Benchmarking and validation of the Desalination Economic Evaluation Code DEEP/V3.1

By

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1. INTRODUCTION

The IAEA Desalination Economic Evaluation Programme (DEEP) was issued as a user-friendly version towards the end of 1998. DEEP is the modified version of the desalination cost evaluation package developed in the eighties by General Atomics and named "Co-generation and Desalination Economic Evaluation" Spreadsheet, CDEE. Although, initially developed for a quick, order of magnitude, assessment of a nuclear or fossil energy based desalination system, over the years DEEP has truly become an international reference code for the techno-economic evaluation of integrated desalination systems.

DEEP software has been under continuous evolution. and consistent development for the last ten years. The earlier concepts of nuclear energy systems have been modified considerably. New concepts have been proposed and analyzed. Similarly, fossil fuelled systems have also undergone important changes due to the integration of various innovations made. Desalination systems have also undergone an asymptotic development in their design.

During the initial development of DEEP, the input data on power costs of electricity producing systems was hastily collected from the analysis of a series of questionnaires sent from the IAEA to Member States which were involved at that time in the feasibility studies of nuclear and fossil energy based power production systems. This input cost data has remained more or less unchanged in the subsequent versions of DEEP. Therefore, modifications and updates have been recognized by DEEP users and were the subject of various IAEA activities. Indeed, such modifications inspired consecutive updates of DEEP itself.

Through the previous years, DEEP was updated constantly within DEEP-1 family (versions 1.0, 1.1, 1.2 and working version 1.7). Both the user interface and model structure were further developed and in 2000 a new upgrade – first version from the DEEP-2 family was released. Its salient feature was the complete modularization of various cases. As the user group enlarged, new ideas as well as criticisms of the DEEP models appeared. Some of them were implemented gradually in different working versions (versions 2.0, 2.1, 2.2, 2.3, 2.4, 2.6). The four year period of continuous development culminated in the development of DEEP 3.0, released in August 2005. Following further development, the latest version of DEEP 3.11 was released in 2007. In fact, most of the of the suggested modifications focused on DEEP models and not much on input data.

It is for such reasons that the IAEA continues to take steps to improve DEEP performance. In its last meeting, the IAEA International Nuclear Desalination Advisory Group (INDAG) strongly recommended that a new activity on DEEP benchmarking and validation be undertaken. The basic motivations for this activity were:

- To harmonize DEEP utilisation, through the exchange of information on DEEP results by as large a group of DEEP users as possible.
- To define, calculate, and analyse few reference DEEP cases by selected experts and compare with results of other benchmark participants.
- To suggest correction or modifications to models in DEEP based on the above analyses.
- Finally, to validate DEEP with known and reliable results or measurements in operating desalination systems.

During the first consultancy meeting held in 2007, a reference benchmark problem was elaborated by experts from Egypt, France, India, Syrian Arab Republic and the United States. A road map was subsequently discussed. This road map is shown in figure 1.

A second consultancy meeting was held in 2008. The DEEP benchmarking is now proposed to all interested Member States.

