Cogeneration of Electricity and Potable Water Using The International Reactor Innovative And Secure (IRIS) Design

D. T. Ingersoll and J. L. Binder
Oak Ridge National Laboratory, USA

V. I. Kostin, Yu. K. Panov, and V. Polunichev
OKB Mechanical Engineering, Russia

M. E. Ricotti and D. Conti
Polytechnic of Milan, Italy

G. Alonso
Instituto National de Investigaciones Nucleares, Mexico

ABSTRACT

The worldwide demand for potable water has been steadily growing and is projected to accelerate, driven by a continued population growth and industrialization of emerging countries. This growth is reflected in a recent market survey by the World Resources Institute, which shows a doubling in the installed capacity of seawater desalination plants every ten years. The production of desalinated water is energy intensive, requiring approximately 3-6 kWh/m^3 of produced desalted water. At current U.S. water use rates, a dedicated 1000 MW power plant for every one million people would be required to meet our water needs with desalted water.

Nuclear energy plants are attractive for large scale desalination application. The thermal energy produced in a nuclear plant can provide both electricity and desalted water without the production of greenhouse gases. A particularly attractive option for nuclear desalination is to couple a desalination plant with an advanced, modular, passively safe reactor design. The use of small-to-medium sized nuclear power plants allows for countries with smaller electrical grid needs and infrastructure to add new electrical and water capacity in more appropriate increments and allows countries to consider siting plants at a broader number of distributed locations.

To meet these needs, a modified version of the International Reactor Innovative and Secure (IRIS) nuclear power plant design has been developed for the cogeneration of electricity and desalted water. The modular, passively safe features of IRIS make it especially well adapted for this application. Furthermore, several design features of the IRIS reactor will ensure a safe and reliable source of energy and water even for countries with limited nuclear power experience and infrastructure. The IRIS-D design utilizes low-quality steam extracted from the low-pressure turbine to boil seawater in a multi-effect distillation desalination plant. The desalination plant is based on the horizontal tube film evaporation design used successfully with the BN-350 nuclear plant in Aktau, Kazakhstan. Parametric studies have been performed to optimize the balance of plant design. Also, an economic analysis has been performed, which shows that IRIS-D should be able to provide electricity and clean water at highly competitive costs.

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 nationally, the geographic distribution of water typically is 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)/m^3 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 (RO) 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 because of 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 primary system reactor” (IPSR). A leading IPSR is the International Reactor Innovative and Secure (IRIS) reactor concept. Like other advanced reactor designs, IRIS has a modular design with enhanced safety and economics.[3] For the several reasons described below, IRIS is especially well suited for deployment in countries with small or medium power grids for producing both electricity and fresh water.

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 21 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(t), and with an expected energy conversion of 33.5%, a single IRIS module is capable of producing 335 MW(e) of electrical output and is expected to be sited with multiple units. As stated earlier, IRIS is a member of the IPSR class of designs, which means that all functions of the primary coolant system (steam generators, pressurizer, primary pumps, etc.) are contained within the reactor pressure vessel. A model of the IRIS reactor vessel and internals is shown in Figure 1.

