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Sensitivity of HTGR Heat and Power Production to Reactor Outlet Temperature, Economic Analysis

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Changing the World's Energy Future

Michael George McKellar, A. M. Gandrik

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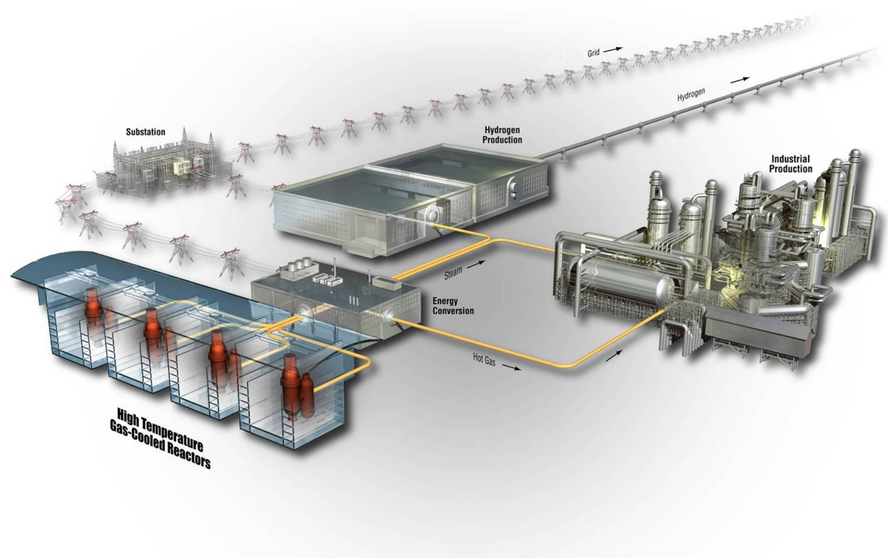

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SENSITIVITY OF HTGR HEAT AND POWER PRODUCTION TO REACTOR OUTLET TEMPERATURE, ECONOMIC ANALYSIS	Identifier: TEV-988 Revision: 1 Effective Date: ~~6/30/2011~~ 07/08/2011	Page: 1 of 31

NGNP Project	Technical Evaluation Study (TEV)	eCR Number: 593302

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0	8/31/2010	All	Newly issued document.
1	07/08/2011	All	Updated economic analysis.

EXECUTIVE SUMMARY

This technical evaluation (TEV) has been prepared as part of a study for the Next Generation Nuclear Plant (NGNP) Project to evaluate the economics of integrating a high-temperature gas-cooled reactor (HTGR) with conventional chemical processes. This TEV addresses the economics of heat and power produced using an HTGR, as well as the effect of increasing the reactor outlet temperature (ROT) on the economic results. These results are preliminary and should be refined as the design of the HTGR progresses, if the design of the HTGR is changed significantly, or if additional refinements of the HTGR capital and/or operating costs become available. The HTGR capital, operating and maintenance (O&M) costs, fuel, and decommissioning costs are based on the correlations and costs presented for a n^{th} of a kind HTGR in TEV-1196 (Idaho National Laboratory [INL] 2011a).

The production of heat and power, as well as the effect of increasing the ROT on process results, has previously been addressed in detail in TEV-981 (INL 2011b). In that report, detailed process models for heat and power production using an HTGR were developed, with a range of reactor outlet temperatures from 650 to 950°C, in 50°C increments. This report is a follow-up to TEV-981 and evaluates the economics of heat and power production, employing either a Rankine or Brayton cycle, for ROTs of 700 to 950°C, in 50°C increments for a single 600 MWt HTGR and a four-pack of 600 MWt HTGRs.. The following conclusions were drawn when evaluating the economics of heat and power production from an HTGR:

- The required selling price of heat and power decreases as the number of reactor modules is increased. This is due to gains in economies of scale for the capital costs and the fact that only an incremental increase in staffing is required for each additional module at multiple module sites.

- The economically optimal ROT for power generation from a Brayton cycle is 850°C, for power generation from a Rankine cycle 700°C, and for steam generation 800°C (steam at 540°C and 17 MPa). The optimal ROT for heat in the form of hot helium is dependent upon the process heat requirements. Figure ES 1 presents the required electricity selling price for the Rankine and Brayton cycles as a function of ROT and Figure ES 2 presents the required heat selling price as a function of ROT for a 12% internal rate of return (IRR).

- An economic sensitivity analysis was performed, it was determined that the uncertainty in the total capital investment can have the largest impact on the required product selling price, followed by the assumed IRR and the debt to equity ratio. Figure ES 3 presents a tornado diagram for the 700°C ROT HTGR with a Rankine power cycle, showing the resulting electricity selling price when varying the baseline economic assumptions.

- A sensitivity analysis on the reactor power level and the number of modules was also performed; the results show that as the reactor power level increases the required selling price of heat and power decreases due to gains in economies of scale for capital and operating costs. Furthermore, as the number of modules are increased the required

selling price of heat and power decreases. This is again due to gains in economies of scale. Figure ES 4 presents the reactor power level and module number results for a HTGR with a Rankine cycle at a ROT of 700°C.

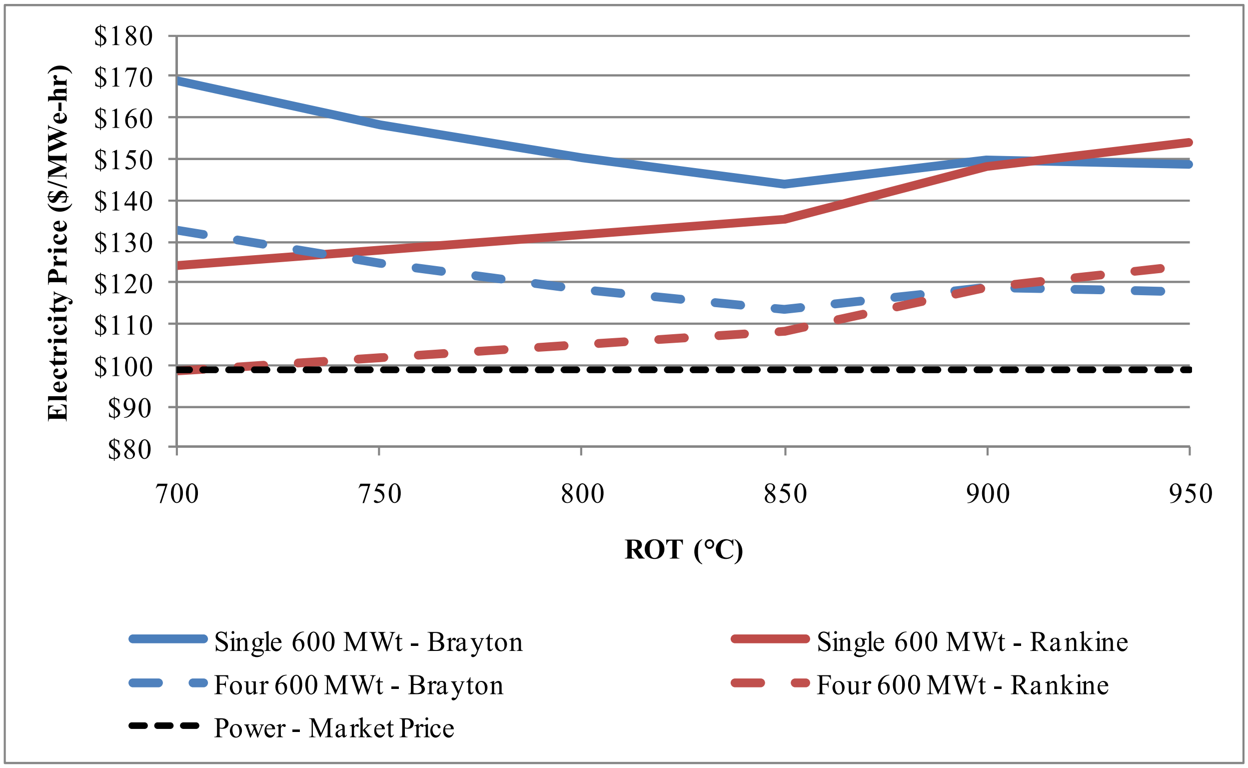

Figure ES 1. HTGR power generation results as a function of ROT, 12% IRR.

