Nuclear Desalination: An Alternative Solution to the Water Shortage

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Abstract: Global water shortage is one of the rising problems that, nowadays and worldwide, Countries and governments have to face. People from many countries have to deal with scarcity of water supply and aquifer pollution that could jeopardize their health and agriculture. Desalination process could be one of the most promising method to hinder such phenomenon. During this work we analyzed different desalination processes and the state of art of the technology. In this paper we carried on a deep evaluation of the state of art of desalination processes. Obviously all these methods need a driving force in terms of energy. With the aim of a more environmental friendly scenario, nuclear energy has been chosen as energy source for different desalination processes, implementing the so called nuclear desalination. Moreover a nuclear scenario analysis has been studied for the UAE (United Arab Emirates), one of the countries that have to deal with water shortage and that presents today an ambitious nuclear program.

Keywords: Nuclear Energy, Desalination, High Temperature Gas Reactors.

1. INTRODUCTION

At the beginning of XXI century, as in the previous one, the worldwide growing energy demand, the rapid consumption of fossil fuel and the environmental sustainability are the main concerns of almost all the country policies.

The greenhouse effect, probably one of the main factor in the rise of the global temperature, could also be one of the main responsible of one of the most tragic phenomena of our time, the global water shortage. More and more countries, not only those belonging to the so-called “third world”, are nowadays threatened by water scarcity or aquifer pollution. It is estimated that, in 2025, many countries will be concerned by those events as, in the nearest future, almost 6 billion people (70% of the future expected world population) will face water shortage and, in the eastern Mediterranean sea only, more than 80 million people will not have enough potable water [1].

One of the most interesting solutions to tackle this issue is given by desalination technologies. Nowadays several countries of the Middle East use desalination technologies to face their scarcity of water supply. As many industrial processes, desalination requires a huge amount of energy, the most coming from fossil fuels. One possible solution to this problem could be adopting different and environmental-friendly energy sources. In this paper, nuclear energy is considered as the potential driving force in desalination processes also because it could compete against fossil fuel in terms of availability and reliability, all essential requirements that must be met in order to feed a desalination plant. From the point of view of the nuclear plant itself, an interesting opportunity is given by HTGRs (High Temperature Gas-cooled Reactors), also thanks to their outlet gas temperature up to 900÷1000 °C [2].

2. BRIEF OVERVIEW OF HTGR CHARACTERISTICS

HTGR presents the possibility to be used in the frame of symbiotic cycles with traditional reactors such as the LWRs (Light Water Reactors) in order to reduce the volume and potential hazard (radiotoxicity) of nuclear wastes [3-8]. Currently the most common nuclear fuel used in LWR is composed by low enriched uranium (<5%) and no significant changes are foreseen in this sense in the near future. As a possible alternative, thorium has proven its excellent potentialities, in particular for long-term perspectives and, especially, for those countries that have abundant reserves of such element [9]; in fact, Th^{232} is fertile and the capture of neutrons transmutes it in U^{233} (a fissile element); unfortunately during this transmutation process, it also generates U^{232}, a significant gamma rays emitter, that make worse the fuel processing and handling.

HTGR can be fed with several types of fuels [10]. At the moment, multiple innovative fuel cycles are being studied with the aim of using Pu (also coming from dismantled nuclear weapons) as fissile element [3].

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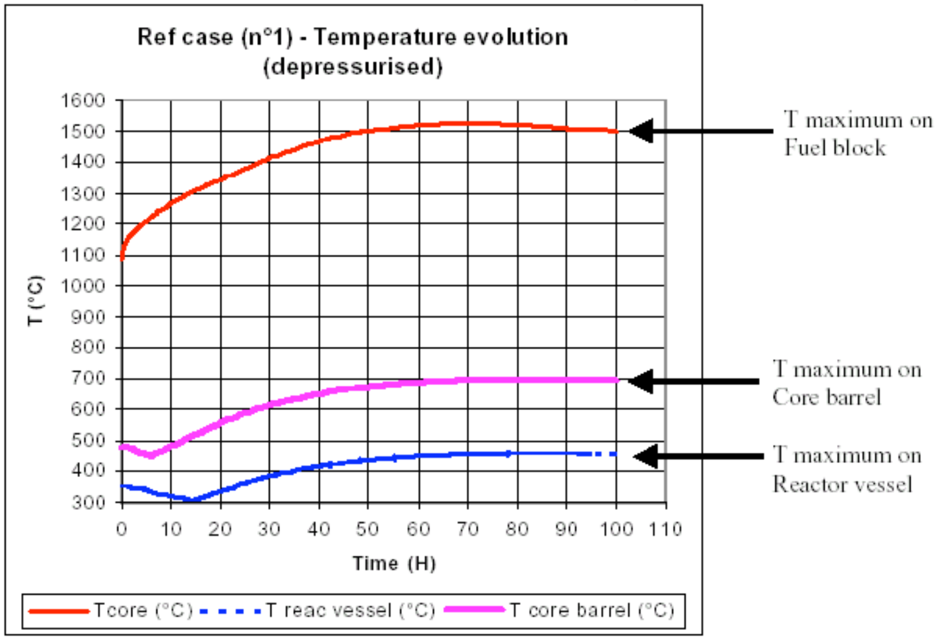

Figure 1: Temperature trend in HTGR where the cooling systems are cut off by incidental phenomena [25].

Another HTGR target is the transmutation of Minor Actinides (MA) into isotopes with a reduced long-term radiotoxicity. Moreover, the structure of the fuel used in HTGR (generally TRISO Coated Particle) has demonstrated (experimentally, in facilities with high neutron fluences) its ability to reach "burn-up" values higher than 700 GWd/t [11], a fundamental characteristic in order to obtain a deep-burn fuel cycle (i.e. a cycle with high consumption of transuranic, TRU, elements).

Usually those facilities adopt He as coolant due to the fact that it is a noble gas, with excellent nuclear, thermal and chemical properties (it is not corrosive for any element [12], with low neutron absorption cross-section and it does not change phase during the operating phase, etc.).

In terms of safety, these reactors present some interesting and peculiar characteristics [5]. The low power density core helps to limit the maximum temperature that can be reached during a potential accident. Thanks to the usage of ceramic materials and graphite as moderator, HTGRs present a considerable heat capacity, with a "slow" thermal response. In case of LOCA (Loss of Cooling Accident), HTGRs are inherently safer in comparison to other traditional reactors; this as a consequence of their remarkable thermal inertia that leads to slow thermal transient. In fact, in case of LOCA, these reactors could be cooled merely by conduction through the ground. In this way it is substantially impossible to reach the critical temperature of 1600 °C that would cause the release of fissile material from the TRISO-CP.

