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REACTOR SELECTION FOR DUAL-PURPOSE DESALINATION PLANTS IN SAUDI ARABIA

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ABSTRACT

This paper presents a general overview about conventional reactors, advanced reactors and small and medium sized reactors are given including the advantages and disadvantages of each reactor. These reactors are: pressurized water reactors (PWR's), boiling water reactors (BWR's), heavy water reactors (CANDU), RBMK reactors, gas cooled reactors (GCR) metal cooled reactors (LMFBR), and advanced water reactors. This led to a subjective selection of the most suitable reactors to be used for dual-purpose desalination plants in Saudi Arabia. Selection criteria for a nuclear reactor are presented, and the results showed that the most suitable nuclear reactors to be used for nuclear desalination in Saudi Arabia are:

1. *Medium size PWR such as AP-600 (USA), AC-600 (China) and PWR several countries.*
2. *Medium size PHWR such as CANDU (Canada) and PHWR (India).*

Keywords: *Nuclear, reactors, desalination, energy, dual purpose, planning.*

الملخص

يعرض هذا البحث نظرة عامة عن المفاعلات النووية التقليدية ، المفاعلات المتقدمة (المتطورة) وكذلك بالنسبة للأحجام الصغيرة والمتوسطة موضحاً مميزات وعيوب كل مفاعل على حده . وقد أدى هذا الاختيار الموضوعي (subjective) للمفاعلات الأكثر ملائمة للاستخدام في محطات التحلية النووية ثنائية الغرض في المملكة العربية السعودية .

تم عرض معايير الاختيار ، وأظهرت النتائج أن المفاعلات النووية المناسبة للاستخدام في محطـات التحليـة ثنائيـة الغرض في المملكة العربية السعودية هي :

١ - مفاعل الماء المضغوط (PWR) متوسط الحجم مثل نوع (AP-600) الأمريكـي الصـنع ، (AC-600) الصيني الصنع . كذلك مفاعلات الماء المضغوط المصنّعة في العديد من الدول .

٢ - مفاعل الماء الثقيل المضغوط (PHWR) متوسط الحجم مثل كانديو (CANDU) الكندي الصـنع وكـذلك (PHWR) المصنّع في الهند .

1. NUCLEAR ENERGY COMPETITIVENESS

An assertion that is heard over and over again is that nuclear electricity is more costly than fossil generated electricity. Is this statement true? When considering the United States of America, there are 109 different operating nuclear power plants. Each of them is unique and were designed by one of four different companies, built over a 30 year period, built in various locations and operated by over a dozen companies with variation in operating training programs, contractor support and management skills.

According to a five year survey by the Utility Data Institute, five of the top 25 electrical power plants in the United States are uranium fuel, all of the remaining of the list are coal burning plants located west of the Mississippi. On the international scale, nuclear electricity is also competitive. Canadian electricity producers provide a large portion of their nuclear electricity to New York. France, which has more than 75 percent of its electricity produced by nuclear, exports nuclear electricity to nearly all of its neighbors. Atomic Energy of Canada, Limited (AECL) will only mention that their international transactions are profitable because it believes that the release of more information could give competitors useful information that would damage their market.

If electrical power were treated as a normal commodity, the question "How much will it cost a new plant to produce a unit of electricity over the life time of the electricity facility compared to other alternatives?" will have a complicated answer that taken into account many factors such as regulatory risk, external cost, technological risks, political risks and market risks. Electricity is not treated as a normal commodity because of the incredible variation in electricity pricing around one country. The cost distribution of nuclear power plants is completely different from those of fossil fuel plants. In a fossil fuel plant the major driving cost is the cost of consumable raw materials such as fuel and chemicals. Fossil fuel prices vary widely depending on their geographic locations and also require expensive transportation infrastructure. On the other hand, nuclear plants, fuel is a minor cost component with engineering design work, personnel costs and regulatory compliance can be higher than comparing fossil plants. The comparison calculations are difficult and based on estimates that are highly inaccurate when long time horizons are considered. The cost of competitive coal and natural gas also increased. For operating power plants, the major cost factor is the operating and maintenance (O&M) and capitalized repair cost. This factor will determine whether the plant will continue to operate in a competitive market place or not.