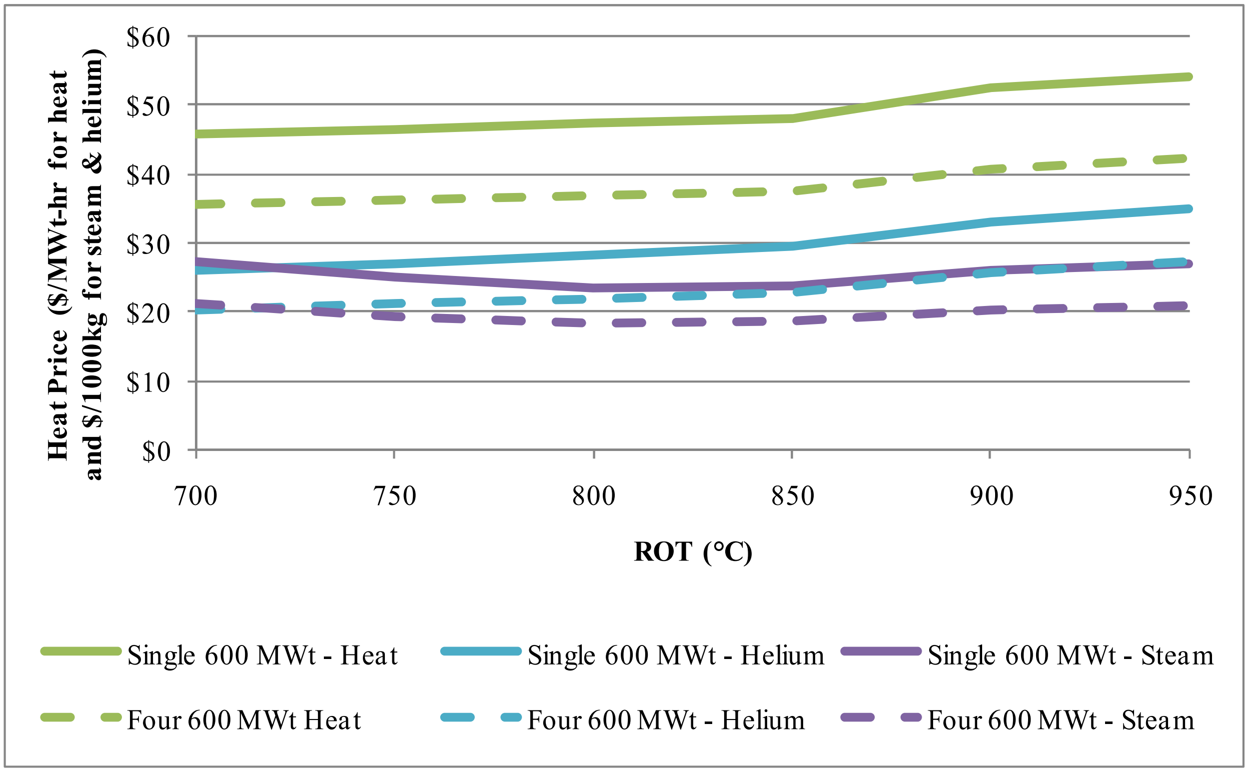

Figure ES 2. HTGR heat generation results as a function of ROT, 12% IRR.

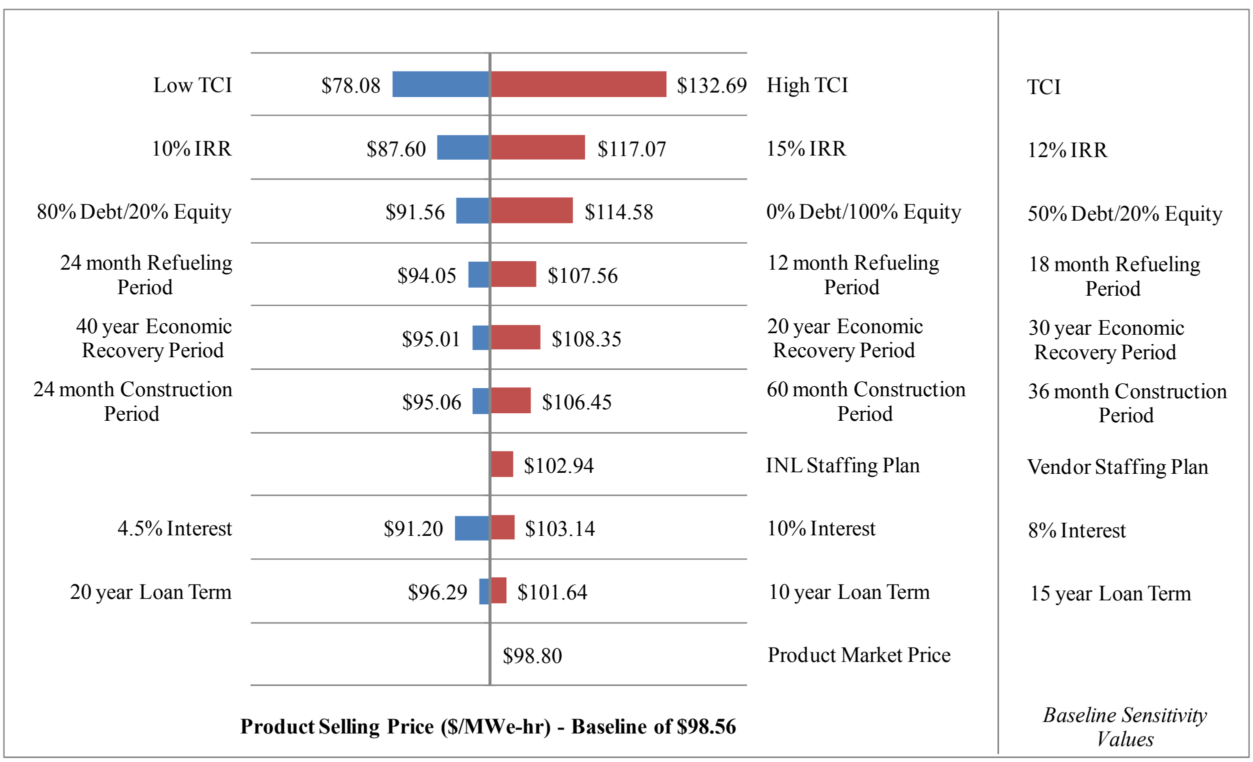

Figure ES 3. HTGR w/ Rankine cycle tornado plot, 4 600 MWt HTGRs, 700°C ROT, 12% IRR.

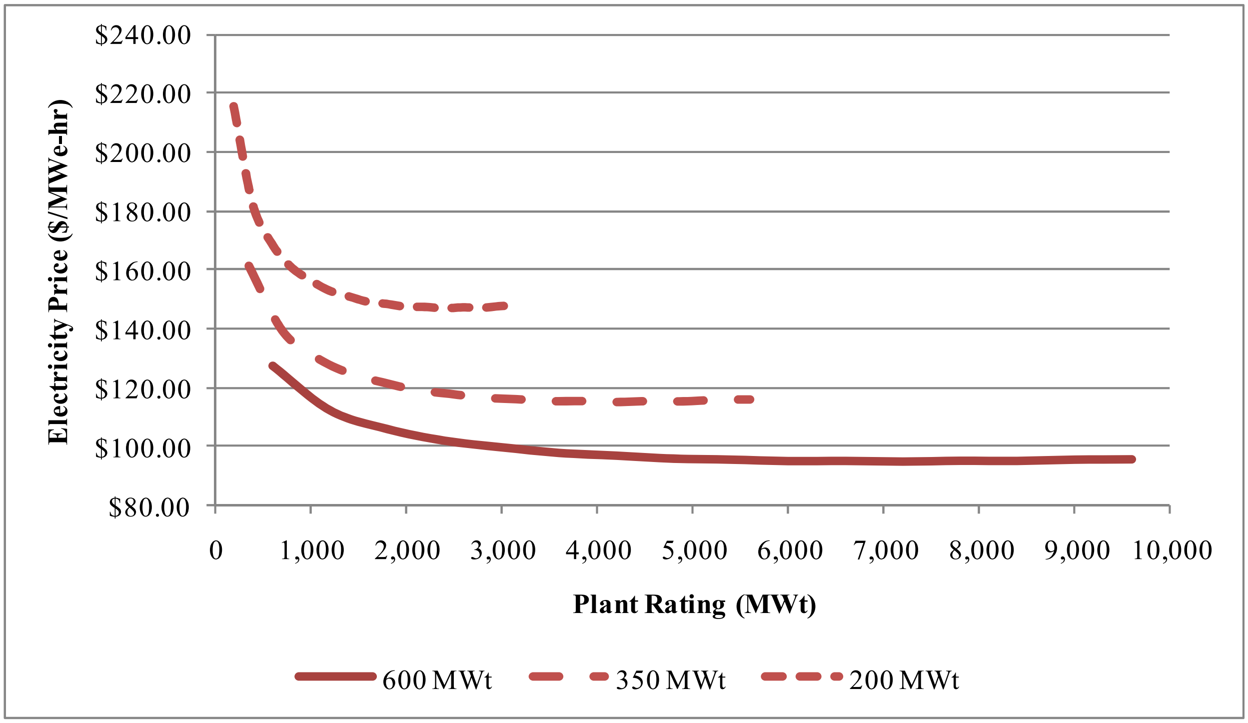

Figure ES 4. HTGR with Rankine cycle, sensitivity to reactor power level and the number of reactor modules, 700°C ROT, 12% IRR.

CONTENTS

ACRONYMS AND NOMENCLATURE

AACE	Association for the Advancement of Cost Engineering
BOE	balance of equipment
ATCF	after tax cash flow
BTCF	before tax cash flow
CEPCI	chemical engineering plant cost index
DOE	Department of Energy
EIA	Energy Information Administration
GIF	GEN-IV International Forum
HTGR	high temperature gas reactor
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
IRR	internal rate of return
MACRS	modified accelerated cost recovery system
MARR	minimum annual rate of return
NGNP	Next Generation Nuclear Plant
NIBT	net income before taxes
O&M	operations and maintenance
PW	present worth
ROT	reactor outlet temperature
TCI	total capital investment
TEV	technical evaluation
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
Mod	module being evaluated
ModF	capital fraction per module
month	current month in reactor construction period
Number	total number of reactor modules
R_k	revenues
t	tax rate
T_k	income taxes
y	exponent for current module

1. INTRODUCTION

This technical evaluation (TEV) has been prepared as part of a study for the Next Generation Nuclear Plant (NGNP) Project to evaluate the economics of integrating a high-temperature gas-cooled reactor (HTGR) with conventional chemical processes. The NGNP Project is being conducted under U.S. Department of Energy (DOE) direction to meet a national strategic need identified in the 2005 *Energy Policy Act* 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 DOE. 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.

