NUCLEAR DESALINATION OPTIONS FOR THE INTERNATIONAL REACTOR INNOVATIVE AND SECURE (IRIS) DESIGN

D. T. Ingersoll, J. L. Binder
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, Tennessee, USA 37831-6172
ingersolldt@ornl.gov, binderjl@ornl.gov

D. Conti, M. E. Ricotti
Polytechnic of Milan
Via Ponzio 34/3
20133 Milan, ITALY
marco.ricotti@polimi.it

ABSTRACT

The worldwide demand for potable water is on the rise. A recent market survey by the World Resources Institute shows a doubling in desalinated water production every ten years from both seawater and brackish water sources. The production of desalinated water is energy intensive, requiring approximately 3-6 kWh per cubic meter of produced desalted water. At current U.S. water use rates, 1 kW of energy capacity per capita (or 1000 MW for every one million people) would be required to meet water needs with desalted water. The choice of the desalination technology determines the form of energy required: electrical energy for reverse osmosis systems, relatively low quality thermal energy for distillation systems, and both electrical and thermal energy for hybrid systems such as pre-heat RO systems.

Nuclear energy plants are attractive for large scale desalination application. Nuclear plants can provide both electrical and thermal energy in an integrated, co-generated fashion to produce a spectrum of energy products including electricity, desalted water, process heat, district heating, and potentially hydrogen generation. A particularly attractive option for nuclear desalination is to couple it with an advanced, modular, passively safe reactor design such as the International Reactor Innovative and Secure (IRIS) plant. This allows for countries with smaller electrical grid needs and infrastructure to add new electrical and desalination capacity in smaller increments and at distributed sites. The "safety by design" nature of the IRIS reactor will ensure a safe and reliable source of energy even for countries with limited nuclear power experience and infrastructure. Two options for the application of the IRIS nuclear power plant to the cogeneration of electricity and desalted water are presented, including a coupling to a reverse osmosis plant and a multistage flash distillation plant. The results from an economic assessment of the two options are also presented.

1 INTRODUCTION

In an increasing number of countries throughout the world, the availability of clean, potable water is already a major concern. Scores of countries are considered to be "water stressed," i.e. their availability of fresh water is less than 2000 m^3 per person per year. Even in countries that have adequate water resources as a whole, the geographic distribution of the water is typically not uniform and selected regions may still be "water stressed" or even "water scarce" (renewable water supply less than 1000 m^3 per person per year). An example of this is the southwest region of the United States, where annual consumption of water has been exceeding water production in recent years.

A well established process for producing potable water is from the desalination of seawater. More than 12,000 desalination plants exist world-wide, with 60-70% of the units being in the Middle East.[1] A recent market survey by the World Resources Institute predicts a doubling in desalinated water production every ten years from both seawater and brackish water sources. This will be driven by continued population growth, rapid industrialization in developing countries, and urbanization. The production of desalinated water is energy intensive, requiring approximately 3-6 kWh(e) per cubic meter of produced desalted water. At current U.S. water use rates, 1 kW of energy capacity per person (or 1000 MW for every one million people) would be required to meet water needs with desalted water. The choice of the desalination technology determines the form of energy required: electrical energy for reverse osmosis systems, relatively low quality thermal energy for distillation systems, and both electrical and thermal energy for hybrid systems such as pre-heat RO systems.

Of the more than 12,000 desalination plants in operation, only about 10 use heat or electricity provided by nuclear power plants, primarily in Japan.[2] Fossil energy sources are the dominant choice. However, there is an increasing concern regarding the environmental impact of burning fossil fuels due to the resulting "greenhouse gases." These environmental concerns, coupled with concerns over energy supply security and an anticipated growth in energy demands, are driving a growing interest in the development and expansion of the nuclear energy options. Nuclear energy offers a clean and abundant energy supply. Also, the current generation of nuclear plants has proven that nuclear energy can be safe and economically competitive with alternative options.

