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Uranium and Nuclear Power

by

Stewart Smith

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EXECUTIVE SUMMARY

Worldwide demand for energy will be more than 50% greater by 2030 if governments continue their present energy policies. Australia is a net exporter of energy, and is well placed to meet this demand. Australia has significant reserves of coal, and has 36% of the world's low cost uranium reserves. This paper focuses on the role of uranium and nuclear power to meet the world's rising demand for energy.

In 2004, uranium was produced in 19 countries. Just two countries, Australia and Canada, accounted for 51% of world production. Australia has the largest reserves of low cost uranium in the world. At the end of 2004, a total of 440 commercial nuclear reactors were operating, requiring about 67,320 tonnes of uranium. Worldwide, identified resources of uranium are sufficient for some 85 years at current usage rates. Advanced reactor technologies involving the recycling of used fuel could extend nuclear resources for thousands of years.

The process of nuclear fission in elements such as uranium produces heat. In a nuclear reactor, this heat is used to generate steam, which drives a generator to produce electricity. Nuclear fission is an extremely potent source of energy. The energy released by the fission of one kilogram of uranium in a typical reactor is equivalent to that released by about 22,000 kg of coal.

Uranium ore is extracted from the earth in much the same manner as other minerals. The ore is then milled to produce uranium oxide, or 'yellow cake'. This is the product that Australia exports. However, uranium oxide cannot be simply fed into a nuclear power station like coal to produce steam. It must be first converted into uranium hexafluoride, enriched, and fabricated into fuel rods. There are many different types of nuclear reactors. The paper explains their operation and differences. More recently, advanced nuclear reactors are being developed with commissioning dates from 2015 expected.

Nuclear waste is often cited as the most important unresolved issue concerning nuclear energy. It is claimed that there is a broad scientific consensus that high level radioactive waste can be safely stored in geological repositories. However, critics of this view note the long time frames involved and that geological landforms change over time.

The economics of nuclear power have been well studied. It can be concluded that in a liberalised electricity market, new nuclear power stations are unlikely to be built without some form of government assistance. This is due to their high capital cost, uncertain construction costs, and the fact that private investors are likely to require a substantial risk premium over coal and gas fired power stations to finance at least the first few nuclear plants.

The Commonwealth Government has commissioned two separate reviews into the role of the nuclear fuel cycle in Australia. In contrast, the NSW Government has stated that legislation introduced in 1986 prohibiting uranium mining or the construction of a nuclear power station will remain.

1.0 INTRODUCTION

Australia is a net exporter of energy, with significant reserves of coal, natural gas and uranium. These reserves are likely to be increasingly in demand. If governments across the world continue current policies the world's energy needs will be more than 50% higher in 2030 than today.[1]

This paper focuses on the role of uranium and nuclear power to meet this rising demand for energy. However, it is impossible to consider one form of energy without reference to others, and the first section of this paper introduces the world context of energy supply and demand.

2.0 THE INTERNATIONAL CONTEXT OF ENERGY SUPPLY AND DEMAND

Worldwide, excluding renewables, there are four main types of energy: oil; coal; natural gas; and uranium. Each of these forms of energy have their own units of measurement (eg, barrels of oil, m^3 of gas), so it is useful to convert them all into an equivalent unit measure called millions of tonnes of oil equivalent (Mtoe).

The table below shows the world primary energy consumption in 2004 in Mtoe. Worldwide, in 2004 9,590 Mtoe were consumed. Of individual countries, the United States was the largest energy user, consuming 23.7 % of world energy in 2004. Next largest was China (13.7 %), followed by the Russian Federation (6.6 %). Australia consumed 115 Mtoe, 1.2 % of world consumption.

World Primary Energy Consumption, 2004

	Oil	**Coal**	**Natural Gas**	**Uranium**	**Total**
	Mtoe	Mtoe	Mtoe	Mtoe	Mtoe
Australia	39	54	22	0	115
Canada	100	31	81	21	231
France	94	13	40	101	248
Germany	124	86	77	38	324
Italy	90	17	66	0	173
Spain	78	21	25	14	138
Japan	242	121	65	65	492
Korea, Rep. Of	105	53	28	30	216
United Kingdom	81	38	88	18	225
United States	938	564	582	188	2,272
Other OECD	365	166	191	55	777
Brazil	84	11	17	3	115

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[1] International Energy Agency, *World Energy Outlook 2005. Middle East and North Africa Insights*. See: http://www.iea.org/Textbase/npsum/WEO2005SUM.pdf, Accessed June 2006.

Iran	73	1	78	0	153
China	309	957	35	11	1,312
India	119	205	29	4	357
Russian Federation	129	106	362	32	629
Other	800	335	634	45	1,814
World	3,767	2,778	2,420	624	9,590

Source: Commonwealth of Australia, 2005, *Energy in Australia 2005*. ABARE, at 9.

In contrast to consumption, the table below shows world energy production for 2004. Again, the United States is the world's greatest energy producer, but has an energy deficit of 876 Mtoe. China consumes slightly more energy than it produces (deficit of 102 Mtoe), whilst the Russian Federation is a significant energy exporter – 525 Mtoe. In the Asia Pacific region, Japan and Korea are heavily dependent on imported energy, whilst Australia exported 240 Mtoe in 2004. Of the Middle Eastern countries, Saudi Arabia had the largest energy exports of 564 Mtoe.

World Primary Energy Production, 2004

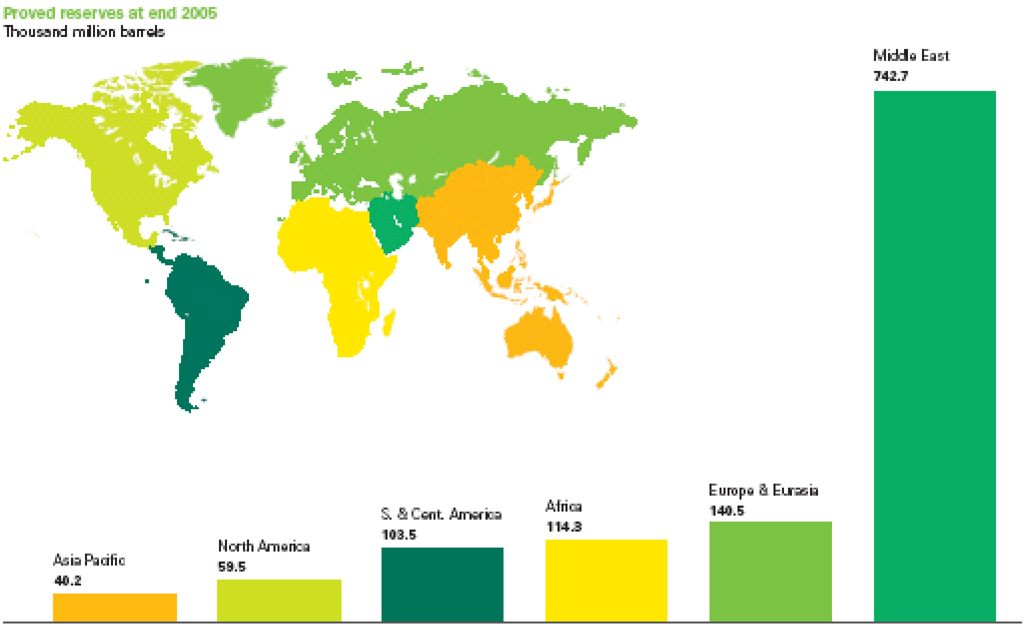
	Oil	Coal	Natural Gas	Uranium[a]	Total
	Mtoe	Mtoe	Mtoe	Mtoe	Mtoe
Australia	23	199	32	101	355
Canada	148	35	165	138	485
Mexico	191	4	33	0	228
Norway	150	0	71	0	221
United Kingdom	95	15	86	0	197
United States	330	567	489	10	1,396
Other OECD	41	186	114	2	342
China	175	990	37	9	1,210
Indonesia	55	81	66	0	203
India	38	189	27	3	256
Iran	203	0	77	0	280
Saudi Arabia	506	0	58	0	564
United Arab Emirates	126	0	41	0	167
Other Middle East	352	1	76	0	429
Russian Federation	459	128	530	38	1,155
Nigeria	122	0	19	0	141
South Africa	0	137	2	10	149
Venezuela	154	7	25	0	185
Other	702	193	477	158	1,530
World	3,868	2,732	2,422	468	9,491

a: for 2003
Source: Commonwealth of Australia, 2005, *Energy in Australia 2005*. ABARE, at 9.

Whilst the above tables provide snapshots of energy production and consumption in 2004, it is also useful to identify what energy resources are located where around the globe. In regard to fossil fuels, the most authoritive source of information is from an annual series released by the company BP. For uranium, the most authoritive source is the 'Red Book', published jointly by the OECD Nuclear Energy Agency and the International Atomic Energy Agency.

2.1 Worldwide Reserves of Oil

The proven world oil reserves at the end of 2005 were 1,200.7 thousand million barrels. Proven oil reserves is defined as those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions. Another measure is known as the reserves to production ration (R/P). This is defined as the reserves remaining at the end of the year divided by the production in that year. The result is the length of time that those remaining reserves would last if production were to continue at that level. At the end of 2005, the world reserve / production ratio was 40.6 years.[2]



Source: BP, *Quantifying Energy. BP Statistical Review of World Energy*, June 2006, at 7.

As can be seen from the figure above, world distribution of proven oil reserves is heavily weighted to the Middle East (61.9 %). OPEC members control 75.2% of total reserves. The Asia Pacific region has the least, with just 3.4% of total proven reserves. At the end of 2004, Australia had proven reserves of 4.0 thousand million barrels of oil, with a reserve /

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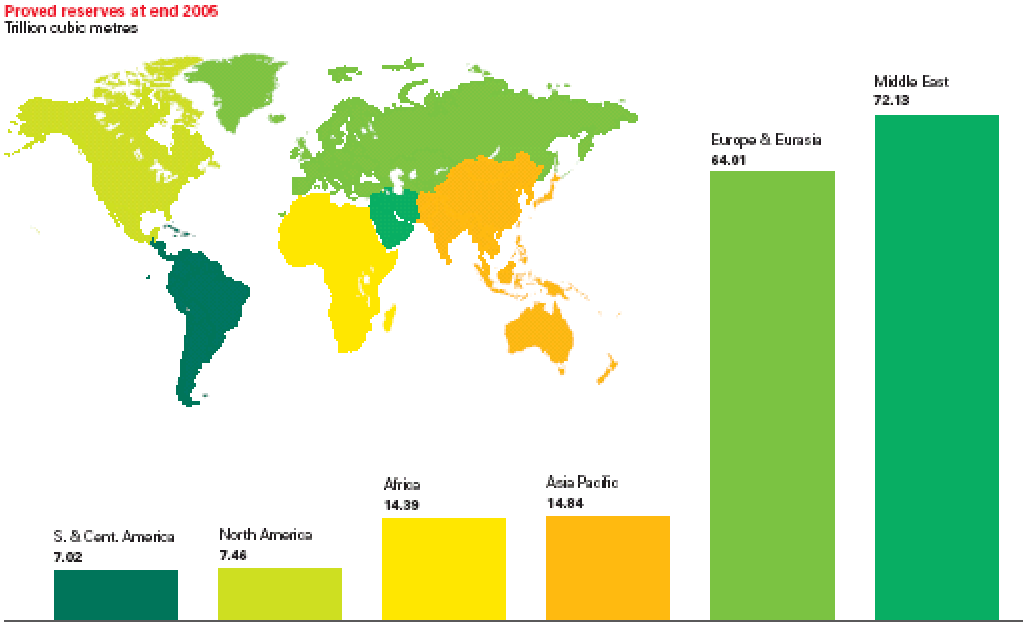
[2] BP, *Quantifying energy. BP Statistical Review of World Energy*, June 2005, at 6.

production ratio of 20 years.[3]

2.2 Worldwide Reserves of Natural Gas

Total world proven reserves of natural gas at the end of 2005 were 179.83 trillion cubic metres, with a reserve / production ratio of 65.1 years. The world distribution of natural gas resources is shown below. The impression is often conveyed in the media that Australia has abundant reserves of natural gas. Whilst this may be so, with proven reserves of 2.52 million cubic metres with a reserve / production ratio of 67.9 years, Australia has only 1.4% of the world proven reserves of natural gas as at the end of 2005. Again, the Middle East has the largest reserves of natural gas (40.1% of total), closely followed by Europe and Eurasia with 35.6% of the world total.[4]

Proven Reserves of Natural Gas at end of 2004



Source: BP, *Quantifying Energy. BP Statistical Review of World Energy*, June 2006, at 23.

2.3 Worldwide Reserves of Coal

World proven coal reserves at the end of 2005 were 909,064 million tonnes, with a reserve / production ratio of 155 years. The Asia Pacific region has the greatest reserves (32.7%) followed by Europe and Eurasia (31.6%). Australian proven coal reserves at the end of 2005 were 78,500 million tonnes, or 8.6 % of the world's reserves. Australia had a reserve / production ratio of 213 years.[5]

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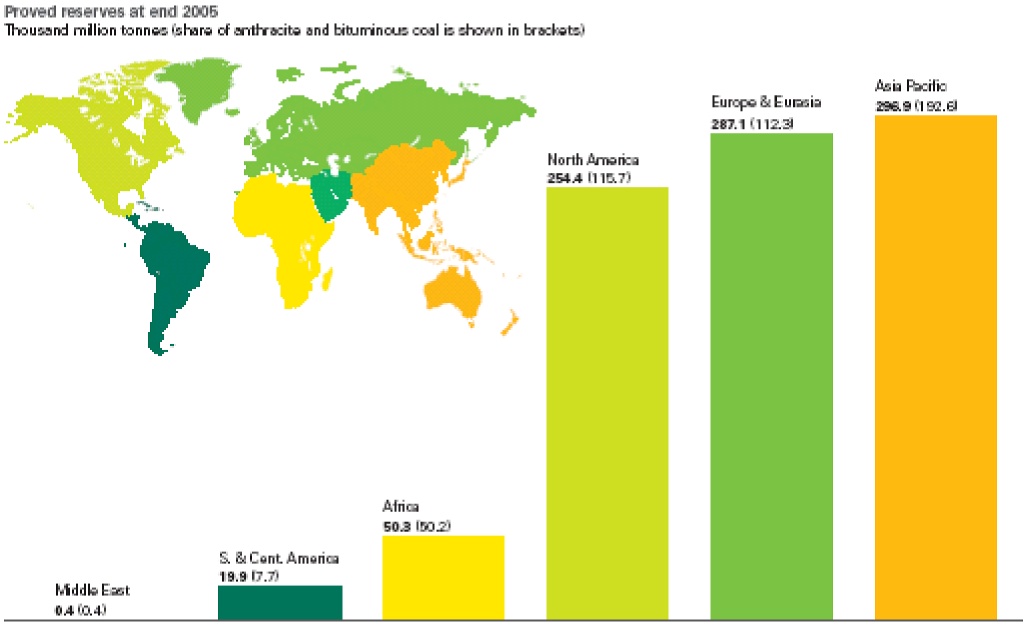
[3] BP, *Quantifying energy. BP Statistical Review of World Energy*, June 2005, at 6.

[4] BP, *Quantifying energy. BP Statistical Review of World Energy*, June 2005, at 22.

[5] BP, *Quantifying energy. BP Statistical Review of World Energy*, June 2005, at 32.



Source: BP, *Quantifying Energy. BP Statistical Review of World Energy*, June 2006, at 33.

2.4 Worldwide Reserves of Uranium

As noted, the most authoritive source of information is from the 'Red Book', published jointly by the OECD Nuclear Energy Agency and the International Atomic Energy Agency. The 21st edition, *Uranium 2005 – Resources, Production and Demand*, provides a statistical profile of the world uranium industry as of 1 January 2005. This section of the Paper is adapted from this publication.

Uranium resources are categorized according to two criteria: the cost of extraction in US dollars; and whether a resource is Reasonably Assured, Inferred or Undiscovered. The definition of these terms is as follows:

- Reasonably Assured Resources refers to uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities which could be recovered within the given production cost ranges with currently proven mining and processing technology, can be specified;
- Inferred Resources refers to uranium that is inferred to exist based on direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits, and knowledge of the deposit's characteristics are considered to be inadequate to classify the resource as Reasonably Assured.
- Undiscovered resources are divided into two groups, Prognosticated resources and Speculative resources. Prognosticated resources are those expected to occur in well-defined geological trends of known deposits. Speculative resources are those thought to exist in geologically favourable, yet unexplored areas. Worldwide, the reporting of Speculative resources is incomplete. Prognosticated reserves are estimated to total 2.5 million tU recoverable <USD 130/kgU, and Total Undiscovered Resources in 2005 amounted to about 10 million tonnes U.

Reasonably Assured and Inferred Resources together are termed Total Identified Resource.

As shown on the tables on the following pages, world wide the Total Identified Resource of uranium <USD 40/kgU was 2,746,380 tonnes. In the cheapest category, Australia held 36% (701,000 tonnes) of the world's reasonably assured resources. As at January 2004, Australia had a reserve to production ratio of 87 years.[6]

The world wide Total Identified Resource of the combined three price categories (<USD 40, <80, <130 kgU) was 11,293,614 tonnes. Of this, Australian resources were 3,261,000 tonnes (28%).

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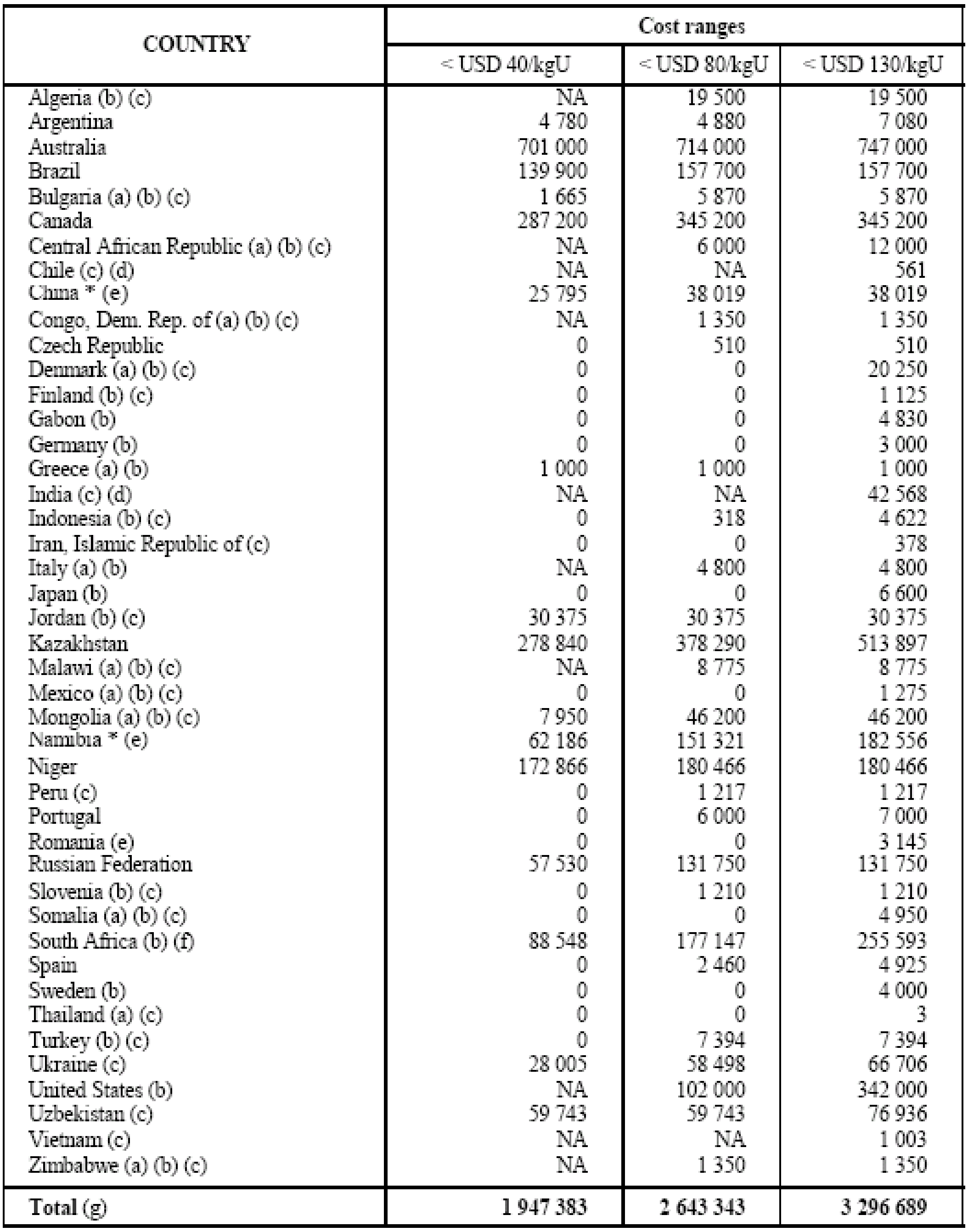
[6] Commonwealth of Australia, *Energy in Australia 2005*, ABARE, 2005, at 3.