In United States, the O&M cost for the nuclear industry have fallen steadily over the past decade. Average O&M cost in 1988, dropped from 2.75 cents per kWh to 2.48 cents per kWh, in 1992 to 1.92 cents per kWh, in 1995, to 1.78 cents per kWh. In 1996 dropped by 35% over a period of eight year.In comparison with coal, the average nuclear O&M cost in 1995 was 1.92 cents per kWh and that of coal which has the lowest production cost of fossil fuel was 1.88 cents per kWh. In 1995, the average O&M cost for natural gas were at 2.68 cents per

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kWh. The existing nuclear power plants are on the average very competitive in terms of production cost for generating electricity. It has to be mentioned that focussing on marginal operating cost does not address the construction of a new plant in a competitive market. The capital cost for a new nuclear power plant far exceeds the capital cost of a new natural gas plant. However, a new nuclear power plant might be competitive with a new natural gas plant when construction costs are capitalized and recovered over a 40-60 year time horizon. When considering short time horizons for expected return on capital in a competitive marketplace, will result in a new natural gas plant in favor of a new nuclear one.

With the current abundance of existing and newly discovered natural gas reserves the change from natural gas to nuclear may not be feasible. Nuclear power plants, when found competitive with fossil plants other factors have to be considered such as lack of agreed solution for the disposal of radioactive waste and spent fuel, concern of regulatory stability and opposition of the national and local levels. There are several factors that affect nuclear electricity competitiveness, the most important ones pertaining to Saudi Arabia are listed below:

1. **Net generating capacity factor**, this is one of the most important structural factors. Small capacity nuclear power plants require a large workforce to operate them. The larger the megawatts generated by the plant, the lower the plant generating cost per kWh. If the Big Rock plant (67 MWe) is taken as an example. The cost of the large staff operating it makes the cost of a unit electricity very high.
2. **Number of units at a site**, sites that have several units usually spread certain cost, such as engineering and security. This reduction in unit cost is increased when the plants at the site are identical.
3. **Variable factors** also determine a plant's competitiveness. They determine the plant needs to make significant capital expenditures to have the plant operating in the near future. This capital expenditure cost must be included in the cost of electricity generation. It is highly possible to have a plant that runs competitive for some period of time and then fails to do so in the near future. Such plants will require a large influx of capital in the near future and if this capital was not included in the cost of electricity the plant will be shut down because lack of competitiveness. The two major capitals facing a nuclear plant are the cost to replace or upgrade steam generators and the cost to replace or upgrade plant systems to obtain license renewal. Several plants in the United States proved to be incompetitive and were forced to shut down such as Zion, Torjan and the Yankee Rowe Plants.
4. **Fossil fuel cost and environmental impact**, the O&M cost, as mentioned earlier, for nuclear power plants is only slightly more than that of coal and lower than that of natural gas plants. As fossil fuel O&M cost increases, nuclear power plants becomes more competitive. Increasing regulations of fossil fuel plant emission may increase the

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costs of fossil fuel generation. Some plants in the United States have shown concern on anticipated substantial increase in the generation of coal power. Coal being the lowest cost fuel, resulted in increase in acid rain and smog pollution problem. Those polluted States have expressed concern to add more regulation on emissions from coal-fired plants. Such a concern is not a problem in Saudi Arabia because of the fact that the Saudi electric utilities are not using coal to produce electricity. However, desalination power plants use crude oil to produce water and electricity. The issue of carbon dioxide production and global warming is at the intentional for front level. Many environmental organization in the United States, Europe and Japan are pushing to curb the generation of carbon dioxide. These environmental issues will adversely affect all fossil fueled generation. The Environmental Protection Agency (EPA) is working to reduce the allowance levels of air pollution such as nitrogen dioxide by reducing the fossil plant emissions. These pollution controls may increase the O&M cost of fossil plants and consequently make the nuclear electricity more competitive. Emissions limits at the level of individual producers such as automobiles or power plants would place values on emission of carbon dioxide. The situation will be similar to existing regulations to control emission of other pollutant from fossil fuel such as sulfur dioxide, nitrogen oxides and particulate matter. When carbon values, the cost of energy users to emit carbon dioxides, are imposed, the relative competition of different energy sources would be changed. The cost of nuclear energy will stay unaffected because it is not dependent on carbon bearing energy sources. Gas fired combined cycle plants have the advantage of releasing the least amount of carbon dioxide per kWh of any other fossil fuels. This is mainly due to their carbon fuel and high generation efficiency. These characteristics render the gas fired combined cycles the least sensitive of the fossil fuelled options to carbon values and the introduction of carbon values on other fossil fuelled options will increase their competitive position of gas fired combined options relative to other fossil fuel options. The gas fired combined cycle will stay as a formidable competitor to non-fossil generation options. The restriction on carbon dioxide emissions could place coal fired and crude oil fired generation at a significant cost disadvantage. The gas fired combined plants would be favored first and then nuclear.