The above described plant features were evaluated by a simulated LOCA performed in 1988 on the German AVR reactor. It is shown that, during the transient caused by the loss of coolant, the fuel and the component temperatures remain, as numerically simulated (Figure **1**), below the risk limits and that the temperature coefficient is kept negative [2]. It should also be emphasized that in this experience heat was removed from the core only by passive means, as it should happen in the current HTGR. The main safety features of these reactors could be summarized as follow:

- "Slow" thermal transients due to the large thermal inertia of the reactor
- In case of LOCA, the decay heat could be removed only by conduction through the ground
- Optimal coolant properties

2.1. Desalination Processes

Desalination is a technology developed in the first half of the twentieth century, although it has found, during its evolution, many obstacles that slowed its worldwide spread. Actually the main three desalination system types are the following:

- Evaporative desalination
- MED: Multiple Effect Distillation
- MSF: Multiple Flash Distillation
- VC: Vapor Compression
- Desalination for permeation
- ED: Electro-Dialysis
- RO: Reverse Osmosis
- Desalination by ion exchange

Nowadays more than 100 countries use desalination techniques to cope with the lack of potable water. In particular, 10 out of these 100 hold more than 75% of the world desalination capacity. In the first place we find Saudi Arabia, with 24% of world capacity, followed by the USA with 16% [1].

The most widely used systems are: the MSF thermal plants and the RO plants, which could account for more than 80% of the world total capacity [13].

2.2. Evaporative Desalination

Heating up to boiling point the sea water yields a steam flux that can be condensed (the so-called distillate), producing the desalinated water.

The condensation heat can be partially recovered through various techniques in order to preliminarily heat the incoming salt water or to generate further steam. In any case, the recovery of condensation heat reduces significantly the total energy consumption of the process. When the energy supply is provided by steam, as it happens in most of the evaporative plants, the GOR (*Gained Output Ratio*) coefficient is used to define the energy efficiency (this is defined as the ratio between the produced water and the feed steam). The GOR is equal to 1 when the condensation heat is not recovered. In industrial plants, heat recovery is usually adopted: standard values are set between an average of 8 to 9 (for example providing 1 kg/h of steam you would obtain 4÷12 kg/h of fresh water).

It is interesting to underline the fact that in evaporation plants it is not permitted to heat up seawater beyond a certain point, in order to avoid the worsening of corrosion phenomena already present (due to the salinity of the fluid). This limit is deeply influenced by facility type and security constraints to which it is bound. In practice, different values of maximum temperature are used, depending on which kind of plants is chosen [13]:

- For MSF plants, the limit is assumed equal to 113°C; in case of chemical pretreatment elements this value can be raised to 120÷125°C
- For MED and VC plants the limit is much lower as it is generally set around 60÷70°C [14]

2.3. MED: Multiple Effect Distillation

These types of systems, shown in Figure **2**, derive from the food industry: like for sugar cane and edible salt production. Since the beginning of desalination activities, some MED plants were built but, due to greater efficiency, better resistance to corrosion and smaller formation of limestone, MSF plants were preferred. During the ‘80s, however, a new interest in the MED process rose and many facilities based on

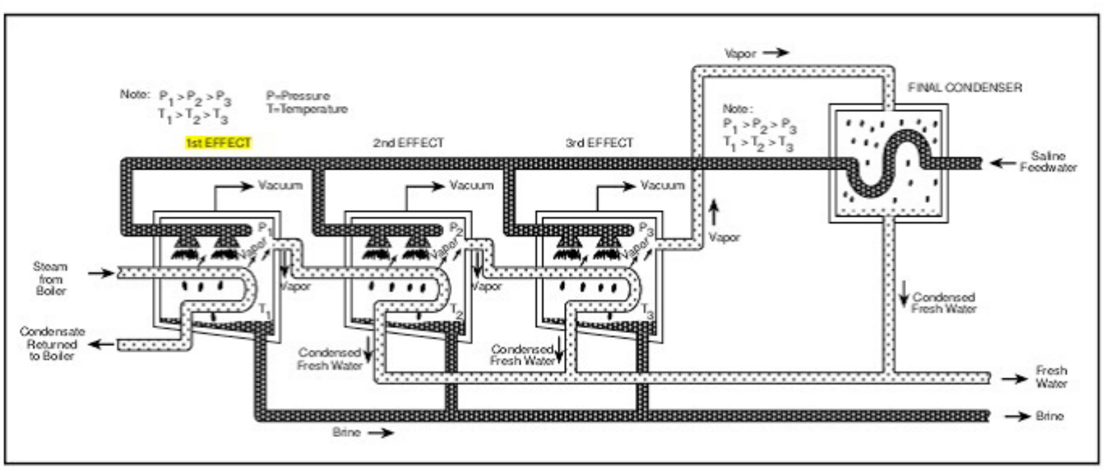

Figure 2: Blueprint of a MED (*Multiple Effect Distillation*) installation [13].

this process were built. In fact, those facilities present the following advantages:

- Lower energy consumption (less than 1.0 kWh/m^3 against, as an example, 5 kWh/m^3 of a RO system) compared to other thermal distillation systems
- Operation at low temperatures (< 70 °C) and at a minimum concentration (< 1.5) in order to avoid corrosion and formation of limestone
- No pre-treatment of incoming water required and greater flexibility on incoming feed water composition guaranteed
- High reliability and ease of construction
- Low maintenance costs
- Continuous operation with minimum need of human supervision
- High degree of flexibility on the primary heat source

The operating logic is quite simple: the train of heat exchanger is designed to condense the steam from the previous step and produce what is necessary for the operation of the next. In the first "stage" heat is provided by an external source (e.g. steam coming from co-generation systems, etc.); the last, instead, is used to heat the seawater inlet. Only a small part of the marine H_2O that is provided at the entrance of the vessels is actually converted into steam, while most of it falls downwards (with high concentration of salts) and takes the name of brine. This part is conveyed in the later stages where partially evaporates, leaving, as it moves forward in the process, a more saline fluid that is eventually sent out of the plant. The efficiency of this kind of plants depends on the number of vessels adopted; generally there is a number of stages ranging from 8 to 16 that operate at temperatures not exceeding 70 °C [14]; from one side, low temperatures allow to limit the production of limestone but from the other, with the aim to obtain the same efficiency, we are forced to increase the number of sections.

2.4. MSF: Multiple Flash Distillation

Approximately 28% of the world desalination plants belongs to MSF type [15]. In the process, the saline feed water is sent to a chemical pretreatment facility where certain chemicals are added to prevent the formation of alkaline limestone in the heat exchangers pipes. The O_2 percentage is reduced in order to limit the corrosion (due to the formation of carbon dioxides). Sea water is preliminarily heated in the modules and then it is heated up until the frost formation temperature limit is reached; then it is subjected to a flash process in a special evaporator.

