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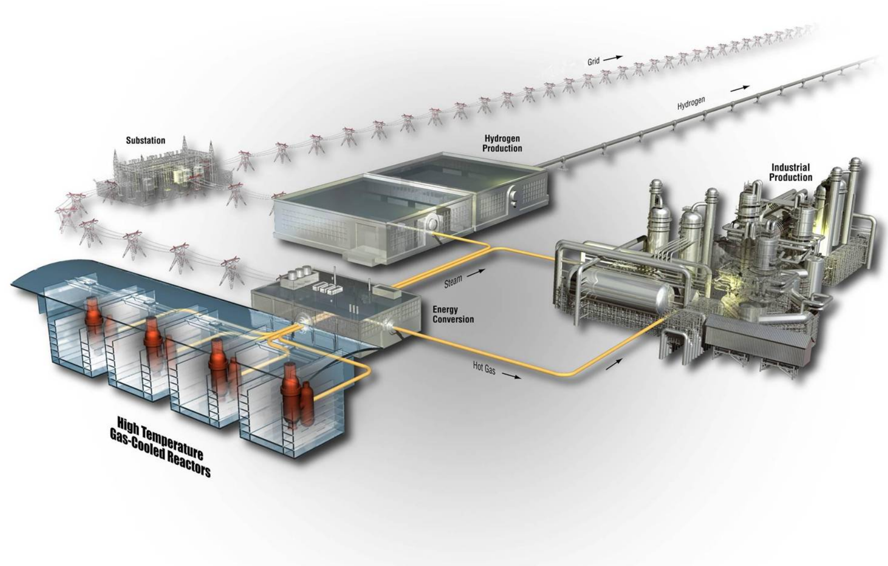
Technical Evaluation Study

Project No. 23843

Integration of HTGRs and Seawater Desalination



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REVISION LOG

Rev.	Date	Affected Pages	Revision Description
0	08/17/2011	All	Newly issued document

CONTENTS

ACRONYMS

AACE	Association for the Advancement of Cost Engineering
ATCF	after tax cash flow
BTCF	before tax cash flow
CEPCI	Chemical Engineering Plant Cost Index
EIA	Energy Information Administration
GIF	GEN-IV International Forum
HTGR	high temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
IRR	internal rate of return
MACRS	modified accelerated cost recovery system
MARR	minimum annual rate of return
MED	multi-effect distillation
MSF	multi-stage flash distillation
MW(e)	megawatt (electric)
MW(t)	megawatt (thermal)
NGCC	natural gas combined cycle
NGNP	next generation nuclear plant
NIBT	net income before taxes
O&M	operations and maintenance
PW	present worth
RO	reverse osmosis
TDS	total dissolved solids
TEV	technical evaluation
TCI	total capital investment
USBR	united states bureau of reclamation

NOMENCLATURE

C_k	capital expenditures
c_months	total number of months in the current modules construction period
CapF	capital breakdown per month
d_k	depreciation

E_k	cash outflows
i'	IRR
k	year
month	current month in reactor/fossil construction period
Number	total number of reactor modules/fossil trains
R_k	revenues
t	tax rate
T_k	income taxes
y	exponent for current module/train

1. INTRODUCTION

This technical evaluation (TEV) addresses potential integration opportunities for single or multiple high temperature gas-cooled reactor (HTGR) modules with production of electricity and purified water from seawater. The TEV has been prepared as part of a study for the Next Generation Nuclear Plant (NGNP) Project to evaluate the integration of HTGR technology with conventional chemical processes. The NGNP Project is being conducted under U.S. Department of Energy direction to meet a national strategic need identified in the *Energy Policy Act of 2005* to promote reliance on safe, clean, economic nuclear energy and to establish a greenhouse-gas-free technology for the production of hydrogen. The NGNP represents an integration of high-temperature reactor technology with advanced hydrogen, electricity, and process heat production capabilities, thereby meeting the mission need identified by the U.S. Department of Energy. The strategic goal of the NGNP Project is to broaden the environmental and economic benefits of nuclear energy in the U.S. economy by demonstrating its applicability to market sectors not being served by light-water reactors.

An HTGR module produces process heat (steam or high-temperature helium), electricity, and/or hydrogen. An HTGR outlet temperature of 750°C for the primary fluid loop is assumed for this study, which reflects the initial HTGR design goals and assumes a conservative outlet temperature; temperatures of up to 950°C are anticipated for advanced HTGR designs. The output from a single HTGR module is assumed to be 600 MW(t). A 25°C approach temperature is also assumed for the heat exchanger between the primary and secondary fluid loops.

Conventional chemical processes generate process heat, electricity, and hydrogen by combusting fossil fuels (i.e., coal and natural gas), resulting in significant emissions of greenhouse gases, such as CO_2 (carbon dioxide). An HTGR could produce and supply these products to conventional chemical processes without generating any greenhouse gases. The use of an HTGR to supply process heat, electricity, or hydrogen to conventional processes is referred to as an HTGR-integrated process.

1.1 Conventional Seawater Desalination

Conventional seawater desalination processes use electricity and/or steam from a conventional electric power station to produce purified water from seawater. Three approaches to seawater desalination are considered in this report: reverse osmosis (RO), multi-stage flash distillation (MSF), and multi-effect distillation (MED). While there are other desalination technologies, these three represent the vast majority of the current market share: RO ~50%, MSF ~44%, MED ~6% (Wilf 2007). The energy requirement for each of these processes is shown in Table 1 (IAEA 2007). RO requires energy only in the form of electricity. MSF and MED require both electricity and heat to desalinate seawater.

Table 1. Energy requirements associated with three desalination technologies.

Parameter	Unit	Process: Reverse Osmosis	Process: Multi-stage Flash Distillation	Process: Multi-effect Desalination
Electricity Requirements	kW hr(e)/m^3	4–7	3–6	0.9–4.5
Heat Requirements	kW hr(th)/m^3	—	45–120	25–160
	GJ/m^3	—	0.16–0.43	0.09–0.58

See Table 3 - Average energy consumption in desalination processes (IAEA 2007).

Typically, purified water generated via the RO process has relatively higher residual total dissolved solids (TDS) than purified water generated via the MSF or MED processes. In desalination plants that include both RO and MSF or MED systems, the water is blended to achieve the desired purified water product. The following sections provide additional details for each of these water purification technologies.

1.1.1 Reverse Osmosis

RO technology, based on a membrane separation process, may be used to generate purified water from a wide range of saline waters. The process was derived from direct osmosis—the spontaneous process by which solvent molecules pass through a semipermeable membrane from a solution of lower concentration into a solution of higher concentration. The driving force for this water flux is the so-called osmotic pressure. For typical seawater at 25°C, the osmotic pressure is higher by 2.51 MPa on the freshwater side of the membrane. If the seawater pressure is higher than the osmotic pressure, the water will move across the membrane in the reverse direction from the saline solution to the pure water. This process is called reverse osmosis (and sometimes hyper-filtration), and is the basic principle underlying reverse-osmosis desalination. Most new seawater desalination plants are based on the reverse osmosis process. A simplified block-flow diagram of the RO process for seawater desalination is shown in Figure 1.

The first step of the RO process is to pump seawater from the ocean. Several chemicals are then added to facilitate the RO process. Iron chloride ($FeCl_3$) is added as a coagulant to remove the fine suspended solids, chlorine (Cl_2) is added to prevent biofouling, and acid is added as needed to adjust the pH to approximately 7.5 to prevent calcium

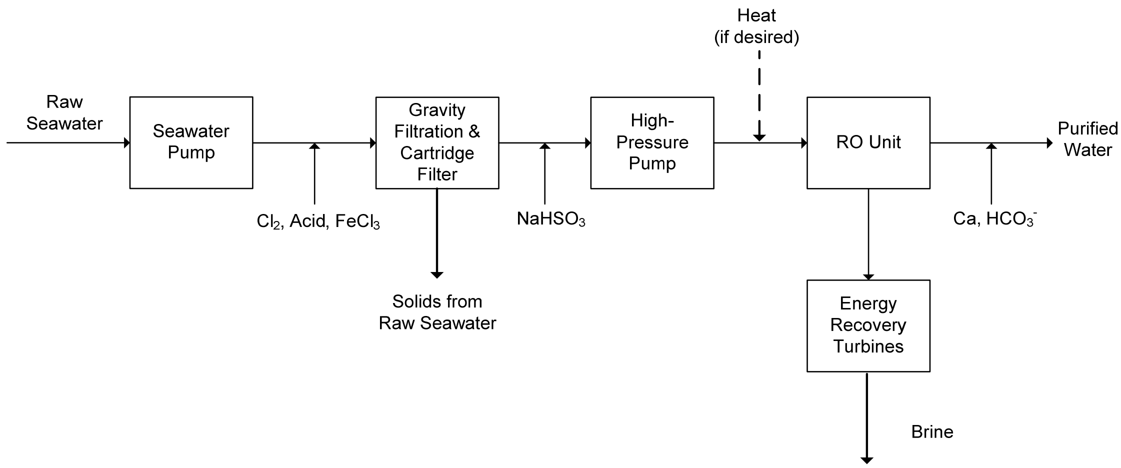

Figure 1. Block-flow diagram for reverse osmosis process to generate purified water from raw seawater.

carbonate caking of the filters and membranes. Raw seawater usually contains significant quantities of colloidal matter and occasionally contains algae and other marine organisms. This material is removed by gravity filtration and cartridge filters before it is fed to the RO Unit. Sodium bisulphate is added following filtering to remove residual chlorine (Micale 2009).

Following pretreatment and filtering of the raw seawater, a high pressure pump increases the pressure of the treated seawater to 5.5 to 7.0 MPa (798 to 1,015 psi). The water leaving the high-pressure pump may be heated to a temperature of 45 to 50°C to improve the efficiency of the RO unit. The pressurized water enters the RO unit where it is separated into permeate (purified water) and concentrate (brine).

The pressure of the brine from the RO Unit is about 0.2 to 0.3 MPa lower than the feed pressure. In order to improve the overall efficiency of the RO plant, energy recovery turbines are used to generate electricity from the pressurized brine solution. In the example shown, energy recovery reduces the overall electricity requirements of the process by 34%. (The overall electricity requirement decreases from 3.96 to 2.6 kWh/m^3.) Lastly, permeate water is stabilized by the addition of calcium and bicarbonate ions to reduce its corrosion potential. The final product from the process is purified water.

1.1.2 Multi-Stage Flash Distillation

MSF produces clean water from seawater by flashing a portion of the seawater into steam in multiple stages. A simplified block-flow diagram of the MSF process is shown in Figure 2.

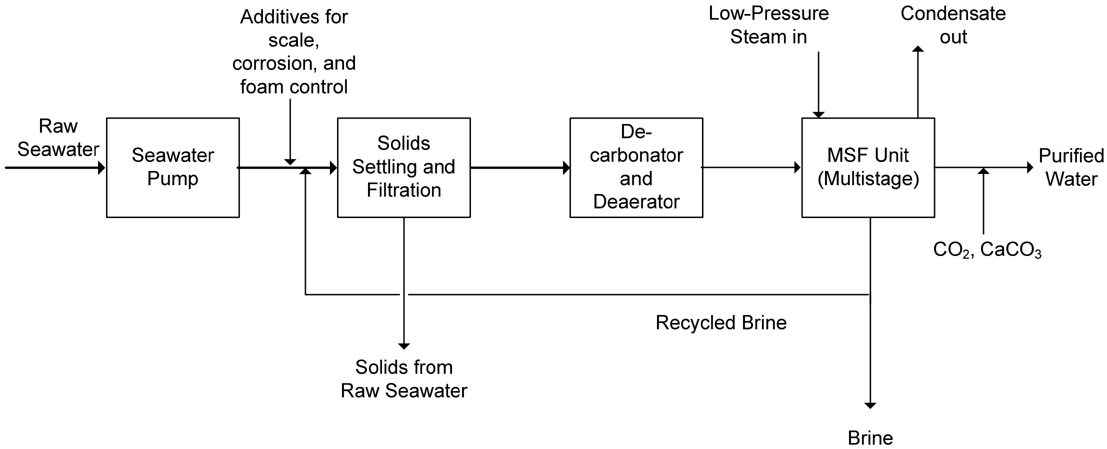

Figure 2. Simplified block-flow diagram of the MSF process for producing purified water from raw seawater.

A seawater pump is used to transport seawater from the ocean to the MSF process. Chemicals are added to the raw seawater entering the process to limit scale formation and corrosion in process equipment and to reduce the amount of foam formed in the MSF process. In order to further reduce scale formation and to improve the efficiency of the MSF unit, the decarbonator removes carbonates and the deaerator removes air from the seawater. The treated brine is heated by low-pressure steam to a top temperature of approximately 110°C. The heated brine is flashed to produce pure water in a series of flash stages. Pure water is collected as condensate in each flash stage. Most modern MSF units consist of 20–28 individual flash stages. The purified water leaving the MSF unit is treated with CO_2 or $CaCO_3$ to control corrosion of piping that carries the purified water to the supply system. A portion of the concentrated brine from the MSF unit is recycled through the system to facilitate system control. Concentrated seawater (brine) is returned to the ocean.

A schematic diagram of a single flash stage is shown in Figure 3. The equipment in each stage includes a bundle of condenser tubes, a demister pad, a condensate collector, and a flashing box. Seawater from the previous stage enters the flashing box on the bottom of one side and exits on the other side. A portion of the seawater flashes to vapor and brine mist. The brine mist is removed by a demister. Seawater on the inside of the condenser tube bundle is heated by the purified vapor condensing on the outside of the tube bundle. The purified condensate drips off the tube bundle, is collected, and removed as purified distillate.