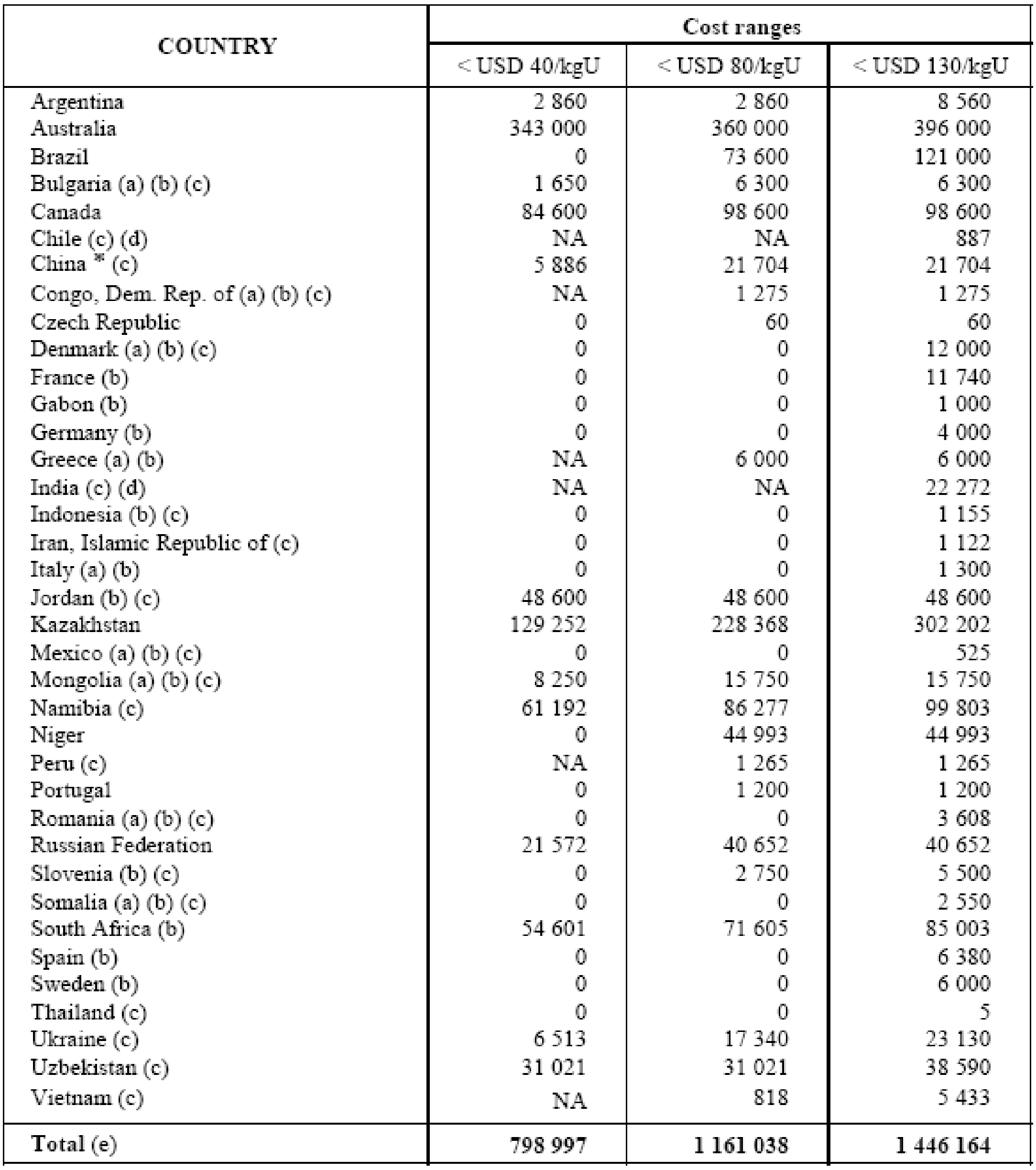
Reasonably Assured Resources of Uranium
(Recoverable resources as of 1 January 2005, tonnes Uranium)



COUNTRY	Cost ranges		
	< USD 40/kgU	< USD 80/kgU	< USD 130/kgU
Algeria (b) (c)	NA	19 500	19 500
Argentina	4 780	4 880	7 080
Australia	701 000	714 000	747 000
Brazil	139 900	157 700	157 700
Bulgaria (a) (b) (c)	1 665	5 870	5 870
Canada	287 200	345 200	345 200
Central African Republic (a) (b) (c)	NA	6 000	12 000
Chile (c) (d)	NA	NA	561
China * (e)	25 795	38 019	38 019
Congo, Dem. Rep. of (a) (b) (c)	NA	1 350	1 350
Czech Republic	0	510	510
Denmark (a) (b) (c)	0	0	20 250
Finland (b) (c)	0	0	1 125
Gabon (b)	0	0	4 830
Germany (b)	0	0	3 000
Greece (a) (b)	1 000	1 000	1 000
India (c) (d)	NA	NA	42 568
Indonesia (b) (c)	0	318	4 622
Iran, Islamic Republic of (c)	0	0	378
Italy (a) (b)	NA	4 800	4 800
Japan (b)	0	0	6 600
Jordan (b) (c)	30 375	30 375	30 375
Kazakhstan	278 840	378 290	513 897
Malawi (a) (b) (c)	NA	8 775	8 775
Mexico (a) (b) (c)	0	0	1 275
Mongolia (a) (b) (c)	7 950	46 200	46 200
Namibia * (e)	62 186	151 321	182 556
Niger	172 866	180 466	180 466
Peru (c)	0	1 217	1 217
Portugal	0	6 000	7 000
Romania (e)	0	0	3 145
Russian Federation	57 530	131 750	131 750
Slovenia (b) (c)	0	1 210	1 210
Somalia (a) (b) (c)	0	0	4 950
South Africa (b) (f)	88 548	177 147	255 593
Spain	0	2 460	4 925
Sweden (b)	0	0	4 000
Thailand (a) (c)	0	0	3
Turkey (b) (c)	0	7 394	7 394
Ukraine (c)	28 005	58 498	66 706
United States (b)	NA	102 000	342 000
Uzbekistan (c)	59 743	59 743	76 936
Vietnam (c)	NA	NA	1 003
Zimbabwe (a) (b) (c)	NA	1 350	1 350
Total (g)	**1 947 383**	**2 643 343**	**3 296 689**

Source: OECD Nuclear Energy Agency and Atomic Energy Agency, *Uranium 2005: Resources, Production and Demand*, 2006, at 15.

Inferred Resources of Uranium
(Recoverable resources as of 1 January 2005, tonnes Uranium)

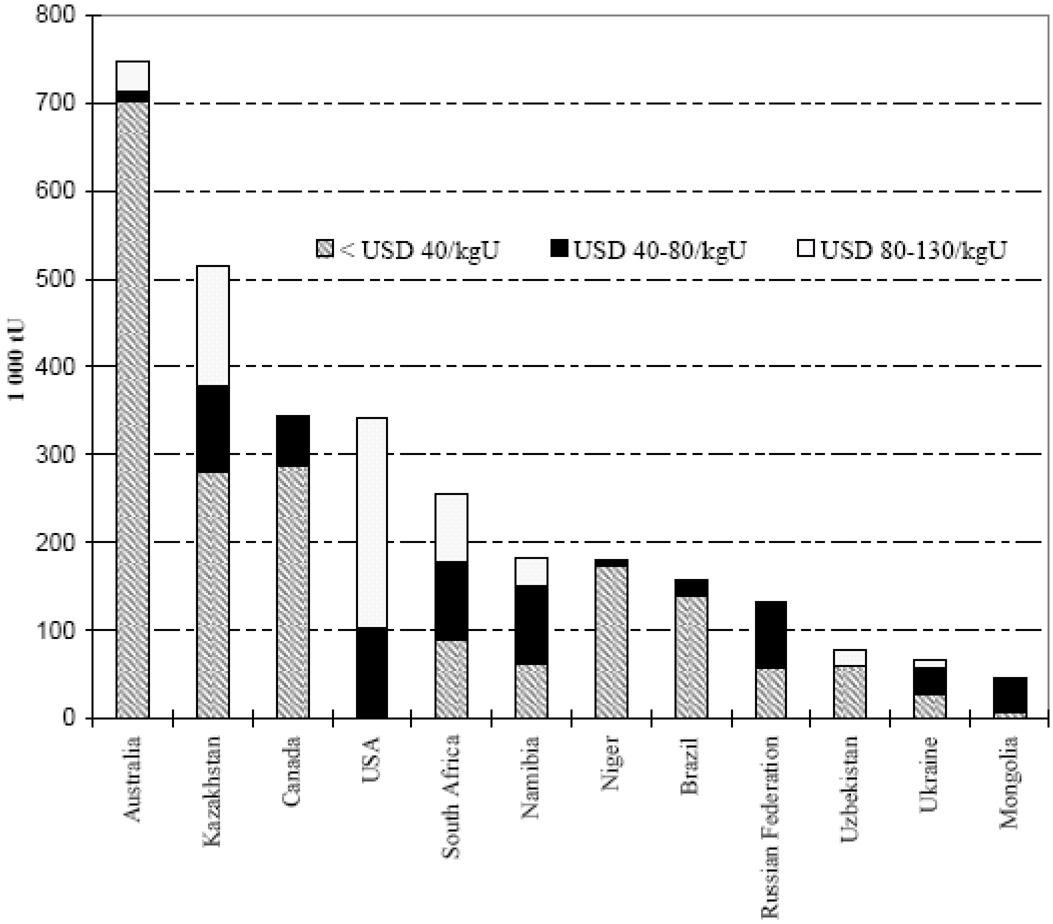


COUNTRY	Cost ranges		
	< USD 40/kgU	< USD 80/kgU	< USD 130/kgU
Argentina	2 860	2 860	8 560
Australia	343 000	360 000	396 000
Brazil	0	73 600	121 000
Bulgaria (a) (b) (c)	1 650	6 300	6 300
Canada	84 600	98 600	98 600
Chile (c) (d)	NA	NA	887
China * (c)	5 886	21 704	21 704
Congo, Dem. Rep. of (a) (b) (c)	NA	1 275	1 275
Czech Republic	0	60	60
Denmark (a) (b) (c)	0	0	12 000
France (b)	0	0	11 740
Gabon (b)	0	0	1 000
Germany (b)	0	0	4 000
Greece (a) (b)	NA	6 000	6 000
India (c) (d)	NA	NA	22 272
Indonesia (b) (c)	0	0	1 155
Iran, Islamic Republic of (c)	0	0	1 122
Italy (a) (b)	0	0	1 300
Jordan (b) (c)	48 600	48 600	48 600
Kazakhstan	129 252	228 368	302 202
Mexico (a) (b) (c)	0	0	525
Mongolia (a) (b) (c)	8 250	15 750	15 750
Namibia (c)	61 192	86 277	99 803
Niger	0	44 993	44 993
Peru (c)	NA	1 265	1 265
Portugal	0	1 200	1 200
Romania (a) (b) (c)	0	0	3 608
Russian Federation	21 572	40 652	40 652
Slovenia (b) (c)	0	2 750	5 500
Somalia (a) (b) (c)	0	0	2 550
South Africa (b)	54 601	71 605	85 003
Spain (b)	0	0	6 380
Sweden (b)	0	0	6 000
Thailand (c)	0	0	5
Ukraine (c)	6 513	17 340	23 130
Uzbekistan (c)	31 021	31 021	38 590
Vietnam (c)	NA	818	5 433
Total (e)	**798 997**	**1 161 038**	**1 446 164**

Source: OECD Nuclear Energy Agency and Atomic Energy Agency, *Uranium 2005: Resources, Production and Demand*, 2006, at 16.

As can be seen from the figure over the page, of countries with major uranium resources Australia has the largest resource in all price categories for reasonably assured resources. Canada has less than half the Australian resources, yet is the largest producer of uranium in the world.

Distribution of Reasonably Assured Resources among Countries with Major Resources



Source: OECD Nuclear Energy Agency and Atomic Energy Agency, *Uranium 2005: Resources, Production and Demand*, 2006, at 18.

In 2004, uranium was produced in 19 different countries. Three of the 19 countries (France, Germany and Hungary) only produce uranium as a consequence of mine remediation efforts. Just two countries, Canada and Australia, accounted for 51% of world production in 2004 and just seven countries, Canada (29%), Australia (22%), Kazakhstan (9%), Russian Federation (8%), Niger (8%), Namibia (8%) and Uzbekistan (5%), accounted for about 89% of world production in 2004.

World uranium production increased by almost 11% from 36,050 tU in 2002 to 40,263 tU in 2004. In 2005, it is estimated that uranium production will progress further to reach 41,250 tU, with the largest increases (>10%) anticipated to occur in Kazakhstan and Uzbekistan.

Uranium also exists in what are referred to as unconventional resources. These are uranium resources that occurs at very low grades or can only be recovered as a minor by-product. This includes uranium resources of about 22 million tones that occur in phosphate deposits. The technology to do this is mature, but high recovery costs limit their utilization.

Thirty-one countries currently consume uranium in commercial nuclear power plants creating an uneven distribution between producing and consuming countries. In 2004, only Canada and South Africa produced sufficient uranium to meet domestic requirements. All others must use secondary sources or import uranium and, as a result, the international trade in uranium is a necessary and established aspect of the uranium market. Secondary sources of uranium include: excess commercial inventories; the expected delivery of low enriched uranium derived from highly enriched uranium warheads; re-enrichment of depleted uranium tails; and spent fuel reprocessing.

At the end of 2004, worldwide a total of 440 commercial nuclear reactors were operating with a net generating capacity of about 369 Gwe, requiring about 67,320 tU. By the year 2025, world nuclear capacity is projected to grow to between about 449 GWe net in the low demand case and 533 GWe net in the high demand case. Accordingly, world reactor-related uranium requirements are projected to rise to between about 82,275 tU and 100,760 tU by 2025.

Significant regional variation exists within these broad projections. Nuclear energy capacity and resultant uranium requirements are expected to grow significantly in the East Asia region (between 90% to over 115% in the low and high cases, respectively) and in the Central, Eastern and South East Europe region (between 34 and 53%). Nuclear capacity and requirements are expected to increase slightly in North America (between 4 and 27%), but decline in Western Europe (between 16 and 26%) as plans to phase out nuclear energy are implemented. However, there are great uncertainties in these projections as there is ongoing debate on the role that nuclear energy will play in meeting future energy requirements.

At the end of 2004, world uranium production (40,263 tU) provided about 60% of world reactor requirements (67,450 tU), with the remainder being met by secondary sources. Uranium production capabilities including existing, committed, planned and prospective production centres supported by Total Identified Resources recoverable at a cost of <USD 80/kgU could satisfy projected world uranium requirements by 2010. However, this would require all expansions and mine openings to proceed as planned and production to be maintained at full capability at all operations. Secondary sources will continue to be necessary to ensure demand is met given challenges associated with achieving full production capability.

As shown in the Table over the page, identified resources of uranium are sufficient for some 85 years at current usage rates. There are also considerable unconventional resources of uranium, and these could considerably lengthen the time that nuclear energy could meet demand. As explained later in this paper, in the longer term the use of advanced reactor technologies involving the recycling of fuel could extend nuclear resources for thousands of years.

The Effect of Changes in Nuclear Technology on Uranium Consumption Rates

Reactor / Fuel Cycle	Years of 2004 world nuclear electricity generation with Identified Resources	Years of 2004 world nuclear electricity generation with total conventional resources[a]	Years of 2004 world nuclear electricity generation with total conventional resources and phosphates
Current Fuel Cycle (Light Water Reactor, once – through)	85	270	675
Pure Fast Reactor Fuel Cycle with Recycling	2,570	8,015	19,930

(a) Total conventional resources includes all cost categories of Reasonably Assured, Inferred, Prognosticated and Speculative resources.

2.5 World Energy Sources - Conclusion

Over the 30 year period 1971 to 2001, the world's primary energy supply increased by 84%, reaching just over 10,000 Mtoe. This equates to a compound growth of about 2.1% per annum, compared to world population growth of 1.6% and gross domestic product of 3% over the same period.

In 1973, oil was by far the largest component in total primary energy supply, 45.1%. This share had fallen to 35% in 2001. Over the same time period, the share of coal dropped slightly, from around 25% to just over 23% in 2001. The share of natural gas increased significantly from 16.2% in 1973 to 21.2% in 2001, as did the share of nuclear energy, increasing from 0.9% to 6.9% in 2001.[7]

World electricity generation rose at an annual rate of 3.7% from 1971 to 2001, greater than the 2.1% growth in total primary energy supply. The use of oil for electricity production has fallen dramatically, from over 21% in 1971 to 7.5% in 2001. Oil has been displaced in particular by the growth in nuclear electricity generation, rising from 2% to just over 17% in 2001. The share of coal remained stable, near 38%, while that of natural gas increased from 13% to 18%. The share of hydro-electricity decreased from 23% to 16.6%, while the share of renewable energies such as solar, wind and geothermal grew, but in 2001 still accounted for only 1.7% of total electricity production.[8]

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[7] International Energy Agency, *30 Key Energy Trends in the IEA & Worldwide*. 2004, at 6.

[8] International Energy Agency, *30 Key Energy Trends in the IEA & Worldwide*. 2004, at 12.

3.0 Uranium Mining in Australia

The existence of uranium ore in Australia has been known since the 1890s. It was first seriously mined and treated from the 1950s to 1971. During this period, the largest uranium producing mines were: Radium Hill, South Australia; Rum Jungle, Northern Territory; and Mary Kathleen, Queensland. Production ceased either when ore reserves were exhausted or contracts filled. Sales were to supply material primarily to USA and UK weapons programs at that time, although much of it was also used in civil electricity production.[9]

The development of civil nuclear power stimulated new uranium exploration activity in the late 1960s. Three new contracts for uranium sales for electric power generation were made between 1970 – 1972. These were: Mary Kathleen Uranium Ltd; Queensland Mines Ltd; and Ranger Uranium Mines Pty Ltd. The Mary Kathleen mine recommenced production in 1976. After 4802 tonnes of uranium oxide concentrate had been produced, it was finally depleted and closed down in 1982.

In 1979 Queensland Mines opened Nabarlek mine in the Northern Territory. The orebody was mined out in one dry season, and the ore stockpiled for treatment from 1980. A total of 10,858 tonnes of uranium oxide was produced and sold to Japan, Finland and France from 1981-88. The mine site is now closed and rehabilitated.

Ranger uranium mine in the Northern Territory received government approval in 1977 and was opened in 1981 with a production rate of 3,300 tonnes per year. It has since expanded to 5,500 tonnes/year capacity. Sales are to Japan, South Korea, France, Spain, Sweden, UK, Canada and the United States. Ranger is owned by Energy Resources of Australia, a subsidiary of Rio Tinto.

With the election of the federal ALP government in 1983, the ALP National Conference amended the Party platform to what became known as the ‘three mines policy’. This policy nominated Ranger, Nabarlek and Olympic Dam as the only mines from which uranium could be exported.