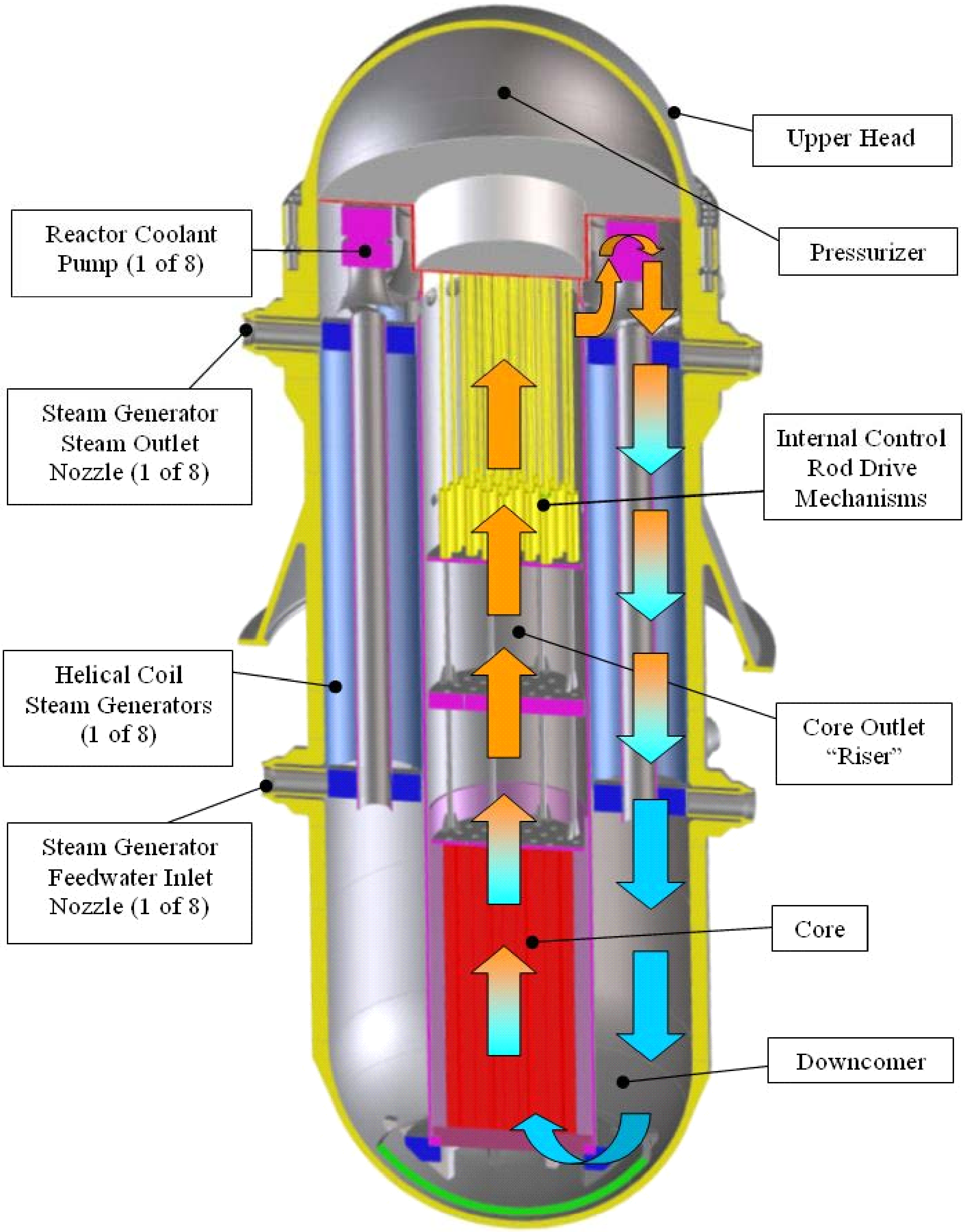

Figure 1. Model of IRIS reactor vessel and primary coolant system.

A unique feature is the safety-by-design™ IRIS philosophy 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. 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 by design. 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 and design iterations on the IRIS safety systems, such as the Automatic Depressurization System (ADS) and the Emergency Heat Removal System (EHRS), the predicted core damage frequency due to internal events,[6] including ATWS (Anticipated Transients Without Scram), is 2×10^{-8}, that is one-to-two orders of magnitude less than for other advanced LWRs.

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

- 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 power plants.
- The international nature of the IRIS project team will help to ensure that the design will be licensable for deployment in the world market.

As will be discussed in a later section, 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.

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:[1]

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 counter-flow 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 primary 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.

