Desalination and Water Treatment 1 (2009) 25–41
www.deswater.com
1944-3994/1944-3986

Alternative primary energy for power desalting plants in Kuwait: the nuclear option I

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Received 25 March 2008; Accepted 22 July 2008

ABSTRACT

Some countries (e.g. Korea, China, India, Pakistan, Japan) were forced to adopt the nuclear energy option to generate electric power Ep (by nuclear power plants NPP) and desalt seawater D (by nuclear desalination ND) due to the rising cost of fossil fuel and its insecure supply. The increase of fuel oil consumption and cost (more than $100 per barrel) motivate other countries, even oil-exporting countries, to look for cheaper alternatives to produce both Ep and D. The locally consumed oil in these countries is deducted from its reserves and/or decreases its income. In addition, the green house gases (GHG) emission resulting from burning fossil fuel contributes to global warming and adversely affects the environment. In Kuwait and other Gulf cooperation countries (GCC), huge amounts of fuel (oil and natural gas) are consumed by co-generation power desalting plants (CPDP) to produce Ep and D. The use of this fuel to produce Ep and D cannot be expanded indefinitely as the oil supplies are finite and dwindling. Thus, less costly and sustainable new sources of energy such as solar, geothermal, wave, and wind energies are explored. The share of usage for these sources are so little and their wide expansions in the next decade are doubtful. Presently, nuclear energy is economically viable, and is a large-scale alternative to fossil fuel for generations of Ep and D. The use of nuclear energy (NE) raises many concerns about its safety, high capital cost, and radiation effects on surroundings and workers in the short and long term. The question raised should not be either to accept NPP or not, as it may be the only choice we have. The real questions are: how and when NPP will be inherently safe, economical, and when can it be applied safely in countries at different stages of development. Nuclear energy can present a sustainable way to produce Ep and D if its standing problems can be resolved. It can become a significant option for meeting the future world energy needs at low cost and in an environmentally acceptable manner. In this paper, the prospects of using nuclear cogeneation power desalting plants (N-CPDP) in Kuwait and some of the GCC are discussed. The conditions required to build NCPDP and its associated problems are outlined and discussed.

Keywords: Nuclear power plant; Cogeneration power desalting plant; Pressurized water reactors; Nuclear safety features; Oil; Gas; Coal; Fuel consumption; Desalted water; Consumption

1. Introduction

Kuwait and other Gulf co-operation countries (GCC) depend on natural gas and oil (non-renewable fossil fuel) to satisfy their energy needs (e.g. generating electric power (Ep), desalting seawater (D), transportation, and industrial and home needs). This fuel demand is continuously on the rise due to the increase of both population and standards of living. Tables 1(a)–1(d) give the population, and electric and fuel energy consumption in some of the GCC (Kuwait, Saudi Arabia, and United Arab Emirates), and Egypt in the years 2001 and 2006 [1],

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Table 1a
Population (in millions) for a sample of GCC countries and Egypt [1]

Country	Kuwait	Saudi Arabia	Egypt	UAE
Population in 2001	2.243	20.976	64.652	3.488
Population in 2006	3.051	23.647	71.348	4.150
Increase ratio in 5 y	0.360	0.1270	0.1040	0.190
Population in 2016 (expected)	5.650	30.050	86.890	5.870

Table 1b
Total annual electric energy consumption (in GWh) and its per capita (in kWh/capita) for a sample of GCC countries and Egypt [1]

Country	Kuwait	Saudi Arabia	Egypt	UAE
Year 2001	31,536	133,674	77,839	43,172
Year 2006	41,277	181,434	108,332	66,768
Per capita in 2006	13,529	7,673	1,518	16,089
Increase ratio in 5 y	0.309	0.357	0.392	0.547
Year 2016 (expected)	70,715	334,243	209,834	159,698

Table 1c
Fuel consumption in equivalent barrel of oil (boe) per day (d) and per year (y), and expected consumption and cost in year 2016 [1]

	Kuwait	SA	Egypt	UAE
Consumption in 2001				
in M boe/d	0.327	1.786	0.982	0.654
in M boe/y	119.4	652.3	358.7	238.9
Consumption in 2006				
in M boe/d	0.45	2.53	1.199	0.924
in M boe/y	164.4	924.1	437.9	337.5
Full fuel oil production in 2006 in M boe/d	2.96	11.8	1.687	3.95
Increasing ratio in 5 y	0.376	0.417	0.221	0.413
Energy consumption in 2016 (expected)				
in M boe/d	0.852	5.077	1.787	1.844
in M boe/y	311.3	1854.3	652.9	673.7
Cost in 2016 in $billion	31.1	185.4	65.3	67.4

Table 1d
Total energy production in equivalent million barrels per day [1]

Year	2001	2002	2003	2004	2005	2006
UAE	3.225	3.307	3.933	3.698	3.746	3.948
SA	9.765	8.986	10.774	11.342	11.907	11.801
Kuwait	2.181	1.969	2.3600	2.561	2.888	2.962
Egypt	1.328	1.353	1.412	1.416	1.456	1.687

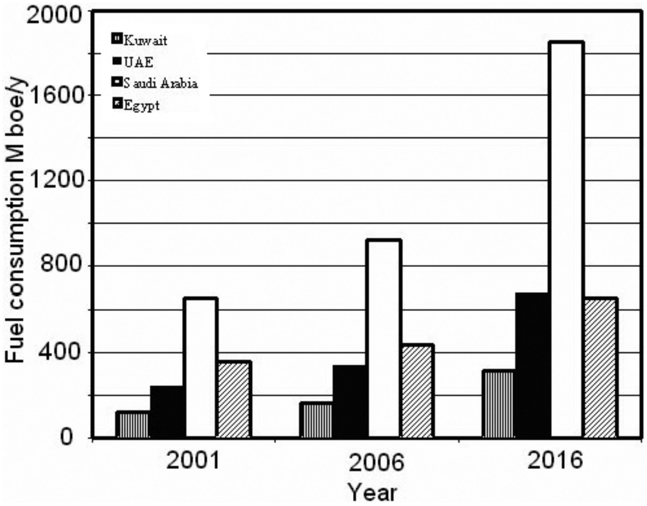

Fig. 1a. Fuel consumption in million equivalent barrels per year.

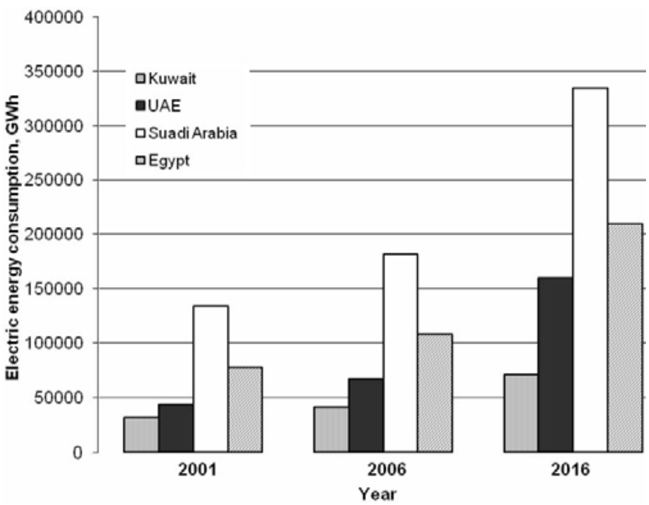

Fig. 1b. Electric power consumption in million equivalent barrels per year.

and expected consumption values in 2016 for the same increasing rates of 2001–2006. The fuel and electric power consumption are given also in Fig. 1.

Table 1(c) shows that the fuel consumed in the three GCC countries is almost doubled every 10 years. The equivalent fuel production in these countries in 2006 in million equivalent barrels of oil per day (M-boe/d) are: 3 for Kuwait, 11.8 for SA, and 4 for UAE. Therefore, their full production can be consumed locally in almost 30 years if the present consumption rates prevail. As for Egypt, its full production is 1.7 M-boe and is expected to be fully consumed in 10 years if the same rate prevails. This necessitates active exploration of alternatives now.

Worldwide, more than 84% of energy needs are satisfied by burning fossil fuel (gas, oil, and coal) (see Table 2, [2]). The ability of these fuels to satisfy the energy

Table 2
Worldwide types of fuel used in generating electric power [2]

Fuel	Percent	Present trends
Oil	39	Short term: Building of additional plants continues.
Coal	25	Building of additional plants continues.
Gas	22	Short term: Building of additional plants continues, gas turbine combined cycle considered the cheapest of fossil fuel plants.
Hydro	7	Building of dams continues, where possible.
Nuclear	6	Stagnant in developed countries, more hope for renewed interest, high expansion rate in emerging countries.
Renewable	1	Gradual expansion continues, with hope to reduce cost.

demands in a sustainable way is unforeseen. This can be gauged by the sharp increase of fuel oil price, more than \$100 per barrel (bbl). Also, the emission of greenhouse gases (GHG) resulting from burning fossil fuel is causing serious environmental problems. Hence, less costly and sustainable new sources of energy should be explored. The share of usage for renewable energy sources such solar, geothermal, wave, and wind energies are so little, and their wide expansion in the near future is doubtful. In spite of the big efforts in Egypt to introduce wind and solar energy, the installed power capacity by wind energy (at the Red Sea coast) is 230 MW; and solar energy is expected to add another 30 MW. These are very small fractions of the total 36 GW capacity needed in less than 10 years. This makes the nuclear energy (NE) as the only economically viable large-scale alternative to fossil fuel. The share of NE in different countries around the world is shown in Fig. 2. This share is close to 80% in France, a high percentage in Eastern Europe, close to 20% in US, and on the rise in Asian countries such as India, Pakistan, Korea, and Japan.

