioxide as the coolant and graphite as the moderator. The gas coolant transfers heat from the reactor core to a set of steam generators that produce steam to drive the electricity-producing turbines. The Magnox reactors use natural uranium in metallic form as fuel and the AGRs use enriched uranium as uranium dioxide, like the LWRs. Like PHWRs, these GCR designs can be refuelled on-load.

Figure A5.4 shows a schematic of an AGR (British Energy, 2006). Both the AGRs and the still operating Magnox reactors have pre-stressed concrete pressure vessels several metres thick that contain the reactor core, the steam generators and the gas circulators.

Figure A5.4: Advanced gas-cooled reactor system

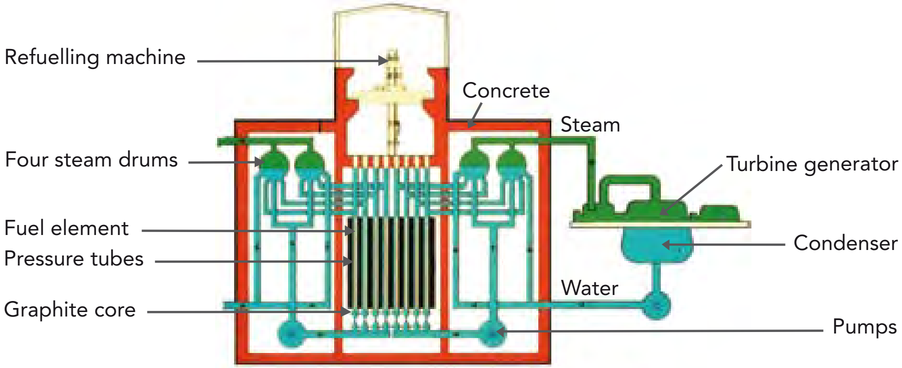


Source: British Energy (2006).

A5.2.5 Light water graphite-moderated reactors (LWGRs or RBMKs)

There are 16 LWGRs, or RBMKs, in operation, 15 in the Russian Federation, and one in Lithuania due to close in 2009. RBMK is a Russian acronym meaning high power channel reactor. Ordinary water is used as the coolant and graphite as the moderator. Pressure tubes containing the fuel run through the graphite core; water is pumped through these tubes. As with a BWR, the coolant boils as it passes through the reactor and the resultant steam is passed directly on to turbine generators. Like the PHWR design, RBMKs can be refuelled while at power. Pressure tube designs allow reactors to be built in areas where it may not be possible to fabricate the large pressure vessels required for a LWR. Figure A5.5 shows a schematic of the RBMK or LWGR system (British Energy, 2006).

Figure A5.5: Light water graphite-moderated reactor system



Source: British Energy (2006).

The RBMK is an early design and does not have some of the inherent safety features of reactors built elsewhere in the world. Unlike other reactor types, power output from the RBMK increases when cooling water is lost. The physics of RBMK reactors is very complex and it was this complexity, plus numerous breaches of safety procedures, which led to the major accident at Chernobyl in 1986. After the accident, extensive safety improvement programmes have been implemented.

A5.2.6 Fast breeder reactors (FBRs)

The reactor types described above are all thermal reactors, where most of the fission is caused by neutrons slowed down by a moderator (water or graphite) to near-thermal energy. In fast reactors, fission is caused by neutrons that have not been slowed down, and so are "fast". On average, FBRs create more neutrons per fission than thermal reactors, so there is an excess of neutrons over the number needed to maintain the chain reaction. These additional neutrons can be used to produce more fuel than the reactor consumes, hence the name breeder reactor. FBRs can potentially increase available world nuclear fuel resources up to sixty-fold and are thus a key element in the sustainability of nuclear energy in the long term. Around 20 fast reactors have been built and operated in a number of countries, though in May 2008 only two were in operation, in France and the Russian Federation (Appendix 1). China, India and Japan are developing them.

A fast reactor core, since it has no moderator, is very compact; the 250 MWe prototype fast reactor in the United Kingdom had a core the size of a large dustbin (British Energy, 2006). They require plutonium fuel or uranium fuel that has around four times the enrichment of typical LWRs. These reactors have usually been cooled by liquid sodium, which is very efficient at removing heat. Sodium can be heated to 500-600°C without being pressurised, so the reactor does not need a pressure vessel. Fast reactors can maintain cooling by natural convection should the cooling pumps fail.

References for Appendix 5

British Energy (2006), "Different types of nuclear power", British Energy Group plc., www.british-energy.com/documents/Different_types_of_nuclear_power.pdf.

IAEA (2008), Power Reactor Information System database (PRIS), International Atomic Energy Agency, www.iaea.org/programmes/a2/.

Mitsubishi (2006), "PWR Fuel Assembly", Mitsubishi Nuclear Fuel Co. Ltd., www.mnf.co.jp/pages2/pwr2.htm.

NEA (2005), *Nuclear Energy Today*, Nuclear Energy Agency, OECD, Paris, France.