The coupling of IRIS to a RO, MSF or MED plant has been explored.[7-8] While all three approaches are viable, it was decided that the reference IRIS-D design will utilize a multi-effect distillation plant because of the extensive experience of OKBM with these types of plants in Russia, where the distillation technology of seawater desalination has been developed and used on a large scale. Research and development activities, performed for several generations of multi-stage evaporation plants, have shown that these plants have considerable advantages in comparison with the plants with flash boiling. This is especially true for plants using horizontal tube evaporators and external film irrigation of tubes, which have good economic performance and are relatively simple to operate and service.

The following issues have been investigated by OKBM for MED desalination plants:

- heat transfer and mass transfer at the heated horizontal tubes; hydraulic and gas-dynamics of tube and inter-tube space; secondary steam separation from evaporated liquid drops; heat transfer intensification by profiling of inside and outside heat transfer surface; water steam drop condensation;
- influence of various factors upon the descaler efficiency for scale formation exclusion on heat transfer surface of the horizontal tube film device and the optimization of the water-chemical conditions for desalination process that minimizes scaling and structural materials corrosive wear;
- various equipment elements strength problems, taking into account influence of various factors including working media corrosive action.

Plants with horizontal tube film evaporators (HTFE) have an advantage over other types of distillation plants from the point of view of thermal and electric energy specific expenses, specific metal content and the overall plant size, i.e. footprint area. The improvement of the characteristics of evaporation desalinating plants, especially for plants with horizontal film evaporators, is related to the use of thermal (steam jet) or mechanical steam compression for these plants, and the creation of hybrid circuits, e.g. the use of flash boiling evaporators as regenerative heaters for such plants.

Three generations of distillation desalinating plants (DDP) have been created in Russia and are widely used in their national economy. The fourth generation is currently under development. The desalinating complex in Aktau, Kazakhstan, which produces more than 120,000 m^3/day output, is equipped with these plants. Also, they operate in the towns of Turkmen-Bashi and Mari in Turkmenistan, Lisichansk and Pervomaiskiy in the Ukraine, Tobolsk and Verkhnia Pishma, Kishtim and Noviy Urengoy, and Novocherkassk in Russia.

Russian distillation desalinating plants are multicolumn plants with the number of stages in each column ranging from 2 to 8. The number of columns and stages is determined on the basis of technical and economic analyses. Of the total volume of desalinated water produced in the world, MED desalination plants generate at present only 10% and the plants with HTFEs even less. But during the past ten years, the increase in output of desalination plants with this type of evaporators has been the highest, and they are considered to have the best prospects for generation of low-cost fresh water.[9]

Figure 2 shows the principal design of the HTFE desalination plant that is proposed for use in the power desalinating complex with IRIS. This design has an output of 840 m^3/h (20,000 m^3/day) per unit.[10-11]