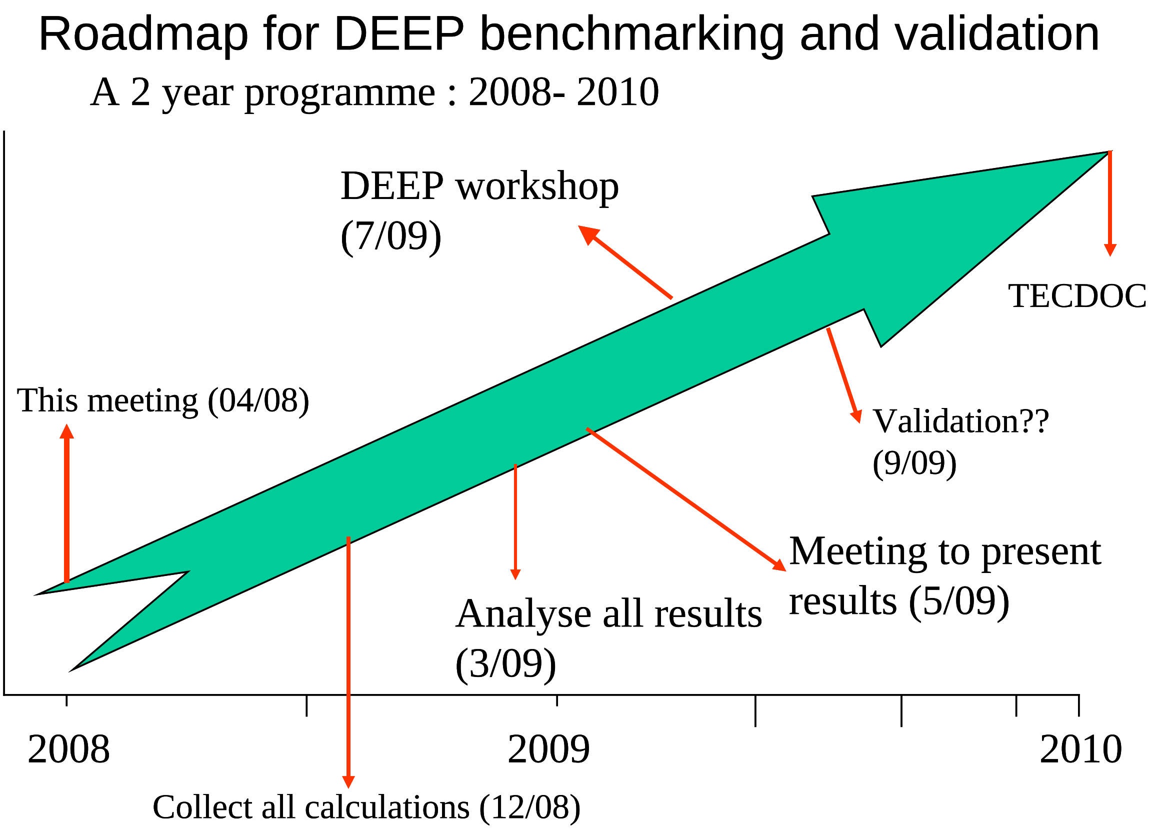

Figure 1: Road map for DEEP benchmarking and validation

2 CORRECTIONS TO SOME DEEP MODELS

2.1 Correction for the net thermal power transferred to the distillation plants

It was felt that before opening DEEP to a large number of users for Benchmarking, some of the observed errors should first be corrected so as not to mask the effect of other options.

The experts made a list of corrections for the immediate, medium term and long term actions.

The first correction proposed and implemented in DEEP is the calculation of the net thermal power transferred to the distillation plant (Qcrm).

DEEP first calculates the parameter Qcr (the heat rejected via the condenser) as

While at first sight it may seem that in the expression of Qcr, one is substracting quantities in two

$$Q_{cr} = Q_{tp} - Peg$$

$$Q_{tp} = Total\ base\ plant\ \ thermal\ \ power,\ (MWt)$$

$$Peg = Pen + Pal$$

$$Pen = total\ \ plant\ net\ elctrical\ \ power\ (MWe)$$

$$Pal = \ plant\ auxiliary\ load\ (MWe)$$

different units (MWe and MWth,) in fact the reject heat to the condenser is the difference of the powers produced in the reactor and the electrical power. In both cases, the units are MW and thus, contrary to what was announced in the Consultancy, the expression for Qcr is correct.

Qcr is then used to calculate Qcrm in the following way in DEEP3.1:

<u>PWRs and PHWRs</u>

*Qcrm=IF(OR(EnPlt="NH";EnPlt="FH";EnPlt="RH"); Qtp*Ebl; SI(TurType="BackPr";Qcr;MIN(Wdrc/Gor/24/3600*(598-0,6*Tcm)*4,1868;(Qtp-Pen)/(1-h))))*

Coal fired plants

*=SI(OU(EnPlt="NH";EnPlt="FH";EnPlt="RH"); Qtp*Ebl; SI(TurType="BackPr";Qcr;MIN(Wdrc/Gor/24/3600*(598-0,6*Tcm)*4,1868;(Qtp-Pen)/(1-h))))*

Gas turbine, combined cycle plants CC

*=SI(OU(EnPlt="NH";EnPlt="FH";EnPlt="RH"); Qtp*Ebl; SI(TurType="BackPr";Qcr;MIN(Wdrc/Gor/24/3600*(598-0,6*Tcm)*4,1868;(Qtp-Pen)/(1-h))))*

If the option is the “extraction turbine” then in DEEP3.1, one verifies the test and selects the minimum between two expressions

(Wdrc/Gor/24/3600(598-0,6*Tcm)*4,1868),*

or,

(Qtp-Pen)/(1-h))))

We have verified that the second expression is dimensionally correct but comes into play only when the required desalting capacity Wdrc is > 280 000 m^3/day. If the user inputs a capacity greater than this value he gets a warning that the production required is higher than what is achievable!

