Optimization of the Coupling of Nuclear Reactors and Desalination Systems
--- Report on the IAEA Coordinated Research Program ---

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Energy and water are essential elements for human existence. Increasing demands worldwide, especially in the developing world, are being intensified both in energy and in freshwater. In many developing countries, the option of combining nuclear energy with seawater desalination is being explored to tackle these two problems.

In 1998, the International Atomic Energy Agency (IAEA) launched a Coordinated Research Project (CRP) on the "Optimization of the Coupling of Nuclear Reactors and Desalination Systems", with the participation of research institutes from interested IAEA Member States. The Research Project focused on the following four main topics:

1) Nuclear reactor design intended for coupling with desalination systems
2) Optimization of thermal coupling of NSSS and desalination systems
3) Performance improvement of desalination systems for coupling
4) Advance desalination technologies for nuclear desalination

The current CRP has been evaluating various coupling configurations of nuclear reactors and desalination systems. Reactor types evaluated in the optimization include a PHWR, PWRs and dedicated heat reactors. The present paper summarizes the overall findings in the CRP, highlighting design optimisation, safety and some economic considerations.

KEYWORDS: nuclear, heat application, desalination, freshwater, demonstration, economics

I. Introduction

There are many reasons which favour a possible revival of the nuclear power production in the years to come: the development of innovative reactor concepts and fuel cycles with enhanced safety features which are expected to improve public acceptance, the production of less expensive energy as compared to other options, the need for prudent use of fossil energy sources, and the increasing requirements to curtail the production of greenhouse gases (GHG), toxic gases, particulates and acid rain, which are all associated with the combustion of fossil fuels.

It is thus expected that this revival would also lead to an increased role of nuclear energy in non-electrical energy services, which, at the moment, are almost entirely dominated by fossil energy sources. Among various utilization of nuclear energy for non-electrical products, using it for the production of freshwater from seawater (nuclear desalination) has been drawing broad interest in IAEA Member States as a result of acute water shortage issues in many arid and semi-arid zones worldwide.

The IAEA's Options Identification Programme (OIP) identified in 1996 several sets of practical technical options for demonstration of nuclear desalination leading to eventual commercial deployment under country-specific conditions.

In 1998, the IAEA initiated a co-ordinated research project (CRP) on "Optimization of the coupling of nuclear reactors and desalination systems" with participation of institutes from nine countries in order to share relevant information, optimize the resources, and integrate related R&D efforts in this area.

This CRP has been examining feasible coupling configurations of nuclear and desalination system for better performance and improved economics. As experience shows, various nuclear reactors can be used as an energy source for heat application purposes. In addition the CRP investigates various reactor types as an option for nuclear desalination. Performance improvement of desalination systems for coupling and advance desalination technologies for nuclear desalination has also been assessed.

The present paper summarizes the overall findings in the CRP, highlighting design optimisation, safety and some economic considerations.

II. Objectives and Scope of the CRP

An IAEA CRP is a tool, which is effectively used to promote exchange of scientific and technical information and implement collaborative research and development in

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1 The paper is prepared by contributions of all Chief Scientific Investigators of the CRP: Mr. N.Masriera (INVAP, Argentina), Mr. J.R.Humphries (CANDESAL, Canada), Mr. H.J. Jia (INET, China), Mr. M.M.Megahed (Scientific coordinator of CRP, NPPA, Egypt), Mr. B.M.Misra (BARC, India), Mr. A.Rusli (BATAN, Indonesia), Mr. Y.D.Hwang (KAERI, Republic of Korea), Mr. M.Tabet (CNESTEN, Morocco), Mr. Y.Baranaev (IPPE, Russia) and Mr. H.Ben-Kraiem (CNSTN, Tunisia).
nuclear technology. The primary objective of this particular CRP is for selected Member States to share relevant information and resources in research activities with respect to those technical features, which have a major impact on performance, economic competitiveness and reliability of nuclear desalination plant concepts.