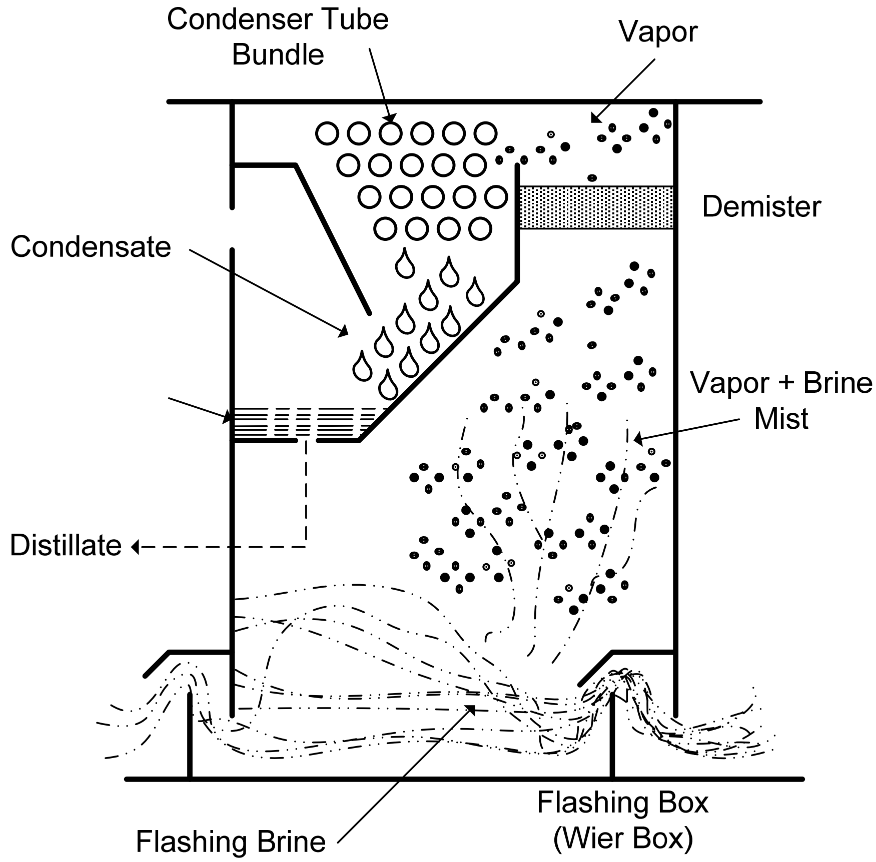

Figure 3. Schematic diagram of a single stage in the MSF unit.

1.1.3 Multi-Effect Distillation

The MED process is the oldest large-scale distillation process. The advantage of MED as compared to MSF is that it produces more pure water from the same quantity of input steam. However, this process has not been widely used in the past because of the lack of operating experience in large-scale MED plant operations and problems with components and materials of construction. Many of these issues have been resolved by adding chemicals to reduce scaling and corrosion and incorporate low-cost aluminum tubing into the MED unit (Ophir and Lokiec 2005). A block-flow diagram of the MED process is shown in Figure 4. The pretreatment system for the MED process is very similar to the MSF process. Seawater is removed from the ocean by a seawater pump, and chemicals are added to the raw seawater entering the process. Filtration removes solids from the seawater and a decarbonator and deaerator further prepare the seawater for processing in the MED unit. A modern MED unit consists of six to 18 individual stages. The final product of this process is purified water.

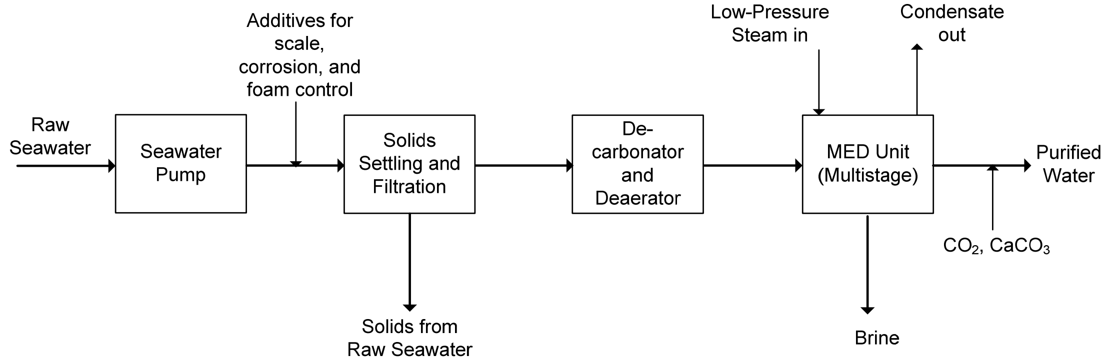

Figure 4. Simplified block-flow diagram of the MED process for producing purified water from raw seawater.

The MED process is thermodynamically the most efficient of all thermal desalination processes because of the simultaneous transfer of latent heat on either side of the heat transfer surface. Warm brine is flashed into clean steam on one side and pure steam is condensed to purified liquid water on the other side of the tube bundle. A schematic diagram of a single stage of the MED unit is shown in Figure 5. Warm brine is sprayed into the MED unit. A portion of the brine is flashed to pure steam on the outside of the condenser tubes and exits the MED unit as pure steam to the next stage. Brine that does not flash is collected in the bottom of this stage and is transferred to the next stage. Pure steam from the previous stage is condensed on the inside of the tubing as it passes through the MED unit. The heat from the condensation of the purified steam supplies the heat required to flash the brine on the outside of the tubes and generate clean steam. The final product is collected from each stage as purified liquid water.

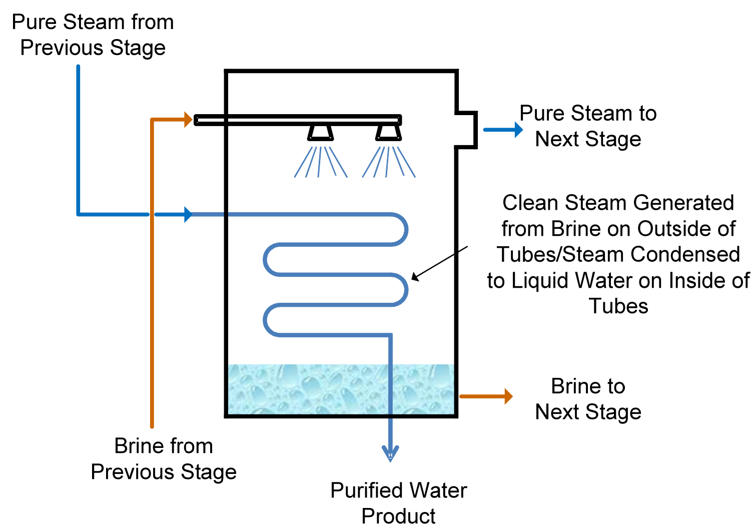

Figure 5. Schematic diagram of a single stage in the MED unit.

1.2 Conventional Seawater Desalination

A simplified block-flow diagram for conventional seawater desalination via the RO process is shown in Figure 6. For the purposes of this report, it is assumed that natural gas is combusted to generate the electricity requirements of the RO plant. Excess electricity is sold to the grid and the plant emits CO_2 to the atmosphere. Purified water is generated in the RO plant from seawater. Concentrated seawater (brine) is returned to the ocean.

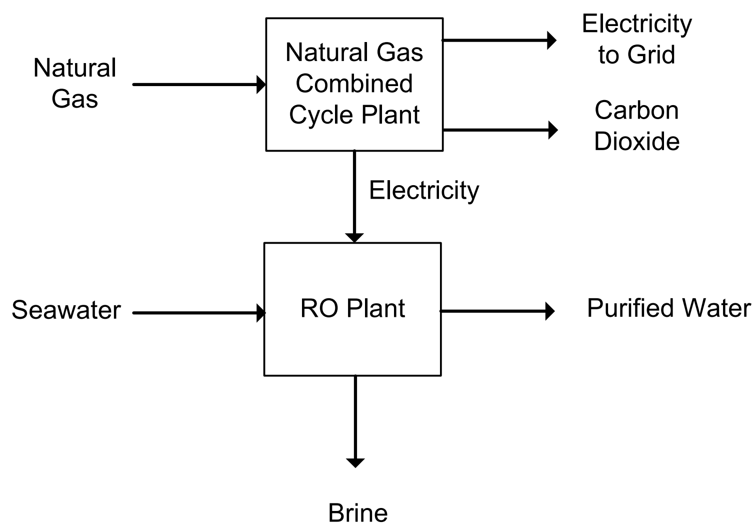

Figure 6. Simplified block-flow diagram for the production of electricity via the natural gas combined cycle (NGCC) process and purified water from the reverse osmosis process.

A simplified block-flow diagram for conventional seawater desalination via the MSF or MED process is shown in Figure 7. For the conventional MSF and MED processes, it is assumed that combustion of natural gas is used to generate electricity and steam. Electricity is generated only by the gas turbine. All steam generated in the NGCC plant is used in the MSF or MED plant. Excess electricity is sold to the grid and the process emits CO_2 to the atmosphere. Purified water is generated in the MSF or MED process. Concentrated seawater (brine) is returned to the ocean.

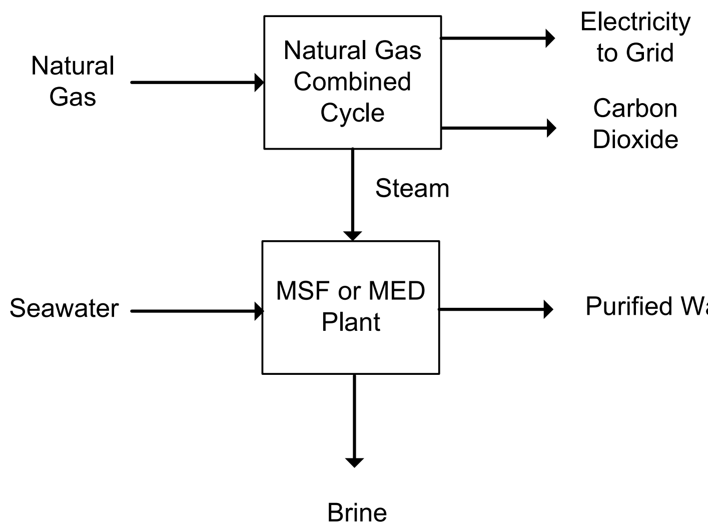

Figure 7. Simplified block-flow diagram for the production of electricity via the natural gas combined cycle process and purified water from the MSF or MED process.

1.3 HTGR-Integrated Seawater Desalination

A block-flow diagram for HTGR-integrated seawater desalination via the RO process is shown in Figure 8. Steam is generated by heat from nuclear fission in the HTGR. Steam is used to generate electricity via the Rankine power cycle. Electricity from the power cycle is used in the RO plant to purify seawater. Excess electricity is sold to the grid.

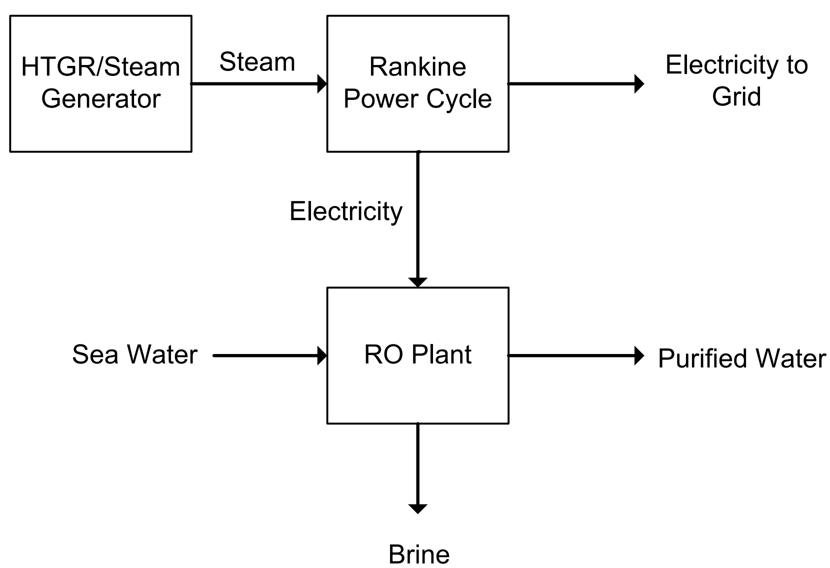

Figure 8. Simplified block-flow diagram for the HTGR-integrated RO seawater desalination process.

A block-flow diagram for HTGR-integrated seawater desalination via the MSF or MED process is shown in Figure 9. Low-pressure steam and electricity is removed from the Rankine cycle low-pressure turbine and is fed to the MSF or MED process. Removal of this low-pressure steam reduces the overall thermal efficiency of the Rankine cycle and reduces electricity production.

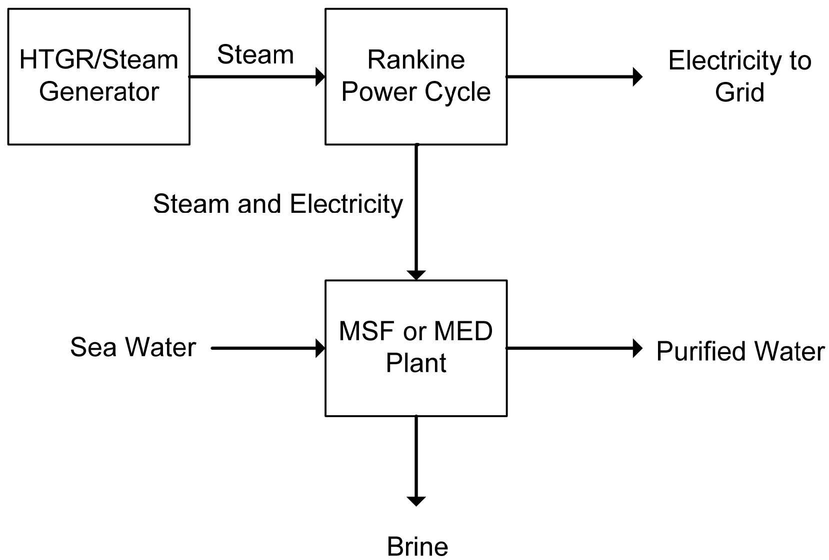

Figure 9. Simplified block flow diagram for the HTGR-integrated MSF or MED seawater desalination process.