To facilitate the anticipated growth in demand for nuclear energy world-wide, several countries including the U.S.A. have initiated the development of the next generation of nuclear plants that offer even greater safety, reliability, and economics, while also reducing the threat of proliferation of special nuclear materials. The "Generation IV" nuclear power program was initiated by the U.S. Department of Energy (DOE) to identify and develop promising next-generation nuclear plant designs. The program was expanded to include several other countries through the implementation of a "Generation IV International Forum" (GIF). In 2003, the GIF selected six advanced reactor designs for long-range development (possible deployment by 2025-2030) and several designs that are viewed as near-term deployable by 2015. One of the reactor types identified in the international near-term deployment set is the "integral pressurized reactor system" (IPRS). An example of an IPRS is the International Reactor Innovative and Secure (IRIS) reactor concept. Like many of the near-term and long-term advanced reactor designs, IRIS is a modular type design with enhanced safety and economics.[3] The IRIS is especially well suited for deployment in countries with small or medium electricity grids for producing both electricity and fresh water. The next section provides a brief overview of the IRIS concept and highlights its features that are amenable to the desalination application. Section 3 briefly discusses common desalination options and Section 4 presents a description of an exergy-based economic analysis of using IRIS to produce fresh water with an RO desalination process. Section 5 presents a potential coupling of IRIS to a multi-stage flash (MSF) distillation plant.

2 IRIS OVERVIEW

The IRIS project was initiated in 1999 as part of the U.S. DOE Nuclear Energy Research Initiative (NERI). The project is led by Westinghouse Electric Company (WEC), and was formed from the outset as a truly international collaboration of industry, national laboratory, and university partners.[3] Currently, there are more than 20 organizations in 10 countries participating in the IRIS project. As a result of the combined talent and resources of the participants, the IRIS design has progressed rapidly, and the project team initiated in October 2002 a pre-application licensing review with the U.S. Nuclear Regulatory Commission.

The IRIS design is based on proven light-water reactor technology, but includes several innovative engineering features that enhance its safety and economics relative to other advanced systems.[4] The total thermal power of IRIS is 1000 MW, and with an expected energy conversion of 33.5%, a single IRIS module is capable of producing 335 MW of electrical output. As stated earlier, IRIS is a member of the integral pressurized reactor system class of designs, which means that all functions of the primary coolant system (steam generators, pressurizer, primary pumps, etc.) are contained within the reactor vessel. A model of the IRIS reactor vessel is shown in Figure 1.