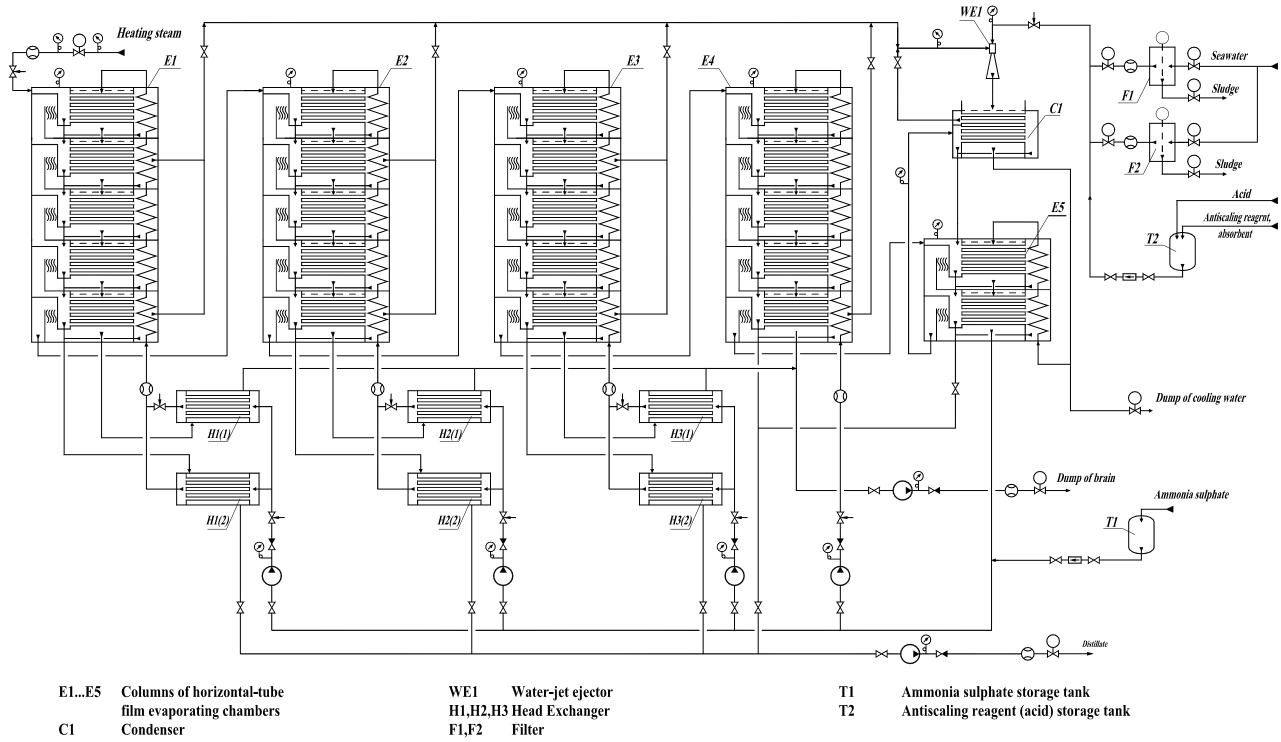

Figure 2. Schematic diagram of Russian desalination plant with horizontal tube film evaporators.

COUPLING OF IRIS REACTOR WITH DISTILLATION PLANT

Coupling IRIS to the DDP requires co-location of the two units with a steam supply loop added between the IRIS secondary system and the DDP. An electrical connection is also required to power the DDP pumps and auxiliary equipment. Because of the direct 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 DDP. Similarly, there would be significant economic impact to the reactor system if brine water from the DDP were to enter the IRIS secondary system. Also, the potential of the DDP operations induce reactor transients must be considered.

An intermediate steam transfer loop is currently included for coupling IRIS to the DDP. The pressure of the intermediate loop is maintained above the pressure of the secondary IRIS loop and the pressure of the seawater loop in the brine heater stage of the DDP so that a failure of the heat exchanger at either end of the intermediate loop will result in an easily detectable pressure drop in the loop and ensure isolation of the fluids in the two plants. 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 flexibility in the operation of both plants.

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, four feedwater heaters, a turbogenerator, and recirculation pumps. The multiple extraction stages of the low-pressure turbine, which provides heat sources for the four feedwater heaters, also enhances the coupling of IRIS to the DDP since there are a range of steam temperatures and pressures conveniently available to drive the intermediate loop to the DDP. A diagram of the coupled IRIS-D plant is given in Figure 3. An intermediate steam loop is added to the low-pressure turbine extraction stage for feedwater heater 4, which provides a 90°C steam supply to the DDP brine heater. The coupling of the intermediate loop with the DDP is shown in Fig. 4.

The parameters of the steam extracted from the low pressure turbine and intermediate circuit depend on the interface circuit with the DDP plant. The following issues were considered in chosing the selected design:

- efficient boiling temperature of sea water at the first evaporation stage;
- structural simplicity of the interface circuit;
- avoiding need for additional development.