The use of NE to generate electric power Ep and desalt seawater D raises many concerns about its safety, high capital cost, and radioactive radiation effects on workers and its surroundings. In spite of these serious concerns, the question is not to accept nuclear energy or not, as it may be the only option we have. The real question should be: how and when nuclear energy would be inherently safe, economic, and when can it be applied safely in countries of different development stages. Nuclear energy can present a sustainable way to produce Ep and D if its standing problems are resolved.

The introduction of NE to Kuwait and other GCC to generate Ep (i.e. NPP) and D (ND) can face public resistance given that these countries have enough fuel oil and natural gas reserve to satisfy their present needs. Also, there are fears of large catastrophic accidents like what happened in Chernobyl, Ukraine, and the Three Mile Island in the US. Moreover, there are standing problems of nuclear waste disposal, nuclear plants de-commissioning, radioactive contaminations, excessive capital and operating costs, lack of nuclear fuel technology and trained personnel in developing countries. It also imposes dependency on the foreign country supplying the NPP to re-fuel the reactor for its entire life. The country supplying the nuclear plant should also have access to the spent (used) fuel to avoid its reprocessing for unlawful uses. It is necessary to have qualified manpower for safe operation and maintenance of the NPP. Thus, Kuwait's personnel, for example, should acquire training in the country supplying the plant, thus requiring additional time and cost. This training is not limited to scientists but to all levels including engineers and technicians. These factors apply to other GCC nations like SA, UAE and Egypt.

The NPP has a high initial capital cost, but low fuel costs. Recently, the construction costs per kW for nuclear plants have fallen considerably due to standardized designs, shorter construction time and more efficient generating technologies. The experience from recently built NPPs has demonstrated that new plants can be built on time and on budget [2]. Also, the initial cost can be reduced to a certain extent by the choice of so called small and medium-sized reactor systems (SMRs). One of the International Atomic Energy Agency (IAEA) reports estimated the medium-sized reactor of 600 MW(e), combined with seawater desalination system of 50,000 m^3/d, can require an initial investment close to US \$1300 million. However, this is an underestimate as will be seen in the paper. The desalination component is in the range of US \$50 million, i.e., less than 4% of the total plant cost [2].

Other recent reports showed that the new NPP offer the most economical base-load electricity, even before the sharp fuel oil price increase in the last two years. This has to be checked as economics of the NPP depends on location. The sharp increase of oil cost favors the NPP financially over other fossil fuel systems. It also provides price stability, energy security, and carbon emissions reduction.

This paper discusses the possibility of adopting nuclear energy to generate Ep and D in Kuwait and its expected problems and merits. The discussion should be valid for other GCC countries.

Some conditions that should be satisfied for a country to adopt the use of the NPP (and nuclear desalination if needed), are:

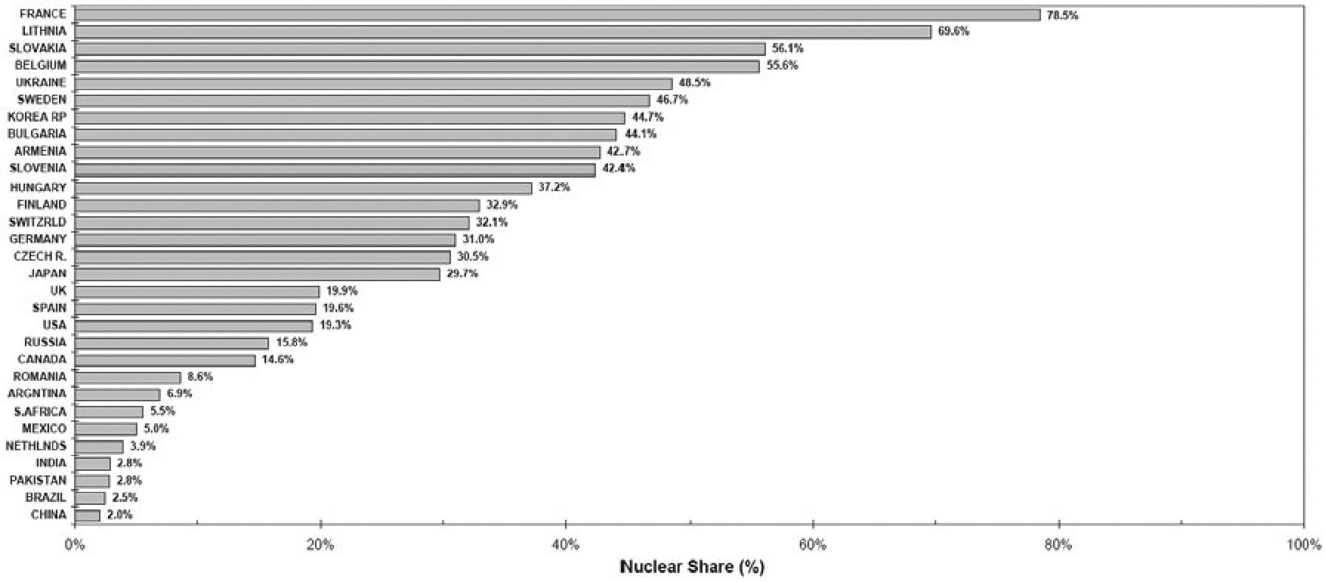

Fig. 2. Share of nuclear power plants in different countries [2].

- Nuclear energy offers clear economic benefits compared to other primary fuels.
- The capacity of the NPP is needed for the country. This applies also to nuclear desalination; and the electric grid is large enough to accept the generating mix with the NPP, of usually high capacity.
- The government has to be committed to secure the safe operation of the NPP, to complete its nuclear fuel cycle; and to impose the legal aspect for the plant.
- The country has an industrial base and the human resources needed to use the NPP.

In this respect, the government should form a committee to check these points, to recommend (or not) the use of NPP, to study the suitable nuclear fuel cycle, and to suggest a site for the plant. This paper presents a preliminary discussion to check if Kuwait is ready for NPP or not.

2. Kuwait fuel consumption and its need to diversify the fuel used

The consumed fuel (oil and natural gas) energy in Kuwait is high and its increasing rate is on the rise. Ministry of Energy data [3] reported that overall fuel consumed in 2005 is equivalent to 150 M-boe/y, or 0.411 M-boe/d. OAPEC [1] reported the consumption increases in 2006 to 0.45 M-boe/d in 2006. The fuel consumed in 2005 increased 76% compared to 1995 (85 M-boe/y or 0.234 M-boe/d). The total 2004 consumed fuel energy consisted of 54% by the CPDP, 28% by the oil sector, 17% by the transportation sector and about 1% by the household sector as shown in Table 3.

The fuel used by the CPDP increased more than 90% in the period of 1995–2005. If this trend prevails, the annual consumed fuel by the CPDP would be 155.2, 295, and 560.3 M-boe by the years 2015, 2025, and 2035 respectively. So, in three decades the CPDP would consume more than half the total oil fuel production of 3 M-bbl/d in Kuwait. This does not include other fuel usage, which is in the range of half the total fuel used. Moreover, the CPDP fuel cost by 2015 would be more than 15 billion dollars if the fuel oil remains at its present cost of $100/bbl. Out of the 0.45 M-boe/d consumed in 2006, only 0.086 M-boe/d was natural gas. So, more than 80% of the fuel consumed in Kuwait was oil.

Thus, shifting to nuclear fuel saves the country from consuming most of its produced oil, the main source of income, in a matter of three decades. This also maximizes its return from selling fuel oil. Oil has generally become too expensive to use in power plants, and it has the great advantage of being portable, and should be conserved for special uses, such as transportation and in the petrochemical industry.

Similar arguments hold for other GCC countries such as SA, the UAE, and Egypt. The fuel consumption in terms of million barrels of oil in years 2001 and 2006 are given in Table 1. Based on the same rate of increase from 2001 to 2006, the expected fuel consumption in year 2016 and its cost in billions of dollars are also given in Table 1 for these countries.

3. Status of power plants in Kuwait and the need for more plants

Kuwait has five main power stations (Doha East, Doha West, Al-Subbiya, Shuaiba South, and al-Zour South). The

Table 3
Kuwait's local consumption of energy in the main sectors (in thousands of barrels) [3]

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Electricity general sector	42,943	46,771	49,009	55,123	58,042	60,254	63,903	68,130	70,669	75,684	81,689
Oil sector	25,187	24,096	27,140	30,410	32,520	29,450	32,396	33,708	38,439	44,059	41,354
Transportation sector	16,004	16,693	17,422	17,781	18,113	18,182	18,953	20,174	21,974	23,703	25,382
Household sector	1,100	1,110	1,153	1,147	1,173	1,184	1,218	1,281	1,325	1,340	1,550
Total	85,234	88,670	94,724	104,461	109,848	109,070	116,470	123,293	132,407	144,786	149,975

Table 4a
Steam and gas turbine power plants in Kuwait by year 2005

Commission date	Capacity (MW) of gas turbines	Commission date	Capacity (MW) of steam turbines	Plant
1965–1968[a]	2× 25	1965–1968	5 × 70	Shuaiba N.
—	—	1970–1974	6 × 134	Shuaiba S.
1981	6 × 18	1977–1979	7 × 150	Doha E.
—	—	1983–1984	8 × 300	Doha W.
1987–1988	4 × 27.75	1987–1989	8 × 300	Azzour S.
		1998–2000	8 × 300	Sabbiya

[a]This plant destroyed during Iraqi invasion.