The HTGR produces high-temperature helium that can be used to produce electricity and/or process heat for export in the form of high-temperature helium or steam. Previous studies conducted by Idaho National Laboratory (INL) over the past year have assumed an HTGR outlet temperature of 750°C; this reflects the initial HTGR design and assumes a more conservative outlet temperature. Additionally, a 50°C temperature approach was assumed between the primary and secondary helium loops when helium was the delivered working fluid. As a result, the maximum helium temperature available for heat exchange in those studies was 700°C.[1]

Although initial HTGR implementations will likely target an HTGR outlet temperature of 700 to 750°C, temperatures of 950°C are anticipated for later designs. Unlike previous INL studies performed, this study removes the 750°C minimum/maximum HTGR outlet temperature assumption. Instead, various reactor outlet temperatures (ROTs) are assessed. For this study, a 25°C temperature approach is assumed between the primary and secondary helium loops, as opposed to the 50°C assumption used in previous studies; this assumption is in line with current specification from the reactor design suppliers. This study investigates the impact of varying ROTs from 700 to 950°C, in 50°C increments. Hence, using the 25°C temperature approach assumption between the primary and secondary loops, high-temperature helium can be delivered at temperatures between 675 and 925°C. Steam delivery temperature is assumed to be constant at 540°C and 17 MPa. HTGR product conditions assumed for this analysis are shown in Table 1.

Table 1. Projected outputs of the NGNP.

HTGR Product	Product Description
Steam	540°C and 17 MPa
High-Temperature Helium	Delivered at 675 to 925°C and 9.1 MPa
Electricity	Generated by a Rankine or Brayton cycle, efficiency dependent upon ROT

[1]. See TEV-666, TEV-667, TEV-671, TEV-672, TEV-674, TEV-693, TEV-704, TEV-953, TEV-954, and INL/EXT-09-16942.

The production of heat and power, as well as the effect of increasing the ROT on process results, has previously been addressed in detail in TEV-981 (INL 2011b). In that report, detailed process models for heat and power production using an HTGR were developed, with a range of reactor outlet temperatures from 650 to 950°C, in 50°C increments. The models documented in TEV-981 are used as the basis for the economic analysis conducted in this report. The process modeling results along with the detailed HTGR costs presented in TEV-1196 are being used to revise the economics for heat and power production. This TEV assumes familiarity with TEV-981 and TEV-1196; hence, detailed descriptions of the process models documented in TEV-981 and the costs documented in TEV-1196 are not presented here.

The economic models used for this analysis have been developed in Microsoft Excel (Excel 2007). This study makes extensive use of these models; this TEV assumes familiarity with Excel. A detailed explanation of the software capabilities is beyond the scope of this study.

This TEV first presents the general process configuration on which the economic models are based. Next, the details of the economic model are discussed. Finally, results of the economic analysis are presented and discussed. These results are preliminary and should be refined as the design of the HTGR progresses, if the design of the HTGR is changed significantly, or if additional refinements of the costs become available.

2. CASES CONSIDERED

Six separate ROTs were identified for economic modeling based on the process models presented in TEV-981, all cases could either produce high-temperature helium, steam, or electricity. The cases are outlined in Table 2.

Table 2. HTGR heat and power cases modeled for a single 600 MWt HTGR.[2]

ROT (°C)	Primary He Loop		Heat Production				Power Production % - Efficiency	
			Secondary He Loop		Steam Loop			
	IHX[3] Duty (MWt)	Circulator Power (MWe)	Delivery Temp. (°C)	Flow Rate (kg/s)	Delivery Temp. (°C)	Flow Rate (kg/s)	Rankine	Brayton
700	639.4	19.7	675	313.3	540	297.7	43.0	33.2
750	641.2	20.6	725	305.7	540	331.3	43.0	36.5
800	642.8	21.4	775	298.5	540	361.0	43.0	39.6
850	644.4	22.1	825	291.8	540	361.4	43.0	42.5
900	645.9	22.8	875	285.4	540	361.8	43.0	45.2
950	647.3	23.5	925	279.4	540	362.2	43.0	47.7

2 Results may differ slightly, less than 1%, from the results presented in TEV-981, due to rounding errors in the correlations developed from the data for use in the economic model for evaluations at ROTs not identified above.

3 Intermediate heat exchanger (IHX) duty, the amount of total heat available for heat transfer. This value is greater than 600 MWt due to heat generated in the primary circulator.

The above cases were evaluated for a 600 MWt HTGR in both a single and four-pack configuration, the duties, power requirements, and flow rates listed above were assumed to increase linearly with the total reactor power level. The baseline facility has a ROT of 750°C and consists of four 600 MWt HTGRs for a total plant rating of 2,400 MWt, when power is produced a Rankine cycle is assumed for the baseline case.

TEV-981 presents multiple temperature return options for the heat generated by the HTGR; however, for the economic analyses it is assumed that the heat for the options using helium would be returned 25°C below the reactor inlet temperature and steam would be returned condensed at the saturation point for ROTs at 800°C and above, for ROTs below 800°C, the steam condensate return is sub-cooled such that the steam generator has a minimum temperature approach of 25°C. This allows for the maximum amount of heat to be transferred from the HTGR to the heat transfer medium; it has no impact on the power generation efficiency. Furthermore, only the circulator power associated with the primary helium loop was accounted for in the economic models.

Again, for detailed descriptions of the process models that provide the basis for the configurations considered for the economic analysis, see TEV-981.

3. ECONOMIC MODELING OVERVIEW

The economic viability of the HTGR processes for heat or power generation was assessed using standard economic evaluation methods, specifically the internal rate of return (IRR). The economics were evaluated for the 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 the cases. The present worth 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 the resulting economic results. Again, the results are preliminary and should be refined as the design of the HTGR progresses, if the design of the HTGR is changed significantly, or if additional refinements of the costs become available.

3.1 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 fifteen percent of full project definition (AACE 2005).

The installed capital costs are based on the capital cost correlations presented in Section 2.6 of TEV-1196 for an n^{th} of a kind HTGR, a mature commercial installation. Preconstruction costs, balance of equipment (BOE) costs, indirect costs, and project contingencies were added in accordance with the costs outlined in Sections 2.1 through 2.5 of TEV-1196. The capital costs presented in TEV-1196 were updated from 2009 to 2010 dollars using the Chemical Engineering Plant Cost Index (CEPCI) shown in Table 3.

Table 3. CEPCI data.

Year	**CEPCI**
2009	521.9
2010	550.8

Table 4 presents the detailed capital cost for a four-pack of 600 MWt HTGRs coupled with a Rankine cycle at an ROT of 750°C. Figure 1 presents a graphical breakdown of capital costs between the HTGR and the power cycle for the baseline configuration.

Table 4. TCI - Four 600 MWt HTGRs at 750°C ROT w/ Rankine Cycle.

Item	**HTGR**	**Rankine Cycle**	**Total**
Reactor Plant Inputs			
Total Reactor Heat/Net Power (MWt, MWe)	2,400	1,032	
Number of Units	4	4	
Capacity per Unit (MWt, MWe)	600	258	
Preconstruction Costs ($\$10^6$)			
Land and Land Rights	10.00		10.00
Licensing Costs	81.00		81.00
Total Preconstruction Costs	*91.00*		*91.00*
Direct Costs ($\$10^6$)			
From HTGR Cost Correlations	1,398.70	474.34	1,873.04
BOE Costs	349.67	118.58	$468.26
Total Direct Costs	*1,748.37*	*592.92*	*2,341.29*
Indirect Costs ($\$10^6$)			
Design Costs	20.00		$20.00
Construction Services	350.36	118.82	469.17
Home Office & Engineering Services	281.90	95.60	377.50
Field Office & Engineering Services	170.84	57.94	228.78
Owner's Costs	201.55	68.35	269.90
Total Indirect Costs	*1,024.65*	*340.70*	*1,365.35*
Base Construction Cost ($\$10^6$)	2,864.02	933.62	3,797.65
Project Contingency ($\$10^6$)	572.80	186.72	759.53
Total Construction Cost ($\$10^6$ 2009)	3,436.83	1,120.35	4,557.18
Total Construction Cost ($\$10^6$ 2010)	**3,627.14**	**1,182.39**	**4,809.53**

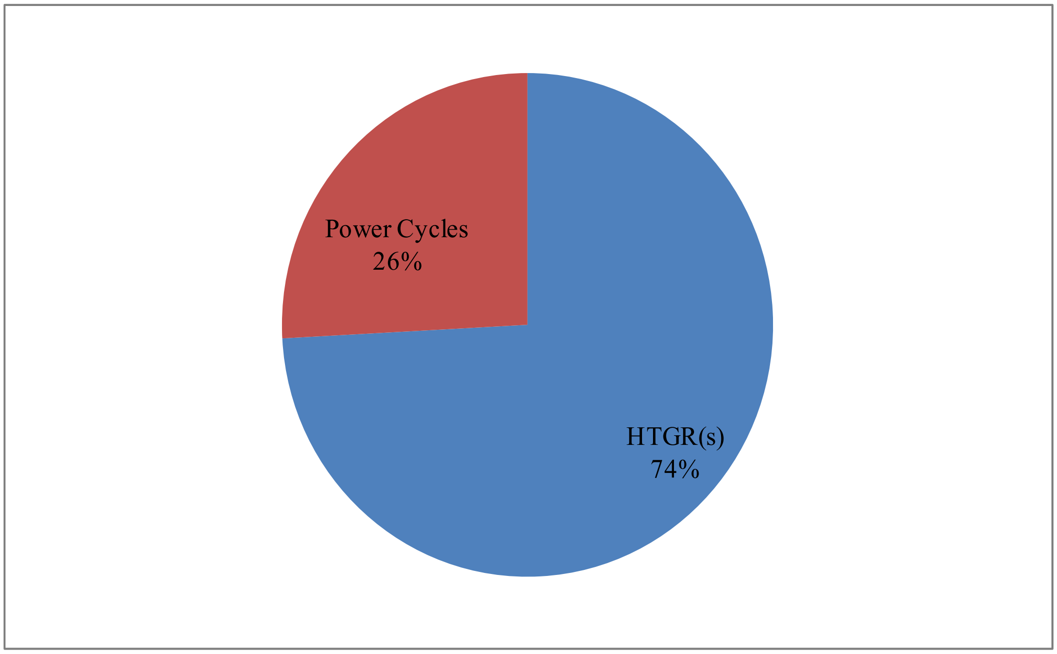

Figure 1. TCI breakdown - Four 600 MWt HTGRs at 750°C ROT, Rankine cycle.