5. **Disregarding independent technology developments,** finding a balance between safety and cost is a question. The cost of nuclear energy increased drastically because of the multiplication of safety regulation of plant's design, construction and operation. The cost of low level radioactive waste has also increased, as an example, in the United States, their cost increased by 13% during the period 1980-1995. This is mostly due to the more stringent requirements on disposal sites and scaring of new disposal sites. Also the cost of plant decommissioning varies depending on the level of residual radioactivity permitted. Siting of nuclear power plants has become a major problem in many different countries because potential neighbors to nuclear facilities protest.

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2. REACTOR TYPES

2.1 Pressurized Water Reactors

Pressurized Water Reactors (PWR's) were originally designed by Westinghouse Bettis Atomic Power Laboratory for military applications. Later, the Westinghouse Nuclear Power Division started manufacturing PWR's for commercial applications and the first commercial PWR in the States was the Shipping-port PWR in Pennsylvania. Also, Asea-Brown-Boveri-Combution Engineering (ABB-CE), Framatorne, Trraftwerk, Mitsubishi, and Siemens manufactured the same type of reactor and built it all over the world.

The reactor consists of 2, 3 or 4 cooling loops and each loop has a separate reactor coolant pump and stream generator. The water in the reactor core passes upward past the fuel assembly at about a temperature 530F to about 590^{0}F. Boiling other than the nucleat boiling in the reactor core is not allowed. The pressurizer which is connected to the reactor coolant system maintains a pressure of approximately 2250 psia. The coolant is pumped to the steam generator. The secondary system which consists of the feed water system, turbines, condensers, pumps at the secondary side of steam generator, and electricity generators. The water is pumped from the feed water system and passes through the secondary side of the steam generator to take heat produced by the primary side of the reactor. The water is converted into steam and rotates the blades of the turbines and then condenses. The condensate is pumped again to the secondary side of the generator to repeat the cycle.

The use of water as a coolant in PWR's is related to the relatively low pressure drops of flow at high rates and the relatively high heat transfer coefficients. A reactor coolant should ideally have the following properties:

1. Non-corrosive properties,
2. Low neutron absorption cross-section,
3. Low melting point,
4. High boiling point,
5. Radiation and thermal stability,
6. Low induced stability,
7. High moderating ratio (for thermal reactors only),
8. No reaction with turbine working fluid,
9. Low pumping power, and
10. High heat transfer coefficient

There is no single coolant that has all of the above properties. However, each coolant has its particular advantages for certain type of reactors. Table 1 shows the advantages and disadvangtages of a PWR.

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Table 1. The advantages and disadvantages of Pressurized Water Reactor

Advantages	Disadvantages
Water is available and inexpensive	Fuel fabrication is expensive
Water technology is very well known	Water must be highly pressurized
Negative temperature coefficient	Fission products radioactivity in the reactor core is high
Water has high heat capacity	Hot water in its pure state is highly corrosive
Core is compact	Fuel must be enriched
Leakage can be tolerated	Heat exchanger and control rods are required
Conversion ratio can be high	To unload and load the core with fuel, reactor must be shut down.
Fission products are contained	Fuel reprocessing is difficult
Superheating steam in separate superheater is possible	Temperature is limited in metallic fuel elements
	Water may flash to steam in case of rupture of the primary loop
	Water reacts with uranium and structural metals under certain conditions.
	Large excess reactivity at operating temperature

2.2 Boiling Water Reactors

Boiling Water Reactor (BWR's) were originally designed by Allis-Chambers and General Electric (GE). The first United States BWR was built at Humboldt Bay in California. The Boiling Water Reactor allows bulk boiling of the water in the reactor core. The operating temperature in the reactor core is about 570^0F at an operating pressure of about 1,000 Psia.