2. PROCESS MODELING APPROACH AND ASSUMPTIONS

The major difference between the HTGR-integrated and conventional desalination processes is the source of low-pressure steam and electricity. The desalination equipment does not change based on whether combustion of natural gas or nuclear fission is used to supply heat for generating steam or producing electricity. This work assumes that the co-generation plant is located adjacent to the desalination plant. The cogeneration plant is sized to supply adequate steam to support a desalination plant that produces 400,000 m^3/day of purified water from seawater. Additional details regarding the approach and assumptions used to model the mass and energy balance for desalination and electricity and steam production are provided below.

2.1 Desalination Model

The mass and energy balances associated with the three desalination processes considered in this report vary widely based on factors such as seawater temperature and salinity. The assumptions used for process modeling calculations are summarized in Table 2. Process modeling calculations were performed using an Excel spreadsheet.

Table 2. Assumptions used to complete process modeling for desalination of seawater.

Parameter	Unit	Process: Reverse Osmosis	Process: Multi-Stage Flash Distillation	Process: Multi-Effect Desalination
Electricity Requirements	kW hr(e)/m^3	4.5	3	2
Gain Output Ratio (GOR)	$Kg_{distillate}$/ $kg_{motive\ steam}$	N/A	8.74 (28 stages) [1]	11.2 (14 effects)[a]
Seawater Temperature	°C	25	25	25
Seawater Salinity	mg/L (ppm)	35,000	35,000	35,000
Top Brine Temperature	°C	N/A	105[1]	70[1]
Fresh Water Output	m^3/day	100,000	100,000	100,000
Density of Fresh Water	kg/m^3	1,000	1,000	1,000
Density of Seawater at 25°C, 30,000 ppm TDS	kg/m^3	1,018	1,018	1,018
Density of Seawater at 25°C, 70,000 ppm TDS[b]	kg/m^3	1,050	1,050	1,050

a. Calculated using default values provided in DEEP 4.0 (IAEA 2000).
b. Based on seawater density calculator: http://www.csgnetwork.com/h2odenscalc.html.

3. PROCESS MODELING RESULTS

Based on the assumptions listed in Table 2, the overall mass and energy balance for each of the desalination methods considered in this report are summarized in Figure 10. Conventional processes combust natural gas to produce electricity and steam. HTGR integrated processes use the HTGR to produce electricity and steam. A detailed summary of the calculations used to develop these results are presented in Appendix A.

The overall mass and energy balance for producing steam and electricity are shown in Figure 11. All calculations were performed based on generating 600 MW(t) of heat. The natural gas and HTGR plants produce only electricity for the RO process but both electricity and low-pressure steam for the MSF and MED processes. A detailed summary of the calculations used to develop these results are presented in Appendix B. A summary of the HYSYS calculations for the NGCC and HTGR Rankine Power cycles are presented in Appendix C.

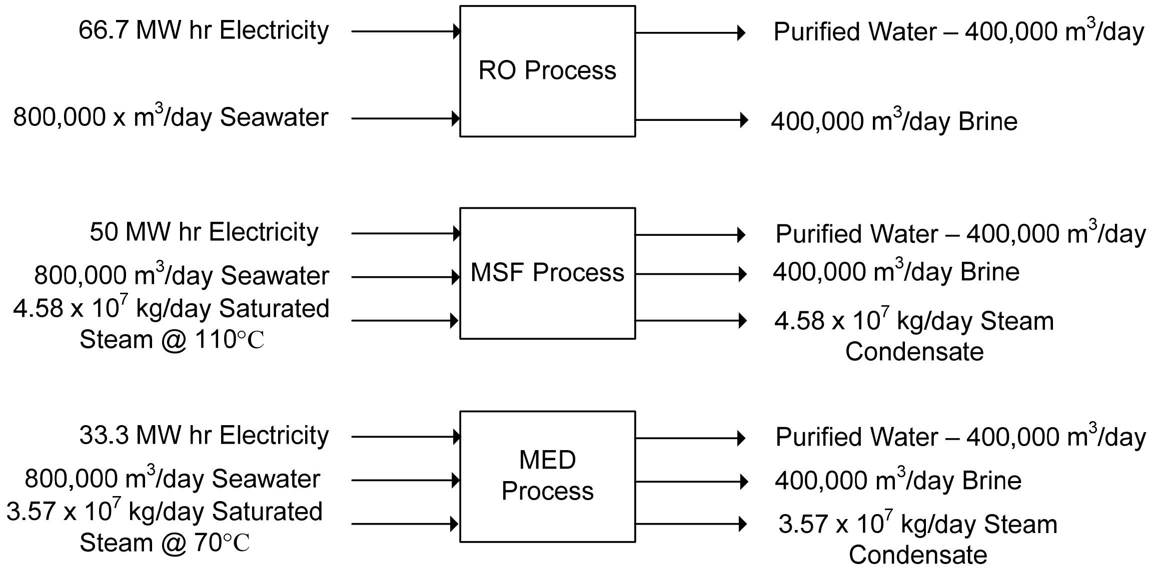

Figure 10. Overall mass and energy balance for the three desalination technologies included in the analysis.

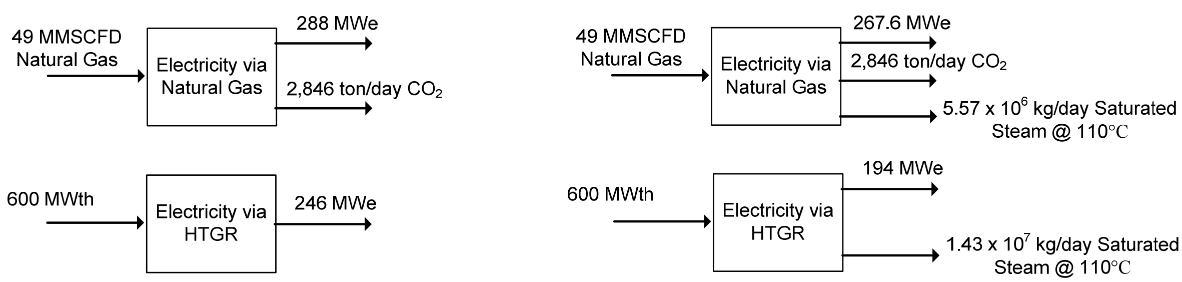

Figure 11. Overall mass and energy balance for generation of electricity only (left) and electricity and low-pressure steam (right) from 600 MW(t) of natural gas or nuclear fuel.

The mass and energy balances for the conventional and HTGR-integrated RO, MSF, and MED cases are shown in Figures 12, 13, and 14 respectively. The basis for the results shown in these figures is the production of 400,000 m^3 of purified water/day. The sizes of the fossil and nuclear heat processes were scaled linearly to meet the needs of each water purification process. A detailed summary of the calculations used to develop these results is presented in Appendix D.

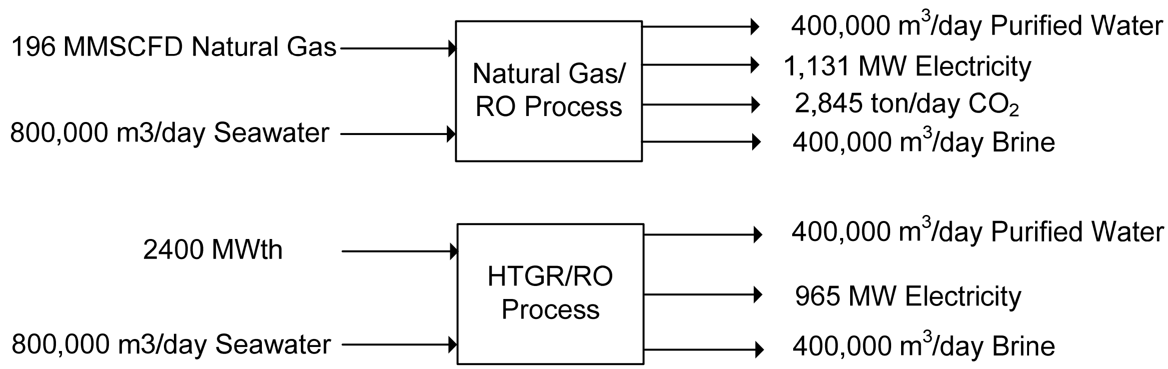

Figure 12. Overall mass and energy balance for production of electricity and purified water from seawater for natural gas and HTGR-integrated RO.

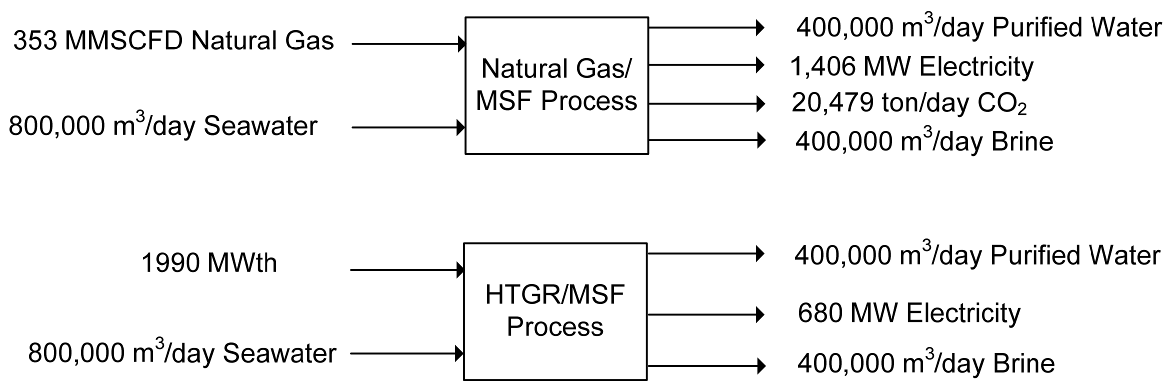

Figure 13. Overall mass and energy balance for production of electricity and purified water from seawater for natural gas and HTGR-integrated MSF.

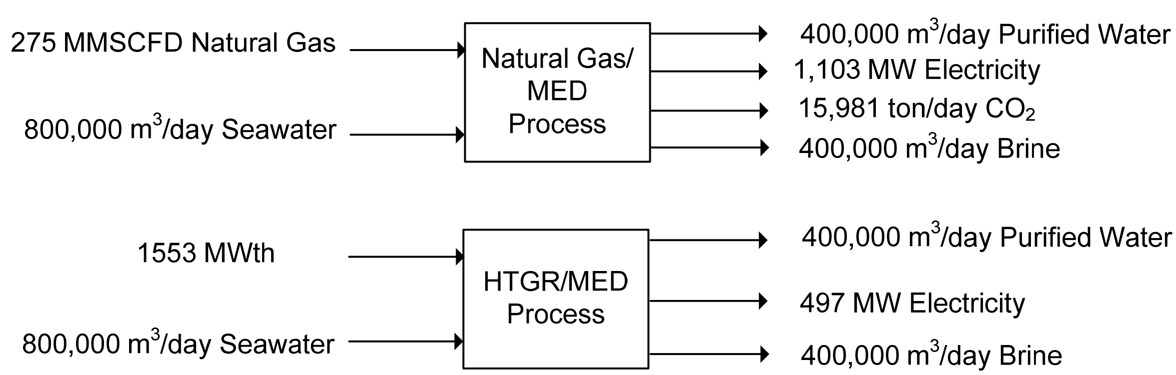

Figure 14. Overall mass and energy balance for production of electricity and purified water from seawater for fossil and HTGR-integrated MED.

4. ECONOMIC MODELING OVERVIEW

The economic viability of the desalination processes was assessed using standard economic evaluation methods, specifically the internal rate of return (IRR). The economics were evaluated for the conventional and HTGR-integrated cases described in the previous section. The total capital investment (TCI)—based on the total equipment costs, annual revenues, and annual manufacturing costs—were first calculated for these cases. The present worth (PW) of the annual cash flows (after taxes) was then calculated for the TCI. The following sections describe the methods used to calculate the capital costs, annual revenues, annual manufacturing costs, and economic results. The calculations assumed that the products being sold are electricity and purified seawater. The results are preliminary and should be refined as the HTGR design progresses, should the design change significantly or additional cost refinements become available.

4.1 Capital Cost Estimation

The Association for the Advancement of Cost Engineering (AACE) International recognizes five classes of estimates. The level of project definition for this study was determined to be an AACE International Class 4 estimate, which has a probable error of -30% and +50% (INL 2011a). A Class 4 estimate is associated with a feasibility study or top-down cost estimate and has one to 15% of full project definition (AACE 2005).

Equipment items for this study were not individually priced. Rather, cost estimates were based on scaled costs for major plant processes from published literature or vendor data. Cost estimates generated in this manner include costs for the fossil power electricity plant (Energy Information Administration [EIA] 2010) and the desalination plant (U.S. Bureau of Reclamation [USBR] 2003). All costs presented are assumed to represent a complete and operable system and include all engineering fees and contingencies. Fixed capital costs were estimated from literature data, scaled linearly with increasing capacity.

Capital costs to install the HTGR are based on the capital cost correlations presented in Section 2.6 of TEV-1196, which apply for a mature commercial n^{th}-of-a-kind HTGR with a reactor outlet temperature of 750°C and a Rankine power cycle. Preconstruction costs, balance of equipment costs, indirect costs, and project contingencies were added in accordance with the costs outlined in Sections 2.1 through 2.5 of TEV-1196 (INL 2011a).