Table 4b
Gas turbine units added or under installation in Kuwaiti power plants

Location	No. of units	Unit capacity, MW	Total capacity, MW	Operating date
Azzour S.	8	125		March 2005
Shuwaikh	6	42	252	15/7/2007
Sabbiya	4	80	320	15/8/2007
Sabbiya	6	45	270	15/8/2007
Doha West	5	40	200	15/7/2007
Shuaiba	3	220	660	
Azzour S.	5	162	810	
Total			3,412	

Table 5
Peak demands and required additional installed capacity

	Kuwait	Saudi Arabia	Egypt	UAE
Peak demand in 2001, MW	7.063	23.582	12.376	8.043
Peak demand in 2006, MW	9.000	31.708	17.300	11.998
Increase ratio in 5 y	0.27	0.26	0.28	0.33
Peak demand in 2016 (expected), MW	14.61	50.04	28.55	21.21
Installed capacity in 2006, MW	10.763	35.885	19.766	17.280
Required Installed capacity in 2016, MW	18.27	62.55	35.69	26.51
Additional capacity needed, MW	7.5	26.67	15.9	9.23

total installed electric power capacity was about 9 GW in 2004, increased to 10.763 GW in 2006, and is expected to become 13.1 GW by the end of the year 2008 due to addition of simple cycle gas turbines GT to face the peak summer load see Tables 4a and 4b).

The heavy use of air conditioning use of mainly desalted seawater for potable water supply and heavily subsidized electricity prices, increased Kuwait's annual electric power consumption per capita to become among the highest in the world, about 13,500 kWh/y per capita. Overall, Kuwaiti power demand is expected to increase annually at 7–9% in the coming years, necessitating the construction of new generating capacity. Table 5 shows the peak loads in years 2001 and 2006 and the expected load in 2016, given the same 2001–2006 rate of increase. The installed electric capacity in 2016 should be about 1.25 of the peak demand. Based on that, the required installed capacity is calculated in Table 5 for Kuwait, SA, Egypt and UAE. Table 5 shows the needed additional installed capacities compared to that of 2006 are in the range of: 7.5 GW for Kuwait, 26.7 GW for Saudia Arabia, 16 GW for Egypt, and 9.2 GW for UAE.

The needed additional power capacities in the four mentioned countries justify one of the conditions required to adopt the use of NPP. The first condition is to prove its economic competitiveness compared with other types of plants. This can be calculated by assuming plant load, generating costs for each type of plant using suitable capital, operating and fuel cost estimates along with plant life expectation and cost of money.

Important factors to be taken into consideration when defining the size and timing of the NPP to be installed are: compatibility with the electric system (size and stability), lead times for the plant construction and its required infrastructure development; and the commercial availability of a NPP of a given size.

Most operating steam turbines in Kuwait have 300 MW capacity each. A new planned plant in Azour N. is expected to have five steam turbines of 500 MW each. Hence, the size of the steam turbines in the suggested NPP should be in the 500 MW range or little more, say 600–700 MW. For example, a suitable choice is the AP600 NPP (of 600 MW nominal capacity), a commercially available pressurized water reactor (PWR) of 600 MW nominal capacity. This size is compatible with the expected electric system of more than 18 GW total capacity and already planned turbine sizes of 500 MW per unit. The expected lead time is 5–6 years. The total expected installed capacities in SA, Egypt, Kuwait and UAE by the year 2016 are 62, 35, 18 and 27 GW respectively. For these capacities, the NPP model AP1000 PWR plant of 1000 MW nominal capacity size is a suitable choice.

4. Status of desalting plants in Kuwait and the need for more plants

The Ministry of Electricity and Water intends to raise the capacity of the desalting capacity from presently 1.5 million m^3/day (Mm^3/d) to 3 Mm^3/d by 2012. The only seawater desalting method used in Kuwait is the multi-stage flash (MSF) system, except for the 30 MIGD (0.137 Mm^3/d) seawater reverse osmosis (SWRO) plant under construction in Shuwaikh. MSF is known by its high consumption of energy (about 260 kJ/kg thermal energy and 4 kWh/m^3 pumping energy). Its consumed specific equivalent work (counting thermal and pumping energy) is in the range of 20 kWh/m^3 when supplied with steam extracted from steam turbines and in the range of 40 kWh/m^3 when the steam is directly supplied from fuel-fired boilers. It is noticed here that the energy consumed by the SWRO is in the range of 4–6 kWh/m^3.

5. Suggested nuclear cogeneration power desalting plant

Recent studies conducted to introduce nuclear CPDP to developing countries suggest, in most cases, the use of light water-pressurized water reactors (PWR) for electric power production; and SWRO and multi-effect boiling (MED) for desalting. Some results of these studies are given in Table 6. Both SWRO and MED are known for their low energy consumption compared to the MSF desalting method, used widely in the GCC.

The light water (LW) PWR are the most used reactors type in power plants (see Table 7). By the end of 2006, there were 264 PWR out of total 435 operating reactors worldwide, and 18 PWR, out of 29 reactors under construction (see Figs. 3 and 4 [4]). Several types of commercially available NPP and their suppliers are given in Table 8. The nuclear fuel used in the LW PWR is enriched uranium. Ordinary water is used as the moderator and coolant in these reactors.

Therefore, the present study is anticipating the choice of the LW PWR known as the AP600 (600 MWe nominal power capacity) for Kuwait and the AP1000 (1000 MWe nominal capacity) for SA, Egypt, and UAE. An extracted condensing steam turbine (ECST) is to be used in both cases. This turbine is to be combined with thermal desalting units such as low temperature LT-MED, MSF, or thermal vapor compression (TVC) desalting units. Low pressure steam is to be extracted from the turbine to supply the heat required for thermal desalting units. Part of the electric power output can be used to drive the SWRO desalting system. The suggested N-CPDP here is similar to that suggested by a French study for Tunisia using the AP600 PWR and LT-MED desalting units [2], and its details are given in the following section.

Most of the nuclear power reactors use enriched uranium produced in developed countries. Natural uranium is used in heavy water reactors which are mainly used in Canada (18 reactors), India (14 reactors), China (two reactors), Korea RP (four reactors), Pakistan (10 reactors), and Romania (one reactor) (see Table 7).

5.1. Suggested pressurized water reactor, the AP600

A sketch of the NPP cycle using AP600 (or AP1000) is shown in Fig. 5 [5]. The AP600 has 619 MWe gross power output, 600 MWe net output, and 1933 MW core thermal output, and 35% net power plant efficiency if the cooling water inlet to the condenser is at 30.5 °C. The primary loop [reactor coolant system (RCS)] enters the bottom of the reactor through four cold legs (inlets) by four pumps, and leaves after being heated by the reactor core through two hot legs (outlet) at the top of the reactor, and are connected to two steam generators. The RCS pumps are directly installed at the bottom of the steam generators. The primary loop transfers the heat generated in the reactor to the two steam generators to produce steam from a secondary water flow.

The two steam generators have total steam output of 1,063 kg/s at 272.7 °C and 5.74 MPa (almost at saturated condition), and 7.21 MPa feed water at the inlet. Both

Table 6
Suggested and under construction nuclear power plant with pressurized light water reactors using enriched uranium

	Country				
	Argentina	Egypt	Tunis	Korea	Russia
Reactor type	CAREM	AP1000	AP600	SMART	RITM 200[a]
Fuel cost cent/kWh(e)	0.72		0.648	0.8	
Power output, MW	125	1000	610	100	18.5
Capital cost $/kWh(e)	1500	2000	2194	1855	3450
Efficiency, %	29		33	30.3	0.25
Lead time, years	5		4	3	
Operation and maintenance, cent/kWh	0.94		0.11		
Electricity cost, $/kWh	0.038		0.035	0.031	0.0408
Life time, years	40	40	40		
Corresponding combined cycle $/kWh	0.043 (for $20/bbl)				
Type of desalting plant	SWRO	MED	MED	MED	
Plant cost, $/(m^3/d)	900	900	900	900	
Capacity, m^3/d	48,000	140,000	48,000	—	100,000
Cost, $/m^3	0.66	0.89	0.758	0.63	0.791

[a]Barge mounted plant.

Table 7
Reactor types and the net electrical power, rectors connected to the grid (Dec. 2006)

Country	PWR		BWR		PHWR		LWGR		FBR		Total	
	No.	MW(e)	No.	MW (e)	No.	MW (e)	No.	MW (e)	No.	MW (e)	No.	MW(e)
Argentina					2	935					2	935
Armenia	1	370									1	376
Belgium	7	5,824									7	5,824
Brazil	2	1,901									2	1,901
Bulgaria	2	1,906			18	12,810					2	1,900
Canada					2	1,300					18	12,010
China	8	6,272									10	7,572
Czech Rep.	6	3,623									6	3,523
Finland	2	976	2	1,720							4	2,090
France	59	63,130									59	53,260
Germany	11	13,968	6	6,371							17	20,339
Hungary		1,755									4	1,755
India			2	300	14	3,277					16	3,577
Japan	23	18,420	32	29,167							55	47,587
Korea RP	18	14,825			4	2,629					20	17,454
Lithunia							1	1,185			1	1,185
Mexico			2	1,360							2	1,360
Netherlands	1	482			1	125					1	482
Pakistan	1	300			1	655					2	425
Romania											1	555
Russia	15	10,954					15	10,219	1	550	31	21,743
S. Africa	2	1,800									2	1,800
Slovakia	5	2,034									5	2,034

PWR: pressurized water reactors, BWR: Boiling water reactors, PHWR: Pressurized heavy water reactors, LWGR: Light water graphite moderator, FBR: Fast breeder reactor.