Table 5 presents the TCI for all ROTs for both heat and power generation options, for single and four-pack reactor configurations for the 600 MWt HTGR. Power is generated using either a Brayton or a Rankine cycle. Table 6 presents the TCI per kWt for the above configurations and Figure 2 presents the TCI per kWt graphically. From these results it clear that the TCI increases as a function of ROT. However, the TCI per kWt decreases with increasing number of modules, i.e. economies of scale are realized. Furthermore, the Brayton cycle has a higher capital cost than the Rankine cycle. Producing heat only reduces capital costs, since no power cycle equipment is required.

Table 5. TCI - HTGR heat and power cases ($\$10^6$ 2010).

Modules	Gen. Option	ROT (°C)					
		700	750	800	850	900	950
1	Heat	1,197	1,229	1,261	1,294	1,479	1,554
	Rankine	1,463	1,525	1,587	1,648	1,863	1,968
	Brayton	1,573	1,637	1,700	1,764	2,020	2,144
4	Heat	3,526	3,627	3,728	3,829	4,414	4,650
	Rankine	4,591	4,810	5,029	5,248	5,950	6,304
	Brayton	4,870	5,084	5,298	5,512	6,350	6,760

Table 6. TCI - HTGR heat and power cases ($/kWt 2010).

Modules	Gen. Option	ROT (°C) 700	750	800	850	900	950
1	Heat	1,995	2,049	2,102	2,156	2,465	2,590
	Rankine	2,439	2,542	2,644	2,747	3,105	3,279
	Brayton	2,621	2,728	2,834	2,940	3,367	3,573
4	Heat	1,469	1,511	1,553	1,596	1,839	1,937
	Rankine	1,913	2,004	2,095	2,186	2,479	2,626
	Brayton	2,029	2,118	2,208	2,297	2,646	2,816

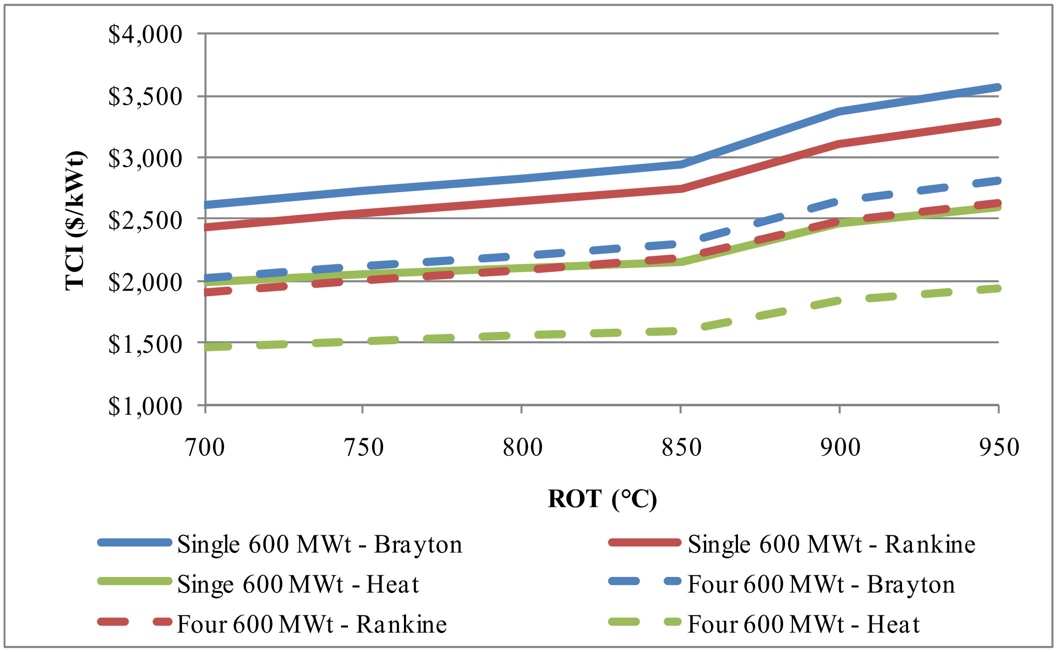

Figure 2. TCI ($/kWt) versus ROT for a single and four-pack of HTGRs.

3.2 Estimation of Revenue

Yearly revenues were estimated for all cases based on the current market price of electricity, $98.80/MWe-hr (Energy Information Administration [EIA] 2011). This is the weighted average retail price to all end users. When heat is sold from the HTGR, the selling price is assumed to be related to electricity price and the power generation efficiency based on the following equation:

$$Heat\ Price = Electricity\ Price * Power\ Generation\ Efficiency \qquad (1)$$

Revenues were also calculated to determine the necessary selling prices of heat and electricity for the HTGR to achieve a specific rate of return, 12%. A stream factor of 90% is assumed for the heat and power generation scenarios. Table 7 presents the revenues for heat generation at the specified IRR and at the market price and Table 8 presents the revenues for power generation at the specified IRR and at the market price. Revenues are only presented for the four-pack of 600 MWt HTGRs as a function of ROT, when power is produced a Rankine cycle is assumed. Results for all cases will be presented in Section 4.

Table 7. Annual revenues, HTGR heat generation as a function of ROT at market price and 12% IRR, four 600 MWt HTGRs.

ROT	Product	Generated		Price			Annual Revenue
700°C	Heat – General	2558	MWt	Market	42.48	$/MWt-hr	**$856,641,082**
					24.08	$/1000-kg	
	Heat – Helium	1253	kg/s		25.34	$/1000-kg	
				IRR	35.60	$/MWt-hr	**$717,852,994**
	Heat – Steam	1191	kg/s		20.18	$/1000-kg	
					21.24	$/1000-kg	
750°C	Heat – General	2,565	MWt	Market	42.48	$/MWt-hr	**$859,031,015**
					24.76	$/1000-kg	
	Heat – Helium	1,223	kg/s		22.84	$/1000-kg	
				IRR	36.20	$/MWt-hr	**$732,039,737**
	Heat – Steam	1,325	kg/s		21.10	$/1000-kg	
					19.47	$/1000-kg	
800°C	Heat – General	2,571	MWt	Market	42.48	$/MWt-hr	**$861,266,648**
					25.42	$/1000-kg	
	Heat – Helium	1,194	kg/s		21.01	$/1000-kg	
				IRR	36.80	$/MWt-hr	**$746,100,071**
	Heat – Steam	1,444	kg/s		22.02	$/1000-kg	
					18.20	$/1000-kg	
850°C	Heat – General	2,578	MWt	Market	42.48	$/MWt-hr	**$863,366,703**
					26.07	$/1000-kg	
	Heat – Helium	1,167	kg/s		21.04	$/1000-kg	
				IRR	37.40	$/MWt-hr	**$760,049,333**
	Heat – Steam	1,446	kg/s		22.95	$/1000-kg	
					18.52	$/1000-kg	
900°C	Heat – General	2,584	MWt	Market	42.48	$/MWt-hr	**$865,346,688**
					26.71	$/1000-kg	
	Heat – Helium	1,142	kg/s		21.07	$/1000-kg	
				IRR	40.87	$/MWt-hr	**$832,394,924**
	Heat – Steam	1,447	kg/s		25.69	$/1000-kg	
					20.27	$/1000-kg	
950°C	Heat – General	2,589	MWt	Market	42.48	$/MWt-hr	**$867,219,592**
					27.34	$/1000-kg	
	Heat – Helium	1,118	kg/s		21.09	$/1000-kg	
				IRR	42.25	$/MWt-hr	**$862,411,530**
	Heat – Steam	1,449	kg/s		27.19	$/1000-kg	
					20.97	$/1000-kg	

Table 8. Annual revenues, HTGR power generation, Rankine cycle, as a function of ROT at market price and 12% IRR, four 600 MWt HTGRs.