The Chemical Engineering Plant Cost Index (CEPCI) was used to adjust equipment prices from previous years to 2010 values as depicted in Table 3.

Table 4 presents the capital cost estimate breakdown for the conventional desalination cases and Figure 15 presents the graphical breakdown for the RO case. Table 5 presents the results for the nuclear-integrated desalination cases and Figure 16 presents the graphical breakdown for the nuclear-integrated RO case.

Table 3. CEPCI data.

Year	CEPCI
2003	402
2004	444.2
2005	468.2
2006	499.6
2007	525.4
2008	575.4
2009	521.9
2010	550.8

Table 4. Total capital investment, conventional desalination cases.

	Total Capital Cost
RO Desalination	
RO Plant	$1,262,202,155
NGCC Plant	$1,171,057,200
Total RO Capital Investment	**$2,433,259,355**
MED Desalination	
MED Plant	$817,966,674
NGCC Plant	$1,112,660,438
Total MED Capital Investment	**$1,930,627,112**
MSF Desalination	
MSF Plant	$1,263,297,161
NGCC Plant	$1,422,404,702
Total RO Capital Investment	**$2,685,701,863**

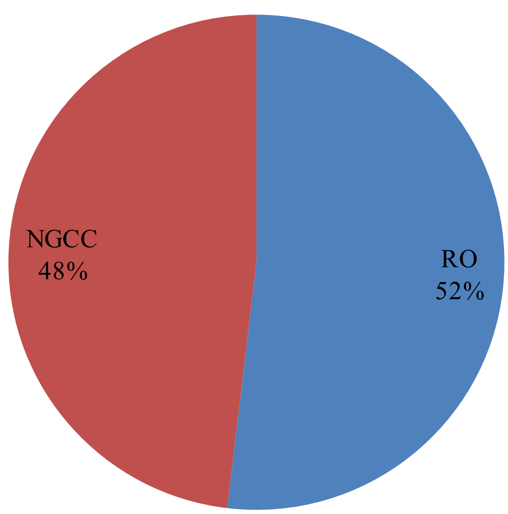

Figure 15. Total capital investment, conventional RO case.

Table 5. Total capital investment, nuclear-integrated desalination cases.

	Total Capital Cost
RO Desalination	
RO Plant	$1,262,202,155
HTGR with Rankine Cycle	$4,809,529,007
Total RO Capital Investment	**$6,071,731,162**
MED Desalination	
MED Plant	$817,966,674
HTGR with Rankine Cycle	$4,575,471,072
Total MED Capital Investment	**$5,393,437,746**
MSF Desalination	
MSF Plant	$1,263,297,161
HTGR with Rankine Cycle	$4,492,005,184
Total RO Capital Investment	**$5,755,302,345**

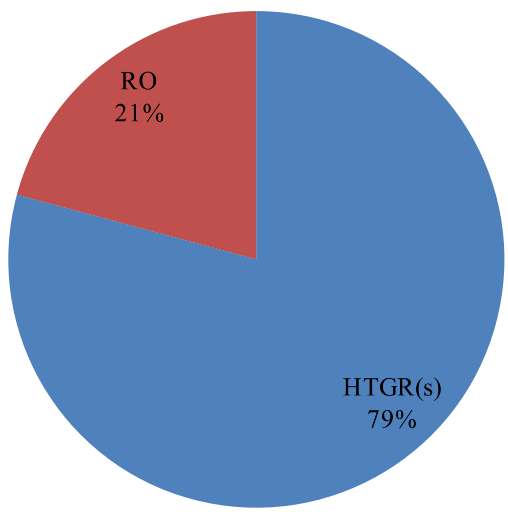

Figure 16. Total capital investment, nuclear-integrated RO case.

4.2 Estimation of Revenue

Yearly revenues were estimated for all cases based on recent price data for the generation of water and electricity. Revenues were estimated for selling water at the market price of $0.79/m^3$ (NUS Consulting 2008). Revenues were also calculated to determine the necessary selling price of water to achieve a specific rate of return, but these revenues are not presented in this TEV. Electricity revenues were estimated for all cases based on the current market price, discounted for transmission and distribution costs, $59.28/MW(e)-hr (EIA 2011a, EIA 2011b). Electricity prices were not varied to achieve a given rate of return, as the economics for generating electricity have already been assessed in TEV-988 (INL 2011b). An overall availability of 90% is assumed for both the fossil and nuclear plants. Revenues for the conventional desalination cases are presented in Table 6 and revenues for the nuclear-integrated desalination cases are presented in Table 7. Again, revenues are only presented for selling water at the market price.

Table 6. Annual revenues, conventional desalination cases.

	Price		Generated		Annual Revenue
RO Desalination					
Electricity	59.28	\$/MW(e)-hr	1,131	MW(e)	\$528,401,196
Water, Market	0.79	\$/m^3	400,000	m^3/day	\$103,436,477
Annual RO Revenue, Water at Market Price					**\$631,837,673**
MED Desalination					
Electricity	59.28	\$/MW(e)-hr	1,104	MW(e)	\$516,198,151
Water, Market	0.79	\$/m^3	400,000	m^3/day	\$103,436,477
Annual MED Revenue, Water at Market Price					**\$619,634,628**
MSF Desalination					
Electricity	59.28	\$/MW(e)-hr	1,404	MW(e)	\$656,366,045
Water, Market	0.79	\$/m^3	400,000	m^3/day	\$103,436,477
Annual MSF Revenue, Water at Market Price					**\$759,802,522**

Table 7. Annual revenues, nuclear-integrated desalination cases.

	Price		Generated		Annual Revenue
RO Desalination					
Electricity	59.28	\$/MW(e)-hr	965	MW(e)	\$451,099,270
Water, Market	0.79	\$/m^3	400,000	m^3/day	\$103,436,477
Annual RO Revenue, Water at Market Price					**\$554,535,746**
MED Desalination					
Electricity	59.28	\$/MW(e)-hr	860	MW(e)	\$401,956,434
Water, Market	0.79	\$/m^3	400,000	m^3/day	\$103,436,477
Annual MED Revenue, Water at Market Price					**\$505,392,911**
MSF Desalination					
Electricity	59.28	\$/MW(e)-hr	806	MW(e)	\$376,741,618
Water, Market	0.79	\$/m^3	400,000	m^3/day	\$103,436,477
Annual MSF Revenue, Water at Market Price					**\$480,178,095**

4.3 Estimation of Manufacturing Costs

Manufacturing cost is the sum of direct and indirect manufacturing costs. Direct manufacturing costs for this project include the cost of raw materials, utilities, and operating labor and maintenance. Indirect manufacturing costs include estimates for the cost of overhead and insurance and taxes (Perry 2008). Natural gas prices for the conventional desalination cases were varied to account for the large fluctuations seen in the market. Costs were calculated for a low ($4.50/ [MSCF thousand standard cubic feet per day]), average ($5.50/MSCF), and high ($12.00/MSCF) industrial natural gas price. High prices correspond to prices from June 2008, low prices are from September 2009, and the average price was chosen to reflect current natural gas prices (EIA 2011c). Only average natural gas prices are presented in the tables that follow. Fixed and variable operations and maintenance (O&M) costs were estimated for the combined natural gas cycle based on recent data from EIA (2010).

O&M, chemical, labor, and insurance costs were lumped into a cost/m^3 of water produced for each desalination method evaluated (USBR 2003). Table 8 describes the manufacturing costs for the conventional desalination cases at the average natural gas price. Again, availability was assumed to be 90%.

Manufacturing costs for the nuclear plant were based on information presented in TEV-1196. HTGR manufacturing costs include O&M costs, fuel costs, and decommissioning costs. The O&M, fuel, and decommissioning costs are based on the total thermal rating of the plant (INL 2011a). O&M and decommissioning costs are presented on an annual basis, while fuel costs are presented as the total refueling cost per core. Table 9 provides the manufacturing costs for the nuclear-integrated desalination cases. Again, availability was assumed to be 90%.

The decommissioning fund payment is calculated using the decommissioning cost in dollars per MW(t) presented in TEV-1196, which is based on NUREG-1307 (NRC 2010). That cost is multiplied by the total reactor power level to determine the total decommissioning cost and then inflated to the year decommissioning will occur, which is based on the economic recovery period. The sinking fund payment is calculated based on the estimated decommissioning cost and a 5% discount rate (GIF 2007).

It is recognized that the HTGR may operate longer than the specified economic recovery period. However, an economically conservative assumption assumes that the reactor is decommissioned at the end of the recovery period.

Table 8. Annual manufacturing costs, conventional desalination cases.

	Price		Consumed		Annual Cost
RO Desalination					
Materials					
Natural Gas, average	5.50	\$/MSCF	196,180	MSCFD	\$354,448,215
NGCC Costs					
Fixed O&M	1.64	\$/MW(e)-hr	1,197	MW(e)	\$15,507,527
Variable O&M	3.43	\$/MW(e)-hr	1,197	MW(e)	\$32,380,234
O&M, Chemical, Labor, and Insurance Costs for Desalination					
RO Desalination	0.30	\$/m^3	400,000	m^3/day	\$39,278,033
			Manufacturing Costs, RO Desalination		**\$441,614,010**
MED Desalination					
Materials					
Natural Gas, average	5.50	\$/MSCF	275,775	MSCFD	\$498,256,340
NGCC Costs					
Fixed O&M	1.64	\$/MW(e)-hr	1,138	MW(e)	\$14,734,218
Variable O&M	3.43	\$/MW(e)-hr	1,138	MW(e)	\$30,765,539
O&M, Chemical, Labor, and Insurance Costs for Desalination					
MED Desalination	0.40	\$/m^3	400,000	m^3/day	\$52,329,685
			Manufacturing Costs, MED Desalination		**\$596,085,781**
MSF Desalination					
Materials					
Natural Gas, average	5.50	\$/MSCF	358,870	MSCFD	\$648,389,034
NGCC Costs					
Fixed O&M	1.64	\$/MW(e)-hr	1,454	MW(e)	\$18,835,954
Variable O&M	3.43	\$/MW(e)-hr	1,454	MW(e)	\$39,330,101
O&M, Chemical, Labor, and Insurance Costs for Desalination					
MSF Desalination	0.50	\$/m^3	400,000	m^3/day	\$65,674,049
			Manufacturing Costs, MSF Desalination		**\$772,229,138**

Table 9. Annual manufacturing costs, nuclear-integrated desalination cases.

	Price		Consumed		Annual Cost
RO Desalination					
Nuclear Costs					
O&M	4.88	$/MW(t)-hr	2,400	MW(t)	**$92,427,123**
Decommissioning Fund Payment					$20,130,091
O&M, Chemical, Labor, and Insurance Costs for Desalination					
RO Desalination	0.30	$\$/m^3$	400,000	m^3/day	$39,278,033
		Manufacturing Costs, RO Desalination			**$151,835,247**
MED Desalination					
Nuclear Costs					
O&M	4.88	$/MW(t)-hr	2,400	MW(t)	**$92,427,123**
Decommissioning Fund Payment					$20,130,091
O&M, Chemical, Labor, and Insurance Costs for Desalination					
MED Desalination	0.40	$\$/m^3$	400,000	m^3/day	$52,329,685
		Manufacturing Costs, MED Desalination			**$164,886,898**
MSF Desalination					
Nuclear Costs					
O&M	4.88	$/MW(t)-hr	2,400	MW(t)	**$92,427,123**
Decommissioning Fund Payment					$20,130,091
O&M, Chemical, Labor, and Insurance Costs for Desalination					
MSF Desalination	0.50	$\$/m^3$	400,000	m^3/day	$65,674,049
		Manufacturing Costs, MSF Desalination			**$178,231,262**
					Cost Per Core
Refueling Cost					**$51,712,273**

4.4 Economic Comparison

Several economic indicators were calculated for each case to assess the economic desirability of desalination. The price of water necessary for an IRR of 12% was calculated for all cases as well as the IRR at the market price for water.

Table 10 lists the economic assumptions made for the analyses.

Table 10. Economic assumptions.

	Assumption
Year Construction Begins	2012
Construction Information	
Preconstruction Period	6 months
Nuclear Construction Period – per Reactor	36 months
Reactor Startup Staggering	6 months
Fossil Construction Period (per Train)	36 months
Train Startup Staggering	6 months
Percent Capital Invested Each Year	S-Curve distribution
Plant Startup Information	
Startup Time	12 months
Operating Costs Multiplier	1.2
Revenue Multiplier	0.65
Economic Analysis Period	30 years
Availability	90%
Inflation Rate	3%
Debt to Equity Ratio	50%/50%
Loan Information	
Interest Rate on Debt	8%
Interest on Debt During Construction	8%
Loan Repayment Term	15 years
Tax Information	
Effective Tax Rate	38.9%
State Tax Rate	6%
Federal Tax Rate	35%
Modified Accelerated Cost Recovery System Depreciation Term	15 year life
IRR	12%

4.4.1 Cash Flow

To assess the IRR and PW of each scenario, it is necessary to calculate the after tax cash flow (ATCF). To calculate the ATCF, it is necessary to first calculate the revenues (R_k), cash outflows (E_k), sum of all noncash or book costs such as depreciation (d_k), net income before taxes, effective income tax rate (t), and income taxes (T_k) for each year (k). The taxable income is revenue minus the sum of all cash outflows and noncash costs. Therefore the income taxes per year are defined as follows (Sullivan 2003):

$$T_k = t(R_k - E_k - d_k) \tag{1}$$

Depreciation for the economic calculations was calculated using a standard Modified Accelerated Cost Recovery System depreciation method with a property class of 15 years. Depreciation was assumed for the TCI for each reactor module and fossil process train with the first charge occurring the year the corresponding HTGR/process train comes online, i.e. when initial revenues are received. Table 11 presents the recovery rates for a 15-year property class (Perry 2008).

Table 11. Modified accelerated cost recovery system (MACRS) depreciation.