In 1988 the Olympic Dam project in South Australia, then a joint venture of Western Mining Corporation and BP Minerals, commenced operations. The Olympic Dam deposit, which also contains copper and gold, is some 350 metres below ground, and is the largest known uranium orebody in the world. In 1996 Western Mining Corporation announced a program to more than double production. This capacity increase was brought online in 1999, at a cost of $1.94 billion, increasing uranium oxide production capacity up to 4,600 tonnes per year. BHP Billiton Ltd took over WMC Resources in mid 2005. BHP Billiton has committed to spending $90 million over two years to assess the potential and to confirm the reserves with a view to doubling the size of Olympic Dam, increasing capacity up to 15,000 tonnes/year of uranium oxide. The capital cost of the increase would be in the order of $5 billion. The pre-feasibility study for this expansion is due to be completed by the end of 2007. Options then include the commissioning of a feasibility study to be

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[9] This section is adapted from: Uranium Information Centre, *Australia’s Uranium and Who Buys It*, see: http://www.uic.com.au/nip01.htm, February 2006. Accessed May 2006.

completed by 2009, with construction of the expanded operations envisaged 2009-13. In 2004, the mine generated $1,100 million in export income. Uranium oxide is sold to: USA; Canada; Sweden, UK; Belgium; France; Finland; South Korea; and Japan.[10]

With the election of the Howard Coalition Government in 1996, the 'three mines policy' was abandoned. With increasing interest in uranium resources, three new projects were identified: Jabiluka in the Northern Territory; Honeymoon in South Australia; and Beverley, also in South Australia. Jabiluka, if developed, will be an extension of the Ranger operation. On 25 February 2005, owners of the Jabiluka deposit, Energy Resources of Australia, announced that it had signed an agreement with the traditional owners of the site, the Mirarr Gundjeihmi Aboriginal people. Under the agreement, ERA must secure Mirarr consent prior to any future mining development of uranium at Jabiluka.[11] To date, agreement has not been reached.

Beverley commenced operation in late 2000, and is licensed to produce 1180 tonnes of uranium oxide per year. The Honeymoon uranium deposit received government approval in November 2001, but is reassessing its reserves and is not yet operational.[12]

Currently Australia exports over 11,000 tonnes of uranium oxide per year. In the five years to mid-2005 Australia exported 46,600 tonnes of uranium oxide with a value of over $2.1 billion to 11 countries around the world.[13]

4.0 THE BASIC PRINCIPLES OF NUCLEAR ENERGY

A nuclear reaction is one that occurs when the nucleus of any atom is changed as a result of collision with some other physical entity, which may be alpha particles, gamma rays, neutrons, protons or even other atoms. Of the many possible nuclear reactions, two, fission and fusion, are of interest because they can produce a tremendous amount of energy. Of these two, only fission has so far been harnessed for electricity production.[14]

4.1 NUCLEAR FUSION

Whereas nuclear fission involves splitting of a heavy atomic nucleus and a consequent release of energy, nuclear fusion is a process of combining light nuclei to form heavier

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[10] Uranium Information Centre, *Australia's Uranium Mines - Olympic*, see: http://www.uic.com.au/emine.htm#olympic, February 2006. Accessed May 2006.

[11] Energy Resources of Australia, *Media Release, Joint Media Statement – Jabiluka Agreement*. 25 February 2005. see: http://www.energyres.com.au/showpdf.php3?id=183, Accessed May 2006.

[12] Uranium Information Centre, *Australia's Uranium and Who Buys It*, see: http://www.uic.com.au/nip01.htm, February 2006. Accessed May 2006.

[13] Uranium Information Centre, *Australia's Uranium and Who Buys It*. See: http://www.uic.com.au/nip01.htm, Accessed May 2005.

[14] Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, *Nuclear Energy Today*, 2003, at 13. See: http://www.nea.fr/html/pub/nuclearenergytoday/welcome.html, Accessed May 2006.

ones. The fusion process releases a large amount of energy, and is the energy source of the sun and stars. Fusion produces no greenhouse gases, and a single fusion power station could generate electricity for two million households. In addition, waste from fusion will not be a long term burden on future generations. Only metal parts close to the fusion centre will become radioactive. The radioactive waste generated will be small in volume and decay over several decades, with the possibility of reuse after about 100 years. The fusion process is inherently safe, and as it is not a chain reaction it can never get out of control. Another advantage is that it is unable to produce fissile materials that could be used to produce nuclear weapons.[15]

The possibility of producing energy for commercial use by fusion has been researched for decades. For fusion to occur, the fusion fuel has to be heated to around 100 million ^{o}C using a variety of techniques. At this temperature, the fuel has changed its state from a gas to a plasma, a state of matter where all the electrons have been stripped from atoms, leaving only the nuclei. The understanding and control of plasma has been a major challenge in the development of fusion power. One line of research is the containment of the plasma in a fusion reactor by magnetic fields.

This is the approach used by the International Thermonuclear Experimental Reactor, known as ITER. In ITER, scientists will study plasmas in conditions similar to those expected in an electricity-generating fusion power plant. The experiment is planned to generate 500 MW of fusion power for extended periods of time, ten times more then the energy input needed to keep the plasma at the right temperature. It will therefore be the first fusion experiment to produce net power. It will also test a number of key technologies, including the heating, control, diagnostic and remote maintenance that will be needed for a real fusion power station. On 24 May 2006 Ministers representing the People's Republic of China, European Union (Euratom), India, Japan, the Republic of Korea, the Russian Federation, and the United States of America met in Brussels to initial the agreement negotiated on the joint implementation of ITER construction, operation, and decommissioning. Detailed plans exist for the construction, operation and decommissioning of ITER, and indicate that, if the ITER Organisation is established in 2006, the first plasma should be possible in ITER by the end of 2016.[16]

Clearly, whilst nuclear fusion holds much promise, a considerable amount of research and development work needs to be done to prove the technology. The rest of this paper focuses on nuclear fission.

4.2 Nuclear Fission

Certain naturally occurring and human-made heavy elements such as uranium and plutonium are relatively unstable. When the nucleus of any such element is impacted by a neutron which it absorbs, it can split into two fragments, releasing at the same time two or three neutrons and energy. This process is known as fission. The fragments of the fission

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[15] The ITER Project, *The Advantages of Fusion*. See: http://www.iter.org/a/index_nav_2.htm, Accessed June 2006.

[16] See the International Thermonuclear Experimental Reactor homepage, http://www.iter.org/index.htm, Accessed June 2006.

are called fission products. The total mass of the products of the reaction is minutely less than the original mass of the atom and impacting neutron, the difference having been converted into energy. As the fission fragments are ejected after the original impact, they begin to collide with nearby atoms and within a millimetre lose most of the their motion energy, which is converted into heat energy. This is the energy that is used to generate electricity. When the free neutrons, which are then released as a result of fission, are absorbed by other nearby fissionable atoms, those too can fission and release more neutrons. This process escalates into what is known as a chain reaction.[17] When this happens over and over again, many millions of times, a very large amount of heat is produced from a relatively small amount of uranium. It is this process, in effect "burning" uranium, which occurs in a nuclear reactor. The heat is used to make steam to produce electricity.[18]

The most efficient neutrons to cause fission in uranium or plutonium are known as thermal neutrons, which have a relatively slow kinetic energy. Those with higher energy are called fast neutrons. All neutrons produced by fission are fast neutrons. A moderator is used to slow the fast neutrons released during fission to the more efficient thermal energies needed in commercial nuclear power plants. In terms of abundance and radioactivity, the most important fission product isotopes resulting from the fission of uranium-235 are radioactive forms of: bromine; caesium; iodine; krypton; strontium; and xenon. These daughter isotopes decay, each in a different period as measured by and referred to as its half-life.

The half-life of a radioactive isotope is the time it takes for half of any given number of atoms to decay. This can vary from less than one second to infinity (ie stable) according to the isotope. After five half-lives, the amount of a radioactive isotope remaining is about 3% of the original amount. After ten half-lives, less than 0.1% remains.

When the nucleus of an atom captures a neutron and does not fission, it may change into another element. In the nuclear reactor, this results in the creation of an important set of long-lived elements which either do not occur or are very rare in nature. These elements - Americium-243, Plutonium-239, and Neptunium-237 - are radioactive, and some, particularly plutonium-239, are themselves capable of being used as nuclear fuel. Because of their long half-lives and high radiological and biological toxicity, they are an important component in nuclear waste.

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[17] Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, *Nuclear Energy Today*, 2003, at 14. See: http://www.nea.fr/html/pub/nuclearenergytoday/welcome.html, Accessed May 2006.

[18] World Nuclear Association, *What is Uranium?* Information Fact Sheets, 2002. See: http://www.world-nuclear.org/education/uran.htm, Accessed May 2006.

Half-Lives of some important isotopes

Isotope	Approximate Half-life (years)
Strontium-90	29
Caesium-137	30
Americium –243	7,400
Plutonium-239	24,000
Neptunium-237	2,140,000

Sources: Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, *Nuclear Energy Today*, 2003, at 15. See http://www.nea.fr/html/pub/nuclearenergytoday/welcome.html, Accessed May 2006.

Nuclear fission is an extremely potent source of energy with a very high energy density. Compared to chemical reactions such as combustion of fossil fuels, fission reactions require a much smaller volume of basic material to produce an equivalent amount of energy. The energy released by the fission of one kilogram of uranium in a typical reactor is equivalent to that released by about: 45,000 kg of wood; 22,000 kg of coal; 15,000 kg of oil and 14,000 kg of liquid natural gas. A 900 MW electric nuclear power station would produce as much electricity in a year as 70 square kilometres of solar panels, or a few thousand windmills taking into account efficiency and availability.[19]

4.3 Uranium Mining and Milling

Uranium ore is extracted from the earth in much the same manner as other minerals such as copper. Worldwide, over 70% of uranium production is achieved by the extraction of ore using conventional open pit or underground mining methods. The remainder is mainly accounted for by in situ leaching, a method whereby a solvent solution is injected underground. This dissolves the uranium into the solution and it is recovered from wells. The Australian Beverley mine is the first Australian mine to use in situ leaching to extract uranium. The Honeymoon deposit will also be mined by in situ leaching if the project proceeds.

Milling is the process through which mined uranium ore is physically treated to a suitable size, then chemically treated to extract and purify the uranium. It also reduces the volume of material to be transported. The milled product is called uranium oxide (U_3O_8), often referred to as ‘yellow cake’ due to its colour and consistency. After high temperature drying, the uranium oxide is packed into 200 litre drums for shipment.[20]

4.4 Conversion

Uranium oxide cannot simply be fed into a power station like coal to produce steam to power turbines. Uranium has to be isotopically concentrated, and made into special fuel

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[19] Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, *Nuclear Energy Today*, 2003, at 15. See: http://www.nea.fr/html/pub/nuclearenergytoday/welcome.html, Accessed May 2006.

[20] Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, *Nuclear Energy Today*, 2003, at 24. See: http://www.nea.fr/html/pub/nuclearenergytoday/welcome.html, Accessed May 2006.

rods. Most reactors cannot run on natural uranium, so the proportion of U-235 must be increased to about 3.5%. To be used in a reactor, firstly uranium oxide is converted into uranium hexafluoride (UF_6). Uranium hexafluoride is a solid at room temperature, and is normally stored and transported in large cylinders holding about 12,000kg of UF_6. The conversion of uranium oxide into uranium hexafluoride is conducted in only a few countries worldwide, as shown below.

Major Uranium Conversion Facilities Worldwide

Country	Site
Canada	Blind River and Port Hope, Ontario
France	Malvesi; Pierrelatte
Russian Federation	Angarsk; Ekaterinburg
United Kingdom	Springfields, Lancashire
United States	Metropolis, Illinois

Source: Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, *Nuclear Energy Today*, 2003, at 24. See http://www.nea.fr/html/pub/nuclearenergytoday/welcome.html, Accessed May 2006.

Uranium hexafluoride must then be enriched to less than 5% Uranium-235, most commonly 3.5%. In the process, about 85% of the natural uranium feed is rejected, referred to as ‘depleted uranium’ or ‘tails’, and is typically stored in large cylinders. Two methods of enrichment are in commercial use: gaseous diffusion and centrifugation. Both are based on enriching uranium hexafluoride. Early plants used gaseous diffusion, but this has high electricity requirements and very large plant sizes. Advances in material technology have led to an increase in centrifugation, resulting in lower enrichment costs, due mainly to a reduction in energy consumption by a factor of 50. Between seven and ten tonnes of natural uranium are required to produce a tonne of enriched uranium in a light water reactor (ie, a reactor that uses normal water as a coolant). The major uranium enrichment facilities worldwide are shown below:

Major Uranium Enrichment Facilities Worldwide

Country	Site	Technology
China	Lanzhou	Centrifuge
	Shaanxi	Centrifuge
France	Tricastin	Gaseous Diffusion
Germany	Gronau	Centrifuge
Japan	Rokkasho-mura	Centrifuge
Netherlands	Almelo	Centrifuge
	Ekaterinburg	Centrifuge
	Krasnoyarsk	Centrifuge
	Seversk	Centrifuge
United Kingdom	Capenhurst	Centrifuge
United States	Paducah	Gaseous Diffusion

Source: Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, *Nuclear Energy Today*, 2003, at 24. See http://www.nea.fr/html/pub/nuclearenergytoday/welcome.html, Accessed May 2006.

The OECD Nuclear Energy Agency describes the enrichment process as a mature service industry with competitive international markets.[21]

4.5 Fuel Fabrication

Enriched uranium then goes to a fuel fabrication plant. This involves the conversion of uranium hexafluoride into uranium dioxide (UO_2) powder, which is then compressed and heated at temperatures up to 1,400 ^{0} Celsius to produce small cylindrical pellets about 2cm long and 1.5cm in diameter. These are loaded into hollow zirconium or stainless steel metal tubes that are then bundled as fuel assemblies. Over 739 fuel assemblies, containing about 46,000 fuel rods would fuel a typical Boiling Water Reactor.[22]

Inside all kinds of reactors, a fission chain reaction occurs in the fuel rods. Fast neutrons are slowed by the moderator (either water, heavy water or graphite) so that they can cause fission. Neutron absorbing control rods are inserted or withdrawn to regulate the speed of the reaction, with the heat of the fission used to make steam. In a light water reactor, the fuel stays in the reactor for about three years, generating heat from both the U-235 and also the fissile plutonium which is formed there. When removed, spent fuel is both hot and radioactive. It is therefore stored under water to remove the heat and to provide shielding from radiation. The fuel rods may then be either reprocessed in those units which have a closed fuel cycle, or prepared for final disposal for those reactors with an open fuel cycle.

4.6 Open and Closed Fuel Cycles

For a nuclear reactor with an open fuel cycle the used fuel rods are stored and not used again. In contrast, a closed fuel cycle reactor reuses the spent fuel. About 96% of the uranium which goes into a reactor emerges again in the spent fuel, although the U-235 concentration is less than one percent. Spent fuel is put through a reprocessing plant where it is chopped up and dissolved in acid. The process separates the two valuable components of the spent fuel: plutonium and unused uranium. Plutonium comprises about 1% of the spent fuel. It is a very good nuclear fuel and can be mixed with depleted uranium, made into fuel rods in a mixed oxide and put back into the reactor as fresh fuel. In the reprocessing plant, the unused uranium from the spent fuel can again be enriched, and used as fresh fuel for a reactor. The closed fuel cycle is thus a more efficient system for making maximum use of the uranium dug out of the ground, by about 30% in energy terms. France, Germany, UK, Russia and Japan and China have adopted the closed fuel cycle for oxide fuels, and across Europe over 35 reactors are licensed to load 20 – 50% of their core with mixed oxide fuel containing up to 7% reactor-grade plutonium.[23] Virtually all the advanced reactor designs under consideration involve a closed fuel cycle, and this is discussed further in the section on Generation IV reactors.

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[21] Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, *Nuclear Energy Today*, 2003, at 26. See: http://www.nea.fr/html/pub/nuclearenergytoday/welcome.html, Accessed May 2006.

[22] A Boiling Water Reactor is a very common type of light water reactor in use worldwide. Ordinary water, used as both coolant and moderator, is allowed to boil in the reactor core. The steam produced is then used to directly generate electricity.

[23] Hore-Lacey, I. *Nuclear Electricity*, Published by the Uranium Information Centre and World Nuclear Association, 7th Edition, 2003, at 6.

4.7 Alternative Nuclear Fuels – Thorium

Thorium is a naturally occurring, slightly radioactive metal discovered in 1828. It is found in small amounts in most rocks and soils, where it is about three times more abundant than uranium. Thorium occurs in several minerals, the most common being the thorium-phosphate mineral, monazite, which contains up to about 12% thorium oxide. Worldwide, economically extractable thorium reserves are about 1,200,000 tonnes. Australia has the largest reserves of about 300,000 tonnes, closely followed by India with 290,000 tonnes.[24]

Thorium, as well as uranium, can be used as a nuclear fuel. Although not fissile itself, thorium-232 will absorb slow neutrons to produce uranium-233, which is fissile. Over the last 30 years there has been interest in utilising thorium as a nuclear fuel since it is three times as abundant in the earth's crust as uranium. Also, all of the mined thorium is potentially useable in a reactor, compared with the 0.7% of natural uranium, so some 40 times the amount of energy per unit mass might be available.

The use of thorium-based fuel cycles has been studied for about 30 years, but on a much smaller scale than uranium or uranium/plutonium cycles. Basic research and development has been conducted in Germany, India, Japan, Russia, the UK and the USA. Test reactor irradiation of thorium fuel to high burnups has also been conducted and several test reactors have either been partially or completely loaded with thorium-based fuel.

Problems of using thorium as a fuel include: the high cost of fuel fabrication due partly to the high radioactivity of U-233; the similar problems in recycling thorium due to highly radioactive Th-228; some weapons proliferation risk of U-233; and the technical problems (not yet satisfactorily solved) in reprocessing. Much development work is still required before the thorium fuel cycle can be commercialised, and the effort required seems unlikely while abundant uranium is available. Nevertheless, the thorium fuel cycle holds considerable potential long-term, and is a key factor in the sustainability of nuclear energy.[25]

5.0 NUCLEAR REACTOR TECHNOLOGIES

A popular method of categorising reactors is according to the type of coolant used. The coolant is necessary to absorb and remove the heat produced by nuclear fission and maintain the temperature of the fuel within acceptable limits. It can then transfer the heat to electricity generating turbines. About 80% of commercial reactors in 2003 were cooled and moderated with ordinary water. These are known as light water reactors, with two major types: Pressurised water reactors, which includes a Russian variant (VVER); and Boiling water reactors. Most of the remaining reactors are cooled either by heavy water or gas. The main reactor types are described below:

5.1 Pressurised Water Reactors

Ordinary water is used both as coolant and moderator. The coolant is kept at a high

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[24] World Nuclear Association, *Thorium*, *Information and Issues Briefs*, November 2004, see: http://www.world-nuclear.org/info/inf62.htm, Accessed June 2006.

[25] World Nuclear Association, *Thorium*, *Information and Issues Briefs*, November 2004, see: http://www.world-nuclear.org/info/inf62.htm, Accessed June 2006.

pressure to keep it liquid at high temperatures (above 300°C). The coolant circulates in the primary system, comprised mainly of the reactor pressure vessel. As it passes through the steam generator, the heat is transferred to boil water in a separate, secondary loop. The steam produced drives the electricity producing turbine generators.

At the beginning of 2003, there were 212 pressurised water reactors worldwide, of which 150 were in France, Japan and the United States.

VVERs

The name is a Russian acronym for a water cooled, water moderated energy reactor. VVERs are in essence, Russian designed pressurised water reactors. The first generation of these reactors needed expensive modification because their original designs did not correspond to contemporary practices in nuclear safety. As a result, some units have been shut down, notably in Bulgaria and the Slovak Republic.

In 2003 51 VVERs were in operation, of which 26 were in the Russian Federation and Ukraine. They are also operating in: Armenia; Bulgaria; the Czech Republic; Finland; Hungary; and the Slovak Republic.

Boiling Water Reactors

Ordinary water is used both as coolant and moderator, but the coolant is kept at a lower pressure than a pressurised water reactor. This allows the coolant to boil, and the resultant steam is passed directly to the turbine generators. While the absence of a steam generator simplifies the design compared to a pressurised reactor, radioactivity contaminates the electricity generating turbine.

In 2003 there were 92 boiling water reactors in nine countries, of which Japan and the United States accounted for 64.

Pressurised Heavy Water Reactors

Known as CANDU reactors (Canadian deuterium uranium), these reactors use heavy water as both coolant and moderator. Heavy water allows natural uranium to be used as the fuel, thereby eliminating the need for and cost of enriching the uranium. However, a separate plant is required to produce the heavy water. An advantage of the CANDU design is that refuelling can take place during operation, whereas pressurised and boiling water reactors must shut down in order to refuel. This feature allows high availability but also increases the complexity of operation.

34 of these reactors were in operation in 2003, of which 14 were in their country of origin, Canada, and the remainder in Argentina; India; Pakistan; Republic of Korea; and Romania.