The coolant is pumped into the reactor core to pickup heat as it moves past the fuel rods. The water is converted into steam and the steam separators removes the water from the steam. Then, the steam passes through high pressure turbine, moisture separators and a low pressure turbine. The steam, after passing through the low pressure turbine is condensed in the condenser which is at vacuum and is usually cooled by sea, ocean or river water. The condensed steam is then pumped to low pressure feed water heaters. The water is then pumped into the reactor core and the same cycle is repeated over and over again.

The BWR has a unique control rods to shut down the reactor and to maintain a uniform power distribution in the reactor core. The control rods are from the bottom by a high hydraulic pressure. The BWR has a suppression to remove the heat release in case of larger quantity of steam is released from the reactor of the reactor re-circulation system. Table 2 lists the advantages and disadvantages of BWR’s.

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Table 2. Advantages and disadvantages of Boiling Water Reactors

Advantages	Disadvantages
Power excursion damps quickly by steam formation	Boiling makes power density limited
The overall thermal efficiency is quite high	Build up of radioactivity in the turbine
Water is inexpensive	Fuel must be enriched
Negative temperature coefficient	Fuel loading and unloading requires special equipment
Temperature of the metal surface is lower for a given steam output condition than that of a PWR.	Design must overcome tendency to negative reactivity due to load increase.
Pressure is lower for given steam output conditions than that of PWR.	Reactor must shut down for loading and unloading of fuel
Some heat exchangers are eliminated	Water flashes to steam in case of primary system rupture
Leakage can be tolerated	Serious trouble may be caused by condenser leakage
Fission products are contained	Separate fired superheater is not conveniently employed
Conversion ratio can be high	
Heat can be taken from water to increase power output	
Water has a short live radioactivity if kept pure	

2.3 Heavy Water Reactor

CANDU reactors are heavy water reactor types. The CANDU was designed by Atomic Energy Canada Limited (AECL) as an option to use natural uranium.

The CANDU reactors use natural uranium, therefore their fuel is cheaper and can relatively give large life time capacity factor. The design consists of a horizontal vessel where the tubes for the fuel rods and cooling heavy water are installed. The heavy water has a high moderating power and low absorption which enable the use of natural uranium.

The deuterium separation unit is an added capital cost in which over the plant life time may be offset by the natural uranium cost reduction. In CANDU reactors, the reactor cooling pumps circulate the heavy water through the reactor core and then to the steam generator in the closed loop similar to that of PWR's.

The moderator heavy water, however, has a separate heat exchanger to cool down the moderator. The pressure in the CANDU reactors is maintained at about 1200 Psia which is lower than that the PWR's. The CANDU reactors have redundant equipment in the secondary system and due to that the operating cycles are longer. Cycle times have been reported to reach 894 days. Due to this, the CANDU reactors have the highest world capacity factors. Another advantage of CANDU reactors is their low fuel burn up, which is in the range of 7,000 MWD per metric ton uranium (MTU). This burn up is considered very low when compared with 40,000 MWD/MTU obtained by BWR AND PWR reactors. Table 3 shows the advantages and disadvangtages of CANDU Reactors.

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Table 3. Advantages and disadvantages of CANDU Reactors

Advantages	Disadvantages
Any fuel including natural uranium can be used Heavy water is a very good moderator which has an excellent moderating power and low absorption High heat capacity for heavy water Negative temperature coefficient High specific power Fission products are contained Radioactivity of coolant, if kept pure, is short lived Can be refueled on-line Low cost of natural uranium, however the reduction in cost may be offset by the additional deuterium separation facility.	Heavy water is expensive, however this cost is substituted by the low natural uranium cost. The primary loop has to be highly pressurized to achieve high temperature without boiling. Hot heavy water in its pure state is highly corrosive Fuel radiation damage Control rods and heat exchanger are required Primary loop has to be leak proof and this requires special precautions during refueling

2.4 RBMK Reactors

The RBMK reactors are unique in which graphite moderator with fuel tubes and coolant tubes passing vertically, through the graphite. The coolant tube pressure is 1000 psi. RBMK, as CANDU reactors can be refueled on line.

The reactor core has a huge graphite blocks to slow down the neutrons. A helium nitrogen mixture is used to increase the heat transfer from the graphite to coolant and to reduce graphite oxidation.

