NUCLEAR POWER DESALINATING COMPLEX WITH IRIS REACTOR PLANT AND RUSSIAN DISTILLATION DESALINATING UNIT

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ABSTRACT

This paper has been prepared as a result of Russian activities on the development of nuclear power desalinating complex (NPDC) with the IRIS reactor plant (RP). The purpose of the activities was to develop the conceptual design of power desalinating complex (PDC) and to evaluate technical and economical indices, commercial attractiveness and economical efficiency of PDC based on an IRIS RP with distillation desalinating plants.

The paper presents the main results of studies as applied to dual-purpose PDC based on IRIS RP with different types of desalinating plants, namely:

- characteristics of nuclear power desalinating complex based on IRIS reactor plant using Russian distillation desalinating technologies;
- prospective options of interface circuits of the IRIS RP with desalinating plants;
- evaluations of NPDC with IRIS RP output based on selected desalinating technologies for water and electric power supplied to the grid;
- cost of water generated by NPDC for selected interface circuits made by the IAEA DEEP code as well as by the Russian TEO-INVEST code;
- cost evaluation results for desalinated water of PDC operating on fossil fuel and conditions for competitiveness of the nuclear PDC based on IRIS RP compared with analog desalinating complexes operating on fossil fuel.

1 INTRODUCTION

Conceptual developments of a power desalinating complex have been performed within the framework of international cooperation of OKBM in the IRIS project.

IRIS – (International Reactor Innovative and Secure) – is a pressurized water modular integral reactor developed by an international consortium under the leadership of Westinghouse.[1,2] Thermal power of the reactor is 1000 MW, and electric power is about 335 MW.

To increase the investment attractiveness of the reactor plant in certain markets, variants of its multipurpose (combined) application for electric energy generation and district heating, or electric energy generation and sea water desalination were considered. The low-potential heat removed at the electric energy generation process is used for the district heating and desalination, thereby considerably increasing the total efficiency of the plant.

Russian distillation desalinating plant with horizontal-tube evaporators with external film tubes irrigation is used in this design. The reactor and desalinating plants are connected through an intermediate circuit.

Feasibility assessment of the power desalinating complex has been performed and the conditions for its competitiveness in comparison with the analogous ones working on fossil fuel have been determined during the development works.

2 SCHEMATIC DIAGRAM OF IRIS REACTOR PLANT INTERFACING WITH DISTILLATION DESALINATING PLANT

The power desalinating complex consisting of an IRIS reactor plant and a Russian distillation desalinating plant (DDP) receiving heat due to the steam extraction from the turbine was selected for consideration.

Transfer of thermal power from the reactor to DDP at minimum losses of temperature difference and the exclusion of possibility that desalinated water may be polluted by radioactivity are the main tasks of the top-level design of a nuclear power desalinating complex and of the development of layout decisions regarding IRIS reactor interfacing with the distillation desalinating plant.

An intermediate circuit in which pressure is higher than in the places of steam extraction and connection with DDP (Fig.1) is used to exclude radioactive pollution at the use of two-circuit power plant in the power desalinating complex with IRIS. The intermediate circuit has two heat exchangers, a pump, pressuriser and pipelines.

