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STATUS OF NUCLEAR POWER REACTOR DEVELOPMENT

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Abstract

Worldwide there are now 439 operating nuclear reactors working in 31 countries with 361 GWe installed power representing ~17% of world demand on electricity. Most of these reactors were designed and developed during the 1960s. For almost five decades, the nuclear power industry has been developing and improving nuclear design and technology towards safer and more reliable operation. With the increase of world demand on energy, 136 new reactors are needed just to maintain the nuclear energy share at the same level by 2025. Several generations of nuclear reactors are commonly distinguished. Generation I reactors were developed in 1950-60s and except for UK, none of them are in operation now. Generation II reactors are typified by the present PWR, BWR, PHWR and LWCR of which most reactors are in operation. With Chernobyl accident in 1986, demand on increasing safety and security opened the door towards generation III reactors. Generation III and (3+) reactors are of advanced design, some of them started operation, and others are under construction or ready to be ordered. Generation IV designs are in the developmental stage and are not expected to be operational before 2030.
The article discusses current status of electricity production, its generation by type and comparative costs, worldwide existing and under construction NPPs and nuclear power reactor generation development.

WORLD DEMAND ON ENERGY

World demand in electricity generation is increasing due to factors including both population and economic growth. This is attributed to: i) world population is expected to increase from 6.7 billion at 2007 to 9.5 billion by 2030, ii) share of developing countries in world energy consumption is growing rapidly due to their increasing industrialization and economic growth. Based on that, the world will need greatly increased energy supply in the next 25 years, from 1.7 PWh in 2007 to 3.3 PWh in 2030.

The main primary sources of energy currently in use on a global scale are: fossil fuels (gas, oil, coal) - accounting for 65%, hydropower and nuclear power accounting for 16% each and others (wood and renewables) accounting for 3%. Fig.1 shows the

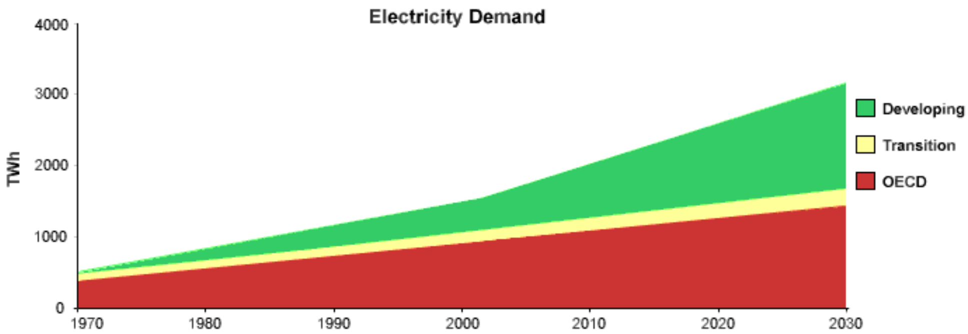

Fig. 1. World electricity demand, 1970-2030

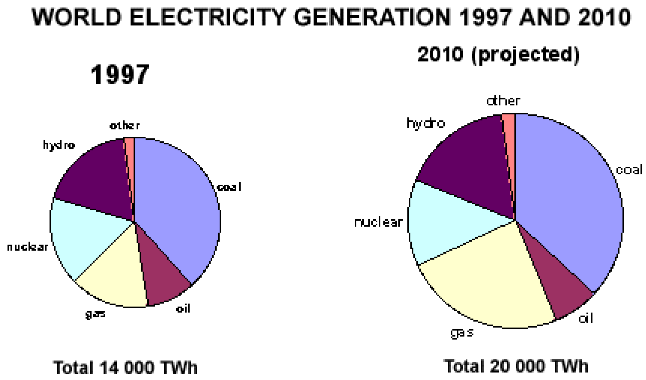

Fig.2. World electricity generation by type

world demand on energy during the period 1970-2030, while Fig. 2 shows world electricity generation by type in 1997 and that projected in 2010.

The Importance of Nuclear Power

Nuclear power is an important ingredient of primary energy sources due to the following: i) increase of demand on electricity generation, ii) need for continual base load electricity, iii) depleting oil and gas resources, iv) nuclear power is environmentally friendly, v) nuclear power has good safety record, vi) nuclear power in economically competitive and vii) new designs are prolifiration resistant.