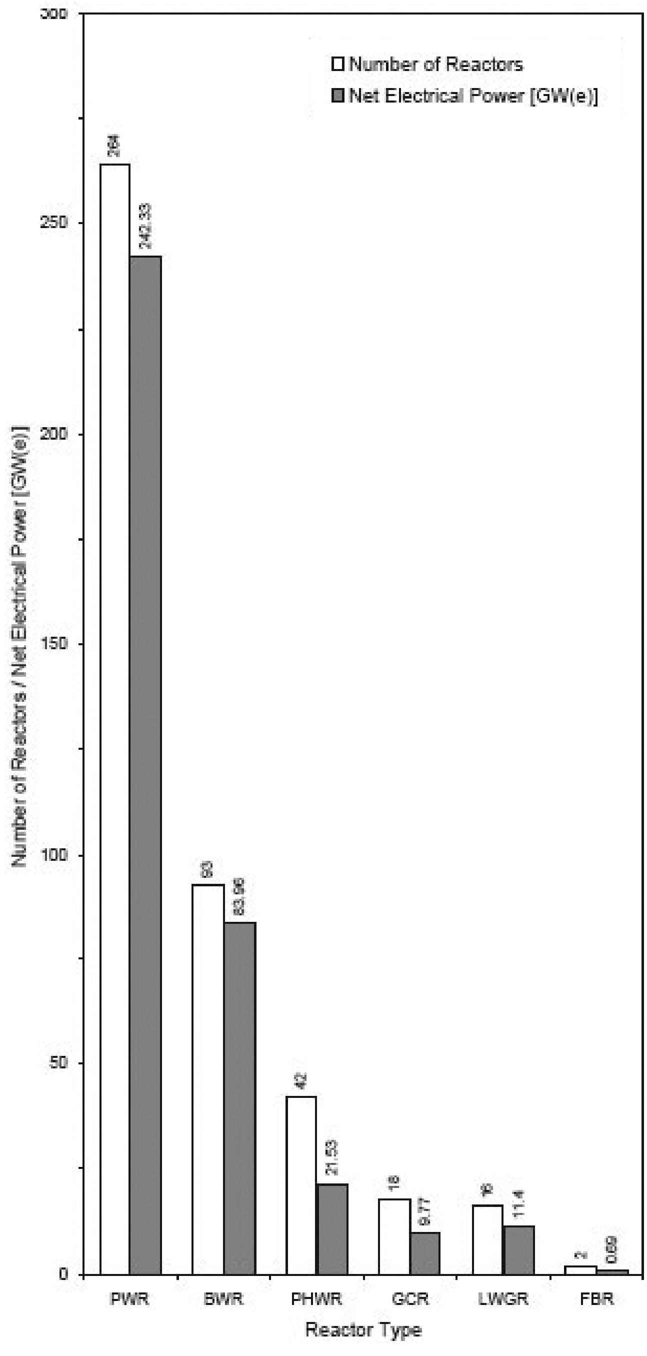

Fig. 3. Nuclear reactors by type and net electrical power (as of 31 Dec. 2006, [4]).

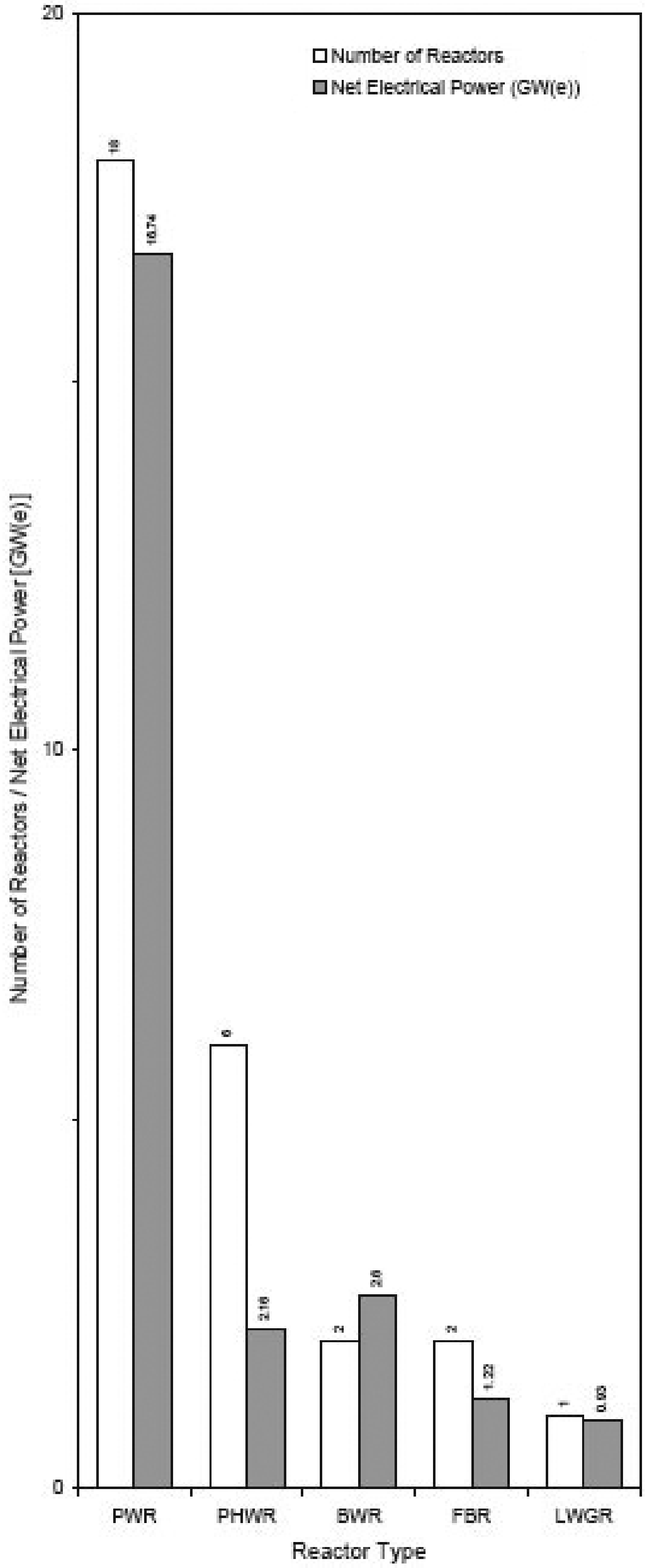

Fig. 4. Nuclear reactors under construction by type and net electrical power (as of 31 Dec. 2006 [4]).

reactor core and steam generators are contained in shielded concrete container (Fig. 6).

The primary flow diagram is given in Fig. 7. This loop includes a pressurizer to maintain the RCS pressure, and compensates any changes in its volume, pressure, or temperature. The RCS includes also a chemical and volume control system (CVCS) to purify the reactor coolant (by filters and demineralizers), and adds or removes boron as necessary.

The generated steam is supplied to the steam turbine driving the electric generator. Steam is exhausted from the

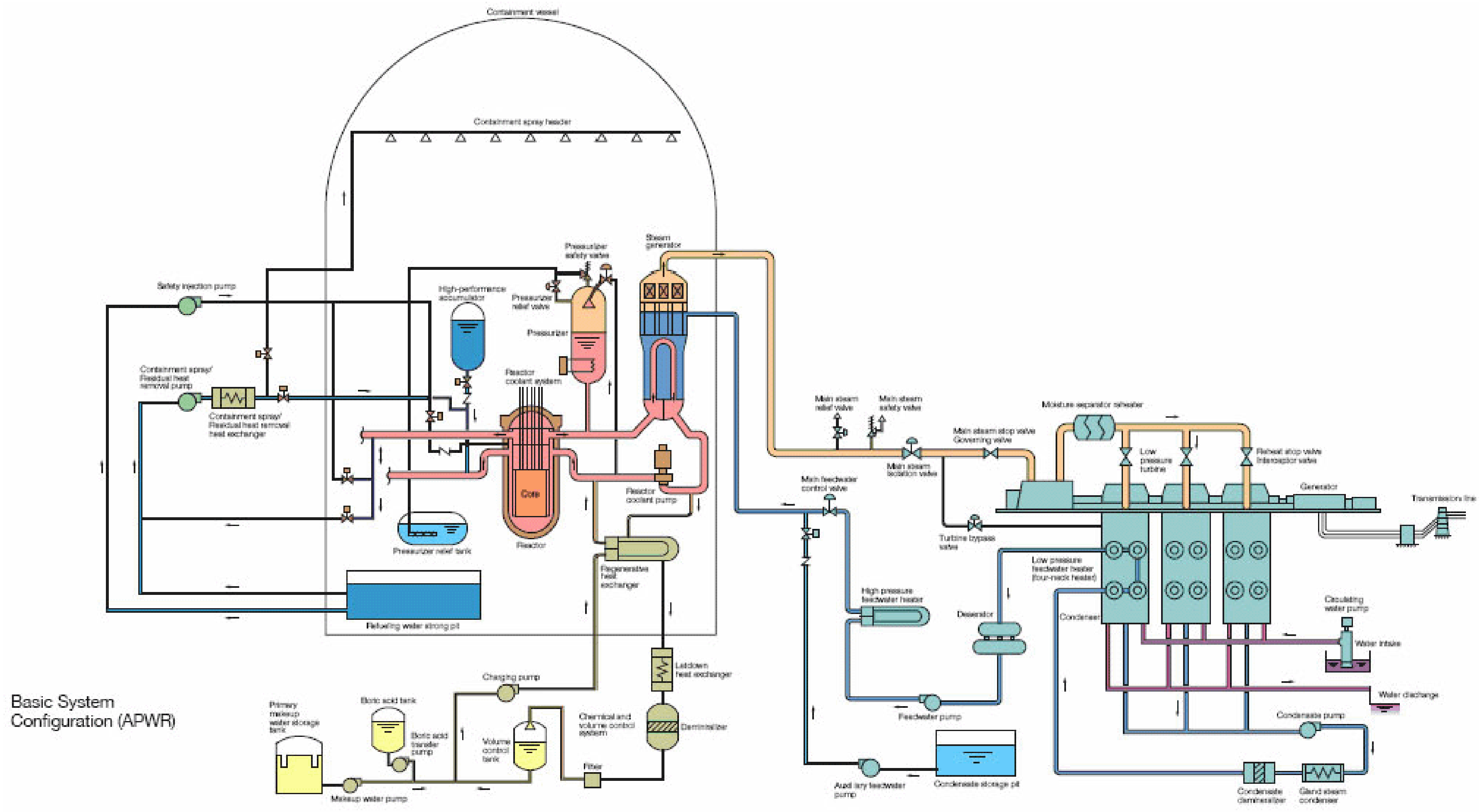

Fig. 5. Sketch of NPP using AP600 PWR [5].