It is not yet clear what is the basis for this. Neither do we know from where the empirical formula for the first term was derived.

In the interest of its simplicity, and its more physical nature, we would recommend that only the first expression be used in future calculations.

The expression for Qcrm would thus read

Qcrm = (Wdrc/Gor/24/3600*(598-0,6*Tcm)*4,1868), where

Tcm = Maximum brine temperature + temperature drop in the first effect.

It has been tested that using this formula, the required capacity is equal to the theoretical production.

2.2 Intermediate term corrections.

These include the correction for GOR (Gain Output Ratio), which at the moment is calculated by an empirical relation.

The proposed correction aims to calculate physically the value of this very important parameter.

DEEP calculate the GOR for MED using an experimental equation:

$$GOR=0.8*Nemed \qquad (1)$$

This very simple equation might not really be a sufficient expression for GOR, which should be thermodynamically calculated as

$$GOR = \frac{\sum_{j=1}^{n} D_j + \sum_{j=2}^{n} d_j}{M_S} = \frac{M_D}{(M_f \times C_{Pf}(T_1 - t_2) + D_1 \times \lambda_1)/\lambda_s} \quad (2)$$

Where λ is the latent heat of vapour, determined by the following experimental equation[1][1]:

$$\lambda = 2589.583 + 0.9156 \times T - 4.8343 \times 10^{-2} \times T^2 \quad (3)$$

And C_{Pf} is the specific heat of the feed water, also determined using following experimental equation[1]:

$$C_{Pf} = \left(A + BT + CT^2 + DT^3\right) \times 10^{-3} \quad (4)$$

Where the parameters A,B,C and D are defined according to the S=TDS of the feed water by the following experimental equation:

$$\begin{aligned} A &= 4206.8 - 6.6197 \times S + 1.2288 \times 10^{-8} \times S^2 \\ B &= -1.1262 + 5.4178 \times 10^{-2} \times S - 2.2719 \times 10^{-6} \times S^2 \\ C &= 1.12026 \times 10^{-2} - 5.3566 \times 10^{-4} \times S = 1.8906 \times 10^{-6} \times S^2 \\ D &= 6.877 \times 10^{-7} + 1.517 \times 10^{-6} \times S - 4.4628 \times 10^{-9} \times S^2 \end{aligned} \quad (5)$$

As is well known, the GOR is mainly related to both heating steam temperature and number of effects Thus a range of heating steam temperature were chosen from 45 up to 125 C^o .

Table 1 show the difference of GOR calculated by the two methods:

Table 1. Comparison of GOR values

Heating steam Temperature (C^o)	Number of effect	GOR (DEEP)	GOR (calculated)
125	34	27.2	22.24
115	30	24	20.52
105	26	20.8	18.61
95	22	17.6	16.5

[1] [1] Ed. Frank Kreith, *Mechanical Engineering Handbook,* Boca Raton: CRC Press LLC, 1999

85	18	14.4	14.13
75	14	11.2	11.54
65	10	8	8.67
55	6	4.8	5.49
45	2	1.6	1.9

Yet another proposal to be implemented in the near future is that so far DEEP calculates the thermodynamic parameters using the Carnot cycle, where as in practice it is the Rankine cycle that is used.

3 FIRST RESULTS OF THE BENCHMARK REFERENCE CALCULATIONS

Using the standard benchmark problem, the experts proceeded to calculate the reference cases for two PWRs (the 900 MWe French PWR and the AP-600 proposed by Westinghouse) and a 900 MWe gas turbine combined cycle plant. All these power plants were coupled to MED, MSF and RO systems. Hybrid MSF/RO and MED/RO have also been calculated.

Some of the main results are summarised in Figures 2 to 4.