Appendix 6: Abbreviations, Acronyms and Units

Abbreviations and Acronyms

A

ABB	Asea Brown Boveri
ABR	advanced burner reactor
ABWR	advanced boiling water reactor
ADS	accelerator-driven system
AGR	advanced gas-cooled reactor
ALARA	as low as reasonably achievable
APWR	advanced pressurised water reactor
ATR	advanced thermal reactor

B

BNFL	British Nuclear Fuel Limited
BWR	boiling water reactor

C

CANDU	Canada Deuterium Uranium
CCS	carbon capture and storage
CDM	Clean Development Mechanism
C-E	combustion engineering
CEA	Commissariat à l'énergie atomique (France)
CER	certified emission reduction
CNNC	China National Nuclear Corporation
CNRA	Committee on Nuclear Regulatory Activities
COL	combined construction and operating licence
COP	Conference of the Parties
CPPNM	Convention on the Physical Protection of Nuclear Material
CRDM	control rod drive mechanism
CTBT	Comprehensive Nuclear Test Ban Treaty

D

DOE	Department of Energy (United States)
DTI	Department of Trade and Industry (United Kingdom)

E

EC	European Commission
EDF	Électricité de France
EIA	Energy Information Administration
EIA	environmental impact assessment
ENEN	European Nuclear Engineering Network
EPR	European pressurised reactor
ESBWR	economic and simplified boiling water reactor
EU	European Union
EURATOM	European Atomic Energy Community (EAEC or Euratom)

F

FBNR	fast bed nuclear reactor
FBR	fast breeder reactor

G

GCR	gas-cooled reactor
GDP	gross domestic product
Gen-III	generation III reactor
Gen-III+	generation III+ reactor
Gen-IV	generation IV reactor
GEH	General Electric – Hitachi Nuclear Energy
GFR	gas-cooled fast reactor
GHG	greenhouse gases
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership

H

HDI	Human Development Index
HEU	highly enriched uranium
HLW	high-level waste
HTGR	high-temperature gas-cooled reactor
HTR	high-temperature reactor

I

IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection

IDC	interest during construction
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
ILW	intermediate-level waste
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
INS	Innovative Nuclear Energy Systems
IPCC	Intergovernmental Panel on Climate Change
ISL	*in situ* leaching
ITER	international thermonuclear experimental reactor

K

KBS-3	Kärnbränslecykelns slutsteg (Swedish concept for deep disposal of spent nuclear fuel)

L

LEU	low-enriched uranium
LFR	lead-cooled fast reactor
LILW	low- and intermediate-level waste
LLW	low-level waste
LLW-LL	low-level waste long-lived
LLW-SL	low-level waste short-lived
LPG	liquefied petroleum gas
LWGR	light water-cooled graphite-moderated reactor
LWR	light water reactor

M

MDEP	Multinational Design Evaluation Programme
MIT	Massachusetts Institute of Technology
MNA	multilateral nuclear approaches
MOX	mixed oxide (fuel)
MSR	molten salt reactor

N

NEA	Nuclear Energy Agency
NEPTUNO	Nuclear European Platform for Training and University Organisations
NGO	non-governmental organisation
NNWS	non-nuclear weapon state

NORM	naturally occurring radioactive material
NPP	nuclear power plant
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRC	Nuclear Regulatory Commission (United States)
NSG	Nuclear Suppliers Group
NWFZ	nuclear weapon-free zone
NWS	nuclear weapon state

O

O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic

P

PBMR	pebble bed modular reactor
PHWR	pressurised heavy water reactor
PM	particulate matter
PRIS	Power Reactor Information System
PSA	probabilistic safety assessment
PSR	periodic safety review
PV	photovoltaic
PWR	pressurised water reactor

Q

QA	quality assurance

R

RAR	reasonably assured resources
R&D	research and development
RBMK	Reaktor Bolshoy Moshnosty Kanalny (high power channel-type reactor)

S

SCWR	supercritical-water-cooled reactor
SFR	sodium-cooled fast reactor
SMR	small or medium reactor
SNF	spent nuclear fuel

SRES	Special Report on Emissions Scenarios

T

THTR	thorium high-temperature reactor
TPES	total primary energy supply
TRU	transuranic

U

UCTE	Union for the Co-ordination of Transmission of Electricity
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

V

VHTR	very high-temperature reactor
VLLW	very low-level waste
VVER	Vodo Vodianoy Energetichesky Reaktor (water-cooled, water-moderated power reactor)

W

WANO	World Association of Nuclear Operators
WNA	World Nuclear Association

Units

billion	1000 million
G	Giga = 10^9
k	kilo = 10^3
M	Mega = 10^6
m	milli = 10^{-3}
T	Tera = 10^{12}

GWyr	gigawatt x year
GW/yr	gigawatt per year
GWd/t	gigawatt-days per tonne
kWh	kilowatt-hour
man-Sv	man sievert

MPa	megapascal
MSWU	million separative work units
Mtoe	million tonnes of oil equivalent
MWe	megawatt electric
MWth	megawatt thermal
ppm	parts per million
t	tonne
t/yr	tonne per year
TBq	terabecquerel
tHM	tonne of heavy metal
tU	tonne of uranium

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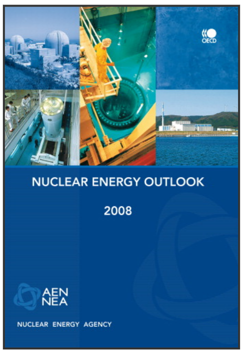

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