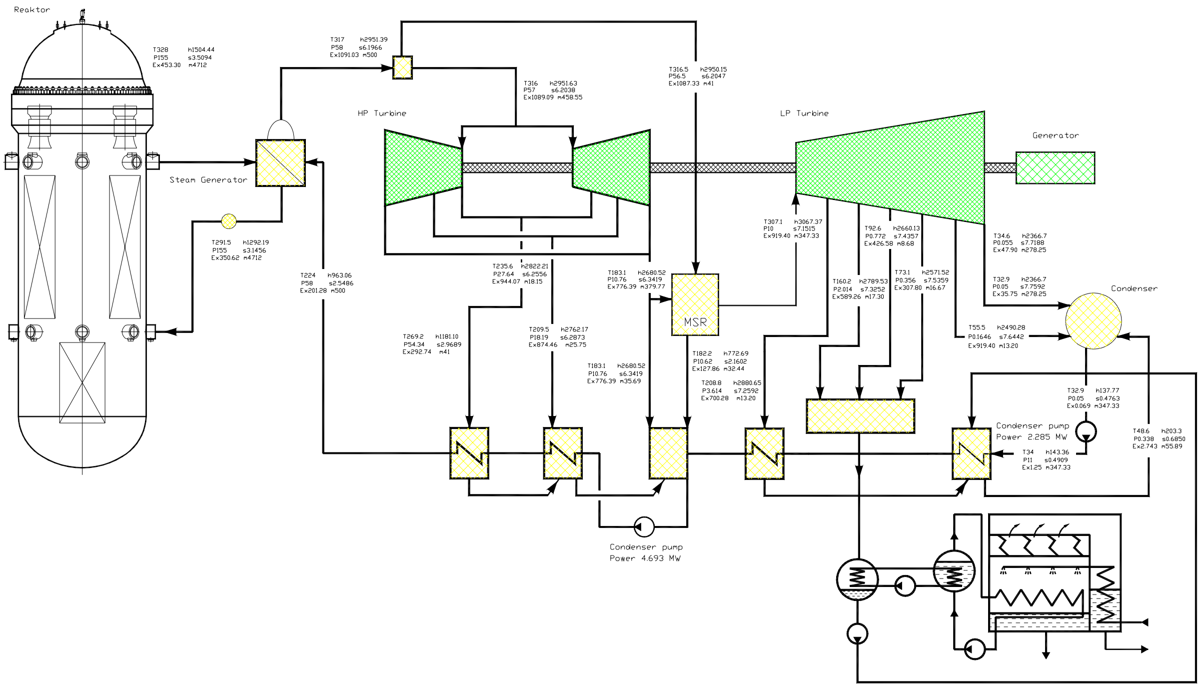

Figure 1. Schematic diagram of IRIS RP interfacing with Russian HTFE DDP.

The parameters of steam extracted from the turbine and intermediate circuit depend on the interface circuit with DDP. The variant was chosen taking into account the following:

- efficient boiling temperature of sea water at the first evaporation stage;
- structural simplicity of the interface circuit;
- possibility of realization without additional investigations.

Feasibility calculations for the conditions of Russia indicated that the optimum temperature of sea water boiling at 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.

As for the embodiment simplicity, Russian DDP designers propose the variant of heat transfer from the intermediate circuit to DDP through the horizontal-tube film evaporator-steam generator (Fig.2). At the adopted sea water boiling temperature at the primary stage this circuit is realized at coolant temperature in the back line of the intermediate circuit not lower than 90°C. In addition to the proposed circuit, another interface circuit was considered, that employs mechanical compressors, three-phase water steam jet compressors, which allow back water decrease in the intermediate circuit to 60-70°C. Even though Russian industry does not fabricate the aforementioned compressors, there is enough engineering knowledge and experience for the realization of the proposed circuit, while the compressors may be fabricated jointly with other IRIS consortium members.

In Russia the distillation technology of sea and salted water desalination have been developed and used on a large scale. Research and development activities, performed for some generations of multi-stage evaporation plants have shown that these plants have considerable advantages in comparison with the plants of momentary boiling. Especially it is attributed to the plants with horizontal tube evaporators with external film irrigation of tubes, having good economical indices and being simple in operation and service.

The following issues have been investigated on these 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 are studied and the organization of the water-chemical conditions for desalination process is developed 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, are solved.

Plants with horizontal tube film evaporators have an advantage in comparison with distillation plants of other types from the point of view of thermal and electric energy specific expenses, specific metal content and the building area. The subsequent improvement of the characteristics of evaporation desalinating plants especially with horizontal film evaporators is connected with the use of thermal (steam jet) or mechanic steam compression for these plants and with the creation of hybrid circuits, for example use of the momentary boiling evaporators as regenerative heaters for such plants.

Three generations of thermodistillation desalinating plants have been created in Russia, which are widely used in the national economy. The fourth generation is currently under creation. The desalinating complex of more than 120000 m^3/day output in Aktau, Kazakhstan, is equipped with these plants. They work 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.

The manufacturing plants of stationary desalinating plants in Russia are "Uralkhimmash" (Ekaterinburg), "Kemerovokhimmash" (Kemerovo), "Atommash"(Volgodonsk), "Penzkhimmash" (Penza).