A MSF plant is divided into several 'flash stage' (typically no more than 40 units) at decreasing pressure (as shown in Figure **3**). When the brine enters a room, a part of the liquid changes state due to the flash caused by the environment that is strictly maintained at a lower pressure compared to the boiling point corresponding to its inlet temperature. The steam generated passes through the upper part of the vessel where, once it reaches the pipes that carry the

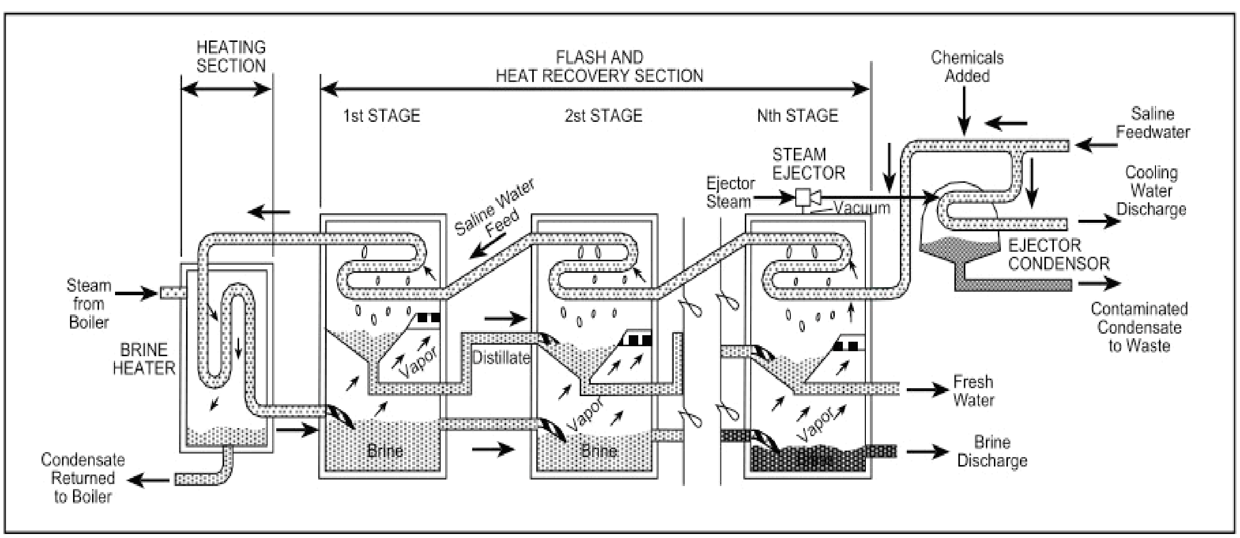

Figure 3: Blueprint of a MSF (*Multiple Flash Distillation*) installation [13].

incoming water to the main heat exchanger, condensates the charge flowing within the pipe, preliminarily heating it and generating desalinated water.

The uncondensed brine, instead, proceeds to the next stage where the process is repeated to a lower temperature and at the corresponding saturation pressure.

2.5. Permeative Dissalator

The membranes are used in three main industrial desalination processes: Electrodialysis (ED), Reverse Electrodialysis (EDR) and Reverse Osmosis (RO). Each of these techniques exploits the properties of the membranes to separate salts from a main flow of sea water. In any case, the three methods are very different from each other: in the ED and in the EDR a potential difference is used while in RO a pressure difference is adopted.

3. ELECTRODIALYSIS

ED was introduced in the early ‘60s (a decade earlier then RO) and is based on the following principles:

- Most of the salts are dissolved in H_2O marine ions (positive or negative)
- These ions may be attracted by electrodes powered by DC with opposite charge
- Permeable membranes can be built so that only a certain kind of positive or negative ions can pass them

Salts dissolved in salty H_2O, such as chloride (valence -), sodium (+), calcium (++) and carbonate (-), counterbalance (canceling it) the overall electric charge. However if these are excited by a DC current they will move in the direction of the opposite charge electrode. If we combine selective membranes to this phenomenon we can extract the salts from the primary flow; in this way the primary charge is desalinated by concentrating the ions in the secondary conducts.

4. REVERSE OSMOSIS

Compared to the electrodialysis, this method is relatively new: its marketing has occurred only in the mid ‘70s. This procedure is based on a pressure control in which the water is desalinated by the interaction with selective membranes (Figure **4**). In this process almost all the overall energy is used to pressurize the water flow against the selective barriers. The operation is quite simple: the incoming brackish water is pumped into a vessel; coming into contact with the selective membranes; a fraction of this, by means of the pressure generated by the pump, passes through the membrane that desalinates it. As a consequence, the remaining brackish water increases its salinity and at the same time a part of the remaining liquid is discharged through a secondary duct. Without this operation the concentration of salt in the area of the feed water would increase without control; this would cause problems such as the generation of super precipitates and the increase of the osmotic pressure across the membrane. The quantity of feeding water discharged upstream the membrane in the secondary duct ranges, as a function of the salinity of the brackish water, from 20 to 70% of the feeding flow.

4.1. Hybrid System: RO System Coupled with an Evaporative One

The combination of RO systems with evaporative systems (MED, MSF) reduces the production cost of H_2O, and, by meansof those systems, we can achieve many of the fundamental requirements that the output water must met to be considered potable. Hybrid systems have different purification levels; these can be obtained, according to the request of the user, in different ways. We can highlight:

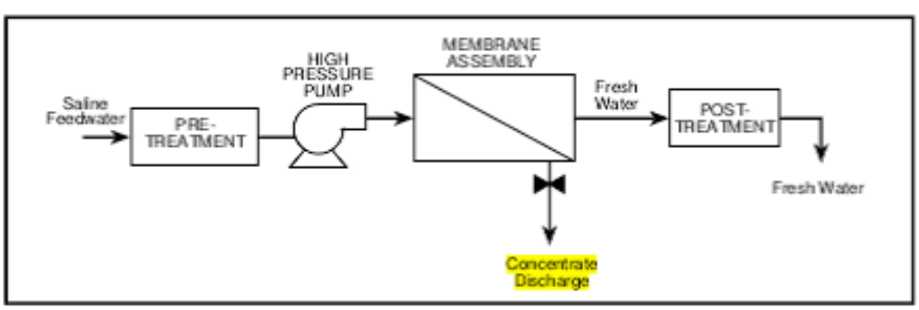

Figure 4: Operation diagram of a RO plant [13].

- drinking water with very low TDS (Total Dissolved Solids), mainly for domestic use
- fresh water for industrial use

The production costs can be reduced by using the incoming brackish water as feeding water for the MSF or the MED plant. It is also possible to pursue the opposite strategy namely using the output of the desalination plant as feeding water for the RO plant. The decrease of flow rate that can be processed by the membranes (caused by the increase in TDS of the feed water) is compensated by the high temperature of the incoming stream that comes from the desalination facilities. In addition to this advantage, the runoff water that comes from the distillation plant is already chemically treated; in this way it is possible to save additional money.

For example, for a MED process, the seawater used as cooling water for the last effect is heated of about 3÷5 °C [13]. This water can be used to feed the RO plant; this slight increase in temperature leads to a reduction of the area of the membranes of about 15÷20%. Hybrid plants as MSF-RO and RO-MED offer interesting prospects for cost reduction making them interesting for potential future developments [16]

4.2. Nuclear Power as an Energy Source for Desalination Plants

Over the past two decades, there has been an increasing interest in the idea of using nuclear energy to power desalination processes. As already anticipated, the concept that lies behind nuclear desalination is quite simple: it consists in feeding the traditional desalination systems with one or more nuclear power plants (NPPs) that can provide energy as electricity and/or heat.