ROT	Product	Generated		Price			Annual Revenue
700°C	Power	1,032	MWe	Market	98.80	$/MWe-hr	**$803,865,254**
				IRR	98.56	$/MWe-hr	**$801,902,681**
750°C	Power	1,032	MWe	Market	98.80	$/MWe-hr	**$803,865,254**
				IRR	101.82	$/MWe-hr	**$828,397,547**
800°C	Power	1,032	MWe	Market	98.80	$/MWe-hr	**$803,865,254**
				IRR	105.07	$/MWe-hr	**$854,892,412**
850°C	Power	1,032	MWe	Market	98.80	$/MWe-hr	**$803,865,254**
				IRR	108.33	$/MWe-hr	**$881,387,278**
900°C	Power	1,032	MWe	Market	98.80	$/MWe-hr	**$803,865,254**
				IRR	118.78	$/MWe-hr	**$966,392,261**
950°C	Power	1,032	MWe	Market	98.80	$/MWe-hr	**$803,865,254**
				IRR	124.03	$/MWe-hr	**$1,009,144,849**

3.3 Estimation of Manufacturing Costs

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.

It was assumed that the reactor would supply only heat when heat is the primary product; the power required for the primary helium circulators is assumed to be purchased from the grid in order to minimize HTGR costs by eliminating equipment associated with power production from the HTGR. The price assumed for purchasing electricity is based on the average industrial electricity purchase price (EIA 2011).

The O&M, fuel, and decommissioning costs are based on the total thermal rating of the plant (INL 2011a). Therefore, these costs are unchanged for a given plant rating regardless of if the reactor is producing heat or power for export. O&M and decommissioning costs are presented on an annual basis, fuel costs are presented as the total refueling cost per core.

Table 9 lists the O&M, fuel, and decommissioning costs for the HTGR for heat and power generation and Table 10 lists the electricity costs as a function of ROT for the HTGR for heat production. Results for O&M and decommissioning costs are presented for a single and four-pack of 600 MWt HTGRs, refueling costs are presented per core. Currently, O&M, fuel, and decommissioning costs are not a function of ROT as they are expected to be relatively constant for all ROTs identified.

The decommissioning fund payment is calculated using the decommissioning cost in dollars per MWt 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, assuming that the reactor is decommissioned at the end of the recovery period is an economically conservative assumption.

Table 9. HTGR O&M, decommissioning, and refueling costs for single and four-pack 600 MWt reactor configurations, valid for all ROTs.

		Consumed	Price	Annual Cost
Single	O&M	600 MWt	7.36 $/MWt-hr	$34,820,406
	Decommissioning Fund Payment			$5,203,782
Four Pack	O&M	2,400 MWt	4.88 $/MWt-h	$92,427,123
	Decommissioning Fund Payment			$20,130,091
				Cost Per Core
Refueling Cost				$51,712,273

As shown in Table 9, O&M costs decrease on a dollar per MWt-hr basis as the number of reactors increases, this is mainly due to the fact that a large portion of the staff is required for the first HTGR and for each additional module only a fraction of the staffing level for the first reactor is required (INL 2011a).

Table 10. Annual electricity cost for HTGR heat production as a function of ROT, HTGR power generation, four 600 MWt HTGRs.

ROT	Consumed	Price	Annual Cost
700°C	78.8 MWe	67.90 $/MWe-hr	$42,190,304
750°C	82.3 MWe	67.90 $/MWe-hr	$44,037,482
800°C	85.5 MWe	67.90 $/MWe-hr	$45,765,402
850°C	88.5 MWe	67.90 $/MWe-hr	$47,388,533
900°C	91.4 MWe	67.90 $/MWe-hr	$48,918,861
950°C	94.1 MWe	67.90 $/MWe-hr	$50,366,428

3.4 Economic Comparison

Several economic indicators were calculated for each case to assess the economic desirability of heat and power generation. The price of heat and electricity necessary for a return of 12% was calculated for all cases as well as the IRR at the market price for heat and electricity. Table 11 lists the economic assumptions made for the analyses.

Table 11. Economic assumptions.

	Assumption
Year Construction Begins	2012
Construction Information	
Preconstruction Period	6 months
Construction Period – per Reactor	36 months
Reactor 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%
MACRS Depreciation Term	15 year life
IRR	12%

3.4.1 Cash Flow

To assess the IRR and present worth (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 (NIBT); the effective income tax rate (t); and the 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):

$$T_k = t(R_k - E_k - d_k) \tag{2}$$

Depreciation for the economic calculations was calculated using a standard Modified Accelerated Cost Recovery System (MACRS) depreciation method with a property class of 15 years. Depreciation was assumed for the TCI for each reactor module with the first charge occurring the year the corresponding HTGR comes online, i.e. when initial revenues are received. Table 12 presents the recovery rates for a 15-year property class (Perry 2008).

Table 12. 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 3 presents the yearly ATCFs for a four-pack of 600 MWt HTGRs at 750°C ROT with a Rankine cycle at a 12% IRR.

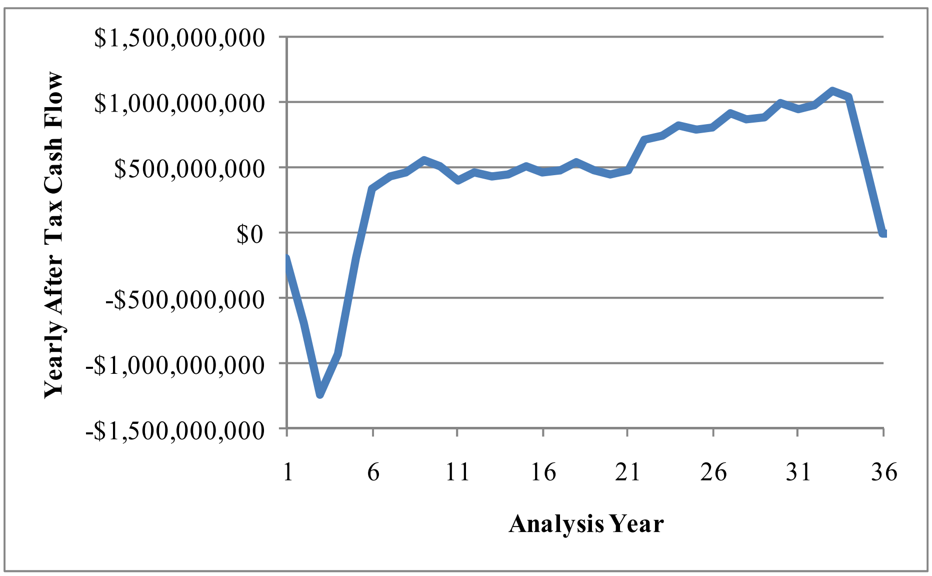

Figure 3. ATCFs, Four 600 MWt HTGRs, 750°C ROT, Rankine cycle, 12% IRR.

The BTCF is defined as follows (Sullivan 2003):

$$BTCF_k = R_k - E_k - C_k \tag{3}$$

The ATCF can then be defined as:

$$ATCF_k = BTCF_k - T_k \tag{4}$$

3.4.1.1 Capital Cash Flows during Construction

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

$$y(Mod) = 0.102 \times \ln(Mod + 0.963) - 0.402 \tag{5}$$

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

$$ModF(Mod) = \left(1 - \sum_{i=1}^{i=Mod} ModF(i-1)\right) \times (Number - (Mod - 1))^{y(Mod)} \tag{6}$$

where *Number* is the total number of reactor modules. The yearly fractional breakdown for each module'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 follows:

$$CapF(month) = 0.5 \times \left(\sin\left(\frac{\pi}{2} + \frac{\pi \times month}{c\_months}\right) + 1\right) - CapF(month - 1) \tag{7}$$

where *month* is the current month in the reactor construction period and *c_months* is the total number of months in the current modules 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 fraction to determine to overall yearly capital fractional breakdown per module. Figure 4 presents the percentage of the TCI spent each year of construction for a four-pack of 600 MWt HTGRs at 750°C ROT with a Rankine cycle.

Figure 4. Percentage of TCI spent each year of construction, Four 600 MWt HTGRs at 750°C ROT, Rankine cycle.

3.4.1.2 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.

3.4.2 Internal Rate of Return

The IRR method is the most widely used rate of return method for performing engineering economic analyses. This method solves for the interest rate that equates the equivalent worth of an alternative's cash inflows to the equivalent worth of cash outflows (after tax cash flow), 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 (MARR) (Sullivan 2003).

$$PW(i') = \sum_{k=0}^{N} ATCF_k (1 + i')^{-k} = 0 \qquad (8)$$

IRR calculations were performed for the calculated TCI for all cases. In addition, the price of heat and electricity necessary for an IRR of 12% and a PW of zero was calculated for each case. All calculations were performed using Excel (Excel 2007).

4. ECONOMIC MODELING RESULTS AND CONCLUSIONS

Figure 5 presents a graphical representation of the required electricity selling price for a 12% IRR. Figure 6 presents the graphical results for the heat selling price for a 12%

IRR. Figure 7 presents the IRR results as a function of ROT selling heat and electricity at the market price.