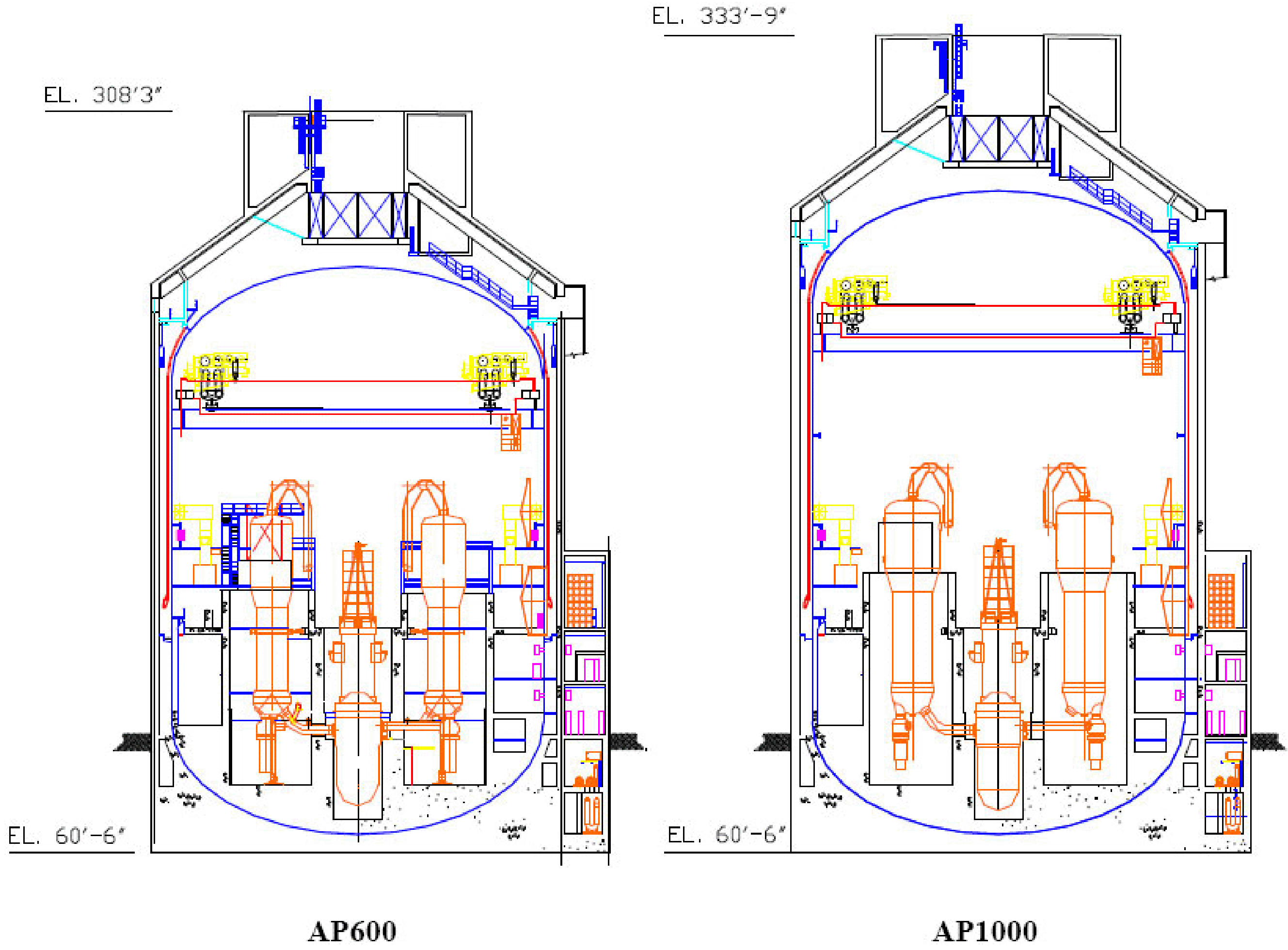

Fig. 6. AP600 and AP1000 shielded containment.

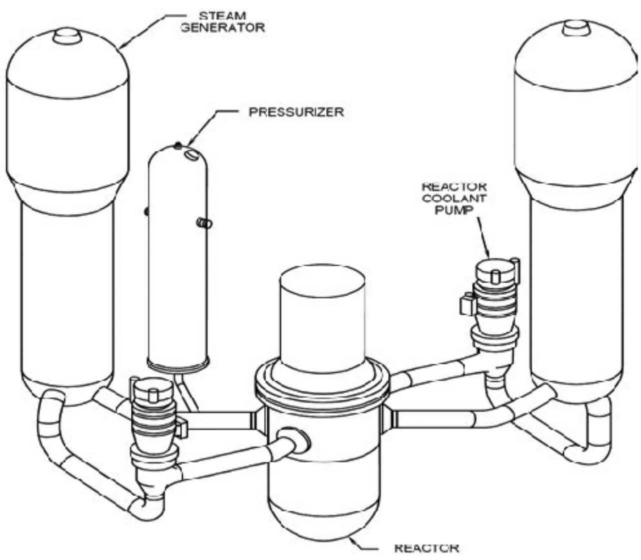

Fig. 7a. Sketch of the reactor combination with steam generator and pressurizer [9].

turbine to the condenser where it condenses by cooling water (once through seawater here). The water condensate is pumped from the condenser to the steam generator through regenerative feed heaters by a series of pumps. The PWR has the advantage that if fuel leaks in the core, no radioactive contaminants pass to the turbine and condenser loop.

The AP600 and AP1000 have simplified designs compared to earlier reactor designs. It provides passive protection from faults and hazards and thus avoids the need for complex control schemes, and reduces the burden on operators during faults. The AP600 is able to maintain core cooling via natural circulation of cooling water, and provision of an induced-draught cooling tower as part of the containment structure, thus avoiding the need for standby emergency generators.

The PWR was originally developed by Westinghouse in the USA. Now, several commercial PWR suppliers emerged: Westinghouse, Babcock and Wilcox; and Combustion Engineering in the USA; Siemens (Kraftwerk

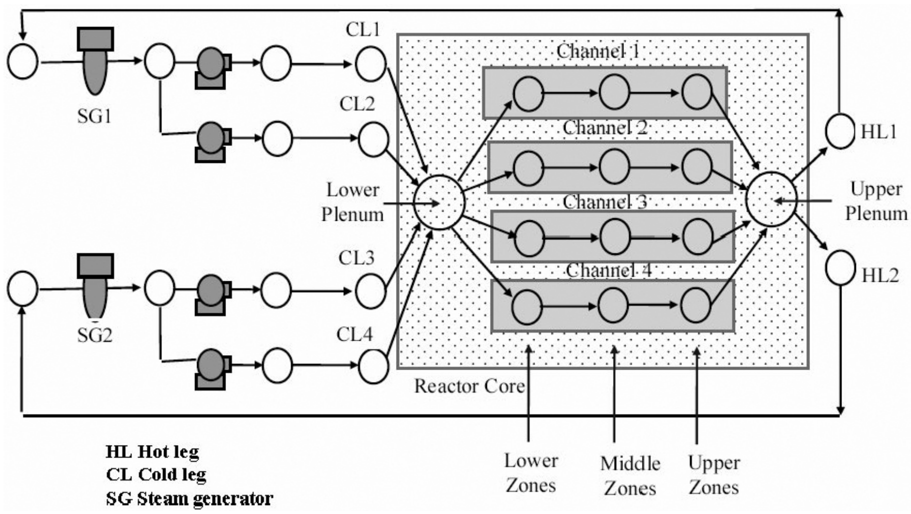

Fig. 7b. Primary loop (reactor coolant system) flow diagram [10].