Ideally, any type of reactor can be coupled to a desalination system; historically LWRs have been the primary subject of study, mainly because of their widespread use; anyway, in the last few years, a particular interest emerged around the possibility to combine the desalination plants with HTGR (Generation III / III+) or with the forthcoming VHTR (Generation IV).

As already shown, there are different types of desalination plants, and the coupling between a NPP and a desalination systems has proved a major advantage for the following processes:

- MSF, MED
- RO
- Hybrids

For plants that exceed 4000 m^3/day, MSF technology is often used, although RO for high rates is quickly gaining ground (as proved by the construction of several high rates RO plants developed in Israel in the last few years) [17, 18].

Clearly the coupling method between a NPP and a desalination plant must be carefully studied. In particular, when those kind of systems are joined, two particular factors have to be considered:

- Changes in the demand of heat/energy in the desalination system must not lead to dangerous situations in the nuclear power station
- An appropriate interface must ensure the complete protection, from the radiological point of view, of output water

From the technical point of view, the most important aspects that must be considered are:

- Quantity of required water
- Amount of produced energy

These considerations play an important role in understanding whether it is smarter to use a cogeneration NPP or an exclusively nuclear “thermal” plant:

- A cogeneration NPP produces both H_2O and energy. However, it presents a limited flexibility and it requires a high initial investment and a rather long "lead time of investment"
- A nuclear “thermal” plant is generally designed to exclusively produce H_2O or steam, it has a reduced "lead time of Investment " in addition to a lower cost and a greater structural simplicity [19]

“Power to water ratio” becomes a very important parameter if a co-generative plant is chosen: this is defined as the power request for every m^3/day of potable H_2O produced; this factor can be strongly limited from the NPP design, and so it can strongly influence the choice of the reactor itself.

Moreover this parameter heavily depends on the geographical position, but it can vary also in function of the season and the year.

The safety of an hybrid desalination plant is linked to:

- The operation of the NPP
- The interfacing between the NPP and the desalination system
- The interaction, particularly during transients, between the NPP itself and the desalination system

An important aspect that should be taken into account in those systems is the potential passage of radioactivity from the NPP to the desalination plant (with a consequent potential contamination of the potable water). This phenomenon can be essentially eliminated by means of multiple barriers and pressure differentials. Obviously the presence of radioactivity in the intermediate and in the desalination loops is continuously monitored; moreover additional controls must be carried out on the output water so that, in case of contamination, it is possible to act immediately .

4.3. "Coupling" General Considerations

In the coupling between a NPP and a desalination plant there is a direct transfer of thermal energy; for this reason there is a strong interaction between the two systems. The operational transients of the first can deeply modify the behavior of the second and vice-versa.

In the case of a co-generation plant producing heat and electricity, the thermal coupling needs some additional considerations: the conversion parts of the NPP, in this case, have to fulfill a double request (load network and steam for the desalination plant) and some specific problems could emerge.

Thermal desalination plants are supplied by a constant steam flow that comes directly from the plant or indirectly from a "backpressure turbines": it is clear that problems involving the NPP and its ability to provide steam to the desalination plant can lead to a collapse in the water production; for this reason, in this type of plant it is advisable to have an alternative heat source (as emergency diesels) that can provide energy in the event of malfunctions and outages of the NPP. The desalination plants that use membranes or electricity are not strictly dependent from the thermal source so they can be placed:

- Far from the NPP: the system is much safer and cannot be involved in any incidental effect driven by a potential accident in the nuclear reactor
- Co-located: from a safety point of view there are several drawbacks (i.e. nuclear accidents can affect desalination facilities), although there could be some advantages as the possibility to use the same staff, a simpler logistic, etc.

It should also be emphasized that, in the latter case, the electrical interdependence between the two installations is generally very limited: the malfunction of one of the two does not preclude the operation of the other. As a matter of fact, even if the desalination plant is directly linked to the NPP, it has also a direct connection with the national electric grid; in this way even in the case of service discontinuances by the NPP, the power is always provided so that the desalination plant can continue to operate fully autonomously (at least for a not so long period of time). Similarly, the NPP is directly connected to the external power grid so that all the energy can be shifted to the national grid in case of an outage of service of the desalination plant.

4.4. Desalination Plant Coupled to Heating Reactors

In case of thermal nuclear plant, the output flow is directly used to feed a desalination plant without electric energy production [13].

As already mentioned, MSF and MED plants can process a liquid to the maximum temperature of respectively 140 °C (MSF) and 65 °C (MED). During the past decade, engineers have tried to rise these limits (in order to increase performance) but all the provided solutions have been discarded because they were not cost-effective. For this reason, an ad-hoc "heating" reactor that could provide steam at a temperature of 140÷150 °C is excellent for being coupled with desalination plants. It should be remarked that these types of reactors have, when compared to traditional power nuclear reactor, a reduced "investment lead time" in addition to lower costs and to a greater structural simplicity. It is possible to underline two different kind of scenarios, based on the steam provided by the heating reactors:

Steam at 2.0÷4.0 bar (120÷140 °C) [13] - In these plants steam is used to feed MSF plants; in order to avoid limestone formation the maximum temperature reached in the pipes is set between 120 and 140 °C [14]; this limit, however, depends on the conditions of the inlet salty water [20]. The great importance of having high operating temperatures inside the system has led to the development of standard chemical pretreatment processes, used to avoid the formation of dangerous alkaline limestone that are highly damaging for the pipes of the desalination plant. A common pretreatment processes of the inlet water is based on acid additivation, in this way it is possible to improve the overall efficiency of the system. In case of a MSF plant, as shown in Figure **5**, a further barrier is needed (in addition to the heat exchanger) to prevent any radioactive leak. For this reason a series of circuits at increasing pressure are used; in particular, the intermediate loop is at a lower pressure if it is compared to the one in which the brine flows. In this way, even in case of damage to the heat exchanger piping (into which the brine flows), we could not have a passage of radioactivity from the intermediate loop (that could have a minimal presence of radioactivity leaked from the primary nuclear loop). As a matter of fact, the negative pressure gradient is used as a barrier to prevent any kind of contamination; in fact the potential residual radioactive particles would be rejected from the pressure gradient preserving the inner circuit from the radiation hazard. This line of defense drastically reduces the possibility of a radioactive leak and this latter becomes possible only in presence of a double failure of the system (there should be a simultaneous structural failure in the heat exchanger and a reversal of pressure in the loops)