Of the total volume of desalinated water produced in the world, multi-stage distillation desalinating plants generate at present only 10 % and the plants with horizontal tube film evaporators even less. But in accordance with the estimations of world experts the output increase rate of desalinating plants with this type of evaporators in the last 10 years has been the highest. They are considered as the plants having the best prospects for generation of the cheapest desalinated water [3].

Russian distillation desalinating plants are multicolumn plants with the number of stages in each column from 2 to 8. The number of columns and stages in them is determined on the basis of technical and economical calculations.

Figure 3 shows the principal diagram of the distillation desalinating plant with the output of 840 m^3/h (20 000 m^3/day) on the basis of horizontal tube film evaporators (HTFE) [4 and 5], which is proposed for the consideration in the power desalinating complex with IRIS.

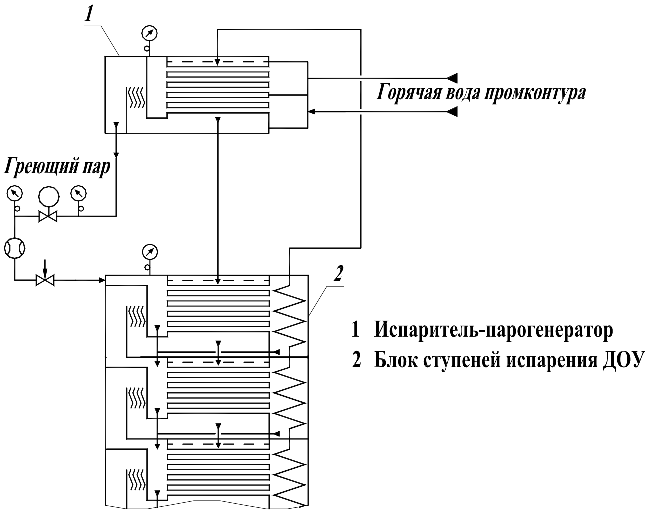

Figure 2. Schematic diagram of the intermediate circuit interfacing with desalinating plant.