Energy Costs Comparison

Table 1 gives electricity production costs for most important generating methods.

Table 1. Energy cost comparison (2004)

Resource	Average Cost (c$/kWh)	Resource	Average Cost (c$/kWh)
Hydro	2-5	Wind	4-10
Nuclear	2-3	Geothermal	6-10
Coal	3-5	Biofuel	8-12
Natural Gas	5-7	Hydrogen Fuel Cell	10-15
Oil	6-8	Solar	15-32

Variation of electricity production average costs (in US$) from different primary energy sources is displayed in Fig. 3 for the period 1995-2005. As is seen only coal and nuclear provide the least accosts.(1995-2005). Numbers in the box are for 2005.

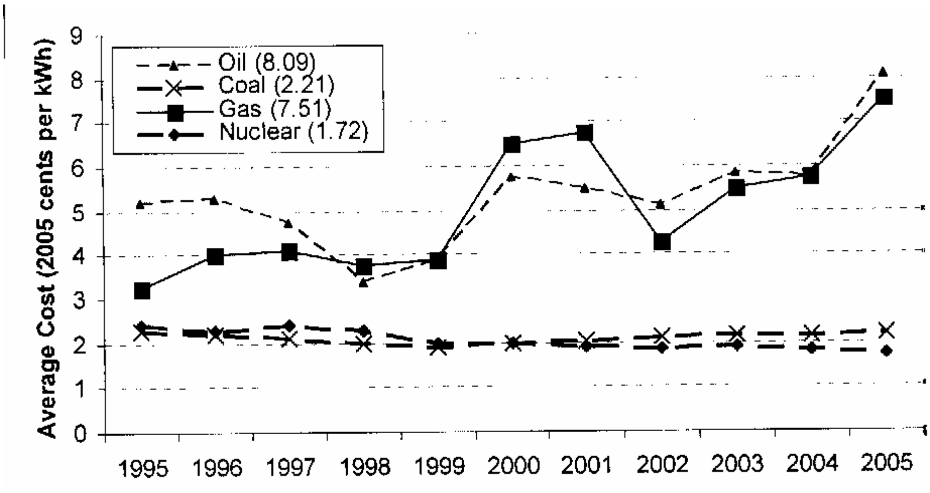

Fig. 3. Electricity production average cost (US$), 1995-2005.

WORLDWIDE EXISTING NUCLEAR POWER PLANTS

Worldwide in 2007, 31 countries are operating 439 nuclear units for electricity generation with total net installed capacity of 361 GWe. This installed power represents 16.7% of the world's electricity generation. Almost half of the world's power reactors are in the U.S. (103 units/98 GWe), France (59 units/63 GWe), and Japan (54 units/46 GWe). Fig. 4 shows the geographical distribution of operating NPP. As is clear concentration is evident in developed countries of North America, Europe and Asia.