Gas-Cooled reactors

There are two types of this reactor, the Magnox and the Advanced Gas-cooled reactor (AGR). Both use carbon dioxide as the coolant and graphite as the moderator. The Magnox uses natural uranium as fuel and the AGR uses enriched uranium.
In 2003, 33 were in use only in the United Kingdom.

RBMK

The name is a Russian acronym meaning large power boiling reactor. Ordinary water is used as the coolant and graphite as the moderator. As with the boiling water reactor, the coolant boils as it passes through the reactor and the resultant steam is passed directly to turbine generators.

17 RBMK plants remain in operation in 2003, of which 15 were in the Russian Federation and two in Lithuania. The RBMK, as an early design, was often built, and some are being operated, without safety characteristics and features required elsewhere. The accident at Chernobyl in 1996 happened to a RBMK type reactor. These reactors are of some concern as they cannot be upgraded to correspond to contemporary safety practices at reasonable cost.

5.2 Fast Breeder Reactors

The reactor types described above are thermal reactors, with most of the fission being caused by thermal neutrons. Fast reactors are designed to make use of fast neutrons, which because of their higher energies, are less likely to be captured. The excess neutrons can be used to convert fertile materials, such as uranium-235 into fissile material, such as plutonium-239. This newly created fissile material can fuel the reactor. It is possible to design a reactor to produce more fuel than it consumes, and these are called breeder reactors. Fast breeder reactors, by creating fuel from non-fissile isotopes and improving the efficiency of utilisation through recycling, can potentially increase available world nuclear fuel resources up to 50 fold.

Breeder reactors in 2002 operated in France; India; Japan and the Russian Federation.[26]

5.3 Advanced Nuclear Reactors – Generation IV Technology

Nuclear reactor technology has been categorised into ‘generations’. The first generation were built in the 1950s and 1960s and were early prototype reactors. The second generation began in the 1970s with the large generating plants that are still in operation today. Generation III was developed more recently in the 1990s with a number of evolutionary designs that offered significant advances in safety and economics, and a number have been built, primarily in East Asia. Advances to Generation III are underway, resulting in several (so-called Generation III+) near-term deployable plants that are actively under development. New plants built between now and 2030 are likely to be built from Generation III+ designs. Beyond 2030, renewed interest in nuclear energy has stimulated a fourth generation of nuclear reactor designs.[27]

Ten countries - Argentina, Brazil, Canada, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom and the United States - have joined together to form the Generation IV International Forum. The Forum’s aim is to

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[26] This section adapted from: Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, *Nuclear Energy Today*, 2003, at 17. See: http://www.nea.fr/html/pub/nuclearenergytoday/welcome.html, Accessed May 2006.

[27] United States of America Department of Energy Nuclear Research Advisory Committee and the Generation IV International Forum, *A Technology Roadmap for Generation IV Nuclear Energy Systems*. December 2002, at 5.

develop future-generation nuclear energy systems that can be licensed, constructed, and operated in a manner that will provide competitively priced and reliable energy whilst satisfactorily addressing nuclear safety, waste, proliferation and public perception concerns. The objective for Generation IV nuclear energy systems is to have them available for international deployment about the year 2030, when many of the world's currently operating nuclear power plants will be at or near the end of their operating licenses.

As part of the Generation IV Forum, it was found that the limiting factor facing an essential role for nuclear energy with the once-through fuel cycle (ie, no fuel recycling) is the availability of repository space for spent fuel. In the longer term, beyond 50 years, uranium resource availability also becomes a limiting factor unless breakthroughs occur in mining or extraction technologies. In contrast, systems that employ a fully closed fuel cycle hold the promise to reduce repository space requirements. Advanced waste management strategies have the potential to reduce the long-lived radiotoxicity of waste destined for geological repositories by at least an order of magnitude. In the most advanced fuel cycles using fast-spectrum reactors and extensive recycling, it may be possible to reduce the radiotoxicity of all wastes such that the isolation requirements can be reduced by several orders of magnitude – for a time as low as 1000 years, after discharge from the reactor. However, this scenario can only be established through considerable research and development on recycling technology. All Generation IV systems employing fuel recycling avoid separation of plutonium from other actinides and incorporate additional features to reduce the accessibility and weapons attractiveness of materials at every stage of the fuel cycle.

The Generation IV International Forum identified six different designs that were the most promising and worthy of collaborative development. These were:

- Gas-cooled fast reactor system;
- Lead-cooled fast reactor system;
- Molten salt reactor system;
- Sodium-cooled fast reactor system;
- Supercritical water-cooled reactor system;
- Very-high temperature reactor system.

An explanation of these systems follows.

The Gas-cooled fast reactor system

This reactor features a fast-neutron spectrum and closed fuel cycle for efficient conversion of fertile uranium and management of actinides. A full actinide recycle fuel cycle with on-site fuel cycle facilities is envisioned. The coolant is helium with a direct gas turbine for high thermal efficiency. This system is ranked the highest in terms of sustainability because of its closed fuel cycle and excellent performance in actinide management. It is rated good in safety, economics, and in proliferation resistance and physical protection. It is primarily envisaged as for electricity production and actinide management, but may also be able to support hydrogen production. The reactor system is estimated to be deployable by 2025.

The Lead-cooled Fast Reactor System

This is a fast-neutron closed fuel cycle reactor with full recycling of fuel envisioned. The reactor is cooled by natural convection and is specifically designed for distributed generation of electricity and other energy products, including hydrogen. The system is top-ranked in terms of: sustainability because a closed fuel cycle is used; and in proliferation resistance and physical protection because it employs a long-life core. It is rated good in safety and economics. The safety is enhanced by the choice of a relatively inert coolant. It is estimated to be deployable by 2025.

The Molten Salt Reactor System

In this system, the fuel is a circulating liquid mixture of sodium, zirconium and uranium fluorides. The molten salt fuel flows through graphite core channels, and the heat generated in the molten salt is transferred to a secondary coolant system, and then through another heat exchanger to the power conversion system. A full actinide recycle fuel system is envisioned. The system is top-ranked for sustainability because of its closed fuel cycle and excellent performance in waste burndown. It is rated good in safety and proliferation resistance and physical protection. It is rated neutral in economics because of the large number of subsystems involved. It is primarily envisioned for electricity production and waste burndown, and is estimated to be deployable by 2025.

The Sodium-cooled Fast Reactor System

This system features a fast-neutron spectrum and closed fuel cycle for efficient conversion of fertile uranium and actinide management. A full actinide recycled fuel cycle is envisioned with two major options: an intermediate size sodium-cooled reactor with a uranium-plutonium-minor actinide-zirconium metal alloy fuel, processed on co-located facilities; or an alternative is a medium to large sodium-cooled fast reactor with mixed uranium-plutonium oxide fuels, processed with advanced facilities at a central location serving a number of reactors. The system is top-ranked in sustainability because of its closed fuel cycle and excellent potential for actinide management, including resource extension. It is rated good in safety, economics and proliferation resistance and physical protection. Based on experience with oxide fuel, this option is estimated to be deployable by 2015.

On February 16 2006 the United States, Japan and France signed an agreement providing the framework for collaboration on research and development of sodium-cooled fast reactor systems. This is the first agreement of its kind within the framework of the Generation IV International Forum.[28]

The Supercritical Water-cooled Reactor System

This Generation IV reactor features two fuel cycle options: the first is an open cycle with a thermal neutron spectrum reactor; the second is a closed cycle with a fast neutron spectrum reactor and full actinide recycling. Both options use a high-temperature, high-pressure water-cooled reactor. Passive safety features similar to those of the simplified boiling

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[28] United States Department of Energy, Office of Public Affairs, *Media Release – Generation IV International Forum Signs Agreement to Collaborate on Sodium-cooled Fast Reactors*. 17 February 2006. See: http://www.energy.gov/print/3218.htm. Accessed June 2006.

water reactor are incorporated. The system is highly ranked in economics because of its high thermal efficiency and plant simplification. It is ranked good in terms of safety, proliferation resistance and physical protection. If the fast spectrum option can be developed (ie, closed fuel cycle), it will also be ranked highly in terms of sustainability. It is estimated to be deployable by 2025.

The Very High Temperature Reactor System

This system uses a thermal neutron spectrum and a once-through uranium cycle. It is primarily aimed at a faster deployment than the other reactor systems, for high temperature process heat applications, such as coal gasification and thermochemical hydrogen production. The reference reactor concept has a helium cooled reactor core. It is highly ranked in terms of economics because of its high hydrogen production efficiency, and in safety and reliability because of the inherent safety features of the fuel and reactor. It is rated good in proliferation resistance and physical protection, and neutral in sustainability because of its open fuel cycle.[29]

5.4 Nuclear Reactors for Near-term Deployment

The Generation IV roadmap also identified reactor designs that could be deployed in the nearer term to 2015. Only those systems whose performance equalled or exceeded those of a Generation III light water reactor were identified. Sixteen designs in five categories were found to be probably deployable by 2015 as follows:

- Advanced Boiling Water Reactors
    - Advanced Boiling Water Reactor II;
    - European Simplified Boiling Water Reactor;
    - High-conversion boiling water reactor;
    - Siedewasser Reactor-1000
- Advanced Pressure Tube Reactor
    - Advanced CANDU Reactor 7000
- Advanced Pressurised Water Reactors
    - Advanced Pressurised Water Reactor 600;
    - Advanced Pressurised Water Reactor 1000;
    - Advanced Power Reactor 1400;
    - Advanced Pressurised Water Reactor Plus;
    - European Pressurised Water Reactor;
- Integral Primary System Reactors
    - Central Agentina de Elementos Modulares;
    - International Modular Reactor;
    - International Reactor Innovative and Secure;
    - System-integrated Modular Advanced Reactor;
- Modular High Temperature Gas-cooled Reactors
    - Gas Turbine Modular High Temperature Reactor;
    - Pebble Bed Modular Reactor.

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[29] United States of America Department of Energy Nuclear Research Advisory Committee and the Generation IV International Forum, *A Technology Roadmap for Generation IV Nuclear Energy Systems*. December 2002, at 14.

In Australia, supporters of nuclear energy have suggested that a Pebble Bed Modular Reactor would be suitable for Australian conditions.[30] The operation of this reactor is explained below.

5.5 The Pebble Bed Modular Reactor

The developers of this technology claim a dramatically higher level of safety and efficiency over other reactors. The fuel is encased in graphite pebbles about the size of a tennis ball, called fuel spheres. The main component of the reactor comprises a steel pressure vessel which holds about 450,000 fuel spheres. The vessel is about 27 metres high and 6 metres in diameter. Helium is used as the coolant and energy transfer medium to drive a closed cycle gas turbine.[31] The fuel spheres recycle through the reactor continuously, about six times each taking six months.

The technology was first developed in Germany. In various forms, it is currently under development by Massachusetts Institute of Technology, the South African company PBMR, General Atomics (U.S.), the Dutch company Romawa B.V., Adams Atomic Engines, INL, and the Chinese company Chinergy, working with Tsinghua University. The South African company is considered the most advanced in both technology and timing of construction. The ultimate aim is for components of the reactor to be pre-fabricated in a central location, and then assembled on site. The modular design means that additional units for a power station can be relatively easily ordered and installed.

In mid-November 2005, it was announced that a new Pebble Bed Reactor would be built at Koeberg, South Africa. Production units will be 165 MW equivalent. Eventual construction cost (when in clusters of four or eight units) is expected to be cost competitive with a generating cost below 3 US cents/kWh. A demonstration plant is due to be built in 2007 for operation in 2010. The first commercial units are expected on line in 2014 and the South African utility Eskom has said it expects to order 24. A design certification application to the US Nuclear Regulatory Commission is expected in 2008, with approval expected in 2012, opening up world markets.[32]

However, others believe that the Pebble Bed technology is unlikely to be available in the United Kingdom market for instance until close to 2020. In addition, costs are necessarily uncertain, with the cost of the demonstration plant itself having escalated by a factor of around seven since 1999. In these circumstances, it is impossible to know what the costs would be for a commercially available, fully licensed Pebble Bed Reactor.[33]

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[30] “Reactors safe for all locations, Labor told.’ in *The Sydney Morning Herald*, 25 May 2006.

[31] South African Pebble Bed Modular Reactor Company, *What is PBMR*. See: http://www.pbmr.com/index.asp?content=4, accessed June 2006.

[32] Uranium Information Centre, Small Nuclear Power Reactors. UIC Nuclear Issues Briefing Paper No 60, June 2006. See: http://www.uic.com.au/nip60.htm, Accessed June 2006.

[33] Sustainable Development Commission, *The Role of nuclear power in a low carbon economy. Paper 4: The Economics of Nuclear Power.* An evidence based report for the Sustainable Development Commission by Science and Technology Policy Research and NERA Economic Consulting, March 2006, at 10.

Since 2004, the South African government has committed significant funding to the project, including programs to train nuclear scientists.[34] In March 2005, the South African company PBMR (Pty Ltd) and the Chinese developers of pebble bed technology, Chinergy of Beijing, entered into a Memorandum of Understanding. The main objective of the Memorandum is to cooperate on demonstration projects in China and South Africa as well as the commercialization of the systems thereafter.[35]

Safety features of the Pebble Bed Modular Reactor

Proponents of the Pebble Bed Reactor claim that the technology is inherently safe. When a pebble-bed reactor gets hotter, the more rapid motion of the atoms in the fuel decreases the probability of neutron capture by Uranium-235 atoms by an effect known as Doppler broadening. When the uranium is heated, its nuclei move more rapidly in random directions, and therefore see and generate a wider range of relative neutron speeds. Uranium-238, which forms the bulk of the uranium in the reactor, is much more likely to absorb fast-moving neutrons. This reduces the number of neutrons available to cause uranium-235 fission, reducing the power output by the reactor. This natural negative feedback places an inherent upper limit on the temperature of the fuel, without any operator intervention.

The reactor is cooled by an inert, fireproof gas, so it cannot have a steam explosion as a light-water reactor can. The coolant has no phase transitions—it starts as a gas and remains a gas. The moderator is solid carbon. It does not act as a coolant, move, or have phase transitions (i.e. between liquid and gas) as the light water in conventional reactors does.

A pebble-bed reactor thus can have all of its supporting machinery fail, and the reactor will not crack, melt, explode or spew hazardous wastes. It simply goes up to a designed "idle" temperature, and stays there. In that state, the reactor vessel radiates heat, but the vessel and fuel spheres remain intact and undamaged. The machinery can be repaired or the fuel can be removed.[36]

The most common criticism of pebble bed reactors is that encasing the fuel in potentially flammable graphite poses a hazard in and of itself. Were the graphite to burn, fuel material could potentially be carried away in smoke from the fire. To prevent this, the reaction vessel is purged of oxygen, usually being replaced with helium. Oxygen entering the vessel would cause the graphite in the fuel pebbles to burn since the reactor operating temperature is around 1500 ^{o}Celsius.

Some designs for pebble bed reactors lack a containment building, potentially making such reactors more vulnerable to outside attack and allowing radioactive material to spread in the case of an explosion. However, an explosion would most likely be caused by an

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[34] PBMR (Pty Ltd), *Project Status*, see: http://www.pbmr.co.za. Accessed June 2006.

[35] PBMR (Pty Ltd), *How did South Africa Come to the Forefront?* See: http://www.pbmr.com/download/HowdidSA.pdf. Accessed June 2006.

[36] Wilkipedia, Pebble Bed Reactor, see: http://en.wikipedia.org/wiki/Pebble_bed_reactor, Accessed June 2006.

external factor, as the design does not suffer from the steam-explosion vulnerability of water-cooled reactors.

Since the fuel is contained in graphite pebbles, the volume of radioactive waste is much greater. However, the waste tends to be less hazardous and simpler to handle. Pebble bed reactors would increase existing storage problems. Defects in the production of pebbles may also cause problems. The radioactive waste must either be safely stored for many human generations, reprocessed, transmuted in a different type of reactor, or disposed of by a method yet to be devised. The graphite pebbles are more difficult to reprocess due to their construction, which is not true of the fuel from other types of reactors. Critics also often point to an accident in Germany in 1986, which involved a jammed pebble damaged by the reactor operators when they were attempting to dislodge it from a feeder tube. This accident released radiation into the surrounding area, and led to a shutdown of the research program by the West German government.[37]

6.0 NUCLEAR WASTE

Radioactive waste management is often cited as the most important unresolved issue concerning nuclear energy, but the OECD Nuclear Energy Agency in 1996 stated that a broad scientific and technical consensus exists among specialists that all categories of radioactive waste can be managed and disposed of in accordance with all regulatory requirements. The Nuclear Energy Agency noted that the perceived absence of a ‘solution’ to the disposal of nuclear waste is jeopardizing the development of the nuclear industry in some countries.[38]

The International Atomic Energy Agency defines radioactive waste as any material that contains a concentration of radionuclides greater than those deemed safe by national authorities, and for which no use is foreseen. Because of the wide variety of nuclear applications, the amounts, types and even physical forms of radioactive wastes vary considerably. Some wastes can remain radioactive for hundreds or thousands of years, while others may require storage for only a short decay period prior to conventional disposal.

The Agency has classed radioactive waste into three main classes:

- Exempt waste;
- Low and intermediate waste; and
- High level waste.[39]

Exempt Waste contains such a low concentration of radionuclides that it can be excluded from nuclear regulatory control because radiological hazards are considered negligible.

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[37] Wilkipedia, Pebble Bed Reactor, see: http://en.wikipedia.org/wiki/Pebble_bed_reactor, Accessed June 2006.

[38] OECD Nuclear Energy Agency, *Nuclear Waste in Perspective*, OECD, 1996, at 13.

[39] International Atomic Energy Agency, *Management of Radioactive Waste*, 1998. See: http://www.iaea.org/Publications/Factsheets/English/manradwa.html, Accessed June 2006.

Low and Intermediate Level Waste contains enough radioactive material so that it requires actions to ensure the protection of workers and the public for short or extended periods of time. Low level waste is generated from both hospitals and industry, as well as the nuclear fuel cycle. It comprises paper, rags, tools, filters etc which contain small amounts of mostly short-lived radioactivity. It does not require shielding during handling and transport and is suitable for shallow land burial. Low level waste comprises 90% of the volume but only 1% of the radioactivity.

Intermediate level wastes contain higher amounts of radioactivity and some requires shielding. It typically comprises resins, chemical sludges and metal fuel cladding, as well as contaminated materials from reactor decommissioning. It makes up some 7% of the volume and has 4% of the radioactivity of all radioactive waste.

High level waste contains sufficiently high levels of radioactive materials that a high degree of isolation from the biosphere, normally in a geologic repository, is required for long periods of time. Such wastes normally require both special shielding and cooling off periods. High level wastes arise from the use of uranium fuel in a reactor, and contain the fission products and transuranic elements generated in a reactor core. HLW accounts for over 95% of the total radioactivity produced by nuclear power generation.[40]

The graph below shows that in 1000 years the majority of the radioactivity has decayed. It takes just under 10,000 years for spent fuel waste to decay so that it is no more radioactive than the original uranium ore.

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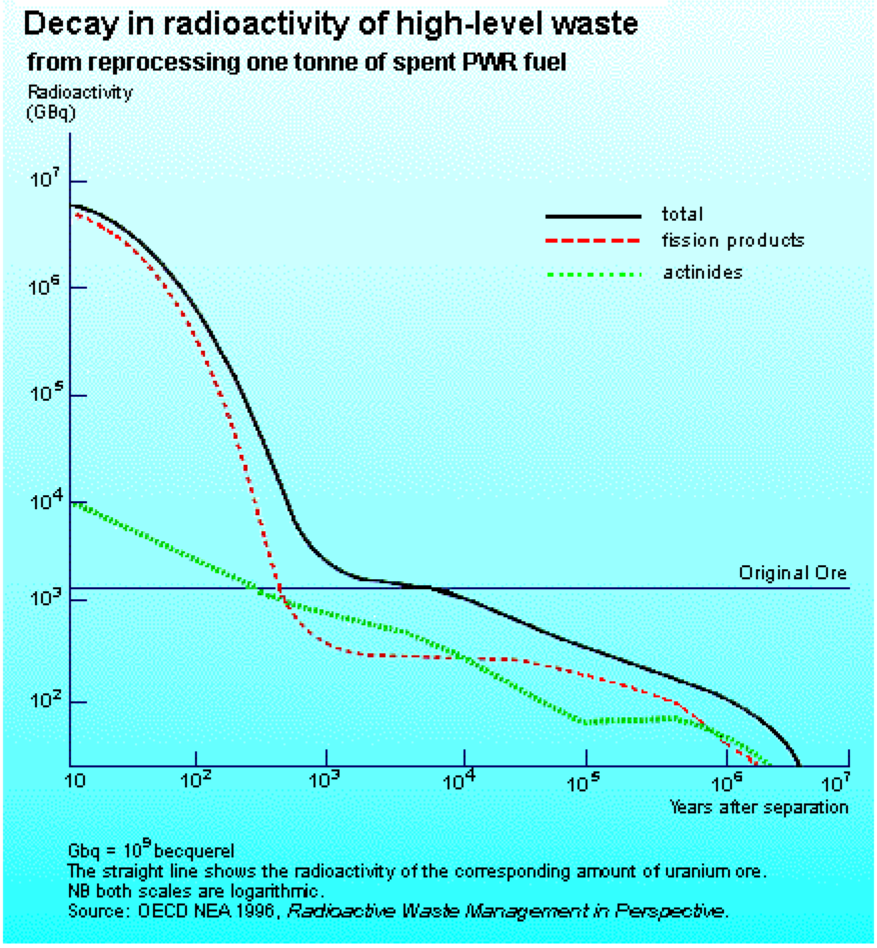
[40] World Nuclear Association, *Waste Management in the Nuclear Fuel Cycle*, February 2006, at 5. See: http://www.world-nuclear.org/info/inf04.htm, Accessed June 2006.