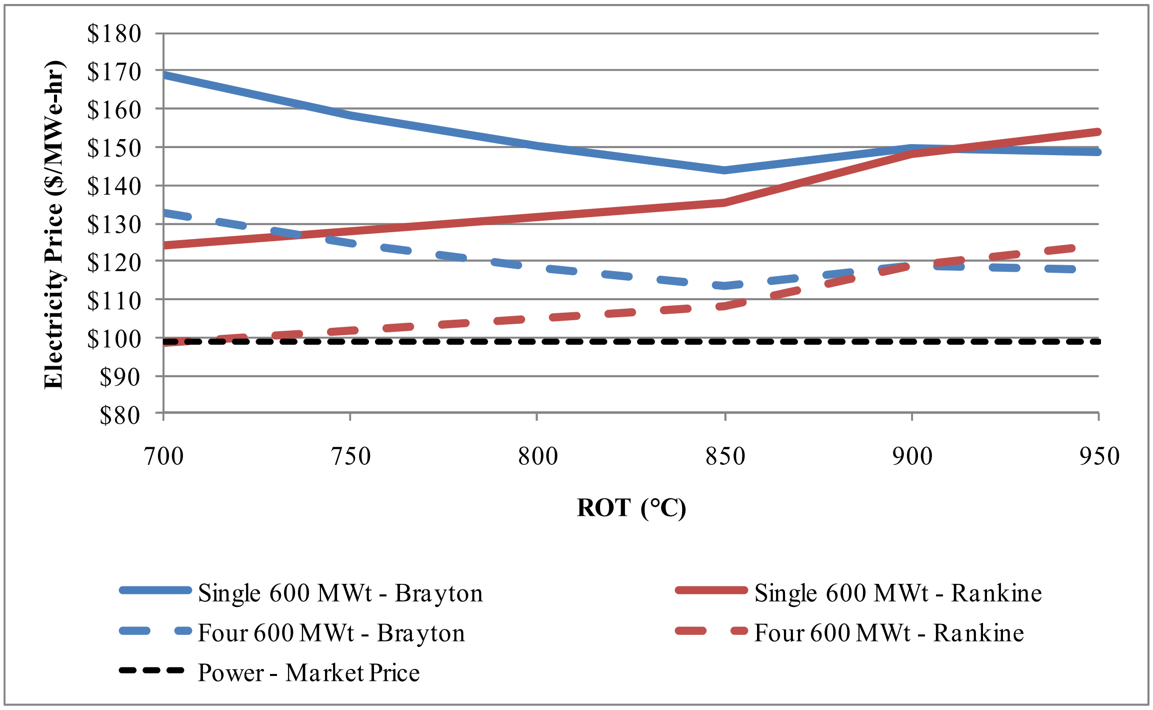

Figure 5. HTGR power generation results as a function of ROT, 12% IRR.

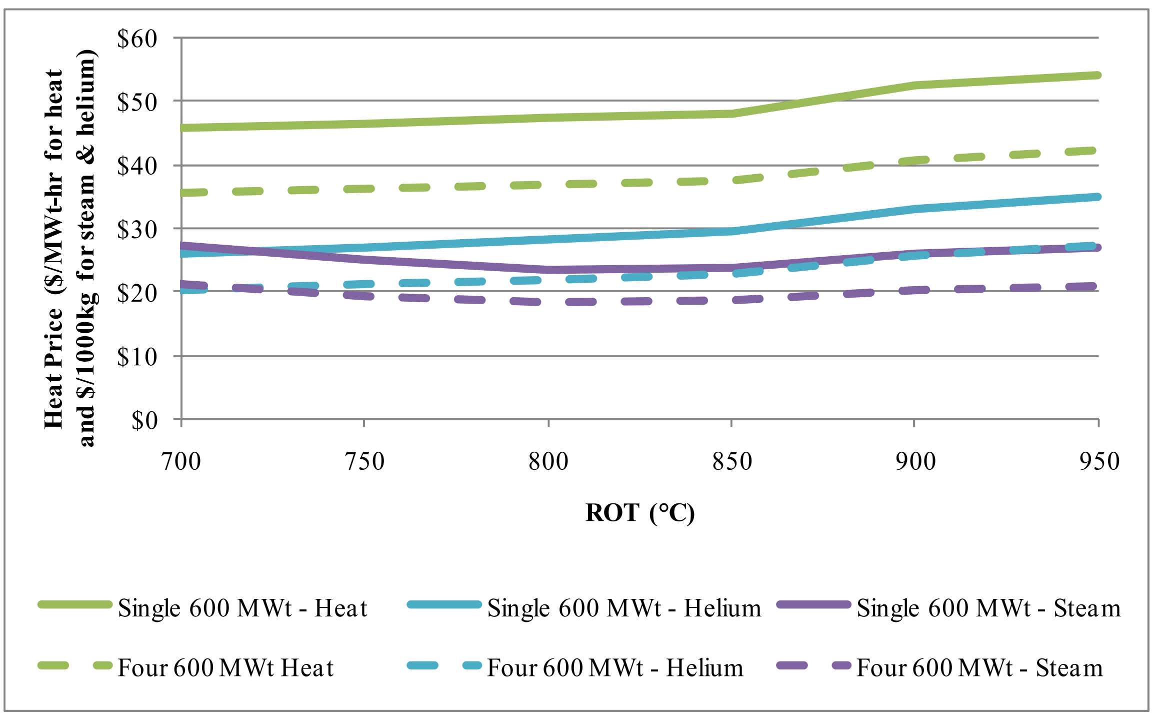

Figure 6. HTGR heat generation results as a function of ROT, 12% IRR.

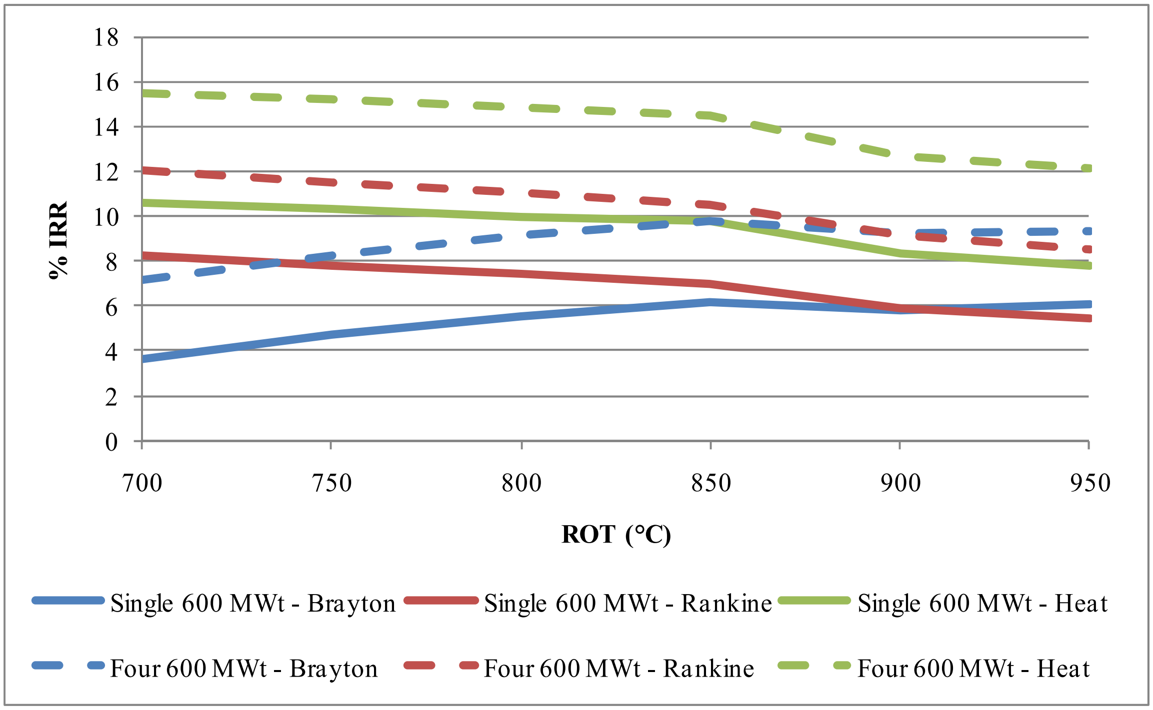

Figure 7. HTGR heat and power IRR results as a function of ROT, at market price.

Table 13 and Table 14 present the economic results as a function of ROT for the HTGR producing heat and power, listing the product price required for a 12% IRR and the IRR at the market price for a four-pack and single 600 MWt HTGR, respectively.

Table 13. HTGR heat and power generation results as a function of ROT, four-pack of 600 MWt HTGRs.

	Generation Option	ROT (°C)					
		700	**750**	**800**	**850**	**900**	**950**
Brayton Cycle	TCI	$4,869,561,912	$5,083,873,031	$5,298,184,150	$5,512,495,270	$6,350,120,800	$6,759,575,010
	Electricity @ IRR ($/MWe-hr)	132.86	124.69	118.50	113.69	118.72	117.81
	% IRR @ Market Price	7.11	8.2	9.1	9.8	9.2	9.33
Rankine Cycle	TCI	$4,590,525,387	$4,809,529,007	$5,028,532,627	$5,247,536,247	$5,950,178,008	$6,303,566,152
	Electricity @ IRR ($/MWe-hr)	98.56	101.82	105.07	108.33	118.78	124.03
	% IRR @ Market Price	12.0	11.5	11.0	10.5	9.1	8.5
Heat Production	TCI	$3,526,033,535	$3,627,142,047	$3,728,250,559	$3,829,359,071	$4,414,105,724	$4,649,598,760
	Heat @ IRR ($/MWe-hr)	35.60	36.20	36.80	37.40	40.87	42.25
	Helium @ IRR ($/1000-kg)	20.18	21.10	22.02	22.95	25.69	27.19
	Steam @ IRR ($/1000-kg)	21.24	19.47	18.20	18.52	20.27	20.97
	% IRR @ Market Price	15.5	15.2	14.8	14.5	12.7	12.1

Table 14. HTGR heat and power generation results as a function of ROT, single 600 MWt HTGR.