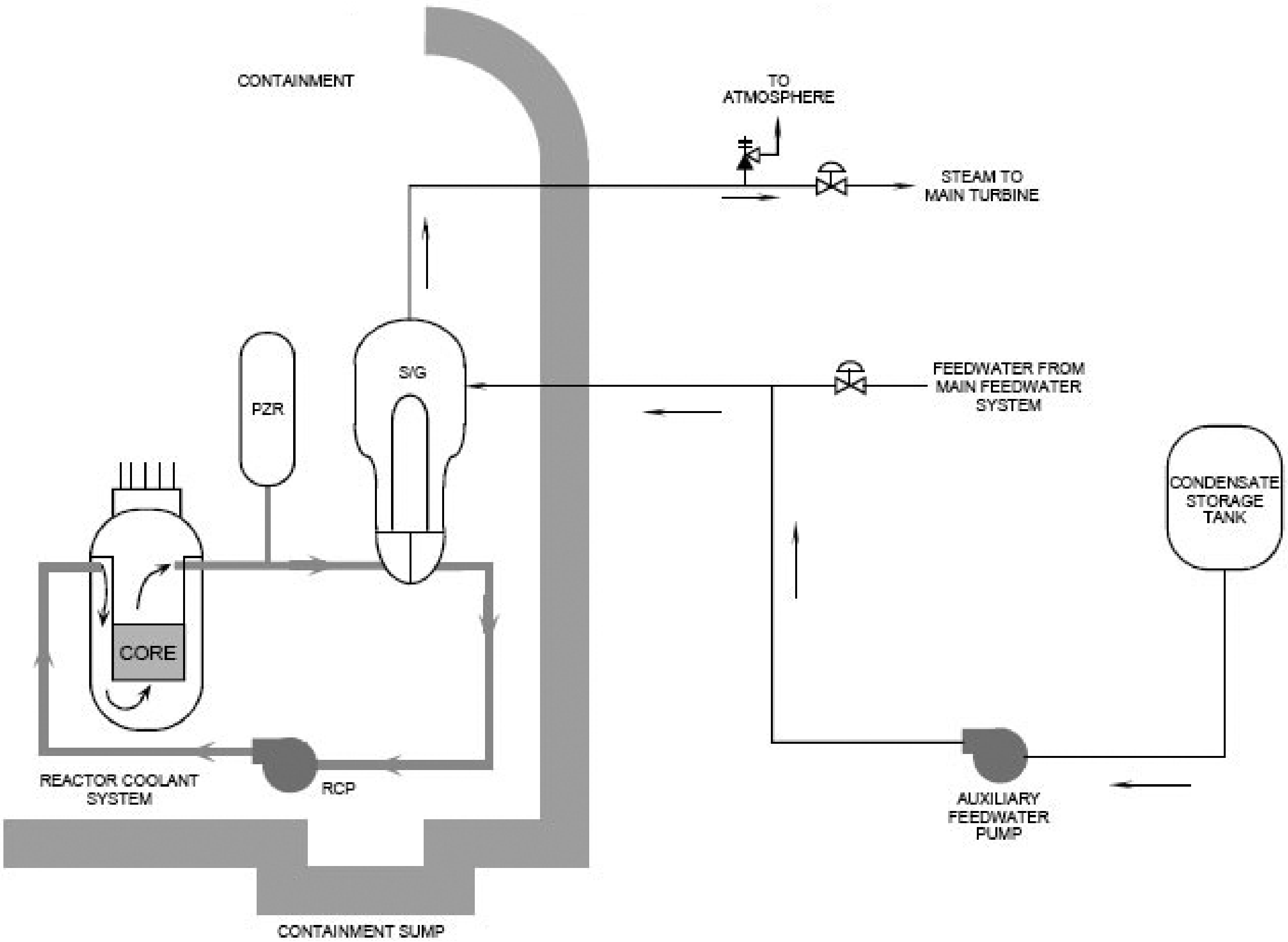

Fig. 8. Steam dump system used to decay heat removal.

Union) in Germany; and Framatome in France, and Mitsubishi in Japan and Agip Nuclear in Italy became PWR licensees. So, the same plant can be ordered from different countries.

Table 8
Advanced nuclear design types and manufacturers

US A PWR	Manufacturers	Size and type
A APWR	Mitsubishi, Japan	1700 MWe advanced pressurized water reactor (APWR)
PER	Areva, France	100 MWe evolutionary APWR
ABWR	GE	1350 MWe Boiling water reactor (BWR)
ESBWR	GE	1380 MWe BWR with passive safety feature
SWR 1000	Framatome ANP	1013 MWe BWR
AP600	BNFL-Westinghouse	610 MWe PWR with passive safety features
AP1000	BNFL-Westinghouse	1090 MWe PWR with passive safety features
IRIS	Westinghouse	100–300 MWe PWR
PBMR	ESKOM	110 MWe modular pebble bed gas-cooled reactor
GT-MHR	General Atomics	288 MWe presmatic graphite moderated gas-cooled reactor
ACR 700	AECL	730 MWe heavy water reactor

5.2. AP600 safety features

5.2.1. Decay heat removal

When the reactor is shutdown, heat is produced by the decay of fission products, and can cause fuel damage. This heat can be removed from the core to the environment by two arrangements:

First, auxiliary feed water pump system circulates water from the condensate storage tank to the steam generator where this water boils (Fig. 8). The resulting steam bypasses the turbine to the main condenser to lose its latent heat. If the steam dump system is not available (for example, there is no circulating water for the main condenser), the steam can be dumped directly to the atmosphere through atmospheric relief valves.

Second, when the decay heat is not sufficient to generate enough steam to continue cooling the primary water carrying the heat from the reactor, a residual heat removal system is used. This system cools the primary flow by using a cooling water system (CCW) in a residual heat exchanger (RHX). The RHX is located inside the injection containment refueling water storage tank (RWST) just above the reactor coolant system.

5.2.2. Emergency core cooling system (ECCS)

The emergency core cooling system (ECCS) cools the reactor core in case a loss of coolant accident (LCA) to prevent fuel damage. It injects large amounts of cool borated water source into the reactor coolant system. The borated water provides extra neutron poisons to ensure that the reactor remains shutdown following the cool down. This water source is called the RWST.

The ECCS has four separate sub-systems (see Fig. 9):

1. A high pressure (HP) injection (or charging) system. This system uses the pumps of the chemical and volume control system to inject water from the refueling water storage tank RWST into the reactor coolant system. It provides water to the core during emergencies when the reactor coolant system pressure remains relatively high (such as a small break in the reactor coolant system, steam break accidents, and leaks of reactor coolant through a steam generator tube to the secondary side).
2. An intermediate pressure (IP) injection system is also designed for emergencies when the primary pressure stays relatively high, such as small to intermediate size primary break. Upon an emergency start signal, the pumps take water from the RWST and pump it into the reactor coolant system.
3. A cold leg accumulators system does not require electrical power to operate. These tanks contain large amounts of borated water.
4. A pressurized nitrogen gas bubble on the top. When the pressure of the primary system drops below certain limit, the nitrogen forces the borated water out of the tank into the reactor coolant system. These tanks are designed to provide water to the reactor coolant system during emergencies in which the pressure of the primary drops very rapidly, such as large primary breaks.
5. A low pressure (LP) injection system (residual heat removal) designed to inject water from the RWST into the reactor coolant system during large breaks, which cause a very low reactor coolant system pressure. In addition, the residual heat removal system allows it to take water from the containment sump, pump it through the residual heat removal system heat exchanger for cooling, and then send the cooled water back to the reactor for core cooling. This method of cooling is used when the RWST is empty after a large primary system break. This is called the long-term core cooling or recirculation mode.

5.2.3. Used nuclear fuel

The fuel used in PWR is usually enriched uranium. The majority of nuclear power reactors in operation and under construction use "enriched" uranium fuel with the

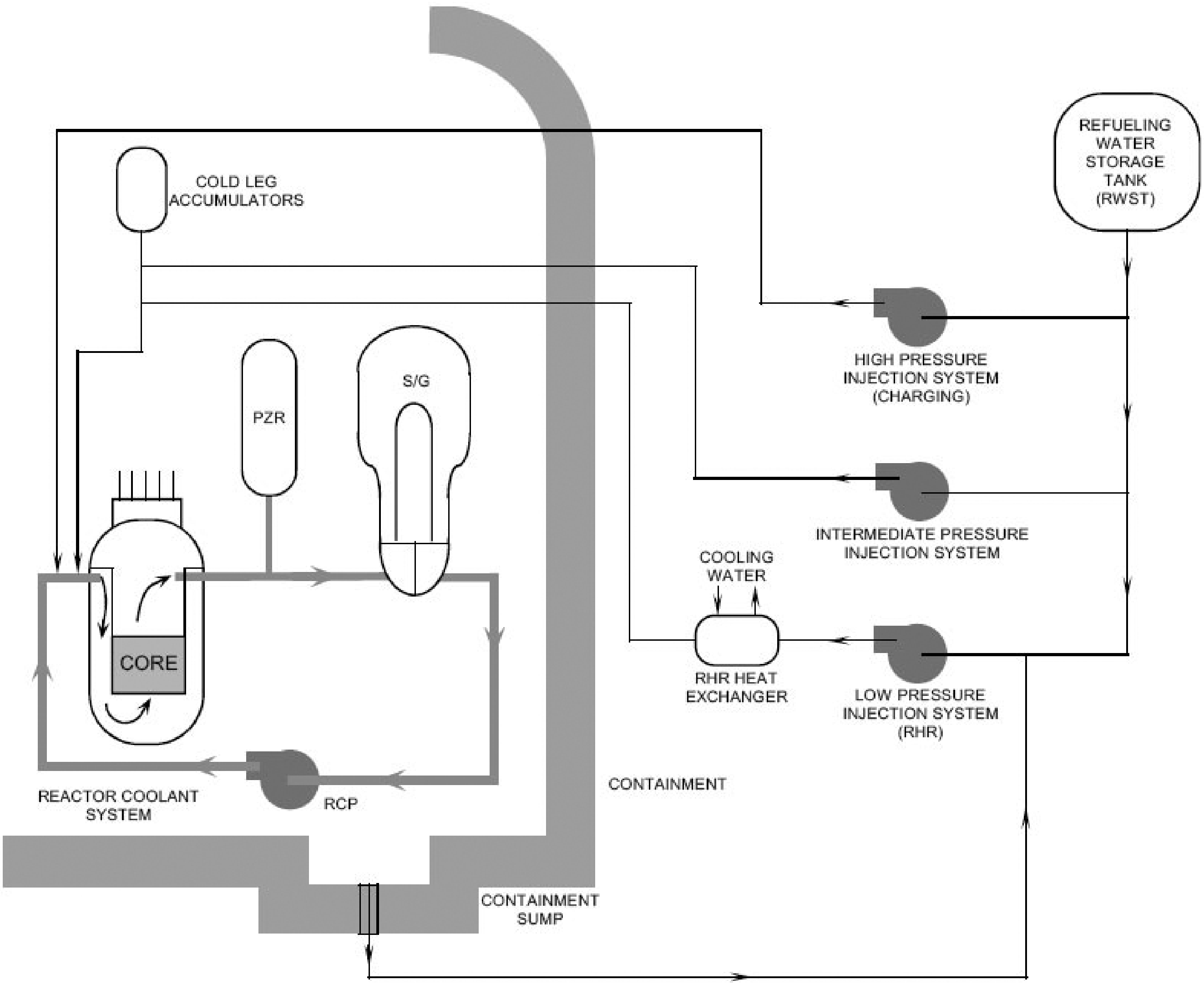

Fig. 9. Emergency cooling system by HP, IP, cold leg and LP.