Decay in radioactivity of high-level waste

from reprocessing one tonne of spent PWR fuel

Gbq = 10^9 becquerel

The straight line shows the radioactivity of the corresponding amount of uranium ore.

NB both scales are logarithmic.

Source: OECD NEA 1996, *Radioactive Waste Management in Perspective*.

Source: World Nuclear Association, *Waste Management and the Nuclear Fuel Cycle*, February 2006, at 5. See http://www.world-nuclear.org/info/inf04.htm, Accessed June 2006. Figure is adapted from OECD Nuclear Energy Agency, *Nuclear Waste in Perspective*, OECD, 1996, at 17.

The generation of electricity from a typical 1000 MW(equivalent) nuclear power station produces approximately 300 m^3 of low and intermediate level waste per year and some 30 tonnes of high level solid packed waste per year. By way of comparison a 1000 MW(equivalent) coal plant produces some 300,000 tonnes of ash per year, containing among other things radioactive material and heavy metals which end up in landfill sites and in the atmosphere. Worldwide, nuclear power generation facilities produce about 200,000 m^3 of low and intermediate level waste and 10,000 m^3 of high level waste each year.[41] The OECD Nuclear Energy Agency states that for a typical large modern pressurized water reactor, the generation of 1 gigawatt (one billion watts) of electricity, enough for the electricity needs of 1-2 million people in an OECD country, will produce about 1 gram of radioactive waste per person per year.[42]

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[41] International Atomic Energy Agency, *Management of Radioactive Waste*, 1998. See: http://www.iaea.org/Publications/Factsheets/English/manradwa.html, Accessed June 2006.

[42] OECD Nuclear Energy Agency, *Nuclear Waste in Perspective*, OECD, 1996, at 20.

Most nuclear utilities are required by governments to put aside a levy to provide for the management and disposal of their wastes. In the United States this levy is 0.1 cents per kilowatt hour, in France it is 0.14 cents per kilowatt hour. To date, some $20 billion has been collected by the United States waste fund, paid by electricity consumers.[43]

6.1 Management and disposal of high level waste and spent fuel

Most countries operating nuclear power plants have or are developing facilities for managing high level waste. Although national strategies differ, the approach and methodologies are often quite similar. Once spent fuel has been removed from a nuclear reactor, it is placed in interim storage at the reactor site. Afterwards, it may be handled in two different ways:

- Placed in storage facilities away from the reactor for 5 to 100 years, conditioned after an appropriate decay period, then stored before final disposal in a geologic repository; or
- Reprocessed after away-from-reactor storage. The resulting liquid high level waste is then immobilized in a stable matrix (i.e. borosilicate glass), and then stored until final disposal in a geologic repository.

Regardless of which option is selected, according to the International Atomic Energy Agency there is broad scientific agreement that deep geologic disposal using a system of engineered and natural barriers to isolate the waste is the best method.[44] The term ‘geological disposal’ refers to the disposal of solid radioactive waste in a facility located underground in a stable geological formation (usually several hundred metres or more below the surface) so as to provide long term isolation of the radionuclides in the waste from the biosphere. Disposal means that there is no intention to retrieve the waste, although such a possibility is not ruled out.

Proponents of the geological repository waste disposal solution also highlight several natural phenomena of radioactive ore bodies. One example is in the Alligator Rivers region in the Northern Territory. At this site, the movement of uranium and its decay products, many of which are similar or identical with components of radioactive waste, was studied using a series of boreholes. It was found that in the weathered layers near the surface, radionuclides had moved only a few tens of metres away from the ore body in millions of years. No detectable movement had occurred in undisturbed deeper layers. Similarly, at Oklo in the African state of Gabon, spontaneous nuclear fission processes continued over several hundred thousand years, creating several tonnes of radioactive wastes. Most of these materials have remained close to where they were formed some 1,800 million years ago.[45]

However, critics of nuclear power identify waste disposal as a key reason why it should not

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[43] World Nuclear Association, *Waste Management in the Nuclear Fuel Cycle*, February 2006, at 4. See: http://www.world-nuclear.org/info/inf04.htm, Accessed June 2006.

[44] International Atomic Energy Agency, *Management of Radioactive Waste*, 1998. See: http://www.iaea.org/Publications/Factsheets/English/manradwa.html, Accessed June 2006.

[45] OECD Nuclear Energy Agency, *Nuclear Waste in Perspective*, OECD, 1996, at 61.

be used. Due to the complexity of the problem and the very long time frames to be considered, predictions about the ability of a repository to contain radioactivity have a significant degree of uncertainty. Adding to this uncertainty are future changes to the climate, as well as changes in human land use patterns and lifestyles. Over the next few hundred thousand years, the earth's climate will go through a number of natural variations while new climate states may emerge as a result of the build up of greenhouse gases.[46] The implication is that no geological repository will be able to guarantee the safe isolation of radioactive waste.

In 1995 the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency put forward the following environmental and ethical basis for geological storage of long-lived nuclear waste.

> After a careful review of the environmental and ethical issues, the members of the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency:
>
> - **consider** that the ethical principles of intergenerational and intragenerational equity must be taken into account in assessing the acceptability of strategies for the long-term management of radioactive wastes;
> - **consider** that from an ethical standpoint, including long-term safety considerations, our responsibilities to future generations are better discharged by a strategy of final disposal than by reliance on stores which require surveillance, bequeath long-term responsibilities of care, and may in due course be neglected by future societies whose structural stability should not be presumed;
> - **note** that, after consideration of the options for achieving the required degree of isolation of such wastes from the biosphere, geological disposal is currently the most favoured strategy;
> - **believe** that the strategy of geological disposal of long-lived radioactive wastes:
>   - takes intergenerational equity issues into account, notably by applying the same standards of risk in the far future as it does to the present, and by limiting the liabilities bequeathed to future generations; and
>   - takes intragenerational equity issues into account, notably by proposing implementation through an incremental process over several decades, considering the results of scientific progress; this process will allow consultation with interested parties, including the public, at all stages;
> - **note** that the geological disposal concept does not require deliberate provision for retrieval of wastes from the repository, but that even after closure it would not be impossible to retrieve the wastes, albeit at a cost;
> - **caution** that, in pursuing the reduction of risk from a geological disposal strategy for radioactive wastes, current generations should keep in perspective the resource deployment in other areas where there is potential

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[46] Smith,B. *Insurmountable Risks: The Dangers of Using Nuclear Power to Combat Global Climate Change.* A Report by the Institute for Energy and Environmental Research, May 2006. See: http://www.ieer.org, Accessed July 2006.

> for greater reduction of risks to humans or the environment, and consider whether resources may be used more effectively elsewhere;
>
> Keeping these considerations in mind, the Committee members:
>
> - **confirm** that the geological disposal strategy can be designed and implemented in a manner that is sensitive and responsive to fundamental ethical and environmental considerations;
> - **conclude** that it is justified, both environmentally and ethically, to continue development of geological repositories for those long-lived radioactive wastes which should be isolated from the biosphere for more than a few hundred years; and
> - **conclude** that stepwise implementation of plans for geological disposal leaves open the possibility of adaptation, in the light of scientific progress and social acceptability, over several decades, and does not exclude the possibility that other options could be developed at a later stage.[47]

In May 2006 the International Atomic Energy Agency and the OECD Nuclear Energy Agency jointly released safety standards for the geological disposal of radioactive waste. The standards noted the following aims of geological disposal:

- To contain the waste until most of the radioactivity, and especially that associated with shorter lived radionuclides, has decayed;
- To isolate the waste from the biosphere and to substantially reduce the likelihood of inadvertent human intrusion into the waste;
- To delay any significant migration of radionuclides to the biosphere until a time in the far future when much of the radioactivity will have decayed;
- To ensure that any levels of radionuclides eventually reaching the biosphere are such that possible radiological impacts in the future are acceptably low.[48]

The first geological repositories for high level and long lived wastes are expected to begin operation around 2010. About 20 more repositories are projected to be commissioned by the end of 2030.[49] The waste management policies for countries with nuclear reactors are summarised in the table below, including whether spent fuel is reprocessed or directly disposed. Finland and Sweden are well advanced with their plans and site selection for direct disposal of used fuel.

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[47] OECD Nuclear Energy Agency, The Environmental and Ethical Basis of Geological Disposal of Long-lived Radioactive Waste, 1995, at 5. See: http://www.nea.fr/html/rwm/reports/1995/geodisp/geological-disposal.pdf, Accessed June 2006.

[48] International Atomic Energy Agency and the OECD Nuclear Energy Agency, *Geological Disposal of Radioactive Waste, Safety Requirements No WS-R-4*, May 2006.

[49] International Atomic Energy Agency, *Management of Radioactive Waste*, 1998. See: http://www.iaea.org/Publications/Factsheets/English/manradwa.html, Accessed June 2006.

Waste Management for Used Fuel from Nuclear Power Reactors		
Country	**Policy**	**Facilities and progress towards final repositories**
Belgium	Reprocessing	Central waste storage & underground laboratory established. Construction of repository to begin about 2035.
Canada	Direct Disposal	Underground repository laboratory established. Repository planned for use 2025.
China	Reprocessing	Central used fuel storage in LanZhou.
Finland	Direct Disposal	Spent fuel storages in operation. Low & intermediate-level repositories in operation since 1992. Deep repository for used fuel under construction near Olkiluoto, open in 2020.
France	Reprocessing	Two facilities for storage of short-lived wastes. Site selection studies underway for deep repository for commissioning 2020.
Germany	Reprocessing but moving to direct disposal	Low-level waste sites in use since 1975. Intermediate-level wastes stored at Ahaus. Used fuel storage at Ahaus and Gorleben. High-level repository to be operational after 2010.
India	Reprocessing	Research on deep geological disposal for high level waste.
Japan	Reprocessing	Low-level waste repository in operation. High-level waste storage facility at Rokkasho-mura since 1995. Investigations for deep geological repository site begun, operation from 2035.
Russia	Reprocessing	Sites for final disposal under investigation. Central repository for low and intemediate-level wastes planned from 2008.
South Korea	Direct Disposal	Central interim HLW store planned for 2016. Central low- & ILW repository planned from 2008. Investigating deep HLW repository sites.
Spain	Direct Disposal	Low & intermediate-level waste repository in operation. Final HLW repository site selection program for commissioning 2020.
Sweden	Direct Disposal	A central used fuel storage facility in operation since 1985. Final repository for low to intermediate waste in operation since 1988. Underground research laboratory for HLW repository. Site selection for repository in two volunteered locations.
Switzerland	Reprocessing	Central interim storage for high-level wastes at Zwilag since 2001. Central low and intermediate-level storages operating since 1993. Underground research laboratory for high-level waste repository, with deep repository to be finished by 2020.
United Kingdom	Reprocessing	Low-level waste repository in operation since 1959. High-level waste is vitrified and stored at Sellafield. Underground HLW repository intended.
USA	Direct Disposal	Three low-level waste sites in operation. 2002 decision to proceed with geological repository at Yucca Mountain.

Source: World Nuclear Association, *Waste Management and the Nuclear Fuel Cycle*, February 2006, at 5. See http://www.world-nuclear.org/info/inf04.htm, Accessed June 2006.

6.2 International Nuclear Waste Disposal Concepts

Currently it is clear that each country that uses nuclear facilities and produces radioactive waste is responsible for managing its own wastes. However, in 2003 the Director-General of the OECD International Atomic Energy Agency, Dr Mohamed ElBaradei, in his annual statement to the UN General Assembly, spoke about international approaches to the nuclear fuel cycle. His first point referred to nuclear proliferation and restricting access to high level nuclear fuel to multinational control. The second referred to the disposal of waste. Dr ElBaradei stated:

> In light of the increasing threat of proliferation, both by States and by terrorists, one idea that may now be worth serious consideration is the advisability of limiting the processing of weapon-usable material (separated plutonium and high enriched uranium) in civilian nuclear programmes - as well as the *production* of new material through reprocessing and enrichment - by agreeing to restrict these operations exclusively to facilities under multinational control. These limitations would naturally need to be accompanied by appropriate rules of assurance of supply for would-be users.
>
> We should equally consider multinational approaches to the management and disposal of spent fuel and radioactive waste. Over 50 countries currently have spent fuel stored in temporary locations, awaiting reprocessing or disposal. Not all countries have the appropriate geological conditions for such disposal - and, for many countries with small nuclear programmes, the financial and human resources required for the construction and operation of a geological disposal facility are daunting.
>
> Taken together, these proposals in my view would provide enhanced assurance to the international community that the sensitive portions of civilian nuclear fuel cycle programmes are not vulnerable to misuse.[50]

Since this speech in 2003, two important documents have been released by the International Atomic Energy Agency. In regards to waste, in October 2004 the Agency released the paper *Developing multinational radioactive waste repositories: Infrastructural framework and scenarios of cooperation*. The paper canvassed three scenarios for developing multinational waste repositories:

- Add-on Scenario: the host country offers to complement its national inventory of wastes for disposal by wastes imported from other countries. Under this scenario, the host country has to have the: political will; technical and financial resources; and the natural conditions such as geology to develop a repository. It is possible that the host country would first develop its waste repository program and then offer these services to partner countries;
- Cooperation Scenarios: three of these scenarios were developed. They are characterised by the participation of partner countries developing a repository program jointly. They are more complex than the add-on scenario, as they involve

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[50] "Statement To the Fifty-Eighth Regular Session of the United Nations General Assembly" by IAEA Director General Dr. Mohamed ElBaradei. 3 November 2003. See: http://www.iaea.org/NewsCenter/Statements/2003/ebsp2003n023.html, Accessed July 2006.

full scale multinational cooperation. The three cooperation scenarios were:

  - Several industrialised countries with relatively small nuclear energy programs decide to cooperate for the disposal of their radioactive waste in a host country satisfying all necessary technical requirements;
  - Countries with small quantities of radioactive wastes and in varying stages of development seek assistance from each other and cooperate to ensure that one of their number acquires all necessary technology and institutional structures;
  - Specialising of repositories for specific types of wastes, possibly combined with arrangements for international exchanges.
- Full international or supranational Scenario: in this scenario, the waste repository is in the control of an international body, that would need to be created. The host country would effectively cede control of the site to the international body. The political sensitivity of this option was acknowledged.[51]

The move towards multinational cooperation in regards to geological waste repositories has significance for Australia. For example, Pangea Resources (1997 – 2002) canvassed geological regions worldwide suitable for a nuclear waste repository. Sites in southern Africa, Argentina, western China and Australia were identified as having the appropriate geological structure for a deep repository. A site in Western Australia was selected on economic and political grounds as the preferred region, and a detailed proposal was developed. The Pangea concept envisaged a dedicated port and rail link to an inland repository site covering around five square kilometres on the surface and 20 square kilometres 500 metres underground. Their business plan was based on taking 75,000 tonnes of spent fuel and high level waste, plus some intermediate level wastes from decommissioning nuclear power stations, over a 40 year period. The plan had: an estimated capital cost of US$6 billion; annual operating costs of US$400 million; total export revenue over 40 years of about US$100 billion; and payment to governments of about US$50 billion (1998 dollars).[52]

The Pangea project raised the profile of the global debate on international repositories. It received support in scientific and business circles worldwide and in Australia. However, political opposition in Australia and in West Australia was strong from the initial announcement. The concept has a continuing support base but Pangea's Australian office has closed and the European Head Office has ceased operations.[53]

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[51] International Atomic Energy Agency, *Developing multinational radioactive waste repositories: Infrastructural framework and scenarios of cooperation.* October 2004, at 17. See: http://www-pub.iaea.org/MTCD/publications/PDF/te_1413_web.pdf. Accessed June 2006.

[52] World Nuclear Association, *International Nuclear Waste Disposal Concepts*. October 2005, at 3. See: http://www.world-nuclear.org/info/printable_information_papers/inf21print.htm, Accessed June 2006.

[53] International Atomic Energy Agency, *Developing multinational radioactive waste repositories: Infrastructural framework and scenarios of cooperation.* October 2004, at 13. See: http://www-pub.iaea.org/MTCD/publications/PDF/te_1413_web.pdf. Accessed June 2006.

In 2001 the Russian parliament passed legislation to allow the import of spent nuclear fuel. In 2003 the Russian city of Krasnokamensk, 7000 km east of Moscow, was suggested as a site for a major spent fuel repository.[54] It has been reported that the United States Government will open negotiations with Russia on a civilian nuclear agreement, opening the way for Russia to import spent nuclear fuel.[55]

The other important document commissioned by the International Atomic Energy Agency was the 2005 paper *Multilateral Approaches to the Nuclear Fuel Cycle*. This paper focused on multilateral approaches to the front and back end of the nuclear fuel cycle, ie, the enrichment of uranium and the reprocessing and disposal of spent fuel. Head of the international Expert Group who wrote the report, Bruno Pellaud, stated:

> Such approaches are needed and worth pursuing, on both security and economic grounds….A joint nuclear facility with multinational staff puts all participants under a greater scrutiny from peers and partners, a fact that strengthens non-proliferation and security…Moreover, they have the potential to facilitate the continued use of nuclear energy for peaceful purposes.[56]

Pellaud noted that multilateral approaches already are followed in Europe, and said they merit close consideration in South Asia and other regions. The report identified the following five multilateral approaches to help increase non-proliferation:

> 1. Reinforcing existing commercial market mechanisms on a case-by-case basis through long-term contracts and transparent suppliers' arrangements with government backing. Examples would be: fuel leasing and fuel take-back offers; commercial offers to store and dispose of spent fuel; as well as commercial fuel banks.
> 2. Developing and implementing international supply guarantees with IAEA participation. Different models should be investigated, notably with the IAEA as guarantor of service supplies, e.g. as administrator of a fuel bank.
> 3. Promoting voluntary conversion of existing facilities to multilateral nuclear approaches, and pursuing them as confidence-building measures, with the participation of Nuclear Proliferation Treaty (NPT) non-nuclear weapon States and nuclear-weapon States, and non-NPT States.
> 4. Creating, through voluntary agreements and contracts, multinational, and in particular regional, multilateral nuclear approaches for new facilities based on joint ownership, drawing rights or co-management for front-end and back-end nuclear facilities, such as uranium enrichment; fuel reprocessing; disposal and storage of

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[54] World Nuclear Association, *International Nuclear Waste Disposal Concepts*. October 2005, at 8. See: http://www.world-nuclear.org/info/printable_information_papers/inf21print.htm, Accessed June 2006.

[55] "Bush offers Russia deal on spent fuel." in *The Sydney Morning Herald*, 10 July 2006.