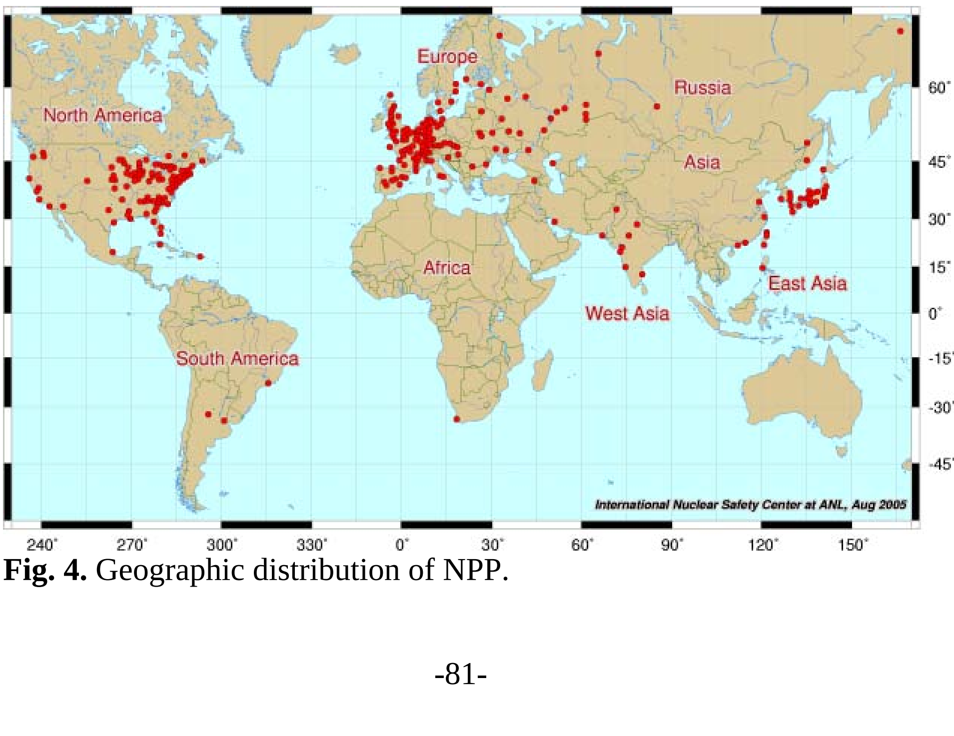

Fig. 4. Geographic distribution of NPP.

Nuclear Power Units in Commercial Operation

Table 2 gives nuclear power reactors in commercial operation categorized by type. Percentage distribution of reactor types are as follow: pressurized water reactors (PWR) 59.9%, boiling water reactors (BWR) 21.0%, gas cooled reactors (CGR) 5.9%, pressurized-heavy water reactors (PHWR) 8.7%, high power channel reactors (HPCR) 3.9%, fast breeder reactors (FBR) 0.6%. Light water reactors which comprise both PWR and BWR represent 80.9% of all commercially operating power reactors, indicating the distinguished features of these reactors in availability, reliability and safety.

Table 2. Nuclear power units in commercial operation

Reactor	Main Countries	Num.	GWe	Fuel	Coolant	Moderator
PWR	US, France, Japan, Russia	263	237	enriched UO_2	water	water
BWR	US, Japan, Sweden	92	81	enriched UO_2	water	water
Gas cooled (Magnox & AGR)	UK	26	11	natural U (metal), enriched UO_2	CO_2	graphite
PHWR (CANDU)	Canada, India	38	19	natural UO_2	heavy water	heavy water
RBMK	Russia	17	13	enriched UO_2	water	graphite
FBR	Japan, France, Russia	3	1	PuO_2 and UO_2	liquid sodium	none
	TOTAL	**439**	**361**			

Table 3. NPP under construction

Country	**China**	**Finland**	**India**	**Iran**	**Japan**	**Korea N.**
Number of reactors	7	1	8	1	2	1
MWe	6400	1600	3638	950	2227	950
Country	**Korea S.**	**Pakistan**	**Romania**	**Russia**	**Ukraine**	**USA**
Number of reactors	4	1	1	4	1	1
MWe	3800	300	650	3600	950	1065

NPP Under Construction, Planned, and Under Consideration

Worldwide, 12 countries are constructing 32 nuclear power units. Nine countries are planning to construct 31 more nuclear power units. Fifteen countries are considering whether to construct 73 more nuclear power units. If all these 136 units are constructed, world nuclear capacity will increase to 484 GWe, a 30 percent increase. The 136 units are needed to maintain nuclear energy's 16% share of the energy mix in 2025. Table 3 gives distribution by countries of NPP under construction during the period 2006-2011. Eighteen of the reactors under construction are of the PWR type. The total power of these units is 26.13 GWe.

NUCLEAR POWER REACTOR GENERATIONS

Four generations are distinguished in the design and construction of nuclear power reactors::

- Generation I. Was developed in the 1950-60s, and outside UK non the reactors are still running today.
- Generation II. Was developed in the 1970-80s. The generation constitutes most of presently working reactors. Reactors of this generation have demonstrated good record of safety, reliability and availability.
- Generation III. Is in advanced stage of design. Reactors of this generation are of simpler and standardized design, higher availability and long operating time. They incorporate passive or inherent safety features.
- Generation IV. Are at concept stage under international joint effort. The reactors of this generation are expected to be available by 2030.

Table 4 summarizes evolution of nuclear power reactors with exmples for each generation.