The overall scope of this CRP is to encompass research and development programmes focused on optimized coupling of nuclear and desalination systems in the following major areas:

- Nuclear reactor design intended for coupling with desalination systems
- Optimization of thermal coupling of NSSS and desalination systems
- Performance improvement of desalination systems for coupling
- Advance desalination technologies for nuclear desalination

The CRP will enable the IAEA and participating institutes to accumulate relevant information on the latest research and development in the field of nuclear desalination and share it with interested Member States. The CRP is expected to produce the best coupling configurations of nuclear and desalination systems, to evaluate their performance and to identify technical features, which may require further assessment for detailed specifications of large-scale nuclear desalination plants.

### III. Reactor Concepts for the Coupling

This CRP examined the optimal coupling configurations of nuclear reactors and desalination systems using different reactor types (Fig. 1). Desalination systems considered were: Multi-stage Flash (MSF), Multi-Effect Distillation (MED) and Reverse Osmosis membrane technology (RO).

![Fig. 1 Nuclear reactors examined for optimal coupling with desalination systems](image)

The design approaches for a nuclear desalination plant are essentially derived from those of the nuclear reactor alone, with some additional aspects to be considered in the design of a desalination plant and its integration with the nuclear system. All nuclear reactor types can provide the energy required by the various desalination processes. The amount of energy (heat or electricity) needed for desalination can be readily supplied by tapping the low-grade steam and/or electricity produced by the nuclear plant. In this regard, it has been shown that Small and Medium Reactors (SMRs) offer the big potential as coupling options to nuclear desalination systems.

### IV. Contents of Research Programmes

The following is an overview of objectives and target products of individual research programmes of participants.

INVAP, Argentina, contributed to the CRP with an objective of developing a flexible modelling tool, DESNU, helpful for evaluating nuclear desalination systems from the safety point of view. Specifically it prepares input files for running RETRAN for evaluating accidental sequences transferring radioactive substances of the reactor cooling system to the water desalination system and eventually to the product water. It contains in its built-in tables optional models of MSF, MED and RO for desalination processes coupled with the balance of plant of an SMR (in principle, a small integral PWR). The scope of all the models were optimised in order to adequately focus on the “residence time per component”, as relevant to the convective phenomena over which the contamination is spread, while minimising the input data requirement from the USER.

RO membrane permeabilities are improved as feedwater temperature into the system is increased. This results in the possibility of “preheating” the feedwater temperature above ambient seawater temperature, thereby giving the potential to reduce the cost of water production. CANDESAL, Canada, expanded this technology by exploring the possible use of low grade waste heat from the nuclear steam supply system using an advanced RO system design technology. CANDESAL carried out a series of experiments using a newly installed test rig in order to experimentally verify its proposed design and operating methodology.

Institute of Nuclear Energy Technology (INET) at Tsinghua University, China, has been developing a dedicated nuclear heating reactor of versatile capacities e.g., 5, 10, 200 MW(th). The objective of the research programme in the CRP is to define an optimized coupling scheme, parameters and performances for an integrated nuclear desalination plant using a 200MW(th) NHR as an energy source. Comparative assessment has led to the selection of a high temperature vertical tube evaporation multi-effect desalination (VTE-MED) scheme for the in-depth examination.

Based on the findings and recommendations of the OIP, Nuclear Power Plants Authority (NPPA), Egypt, decided to construct an experimental RO facility at its site in El-Dabaa to validate the concept of feedwater preheating. NPPA research project has the following objectives:

- Overall: to investigate experimentally whether the preheated feedwater can be realized in actual operation.
- Short-term (~3 years): to study the effect of feedwater
temperature and pressure on RO membrane performance over a range of temperatures (20-45°C) and pressures (5.5-6.9 MPa).

- Long-term: to study the effect of feedwater temperature and pressure on RO membrane performance as a function of time.

Bhabha Atomic Research Centre (BARC), India, is undertaking a nuclear desalination demonstration project at Kalpakkam to set up a hybrid 6300 m³/d (4500 m³/d MSF and 1800 m³/d SWRO) sea water desalination plant coupled with two units of 170 MW(e) PHWRs at the Madras Atomic Power Station (MAPS). The requirements of seawater, steam and electrical power for the desalination plants are met from MAPS I & II which are around 1.5%, 1.0% and 0.5% of that available at MAPS. The hybrid plant has provision for redundancy, utilization of streams from one to other and production of two qualities of products for their best utilization. The project has the main objective of demonstrating the capability for design, fabrication and operation of large size future plants.