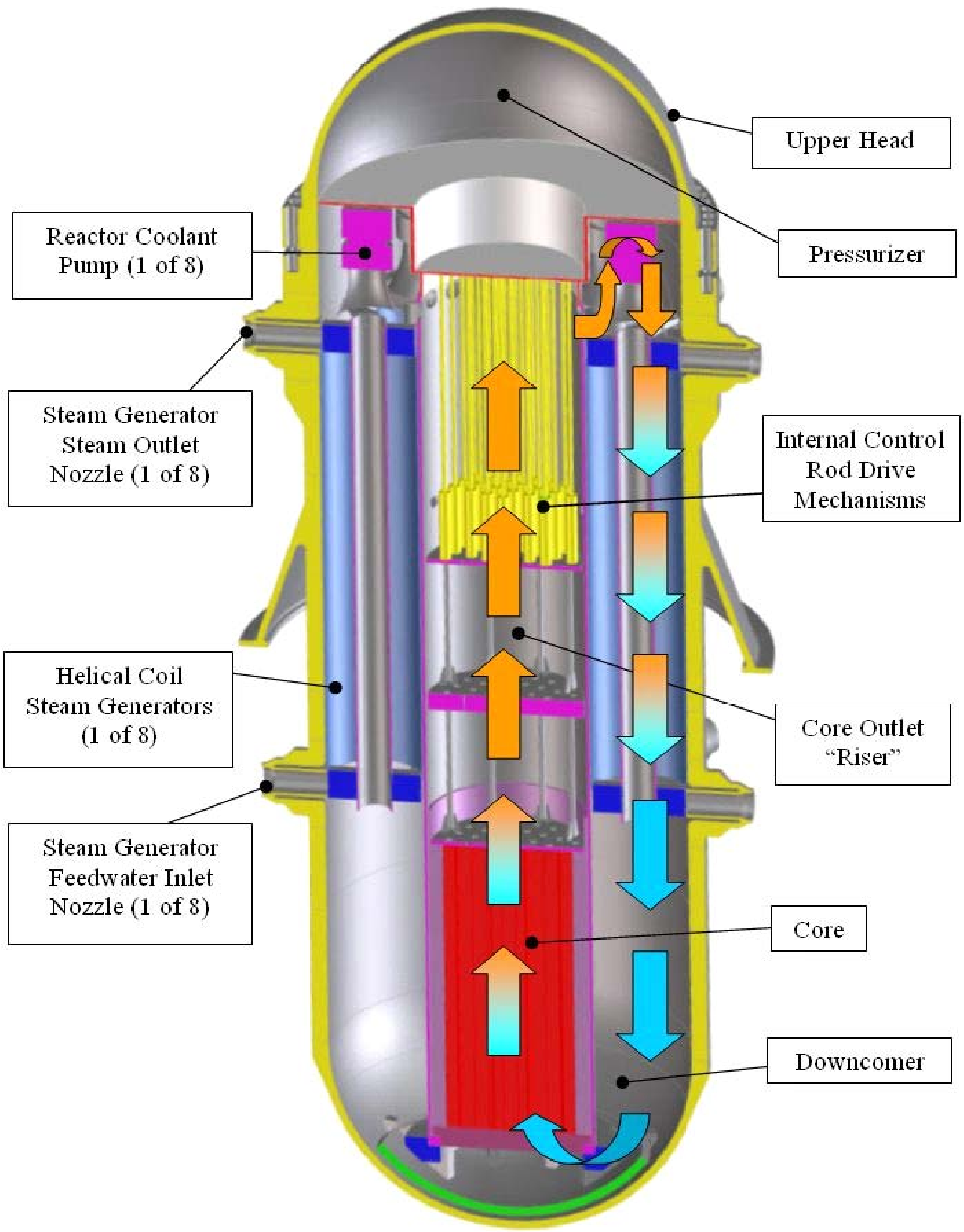

Figure 1. Model of IRIS reactor vessel and primary coolant system.

IRIS uses the concept of "safety by design," which means that design choices are made to eliminate the potential for accidents to occur rather than adding systems to respond to the consequences of accidents. For example, by using an integral system, several potentially severe accident scenarios are avoided, such as medium-to-large pipe break loss-of-coolant accidents (LOCA). For those accident scenarios that can not be precluded, the design is such that the consequences of the accident are greatly reduced through inherent or passive means. An example of this is the spherical, high-design-pressure containment vessel that encloses the reactor vessel and safety systems. In the event of a small pipe break in the secondary system, the pressure inside and outside the reactor vessel equalizes very rapidly and prevents the core from being uncovered by coolant.

In addition to the "safety by design" philosophy, the IRIS design team also uses a philosophy of "reliability by design." Probabilistic risk assessment (PRA) methods are being used in the early stages of the design process to make component and subsystem design choices based on their impact on potential system failures.[5] Using this approach, design iterations on the IRIS safety systems such as the Automatic Depressurization System (ADS) and the Emergency Heat Removal System (EHRS) have resulted in the likelihood of predicted core damage frequency due to internal events that is one-to-two orders of magnitude less than for advanced LWRs.

Because of these features and other, IRIS is especially well suited for desalination applications. Specifically:

- The international nature of the IRIS project team will help to ensure that the design will be licensable for deployment in the world market.
- The modular sizing of IRIS will allow countries with small-to-medium power requirements to install capacity to their electrical grid in smaller increments and increase additional capacity as their power and water demands warrant and their infrastructure will support.
- The enhanced safety margins will provide additional flexibility in the siting of the reactor to better match electrical and water use demographics. This will also encourage countries with modest nuclear infrastructure to build and operate nuclear plants.

As will be discussed in a Section 5, the design of the IRIS power conversion system also facilitates coupling to a desalination plant due to the multistage feedwater heater arrangement, which provides easy access to a range of steam temperatures and pressures.

3 DESALINATION OPTIONS

There are a number of processes that have been demonstrated for producing fresh water from seawater, but for the purposes of nuclear desalination, there are three primary processes:[6]

1. *Multi-Effect Distillation (MED):* In each MED "effect" (stage), heat is transferred from condensing water vapor on one side of a tube bundle to the evaporating brine on the other side of the tubes. This process is repeated successively in each of the successive effects at progressively lower pressure and temperature, driven by the vapor from the preceding stage. In the last effect at the lowest pressure, the water vapor condenses in the heat rejection heat exchanger, which is cooled by incoming seawater. The condensed distillate is collected from each effect and some of the heat may be recovered by flash evaporation at a lower pressure. Low pressure saturated steam is used as a heat source, which is supplied by steam boilers or dual-purpose plants (co-generation of electricity and steam).
2. *Multi-Stage Flash Distillation (MSF):* Seawater passes through tubes in each evaporation stage where it is progressively heated. Final seawater heating occurs in the brine heater by the heat source (steam heat exchanger). The heated brine flows through nozzles into the first stage, which is maintained at a pressure slightly lower than the saturation pressure of the incoming stream. As a result, a small fraction of the brine flashes forming pure steam. The heat to flash the vapor comes from cooling of the remaining brine flow, which lowers the brine temperature. Subsequently, the produced vapor passes through a mesh demister in the upper chamber of the evaporation stage where it condenses on the outside of the condensing brine tubes and is collected in a distillate tray. The heat transferred by the condensation warms the incoming seawater as it passes in counterflow through the stage. The remaining brine passes successively through all of the stages at progressively lower pressures, where the process is repeated. The hot distillate flows as well from stage to stage and cools itself by flashing a portion into steam which is recondensed on the outside of the tube bundles.
3. *Reverse Osmosis (RO):* Reverse osmosis is a membrane separation process in which pure water is "forced" out of a concentrated saline solution by flowing through a membrane at high static transmembrane pressure differences. These pressure differences have to be higher than the osmotic