Table 4. Evolution of nuclear power reactors

Evolution	Example
Generation I Early 1950s to late 1960s	Early Prototypes: - Shippingport / Dresden, Fermi I - Magnox - VK-50, BiNPP
Generation II (1970 – 90)	Commercial power reactors: - LWR (PWR & BWR) / - CANDU - RBMK/WWER
Generation III Improvements of designs started in late 1980s	Evolutionary and Advanced designs: - APWR. ABWR / WWER 1200 - AP 600/1000 / GT-MHR, PBMR
Generation IV	Innovative designs

Generation II Nuclear Power Reactors

In what follows we summarize most important features of generation II reactors. The importance of this generation is that it constitutes more than 99% of now running reactors, and expected to be in operation for the next 20 years till their planned outage.

Pressurized Water Reactor (PWR)

Primary water pressurized to about 160 bar act as both the moderator and the coolant. The fuel is up to 5% enriched UO_2 in Zircaloy tubes. The primary water heats water in a secondary circuit to produce steam. The reactor is housed in a containment building. The thermal efficiency is about 32%.

Boiling Water Reactor (BWR)

Essentially is a PWR without the steam generator and the secondary circuit. Water at a pressure of about 70 bar is pumped through the core and, since it is at a lower pressure compared to the PWR, steam is generated in the primary circuit. About 10% of the water is converted to steam and goes to the steam turbine. After condensing it is pressurized and returned to the coolant. The power density of a BWR is about half that of a PWR with lower temperature and pressure, but the efficiency is similar.

CANadian DeUterium Reactor (CANDU)

Heavy water is used as both the moderator and the coolant. Natural UO2 in Zircaloy tubes is used as the fuel. The fuel tubes pass through a tank of heavy water. Heavy water is pumped through the fuel tubes at about 90 bar pressure and then to a steam generator as in a PWR. The power density is about 1/10th that of a PWR.

High Temperature Gas-cooled Reactor (HTGR)

These are graphite moderated, helium cooled reactors. The fuel is a coated particle to contain the fission products. Water has been used in the secondary circuit to generate steam. Recently a direct cycle (single loop) gas turbine concept has been developed.

Liquid Metal Fast Reactor (LMFR):

Liquid metal transports heat very efficiently and only lightly moderates the neutrons from fission. LMFRs consequently need more fissile material to keep the chain reaction going. The core may also contain fertile material to produce new fuel. Since they can breed fuel, they are also known as breeder reactors. Sodium has been used as the most common form of liquid metal for the reactors. Enriched uranium and Plutonium dioxide and metals have been used as fuel. Operate at a much lower pressure compared to the common light water reactors.

Other Reactor Types:

There are two reactor types developed and built only in the UK, Magnox and AGR, which are still operating.

Magnox is a carbon-dioxide cooled (at about 20 bar pressure), graphite moderated reactor. It has natural uranium fuel in a Magnesium alloy cladding. Overall thermal efficiency is about 30%.

The AGR, Advanced Gas Cooled Reactor, is a gas-cooled reactor with graphite moderation and carbon-dioxide as the coolant at a pressure of about 40 bar. The fuel is 3% enriched uranium-dioxide and clad in Stainless Steel. Its thermal efficiency is about 40%. It is a unique UK design.

Similarly, the Graphite Moderated Boiling Water Reactor ***(RBMK)*** is an older Russian design and built only in the former Soviet Union. The RBMK core is an assembly of graphite blocks through which runs the pressure tubes containing the fuel. Water is pumped through these tubes where it boils to steam. The fuel is 2% enriched uranium dioxide in Zircaloy tubes. Table 5 summarizes materials used in generation II reactors.