The research in the framework of this CRP has the main objective of collecting relevant data for improving the hybrid desalination system performance using experimental facilities. The facilities and experiences of 425 m³/d MSF pilot plant, 30 m³/d Low Temperature Evaporation (LTE) pilot plant at Trombay are being used for the studies and prediction of performance of a hybrid system to be installed on the Kalpakkam demonstration plant. The LTE facility is connected to the experimental reactor CIRUS for using its low grade waste heat. The 100 m³/d seawater reverse osmosis (SWRO) pilot plant with an energy recovery turbine provides useful data. It has a provision of testing various types of membrane elements at different temperatures to collect data for preheat RO. A ultrafiltration (UF) pretreatment system has been recently installed in this plant.

National Atomic Energy Agency (BATAN) in Indonesia initiated a pre-feasibility study of an integrated nuclear desalination plant on its island MADURA, east of Java, in 2000. The research programme in this CRP started initially intending to generate a co-production plant concept, which can contribute to this pre-feasibility study. Since the agreement was reached between BATAN and KAERI, Republic of Korea, to implement the study jointly under the IAEA TC programme, the research programme shifted its focus to basic experimental investigation of desalination process for improving its performance. For example, biofouling phenomena in membranes were simulated as a function of organic absorbents in feedwater.

The Korea Atomic Energy Research Institute (KAERI), Republic of Korea, is setting a set of optimum coupling parameters between its newly designed small size co-generating reactor SMART and the desalination facility for the water production capacity of 40,000m³/day and the electricity generation of about 90MW. SMART is an integral type advanced pressurized water reactor with a rated thermal capacity of 330MW. The research programme in CRP is being conducted to define the best coupling option between SMART and desalination system and to establish a set of optimal coupling parameters and their interfacing conditions for the selected coupling option.

The Moroccan Centre National de l’Energie des Sciences et des Technique Nucleaires (CNESTEN) joined the CRP in 2001 with the objective of investigating the optimal coupling of nuclear reactors and desalination systems for Moroccan sites, taking into account the energy and water demand and with emphasis on a new generation SMR.

In the Russian Federation Institute of Physics and Power Engineering (IPPE) is taking an initiative in coordinating four institutes (IPPE, OKBM, RDIPE and JSC “Malaya Energetica”) in a research programme to investigate effective utilization of Russian SMRs for a nuclear desalination complex. Nuclear reactors being evaluated as the energy source for the desalination plant are: (i) a barge-mounted co-generating reactor KLT-40C; (ii) an integrated small PWR NIKA-70; and (iii) a dedicated heating reactor RUTA. Various coupling configurations have been technically and economically evaluated. For economic evaluation the IAEA software DEEP was used with necessary modifications.

Construction of a pilot plant based on a floating power unit (FPU) with KLT-40C reactors is planned for 2005-2006. The co-generation plant will be sited at the shipyard in Severodvinsk, Arkhangelsk Region, in the western North Sea area, where the FPU is being manufactured. The project will provide full-scale demonstration of nuclear technology suitable also for nuclear desalination.

Centre National des Sciences et Technologies Nucleaires (CNSTN) of Tunisia intends through the selection of a suitable desalination process in the country for coupling with a nuclear reactor in the framework of this CRP to develop human resources. Main focus is being placed on comparative economic assessment of possible coupling combinations of nuclear reactors and desalination process using the IAEA software DEEP.

V. Some Highlights of Results

5.1. Optimized Configuration and Performance

In the research programme at INET a nuclear seawater desalination plant, which couples a VTE-MED process with a natural circulation nuclear heating reactor, was studied. A dual-tower stacked VTE-MED test unit has been installed at INET with the designed top brine temperature of 120°C, raw seawater mass flow rate of 3300 kg/h and the freshwater production rate of about 240 kg/h. The main equipment and flow schematic diagram of the test unit are shown in Fig. 2.
transfer characteristics and the distillation process have been carried out on the test unit under the real thermal-hydraulic parameters.