pressure between the solution and the pure water (about 60 bar). The saline feed is pumped into a closed vessel where it is pressurized against the membrane to 70-80 bar. As a portion of the water passes through the membrane, the salt content in the remaining feed water increases, therefore a portion of this solution is constantly discharged without passing through the membrane. A pure RO process requires only electricity to power the pumps needed to create the pressure head. However, an external heat source may be used to preheat the seawater to improve the efficiency of the RO process.

The biggest distinction in the three methods is the way that they couple with the power source. The RO plant has the most straightforward coupling, and hence is the most flexible, since it requires only electricity input from the power plant. Therefore, it is not necessary to even co-locate the power plant and the desalination plant, although there may be an advantage to do this in terms of shared infrastructure. If co-located, low grade steam or hot water from the power plant can be used to pre-heat the saltwater feed of the RO plant to improve its efficiency. Both the MED and MSF plants require a heat source such as a steam line from the secondary side of the nuclear plant. While this coupling is still relatively straightforward, there are design choices that have implications on the safety, reliability, and flexibility of operation for both the power plant and the desalination plant. These are discussed in Section 5. This paper discusses the coupling of IRIS to only an RO and a MSF plant. Coupling to a MED plant is being studied by another IRIS team organization and will be presented elsewhere.

4 IRIS AND REVERSE OSMOSIS OPTION

As stated above, coupling IRIS to an RO desalination plant is straightforward and requires only an electrical connection between the two plants. However, the economics of a coupled plant are more complicated because the costs charged for electricity generation and water production depend on how costs associated with the power plant or the desalination plant are accounted. Researchers at the Polytechnic of Milan (POLIMI) performed an economic analysis of a coupled IRIS-RO plant based on the relative "exergy" associated with the production of electricity and fresh water.[7] Exergy is the maximum mechanical work that is required to bring a system from its present state to a state of stable equilibrium with its surroundings. A cost analysis for the general case of a coupled nuclear-desalination plant is given below followed by the simplifications that results from using an RO plant.

The overall annual expenditures of integrated plants are the annual costs ($/yr) that arise in producing the two final products, i.e. potable water and electricity. The overall expenditures are made up of fixed expenditures such as capital cost, personnel cost, insurance and preventive maintenance cost, and variable expenditures such as fuel cost and consumable operating materials cost.

The overall annual expenditures C_0 of the integrated plants are divided into the following components:

- electricity generation expenditures C_{El} , allocated exclusively to the generation of electricity supplied both to the grid and to the desalination plant;
- steam production expenditures C_S for providing heat to the desalination plant, allocated exclusively to the production of potable water;
- common electricity and steam production expenditures C_C;
- remaining water production expenditures C_{W*}.

$$C_0 = C_{El} + C_S + C_C + C_{W*}$$

The common electricity and steam production expenditures C_C are allocated to the two forms of energy produced, electricity and steam, proportional to the exergy flows E_E and E_S that are required to produce these two energy forms. Hence, the electricity generation expenditures C_{E*} to generate electricity and the steam production expenditures C_{S*} are calculated by the following equations:

$$C_{E*} = C_{El} + \frac{E_E}{E_E + E_S} \cdot C_C$$
$$C_{S*} = C_S + \frac{E_S}{E_E + E_S} \cdot C_C$$

C_{E*} is further divided into expenditures for generation of electricity for sale, C_E and generation of electricity supplied to the seawater desalination plant C_{EW}, proportional to the saleable electricity P_E supplied to the grid and the electricity P_W supplied to the desalination plant, according to the following formulae:

$$C_E = C_{E*} \cdot \frac{P_E}{P_E + P_W}$$

$$C_{EW} = C_{E*} \cdot \frac{P_W}{P_E + P_W}$$

Finally, the water production expenditures C_W are calculated by:

$$C_W = C_{W*} + C_{EW} + C_S$$

Dividing C_E and C_W by the respective units produced, leads to the electricity generation cost $\mathbf{c_E}$ in \$/kWh(e) and the potable water production cost $\mathbf{c_W}$ in \$/m^3.