Year	Recovery Rate	Year	Recovery Rate
1	0.05	9	0.0591
2	0.095	10	0.059
3	0.0855	11	0.0591
4	0.077	12	0.059
5	0.0693	13	0.0591
6	0.0623	14	0.059
7	0.059	15	0.0591
8	0.059	16	0.0295

The ATCF is then the sum of the before-tax cash flow (BTCF) minus the income taxes owed. Note that the expenditures for capital are not taxed but are included in the BTCF each year there is a capital expenditure (C_k); this includes the equity capital and the debt principle. Figure 17 presents the yearly ATCFs for the nuclear-integrated RO desalination case at a 12% IRR.

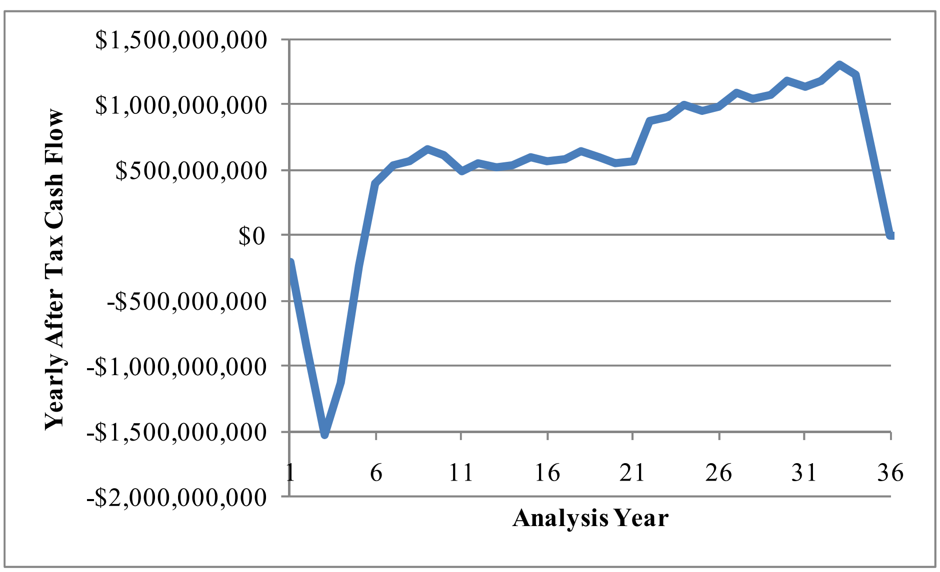

Figure 17. ATCFs, HTGR-integrated RO desalination, 12% IRR.

The BTCF is defined as (Sullivan 2003)

$$BTCF_k = R_k - E_k - C_k. \tag{2}$$

The ATCF can then be defined as

$$ATCF_k = BTCF_k - T_k. \tag{3}$$

4.4.1.1 Capital Cash Flows during Construction

Capital cash flows for the HTGR and fossil processes during construction were calculated for each year of construction based on two separate correlations. First, the percentage of capital assigned to each module or train was calculated based on an exponential correlation (Demick 2011). The exponent for the correlation is calculated based on the current module/train number so that

$$y(Mod) = 0.102 \times \ln(Mod + 0.963) - 0.402 \tag{4}$$

where *y* is the exponent for the current module/train and *Mod* is the module/train being evaluated. The capital fraction is then determined for each module/train by

$$ModF(Mod) = \left(1 - \sum_{i=1}^{i=Mod} ModF(i-1)\right) \times (Number - (Mod - 1))^{y(Mod)} \tag{5}$$

where *Number* is the total number of reactor modules or process trains. The yearly fractional breakdown for each module's/train's capital is calculated by applying a generic standard cumulative distribution, the S-Curve, as recommended by the GEN-IV International Forum (GIF) (2007). The capital breakdown per month is calculated as

$$CapF(month) = 0.5 \times \left(\sin\left(\frac{\pi}{2} + \frac{\pi \times month}{c\_months}\right) + 1\right) - CapF(month - 1) \tag{6}$$

where *month* is the current month in the reactor/fossil construction period and *c_months* is the total number of months in the current module's/train's construction period. The capital fraction for each year is calculated by summing the capital fraction for the corresponding months. The yearly capital fractions are then multiplied by the module/train fraction to determine to overall yearly capital fractional breakdown per module/train.

Figure 18 presents the percentage of TCI spent each year of construction for the HTGR-integrated RO desalination case.

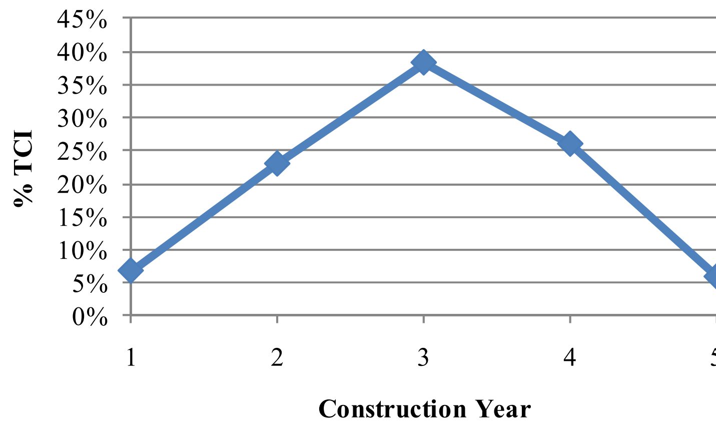

Figure 18. Percentage of TCI spent each year of construction, HTGR-integrated RO desalination.

4.4.1.2 Reactor Refueling Cash Flows

Reactor refueling charges occur in the year a refueling is scheduled. The occurrences are determined based on the total number of reactor modules, when the modules come online, and the specified refueling period.

4.4.2 Internal Rate of Return

The IRR is the most widely used method for performing engineering economic analyses. It solves for the interest rate that equates the equivalent worth of an alternative's cash inflows to the equivalent worth of cash outflows (ATCF), i.e., the interest rate at which the PW is zero. The resulting interest is the IRR (i'). For the project to be economically viable, the calculated IRR must be greater than the desired minimum annual rate of return (Sullivan 2003).

$$PW(i') = \sum_{k=0}^{N} ATCF_k (1+i')^{-k} = 0 \quad (7)$$

IRR calculations were performed for all cases of the calculated TCI. The price of heat and electricity necessary for an IRR of 12% and a PW of zero was also calculated for each case. All calculations were performed using Excel.

A CO_2 tax was added to the calculations in all cases to determine the price of water necessary for a 12% IRR and a CO_2 tax of \$0/ton to \$200/ton, which was then added to the existing yearly tax liability.

5. ECONOMIC MODELING RESULTS

Table 12 presents the results for the conventional desalination and the nuclear-integrated desalination cases, for low, average, and high natural gas prices, presenting the IRR for selling water at the market price, and the water selling price required for a 12% IRR. Figures 19 through 21 present the necessary selling price of water for a 12% IRR as a function of the natural gas price for the RO, MED, and MSF processes.

Table 12. Conventional and nuclear desalination economic results[a].

	RO Desalination TCI		**MED Desalination TCI**		**MSF Desalination TCI**	
	IRR-%	**$/m^3**	**IRR-%**	**$/m^3**	**IRR-%**	**$/m^3**
Desalination	$2,433,259,355		$1,898,039,582		$2,647,408,183	
Low NG:	9.5	0.79	3.7	0.79	1.0	0.79
$4.50/MSCF	12.00	1.27	12.00	1.93	12.00	2.76
Desalination	$2,433,259,355		$1,898,039,582		$2,647,408,183	
Average NG:	6.4	0.79	-6.4	0.79	N/A	0.79
$5.50/MSCF	12.00	1.79	12.00	2.66	12.00	3.71
Desalination	$2,433,259,355		$1,898,039,582		$2,647,408,183	
High NG:	N/A	0.79	N/A	0.79	N/A	0.79
$12.00/MSCF	12.00	5.17	12.00	7.41	12.00	9.90
HTGR Desalination	$6,071,731,162		$4,575,471,072		$5,755,302,345	
	2.5	0.79	1.6	0.79	0.2	0.79
	12.00	4.34	12.00	4.20	12.00	4.83

a . When the IRR is listed as N/A it indicates that the manufacturing costs exceed the revenues.

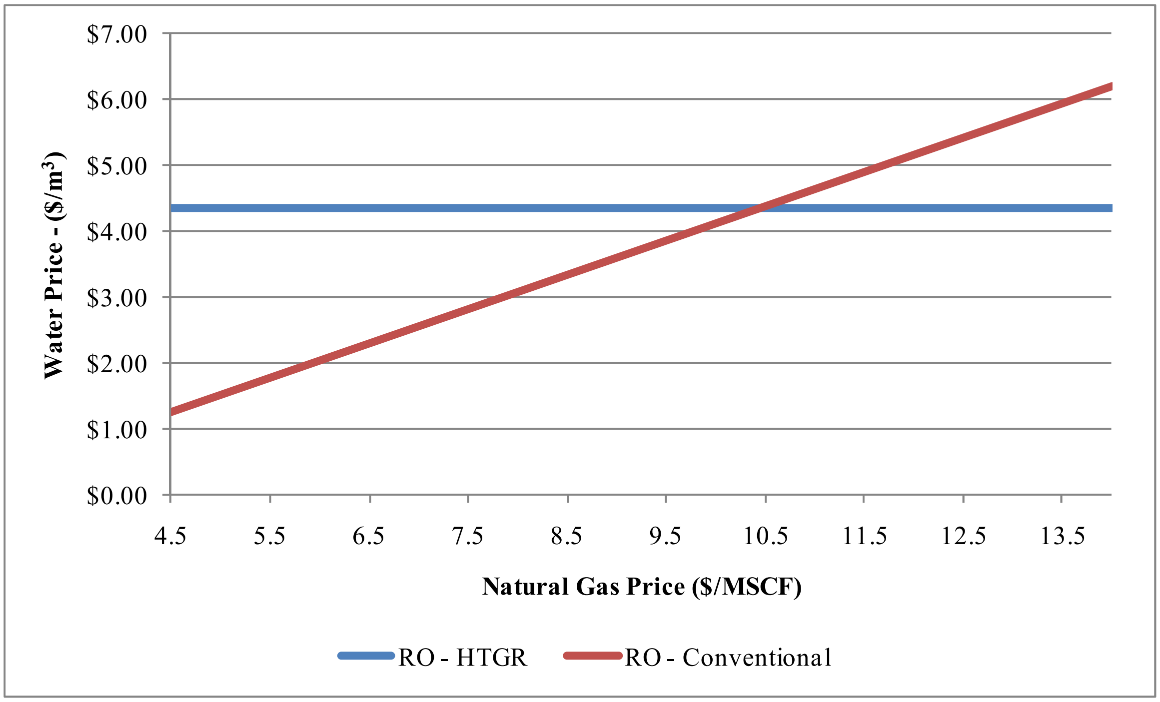

Figure 19. Conventional and nuclear RO desalination, water price as a function of natural gas price, 12% IRR.

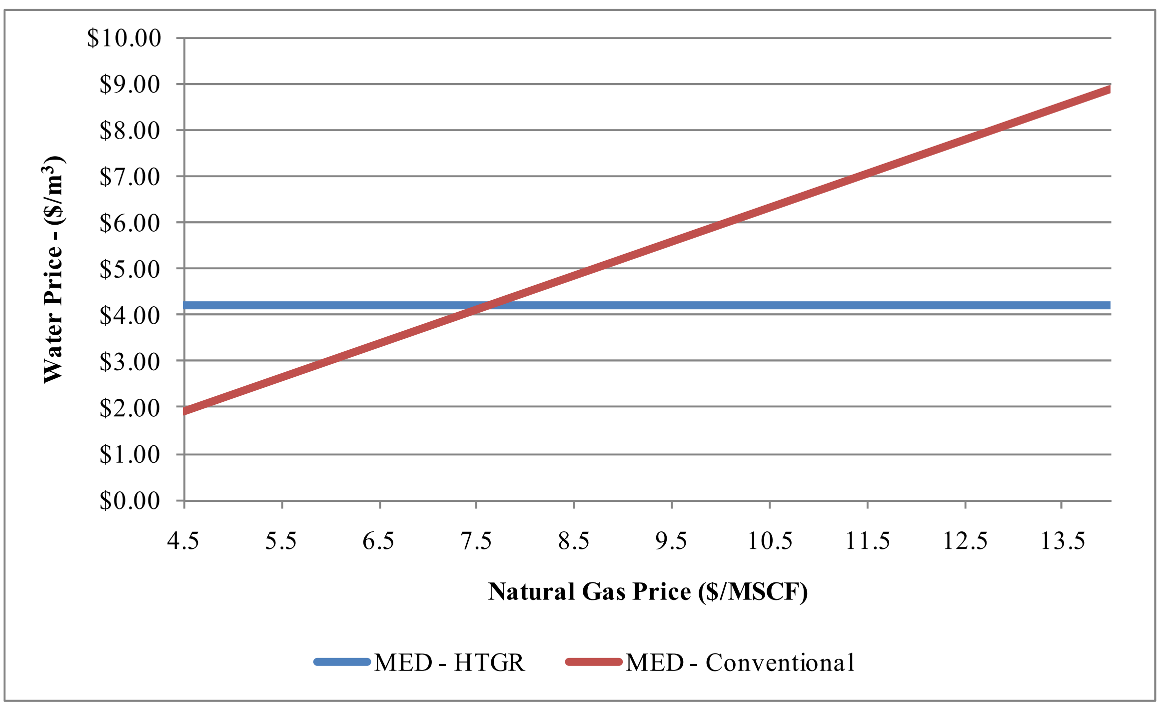

Figure 20. Conventional and nuclear MED desalination, water price as a function of natural gas price, 12% IRR.