![Fig. 2 Schematic diagram of the test unit at INET](image)

Fig. 2 Schematic diagram of the test unit at INET

Optimal coupling concept of the integrated SMART nuclear desalination plant was developed at KAERI. In the coupling of a desalination system with SMART, the safety and economy were taken into account as the most important factors.

The desalination plant consists of 4 units (unit water production capacity: 10,000 m³/day) of MED-TVC process and coupled with SMART through the intermediate heat transfer loop (steam transformer). The major coupling parameters and the interfacing conditions were optimized through sensitivity studies on water production cost and the thermal performance of the coupling system.

Also, an analysis on water production costs and a safety assessment of the potential disturbances of the integrated nuclear desalination plant was conducted. The analysis result on water cost shows that the calculated water production costs are in the range comparable to or more economically than the other options. Any possible transient events of the desalination system do not give adverse impacts on the reactor safety. The safety analyses of SMART show that the key safety parameters for transients caused by the potential disturbances of the desalination plant are well within the safety limits and the system remains in a safe stable state.

5.2. Safety Considerations

Although the coupling of a desalination system to a nuclear power plant is unlikely to introduce any additional risk in terms of reactor safety, it is still a major plant modification and a review of the safety analysis of the plant is needed. This implies verifying that the coupling does not introduce an unacceptable path for radiological contamination towards the critical group, which requires both deterministic and probabilistic analysis. The deterministic assessment could be made by different procedures, analytical or computer-based, but there are clear advantages by using an approach close in style and tools to the safety assessment of nuclear power plants. Therefore it is reasonable to analyse the use of the codes most widely used in nuclear safety analysis, RETRAN for instance.

DESNU modelling tool enables to produce RETRAN input files for the modelling of an NDP without requiring specialised knowledge. The input parameters of the spreadsheet are mainly operational and geometrical data easily available, and the model produced has a coherent nodalization allowing conceptual assessment of NDP designs.

INVAP, Argentina, provided application results for a generic design, but the production of models for safety analysis and licensing is plant specific and to be done by the USER with experience and specialisation, both on modelling and on safety. DESNU is effectively reviewed by its application to specific projects at KAERI (Republic of Korea), BARC (India) and IPPE (Russian Federation).

5.3. Experimental Verifications

Preliminary calculations carried out at NPPA foresee that the utilization of pre-heated feedwater will lower the operating pressure necessary to produce a certain permeate flow rate, as shown in Fig. 3.

![Fig. 3 Feedwater Pressure versus Temperature for a permeate flow rate (NPPA)](image)

Fig. 3 Feedwater Pressure versus Temperature for a permeate flow rate (NPPA)

Despite the increase in feedwater salinity, product water quality will meet WHO standards. This will lead to significant economic benefits if the pre-heating will have no adverse effects on membrane lifetime. A test facility is being constructed at El-Dabaa, Egypt, which will provide useful information to verify these features.

Experimental results from the demonstration testing carried out using the test rig installed at CANDESAL Inc. have behaved as expected based on analytical performance.
models, validating the advanced design concept and confirming that the performance improvements indicated by the analyses can be achieved in operating systems. The results of the testing are displayed in Fig. 4, which shows significant increases in permeate production for a fixed feedwater flow as feedwater temperature and pressure are increased. Although not illustrated on the figure, permeate TDS remained below 500 ppm throughout the test sequences. Further demonstration testing is planned using a 1000 m$^3$/d containerized system, currently under design, coupled to an existing nuclear power reactor.

![Fig. 4 Permeate production vs. feedwater temperature and pressure](image)

Salient performance of an MSF-RO hybrid desalination system is being demonstrated at the demonstration facility connected to two units of PHWRs at Kalpakkam, India.