Since the case of coupling to an RO plant does not require any steam withdrawal from the nuclear plant secondary system, costs are allocated in a different manner: the total power plant costs are allocated to electricity generation, proportional to the electricity sold to the grid, so that:

$$C_E = (C_{El} + C_C) \cdot \frac{P_E}{P_{net}}$$

The costs of the desalination plant, the incremental cost of the electrical connection between the power plant and the desalination plant and the cost of the power plant proportional to the amount of electricity required by the desalination plant, are then allocated to the potable water production:

$$C_W = C_{W*} + C_S + (C_{El} + C_C) \cdot \frac{P_W}{P_{net}}$$

The methodology for assessing the integrated plant configurations is based on computing the life-time levelized equivalent electricity cost and the life-time levelized potable water cost. These levelized production costs are then obtained by standard cost accounting relationships for determining the present value of all year-by-year expenditures and dividing that amount by the present value of the product generated over the life of the plant.

The key parameters used to compute electricity and water costs from a coupled IRIS-RO plant are given in Table 1. The date of initial operation was chosen to be 2010, which is overly optimistic but does not impact the results significantly. A deployment date of 2015 is more realistic for IRIS. Also, the cost estimates for IRIS are based on a preliminary top-down economic evaluation and are intended only to be representative of likely costs. The results of the economic assessment are given in Table 2.[6] The electricity cost of 2.7 ¢/kWh is attractive, as expected, and the water cost of 73 ¢/m^3 is favorable for regions of the world with limited water resources.

For comparison, the same parameters given in Table 1 were input into the Desalination Economic Evaluation Program (DEEP) developed and distributed by the International Atomic Energy Agency (IAEA).[7] DEEP is a Microsoft Excel application that provides a common basis for predicting costs of numerous different power plants (nuclear and non-nuclear) coupled to one of several possible desalination plants. The program does not contain a specific model for IRIS, so the standard pressurized water reactor (PWR) option was used

Table 1. Key parameters for predicting electricity and water costs from an IRIS-RO coupled plant.

General Parameters			**IRIS Plant Parameters**	
Begin operation[a]	Jan. 1, 2010		Thermal power per module	1000 MW(t)
Real discount/interest rate	8%		Net electrical power per module	335 MW(e)
Economic lifetime	30 years		Thermal efficiency	33.5%
RO Plant Parameters			Total investment cost[b]	$385M
Desalination capacity	144,000 m^3/d		Specific investment cost	$1155/kWh(e)
Desalination capacity per unit	24,000 m^3/d		Average load factor[c]	90%
Number of units	6		Construction time	36 months
Base cost per unit	$24M		Fixed O&M costs[b]	$23M
Average seawater temperature	28°C		Variable costs[b]	$0.006/kWh(e)
Total dissolved solids	45,000 ppm		Primary pressure	15.5 MPa
Plant load factor	91%		Primary temperature (out/in)	328/292°C
Feedwater pressure	72 bar		Number of primary circuits	8
Recovery ratio	35%		Secondary pressure	5.8 MPa
Specific electricity consumption	5.5 kWh(e)/m^3		Secondary temperature (in/out)	317/224°C
Seawater flow rate	2857 m^3/h		Cost percentage of turbomachinery	20%

[a]Actual anticipated deployment of IRIS is 2015; [b]Representative costs based on earlier IRIS design;

[c]Actual availability expected to be in excess of 96%.

Table 2. Estimated product costs for an IRIS-RO coupled plant.

Capital charge for turbomachinery	7.68 M$/yr
Capital charge for electrical connection to RO plant	2.00 M$/yr
Remaining capital charge for IRIS	70.26 M$/yr
Capital charge for desalination plant	25.42 M$/yr
Total cost	105.35 M$/yr
Electricity cost	0.027 $/kWh(e)
Potable water cost	0.73 $/m^3

instead. The DEEP analysis, which yielded a levelized electricity cost of 3.8 ¢/kWh(e) and a potable water cost of 74 ¢/m^3, is consistent with the IRIS-specific evaluation. The higher cost of electricity calculated by DEEP is due to differences in the standard PWR model used in DEEP compared to IRIS-specific plant performance characteristics.