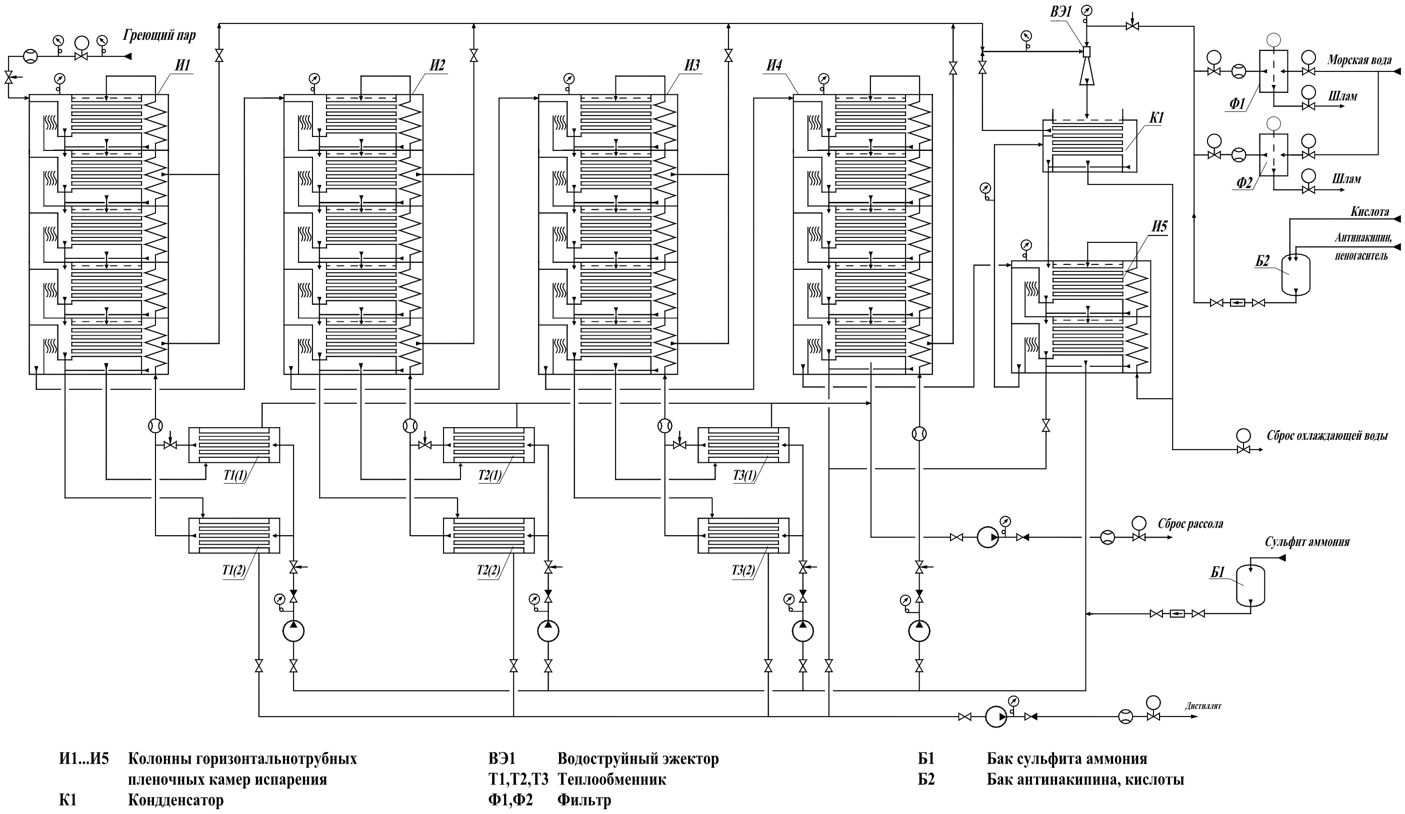

Figure 3. Schematic diagram of Russian DDP with HTFE

This distillation desalinating plant has 22 evaporation stages.

The most important problem for DDP is the protection of equipment heat-exchange surfaces against scale and corrosion. For the protection against scale Russian industry produces descalers PAF-13A, IOMS or SK-110, which are added to the initial sea water. Descaler type is chosen depending on the content of desalinated water. If necessary, a defoamer is added to the desalinated water.

Main structural materials for DDP equipment are: aluminium arsenious brass for heat-exchange tubes in heat-exchangers and condensers; stainless steel for the equipment elements in contact with sea water; and, carbon steel for the remaining elements [3].

3 TECHNICAL AND ECONOMICAL INDICES OF POWER DESALINATING COMPLEXES

3.1 Initial data for technical and economical calculation

The data of ref. 6 are used as initial data for technical and economical calculation, and are listed in Table 1. (Some of the data are based on a preliminary assessment, but were nevertheless deemed appropriate for the purpose of this study.).

Table 1. Main parameters assumed in analysis.

Parameter	Value
1. Reactor plant thermal capacity, MW	1000
2. Rated power output of NPP with IRIS RP, MW	343.4
3. IRIS RP house loads, MW	10
4. NPP with IRIS RP power output supplied to the grid, MW	333.4
5. RP thermal efficiency, %	33.5
6. Reactor type	PWR
7. Primary circuit pressure, MPa	15.5
8. Coolant temperature at core inlet/ outlet, °C	291.5/328
9. Fuel type	UO_2
10. Enrichment, %	4.95
11. Uranium inventory, kg	48500
12. Refueling interval, month	30
13. Number of fuel assemblies in the core	89
14. Number of fuel rods in assembly	264
15. Core power density, kW/l	51.26
16. Steam pressure at SG outlet, °C	5.8
17. Coolant temperature at SG inlet/ outlet, °C	317/224
18. Construction capital costs, mln. $	$385^{\#}$
19. Specific capital costs for NPP with IRIS RP, $/kW·h	$1155^{\#}$
20. Construction period for NPP with IRIS RP, month	36
21. Annual fuel costs, $\$/kW_e$	4.55
22. Annual costs for NPP decommissioning, $/kW·h	1.0
23. Capacity factor	$0.9^{\$}$
24. Credit cost of money, %	8.0
25. Average sea water temperature for RP cooling, °C	28
26. Steam condensation temperature in condenser, °C	32.9
27. DDP specific capital costs, $\$/(m^3$ day)	1200
28. Annual costs for management personnel, thousand $/yr. per person	75
29. Annual costs for maintenance staff, thousand $/yr. per person	32
30. Specific costs for chemicals intended for prior water conditioning, $\$/m^3$	0.03
31. Specific costs for chemicals intended for final water conditioning, $\$/m^3$	0.02
32. DDP service life, yr.	30
33. Chemicals for DDP (for one unit), t/yr.	
- descaler + defoamer	84
- sulfamine acid	56
- sodium alkali	32
- sodium sulfite	6.3
- chlorine	90
32. Salt concentration at DDP outlet, ppm	3