[56] International Atomic Energy Agency, "Expert Group Releases Findings on Multilateral Nuclear Approaches. Staff Report". 22 February 2005. See: http://www.iaea.org/NewsCenter/News/2005/fuelcycle.html, Accessed June 2005.

spent fuel (and combinations thereof). Integrated nuclear power parks would also serve this objective.
5. The scenario of a further expansion of nuclear energy around the world might call for the development of a nuclear fuel cycle with stronger multilateral arrangements – by region or by continent - and for broader cooperation, involving the IAEA and the international community.[57]

6.3 Australian Radioactive Waste Plans

At present Australia has about 3700 cubic metres of low-level waste awaiting proper disposal. Over half of the present material is lightly-contaminated soil from CSIRO mineral processing research over 30 years ago. Annual arisings are small, about 40 cubic metres, equivalent to three truckloads. In addition, there are about 500 cubic metres of long lived intermediate level waste, with annual arisings of about 5 cubic metres from all sources nation wide.[58]

In 1992 the Commonwealth Government, with the support of State and Territory Governments, announced a project to construct a near-surface repository for disposal of Australia's low level and short-lived intermediate level radioactive waste. A site selection process ultimately resulted in the selection of three possible sites near Woomera in South Australia. On 7 July 2003, the Commonwealth, using the urgency provisions of the *Lands Acquisition Act 1989* (LAA), compulsorily acquired one of the sites and its associated access route.

As a separate development, in 2001 the Australian Government announced that it would establish a safe, purpose-built facility on Commonwealth land for the storage of long-lived intermediate level radioactive waste produced by Australian Government agencies.

However, on 21 June 2004, the Full Court of the Federal Court of Australia quashed the Commonwealth's Woomera land acquisition, ruling that the Commonwealth had misused the urgency provisions of the LAA in acquiring the site. Following this decision, the Prime Minister announced on 14 July 2004 that the Australian Government was abandoning the national repository project. At the same time, Mr Howard announced that the Australian Government will construct co-located facilities on Commonwealth land to manage low and intermediate level radioactive waste generated by Australian Government agencies. The States and Territories then became responsible for the management of radioactive waste generated by government agencies, individuals and organizations within their jurisdiction.[59]

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[57] International Atomic Energy Agency, *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report submitted to the Director General of the International Atomic Energy Agency*. February 2005, at 15. See: http://www.iaea.org/Publications/Documents/Infcircs/2005/infcirc640.pdf, Accessed June 2006.

[58] World Nuclear Association, *Radioactive waste repository & store for Australia*. August 2005. See: http://www.world-nuclear.org/info/inf72.htm, Accessed June 2006.

[59] Commonwealth of Australia, Department of Science, Education and Training, *National Repository Project*. See: http://www.radioactivewaste.gov.au, Accessed July 2005.

On July 15 2005 the Minister for Education, Science and Training, the Hon Dr Brendan Nelson MP, announced three potential locations to be investigated for the Commonwealth Radioactive Waste Management Facility. The three locations are Department of Defence properties located near Katherine and Alice Springs in the Northern Territory:

- Fishers Ridge, Department of Defence property, southeast of RAAF Base Tindal;
- Mt Everard, Department of Defence property, northwest of Alice Springs; and
- Harts Range, Department of Defence property, northeast of Alice Springs.[60]

In late 2005 the Australian Parliament passed the *Commonwealth Radioactive Waste Management Act 2005* to ensure that the Commonwealth can proceed with certainty to establish the Facility. Once a preferred site is selected, the proposal to construct the Facility at that site will be referred to the Minister for the Environment and Heritage for assessment under the *Environment Protection and Biodiversity Conservation Act 1999*. The Commonwealth regulatory agencies, the Department of the Environment and Heritage and the Australian Radioactive Protection and Nuclear Safety Authority (ARPANSA), have agreed to a joint environmental assessment and siting licence process. The assessment process, including the development of an environmental impact statement, is expected to take about two years. Should approval to site the Facility be granted, licences for construction and operation of the facility will then need to be obtained from ARPANSA. It is estimated that, assuming all regulatory approvals are given, the Commonwealth Radioactive Waste Management Facility will be ready to accept radioactive waste in 2011.[61]

7.0 AUSTRALIAN URANIUM AND NON-PROLIFERATION

The *Treaty on the Non-Proliferation of Nuclear Weapons* (NPT) is the centerpiece of the international nuclear non-proliferation regime. Since coming into force in 1970, the Treaty has become almost universal, with 189 parties to it. Only three states - Israel, India and Pakistan, remain outside the Treaty. A fourth, the Democratic People's Republic of Korea, announced its withdrawal from the Treaty in 2003.

Under the Treaty, non-nuclear weapon states commit not to acquire nuclear weapons, and to conclude an agreement with the International Atomic Energy Agency (IAEA) for the application of IAEA safeguards to all their nuclear material to verify their compliance with this commitment. The IAEA is the verification authority for the Treaty.

The Australian Government has two nuclear regulatory agencies: the Australian Safeguards and Non-Proliferation Office (ANSO); and the Australian Radiation Protection and Nuclear

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[60] Commonwealth of Australia, Department of Science, Education and Training, *Managing Australia's Radioactive Waste*. See: http://www.radioactivewaste.gov.au, Accessed July 2005.

[61] Commonwealth of Australia, Department of Education, Science and Training, *About Locations, Assessment and Approval*, See: http://www.radioactivewaste.gov.au/pdf_documents/fact_sheets/RadWaste_Fact_Sheet_ABOUT_LOCATIONS_ASSESSMENT_AND_APPROVAL_005.pdf, Accessed July 2006.

Safety Agency (ARPANSA). ARPANSA is responsible for protecting the health and safety of people and the environment from the harmful effects of radiation. The principal focus of ANSO's work is on international and domestic action to prevent the proliferation of weapons of mass destruction, including nuclear, chemical and biological. ASNO is responsible for nuclear safeguards and physical protection. ASNO ensures that nuclear materials - uranium, thorium and plutonium, and nuclear items - facilities, equipment, technology and nuclear-related materials, are used only for authorised purposes, are properly accounted for, and are protected against unauthorised use. An important part of this responsibility is ensuring that Australia's treaty commitments are met, particularly that nuclear activities are conducted for exclusively peaceful purposes.[62]

Australia's uranium export policy is designed to provide assurances that exported uranium and its derivatives cannot facilitate the development of nuclear weapons or be used in other military programs. This is done by accounting for amounts of Australian-Obligated Nuclear Material (AONM) as it moves through the nuclear fuel cycle. Australian uranium may only be exported to countries that have a bilateral safeguards agreement with Australia.

In summary, Australia's uranium export policy is that:

- Australian uranium may only be exported for peaceful non-explosive purposes under Australia's network of bilateral safeguards Agreements, which provide for:
    - coverage of uranium exports by IAEA safeguards from the time they leave Australian ownership;
    - continuation of coverage by IAEA safeguards for the full life of the material or until it is legitimately removed from safeguards;
    - fallback safeguards in the event that IAEA safeguards no longer apply for any reason;
    - prior Australian consent for any transfer of AONM to a third party, for any enrichment beyond 20 per cent of uranium-235 and for reprocessing of AONM, and
    - physical security requirements;
- Australia retains the right to be selective as to the countries with which it is prepared to conclude safeguards arrangements;
- Non-nuclear weapon state customer countries must at a minimum be a party to the NPT and have concluded a fullscope safeguards Agreement with the IAEA;
- Nuclear weapon state customer countries must provide an assurance that AONM will not be diverted to non-peaceful or explosive uses and accept coverage of AONM by IAEA safeguards; and
- Commercial contracts for the export of Australian uranium should include a clause noting that the contract is subject to the relevant bilateral safeguards arrangement;
- On 4 May 2005 the Australian Government announced that it is further tightening its export policy. As a pre-condition for the supply of Australian obligated uranium to non-nuclear weapon states, recipients must have signed the Additional Protocol with the IAEA.[63] The Additional Protocol, a legal document with the IAEA, has as

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[62] Australian Safeguards and Non-Proliferation Office, *Annual Report 2004-2005*, at 28.

[63] Australian Government, *Australia' Uranium Export Policy*. See: http://www.dfat.gov.au/security/aus_uran_exp_policy.html, Accessed July 2006.

> its principal aim to enable the IAEA inspectorate to provide assurance about both declared and possible undeclared activities. Under the Protocol, the IAEA is granted expanded rights of access to information and sites, as well as additional authority to use the most advanced technologies during the verification process.[64]

A full discussion on nuclear non-proliferation issues is beyond the scope of this paper. However, it is useful to conclude with some comments from the Annual Report of the Australian Safeguards and Non-Proliferation Office:

> Perhaps the most serious technical challenge that has emerged to IAEA safeguards is the detection of undeclared nuclear activities, especially centrifuge enrichment plants. The recent cases of Iran (which had engaged in undeclared nuclear activities for almost 20 years) and Libya (which was able to buy a centrifuge plant off the shelf through the AQ Khan criminal supply network) shows the need for improvements across the board in detection methodology and information sharing, as well as in national controls over manufacture and trade in sensitive technologies. The IAEA's capabilities are improving, but further assistance from governments is required.
>
> … The greatest challenge for the non-proliferation regime is the weakening of political support for the NPT itself. This can be seen in the most recent NPT Review Conference held in May 2005, which failed to agree to any final document, notwithstanding that proliferation is widely seen as one of the most serious issues in contemporary international affairs.
>
> … Far from outliving its usefulness, the NPT is as important today as it ever has been, even more so given current proliferation challenges. Arguably, it is only by luck that the world has survived the last 60 years without nuclear war. This does not allow governments to be complacent about the dangers of proliferation. Proliferation threatens the vital national interests of all countries, rich and poor, strong and weak, 'North' and 'South' alike, and it is imperative that all support the Treaty and IAEA safeguards with a vigour and commitment not currently in evidence.[65]

8.0 THE ECONOMICS OF NUCLEAR POWER

The economics of nuclear power have been well studied and commented upon around the world over recent years. As will be demonstrated below, the cost basis of nuclear power is very different from that of traditional fossil fuel power stations. In the latter, the power station is relatively cheap to construct and the price of the fossil fuel has an important impact on the electricity generating price. The reverse is true for nuclear power plants, which have a very high capital cost but a low fuel cost. For those investing in fossil fuel generating technologies, risks include: rising fossil fuel prices; the potential for governments to impose a carbon tax on carbon emissions; and other regulatory structures that force electricity retailers to buy electricity from zero emission sources. For nuclear

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[64] International Atomic Energy Agency, *Safeguards Overview: Comprehensive Safeguards Agreement and Additional Protocols.* See: http://www.iaea.org/Publications/Factsheets/English/sg_overview.html, Accessed July 2006.

[65] Australian Safeguards and Non-Proliferation Office, *Annual Report 2004-2005*, at 12.

power stations, two uncertainties in particular increase the risks of new nuclear power investments: the long lead time for projects; and the high up-front capital cost and the lack of flexibility.[66]

In a liberalised electricity market, the private sector must weigh up these risks with the prospect of which technology can produce the best returns. How the market assesses these issues and interacts with governments to develop new power generation systems will have implications for decades to come.

This section of the paper analyses the economics of nuclear power, firstly from a global perspective, and then for Australian conditions.

8.1 The International Context of Nuclear Economics

There have been several international studies on the economics of nuclear power released in the last 12 months or so. One of the most recent was done for the United Kingdom Sustainable Development Commission, which is the Government's independent 'watchdog' on sustainable development, reporting to the Prime Minister and the First Ministers of Scotland and Wales. In this study, it was noted that nuclear power in the United Kingdom would compete largely with gas-fired power. In addition, the costs of wind power were also included as it is becoming the predominant renewable energy technology.

The percentage proportion of electricity generating costs for the three technologies is presented below. Up to 75% of the cost of electricity from a nuclear power plant is the upfront capital or construction cost, compared to up to 40% for a gas plant. In contrast, the proportion of fuel cost for a nuclear plant is no more than 10%, but up to 65% of a gas power station.

Representative Proportions of Electricity Generating Costs – Percentage

	Nuclear	**Combined Cycle Gas Turbine**	**Renewable (Wind)**
Construction or capital (including interest during construction)	60 – 75	30 – 40	85 – 90
Fuel	5 – 10	50 – 65	0
Operation and Maintenance	8 – 15	5 – 10	5 – 15
Back-end	*	0	0

Source: Sustainable Development Commission, *The Role of nuclear power in a low carbon economy*. Paper 4: The Economics of Nuclear Power. An evidence based report for the Sustainable Development Commission by Science and Technology Policy Research and NERA Economic Consulting, March 2006, at 7.

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[66] Noe van Hulst, International Energy Agency, "World Energy Outlook and the Role of Nuclear Energy." In Nuclear Energy – Yesterday's mistake or tomorrow's solution? An IEE and IEEE Event Conference, Dublin, 9 March 2006. See: www.worldenergyoutlook.org/speeches.asp.

As nuclear power plants have relatively high capital costs but low operating costs, they run most economically at very high load factors, meeting the demand for base-load electricity.

These differing cost bases immediately introduce different variables to determine the cost of power from different generating technologies. For fossil fuels, assumptions must be made on the cost of gas (and/or coal) with projections for the next 40 years or so. As the price of fuel is the major determinant of the price of electricity for a fossil fuelled plant, the assumptions used are an important variable to compare electricity prices from power stations of different technologies. In contrast, for a nuclear power station, expectations about the construction cost and the discount rate used can often determine whether a proposed plant is viable or not.

The asterisk in the previous table against back-end costs, for waste and decommissioning, reflects a number of uncertainties. First, costs are affected by the decision whether or not to reprocess spent fuel, or to treat it as waste. Secondly, both decommissioning and waste management costs are highly uncertain because there is so little relevant commercial experience. However, these costs are likely to be very small as a percentage of generation costs. Some calculations suggest less than 1%. To provide funds for these back-end costs, common practice for privately owned nuclear power plants is to require owners to establish a segregated trust fund and allow the fund to accumulate by annual contributions for at least the expected plant lifetime.[67]

Having identified that capital costs and associated construction times are the most important determinant of generating costs of any future nuclear plant in the United Kingdom, the authors of the Sustainable Development Commission report observed that a major problem is the lack of relevant data sources on these costs. This is because neither of the two most likely reactor types to be built in the UK (and potentially also for Australia), the Westinghouse AP 1000 and the European Pressurised Water Reactor (EPR), have been built anywhere in the world. However, the first EPR started construction in Finland in 2005 and France is likely to start a second unit in 2006. Both technologies have established regulatory clearance in important markets: the AP1000 in the USA and the EPR in Finland and France. Data on the capital costs of nuclear power suffer in the following ways:

- A significant part of the explanation for the differences between capital cost between different studies is variation in assumptions about the number of reactors built. A program of essentially identical reactors, usually a minimum of eight or ten, is expected to lead to significant reductions in average capital cost per kw as a result of learning and batch production. Korean data suggests that the seventh and eighth units in a series may have capital costs per kilowatt up to 28% below the costs of units one and two in the series. Much confusion results from the fact that not all studies on nuclear capital costs make clear whether or not a single reactor or

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[67] Sustainable Development Commission, *The Role of nuclear power in a low carbon economy. Paper 4: The Economics of Nuclear Power.* An evidence based report for the Sustainable Development Commission by Science and Technology Policy Research and NERA Economic Consulting, March 2006, at 7.

program is being assumed. To reap the full benefits of learning requires a commitment to a scheduled program of identical reactors at the first decision point. This, when combined with the large unit size of potential new reactors is a source of inflexibility;

- Much, if not all of the data on capital costs can be traced back to industry sources, usually reactor vendors. Whilst this is inevitable, it does little for confidence in the balanced nature of the figures;
- Where vendors enter into contracts for reactor sales, data may well become more realistic because vendors may lose money if they contract too low. However, only one contract exists, for Finland, and the data released is aggregative and rounded. Vendors may also pursue 'loss leaders' on early contracts in the expectation of later, more profitable contracts as learning takes place. Finally, 'turnkey contracts', where the vendor commits to build a reactor at a fixed price, are unlikely to indemnify clients against all risks – for example 'force majeure' (ie, act of God) clauses.[68]

These preliminary comments must be kept in mind for the next section of the paper, which canvasses electricity generation costs from different technologies.

One of the most authoritive sources of information about the projected costs of generating electricity comes from a 2005 publication by the OECD. In this study, cost data were provided for 130 power plants, including: nuclear; coal-fired; gas-fired; wind power; solar; and combined heat and power. Based on information provided by different countries, the 'levelised lifetime cost approach' was used. This calculated generating costs for the different technologies using generic assumptions: an economic lifetime of 40 years; average load factor for base load plants of 85%; and discount rates of 5% and 10%. The levelised generation costs were:

- Coal-fired Plants:
  - 5% discount rate: between 25 and 50 US$MWh for most coal-fired plants;
  - 10% discount rate: between 35 and 60 US$MWh, for nearly all coal-fired plants;
- Gas-fired Generating Technologies:
  - 5% discount rate: between 37 and 60 US$MWh;
  - 10% discount rate: between 43 and 63 US$MWh;
- Nuclear Generating Technologies:
  - 5% discount rate: between 21 and 31 US$MWh (except for two);
  - 10% discount rate: between 30 and 50 US$MWh (except for two);
- Wind Generating Technologies:
  - 5% discount rate: between 35 and 95 US$MWh, but for a large number of plants are below 60 US$MWh;
  - 10% discount rate: between 45 and more than 140 US$MWh;

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[68] Sustainable Development Commission, *The Role of nuclear power in a low carbon economy. Paper 4: The Economics of Nuclear Power.* An evidence based report for the Sustainable Development Commission by Science and Technology Policy Research and NERA Economic Consulting, March 2006, at 17.

- Solar Generating Technologies:
  - For solar plants the availability/capacity factors varied from 9% to 24%;
  - 5% discount rate: at the higher capacity factor costs are reaching 150 US$MWh;
  - 10% discount rate: at the higher capacity factor costs are more than 200 US$MWh.
  - At the lower capacity factor costs are reaching or well above 300 US$MWh.
- Combined Heat and Power Generating Technologies:
  - 5% discount rate: between 25 and 65 US$MWh;
  - 10% discount rate: between 30 and 70 US$MWh.[69]

The above costs indicate that, from a global perspective, nuclear power is very competitive with both coal and gas-fired power. In regards to renewable sources, wind technology is clearly cheaper than solar, which is the most costly of all the reported technologies. Combined heat and power generating technologies are competitive, but costs are highly dependent on the use and value of the co-product, the heat, and thereby are very site specific.

The OECD noted that markets for natural gas are undergoing substantial changes, and coal markets are under influence from new factors. Environmental policy is playing an increasingly important role, which will influence fossil fuel costs. In addition, security of energy supply remains a concern for most OECD countries. The OECD concluded that the levelised costs of generation in each country were sensitive to the discount rate used and the projected prices of natural gas and coal. The preferred generating technology will depend on the specific circumstances for each project. On a global scale there is room and opportunity for all efficient generating technologies.[70]

Worldwide, there are six or so relatively major studies on nuclear economics that are consistently repeated in the literature. The Sustainable Development Commission summarised them, with the overall projected cost of producing electricity from: nuclear; coal; and combined cycle gas power plant from six different studies shown below. It is clear that even within a single jurisdiction, for instance the United States, there remain wide divergences between cost expectations.

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[69] OECD, Nuclear Energy Agency, International Energy Agency, *Projected Costs of Generating Electricity, 2005 Update.* 2005, at 78.

[70] OECD, Nuclear Energy Agency, International Energy Agency, *Projected Costs of Generating Electricity, 2005 Update.* 2005, at 14.

Overall Cost Estimates of Nuclear Electricity Production from Six Studies

Study	Nuclear	Coal	Combined Cycle Gas	Wind
Mass. Inst. Tech. (2003)	6.7 c/kWh ($US)	4.2	3.8 – 4.1	
Royal Academy Engineers (2004)	2.26 p/kWh £	2.5-3.2	2.2	3.7
OECD NEA (2005)	3 – 5 c/kWh ($US)	3.5 – 6 c/kWh	4.0 – 6.3 c/kWh	4.5 – 14.0 c/kWh
Uni. Of Chicago (2004)	4.7-7.1 c/kWh ($US)	3.3-4.5 c/kWh	3.3-4.5 c/kWh	
Scully (2002)	3.8–4.2c/kWh ($US)			
Tarjanne & Luostarinen (2002-Finland)	2.37 euro cents/kWh	2.81	3.23	5

Source: Sustainable Development Commission, *The Role of nuclear power in a low carbon economy*. Paper 4: The Economics of Nuclear Power. An evidence based report for the Sustainable Development Commission by Science and Technology Policy Research and NERA Economic Consulting, March 2006, at 20.

MIT: Massachusetts Institute of Technology, *The Future of Nuclear Power: an Interdisciplinary MIT Study*. Boston MIT, 2003

Royal Academy of Engineering, *The Cost of Generating Electricity*. London. The Royal Academy of Engineering, 2004.

OECD Nuclear Energy Agency / International Energy Agency, *Projected Costs of Generating Electricity*, 2005.