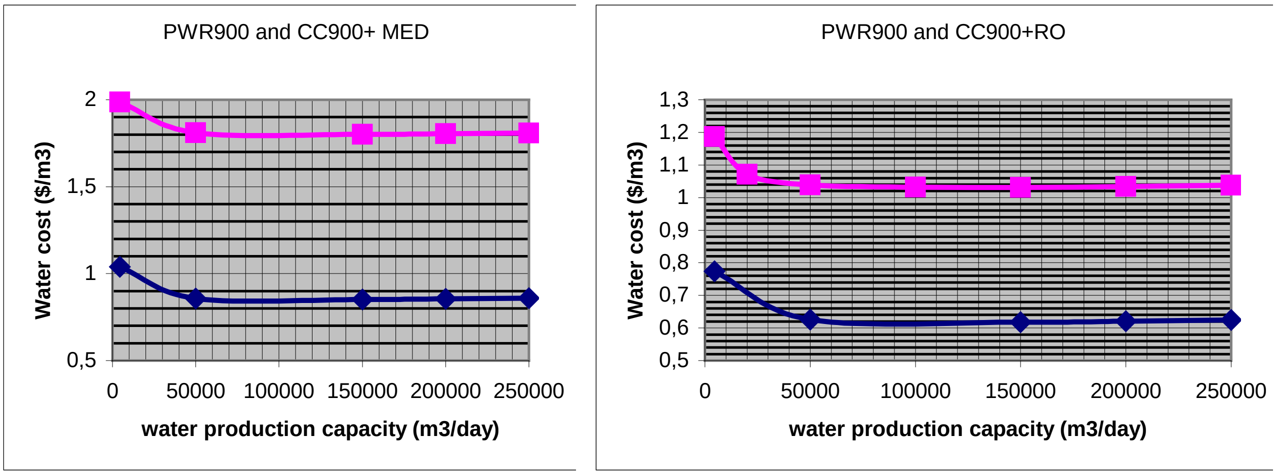

Figure 2: PWR900 (blue curve) and CC-900 water costs when coupled to MED and RO systems