5 IRIS AND MULTISTAGE FLASH DISTILLATION OPTION

Coupling IRIS to an MSF desalination plant requires co-location of the two units with a steam supply loop provided from the IRIS secondary system to the MSF plant. Electrical connection is also required to power the MSF pumps and auxiliary equipment. Because of the more intimate coupling of the nuclear plant and the desalination plant, safety and reliability become a significant concern. For example, the plants must be coupled in a manner that ensures that no radionuclides can be carried over to the fresh water side of the MSF plant. Also, there would be significant economic impact to the reactor system if the salinity of the secondary coolant were increased significantly.

An intermediate steam transfer loop is currently considered for coupling IRIS to the MSF plant. The pressure of the intermediate loop is maintained below the pressure of the seawater loop in the brine heater stage of the MSF plant so that a failure in the brine heater tube bundle will result in mass flow into the intermediate loop. The salinity of the intermediate loop will be monitored to detect such a failure. The intermediate loop will also be monitored for radioactivity to identify any failures of the heat exchanger on the IRIS side of the loop. The additional cost of the intermediate loop is justified by the increased safety provided by the additional barriers between the primary coolant and the product water, and also by enhanced flexibilities in the operation of both plants. However, further studies may show that the additional loop is not required since the IRIS steam generators (SG) are expected to be more reliable than traditional PWR loops. Specifically, the SGs are designed for full system pressure with very small water inventory on the secondary side, the capability for fast detection of a primary-to-secondary leak, and fast isolation of the secondary loop in the case of SG tube rupture events. As assessment of the cost/benefit of the intermediate loop will be performed.

The current IRIS power conversion system consists of a high-pressure turbine, a low-pressure turbine with multiple extraction stages, a multistage steam reheater, a condenser, six feedwater heaters, a turbogenerator, and recirculation pumps. The multiple extraction stages of the low-pressure turbine, which provides heat sources for the six feedwater heaters, also enhances the coupling of IRIS to the MSF plant since there are a range of steam temperatures and pressures conveniently available to drive the intermediate loop to the MSF plant. Key parameters for the feedwater heaters are listed in Table 3. A diagram of the coupled IRIS-MSF plant is given in Figure 2. An intermediate steam loop is added to the low-pressure turbine extraction stage supplying steam to feedwater heater #5. This provides a 100°C steam supply to the MSF brine heater.

Table 3. Key parameters for the six feedwater heaters in the IRIS secondary system.

	FWH 1	**FWH 2**	**FWH 3**	**FWH 4**	**FWH 5**	**FWH 6**
Extraction stage pressure (bar)	28.6	11.3	6.9	4.4	1.4	0.4
Extraction stage flow (kg/s)	40.8	17.1	12.1	25.6	20.1	13.1
Shell pressure (bar)	26.3	10.7	6.3	4.1	1.3	0.4
Shell temperature (°C)	227	183	161	144	106	74.7
Feedwater flow (kg/s)	503	384	384	384	384	384
Feedwater temperature in (°C)	182	158	141	104	71.9	45.3
Feedwater temperature out (°C)	224	180	158	141	104	71.9