- Steam at 0.3÷0.4 bar (70÷80 °C) [13] - In this kind of plants the feeding steam is provided at a temperature of 69÷76 °C and at a pressure of 0.3÷0.4 bar, values that are significantly lower when compared to the previous case. At those temperatures it is not possible to use the flow directly into a MSF plant; instead MED plants are chosen as possible targets. As already anticipated, this kind of facility deals with lower temperatures (maximum 60÷65 °C) and the coupling conditions are facilitated by the lower operating conditions. In case of a MED coupling, as shown in Figure **6**, an additional safety loop is required; in particular this has to operate in a loop with high quality H_2O, it will be used as heat exchanger for the open cycle that produces potable H_2O. In such layout, the primary heat exchanger is used as an interface between the NPP and the intermediate loop; the heated pressurized water will partially evaporate in apposite "flash tank" and the produced steam is sent to the MED plant where it is used in the desalination process; meanwhile the remaining liquid is recovered and channeled, through a

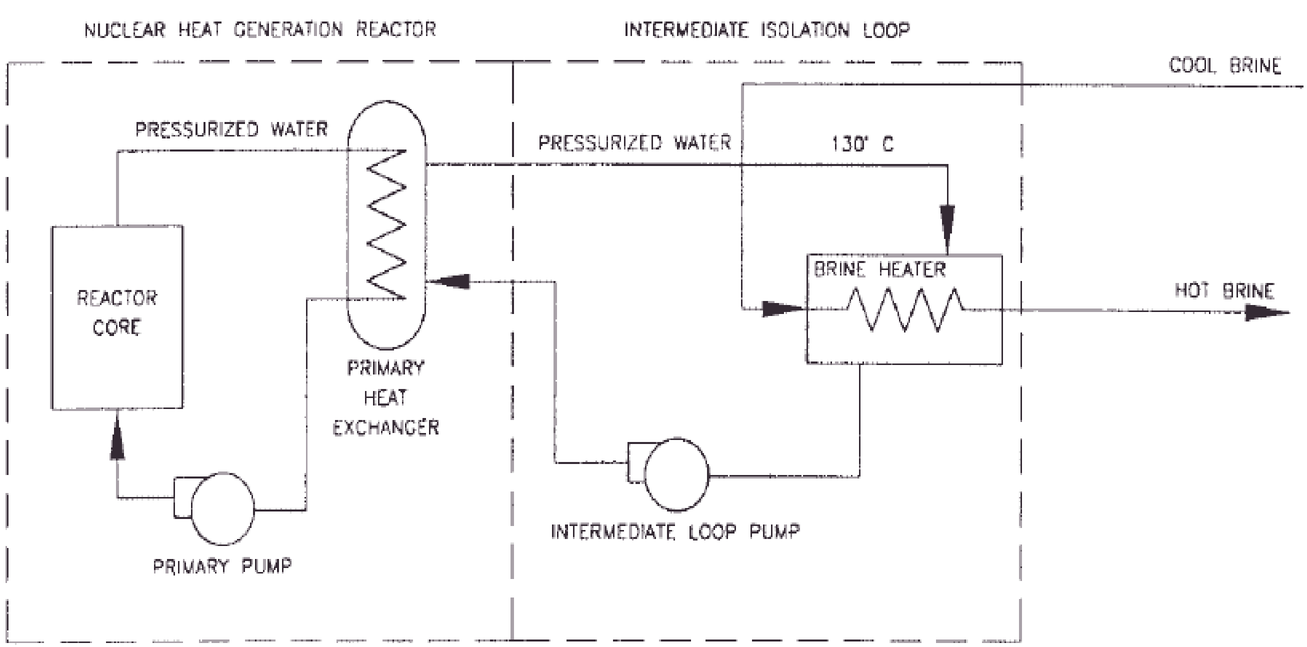

Figure 5: Intermediate circuit between the thermal reactor and the MSF desalination plant [13].

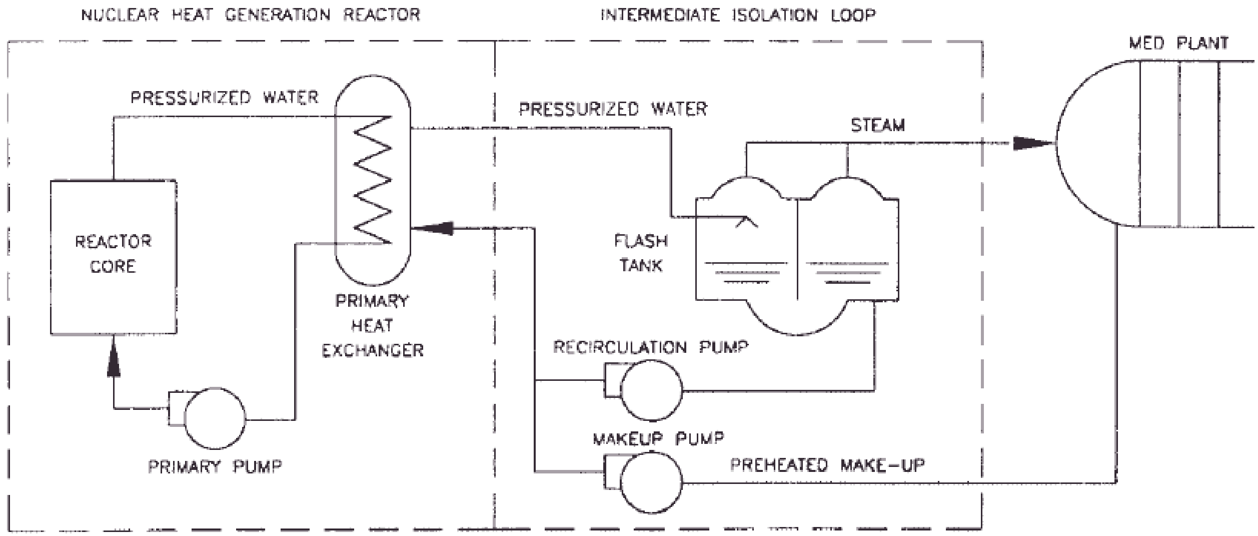

Figure 6: Intermediate circuit between the thermal reactor and the MED desalination plant [13].

recirculating pump, to the main heat exchanger. Before getting there, the water flow is mixed with the condensate that comes from the MED plant.

4.5. Desalination Plant Coupled to Co-Generation Reactors

In co-generation plants, steam can be taken at specified positions of the loop in order to be used in the desalination plant. In any case safety barriers must be set between these two plants in order to avoid any kind of nuclear contamination in the circuit that elaborates the potable water.

Two types of cogeneration can be defined:

- Parallel co-generation
- Serial co-generation

In the first one, electricity is produced as a co-product of the desalted water; and the total amount of steam that reaches the turbines (X) is evaluate as:

X=1-M

where M is the amount of steam that is used in the desalination plant This configuration allows a better flexibility in the production of electric power. However, the total energy consumption would be the same as if the steam for desalination and electricity had been produced separately. In the second type of co-generation, the total amount of steam first evolves in the turbines and only at the outlet of the last stage it is conveyed to the desalination plant. This solution is cheaper when compared to the parallel co-generation. In fact, from an energetic point of view, it is more convenient to transform the majority of steam enthalpy into mechanical energy at high temperatures (greater exergetic content) and only after using heat at low temperatures in the desalination plant. By increasing the pressure outlet value in the turbines it is possible to increase the temperature of the fluid that is provided to the desalination plant; obviously by doing this, the output work generated by the turbines decreases; for this reason it is essential to carry out a careful process of optimization in order to maximize the efficiency without energetically penalizing the desalination plant [13].