- Based on a preliminary top-down economic evaluation

$ - actual capacity factor expected to be above 96%

3.2 The results of technical and economical assessment of desalinating complex options based on IRIS RP

Resulting from the technical and economic analysis, costs of the desalinated water and NPDC electric power on the basis of IRIS RP with DDP have been calculated according to two methods (IAEA and TEO-INVEST). The boundary tariffs for the desalinated water and NPDC electric energy, the terms of their payback, profit and project profitability coefficient have been determined.

Technical and economical indices of nuclear power desalinating complex based on IRIS RP with DDP are given in Table 2. Two power desalinating complex variants have been estimated:

- 140 000 m3/day desalinated water output (Variant 1)
- 100 000 m3/day desalinated water output (Variant 2).

Table 2. Technical and economical indices of nuclear power desalinating complex based on IRIS RP with DDP

Parameter	Variant 1	Variant 2
1 Power desalinating complex output, thousand m^3/day	140	100
2 Number of desalinating plant units	7	5
3 Desalinating plant unit output, thousand m^3/day	20	20
4 Desalinating plant power consumption, MW	5.21	3.72
5 DP intermediate loop power consumption, MW	0.4	0.28
6 Thermal capacity supplied to DDP, Gcal/h	175	125
7 Loss of thermal capacity of the main turbine of IRIS RP as a result of steam supply to DDP, MW	48.7	33.1
8 Rated electric power of IRIS RP, MW	343.4	343.4
9 IRIS RP house loads, MW	10	10
10 NPP with IRIS RP electric power supplied to the grid, MW	333.4	333.4
11 Power desalinating complex electric power supplied to the grid, MW	279.09	296.30
Technical and economical indices of IRIS RP power unit		
12 Specific construction costs for RP power unit, $\$/\mathrm{kW}_e$	1155$^{\#}$	1155$^{\#}$
13 Capital construction costs for NPP with IRIS RP, mln. \$	385$^{\#}$	385$^{\#}$
14 Electric power prime cost, cent/ kW·h, obtained by: - IAEA DEEP code - Russian code - Ref. 6	 3.0 3.0 2.7	 3.0 3.0 2.7
Technical and economical indices of desalinating unit		
15 Specific construction costs for single power unit of desalinating plant $\$/(\mathrm{m}^3\ \mathrm{day})$	1200	1200
16 Capital construction costs for desalinating plant (including intermediate loop, structures for water intake and discharge)	192.7	142.01
17 Desalinated water prime cost $\$/\mathrm{m}^3$, obtained by - IAEA DEEP code - Russian code - Ref. 6 (for back osmosis)	 0.839 0.804 0.737	 0.852 0.815 -

- Based on a preliminary top-down economic evaluation

The estimated cost obtained by various methods is rather consistent. For example, in the given interface circuits of IRIS RP with GTPA-840 DDP, the prime cost of power generated by IRIS RP is estimated at 3 cent/kW·h, while in ref. 6 it is 2.7 cent/kW·h. Desalinated water prime cost for DDP is 0.839 $\$/\mathrm{m}^3$ at 140 000 m^3/day output, in ref. 6 for back osmosis it is 0.735 $\$/\mathrm{m}^3$. At DDP output decrease to 100 000 m^3/day, desalinated water prime cost increases to 0.852 $\$/\mathrm{m}^3$. When using identical values of the input data, the assessment results of the desalinated water prime cost and of the electric energy prime cost as per the DEEP and TEO-INVEST codes are within 5 % of each other, see Table 2).