Feasibility calculations for the OKBM DDP design indicated that the optimum temperature of sea water boiling in the first stage is in the range of 85-95°C. At these temperatures the efficiency of domestically produced descalers is rather high and the corrosion rate is low. An additional interface circuit was also considered that employs mechanical compressors and three-phase water steam jet compressors. This would allow a decrease in the return water of the intermediate circuit to 60-70°C.

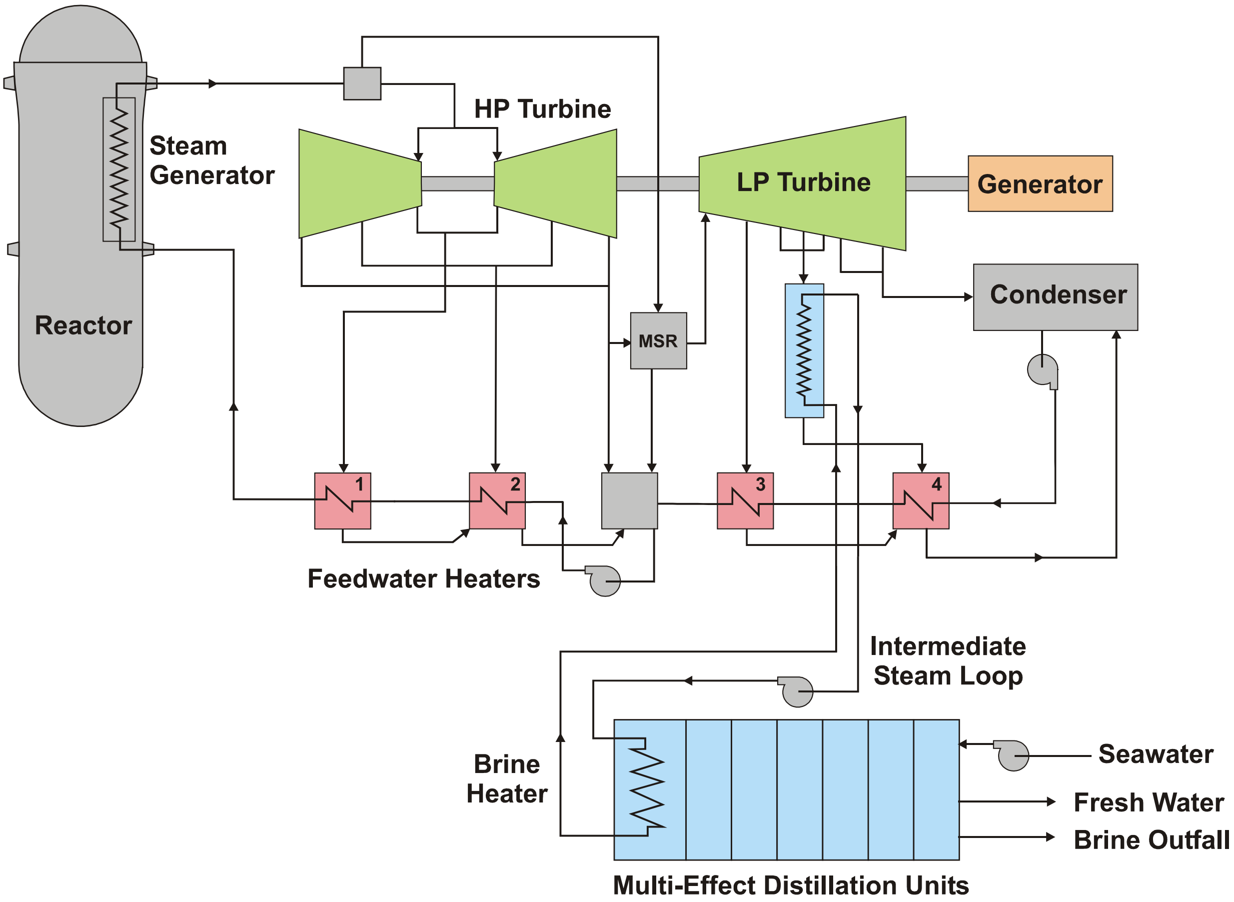

Figure 3. Schematic diagram of IRIS reactor unit interfacing with MED desalination plant.