Beside the reactor core, it has two steam generators and two reactor cooling system with headers that feed the pressure tube in the reactor. Boiling is allowed to occur and the steam passes to separator and to turbine, similar to the BWR. To lower the radioactivity level on the turbine, steam separators introduce delay. The BWR does not have such advantage. Table 4 shows the advantages and disadvangtages of RBMK Reactors.

Table 4. Advantages and disadvantages of RBMK Reactors

Advantages	Disadvantages
Low core power density allows to withstand station blackout and loss of power events up to an hour with no expected core damage. Can be refueled on-line Graphite moderators allows to use fuels not suitable for other water moderated reactors	Positive void coefficient Accident and safety systems are limited Lack of massive concrete steel containment Flawed separation and redundancy of safety and electrical systems Limited Capacity for suppression of steam in the graphite stack.

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2.5 Gas Cooled Reactors

Gas cooled reactors (GCR) are moderated by graphite and cooled by carbon dioxide which circulates at a pressure around 230 psi. Gas cooled reactors are fuelled by natural uranium metal with a magnesium alloy known as Magnox as a cladding.

The newer Advanced Gas Cooled Reactors (AGR) use a slightly enriched uranium dioxide clad with stainless steel and carbon dioxide as a coolant. Table 5 shows the advantages and disadvangtages of Carbond Dioxide Graphite Reactors.

Table 5. Advantages and disadvantages of Carbon Dioxide Graphite Reactors

Advantages	Disadvantages
Coolant is inexpensive Corrosion by coolant is negligible Ordinary leakage is tolerable Gas turbine can be used Different fuel can be used including natural uranium Capture cross-section of coolant is low Coolant does not react with fuel Can be operated with negative temperature coefficient Higher operating temperature with a higher thermal efficiency Not susceptible to accidents of the types possible with water moderated/cooled reactors.	Reactor and heat exchangers are large and expensive Heat transfer is low Power density is also low Dissociation of carbon dioxide at above 300 ^{0}C Cooling gas must be pressurized

2.6 Metal Cooled Reactors

Metal Cooled Reactors are usually cooled by liquid sodium or a combination of Sodium and potassium. They are usually called fast breeder reactors, or liquid metal fast breeder reactor (LMFBR). Some of the difficulties associated with them are a result of the natural growth of any new technology, and then the high price when compared to alternative power sources. No commercially viable LMFBRs are currently in operation, however, test programs are proceeding. Table 6 shows the Advantages and disadvantages of LMFBRs Reactors

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Table 6. Advantages and disadvantages of LMFBRs Reactors

Advantages	Disadvantages
No moderator No reaction of sodium with uranium or thorium High heat transfer rates Electromagnetic pumps can be used with high efficiency Fuel may be bonded into container with liquid metal	Sodium reacts with water violently Serious radiation damage Sodium must not have oxygen Difficult fuel handling Sodium becomes radioactive Precautions must be taken to contain sodium that may leak out of the primary or secondary system. Coolant must be heated to avoid being freezed High thermal stress

2.7 Advanced Water Reactors

It is typical, as experience is gained, opportunities arise for improving performance and economics of technology. The nuclear industry has a very large experience with water reactors. In order to continue to utilize nuclear power to maintain national energy security in the future, it is vitally important to take advantage of already gained experience to further improve future water reactors. Hence, many industrialized countries have extensive programs to advance the technology of water reactors. The objectives of advanced water reactor development is to improve safety and reduce environmental impacts and at the same time provide further reduction in the cost of electricity generation. Environmental and public health benefits are to be gained though improving reactor design and operation to reduce the already probability and potential consequences of accidents of reactor operations. Many of the lessons and experience gained from the past thirty years of water reactor operation will continue to be applied to the design and operation of existing water reactors. Examples of these lessons are the 1979 accident at Three Mile Island and the 1986 accident at Chernobyl.

Many different approaches are taken to further improve water reactors. In some cases, incremental modifications in design are being incorporated in plants being built. There improvements include those to make plants easier and more economical to operate and maintain, those to reduce the already low residual risk of reactor operation and those to increase the efficiency of fuel utilization. In other cases, designs are being changed to reduce plant complexity and to improve safety. Example of these improvements include new design for containment structure which can be cooled by natural circulation only. These programs will take a number of years to develop and are yet not ready for construction commitments. More revolutionary designs are being developed which may require prototype plant operations to test design prior to a commercial release [NCA, 1989].