3.3 Competitiveness conditions of nuclear power desalinating complexes compared with PDC using fossil fuel.

3.3.1 The comparison using the DEEP code for several options

The comparison was made using the DEEP code for the following options
- NDPC on the basis of two KLT-40S RPs and HTFA DDP-type distillation plants;
- desalinating complex with DDP using boiler on black oil and coal;

In addition, the comparative analysis using TEO-INVEST code has been performed for the following options:
- NDPC on the basis of two KLT-40S RPs and HTFA DDP-type distillation plants;
- co-generation plant with steam-gaseous plant (SGP) operating on natural gas.

In these analyses, the power sources indices were compared at accepted identity of type of desalinating plants and their interface circuits with power sources.

3.3.2 Comparison of the results of calculations, performed by the DEEP code.

The NPDC was compared with PDCs burning fuel oil and coal under comparable conditions: equal electric power of PDC, equal plant capacity factor and identical desalinating method.

The prime cost of desalinated water was considered as competitiveness criterion.

The comparative analysis showed that nuclear PDC with IRIS RP could compete with PDC burning fossil fuel under the following conditions (no account of the charge for ecological damage due to fissil fuel burning):
- at fuel oil cost more than 70 \$/t (for boiler burning fuel oil);
- at coal cost more than 46 \$/t (for boiler burning coal).

The international journal World Energy Outlook IEA for 1998 year predicts that the world market costs of energy resources will exceed these boundary values already by 2010, therefore, IRIS with its targeted deployment starting in the 2012-2015 period should from the beginning be a cost-effective.solution.

3.3.3 Comparison of results of calculations by TEO-INVEST code.

Results of assessment determining NPP competitiveness conditions compared with SGP of the similar power level are expressed in the lower boundaries of specific capital cost values for construction of co-generation plant with SGP and cost of fossil fuel. Above this boundary the notorious advantage of NPP over SGP is ensured (see Table 3).

Table 3. Boundary conditions for NPP competitiveness compared with the same of SGP.

NPDC type	Conditions for competitiveness of NPP	
NPP on the basis of IRIS	Specific capital costs for SGP	≥ 850 \$/kWe
	Gas cost	≥ 70 \$/thousand m^3
	Gas flow rate	≥ 205 g/kW·h
	Specific capital costs for SGP	≥ 850 \$/kWe
	Gas cost	≥ 55 \$/thousand m^3
	Gas flow rate	≥ 205 g/kW·h

It follows from the comparison that at the world market prices of the natural gas, exceeding 70 \$/thousand m^3, all considered nuclear options provide essential advantage over SGP for generated electric power cost that automatically provides the advantage for the desalinated water cost at same other conditions. Additional advantage for nuclear may be achieved if the NPP construction and/or nuclear fuel supply within the IRIS consortium include design and fabrication activities performed by Russian companies, which are expected to be able to provide these services at the costs competitive and lower than the world ones.

Accounting for the environmental impact of power source on fossil fuel further intensifies the advantage of a nuclear-based PDC.

CONCLUSION

Within the IRIS team design activities of a dual-purpose (electricity-desalination) power plant, the Russian participants have performed the following activities:

- Analysis of technological parameters and characteristics of nuclear power desalinating complexes based on the IRIS reactor plant and desalinating (distillation with devices of HTFA-type) plants was carried out.
- Advanced interface circuits of IRIS plant with distillation desalinating plants of HTFA-type were selected.
- Necessity to develop steam generation circuit equipment being a part of the selected interface circuit for HTFA distillation desalinating plant in conformity with IRIS RP was revealed.
- Productivity of NPDC nuclear desalinating complexes based on the selected reactor and desalinating technologies by water and power supplied to the grid was evaluated.
- Cost of generated water for the selected interface circuits by IAEA DEEP code as well as by Russian TEO-INVEST code was evaluated.
- Cost of desalinated water of PDC burning fossil fuel was evaluated and competitiveness of nuclear PDC with IRIS RP was determined.
- Optimization of parameters of NPDC based on IRIS RP aimed to improve performance characteristics is carried out.

Based on the predicted cost of fossil fuels (gas and coal) beyond 2010, this preliminary analysis has demonstrated that a desalination complex employing IRIS will be economically attractive from its initial deployment, which is targeted for the 2012-2015 timeframe.

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