Table 5. Generation II power reactor materials

Reactor	**PWR**	**BWR**	**CANDU**	**HTGR**	**LMFR**
Fuel Form	UO_2	UO_2	UO_2	UO_2, ThO_2	PuO_2, UO_2
Enrichment	3.5% U235	2,5% U235	Natural U	93% U235	15% Pu239
Cladding	Zircaloy	Zircaloy	Zircaloy	Graphite	Stainless Steel
Control	B_4C or Ag-In-Cd rods	B_4C rods	Moderator Level	B_4C rods	Tantalum or B_4C rods
Moderator	Water	Water	H. Water	Graphite	None
Coolant	Water	Water	H. Water	He-gas	Liquid Na
Vessel	Steel	Steel	Steel	Prestressed Concrete	Steel

Generation III Nuclear Power Reactors

These are of advanced design based on the accumulated experience with generation II reactors. Design goals aim at: i) component structure simplification, ii) large margins to limit system challenges, iii) longer grace periods to response to emergency situations, iv) high availability, v) competitive economics, vi) compliance with internationally recognized safety objectives and vii) improving severe accident prevention and mitigation. Third-generation reactors have: 1- a standardised design for each type to expedite licensing, reduce capital cost and reduce construction time, 2- a simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets, 3- higher availability and longer operating life - typically 60 years, 4- reduced possibility of core melt accidents, 5- minimal effect on the environment, 6- higher burn-up to reduce fuel use and the amount of waste and 7- burnable absorbers ("poisons") to extend fuel life.

The greatest departure from second-generation designs is that many incorporate passive or inherent safety features, which require no active controls or operational intervention to avoid accidents in the event of malfunction, and may rely on gravity, natural convection or resistance to high temperatures.

Table 6 summarizes major evolutionary designs as implemented in generation III light water reactors

Table 6. Gen. III major evolutionary designs of light water reactors

Reactor	Power MWe	Organization	Status/Significant Features
AP 600	600	Westinghouse (Former ABB)	Design certified by US NRC in 1999 (AP = Advanced Passive).
AP 1000	1000	Westinghouse	Upgraded from AP 600, design certified by NRC in Dec. 2005.
System 80+ PWR	1350	Westinghouse	Design certified by NRC in Dec. 2005.
APWR	1530	Mitsubishi, Japan Westinghouse, USA	First unit planned at Tsuruga site in Japan.
EPR	1545	Framatome ANP, France/Germany	Meets EUR requirements. 60-year life. Under construction in Finland, Olkiluoto3.
WWER	1000/640	Gidropress & Atomenergoproject, Russia	Design complete for 640. Several 1000 under construction in Russia, China, India and Iran.
KSNP	1000	Korea Electric Power Company, S. Korea	Six operating on ROK, and 2 under construction.
APR-1400	1400	KEPCO & Korean Industry	Based on System 80+ design, has received design certification. 60-year plant life. Expected to be built by 2010.
AC 600/1000	600/ 1000	NPIC, China	Similar to AP-600/1000 designs. Expected in 2010.
ABWR	1360	GE, Hitachi and Toshiba	Two operating and ten planned in Japan. Design based on well-proven active safety systems.
ABWR-II	1700	Japanese utilities and GE- Hitachi- Toshiba	Economy of scale design under consideration.
ESBWR	1380	GE, USA	Incorporates economy of scale with passive safety, Design life 60 years.
SWR 1000	1000	Framatome ANP, Germany	Design complete based on German utility experience. Active and passive safety systems. 60 years design life.
BWR 90+	1500	Westinghouse Atom, Sweden.	Evolutionary version of earlier ABB Atom design.

Small and Medium Sized Power Reactors

There is revival of interest in small and medium sized units for generating electricity from nuclear power, and for dual purpose use. The interest is driven both by a desire to reduce capital costs and to provide power away from main grid systems. Currently ~ 150 SMRs are operational in the world: 41 with powers< 300 MWe, 109 with powers between 300 and 700 MWe. These are : 32 gas cooled reactors in UK

(AGR and CGR), 32 PWR, 29 WWER and 27 HWR. Major drive has become towards integral reactors, where the core, pumps, pressurizers and steam generators are contained inside a single pressure vessel. SMRs are simpler in construction due to smaller size, they better match smaller electric grids. The inherent reactor shutdown and passive decay heat removal capability of some designs, in combination with modern advanced control and communication systems mat even facilitate remote operation with fewer operators. Table 7 summarizes information available on Gen. III small and medium-sized reactors.

Table 7. Types and features of SMRs.