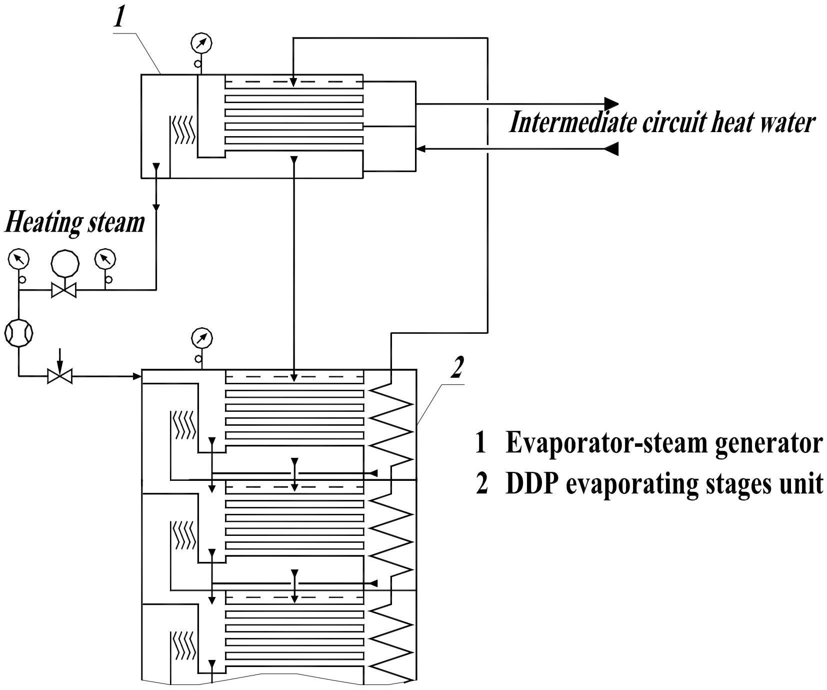

Figure 4. Schematic diagram of the intermediate circuit interfacing with desalination plant.

ECONOMICS ASSESSMENT

The cost of the desalinated water and electric power output from an IRIS-D plant have been calculated using two methods: the Desalination Economic Evaluation Program (DEEP) provided by the IAEA[12] and the Russian TEO-INVEST code. The boundary tariffs for the desalinated water and electricity, the terms of their payback, profit and project profitability coefficient have been determined. These assessments are based on the technical and economic parameters of the IRIS-D nuclear power and desalinating complex given in Table 1.

The estimated costs obtained by various methods are reasonably consistent, as shown in Table 2. For example, with the given interface circuits of IRIS with a GTPA-840 DDP, the prime cost of power generated by IRIS is estimated at 3.0 ¢/kW·h, while in Ref. 13 it is 2.7 ¢/kW·h. The prime cost of desalinated water for the DDP is 0.839 $\$/m^3$ at 140,000 m^3/day output compared with 0.735 $\$/m^3$ in Ref. 13 for a reverse osmosis plant and 1.44 $\$/m^3$ in Ref. 7 for a multi-stage flash distillation plant. When using identical values of the input data, the assessment results of the desalinated water prime cost and of the electric energy prime cost predicted by the DEEP and TEO-INVEST codes are within 5% of each other (see Table 2).

Also listed in Table 2 is the net electrical power supplied to the grid: 279 MW(e). This accounts for house-keeping power requirements for both the IRIS plant and the DDP and the loss of thermal efficiency resulting from the DDP coupling. Hence, the IRIS-D power and desalination complex is capable of producing significant electrical output and fresh water capacity from a single IRIS module and a seven-unit DDP.