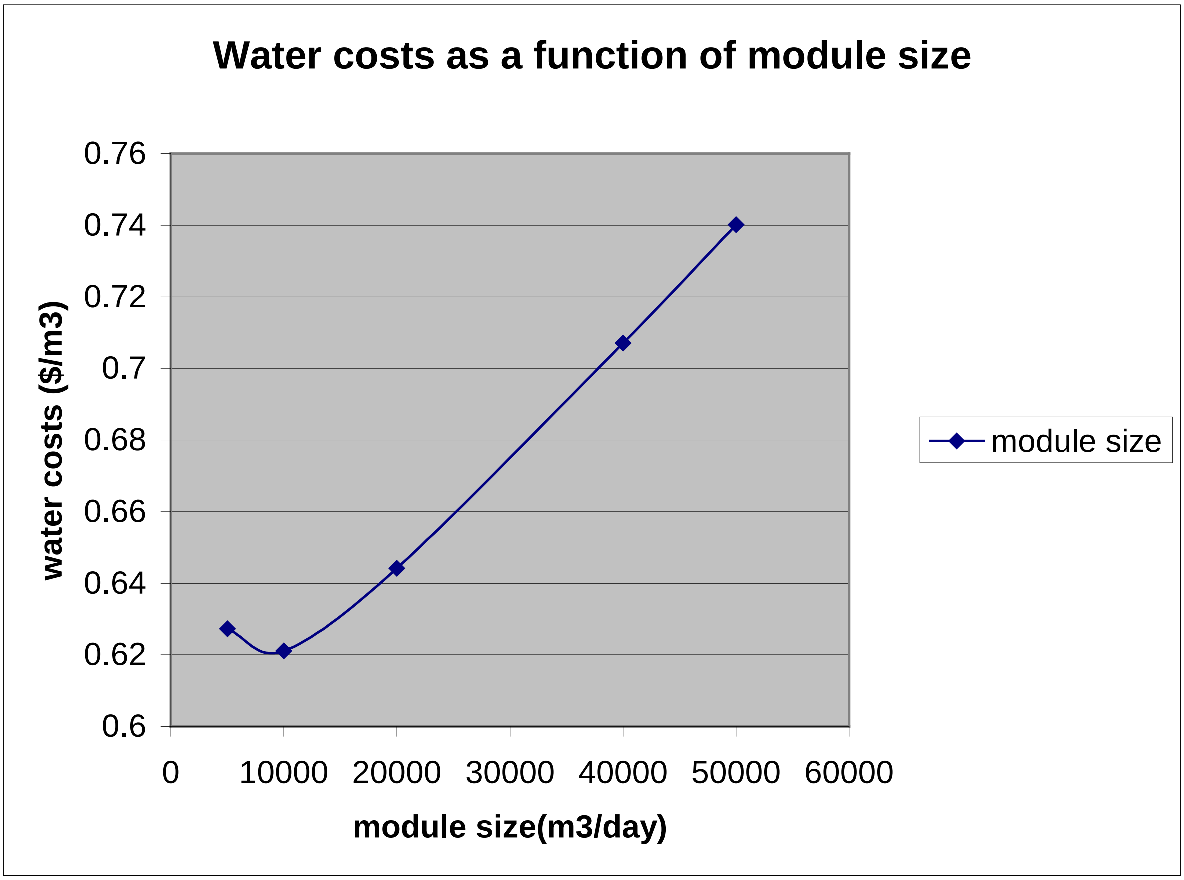

Figure 3: Influence of module size (RO plant) on the water cost

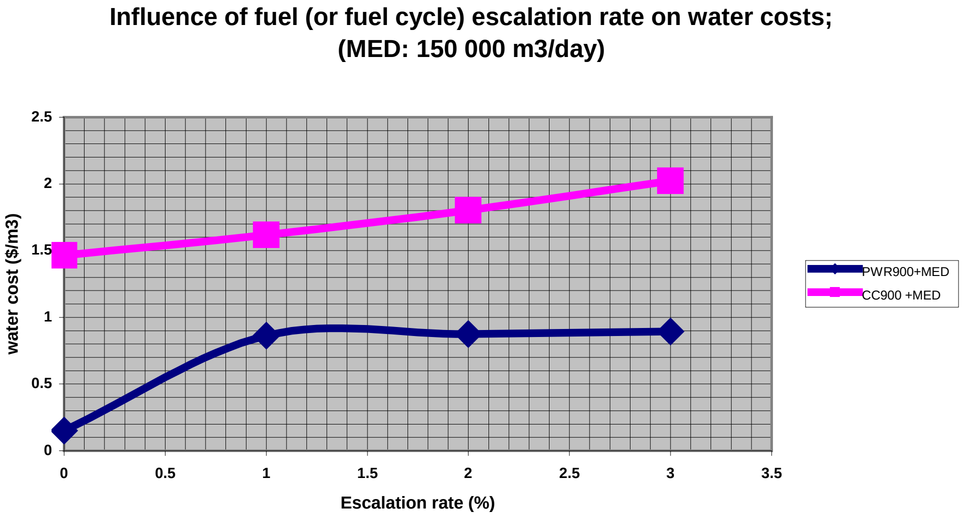

Figure 4: Influence of fuel (or fuel cycle) cost escalation on water costs

4 IMPROVING UTILIZATION OF DEEP

Yet another aspect of this rather intensive utilisation of DEEP is the fact that there are always new users of DEEP. Such newcomers either do not spend enough time to review the background behind the DEEP models or in some cases pay no attention to some of the important parameters whose values are site and case dependent or can not be taken as default values. For example, changing the value of the maximum brine temperature from 65°C (default value for nuclear reactors) to 120°C (default value for a gas turbine, combined cycle plant) may result in a 30% error on the water costs! Similarly, choosing a very low or very high module size can affect the water costs in a substantial manner.

5 CONCLUSIONS

The DEEP benchmark is now well on the way. It is to be shortly proposed to a large number of interested Member States.

First results from reference calculations have confirmed the following observations:

- Nuclear systems have much lower water and electricity costs as compared to fossil fuelled systems.
- Escalation in fuel cycle costs do not significantly affect the water costs for nuclear systems. On the contrary fuel cost escalation very significantly increase the water costs for fossil energy based systems.
- Although not shown here, results from hybrid system calculations also show the same tendencies.

A more detailed analysis, based on all the results, will be made in the near future.