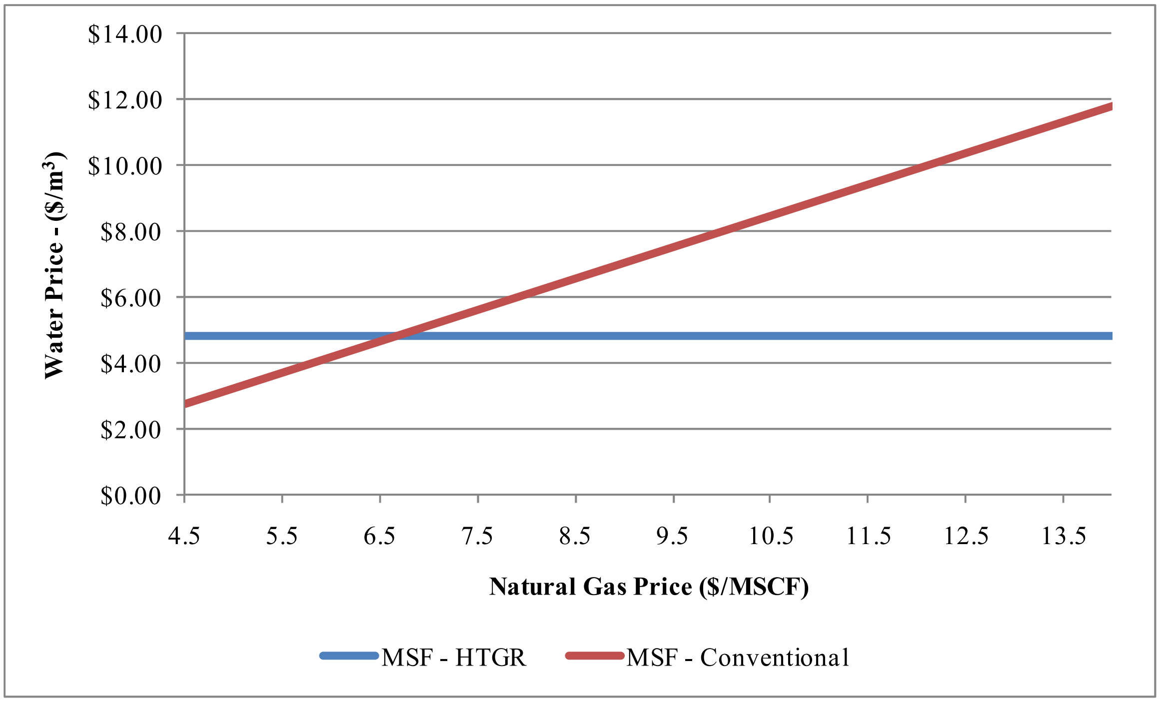

Figure 21. Conventional and nuclear MSF desalination, water price as a function of natural gas price, 12% IRR.

From these results, it is apparent that the nuclear-integrated desalination option provides economic stability with respect to fluctuations in natural gas prices. Only at higher natural gas prices do the nuclear-integrated desalination processes economically outperform the conventional processes. The natural gas price for the RO process must be at or above $10.50/MSCF in order for the nuclear-integrated case to economically outperform the conventional case. The natural gas price for the MED and MSF processes drops to approximately $7.50/MSCF and $6.50/MSCF, respectively, for the nuclear-integrated options to outperform the conventional cases. This is because both heat and power are being used in the desalination process, whereas only power is used in the RO process.

Table 13 presents the carbon tax results for the conventional and nuclear-integrated desalination cases at the average natural gas price. Figures 22, 23, and 24 depict the carbon tax results for the conventional and nuclear-integrated desalination cases for an average natural gas price and a 12% IRR.

The carbon tax results show that the nuclear-integrated desalination cases only outperform the conventional desalination case at a 12% IRR and average natural gas price when the carbon tax is around \$80/ton-CO_2 for the RO case, \$35/ton-CO_2 for the MED case, and \$20/ton-CO_2 for the MSF case. Again, the CO_2 tax required decreases for the MED and MSF cases as CO_2 emission increase for the conventional cases given the large heat requirements.

Table 13. Conventional and nuclear desalination carbon tax results at 12% IRR and average natural gas price.

Carbon Tax $/ton		RO Desalination Water Price ($\$/m^3$)	MED Desalination Water Price ($\$/m^3$)	MSF Desalination Water Price ($\$/m^3$)
Conventional Desalination	0	1.79	2.66	3.71
	50	3.28	4.76	6.45
	100	4.80	6.92	9.25
	150	6.33	9.07	12.06
	200	7.87	11.23	14.87
HTGR Desalination	0	4.34	4.20	4.83
	50	4.34	4.20	4.83
	100	4.34	4.20	4.83
	150	4.34	4.20	4.83
	200	4.34	4.20	4.83

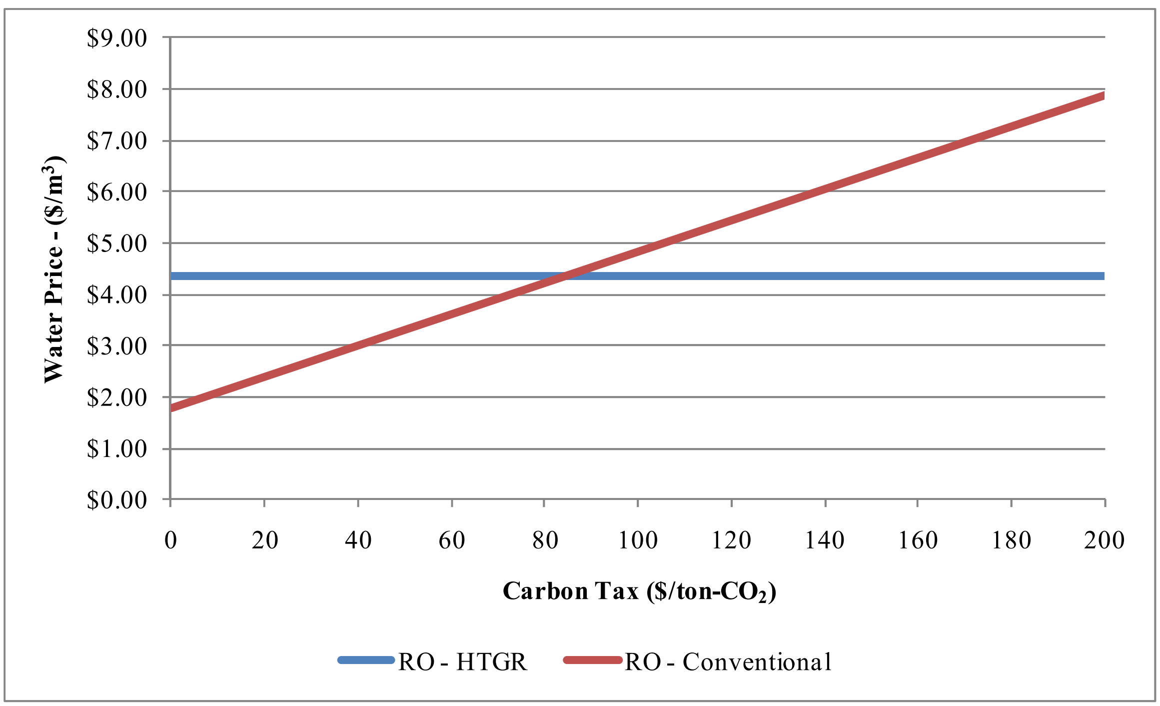

Figure 22. Conventional and nuclear RO desalination, water price as a function of a carbon tax, 12% IRR, average natural gas price.

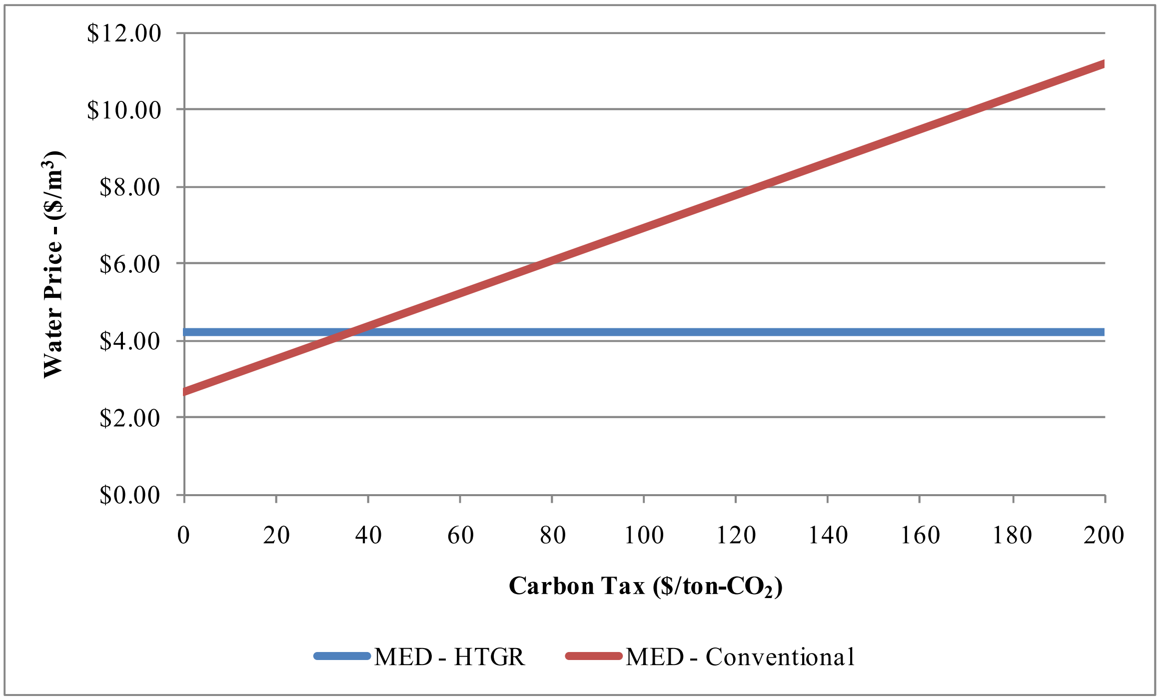

Figure 23. Conventional and nuclear MED desalination, water price as a function of a carbon tax, 12% IRR, average natural gas price.

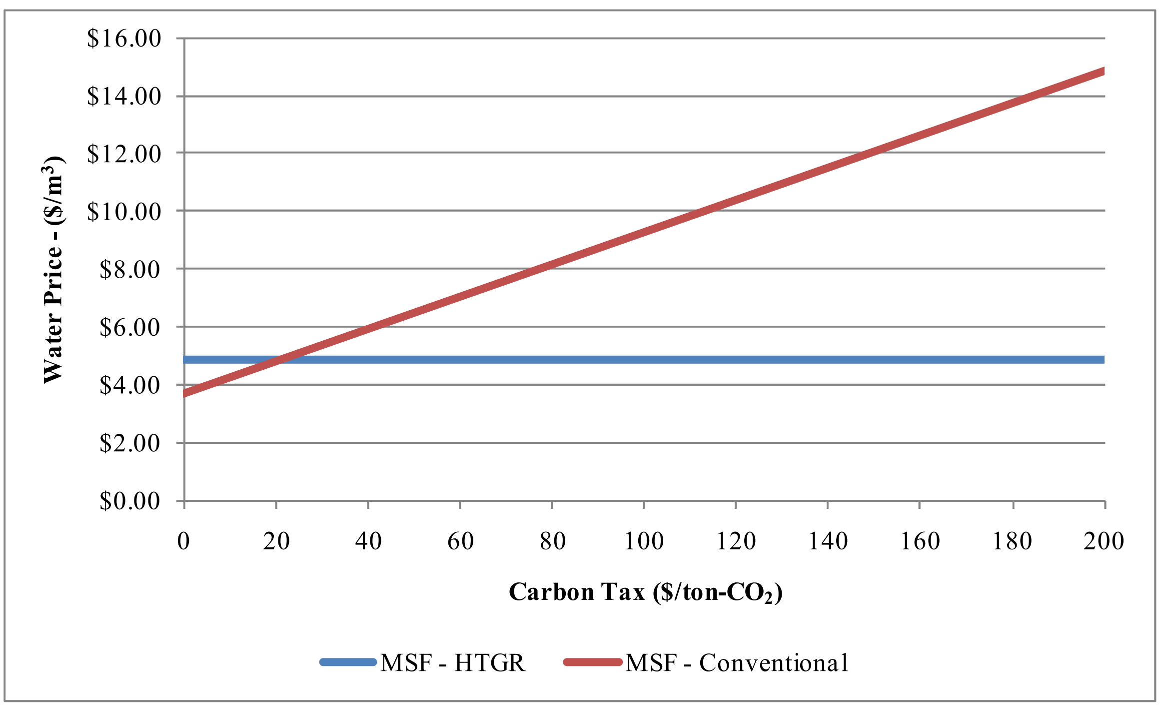

Figure 24. Conventional and nuclear MSF desalination, water price as a function of a carbon tax, 12% IRR, average natural gas price.

6. SENSITIVITY ANALYSIS

A sensitivity analysis was conducted for the nuclear-integrated desalination cases to assess the impact various changes in the baseline economic assumptions would have on the required product selling price. The result of this sensitivity analysis is a tornado diagram, which is useful in comparing the relative importance of variables, where the sensitive variable is varied while all other variables are held at baseline values.

The baseline economic assumptions for the sensitivity analysis were varied to determine the effect on the product selling price for the HTGR-integrated cases only. Table 14 lists the values used in the economic sensitivity analysis.

Table 14. Lower, baseline, and upper values used in the economic sensitivity analysis.

	Lower Value	**Baseline Value**	**Upper Value**
IRR (%)	10	12	15
Debt Ratio (%)	80	50	0
Debt Interest Rate (%)[b]	4.5	8	10
Loan Term (years)	20	15	10
Construction Period per HTGR (months)	24	36	60
HTGR Staffing Level		Design Supplier	INL Staffing[c]
Economic Recovery Period (years)	40	30	20
HTGR TCI	-30%	TCI	+50%
HTGR Refueling Period (months)	24	18	12

The sensitivity analysis was conducted for each desalination process evaluated.