The SWRO plant, which is already commissioned, operates at relatively lower pressure (5.1 MPa during the 1st year and 5.4 MPa during the 3rd year) to save energy, employs lesser pre-treatment (because of relatively clean feed water from MAPS outflow) and aims for longer membrane life resulting in lower water cost. The MSF plant which is in advanced stage of completion is designed for higher top brine temperature with Gain to Output Ratio (GOR) of 9:1 and utilizes less pumping power (being long tube design)\(^1\).

Figure 5 shows a view of SWRO membrane modules at Kalpakkam.

![Fig. 5 View of SWRO membrane modules at Kalpakkam](image)

The design parameters and operating data of SWRO plant during the two months in early 2003 are given in Table 1.

### Table 1 Design values & operating data of 1800m$^3$/d SWRO plant, NDDP

<table>
<thead>
<tr>
<th>Design values</th>
<th>Operating data during 1st one month of commissioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treated water quality</td>
<td></td>
</tr>
<tr>
<td>• NTU&lt; 0.5</td>
<td>• NTU&lt; 0.2</td>
</tr>
<tr>
<td>• SDI&lt; 3.0</td>
<td>• SDI&lt; 3.0</td>
</tr>
<tr>
<td>• ORP reading&lt;160 mV</td>
<td>• ORP reading&lt;160 mV</td>
</tr>
<tr>
<td>• pH: 6.5</td>
<td>• pH: 6.5</td>
</tr>
<tr>
<td>• Temperature&lt; 35°C</td>
<td>• Temperature&lt; 35°C</td>
</tr>
<tr>
<td>RO section parameters</td>
<td></td>
</tr>
<tr>
<td>• Feed TDS: 35,600 ppm</td>
<td>• Feed TDS: 24,000-35,000ppm</td>
</tr>
<tr>
<td>• Recovery: 35 %</td>
<td>• Recovery: 35 %</td>
</tr>
<tr>
<td>• Working Pressure: 5.1 MPa after 3</td>
<td>• Working Pressure: 3.8 – 4.6 MPa @ 28°C.</td>
</tr>
<tr>
<td>ro years @ 30°C</td>
<td></td>
</tr>
<tr>
<td>Permeate quality</td>
<td></td>
</tr>
<tr>
<td>• TDS: 100 – 140ppm</td>
<td>• TDS: 100 – 140ppm</td>
</tr>
<tr>
<td>• pH: ~ 5.5</td>
<td>• pH: ~ 5.5</td>
</tr>
<tr>
<td>Product quality (after post-</td>
<td></td>
</tr>
<tr>
<td>treatment)</td>
<td></td>
</tr>
<tr>
<td>• TDS: &lt; 500ppm</td>
<td>• TDS: 150 – 230ppm</td>
</tr>
<tr>
<td>• pH: 7.5-8.0</td>
<td>• pH: 7.5-8.0</td>
</tr>
<tr>
<td>• LSI: Slightly positive.</td>
<td>• LSI: -0.3 at pH: 7.7</td>
</tr>
</tbody>
</table>

Energy Consumption

- 6 kW-hr/m$^3$
- ~ 5.0 kW-hr/m$^3$

Figure 6 shows the arrangement of the MSF modules at Kalpakkam.

![Fig. 6 Layout of 4500 m$^3$/d MSF Desalination Plant](image)

### 5.4. Economic Evaluation

Utilization of the FPU with KLT-40C reactors is considered in Russia as most realistic to implement a nuclear desalination plant (NDP) based on Russian nuclear technology.
Construction of a Floating Power Unit (FPU) pilot plant with KLT-40C reactors is planned for 2006. The co-generation plant will be sited at the shipyard in the western North Sea area where the FPU is being manufactured. Table 2 shows main technical characteristics of the FPU.