In Figure **7** the typical scheme for a combined cycle that connects a power reactor with a MSF plant is shown; it is possible to observe the intermediate safety loop that uses high quality H_2O to provide contamination protection to the MSF plant.

In Figure **8** we can observe a typical configuration of a power plant connected to a MED facility.

Finally, in Figure **9**, a hybrid plant is presented this is a MED installation combined with a RO facility (the latter uses the electrical energy provided by the NPP).

4.6. Hypothetical Scenarios: United Arab Emirates (UAE)

The main reasons that led us to focus on the UAE for our scenario analysis of the future productive capacity of desalinated water by means of nuclear power plants are the following:

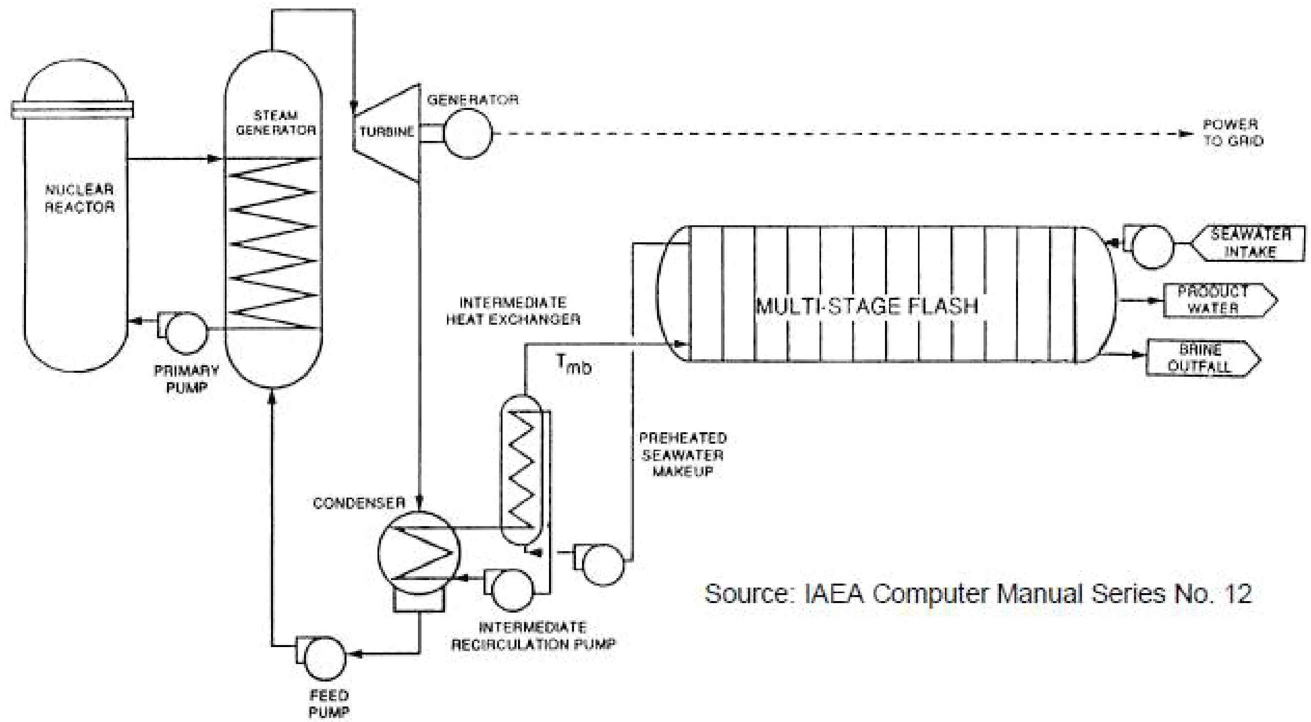

Figure 7: Schematic diagram of a nuclear power reactor coupled to an MSF plant [13].

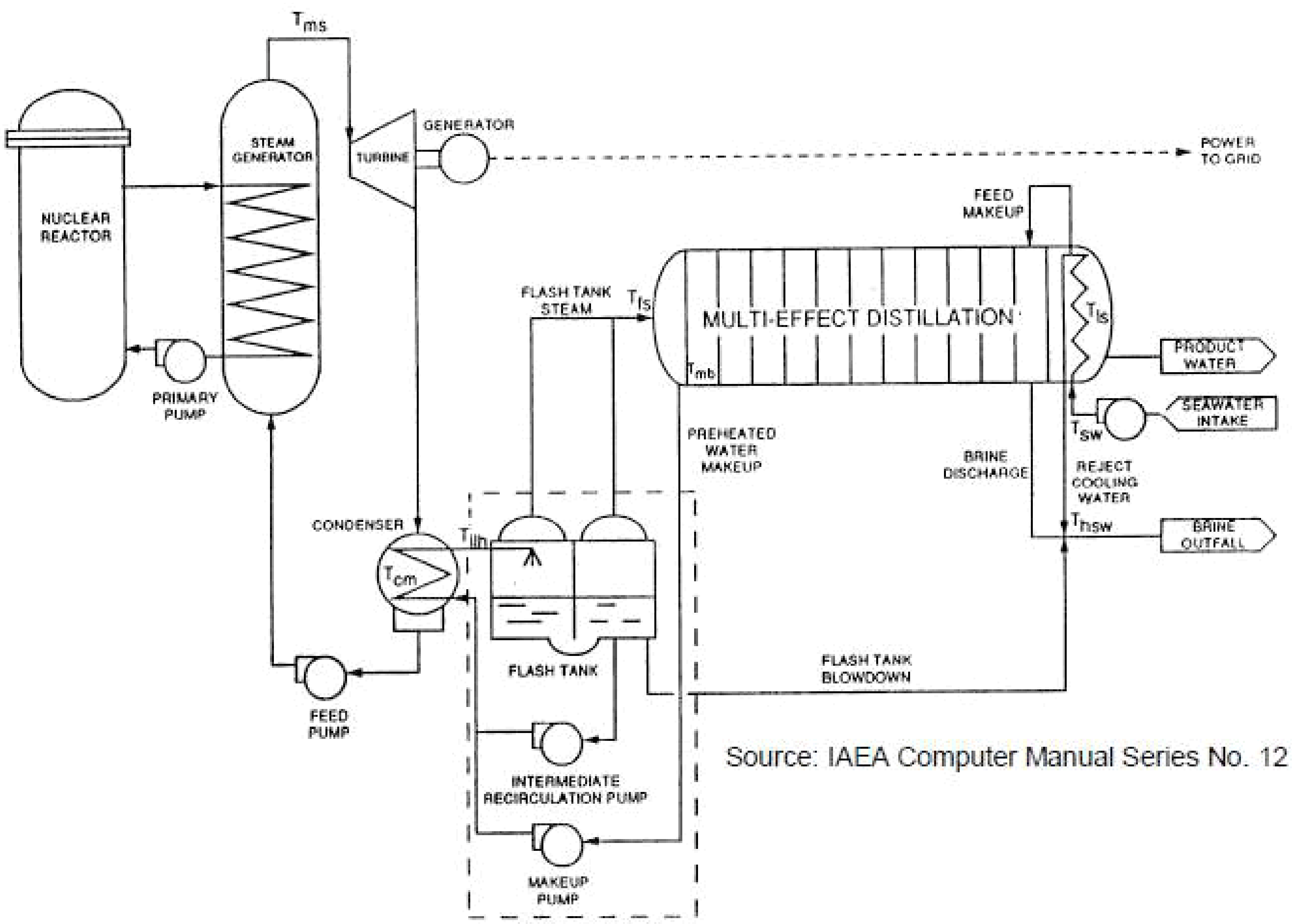

Figure 8: Coupling between a MED plant and a nuclear reactor [13].