Table 15 summarizes the results of the sensitivity analysis listing the required product selling prices for the various nuclear-integrated desalination cases as well as the percent change in the product selling price versus the baseline case. The tornado plots are presented in Figures 25, 26, and 27 for the HTGR-integrated RO, MED, and MSF desalinations, respectively.

From the economic sensitivity analysis, the uncertainty in the HTGR TCI (AACE Class 4) can have the largest impact on the required product selling price, followed by the assumed IRR and the debt-to-equity ratio.

b. The debt interest rate selected in the sensitivity analysis is also used for the interest on debt during construction.

c. The INL staffing level is outlined in TEV-1196. It assumes 595 employees for a four-pack facility versus the design supplier estimate of 418 employees (INL 2011a).

Table 15. Results from the economic sensitivity analysis, nuclear-integrated desalination.

	Nuclear-Integrated RO Desalination		**Nuclear-Integrated MED Desalination**		**Nuclear-Integrated MSF Desalination**	
	$\$/m^3$	% Change	$\$/m^3$	% Change	$\$/m^3$	% Change
Baseline Product Price	**4.34**	—	**4.20**	—	**4.83**	—
IRR						
10%	3.44	-21	3.40	-19	3.98	-18
15%	5.85	35	5.54	32	6.26	30
Debt Ratio						
80%	3.77	-13	3.69	-12	4.28	-11
0%	5.65	30	5.36	28	6.06	25
Debt Interest Rate						
4.5%	3.74	-14	3.66	-13	4.26	-12
8%	4.71	9	4.53	8	5.18	7
Loan Term						
20 years	4.15	-4	4.03	-4	4.65	-4
10 years	4.59	6	4.42	5	5.06	5
Construction Period						
24 months per HTGR	4.11	-5	3.98	-5	4.61	-5
60 months per HTGR	4.85	12	4.68	11	5.30	10
Staffing Level						
INL Staffing	4.61	6	4.47	6	5.10	6
Economic Recovery Period						
40 years	4.06	-6	3.94	-6	4.56	-6
20 years	5.12	18	4.90	17	5.57	15
HTGR TCI						
-30% TCI	3.01	-31	2.93	-30	3.59	-26
+50% TCI	6.55	51	6.30	50	6.89	43
Refueling Period						
24 months	4.06	-6	3.92	-7	4.55	-6
12 months	4.90	13	4.75	13	5.38	11
Product Market Price	0.79	-82	0.79	-81	0.79	-84

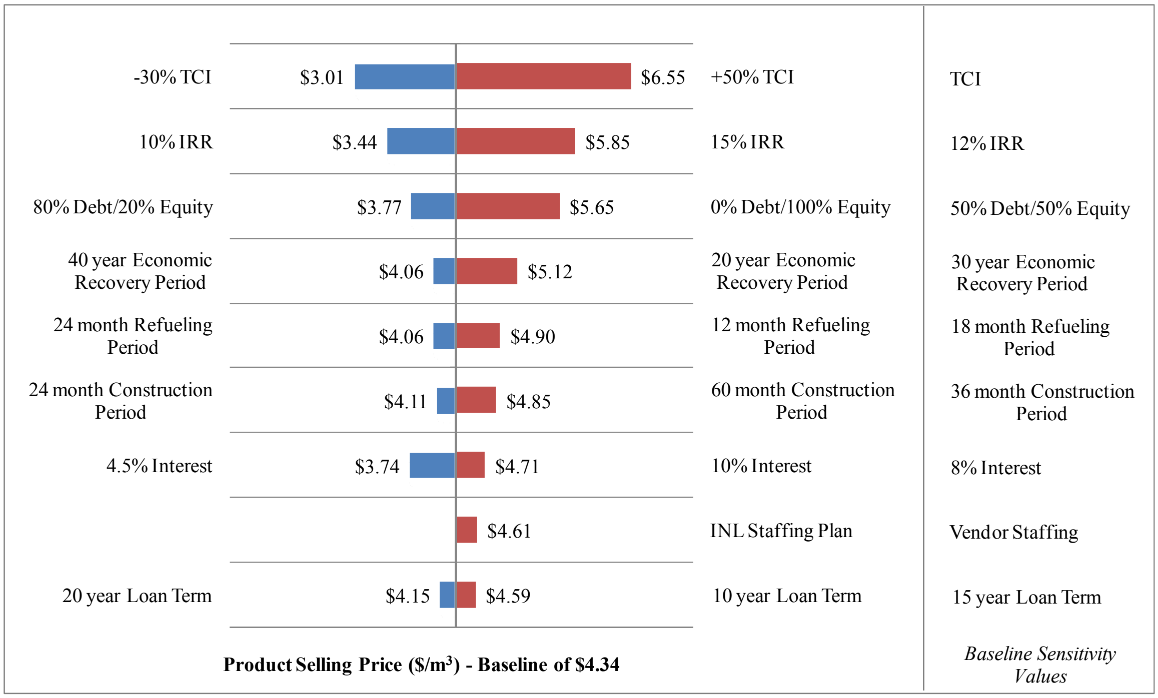

Figure 25. HTGR RO sensitivity analysis.

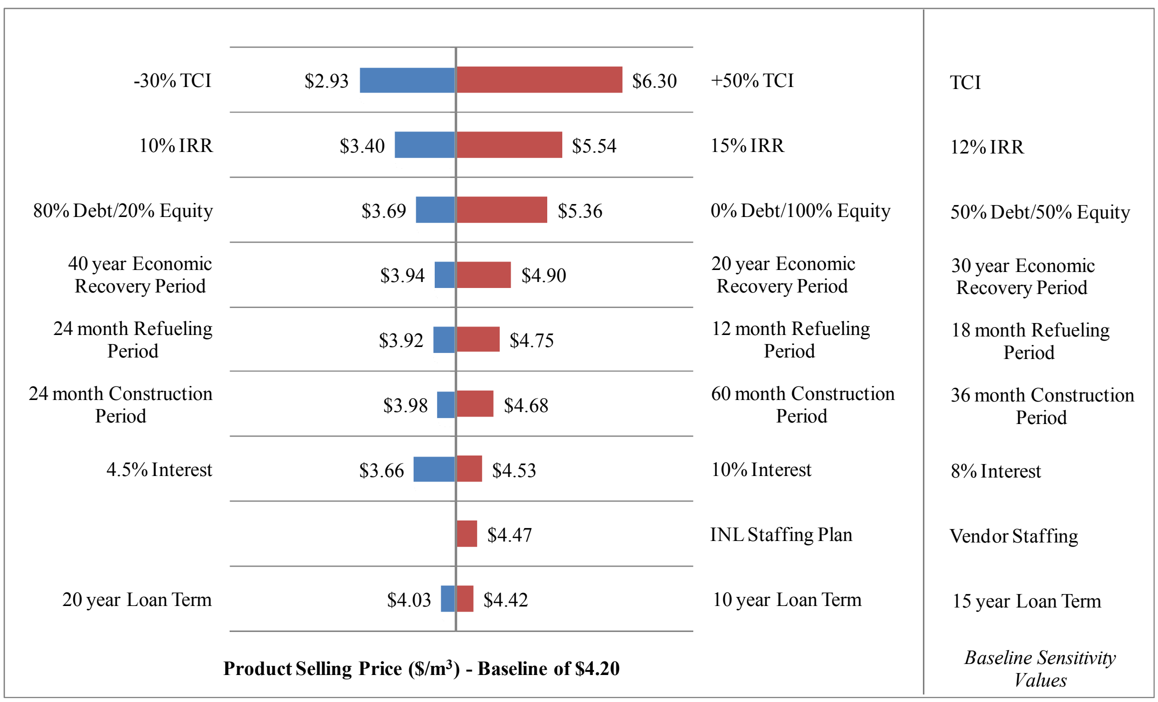

Figure 26. HTGR MED sensitivity analysis.

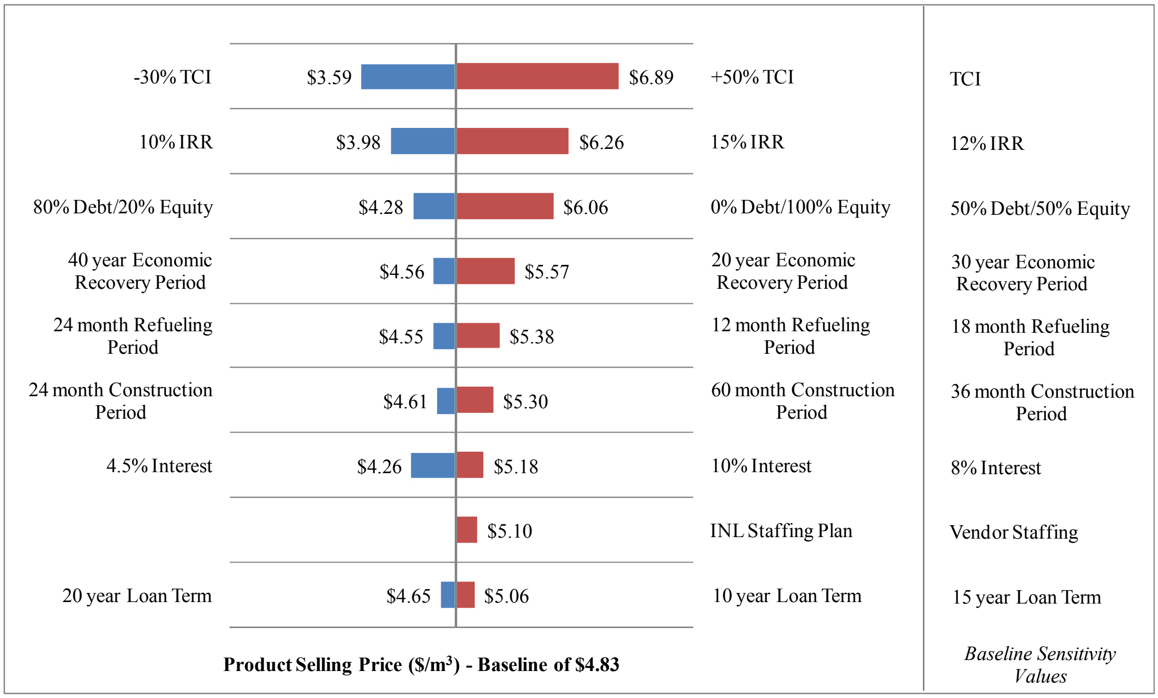

Figure 27. HTGR MSF sensitivity analysis.

7. DISCUSSION

This TEV compared the overall mass and energy balances associated with conventional and HTGR-integrated electricity production and seawater desalination. The results indicate that the production of purified water from seawater may be accomplished with either natural gas or an HTGR.

The economics of all processes are driven by electricity production. It is anticipated that the major revenue stream from an integrated plant would be generated by the sale of electricity and that the purified water would be the minor revenue stream. Also, based on the results of the analysis, it is understandable why most new seawater desalination plants are based on RO technology. Since these plants require only electricity they are not required to be co-located with the electrical power plant. The MSF and MED technologies, which use low-pressure steam and electricity, must be located near a readily accessible low-pressure steam source.

Importantly, there are other options that should be added to this evaluation as additional design and operational details become available. For example, low temperature thermal desalination plants have been envisioned. These plants would use the low-grade heat from the Rankine cycle (45°C) to desalinate seawater. The plants would operate on the very small temperature difference between the low grade heat rejection of an HTGR or fossil plant to flash seawater and produce purified water. This approach could be much cheaper than current methods when coupled to an electric generating station, but the data available to perform such an analysis is presently inadequate. Once the necessary data are available, it is recommended that this process be evaluated and compared to the RO, MSF, and MED processes.

8. CONCLUSIONS AND RECOMMENDATIONS

This study concludes that both an NGCC power plant and an HTGR power plant are capable of supplying the electricity and steam needed to desalinate seawater, and that the economics of desalination in an integrated plant are highly dependent on the economics of electricity production.

The results obtained from this study are based on a seawater temperature of 30°C and a salinity of 30,000 mg/L (ppm). If a plant of significantly different temperature and salinity are desired, additional study would be required. However, since the economics of the process also depend on the economics of electricity generation, it is recommended that the market for electricity be considered when evaluating a potential location for water purification.

9. REFERENCES

AACE, 2005, Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Process Industries, AACE International Recommended Practice No. 18R-97.

Demick, L., 2011, HTGR Cost Information, personal communications.

EIA, 2010, “Updated Capital Cost Estimates for Electricity Generation Plants,” U.S. Energy Information Administration, November 2010.

EIA, 2011a, Average Retail Price of Electricity to Ultimate Customers: Total by End-Use Sector (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html), April 14–29, 2011.

EIA, 2011b, Electricity Explained: Factors Affecting Electricity Price (http://www.eia.gov/energyexplained/index.cfm?page=electricity_factors_affecting_prices), July 28, 2011.

EIA, 2011c, Monthly United States Natural Gas Industrial Price (http://www.eia.gov/dnav/ng/hist/n3035us3m.htm), June 29–July 6, 2011.

Excel 2007, Version 12.0, Redmond, Washington: Microsoft Corporation, 2007.

GIF, 2007, Cost Estimating Guidelines for Generation IV Nuclear Energy Systems, GIF/EMWG/2007/004, Rev. 4.2.

IAEA, 2007, IAEA-TECDOC-1524, “Status of Nuclear Desalination in IAEA Member States,” International Atomic Energy Agency, January 2007.

IAEA, 2000, IAEA-TECDOC-1186, "Examining the Economics of Seawater Desalination Using the DEEP Code, International Atomic Energy Agency, November 2000.