Table 1. Key Parameter List for IRIS-D Plant

General Parameters	
Begin operation	Jan. 1, 2015
Discount/Interest rate	8%
Economic lifetime	30 years
IRIS Parameters (per module)	
Thermal power	1000 MW(t)
Thermal efficiency	33.5%
Total electrical power	335 MW(e)
IRIS housekeeping load	10 MW(e)
Total construction cost*	$385,000,000
Specific construction cost*	1155 $/kWh
Average load factor	95%
Construction time	36 months
Annual operating and maintenance cost	$23,000,000
Specific O&M cost	0.008 $/kWeh
Primary pressure	15.5 MPa
Primary inlet temperature	292°C
Primary outlet temperature	328°C
Number of primary circuits	8
Secondary pressure	5.8 MPa
Secondary inlet temperature	317°C
Secondary outlet temperature	224°C
Number of feedwater heaters	4
Desalination Plant Parameters	
Total capacity	140,000 m^3/d
Capacity per unit	20,000 m^3/d
Number of units	7
Plant power consumption	5.2 MW(e)
Intermediate loop power consumption	0.4 MW(e)
Construction cost per unit	$24,000,000
Service life	30 years
Average seawater temperature	28°C
Total dissolved solids	45,000 ppm
Plant load factor	90%
Management personnel cost per person-year	$75,000
Maintenance personnel cost per person-year	$32,000
Specific chemical costs	0.05 $/$m^3$

* - Based on a preliminary top-down economic evaluation

Table 2. Economic Performance of IRIS-D Nuclear Power Desalinating Complex

Electric power supplied to the grid [MW(e)]	279.1
Electric power prime cost (¢/ kW·h) obtained from:	
- IAEA DEEP code	3.0
- Russian TEO-INVEST code	3.0
- Ref. 13 (IRIS+RO plant)	2.7
- Ref. 7 (IRIS+MSF plant)	3.8
Desalinated water prime cost ($/m^3) obtained from:	
- IAEA DEEP code	0.839
- Russian TEO-INVEST code	0.804
- Ref. 13 (IRIS+RO plant)	0.737
- Ref. 7 (IRIS+MSF plant)	1.44

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 a MED desalination plant provides attractive economics for both the electricity and fresh water produced by the coupled power and desalination complex.

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,” *Nucl. Eng. Design 230, pp 151-167 (*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. Finnicum, A. Maioli, Y. Mizuno, J. Viais, G. Mendoza, G. Alonso, IRIS Preliminary PRA Analysis, *Proc. GLOBAL 2003*, November 16-20, 2003, New Orleans, LA, USA.

[7] D. T. Ingersoll, et al, “Nuclear Desalination Options for the International Reactor Innovative and Secure (IRIS) Design,” Proceedings of the 5th Interantional Conference on Nuclear Option in Countries With Small and Medium Electricity Grids, Dubrovnik, Croatia, May 16-20, 2004.

[8] V. I. Kostin, et al, “Nuclear Power Desalinating Complex With IRIS Reactor Plant and Russian Distillation Desalinating Unit,” Proceedings of the 5th International Conference on Nuclear Option in Countries With Small and Medium Electricity Grids, Dubrovnik, Croatia, May 16-20, 2004.

[9] Yu. Panov, V. Polunichev, K. Zverev, “Use of Reactor Plants of Enhanced Safety for Sea Water Desalination, Industrial and District Heating,” IAEA-TECDOC-923 (1997).

[10] Yu. Panov, V. Polunichev, “Equipment and Material for Coupling Interfaces of a Nuclear Reactor With Desalination and Heating Plants Based on Floating NHPS,” IAEA-TECDOC-1056 (1998).

[11] Yu. Panov, V. Polunichev, “Nuclear Head Applications: Design Aspects and Operating Experience,” IAEA-TECDOC-1056, p. 249-262 (1998).

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

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