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There are few projects being carried out in some of the OECD countries such as the French advanced PWR which is under construction in Chooz, France. This PWR is 1400 MWe and aims at reducing the cost of nuclear electric power through the use of advanced components such as heat exchangers, turbines and pumps that lower the capital cost and increase safety. Other countries have similar near term advanced water reactor projects, as an example, there are three large advanced PWRs were recently completed in Germany. The United Kingdom's first commercial PWR was recently completed. A large advanced BWR designed jointly by USA and Japan is currently under construction. Also, two mid size (about 600 MWe) advanced LWRs are under development in the United States. The major focus is plant simplification, as an example, the advanced PWR has 32% fewer values, 35% fewer pumps, and 45% less pipes than a traditional PWR of comparable output. Such simplifications are expected to greatly enhance reliability and safety of plant operation. Major emphasis is exerted on passive safety features which put less reliance on human intervention for accident management, as an example, the emergency core cooling system will not rely on pumping systems requiring diesel generated electric power and containment can be cooled using natural circulation.

The PLUS (Process Inherent Ultimate Safety) reactor is under development in Sweden. Because this reactor has remarkable departure from existing water reactor systems, such as reactivity control and primary coolant system configuration, a large scale prototype should probably be constructed to confirm the reliability of the system before commercial commitment. Pederson et al. [1988].

2.8 Small and Medium-sized Reactors (SMRs)

The choice of reactors ranges is arbitrary. However, in common practice one has to take the upper unit of the range of small and medium-sized reactors as approximately half the power of the largest reactor. The ranges might be taken as:

- Very small reactors: < 150 Mwe
- Small reactors: 150-300 Mwe
- Medium reactors: 300-700 Mwe
- Large reactors: > 700 Mwe

The objective of medium reactors is electricity generation and co-generation in which heat and electricity can be supplied simultaneously; however, the main products remains into the interconnected electricity grid of suitable size (at least 6 to 10 times the power of the unit) and usually operated as bas load plants. When medium reactors are operated in co-generation mode, the heat supply would be about 20% of the energy generated. The economic competitiveness of medium reactors with equivalent alternative fossil fueled plants is expected under most conditions.

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Small reactors, on the other hand are either power or generation reactors which may have a considerable share of heat supply. As a consequence, of this, small reactors used for electricity generation only or co-generation mode are not expected to economically competitive with equivalent alternative fossil fueled plants. Small reactors are intended for special situations where the interconnected grid size does not allow the introduction of medium or large sized reactor [IAEA, 1995].

Very small reactors are not, however, included for electricity production under competitive commercial conditions as a base load unit. It is very clear that very small reactors are not regarded as competitors to large, medium or even small reactors. Very small reactors are mainly designed for specific objectives such as electricity and heat or heat only (at either high or low temperature) for oil extraction, desalination, district heating, etc. Small reactors could serve as good focal projects and stimulus for the development of nuclear infrastructure in countries starting nuclear power programs.

Small and medium reactors are not down sized versions of large reactors, indeed, they are taking new design approaches that make them simpler, easier to operate and maintain, and make use of passive and inherent safety components and systems. Such safety features are loaded to protect the plant against severe accidents that can hardly be compromised by malfunction equipment or human intervention.

Some examples of small and medium reactors are the AP-600 which is a Westinghouse advanced passive PWR (AP-600). This reactor is 600 MWe which is based on proven technology with an emphasis on passive safety features. The AP-600 passive safety system include the passive core cooling system (PXS), the main control room habitability system and the passive containment system (PCS).

Another example is VVER-640 (V-407) which is developed in Russia by OKB "Gidropress", the Russian National Research Center "Kurchatov Institute" and LIAEP. The VVER emergency core cooling system includes the following sub-system:

- Deliberate emergency depressurization
- Hydrotanks under atmospheric pressure
- Hydrotanks with nitrogen under pressure

The system for passive heat removal from the containment include storage tanks of cooling water, connecting pipelines, and coolers. Steam released to the containment condenses on the heat exchange surface of the cooler gives heat to the storage tank of water by circulation.