University of Chicago, *The Economic Future of Nuclear Power – a study conducted at the University of Chicago*, 2004.

Scully Capital, *Business Case for New Nuclear Power Plants: Bringing public and private resources together for nuclear energy*. 2002.

Tarjanne, Risto, and Kari Luostarinen. *Economics of Nuclear Power in Finland*. Lappeenranta, Finland: Lappeenranta University of Technology, June, 2002.

The above studies demonstrate the complexity from an international perspective in comparing the costs of electricity from various sources. Costs are often very country specific, making it difficult to translate directly into meaningful data for Australian conditions. However, some general conclusions can be drawn. Firstly, the competitiveness of nuclear energy mainly depends on the capital cost of the plant together with the discount rate used. A reduction in nuclear capital costs is likely once the 'first of a kind' costs are absorbed. Finally, any greenhouse gas abatement mechanisms that add to the price of fossil fuels will improve the competitiveness of nuclear power.

8.2 The Economics of Nuclear Power in Australia

A report prepared for the Australian Nuclear Science and Technology Organisation (ANSTO) analysed the potential of nuclear energy in Australia, primarily from the financial standpoint. The author of the report, Professor Gittus, developed a financial model to forecast the cost of generating electricity in Australia from new power stations, including nuclear, coal and combined cycle gas turbine. The parameters of his model are shown below:

Parameters of the Gittus Financial Model of the Cost of Generating Electricity from new Power Stations in Australia

	Nuclear	**Coal**	**Combined Cycle Gas Turbine**
MegaWatts equiv	1250	500	400
Efficiency %	35	41	55
Investment Cost M$	3,556	662	373
Investment Cost A$/kWequiv	2,846	1,324	931
Fuel Price A$/MWh	1.63	6.83	17.78
Fuel costs of electricity, A$Mwe	4.65	16.69	32.34
Annual fixed operation and maintenance costs, % of investment	1.5	2	1.5
Variable operation and maintenance costs, A$/Mwe	5.55	8.00	0.50
Economic lifetime yrs	40	25	25
Interest rate %	5	5	5
Annuity factor %	5.83	7.10	7.10

Source: Gittus,JH. *Introducing Nuclear Power to Australia. An Economic Comparison. A Report* Prepared for the Australian Nuclear Science and Technology Organisation, March 2006, at 53.

Gittus claimed that the above parameters should be a good representation of modern designs for new nuclear, coal-fired and CCGT power stations. However, it seems unlikely that a new coal or CCGT power station would have an economic lifetime of 25 years, compared to the predicted lifetime of a nuclear station of 40 years. Nevertheless, with these parameters, Gittus forecasted the generation costs as follows:

Gittus Model of Generation Cost Forecasts for new Power Stations

	Nuclear	Coal	CCGT
Generation Cost A$/MWeh	36.34	39.77	42.84

Source: Gittus, JH, *Introducing Nuclear Power to Australia. An Economic Comparison*. A Report Prepared for the Australian Nuclear Science and Technology Organisation, March 2006, at 54.

From the Gittus analysis, the cost of electricity from a new nuclear power station is cheaper than that from both coal and CCGT. Gittus then compared his projected costs in Australian dollars against those of other countries, as per the 2005 OECD report noted above, as shown below:

A$/Mweh	**Nuclear**	**Coal**	**CCGT**
Finland	37.71	49.73	
France	34.70	45.49	53.56
Germany	39.07	48.09	66.94
Switzerland	39.35		59.57
Netherlands	48.91		82.52
Czech Republic	31.42	40.17	67.90
Slovakia	42.76	65.30	76.37
Romania	41.81	62.16	
Japan	65.58	67.63	71.18
Korea	31.97	29.51	63.53
USA	41.12	37.02	63.80
Canada	35.52	42.49	54.65
Australia, Gittus model	38.20	40.83	43.55

Source: Gittus, JH, *Introducing Nuclear Power to Australia. An Economic Comparison*. A Report Prepared for the Australian Nuclear Science and Technology Organisation, March 2006, at 54.

Excluding Australia and Japan, Gittus notes that the average cost of nuclear generation for all the above countries is A$38.58 MWeh. Virtually the same as the forecast cost of $38.20 for Australia using the same 85% load factor as was used for the other 12 OECD countries. Using this comparison, Gittus is confident that his model is correct. Gittus then states: "…in all 12 countries, nuclear is the least expensive, followed by coal and then CCGT."[71] However, it is clear from the above table that both the USA and Korea have cheaper coal sources than nuclear.

Gittus says that the above costs are those for a nuclear plant that is built to time and cost and operated to cost. However, Australia would have to learn the 'first of a kind' construction lessons and operating procedures that inevitably add to the cost. He then developed a financial plan to build a nuclear power station in Australia, based on building the 5th and possibly later Westinghouse AP1000 reactor in the world (the first four having being built in for example the United States). Under this plan, the Government would advance a 'first of a kind' insured loan, which would be repaid to the Government, together with a premium, out of revenues from the power station once it began to generate electricity. The risk that the loan proved inadequate to cover 'first of a kind' expenses would be covered to the extent possible by insurance. Gittus identifies both construction risks and operational risks. In regards to construction risks, there is a chance that the 'first

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[71] Gittus, JH, *Introducing Nuclear Power to Australia. An Economic Comparison*. A Report Prepared for the Australian Nuclear Science and Technology Organisation, March 2006, at 57.

of a kind' loan advanced by the Government is inadequate. The cost of this would be insured amongst various parties according to the following provisional divisions:

- Insurers take 19% of the construction risks. They will be paid to do this by means of a retrospective premium, taken out of the profits the station makes once it is generating electricity. There will be a chance that for unforeseen reasons the 'first of a kind' cost exceeds the estimate and in this case the insurers will have to top it up;
- Government takes 56% of the construction risks. As above, they will be paid a retrospective premium. However, there will be a chance that for unforeseen reasons the 'first of a kind' cost exceeds the estimate and in this case the government will have to help the insurers top it up;
- Shareholders, Banks, the Vendor and the Owner take 25% of the risks. The insurer and government may insist that these groups take on more of the risk;
- The fuel supplier and electricity distributors may also take on some of the risk.

For operational risks the following division was suggested:

- Government takes, as governments have done with all existing nuclear power stations, half the operational risk. It does this by agreeing to pay all costs to third parties of the most severe nuclear accidents;
- Most of the remaining operational risk is shared equally between insurers, shareholders, banks, the vendor and owner of the plant.

Once these risks were factored in to the price of new nuclear power station in Australia, Gittus developed new costs for generating electricity, as shown below:

Scenario	**Cost of Electricity A$MWeh**
World's first AP1000, owner takes entire risk	67
World's 5th to 9th AP1000, owner takes entire risk	46
World's 5th to 9th AP1000, government, owners and other stakeholders share the risk	38
Reference case: settled down cost	36

From this analysis, it can be seen that if Australia builds the world's first AP1000, with the owner taking the entire risk, then the cost of electricity is virtually double that of the reference case. This is due to the 'first of a kind' costs, and clearly makes this uneconomic. In recognition of this, the United States government has offered to pay half the capital cost of the first six new nuclear power stations to be built in that country and to subsidise the electricity that they produce.

If Australia builds the world's 5th to 9th AP1000, again with the owner taking the entire risk, it is still not an economic proposition. It is only when government is prepared to take some of the risk that nuclear power becomes economic in Australia, with an electricity cost of A$38MWeh. In this case, as per the Gittus financial plan, the Government is asked to be a source of debt and to act as the insurer of the 'first of a kind' costs. This loan is designed to be repaid.

However, if the Gittus risk-sharing financial plan was not adopted, a direct government subsidy would be required to make the cost of electricity competitive with coal. For the world's 5th to 9th AP1000 reactors, this would need to be a government subsidy of 14.31% of the capital cost of the 5th plant together with a subsidy of 21.41% of the cost of electricity for the first 12 years of operation.[72]

8.3 Nuclear Economics: Conclusion

In Europe, North America and Australia electricity supply industries have seen a transition from vertically integrated franchise monopoly structures (typically State-owned or regulated in the United States and Australia) to unbundled companies trading in liberalised wholesale markets. With the exception of the recent Finnish (2004) and French (2005) European Pressurized Water reactors, there have been no new nuclear power stations built in the last decade in liberalised electricity markets.[73]

In liberalised electricity markets, investments are profit motivated with the choice of technology left to the market. Roques *et al* argue that even if the costs of nuclear electricity generation are the same as other technologies, it is likely to remain unattractive to investors for the following reasons:

- Investors have a strong preference for a short payback period, which makes investments with short lead time more attractive. Nuclear power station lead times are much longer than coal or gas fuelled stations;
- Construction costs for nuclear power stations are two to four times greater than for a combined cycle gas turbine station;
- The lack of recent experience with building a nuclear power station makes it difficult to get reliable cost estimates. The history of nuclear electricity includes a list of seriously delayed construction and cost overruns. Investors must also confront the regulatory and political challenges associated with obtaining a licences to build and operate a plant at a specific site;
- The greater size of nuclear technology exposes investors to greater downside risks.[74]

Conversely, there are potentially two attributes of nuclear power generation that could make it more appealing to investors. These are:

- Rising fossil fuel prices, carbon trading or carbon taxes will make nuclear power more competitive compared to fossil fuel plants. Already, in Europe carbon

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[72] Gittus, JH, *Introducing Nuclear Power to Australia. An Economic Comparison*. A Report Prepared for the Australian Nuclear Science and Technology Organisation, March 2006, at 126.

[73] Roques, FA *et al*, "Nuclear Power: a Hedge against Uncertain Gas and Carbon Prices?" in *Energy Journal*, Vol 27, No 4, 2006, at 1.

[74] Roques, FA *et al*, "Nuclear Power: a Hedge against Uncertain Gas and Carbon Prices?" in *Energy Journal*, Vol 27, No 4, 2006, at 4.

dioxide emissions are now priced by the emissions trading scheme;

- Secondly, investing in nuclear plants can be thought as a form of hedging against the volatility and risk of fossil fuel and carbon prices for a generating company. For a company already operating a fossil fuel plant, investing in a nuclear plant reduces the company's overall exposure to fossil fuel prices.[75]

The conclusion of Roques *et al* is similar to what the financial modelling work of Gittus has shown for Australia. Roques *et al* stated:

> Despite recent revived interest in nuclear power, the prospects for merchant nuclear investment in liberalised industries without government support do not seem promising. The reason is relatively simple: quite apart from overcoming any regulatory and public opinion difficulties, the risks of nuclear power have been adversely affected by liberalisation. High capital cost, uncertain construction cost, and potential construction and licensing delays are likely to lead private investors to require a substantial risk premium over coal and gas fired power plants to finance at least the first few nuclear units.[76]

9.0 NUCLEAR DEVELOPMENTS – A WORLD PERSPECTIVE

This section compares the energy policies of three Western countries with quite different approaches to energy supply and security. The United States, United Kingdom and Germany are discussed.

9.1 United States

After four years of negotiation, and the country's first comprehensive energy legislation in 13 years, the *Energy Policy Act of 2005* was passed. The legislation is broad and includes provisions for: energy efficiency; renewable energy; oil and gas; clean coal technologies; nuclear; vehicles and fuels; automobile efficiency; hydrogen; electricity; and ethanol and motor fuels. The thrust of the legislation may be gleamed from a speech at a nuclear power plant from the President of the United States, George W. Bush:

> I've come to this important power plant, to talk about how the United States can have a diversified energy policy that makes us less dependent on foreign sources of oil and more dependent on renewable sources of energy.
>
> [After discussing an increased role of ethanol blended fuels and hybrid cars] …A third way to help this country remain an economic leader when it comes to the cars you drive is hydrogen. … One fellow reminded me, wisely, it costs—it takes quite a bit of power to make hydrogen. An interesting way to make hydrogen on an economic basis would be through nuclear power. But we're spending money and time and effort, all aimed at making sure that the automobiles of the future will require less crude oil.

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[75] Roques, FA *et al*, "Nuclear Power: a Hedge against Uncertain Gas and Carbon Prices?" in *Energy Journal*, Vol 27, No 4, 2006, at 8.

[76] Roques, FA *et al*, "Nuclear Power: a Hedge against Uncertain Gas and Carbon Prices?" in *Energy Journal*, Vol 27, No 4, 2006, at 20.

> … For the sake of economic security and national security, the United States of America must aggressively move forward with the construction of nuclear power plants. Other nations are.
>
> … I understand the need to get off oil. I understand the need to work on renewable sources of energy. … You know, I hope that when my grandchildren and some of your children start taking their driver's test, they'll be cranking up a hydrogen-powered automobile, with hydrogen produced from electricity generated from plants such as these.[77]

Highlights of the *Energy Policy Act of 2005* relevant to this paper are as follows:

Clean Coal Technologies

- Provided a $1.8 billion authorization for the Secretary of Energy to carry out the Clean Coal Power Initiative, which will provide funding to those projects that can demonstrate advanced coal-based power generating technologies that achieve significant reductions in emissions;
- In February 2003 the United States government announced FutureGen. This is a $1 billion prototype project intended to create the world's first zero-emissions fossil fuel electricity plant, incorporating hydrogen production.

Nuclear

- 'Standby support' to offset the financial impact of delays beyond industry's control that might occur during construction and at the start of operations for as many as six new nuclear reactors. This covers the full cost of delay for the first two reactors, up to US$500 million each, and 50% of the delay costs, up to US$250 million each for reactors three to six;
- Re-authorisation of the *Price-Anderson Act,* the framework for industry self-funded liability insurance, for 20 years;
- A production tax credit of 1.8 cents per kilowatt hour for the first 6,000 megawatt hours from new nuclear power plants for the first eight years of their operation.
- Authorization of a US$1.25 billion to fund a prototype Next Generation Nuclear Plant project at Idaho National Laboratory that would produce both electricity and hydrogen;
- Authorization of funding for the Advanced Fuel Cycle Initiative, which would foster research and development aimed at developing advanced nuclear power plants.[78]

Hydrogen

- Launched a program to get hydrogen-powered automobiles on the road by 2020 along with the necessary infrastructure to provide for the safe delivery of hydrogen

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[77] Nuclear Energy Institute, *Speech by President George W. Bush*. Limerick Generating Station, Pottstown, Pennsylvania, 24 May 2006. See: http://www.nei.org/index.asp?catnum=4&catid=954, Accessed July 2006.

[78] Nuclear Energy Initiative, *Congress Passes First Comprehensive Energy Bill in 13 Years.* See: http://www.nei.org/documents/Energy_Bill_2005.pdf, Accessed July 2006.

fuels. Authorized at $2.15 billion over five fiscal years;

- The hydrogen program, to be conducted as a public/private partnership, is to address the production of hydrogen from diverse sources, including fossil fuels, hydrogen-carrier fuels and renewable energy resources including biomass and nuclear energy. The program also addresses pipeline hydrogen transmission, convenient refueling, advanced vehicle technologies, hydrogen storage and the development of necessary codes and standards.[79]

On February 20 2006, the President announced the Advanced Energy Initiative. President Bush stated in the foreward to the Initiative:

> For the sake of our economic and national security, we must reduce our dependence on foreign sources of energy – including on the natural gas that is a source of electricity for many American homes and the crude oil that supplies gasoline to our cars.[80]

The Initiative announced increased funding for two areas:

- Changing the way vehicles are fuelled: greater use of technologies that reduce oil use by improving efficiency, expansion of alternative fuels from homegrown biomass, and development of fuel cells that use hydrogen from domestic feedstocks. This included the goal of enabling large numbers of Americans to choose hydrogen fuel cell vehicles by 2020;
- Changing the way electricity is produced: by generating more electricity from clean coal, advanced nuclear power, and renewable resources such as solar and wind. This included the funding of a new body, the Global Nuclear Energy Partnership. This initiative involves working with other nuclear advanced countries to develop advanced reactors and new methods to recycle spent nuclear fuel. The intent is to reduce the amount of nuclear waste and eliminate many of the nuclear byproducts that could be used to make nuclear weapons.[81]

It is evident that the aim of the current policy of the United States is to reduce dependence on foreign sources of energy. To do this, policies have been implemented to encourage the development of new nuclear power plants, together with developing a hydrogen economy. The two are intricately linked. As shown in this paper, several of the Generation IV family of nuclear plants are being designed with hydrogen co-production facilities.

The scale of facilities needed to replace current motor vehicle fuel use in the United States with hydrogen is staggering. In the order of 136,500,000 tonnes of hydrogen would be required each year. About 7,100 TWh of electricity would be needed to produce this

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[79] US House Committee on Energy and Commerce Press Office, *Energy Policy Act of 2005*, April 2005. See: http://energycommerce.house.gov/108/0205_Energy/05policy_act/EPACT%202005%20Committee%20Print%20Highlights.pdf, Accessed July 2006.

[80] The White House, National Economic Council, *Advanced Energy Initiative*, February 2006.

[81] The White House, National Economic Council, *Advanced Energy Initiative*, February 2006, at 1.

hydrogen. If a once through fuel cycle was used with current light-water reactors, over 145,000 tonnes of uranium would be needed each year. With Generation IV high temperature gas reactor technologies, the production of this hydrogen would require 565 dedicated high temperature gas reactors. If the reactors incorporated fuel recycling, they would consume only 4,000 tonnes of uranium per year.[82]

9.2 The United Kingdom

In February 2003 the United Kingdom Government released an energy White Paper which outlined four goals:

- To cut carbon dioxide emissions by some 60% by about 2050, with real progress by 2020;
- To maintain reliable energy supplies;
- To promote competitive markets in the UK and beyond;
- To ensure that every home is adequately and affordably heated.[83]

The White Paper noted that the Government does not intend to set targets for the share of total energy or electricity supply to be met from different fuels. Instead, the creation of the market framework, together with policy measures, will give investors and consumers the right incentives to find the balance to effectively meet overall goals. However, specific measures are needed to stimulate the growth in renewable energy to allow it to achieve economies of scale.

The Paper highlighted the January 2000 government aim that renewable sources supply 10% of electricity by 2010, and proposed that this be doubled by 2020. The support for nuclear power generation was not so clear. In regard to nuclear power sources, the 2003 White Paper stated:

> Nuclear power is currently an important source of carbon-free electricity. However, its current economics make it an unattractive option for new, carbon-free generating capacity and there are also important issues of nuclear waste to be resolved. These issues include our legacy waste and continued waste arising from other sources. This White Paper does not contain specific proposals for building new nuclear power stations. However we do not rule out the possibility that at some point in the future new nuclear build might be necessary if we are to meet our carbon targets. Before any decision to proceed with the building of new nuclear power stations, there will need to be the fullest public consultation and the publication of a further white paper setting out our proposals.[84]

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[82] OECD Nuclear Energy Agency and the International Atomic Energy Agency, *Uranium 2005: Resources, Production and Demand*. 2006 at 77.

[83] United Kingdom Government, *Energy White Paper, Our Energy Future – Creating a Low Carbon Economy*, February 2003, at 11. See: http://www.dti.gov.uk/files/file10719.pdf, Accessed July 2006.

[84] United Kingdom Government, *Energy White Paper, Our Energy Future – Creating a Low Carbon Economy*, February 2003, at 12. See: http://www.dti.gov.uk/files/file10719.pdf, Accessed July 2006.

In November 2005 the Prime Minister Tony Blair announced a review of the progress of the 2003 White Paper goals. The subsequent energy review was released on 11 July 2006, to be followed by a White Paper around the end of the year. The energy review maintained the focus on reducing carbon emissions by 60% by 2050, and was considerably more supportive of nuclear power than the 2003 White Paper.