proportion of U-235 isotope raised from the natural level of 0.7% to about 3.5% or slightly more. The enrichment process removes about 85% of the U-238 by separating gaseous uranium hexafluoride into two streams: one stream is enriched to the required level of U-235 and then passes to the next stage of the fuel cycle. The other stream mostly U-238, depleted in U-235, is called "tails". After enrichment, the uranium dioxide (UO2) powder is fired in a high-temperature, sintering furnace to create hard, ceramic pellets of enriched uranium dioxide. The cylindrical pellets are then put into tubes of a corrosion-resistant zirconium metal alloy (Zircaloy) which are backfilled with helium to aid heat conduction and detect leakages. The finished fuel rods are grouped in fuel assemblies, called fuel bundles, which are inserted in the reactor core. A safety measure of the PWR design is that it does not contain enough fissile uranium to sustain a prompt critical chain reaction (i.e. sustained only by prompt neutron). Avoiding prompt criticality is important as a prompt critical chain reaction could very rapidly produce enough energy to damage or even melt the reactor (as is suspected to have occurred during the accident at the Chernobyl plant). In the AP600, the fuel inventory is 66.9 tons of uranium with average linear heat rate = 13.5 kW/m, average fuel power density = 28.89 kW/kg U, average core power density (volumetric) = 78.82 kW/l, and thermal heat flux, Fq = 2.60 kW/m^2.

The enrichment (range) of first core is 1.9–3.7 Wt% U-235, and enrichment of reload fuel at equilibrium core 4.8 Wt% U-235, and operating fuel cycle time length = 24 months. The average discharge burn-up of fuel (nominal) is 55,000 MWd/t.

Generally, reactor power can be viewed by the steam demand (flow rate) by the turbine. Boron and control rods

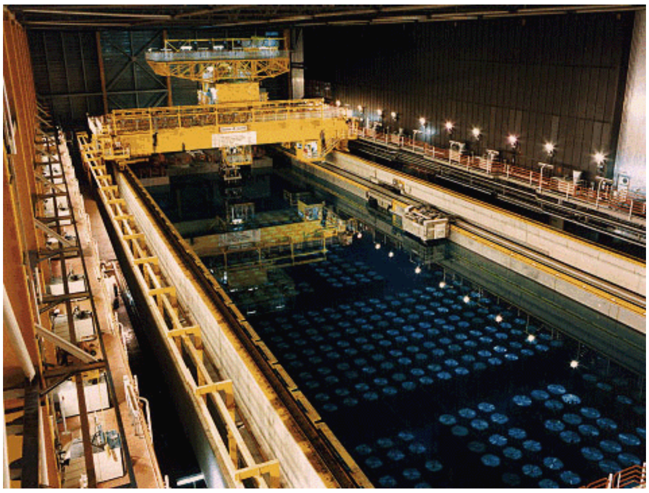

Fig. 10. Storage pond for spent fuel at UK reprocessing plant, the nuclear fuel cycle, http://www.uic.com.au/nfc.htm.

are used to maintain primary system temperature at the desired point. The power is decreased by throttling (partial shutting) the turbine inlet valves. This increases the temperature of the primary loop and in turn causes the reactor to fission less and decreases its power. The operator could then add boric acid and/or insert control rods to decrease temperature to the desired point.

Spent fuel (used) waste is a radiological hazard that posses health and safety risks to society. The spent fuel assemblies taken from the reactor core are highly radioactive and give off a lot of heat. They are therefore stored in special ponds which are usually located at the reactor site (Fig. 10) to allow both their heat and radioactivity to decrease. The water in the ponds serves the dual purpose of acting as a barrier against radiation and dispersing the heat from the spent fuel. Spent fuel can be stored safely in the ponds for long periods. It can also be dry stored in engineered facilities, cooled by air. However, both kinds of storage are intended only as an interim step before the spent fuel is either reprocessed or sent to final disposal. The longer it is stored, the easier it is to handle, due to decay of radioactivity.

The continued storage of spent fuel at reactor sites imposes additional radiological risks on the utilities. In California the spent fuel keeps the coastal lands adjacent to its storage facilities inaccessible to the public.

6. NPP economic competitiveness

The NPP economy can be compared with that of the currently preferable combined gas/steam cycle (CCGT). The CCGT cycle has high efficiency (≅ 0.48 in the hot Kuwaiti climate), and reasonably low capital cost. For both NPP and CCGT, the cost to generate electric can be

Table 9a
Capital cost of different power cycles of different capacities (in service year = 2007, nominal $ 2007)

	Size, MW	$/M Wh
Conventional combined cycle (CC)	500	87.89
Conventional CC-duct fired	550	88.77
Advanced combined cycle	800	81.90
Conventional simple cycle	100	313.42
Small simple cycle	50	346.37
Advanced simple cycle	200	248.52
Integrated gasification combined cycle (IGCC)	575	74.70
Advanced nuclear	1000	67.01
Fuel cell–molten carbonate	2	86.96
Fuel cell–proton exchange	0.03	111.10
Fuel cell–solid oxide	0.25	68.75
Solar–concentrating PV	15	116.23
Solar–parabolic trough	63.5	154.86
Solar–photovoltaic (single axis)	1	256.29
Solar–Stirling dish	15	312.10
Wind–class 5	50	60.78

Table 9b
General advanced nuclear power plant cost estimates

Study	Estimate date	Cost estimate, $/(kWe)
International Energy Agency	2001	$1,100 (overnight cost, US)
US Energy Information Administration	2001	$2,300 (overnight cost, US, first-of-a-kind reactor)
UK Energy Review	2001	$2,600–$3,300 (total construction cost, UK)
Keystone Report	2007	$2,950 (overnight cost, U.S) $3,600-$4,000 (total capital cost, US)
EPRI	2007	$2,000–$2,400 (low contingency) $3,260–$3,720 (high contingency) (all-in cost, US)

calculated from capital, fuel, and operation and maintenance (O&M) costs. For NPP, funds should be saved during the plant operation to cover the cost of decommissioning the plant at the end of its life. In year 2007, the capital cost of the NPP using light water PWR was estimated as $2865/kW for the AP1000 of 1000 MWe nominal capacity [5,6]. There are many estimations about this capital cost. For example, Table 9 was taken from a California report about nuclear energy costs in 2007 [7].

It is interesting here to mention that the NPP is not much cheaper than renewable energies such as solar, as

Table 10
Instant cost

Technology cost at $2006 end	Gross capacity, MW	$/kW
Nuclear	1000	2865
Conventional combined cycle	500	784
Combined cycle with auxiliary firing	550	803
Simple gas turbine cycle	50	857
Simple gas turbine cycle	100	793
Advanced simple gas turbine cycle	200	610
Solar concentrating PV	15	5000
Solar parabolic trough	63.5	3900
Solar photovoltaic (single axis)	1	9321
Wind	50	1900

shown in Table 10. This table shows that the capital cost/kW reported for wind energy is even less than that for NPP. The problem with the wind energy is the small and intermittent power capacity per unit.

The decrease of the NPP size increases its cost per kW. Hence, it is assumed that for the AP600 of 600 MW nominal capacity, the cost/kW is 15% higher than that of the AP1000. Thus, the cost for NPP using the AP600 is considered in the calculations as $3438/kW. When a 3000 MW total capacity plant is installed by using NPP of five units (5×AP600), the capital cost would be $2,062.8 million dollars ($M) per unit and 10,314 $M for five units. Similarly for CCGT, the capital cost per kW was given as $803/kW, and the cost for each 600 MW group (say two gas turbines and one steam turbine) is 481.8 $M, and 2,409 $M for five units of a total 3000 MW capacity. This shows that the NPP capital cost is more than four times that of CCGT.

For an 8% interest rate and a 100 $M loan to be paid back over 30 years (y), the interest along the 30 y is approximately 120 $M (= 100 $M×0.08×30/2). The total payment (principal and interest) is 220 $M over the 30 y divided by a fixed payment of (220 $M/30 =) 7.33 $M each year. The ratio A = 7.33/100 = 7.33% is called the fixed charge rate, and the annual fixed payment would be A×total capital cost. The annual fixed payment, after the first year, has a lower real value (compared to today or present money value) due to the inflation. The real value of these payments in terms of today's value of money (dollars) is called the present levelized value (P), and can be calculated by (see [8,9]):

$$P = \frac{A}{30} \frac{1-(1+i)^{-n}}{i}$$

where i is the inflation rate, n is the number of years, and A is fixed payment per year. For n = 30, and i = 3%, the term $\frac{1-(1+i)^{-n}}{i}$ is equal to 19.6. The annual levelized present value of the capital for the NPP and CCGT plants is calculated and given in Table 11. The nuclear fuel energy cost as reported by eight studies was in the range between 0.3 to 1.4 ¢/kWhe. If the nuclear fuel energy cost is 1.4 ¢/kWhe (based on 33% plant efficiency), and the plant capacity factor is 80%, the power generated in the first year is 21,024 GWh, and the nuclear fuel energy cost is 290.43 $M.