Reactor	**MWe**	**Country of Origin**	**Status/ Important Features**
IRIS	100-300	USA-led Multinational	Integral, 8-year core, under design
SMART	300 MWt	R. Of Korea	Integral, 65 MWt pilot to be built
VK-300	250	Russia	Based on VK-50 BWR. Dual use possible
IMR	<300	Japan	Integral PWR
HABWR	600	Japan	Forced circulation BWR
HSBWR	300-600	Japan	Natural circulation BWR
SSBWR	150	Japan	Small nat. circ. BWR
LSBWR	100-300	Japan	Long life core.
NHR-200	200 MWt	China	Upgrade from NHR-5 for non-electricity use.
PBMR	110	Germany/S. Africa	Pebble-bed gas cooled reactor
GT-MHR	285	US, Japan. France, Russia	Gas cooled prismatic reactor, direct gas turbine
4S	50-100	Japan	Sodium cooled fast reactor
BREST	300	Russia	Lead cooled, mono-nitride fuel
ENHS	50	USA	Lead-Bismuth cooled, modular fast reactor.

Generation IV Nuclear Power Reactors

An international task force named Generation IV International Forum (GIF) has been initiated in 2000 and formally chartered in 2001. The forum consists of 10 countries led by USA that are committed to joint development of the next generation of nuclear technology. The GIF countries are: Argentina, Brazil, Canada, France, Japan, Korea (Rep. of), S. Africa, Switzerland, UK and USA, along with EU. They agreed on six nuclear reactor technologies for development between 2010-2030. All of the agreed technologies are based on reactors that operate at higher temperatures than today's reactors. In particular four of the systems are designed for hydrogen production. The six systems are: Gas cooled Fast Reactors (GFR), Lead cooled Fast Reactors (LFR), Sodium cooled Fast Reactors (SFR), Molten Salt Reactors (MSR), Super critical Water cooled Reactors (SWR) and Very High temperature Gas cooled Reactors (VHGR), see Table 8. All of them represent advanced features in sustainability, economics, safety, reliability and proliferation resistance.

Table 8. Design information on Gen.IV reactros.

Reactor	**Gas cooled Fast Reactors**	**Lead cooled Fast Reactors**	**Sodium cooled Fast reactors**
Neutron Spectrum	Fast	Fast	Fast
Coolant	Helium	Pb.Bi	Na
Temp. (^oC)	850	550-800	550
Pressure	High (7-15 MPa)	Low	Low
Fuel	U-238 battery model (15-20y)	U-238 battery model (15-20y)	U-238 & MOX
Fuel Cycle	Closed on site	Closed regional	closed
Power (MWe)	290	50-1200	150-1500
Uses	Electricity & Hydrogen	Electricity & Hydrogen	Electricity
Reactor	**Molten Salt Reactors**	**Super critical Water cooled Reactors**	**Very High temperature Gas Reactors**
Neutron Spectrum	Epithermal	Thermal or fast	Thermal
Coolant	Fluoride salts	Water	Helium
Temp. (^oC)	700-800	510-550	1000
Pressure	Low	Very high	High
Fuel	UF in salt	UO2	UO2 prism or pebbles
Fuel Cycle	Closed	Open (thermal) Closed (fast)	Open

Power (MWe)	1000	1500	250
Uses	Electricity & Hydrogen	Electricity	Hydrogen & Electricity

Cost Comparison

Finally, Table 9 gives cost comparison between nuclear (Gen. II and III) and conventional (coal) electricity generation options. The two options are good examples for basic load electricity generation systems that are believed to dominate the generation market in the after-oil future. Comparison is based on the 2005 cost estimates.

Table 9. Cost Comparison (c$/kWh)

Type	**Capital**	**Op. & Main.**	**Fuel**	**Decomm.**	**Total**
Median experience	5.6	1.3	0.72	0.05	7.7
Best experience	2.8	0.91	0.64	0.05	4.4
APWR	2.2	0.91	0.64	0.05	3.8
AP- 600	2.2	1.04	0.64	0.07	4.0
Coal	2.1	0.59	2.1	0.01	4.8

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REFERENCES

Our source of information was the data available on the internet as assessed during 2007 on energy, electricity generation, nuclear power reactors, nuclear power plants, etc. Sites are those of World Energy Council, World Nuclear Association, US Department of Energy, International Atomic Energy Agency, Uranium Information Center, Wikipedia, sites of nuclear power reactor vendors, other sites of relevant importance. Other source was the attendance of selected conferences on nuclear power generation and utilization.