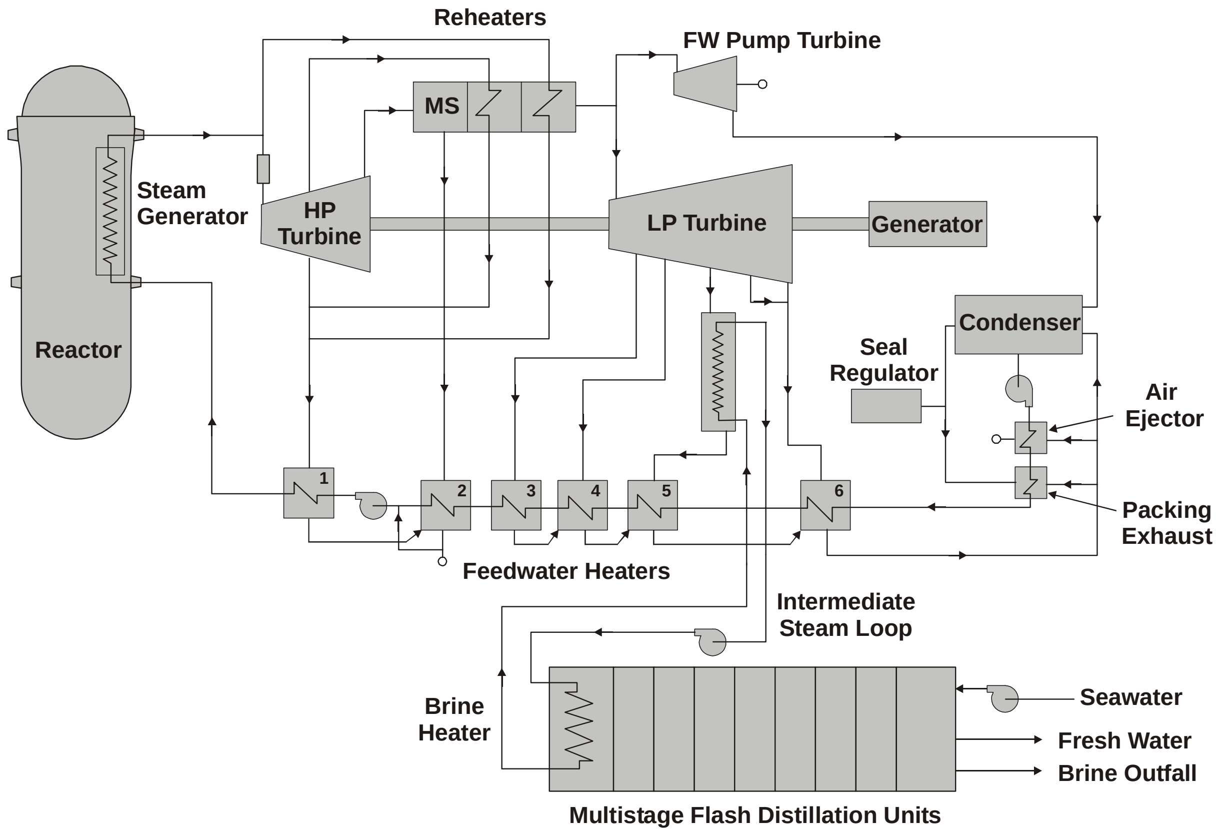

Figure 2. Diagram of MSF plant coupled to the IRIS power conversion system.

The DEEP code was used to estimate the cost of electricity and water using the coupled IRIS-MSF approach. Using similar economic parameters as were used for the IRIS-RO plant described in Section 4, the levelized electricity costs were the same in both cases, i.e. \$0.038/kWh(e). However, the cost of the potable water produced from the MSF plant is calculated to be \$1.44/m^3, compared to half that value (\$0.73/m^3) for the RO plant. The difference is almost entirely due to the difference in specific unit cost for the desalination plants. In the case of the RO plant, a specific unit cost of \$1000/m^3 was used, whereas a cost of \$1800/m^3 is used for the MSF plant. Improvements in desalination technology have already begun to favorably impact the economics of RO plants more than MSF plants and this trend is likely to continue, so it is expected that the cost discrepancy between the two types of desalination plants will continue to increase in favor of the RO process.

A number of additional DEEP cases were computed in which only the “maximum brine temperature” input parameter was changed. The results are presented in Figure 3, which plots both the gain output ratio (GOR) and the specific investment cost of the MSF plant. The gain output ratio is defined as the mass of fresh water produced divided by the mass of steam used to produce the fresh water, hence it is a measure of the thermal efficiency of the system. As is seen in the figure, the GOR increases monotonically with increasing brine temperature; however, the MSF plant cost has a minimum at approximately 82-83 °C. The rise in plant cost, despite the increased efficiency at higher brine temperatures, is likely due to the additional chemical requirements to reduce brine scaling and due to equipment replacements resulting from accelerated corrosion of metal components at higher brine temperatures.