	Generation Option	ROT (°C)					
		700	**750**	**800**	**850**	**900**	**950**
Brayton Cycle	TCI	$1,572,800,301	$1,636,549,101	$1,700,297,901	$1,764,046,701	$2,020,416,351	$2,143,821,866
	Electricity @ IRR ($/MWe-hr)	168.94	158.28	150.18	143.86	149.84	148.44
	% IRR @ Market Price	3.6	4.7	5.5	6.2	5.8	6.1
Rankine Cycle	TCI	$1,463,387,304	$1,524,968,086	$1,586,548,867	$1,648,129,649	$1,863,289,707	$1,967,544,289
	Electricity @ IRR ($/MWe-hr)	124.04	127.73	131.42	135.11	148.01	154.25
	% IRR @ Market Price	8.2	7.8	7.4	7.0	5.9	5.4
Heat Production	TCI	$1,197,264,341	$1,229,371,346	$1,261,478,350	$1,293,585,355	$1,479,271,635	$1,554,052,441
	Heat @ IRR ($/MWe-hr)	45.84	46.58	47.32	48.06	52.47	54.22
	Helium @ IRR ($/1000-kg)	25.98	27.14	28.31	29.49	32.99	34.89
	Steam @ IRR ($/1000-kg)	27.34	25.04	23.41	23.8	26.02	26.92
	% IRR @ Market Price	10.6	10.3	10.0	9.8	8.3	7.8

For power generation using a Brayton cycle, the above results show that as the ROT is increased the required selling price of electricity to achieve a given IRR decreases until the ROT reaches 850°C. This decrease is due to gains in the Brayton cycle efficiency as ROT increases. From 850 to 900°C the required selling price of electricity increases to achieve the given IRR. This is due to the increase in the capital cost of the HTGR for higher temperature operation; see TEV-1196 for a more detailed discussion on capital cost increases. The selling price of electricity begins to decrease again from 900 to 950°C due to gains in power generation efficiency. Correspondingly, when selling electricity at the market price, the IRR increases from the minimum at 700°C to a maximum at 850°C, then decreases at 900°C and begins to increase again at 950°C. When comparing the single versus four-pack configurations, it is apparent that a multiple module facility either increases the IRR at the market price or decreases the required selling price of electricity to achieve a given IRR. Economically, the optimal operating temperature for the Brayton cycle is 850°C.

For power generation using a Rankine cycle, the above results show that as the ROT is increased the required selling price of electricity to achieve a given IRR increases with increasing ROTs. This is because the Rankine cycle efficiency is constant at 43%, regardless of the ROT, as the Rankine cycle steam pressure is fixed; to offset the increased capital cost with fixed power generation capacity the selling price of electricity must increase. Correspondingly, when selling electricity at the market price, the IRR decreases from the maximum at 700°C to a minimum at 950°C. When comparing the single versus four-pack configurations, it is apparent that a multiple module facility either increases the IRR at the market price or decreases the required selling price of electricity to achieve a given IRR. Economically, the optimal operating temperature for the Rankine cycle is 700°C. Comparing the Brayton and the Rankine cycle, the Brayton cycle begins to economically outperform the Rankine cycle only at ROTs above 900°C, due to gains in efficiency offsetting the increased capital costs.

For heat generation, the above results show that as the ROT is increased the required selling price of generic heat (MWt-hr) and helium to achieve a given IRR increases with increasing ROTs. This is because the small increase in available heat for export is not enough to offset the increased capital cost. For steam generation, the selling price of steam per kilogram decreases from 700 to 750°C, and reaches a minimum around 800°C; then the price increases again with increasing ROTs. This is because the temperature of the steam stream is fixed at 540°C. As a result, for ROTs at 800°C and above, steam would be returned condensed at the saturation point; for ROTs below 800°C, the steam condensate return is sub-cooled in order to take advantage of the full amount of heat available for transfer, thereby reducing the amount of steam produced[4]. Correspondingly, when selling heat at the market price, generic heat (MWt-hr) and helium, the IRR decreases from the maximum at 700°C to a minimum at 950°C. For steam production the IRR is maximized at 800°C. When comparing the single versus four-pack

[4] Even at an ROT of 800°C several degrees of sub-cooling would be required to prevent cavitation in the condensate pumps; therefore, the optimum ROT may change slightly as the design progresses.

configurations, it is apparent that a multiple module facility either increases the IRR at the market price or decreases the required selling price of heat to achieve a given IRR. The economically optimal operating temperature for heat generation is dependent upon the end user's process heat requirements. For steam production at 540°C and 17 MPa, the economically optimal temperature for the current study is 800°C. However, this result will change if different steam conditions are required.

5. SENSITIVITY ANALYSES

Two sensitivity analyses were conducted for heat and power generation. The first sensitivity analysis assesses the impact on the required product selling price for various changes in the baseline economic assumptions; the result of this sensitivity analysis is a tornado diagram. A tornado diagram 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 second analysis was to assess the impact of varying the base reactor power level and the number of reactor modules on the economic results.

5.1 Economic Assumptions Sensitivity

For economic assumptions sensitivity analysis, the baseline economic assumptions were varied to determine the effect on the product selling price. Table 15 lists the values used in the economic sensitivity analysis.

Table 15. 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 (%)[5]	4.5	8	10
Loan Term (years)	20	15	10
Construction Period per HTGR (months)	24	36	60
Staffing Level		Design Supplier	INL Staffing[6]
Economic Recovery Period (years)	40	30	20
TCI	-30%	TCI	+50%
Refueling Period (months)	24	18	12

The sensitivity analysis was conducted for each power cycle type and for steam generation. The optimal ROTs identified in the previous sections were used to perform the sensitivity analysis, 850°C for the Brayton cycle, 700°C for the

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

[6] 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 2011).

Rankine cycle, and 800°C for steam production at 540°C and 17MPa. All configurations assume a four-pack of HTGRs.

Table 16 summarizes the results of the sensitivity analysis listing the required product selling prices for the various cases as well as the percent change in the product selling price versus the baseline case. The tornado plots are presented in Figure 8, Figure 9, and Figure 10 for the Brayton cycle, Rankine cycle, and steam production, respectively.

Table 16. Results from the economic sensitivity analysis, all cases assume four 600 MWt HTGRs.

	Brayton Cycle 850°C – Electricity		**Rankine Cycle 700°C – Electricity**		**Heat 800°C – Steam Production**	
	$/MWe-hr	% Change	$/MWe-hr	% Change	$/1000-kg	% Change
Baseline Product Price	**113.69**		**98.56**		**18.20**	
IRR						
10%	100.39	-11.7	87.60	-11.1	16.42	-9.8
15%	136.17	19.8	117.07	18.8	21.21	16.5
Debt Ratio						
80%	105.17	-7.5	91.56	-7.1	17.08	-6.2
0%	133.19	17.2	114.58	-16.3	20.77	14.1
Debt Interest Rate						
4.5%	104.75	-7.9	91.20	-7.5	17.02	-6.5
8%	119.26	4.9	103.14	4.6	18.94	4.1
Loan Term						
20 years	110.93	-2.4	96.29	-2.3	17.84	-2.0
10 years	117.44	3.3	101.64	3.1	18.70	2.7
Construction Period						
24 months per HTGR	109.44	-3.7	95.06	-3.6	17.64	-3.1
60 months per HTGR	123.29	8.4	106.45	8.0	19.48	7.0
Staffing Level						
INL Staffing	118.13	3.9	102.94	4.4	19.07	4.8
Economic Recovery Period						
40 years	109.46	-3.7	95.01	-3.6	17.61	-3.2
20 years	125.43	10.3	108.35	9.9	19.82	8.9
TCI						
-30% TCI	88.79	-21.9	78.08	-20.8	14.90	18.1
+50% TCI	155.19	36.5	132.69	34.6	23.71	30.2
Refueling Period						
24 months	109.13	-4.0	94.05	-4.6	17.31	-4.9
12 months	122.80	8.0	107.56	9.1	19.99	9.8

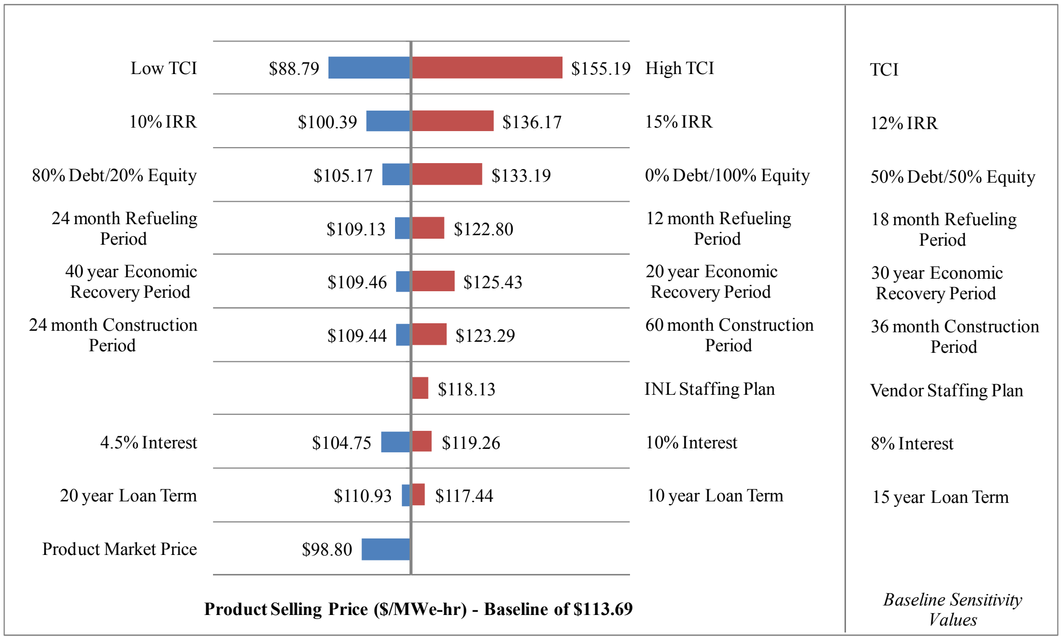

Figure 8. Brayton sensitivity analysis, four-pack 600 MWt HTGRs 850°C ROT.