INL, 2011a, "Assessment of High-Temperature Gas-Cooled (HTGR) Capital and Operating Costs," Idaho National Laboratory, TEV-1196, Rev. 0, April 29, 2011.

INL, 2011b, "Sensitivity of HTGR Heat and Power Production to Reactor Outlet Temperature, Economic Analysis," Idaho National Laboratory, TEV-988, Rev. 1, June 30, 2011.

Micale, G., A. Cipollina, and L. Rizzuti, "Seawater Desalination: Conventional and Renewable Energy Processes," Springer-Verlag Berline Heidelbert, 2009.

NRC, 2010, Report of Waste Burial Charges: Changes in Decommissioning Waste Disposal Costs at Low-Level Waste Burial Facilities, NUREG-1307, Rev. 14.

NUS Consulting, 2008, Average Water Costs Increase by 7.3% (http://www.marketwire.com/press-release/Average-US-Water-Costs-Increase-by-73-903477.htm), September 24, 2008–June 30, 2011.

Ophir, A. and Lokiec, F., "Advanced MED Process for Most Economical Sea Water Desalination," Desalination 182, pp. 187-198, 2005.

Perry, R.H., and D.W. Green, 2008, *Perry's Chemical Engineers' Handbook* (8th Edition), New York: McGraw Hill.

Sullivan, W.G., E.M. Wicks, and J.T. Luxhoj, 2003, *Engineering Economy*. Upper Saddle River: Printice Hall.

USBR, 2003, "Design Handbook for Planners: Desalination and Water Purification Research and Development Program," U.S. Department of the Interior Bureau of Reclamation, Report No. 72, 3rd Edition, July 2003.

Wilf, M., 2007, "Desalination," *Kirk-Othmer Encyclopedia of Chemical Technology*, New York: John Wiley & Sons.

10. APPENDIXES

Appendix A, Mass and Energy Balance Calculations for Reverse Osmosis, Multi-stage Flash Distillation, and Multiple Effect Distillation

Appendix B, Power Cycle Efficiency and Carbon Dioxide Emissions Calculations

Appendix C, HYSYS Runs – Power Cycle Efficiencies for NGCC and HTGR Powered Rankine Cycles

Appendix D, Fossil and HTGR Integration with RO, MSF, and MED Calculations

Appendix A

Mass and Energy Balance Calculations for Reverse Osmosis, Multi-Stage Flash Distillation, and Multiple Effect Distillation

The overall mass and energy balance calculations for RO, MSF, and MED are based on a purified water production rate of 400,000 m^3/day. The assumptions used to complete these calculations are presented in Table 2 in the main body of this Technical Evaluation (TEV). The calculations are shown in separate sections for RO, MSF, and MED.

RO

The RO plant requires only electricity and seawater. Based on the assumptions provided in Table 2 the amount of electricity needed to produce purified water from seawater is 4 kWe hr/m^3. The amount of electricity required to support a 100,000 m^3/day plant is calculated as

$$400{,}000\,\frac{m^3}{day} \times 4\,\frac{kWe\;hr}{m^3} \times \frac{MWe}{1{,}000\;kWe} \times \frac{day}{24\;hrs} = 66.7\;MWe. \tag{A-1}$$

MSF

The MSF plant requires both electricity and steam. The electricity needs of the plant are calculated from the value provided in Table 2 for the MSF plant, 3 kWe hr/m^3 as

$$400{,}000\,\frac{m^3}{day} \times 3\,\frac{kWe\;hr}{m^3} \times \frac{MWe}{1{,}000\;kWe} \times \frac{day}{24\;hrs} = 50\;MWe. \tag{A-2}$$

The steam needs of the MSF plant are calculated from the GOR of 8.85 kg purified water per kg of steam (saturated steam at 110°C) as

$$400{,}000\,\frac{m^3}{day} \times 1\,\frac{kg\;steam}{8.85\;kg\;water} \times \frac{1{,}000\;kg\;water}{m^3} = 4.58\times 10^7 kg\;steam/day. \tag{A-3}$$

For the Rankine cycle associated with the MSF plant, this means that 4.58×10^7 kg steam/day would be removed from the low pressure turbine. In order to simplify the analysis, the overall size of the fossil and high temperature gas-cooled reactor (HTGR) plants was sized to generate the required amount of steam, 4.58×10^7 kg steam/day.

MED

The MED plant requires both electricity and steam. Based on the value provided in Table 2, 2 kWe hr/m^3, the electricity needs of the MED plant are calculated as

$$400{,}000\,\frac{m^3}{day} \times 2\,\frac{kWe\;hr}{m^3} \times \frac{MWe}{1{,}000\;kWe} \times \frac{day}{24\;hrs} = 33.3\;MWe. \tag{A-4}$$

The steam needs of the MED plant are calculated from the GOR of 12.2 kg purified water/kg steam (saturated steam at 110°C) as

$$400{,}000\ \frac{m^3}{day} \times \frac{1\ kg\ steam}{12.2\ kg\ water} \times \frac{1{,}000\ kg\ water}{m^3} = 3.57\ \times 10^7 kg\ steam/day. \qquad \text{(A-5)}$$

For the Rankine cycle associated with the MED plant, this means that 3.57×10^7 kg steam/day would be removed from the low pressure turbine. In order to simplify the analysis, the overall size of the natural gas and HTGR plants was sized to generate the required amount of steam, 3.57×10^7 kg steam/day.

Appendix B

Power Cycle Efficiency and Carbon Dioxide Emissions Calculations

Power Cycle Efficiency

Power cycles considered in this Technical Evaluation (TEV) include the Rankine cycle for the high temperature gas-cooled reactor (HTGR) and the natural gas combined cycle (NGCC). The Rankine cycle model used for calculating overall thermal efficiencies is based on the cycle presented in "Steam, Its Generation and Use – Edition 41." (see Figure 10 on page 2-18). This cycle consists of high-, intermediate-, and low-pressure turbines. The highest steam pressure in this cycle is 24 MPa (3,481 psi) and the highest steam temperature is 593°C (1,099°F). The HYSYS calculations were scaled to utilize 600 MW(t) of heat produced by an HTGR. With these conditions, the flow rate of the lowest pressure steam (saturated steam at a temperature of 110°C) in the final turbine of the Rankine cycle is 159.7 kg/sec (174.9 kg/sec * 0.9131 = 159.7 kg/sec – see HYSYS calculations presented in Appendix C). This steam is a reasonable selection for use in the MSF or MED process.

Based on calculation performed using HYSYS, the overall thermal efficiency of the HTGR-integrated Rankine power cycle was calculated to be 43% (see HYSYS calculations presented in Appendix C), and 600 MW(t) of nuclear heat would generate 258 MW(e). Similarly, the efficiency of the NGCC process was calculated to be 49.77% and 600 MW(t) would generate 299 MW(e).

HYSYS calculations were used to estimate the overall thermal efficiency of the HTGR-based Rankine cycles if some or all of the low pressure steam was removed from the final steam turbine. The results of the analysis are presented in Table B.1. As the amount of steam removed from the low-pressure turbine increases, the overall power cycle efficiency decreases. In order to simplify the analysis, the heat provided to the power cycle was scaled to generate the exact amount of low-pressure steam needed to support the MSF and MED processes. In other words, the overall power cycle efficiency for RO is assumed to be 41%, and the electrical efficiency for MED and MSF is assumed to be 32.4%, since these two processes use low-pressure steam from the Rankine power cycle.

Table B-1. Overall thermal efficiencies of a subcritical 600 MW(t) Rankine power cycle as low-pressure steam is removed from the final low-pressure turbine.

Description	Flow Rate of Steam Removed from Low-Pressure Turbine (kg/second)	Overall Power Cycle Efficiency
No low-pressure steam removed from Rankine cycle	0	43%
100% of low-pressure steam (saturated steam at 110°C) removed from Rankine cycle	159.7	34.16%

The overall thermal efficiency for generating electricity in the NGCC plant is 49.77%. This high efficiency is attained by operating a gas turbine in the natural gas combustion chamber and utilizing the steam generated in the combustion chamber to generate power in a Rankine cycle to generate electricity as shown in Figure 6 in the main body of this TEV. Based on HYSYS calculations, the gas turbine in an NGCC plant has a thermal efficiency of 33.63%. The Rankine cycle of the NGCC plant has a thermal efficiency of 16.14% for a combined overall efficiency of 49.77%. It assumed that all the steam, generated by the hot combustion gas leaving the turbine, generates low-pressure steam (saturated steam at 110°C) that is utilized by the MED and MSF distillation processes. The flow rate of steam for a 600 MW(t) NGCC plant is 147.2 kg/sec (1.27 $\times 10^7$ kg/day). If this steam is used/removed from the steam cycle, the thermal efficiency of the Rankine cycle portion of the NGCC is reduced from 16% to 16 × 32.4/41 = 12.6% and the overall thermal efficiency of the NGCC plant is 32 + 12.6 = 44.6%.

Fuel Consumption and Carbon Dioxide Emissions Calculations

The estimated carbon dioxide emissions from the natural gas fired plant were performed in HYSYS. The results of the calculations are shown in Appendix C.

HTGR – Fuel Use and Carbon Dioxide Emission Calculations

The quantity of fuel required to support HTGR operations was estimated based on information presented in the General Atomics Pre-Conceptual Design. The information presented in this report is based on a prismatic reactor. Additional study would be required to develop estimates for the pebble bed concept.

The prismatic reactor fuel is described in the General Atomics Conceptual Design Report for the SC-MHR. The fuel itself is compressed into cylindrical compacts that are loaded into graphite blocks. The amount of fuel required is based on actual uranium fuel and the amount of waste generated is based on the carbon block/fuel combination. This is why the volume of waste produced is significantly greater than the amount of fuel provided. The calculation is based on the following factors: (1) the mass of uranium per fuel element of 4.425 kg/fuel element, (2) 510 fuel elements replaced during refueling, and 3) refueling occurs every 530 days.

For a 600 MW(t) reactor, the amount of fuel used per day is

$$4.425\ \frac{kg\ U}{fuel\ element} \times \frac{510\ fuel\ elements}{530\ days} = 4.26\ kg/day \tag{B-1}$$

For the purposes of this report, it is assumed that the uranium is converted to heavy metal waste with the same mass as the uranium fed to the process.

It is assumed that there are no carbon dioxide emissions from HTGR-integrated processes.

Appendix C

HYSYS Runs—Power Cycle Efficiencies for Natural Gas Combined Cycle and High Temperature Gas-cooled Reactor Powered Rankine Cycles

Electronic files in this appendix attached to native file.

Appendix D

Fossil and High Temperature Gas-cooled Reactor Integration with Reverse Osmosis, Multi-Stage Flash Distillation, and Multi-Effect Distillation Calculations

Reverse Osmosis Calculations

The Reverse Osmosis (RO) process requires only electricity. To integrate power generation with RO, a common basis of 2,400 MW(t) to the high temperature gas-cooled reactor (HTGR) or Natural Gas Combined Cycle (NGCC) plant was used. The amount of electricity exportable to the grid was calculated based on the overall thermal efficiency of the fossil or HTGR power plant and the amount of electricity needed to purify 400,000 m^3 of seawater per day. The calculations for each are provide below.

Natural Gas Combined Cycle power plant combined (net thermal input of 2406 MW(t) – 2406 MW(t) × 0.4977 = 1,198 MW(e)) with an RO plant:

$$1{,}198\ MWe - 66.8\ MWe = 1131\ MWe. \qquad \text{(D-1)}$$

HTGR-integrated Rankine cycle power plant (2,400 MW(t) × 0.43 = 1032 MW(e)) combined with an RO plant:

$$1032\ MWe - 16.7\ MWe = 965\ MWe. \qquad \text{(D-2)}$$

Multi-Stage Flash Distillation Calculations

The Multi-Stage Flash Distillation (MSF) process requires both electricity and steam. To complete the integration of electrical power requirements, the amount of electricity needed to support the 400,000 m^3/day MSF process, 50 MW(e), was subtracted from the electricity produced by the Rankine Cycle. The size of the power plant was scaled to provide adequate steam, 4.58×10^7 kg/day, to support the MSF process as shown in the following equations.

With these assumptions, the size of the NGCC power plant required to support a 400,000 MSF plant is

$$\frac{4.58\times10^7\ \frac{kg\ steam}{day}}{1.27\times10^7\ \frac{kg\ steam}{day}} \times 1200\ MWt = 4329\ MWt. \qquad \text{(D-3)}$$

With these assumptions, the size of the HTGR power plant required to support a 400,000 MSF plant is

$$\frac{4.58\times10^7\ \frac{kg\ steam}{day}}{1.38\times10^7\ \frac{kg\ steam}{day}} \times 600\ MWt = 1990\ MWt. \qquad \text{(D-4)}$$

Multi-Effect Distillation Calculations (see Figure 14)

The Multieffect Distillation (MED) process requires both electricity and steam. To complete the integration of electrical power requirements, the amount of electricity needed to support production of 400,000 m^3 of water/day via the MED process, 33.3 MW(e), was subtracted from the electricity produced by the power plant. The size of the power plant was scaled to provide adequate steam, 1.13×10^7 kg/day, to support the MED process as shown in the following equations.

With these assumptions, the size of the NGCC power plant required to support a 400,000 m^3/day MED plant is

$$\frac{3.57 \times 10^7 \frac{kg\ steam}{day}}{1.27 \times 10^7 \frac{kg\ steam}{day}} \times 1200\ MWt = 3378\ MWt. \quad \text{(D-5)}$$

With these assumptions, the size of the HTGR power plant required to support a 400,000 m^3/day MED plant is

$$\frac{3.57 \times 10^7 \frac{kg\ steam}{day}}{1.38 \times 10^7 \frac{kg\ steam}{day}} \times 600\ MWt = 1553\ MWt. \quad \text{(D-6)}$$