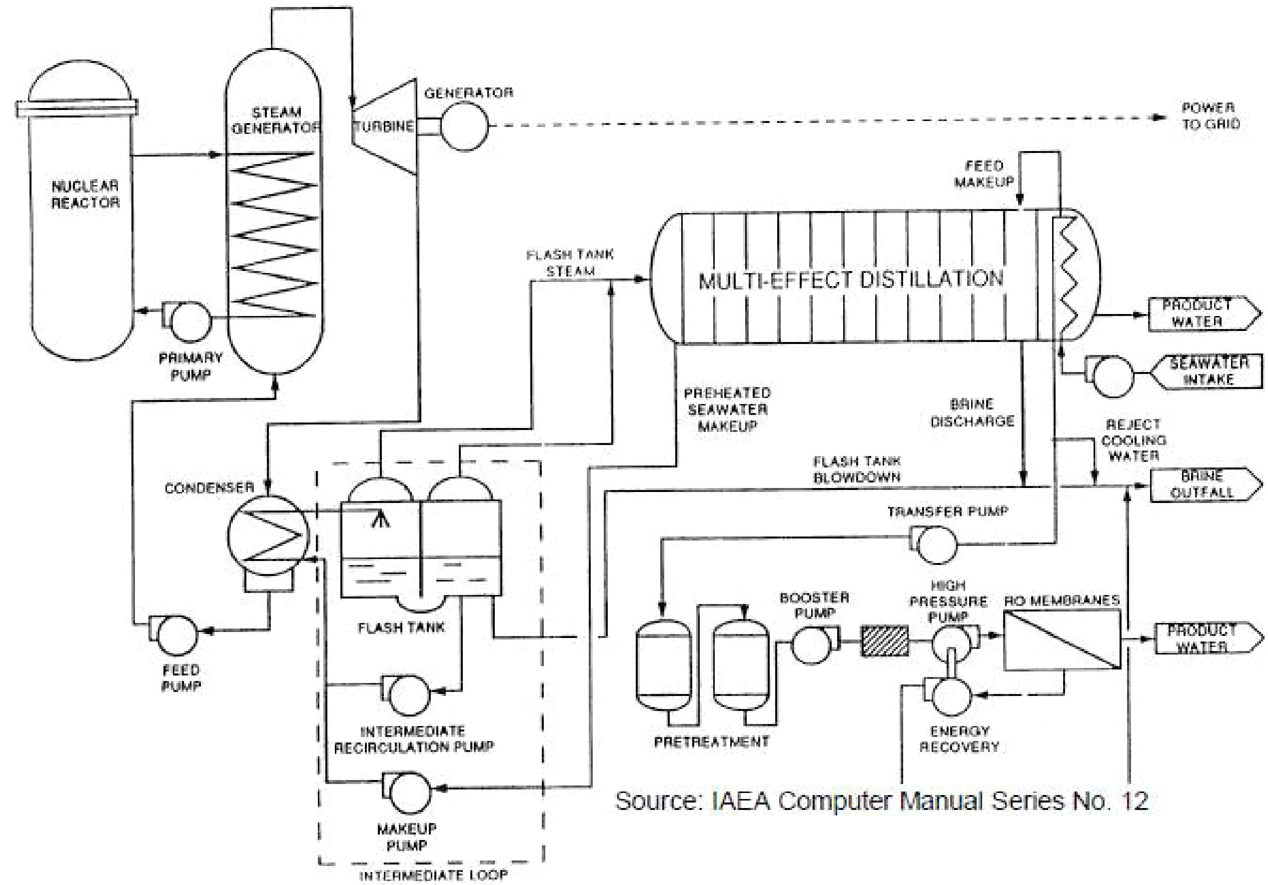

Figure 9: Coupling between an hybrid MED/RO plant and a nuclear reactor [13].

Table 1: Work Planning [27]

Type		MWe gross	Construction start	Start up
Barakah 1	APR-1400	1400	July 2012	5/2017
Barakah 2	APR-1400	1400	May 2013	2018
Barakah 3	APR-1400	1400	September 2014	2019
Barakah 4	APR-1400	1400		2020
Total		5600		

- UAE have recently launched a national nuclear program.
- UAE are a strongly growing economy and have a long term political stability.
- UAE are one of the countries that already is highly dependent on desalination plants.
- UAE have recently shown the necessity to reduce their dependence on fossil fuels for both economical and geopolitical reasons.

In December 2009, UAE have signed a contract with the South Korean company KEPCO for the construction of 4 reactors APR-1400 of 1400 MW_e each (the first is going to be finished in 2017). The contract is valued around $ 20.4 billion [21]. It is expected, as agreed, that by 2020 all 4 plants will go into full operation (Table **1**), and the energy produced by these power plants is going to be 75% less expensive than now [21].

UAE have scarcity of ground water, but they are statistically one of the biggest consumer of potable water in the world. It is estimated that the average resident of the UAE uses about 550 liters of water per day, about three times more than a European and about 82% more than the global average [22]. So far, UAE produce about 40% of potable water through desalination processes but it is expected that in coming years they are going to reach values of 70% (also due to the gradual reduction and pollution of groundwater in the country).

After Saudi Arabia, UAE are in fact the second largest producers of desalinated water in the world. It is estimated that every year UAE spend around $ 800 million for the maintenance and development of new facilities and it is expected that this expenditure will increase by 300% over the next six years, for a total that will be approximately $ 3.2 billion [23, 24]. Recently UAE is experiencing a significant increase in prices for desalinated water, mainly due to the increased cost of energy (for reasons related to significant fluctuations in the gas market and due to an increase in domestic use of this resource). It is recorded that up to 8 years ago, the cost per 1000 litres of desalinated water was around $ 0.50; today it is practically impossible to provide this amount of water below $ 0.60. For this reason, UAE are taking into consideration new sources of power for feeding their desalination plants, as demonstrated by the recent construction of the world's largest solar facility of this kind.

Starting from this background, it is clear why UAE are an excellent candidate for our kind of study.