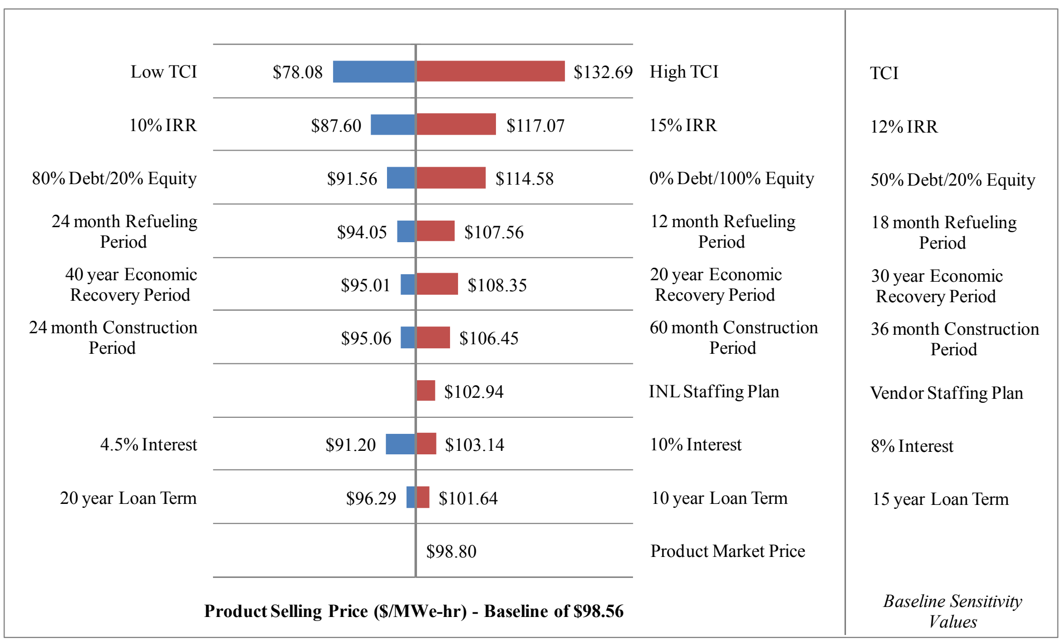

Figure 9. Rankine sensitivity analysis, four-pack 600 MWt HTGRs 700°C ROT.

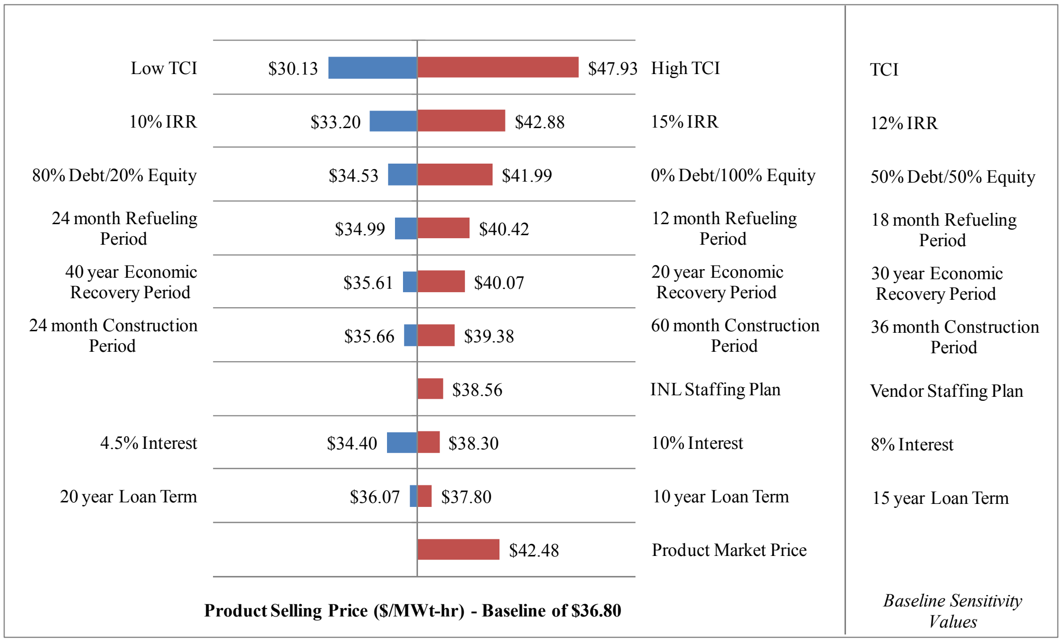

Figure 10. Steam generation sensitivity analysis, four-pack 600 MWt HTGRs 800°C ROT.

From the economic sensitivity analysis, the uncertainty in the TCI can have the largest impact on the required product selling price, followed by the assumed IRR and the debt to equity ratio. The other factors in general, have less than a 10% change on the required product selling price.

5.2 Reactor Size and Module Number Sensitivity

For the reactor size and module number sensitivity analysis, the base reactor size and the number of reactor modules was varied to determine the effect on the product selling price. The reactor power levels include 200 MWt, 350 MWt, and 600 MWt for one to 16 reactor modules. The data for this sensitivity analysis will not be presented in full; rather the results are only presented graphically to display the trends. Furthermore, the trends are only presented for the Rankine cycle at 750°C, i.e. the baseline case. The Brayton cycle and heat generation results will follow the same general trend.

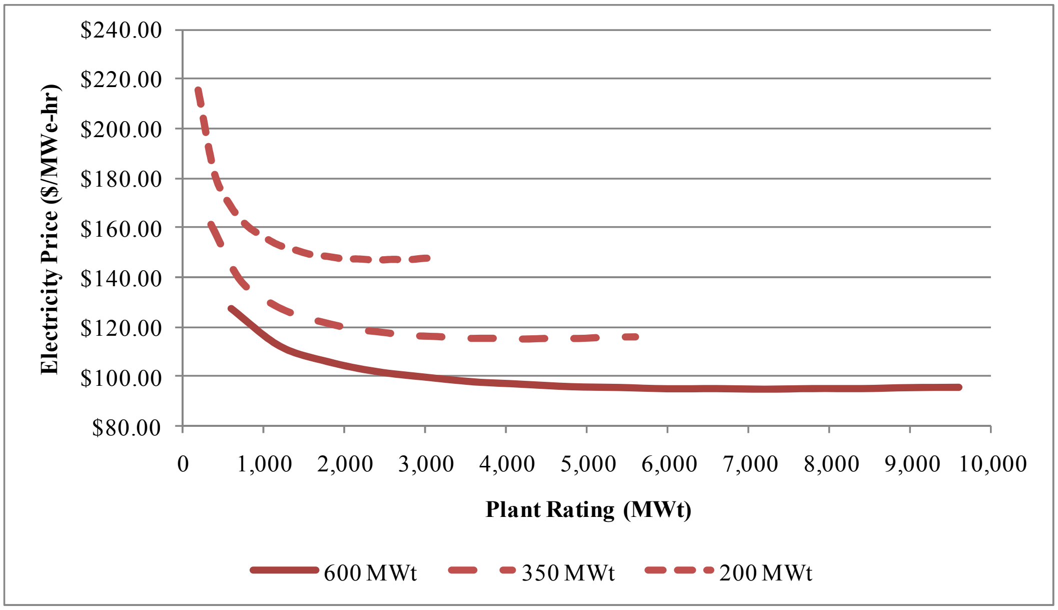

Figure 11. HTGR size and number sensitivity analysis, Rankine cycle 750°C ROT.

From this sensitivity analysis, it is shown that as the reactor power level increases the required selling price of power decreases due to gains in economies of scale for the capital cost, as well as the fact that the number of employees remains constant regardless of power level. Furthermore, as the number of modules are increased the required selling price of power decreases. This is again due to gains in economies of scale for the capital costs as well as the incremental staffing increase required when multiple units are located at a single location.

6. FUTURE WORK AND RECOMMENDATIONS

As the design of the HTGR progresses towards finalization, this TEV will be updated if the design of the HTGR is changed significantly or if additional refinements of the capital, O&M, fuel, and decommissioning costs become available.

The costs utilized in this study were developed for the prismatic block reactor configuration. Costs for the pebble bed reactor configuration will be included in a future revision of the TEV, when TEV-1196 is updated; however, the capital costs are roughly equivalent and the difference does not affect the overall accuracy of the estimates for both prismatic and pebble bed configurations (INL 2011a).

Co-generation scenarios are being developed for both the Rankine and Brayton cycles. When the co-generation analyses are complete, this TEV should be updated to include the economics for co-generation configurations.

A TEV is being developed which assesses the economics of natural gas combined cycle and pulverized coal electricity generation. This TEV should be updated to include a comparison of required electricity selling price for the HTGR versus the fossil generation options.

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