A feature of the UK energy environment is the need for new power stations, equivalent to about one-third of present generating capacity, over the next two decades. This is to meet both new demand and replace older power stations. To achieve this, the review proposed new measures to improve the market framework for new investment. The emphasis on reducing carbon emissions is evident. The measures were:

- A strong commitment to carbon pricing in the UK, through improving the operation of the European Union Trading Scheme;
- A strengthened commitment to the Renewables Obligation;
- Proposals for reform of the planning regime for electricity projects;
- A clear statement of the Government's position on new nuclear power stations;
- New arrangements for providing improved information about future trends in energy supply.[85]

In relation to nuclear power stations, the Energy Review noted that higher projected fossil fuel prices, together with the introduction of a carbon price to place a value on carbon dioxide, have improved the economics of nuclear power. The Review concluded that new nuclear power stations would make a significant contribution to meeting energy policy goals. It will be for the private sector to fund, construct and operate new nuclear plants and to cover the full cost of decommissioning and waste management. However, the government proposes to address potential barriers to new nuclear plants, as follows:

- Pre-licensing: this would allow developers to apply for pre-licensing approval for a generic reactor design before committing significant sums of capital to planning and construction. Developers should then be confident that their site licence application would be approved by the regulatory authorities without significant (and potentially costly) design modifications to address unresolved issues;
- Planning: the last nuclear reactor built in the United Kingdom underwent a public inquiry that took 73 months. The Government is clear about the need for a full public discussion about nuclear power. However, this should be done upfront, in advance of any planning applications. This will avoid the same national issues arising as part of the consideration of every proposal, therefore allowing public inquiries to focus on the local issues. The proposals included:
    - Streamlining the planning process for all large electricity infrastructure projects;
    - Setting out a proposed framework for the consideration of the issues relevant to new nuclear build and the context in which public inquiries should be held. This framework will be published in a White Paper around

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[85] United Kingdom Government, Department of Trade and Industry, *The Energy Challenge. Energy Review Report 2006*. July 2006.

> the turn of the year. It will include a nuclear 'statement of need' and set out the national strategic and regulatory issues that are most appropriately discussed through processes other than the planning inquiry.[86]

9.3 Germany

With the German elections in 1998 a coalition government was formed between the Social Democratic Party and the Green Party. The new government, having campaigned during the election that it would phase out nuclear power in the country, began negotiations to achieve this. In mid June 2000, the government reached an agreement with energy companies to begin the gradual closing down of the country's 19 nuclear power stations.[87]

A new *Nuclear Power Act 2002* was passed to legislate the above decision. Replacing the *Atomic Energy Act of 1959*, which promoted the use of nuclear power, the 2002 legislation:

- Brought the use of nuclear power to a legislated end;
- Restricted the operation of present nuclear plants to 32 years from the date of start up. After this period, the right of operation expires. Nuclear power is planned to be phased out completely by 2020. The Act outlined a maximum amount of electricity that each plant can produce during the rest of their operational period. However, the electricity volumes of older nuclear plants can be transferred to newer plants;
- No construction or operation of new nuclear plants will be allowed;
- Waste disposal is restricted to direct final storage – previously spent fuel waste was sent for reprocessing in either France or the United Kingdom.[88]

Given the age of the nuclear plants, the decision to retire plants at 32 years of age meant that they had an average of 12 years left to operate. The Stade nuclear reactor near Hamberg was the first plant to be closed in 2003, followed by another in Obrigheim in May 2005. The next to close is reported to be in February 2007.[89]

In 2000 the *Renewable Energy Sources Act* was passed. The Act obliges the electricity grid system operators to feed in the electricity generated from renewable sources, which are not yet economically competitive, as a priority, and to pay generators legally fixed minimum fees for this electricity. The goals of the German government are:

- Sustainable development of energy supply, climate, nature and environment protection;

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[86] United Kingdom Government, Department of Trade and Industry, *The Energy Challenge. Energy Review Report 2006*. July 2006, at 121.

[87] "Germany renounces nuclear power" in *BBC News*, 15 June 2000. See: http://news.bbc.co.uk/1/hi/world/europe/791597.stm, Accessed July 2006.

[88] German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, *General Information – Nuclear Safety.* See: http://www.bmu.de/english/nuclear_safety/information/doc/4300.php, Accessed July 2006.

[89] "Germany shuts down nuclear plant." In *BBC News*, 11 May 2005. See: http://news.bbc.co.uk/2/hi/europe/4536203.stm, Accessed July 2006.

- Increasing the share of renewable energy in electricity consumption to at least 12.5% by 2010 and at least 20% by 2020. The share of renewables in primary energy consumption should total 4.2% in 2010 and 10% by 2020;
- Reduced external costs of energy supply and increased supply security by means of reduced dependence on energy imports.

Due to the implementation of the *Renewable Energy Sources Act*, in 2005 10.2% of German electricity generation came from renewable sources. The fee payments to renewable plant operators was almost 4.1 billion euros in 2005. The resulting additional cost as compared with the costs for electricity generated from conventional energy forms was around 2.4 billion euros in 2005. However, the Government claims that the monthly costs for a household resulting from the Act will increase to a maximum of 2.8 euros/month by the middle of the next decade, and will then decrease.[90]

Whilst the Social Democratic Party / Green Party coalition government is no longer in power, the current German coalition government's (Social Democratic Party / Christian Democratic Union Party) aim is to increase the proportion of renewable sources of electricity to 20% or more by 2020. However, this still requires other generation sources to produce the other 80% of the electricity. Noting this, the German Federal Minister for the Environment, Sigmar Gabriel, recently stated:

> …Even a significant improvement in energy efficiency will not enable us to meet our electricity needs with renewables alone by 2020. However, if we want to phase out nuclear power by that time… we must continue to use gas and also coal. It would be fanciful to think otherwise and would serve to boost the nuclear lobby. Completely substituting coal with gas is neither feasible in terms of the gas supply situation, nor is it affordable. …
>
> Germany can develop power plants with significantly higher efficiency factors and hence dramatically lower carbon dioxide emissions. And Germany especially has the know-how and financial power to research and develop technologies for the capture and sequestration of carbon dioxide from coal-based electricity generation. Our aim is a carbon dioxide free power plant.[91]

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[90] German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, *What Electricity From Renewable Energies Costs*. Abridged Version. February 2006. See: http://www.bmu.de/english/renewable_energy/downloads/doc/36865.php, Accessed July 2006.

[91] German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, *Germany remains at the forefront of climate protection*. Speech by Sigmar Gabriel, Federal Minister for the Environment, Nature Conservation and Nuclear Safety. 29 June 2006. See: http://www.bmu.de/english/emissions_trading/current/doc/print/37401.php, Accessed July 2006.

World Developments: Conclusion

These reviews of the United States, United Kingdom and Germany demonstrate vastly different approaches to energy security and supply. Germany has clearly renounced the nuclear option. The United Kingdom approach is to incorporate a strong carbon pricing mechanism, together with multiple electricity generation sources. Whilst nuclear is welcomed, unlike renewable sources, it will not be financially supported by the government. In contrast, support for renewables in the United Kingdom is likely to be the equivalent of £1 billion per year by 2010.[92] The United States has actively promoted, including subsidies, new nuclear power stations, together with funding for the development of the hydrogen economy.

10.0 A SUMMARY OF ARGUMENTS FOR AND AGAINST THE NUCLEAR INDUSTRY

Proponents of the nuclear industry claim that it is safe, nuclear power is cost effective and produces virtually no greenhouse emissions. A summary of arguments supporting the nuclear fuel cycle is as follows:

- In all countries using nuclear energy there are well established procedures for storing, managing and transporting nuclear wastes. These are funded by electricity users. Wastes are contained and managed, not released. Storage is safe and secure, plans are well in hand for eventual disposal;
- Nuclear power is the only energy-producing industry which takes full responsibility for managing all its wastes, and bears the cost of this;
- The nuclear industry has an excellent safety record, with some 12,000 reactor years of operation spanning five decades. Even a major accident and meltdown in a typical reactor would not endanger its neighbours. Some Soviet designed and built reactors have been a safety concern for many years, but are much better now than in 1986. The Chernobyl disaster was basically irrelevant to any western reactor, or any that might be built today;
- In regard to reactors and terrorist attacks, any reactor licensable in the west has a substantial containment structure and most also have a very robust pressure vessel and internal structures. Civil power station waste and spent fuel storage is also robust and often below ground level;
- Nuclear electricity is mostly competitive with coal, in some places it is cheaper, in some more expensive. If external costs are accounted for, nuclear is very competitive. Wind power typically costs much more than nuclear - often twice as much per kWh;
- Renewable energy sources may be used as much as possible, but intrinsic limitations (diffuse, intermittent sources) mean that wind and sun can never economically replace sources such as coal, gas and nuclear for large-scale, continuous, reliable supply;
- Currently nuclear energy saves the emission of 2.3 billion tonnes of CO_2 relative to coal. For every 22 tonnes of uranium used, one million tonnes of CO_2 emissions is

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[92] United Kingdom Government, *Energy White Paper, Our Energy Future – Creating a Low Carbon Economy*, February 2003, at 12. See: http://www.dti.gov.uk/files/file10719.pdf, Accessed July 2006.

averted. Energy inputs to nuclear power produce only a few (eg 2-5) percent of the CO_2 emissions saved.[93]

Physicist Colin Keay argues from the perspective that Australia should mine uranium and manufacture fuel assemblies, which we would then lease to countries needing reactor fuel to produce electricity. An essential condition of the lease is that rods must be returned to Australia to salvage their plutonium content, to avoid it being used for military purposes. The plutonium would then be recycled through the use of mixed oxide reactor fuel to keep it out of the waste stream. The scope for disasters is also limited by leasing the fuel rods only for use in reactors of proven safe design. Keay concludes that nuclear power is the only proven way of meeting the terms of the Kyoto Protocol for the reduction of greenhouse gases, and for the production of hydrogen for the 'hydrogen economy'.[94]

Arguments against the use of nuclear power encompass several areas, ranging from the problems of waste to concerns about nuclear proliferation. Australian conservation groups argue the following:

- Nuclear power is a limited and problematic response to climate change. Nuclear power is almost exclusively used for electricity generation, which is responsible for less than one third of global greenhouse emissions. The potential for nuclear power to help reduce greenhouse gas emissions by replacing fossil fuels is limited. Nuclear power is being promoted as the solution to climate change, as a technical fix. Clearly it is no such thing;
- Nuclear power is not a 'renewable' energy source. High grade uranium ores are limited and total conventional uranium reserves is sufficient for about 200 years at the current rate of consumption;
- Claims that nuclear power is 'greenhouse free' are incorrect as substantial greenhouse gas emissions are generated across the nuclear fuel cycle. Nuclear power emits more greenhouse gases per unit of energy than most renewable energy sources, and the comparative deficit will widen as uranium ore grades decline;
- Hazards associated with nuclear power include: the risk of catastrophic accidents; routine releases of radioactive gases and liquids from nuclear plants; the intractable problem of nuclear waste; and the risk of terrorism and sabotage;
- Global expansion of nuclear power could contribute to an increase in the number of nuclear weapon states – as it has in the past. Nuclear expansion would also increase the availability of nuclear materials for use in nuclear weapons or radioactive 'dirty bombs' by terrorist groups;
- A nuclear weapon powerful enough to destroy a city requires 10 kilograms of plutonium. The civil nuclear power industry has produced 1,600 tonnes of plutonium. If 99% of this plutonium is protected from military use, the remaining 1% would suffice for 1,600 nuclear weapons;
- Nuclear smuggling, much of it from civil programs, presents significant challenges;

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[93] Uranium Information Centre, *The Nuclear Debate*. Nuclear Issues Briefing Paper 43. November 2005. See: http://www.uic.com.au/nip43.htm, Accessed July 2006.

[94] Keay,C. *Nuclear Common Sense*. The Enlightenment Press. 2003.

- Civil nuclear power plants are potentially ‘attractive’ targets for terrorist attacks;
- Radioactive wastes arise across the nuclear fuel cycle. Reprocessing of spent fuel poses a major proliferation risk and also releases significant quantities of radioactives waste into the sea and air;
- Not a single repository exists anywhere in the world for the disposal of high level waste, with only a few countries having identified sites. Attempts to establish international repositories are likely to be unpopular and unsuccessful;
- The nuclear industry transfers risks and costs to future generations;
- The ‘safe and clean’ image being pushed by nuclear proponents seriously misrepresents the true performance of the industry. Nuclear accidents and near misses are common, and radioactive emissions are routine;
- The real solutions to climate change are energy efficiency and renewable sources of energy.[95]

11.0 THE FUTURE OF THE AUSTRALIAN NUCLEAR FUEL CYCLE

As noted, Australia is the world’s second largest exporter, and has the world’s largest reserves of uranium. The last major government commissioned report on the role of Australia in the nuclear industry reported in 1984 to then Prime Minister Hawke. It concluded:

- That exports of Australian uranium should not be limited as a matter of principle, but should be permitted subject to stringent conditions of supply designed to strengthen the non-proliferation regime;
- That Australian participation in stages of the nuclear fuel cycle in addition to uranium mining and milling should be permitted, where such participation promotes and strengthens the non-proliferation regime;
- That Australia provide support and encouragement for Australian participation in research and development on the disposal of high level radioactive waste and for co-operation with other countries and with international agencies in such research.[96]

Whilst the Hawke ALP Government accepted most of the recommendations of the report, it rejected several of the most crucial to the development of the nuclear industry in Australia. Prime Minister Hawke stated:

> The Government has made it clear that the mining and export of uranium will continue subject to strict safeguards conditions, but only from the Narbalek, Ranger and Olympic Dam mines. The Government has decided that the development of further stages of the nuclear fuel cycle in Australia will not be permitted.[97]

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[95] Green,J. *Nuclear Power. No solution to climate change*. A paper prepared for Friends of the Earth (Australia), Australian Conservation Foundation, Greenpeace Australia Pacific, Medical Association for the Prevention of War, Public Health Association of Australia, and the Climate Action Network of Australia, September 2005.

[96] Commonwealth of Australia, *Australia’s Role in the Nuclear Fuel Cycle. A report to the Prime Minister by the Australian Science and Technology Council*, May 1984.

[97] *Government Response to the ASTEC Report on Australia’s Role in the Nuclear Fuel Cycle: Statement by the Prime Minister.* ND.

More recently, the Australian government has commissioned two separate bodies to investigate aspects of the nuclear fuel cycle in Australia. In 2005 the Australian Minister for Industry, Tourism and Resources, the Hon Ian Macfarlane MP, announced the establishment of the Uranium Industry Framework. The Steering Group to oversee the development of the Framework first met on 11 August 2005. The Framework will identify opportunities for, and impediments to, the development of the Australian uranium industry in the short, medium and longer term, and recommend actions aimed at:

- Increasing Australia's international competitiveness and facilitating increased exploration, mining and export of Australia's uranium resources;
- Ensuring a consistent, effective and efficient regulatory regime for uranium mining in Australia; and
- Fostering broader community understanding and acceptance of the economic and social benefits derived from having a safe, secure, efficient and productive Australian uranium mining industry.[98]

The Steering Group initially established three working groups:

- Competitiveness Working Group: focusing on: skills / nationally accredited training; and issues affecting the transport of uranium in Australia.
- Regulation Working Group: focusing on: ways to improve the regulatory environment for uranium mining; and working to establish a uranium royalty regime in the Northern Territory.
- Communication Working Group: this group is focusing on three areas: ways to engage stakeholders and how to provide information on aspects of the uranium industry; how to facilitate land for uranium exploration and mining whilst respecting cultural, historical and environmental concerns; and benchmarking countries for uranium exploration and mining in areas such as royalty regimes and customer satisfaction.

At their January 2006 meeting, the Steering Group established a fourth working group, which could possibly be the most controversial. This group is responsible for considering how material stewardship proposals, based on a whole-of-life-cycle approach, could assist the sustainable development of the Australian uranium industry.[99] In other words, this working group is looking at developing a strategy for exporting uranium, enriched or not, then re-importing the spent nuclear waste to a respository located somewhere in Australia.

On 6 June 2006, the Prime Minister the Hon John Howard MP announced the appointment of a taskforce to undertake an 'objective, scientific and comprehensive review into uranium mining, processing and the contribution of nuclear energy in Australia in the longer term.'[100] The taskforce, chaired by Dr Ziggy Switowski, is due to report by the end of this

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[98] Australian Government, Department of Industry, Tourism and Resources, *Uranium Industry Framework Steering Group Communique.* 11 August 2005. See: http://www.industry.gov.au/uif, Accessed July 2006.

[99] Australian Government, Department of Industry, Tourism and Resources, *Uranium Industry Framework Newsletter. Issue 1 – January 2006.* See: http://www.industry.gov.au/uif, Accessed July 2006.

[100] Australian Government, Department of Prime Minister and Cabinet, *Uranium Mining,*

year. The taskforce has released an Issues Paper, outlining the types of questions the taskforce is likely to consider. The Issues Paper noted three areas likely to be reported on as follows:

- Economic issues;
    - Uranium mining and export capacity;
        - Global demand;
        - Australian uranium industry;
        - Global supply of uranium;
        - Impediments to growth of Australian uranium exports;
        - Alternatives to uranium;
    - Other components of the nuclear fuel cycle;
        - Uranium conversion, enrichment, fabrication and reprocessing;
        - Nuclear waste management;
    - Nuclear power:
        - Economics of nuclear power generation;
        - Competitiveness of nuclear power;
        - Australian electricity demand;
    - Nuclear research and development.
- Environmental issues;
    - Greenhouse implications of nuclear power;
    - Other environmental implications of involvement in the fuel cycle;
- Health, Safety and Proliferation issues;
    - Health and safety implications of nuclear energy;
    - Nuclear waste processing and storage issues;
    - National security implications relating to nuclear energy;
    - Nuclear proliferation issues.[101]

The Australian Government has therefore established two ‘taskforces’ into the nuclear fuel cycle. The first, in August 2005, to identify opportunities for the development of the Australian uranium industry, including accepting international nuclear waste. The second, established some 10 months later in June 2006, to undertake an ‘objective, scientific and comprehensive review’ of the same or similar issues, including nuclear power generation.

12.0 THE NUCLEAR LEGISLATIVE FRAMEWORK IN NEW SOUTH WALES

In 1986 during the period of the Wran ALP Government, the *Uranium Mining and Nuclear Facilities (Prohibitions) Act* was passed. The then Coalition Opposition did not vote against the Bill, but described it as ‘a nonsense and a sham’.[102] The Act prohibited the following:

Processing and Nuclear Energy Review. See: http://www.dpmc.gov.au/umpner/index.cfm, Accessed July 2006.

[101] Australian Government, Department of Prime Minister and Cabinet, *Uranium Mining, Processing and Nuclear Energy Review. Issues Paper* See: http://www.dpmc.gov.au/umpner/index.cfm, Accessed July 2006.

[102] *NSW Parliamentary Debates*, *Uranium Mining and Nuclear Facilities (Prohibitions) Bill*, Second Reading Speech, 2 December 1996, at 7667.

- Prospecting or mining for uranium;
- Constructing or operating certain nuclear facilities, including:
    - a facility for the conversion of uranium ore into uranium hexafluoride or any other chemical in order to enable its enrichment;
    - an isotope separation plant or other facility for the enrichment of nuclear material;
    - a fabrication plant or other facility for transforming nuclear material into a form suitable for use as fuel in a nuclear reactor;
    - a nuclear reactor, whether or not designed for the purpose of generating electricity;
    - a reprocessing plant or other facility for the chemical separation of fuel that has been irradiated in a nuclear reactor;
    - a separate storage installation for the storage or disposal of any nuclear material (including radioactive waste material) in the nuclear fuel cycle.
- Any State authority to construct or operate a nuclear reactor to generate electricity.

However, the Act included the provision that nothing prevents: the construction or operation, under an Act of the Commonwealth, of a nuclear facility by the Australian Atomic Energy Commission or by any authority of the Commonwealth that replaces that Commission; the construction or operation of a facility for the storage or disposal of any radioactive waste material resulting from the use of nuclear materials for research or medical purposes; or the operation of a nuclear powered vessel.

More recently, the NSW Premier Morris Iemma stated that whilst the Federal ALP Party may engage in the debate to abolish Labor's no new uranium mines policy, the NSW Government will not be changing its legislation.[103]

13.0 CONCLUSION

This paper has shown that world energy needs are rapidly increasing, with predictions of energy requirements being 50% greater in 2030 than today if world policies remain the same. Australia, as a net exporter of energy, is well placed to meet this increase in energy demand. However, the nation has limited supplies of oil, and is vulnerable to supply disruptions and price escalations of this strategically important energy source.

Globally, there are two major influences on energy policy: climate change concerns and energy security. To support their argument for a low carbon future, conservationists promote the 'scientific consensus' that climate change is real and that action needs to be taken now to reduce carbon emissions. However, they reject the notion that nuclear power is the best way to reduce emissions. They also reject the 'scientific consensus' that nuclear waste can be safely disposed of. In contrast, promoters of nuclear power argue that the world cannot meet energy demand without it, especially with the possible future transition to the 'hydrogen economy'. With some 36% of the world's cheap uranium resources, this is a debate that Australia cannot ignore.

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[103] "Iemma says NSW ban on uranium mining will stay." In *AAP*, 25 July 2006.

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