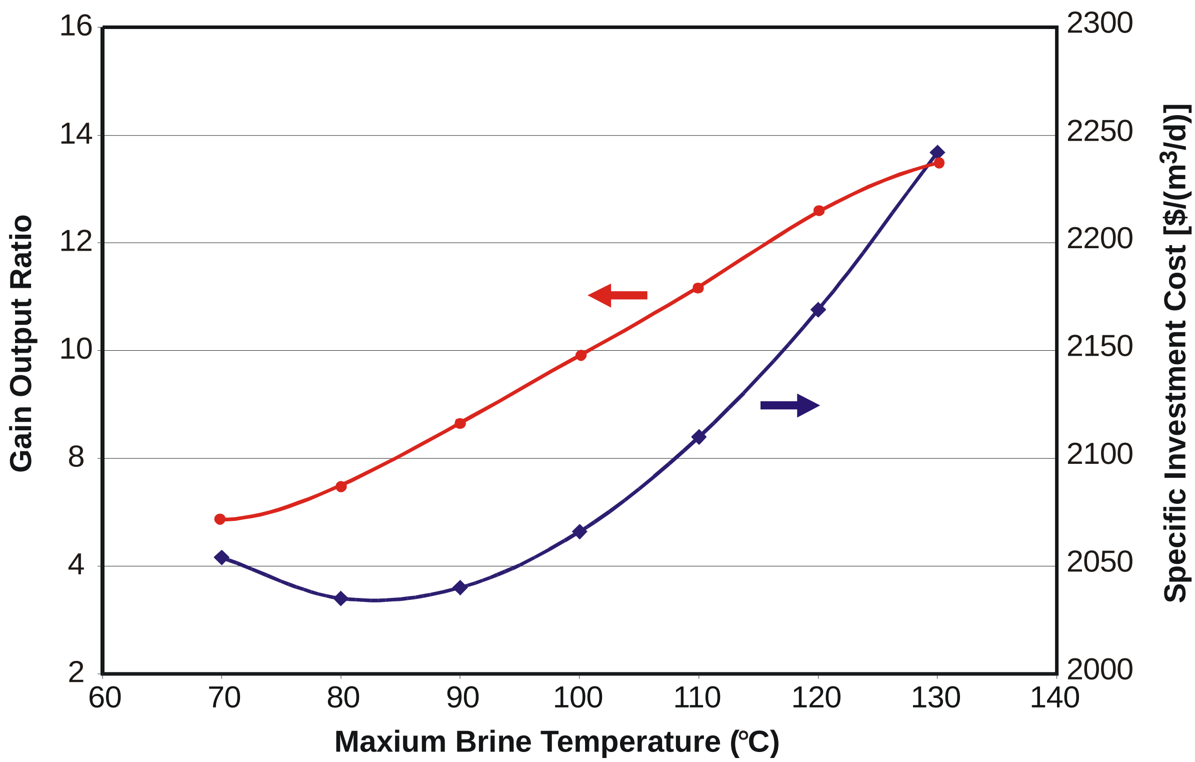

Figure 3. Dependence of GOR and specific investment cost on maximum brine temperature.

6 SUMMARY

The coming decades will almost certainly see an expansion in the use of nuclear energy world-wide. This will be driven by the need for increased electricity and also for the desalination of seawater to meet the increasing need for fresh water supplies. For many countries, especially those that have little or no nuclear infrastructure, small modular plants offer the best solution for providing additional power in appropriate increments, and also for matching power and water needs to non-uniform population distributions. The IRIS reactor design is especially well suited for this application. Preliminary studies have shown that combining IRIS with an RO desalination plant provides attractive economics for both the electricity and fresh water produced by the plants. Also, IRIS is attractive for coupling to an MSF desalination plant, although the economics of the water produced in this type of plant appears less favorable than for the RO plant.

REFERENCES

[1] *Introduction of Nuclear Desalination: A Guidebook,* International Atomic Energy Agency, Technical Reports Series No. 400 (2000).

[2] *Design Concepts of Nuclear Desalination Plants*, International Atomic Energy Agency, IAEA-TECDOC-1326 (November 2002).

[3] M.D. Carelli, "IRIS: A global approach to nuclear power renaissance," *Nuclear News*, Vol. 46, No. 10, pp. 32-42. American Nuclear Society (September 2003)

[4] M. D. Carelli et al., "The Design and Safety Features of the IRIS Reactor," to be published in *Nucl. Eng. Design (*May *2004).*

[5] M. D. Muhlheim and J. W. Cletcher, "Use of PRA Techniques to Optimize the Design of the IRIS Nuclear Power Plant," Proceedings of the GENES4/ANP2003 Conference, Kyoto, Japan, (September 2003).

[6] D. Conti, "Thermodynamic and Economic Evaluation of Co-Production Plants for Electricity and Potable Water," Project paper, Polytechnic of Milan (2003).

[7] *Desalination Economic Evaluation Program (DEEP): User's Manual*, International Atomic Energy Agency, Computer Manuals Series No. 14 (2000).