Table 11
Power cost calculation for NPP using AP600 and AP1000 units with CCGT

Items	AP600	AP1000	CCGT
Capital cost	10,314.00	8,595.00	2,409.00
Annual fixed payment	756.33	630.27	176.65
Levelized present value annual, $M	494.13	411.78	115.41
Incremental capital expenditure, $M (kWe-y)	60.00 20	60.00 20	18.00 6
Fixed O&M cost, $M/(kWe/y)	408.00 20	408.00 136	60.00 20
Fuel	Uranium	Uranium	Natural gas
Power output/y, GWh	21,024	21,024.00	21,024.00
Thermal energy input/y, GWh	63,709.00	63,709.00	43,800.00, (157,680× 10^6GJ
Fuel cost	290.43	290.43	1,709.25
Variable O&M	14.58 $4.86/kW-y	14.58	84.10 $4/MWh
Nuclear waste fee, $1/MWh	21.02	21.02	0.00
De-commissioning cost	35.00	35.00	0.00
Annual total cost	1,288.17	1,240.80	1,986.50
Power cost $/MWh	61.27	59.02	94.49

The CCGT can be operated either by natural gas and/or heavy oil. The cost of the heavy oil in US escalated from $148.1 to $365/ton from 2001 to 2006. This is almost a 20% annual increase, and in 2007, the cost is expected to be $438/ton for the same increasing rate. If the heating value of this oil is 40 MJ/kg, then the fuel cost/GJ is 438/40 = $10.95/GJ. Similarly, the natural gas cost increased in the UK from $4.5 to $9.7/million BTU from 2001 to 2006, and is expected to be $11.3/MBTU for ($10.72/GJ) in 2007 for the same increasing rate. Since in Kuwait both heavy oil and natural gas are used, the average cost of $10.84/GJ is used in the calculations.

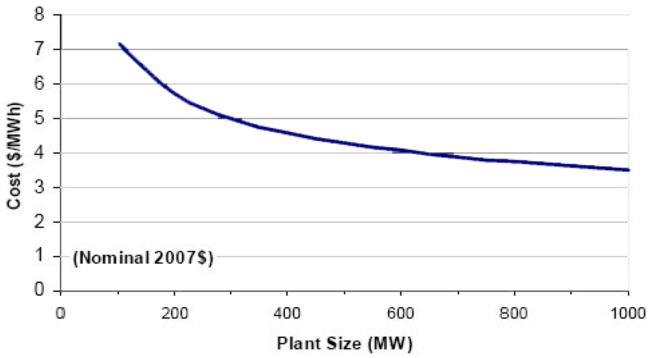

Fig. 11. Variable O&M of combined gas–steam cycle.

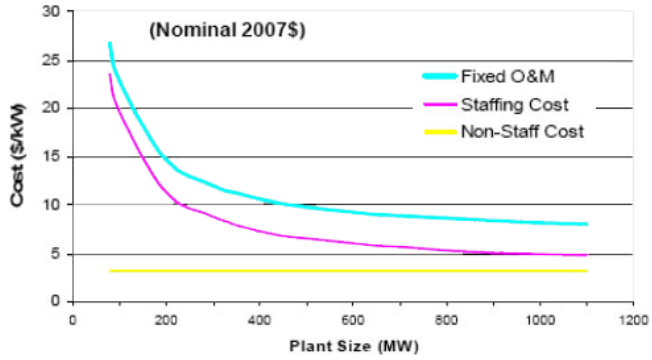

Fig. 12. Fixed O&M of combined gas–steam cycle.

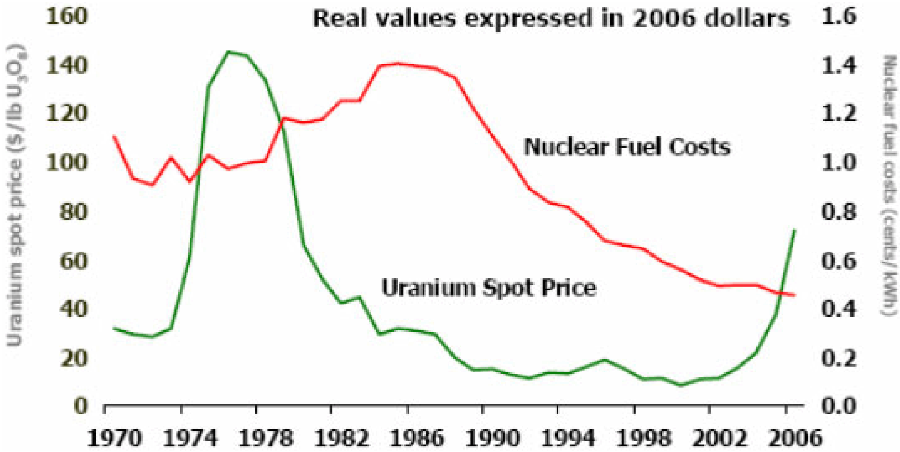

Fig. 13. Nuclear fuel cost and uranium spot prices.

For the CCGT and the same 80% capacity factor, the fuel thermal energy input (21,024×3600/0.48 =) 157,680× 10^6 GJ, and its cost is 1,709.25 $M.

The results of the calculations are tabulated in Table 11 and show that the final power cost is $61.27/MWh when NPP is used, and $94.5/MWh when CCGT are used. *The calculations show that for NPP using AP600, the power cost is 35.2% cheaper than that of CCGT.*

As for other countries SA, Egypt, and UAE where AP1000 type is suggested, the capital cost is $2865/kW is used, and the AP1000 unit cost is 2850 $M, and the power cost is $59.02/MWh. *This is 39.7% cheaper than that of CCGT.*

In Table 11, the following assumptions were made:

- The decommissioning cost is taken as 350 $M/1000 MW. The nature of NPP plant cannot be abandoned without significant costs to clear the site from radioactive contamination. These costs must be accumulated during the life of the plant as required by the US Nuclear Regulatory Commission.
- The fixed and variable operation and maintenance costs were taken from Figs. 11 and 12 [6].
- The nuclear ful cost was taken as the highest cost given in Lam [10] and shown in Fig. 13.

Table 12
Power cost calculated by California energy group [8] (in service year = 2007 (nominal $ 2007)

	Size, MW	$/MWh
Conventional combined cycle (CC)	500	87.89
Conventional CC-duct fired	550	88.77
Advanced combined cycle	800	81.90
Conventional simple cycle	100	313.42
Small simple cycle	50	346.37
Advanced simple cycle	200	248.52
Integrated gasification combined cycle (IGCC)	575	74.70
Advanced nuclear	1000	67.01
Fuel cell–molten carbonate	2	86.96
Fuel cell–proton exchange	0.03	111.10
Fuel cell–solid oxide	0.25	68.75
Solar–concentrating PV	15	116.23
Solar–parabolic trough	63.5	154.86
Solar–photovoltaic (single axis)	1	256.29
Solar–Stirling dish	15	312.10
Wind–class 5	50	60.78

The power cost was calculated by the energy group in California for NPP, CCGT, and other types of energy sources, including renewable energy, and the results are given in Table 12. The levelized cost/MWh in this table is higher than that in Table 11 for different reasons: they included some cost items which were not included in Table 11 such as: return of 15% for NPP and 12% for combined cycle.

Table 12 shows that the power cost generated by wind energy and some types of the fuel cells (of low power capacity) are in the same range of the NPP and lower than those of the CCGT.

7. Combining the AP600 with desalting plants

The combination of the suggested PWR with different desalting plants is discussed in Part II of this study.

8. Conclusions

Kuwait, SA, the UAE and Egypt are ready to consider the option of using NPP for their cogeneration power desalting plants because:

- The source of the fossil fuels used (oil and natural gas) is limited and is expected to be consumed locally within 30 years in SA, UAE, and Kuwait, and in 10 years if the same rate of consumption continues. The locally consumed oil in any of these countries is deducted from its reserves and/or decreases its income. This fuel source is the main source of income in the GCC counties.
- The needed additional installed capacities in 10 years compared after 2006 are in the range of 7.5 GW for Kuwait, 26.7 GW for SA, 16 GW for Egypt, and 9.2 GW for UAE. These are high enough to consider the use of NPP.
- The use of NPP is more economically competitive compared with the most efficient combined gas/steam combined cycle (G/STCC). The cost of electric power in $/MWh by NPP is at least one-third cheaper than that of G/STCC.

References

[1] OAPEC Statistical Year Book, 2007.
[2] Economics of Nuclear Desalination: New Development and Site Specific Studies, IAEA–TECDOC-1561, 2007.
[3] Kuwaiti Ministry of Energy, website [http://www.moo.gov.kw].
[4] Nuclear Power Reactors in the World, IAEA, Vienna, 2007.
[5] Mitsubishi nuclear plants, pamphlet, Mitsubishi Co., Japan.
[6] Comparative cost of California central station electricity generation technologies, Final staff report, CEC-200-2007-011-SF, 2007.
[7] Nuclear Power Joint Fact Finding, June 2007, The Keystone Center; Navigant Consulting estimates 2007, The Future of Nuclear Power.
[8] Final consultant report, Integrated Energy Policy Report, California Energy Commission, CEC-100-2007-005-F, 2007.
[9] K.W. Li and A.P. Priddy, Power Plant System Design, Wiley, New York, 1985.
[10] Reactor Concepts Manual, Pressurized Water Reactor Systems, USNRC Technical Training Center 4-1 0603.
[10] W.K. Lam, Advanced Pressurized Water Reactor Simulator User Manual, Cassiopeia Technologies Inc, Canada, 2006.
[11] Pressurized water reactor simulator, IAEA-TCS-22/02, 2005.