The Indian PHWR is a small size reactor which is a 220 MWe advanced heavy water reactor and is developed by Bhabha Atomic Research Center in India. The PHWR uses heavy water as a moderator and light water as a coolant and thorium fuel. The safety approach of the PHWR is based on the incorporation of passive safety system

3. SELECTION CRITERIA FOR A NUCLEAR REACTOR

After giving a general overview about conventional reactors, advanced rectors and small and medium sized reactors, it will be advantageous to lay down the selection-criteria for a nuclear reactor suitable for desalination of sea water in Saudi Arabia. The following selection criteria will be used in this paper.

1. Liquid metal reactors are excluded because they do not seam to be commercially competitive on the short and medium term in nuclear power market.
2. High temperature gas cooled reactors do not also seem to be promising on the long term in the nuclear power market.
3. Very small reactors do not seem to be economically competitive to alternative power plants of the same power output.
4. Reactor design that are not commercially available is eliminated.
5. Boiling water reactors are very much less alternative than pressurized water reactors because boiling water reactors may require additional systems for safe coupling with desalination plants.
6. The reactor has to fit within nearly $1/6^{th}$ of the grid size.

When implementing the above criteria on several reactors design, the reactors, which could be considered for nuclear desalination are:

1. Medium size PWR such as AP-600 (USA), AC-600 (China) and PWR several countries.
2. Medium size PHWR such as CANDU (Canada) and PHWR (India).

Regarding AP-600 and the medium size PWR, their design is under development in the USA and is expected to be completed and licensed very soon. The AC-600 has not been designed for integration with seawater desalination, however, this is expected to be done on a short term.

The CANDU-3, which is a medium size reactor, is development in Canada for a number of years. Extensive studies have been carried on both as electricity generation and as a concept combined with seawater desalination. The CANDU-6 is available currently on a commercial basis. India is operating a number of PHWR and they have been proposed to use electricity and steam for a combined MSF-RO desalination facility.

As has been mentioned earlier, large reactors are excluded because of mainly two reasons. Firstly, the electric grid in Saudi Arabia is not expected to fit more than one large reactor in

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the forecasted period. Secondly, having one large reactor situated in one location will require a huge transportation cost to supply the whole region with desalinated water.

Small and very small reactors are not commercially competitive and they are also excluded. The search is narrowed down to a variety of medium reactors such as PHWRs and PWRs.

The Indian PHWR-500 excluded due to the fact that it uses thorium as a fuel and the thorium is only manufactured by few countries in the world. Besides the fore mentioned reason, the PHWR-500 Indian experience is very limited. Regarding the AC-600, it is also excluded due to the limited technology of China in this regard and the unknown future of economical and political circumstances of the regime.

The remaining competing reactors are the Canadian CANDU and the American AP-600 medium reactors. The selection between the two is difficult. However, the main influential decision factors are the economic ones. These economical factors include capital cots, operation and maintenance cost, man power development, possibility of local manufacturing of certain parts and systems and optimum inclusion of reactor electricity output into the electricity demand over the forecasted years. The above mentioned factors can not be decided upon now and one has to wait until they are investigated thoroughly. A thorough investigation is, however, recommended for a further work.

Regarding the cost of nuclear reactors, there is no simple straight forward answer. Different types of nuclear reactors cost different amounts, depending on a variety of factors. Plus, the cost of construction of even the same types of reactor vary from country to country because of the differing regulatory burdens, costs of public inquiries and planning permission applications and labor and parts costs. Also, since there is a large capital cost associated with building a nuclear reactor, the interest rates for loans will have a major effect on the overall cost. Therefore, there is no single answer, and certainly no "Off-the–Shelf" price list. The economic argument in favor of nuclear is that once built, they are very much cheaper to run than most other forms of large scale electricity generation since some reactors are now entering their third and fourth decades of operation, over this period of time the cost per unit electricity generated is acceptable and they do generate an overall profit, but the rate of return of profit is less than that for Combined – Cycle Turbine Stations, for example.

4. CONCLUSION

Just to put things into perspective, Britain's most modern nuclear reactor, the PWR at Sizewell B cost, about 3.2 billion pound sterling to build. It is a modified Westinghouse PWR, and other countries similar power stations have been built for perhaps a third or more less. It was expensive in UK because it was the first PWR and because UK government and regulators insisted upon a lot of additional safety related features which increased the cost.

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