The idea behind our scenario study is to employ 4 modern HTGRs (similar to HTR-PM plants, actually under construction in China, each with a power of 210 MW_e, roughly equivalent to 450 MW_t) in cascade to four APR-1400 (with an overall power of 5600 MW_e, roughly equivalent to 16000 MW_t) that are already under construction in UAE. The idea to add some HTR-PM has the ultimate goal of making the production both of energy and desalinated water more efficient, and, moreover, at the same time, of improving the nuclear fuel cycle, by reducing the radiological hazard and the volume of the nuclear waste produced by the APR-1400 (produced as spent fuel) to be disposed.

In the present study we assumed to introduce the 4 APR-1400 sequentially from 2017 to 2020 (as the UAE nuclear program foresees) and 4 HTR-PM from 2025 to 2028.

The entire fleet is designed to go into full service by 2030. Assuming:

- a fresh water consumption of 9000 millions of cubic meter.
- a coverage of the national water demand by the desalination plant equal to 75% (6750 millions of cubic meter).

it was estimated that the various reactors may support a total of 16 RO plants and a MSF facility. These, during full operation, could provide 19% of the fresh water request; in fact the 16 RO plants and the single MSF would ensure a water production of:

$$1252 \cdot 10^6\,\mathrm{m}^3(\mathrm{RO}) + 22 \cdot 10^6\,\mathrm{m}^3(\mathrm{MSF}) \cong 1274\ \mathrm{Mm}^3(\mathrm{RO}+\mathrm{MSF})$$

To this value, we should add the remaining energy provided by the APR-1400, that is equal to 44150

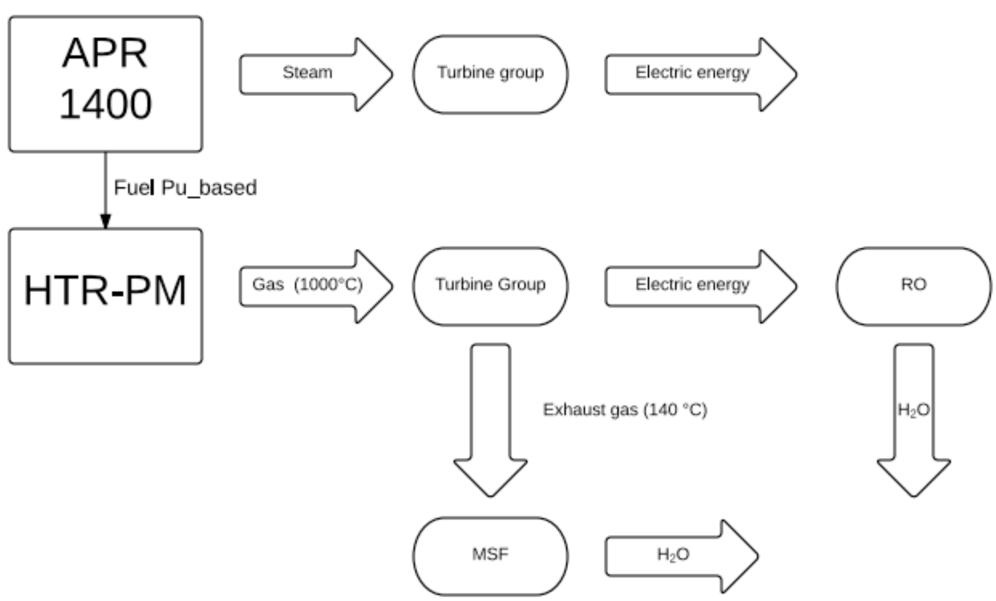

Figure 10: Hypothesized symbiotic cycle [25].

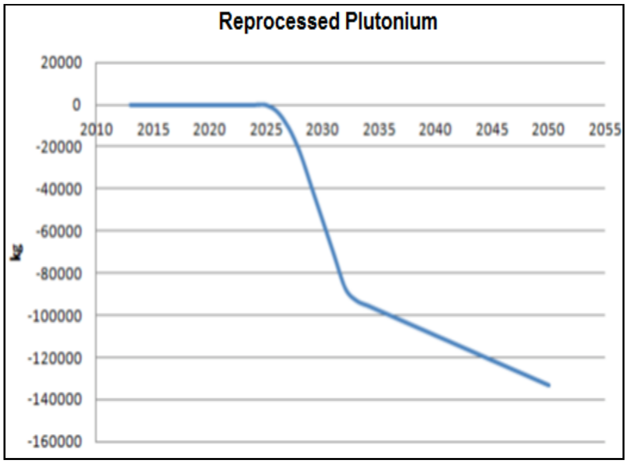

Figure 11: Burn-out of the exhaust combustible thanks to the HTR-PM [25].

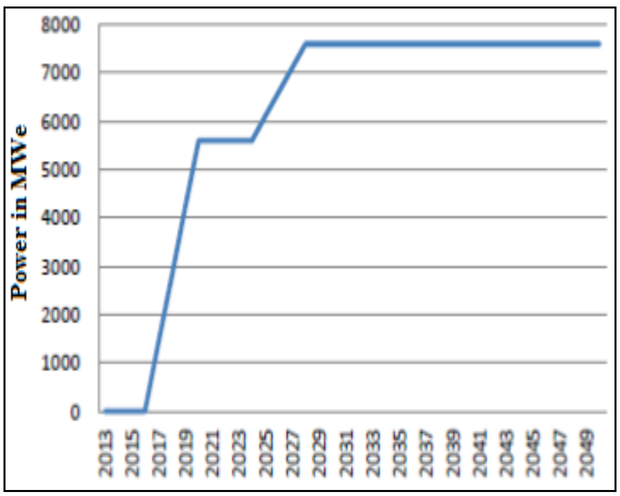

Figure 12: Production of electrical power through the reactors APR-1400 and HTR-PM [25].

GWh, that would be introduced in the national electric grid, covering in this way about 16% of the national demand (value updated to 2030 that takes into account the current growth rate in energy demand).

These results have been obtained through the implementation of only 4 HTR-PM reactors, the cost of which is estimated around $ 1÷1.5 billion [26]. This will take to an overall investment of about $ 5 billion. From the point of view of the desalination plants it should be underlined that the RO facilities could be easily reconverted in order to use the electric energy provided by the NPP; for the MSF plant UAE should face a new investment, in fact the plant should be built from scratch.

In conclusion, the implementation of the HTR-PM reactors could be an excellent alternative to the use of fossil fuels that would allow:

- Reduction in CO_2 emissions
- Lower dependence of the UAE from natural gas (and fossil fuels in general)
- Increase in production capacity of desalinated H_2O
- Reduction of the overall hazard and quantity of nuclear waste

Finally UAE could become one of the first nations dealing with this technology with all the related advantages for the local industry.

At the moment, UAE have the political and economic strength to begin the project. Furthermore, the increasing interest of this nation in nuclear technology could make this scenario study even more achievable. There are related technological challenges but totally surmountable and the implementation of such technologies could make UAE one of the leading nations in this field.

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