**Table 2** Main technical characteristics of FPU

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Number of reactors</td>
<td>2</td>
</tr>
<tr>
<td>2. Reactor type</td>
<td>KLT-40C/PWR</td>
</tr>
<tr>
<td>3. Reactor thermal capacity, MW</td>
<td>2x150</td>
</tr>
<tr>
<td>4. Steam generating capacity, t/h</td>
<td>2x240</td>
</tr>
<tr>
<td>5. Installed power of turbine generator, MWe</td>
<td>2x35</td>
</tr>
<tr>
<td>6. Saleable power in co-generation mode, MWe</td>
<td>2x32.5</td>
</tr>
<tr>
<td>7. Maximum saleable power, MWe</td>
<td>2x30</td>
</tr>
<tr>
<td>8. Heat supplied to district heating system, Gcal/h</td>
<td>2x25</td>
</tr>
</tbody>
</table>

A project of a nuclear desalination complex with an FPU is under development in the frame of a Russian-Canadian Project. The project is based on Russian nuclear technology and Candesal’s advanced RO desalination process and equipment. Figure 7 shows one of several coupling options of hybrid scheme under consideration.

**Table 3** Water cost for different coupling options

<table>
<thead>
<tr>
<th>Water Plant Capacity (m³/day)</th>
<th>Desalination Process</th>
<th>Water Cost ($/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120,000 m³/day: Hybrid</td>
<td>RO_1</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>RO_2</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>RO_3</td>
<td>0.61</td>
</tr>
<tr>
<td>180,000 m³/day: Hybrid</td>
<td>RO_1</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>RO_2</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>RO_3</td>
<td>0.60</td>
</tr>
<tr>
<td>240,000 m³/day: Hybrid</td>
<td>RO_1</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>RO_2</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>RO_3</td>
<td>0.60</td>
</tr>
<tr>
<td>300,000 m³/day: Hybrid</td>
<td>RO_1</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>RO_2</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>RO_3</td>
<td>0.59</td>
</tr>
</tbody>
</table>

- The hybrid system has an MED (40,000 m³/d) and RO.
- RO_1 receives heat from the FPU condensers,
- RO_2 receives heat from the FPU condensers and from the steam turbine extractions
- RO_3 receives heat from the steam turbine extractions.

The combination of FPU+Hybrid gives the lowest Water Cost and Maximum Power to the Grid.

**VI. Overall CRP Conclusion**

Interest in nuclear desalination has been growing in many Member States over the past decades as one of the feasible means to tackle the issue of freshwater shortages in arid and semi-arid regions around the world. Many IAEA Member States initiated relevant R&D programmes for investigating its feasibility under country-specific conditions.

This paper discussed results and progress of a CRP launched as the first IAEA CRP on nuclear desalination in 1998 and facilitated to share the relevant information, optimize the resources, and integrate related R&D efforts by several institutes from interested IAEA Member States. In the course of the CRP, participants performed design optimization of the coupling configuration of various nuclear reactors and desalination systems, thermal-hydraulic performance and safety analyses as well as economic assessment of the selected coupling configuration, and experimental verification of selected desalination processes.

Reactor types evaluated include PWRs, PHWRs and NHR. Overall findings of the CRP include the following.

- Optimum heat extraction conditions for the desalination system have been determined for each combination of the reactor and the desalination system considered.
- Safety analyses have shown that no adverse transients of the integrated system are foreseen beyond the safety map of the nuclear system itself.
- A spreadsheet-base modelling tool has been developed for preparing input files for the conceptual analysis of
possible carryover of radioactive substances from the nuclear reactor to the product water.

- Experimental verification of the performance improvement of the RO process is being attempted by providing preheat feedwater to the system in order to utilize low grade waste heat of the nuclear system.

The CRP has confirmed the technical potential of the integrated nuclear desalination system using water-cooled reactors (PWR, PHWR and NHR). The next step will be to evaluate economic optimization under country-specific conditions. Technical evaluation of other reactor types for nuclear desalination application is also a topic of interest.

References

7) B.M. Misra and H.K. Sadhukhan, “National programmes and activities on nuclear desalination in India”, IAEA Symposium on Desalination of Seawater, Taejeon, Republic of Korea (May 1997)
10) Alicia S. Doval and Nestor A. Masriera, “Analysis of desalination system models relevant for the safety evaluation of a nuclear desalination plant”, IDA World Congress on Desalination and Water Reuse, San Diego (September 1999)