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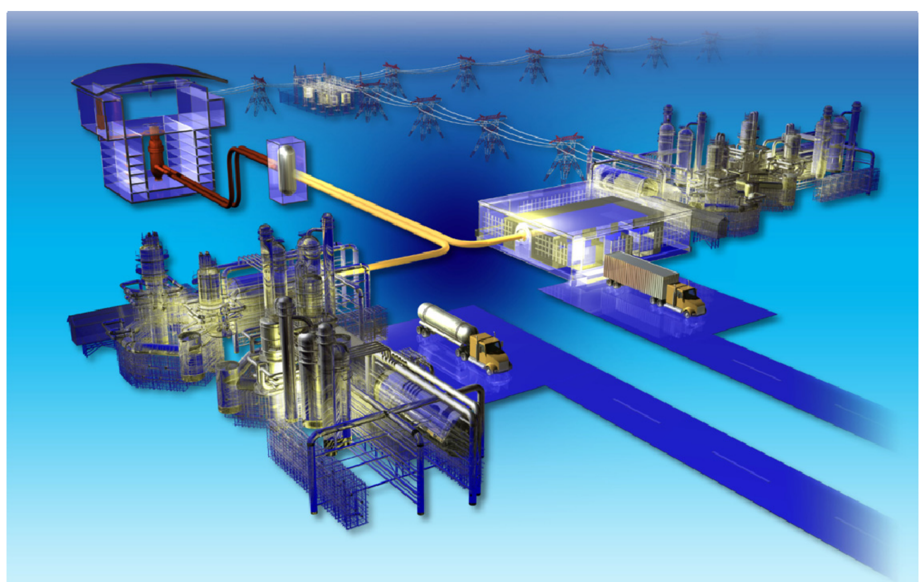
Technical Evaluation Study

Project No. 23843

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



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SENSITIVITY OF HTGR HEAT AND POWER PRODUCTION TO REACTOR OUTLET TEMPERATURE, ECONOMIC ANALYSIS	Identifier: TEV-988 Revision: 0 Effective Date: 09/15/10 Page: 1 of ~~23~~ 22 TKA 9-2-10

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Signatures

Signature and Typed or Printed Name	Signature Code	Date (mm/dd/yyyy)	Organization/Discipline
Lee Nelson for A. M. Gandrik	P	8/31/2010	NGNP Engineering Support
Michael G. McKellar M. G. McKellar	P	8/31/2010	NGNP Engineering Support
Richard D Boardman R. D. Boardman	C	8/31/2010	NGNP Engineering Support
Lee Nelson for M. W. Patterson	C	9/1/2010	NGNP Engineering Technical Manager
[signature] P. M. Mills	A	9/01/10	NGNP Engineering Director

P For preparer of the document.

A For approval: This is for non-owner approvals that may be required as directed by a given program or project. This signature may not be applicable for all uses of this form.

C For documented review and concurrence.

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REVISION LOG

Rev.	Date	Affected Pages	Revision Description
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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 subject to change, as the HTGR cost estimate currently is not a function of the ROT, power generation configuration, or heat generation type, i.e., generation of helium or steam. This TEV will be updated when the HTGR cost estimate update is complete.

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 (Idaho National Laboratory [INL] 2010). 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 the cases modeled. However, as the HTGR cost estimate is currently not a function of the ROT, conclusions regarding the impact of changes in the HTGR ROT on the economic results will be deferred until the HTGR cost estimate is completed.

As a result, before comprehensive conclusions can be made, a refined estimate of the HTGR capital cost, annual fuel costs, and annual operation and maintenance costs should be developed, including sensitivity to ROT, power generation configuration, and heat generation type, i.e., generation of helium or steam.

CONTENTS

ACRONYMS AND NOMENCLATURE

AACE	Association for the Advancement of Cost Engineering
ATCF	after tax cash flow
BTCF	before tax cash flow
CEPCI	chemical engineering plant cost index
DOE	Department of Energy
EIA	Energy Information Administration
HTGR	high temperature gas cooled 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
NETL	National Energy Technology Laboratory
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_1	cost of equipment with capacity q_1
C_2	cost of equipment with capacity q_2
C_k	capital expenditures
d_k	depreciation
E_k	cash outflows
i'	IRR
k	year
n	exponential factor
q_1	equipment capacity

q_2	equipment capacity
R_k	revenues
t	tax rate
T_k	income taxes

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 *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 electricity and/or process heat 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.[a]

Although initial HTGR implementations will likely target an HTGR outlet temperature of 750°C, temperatures of 950°C are anticipated for later designs. Unlike previous INL studies performed during the last year, 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 study investigates the impact of varying ROTs from 650 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 625 and 925°C. Steam delivery temperature is assumed to be constant at 540°C. HTGR product conditions assumed for this analysis are shown in Table 1.

Table 1. Projected outputs of the HTGR.

HTGR Product	Product Description
Steam	540°C and 17 MPa
High-Temperature Helium	Delivered at 625 to 925°C and 9.1 MPa
Electricity	Generated by Rankine cycle, with efficiency dependent upon ROT

a. 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 2010). 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. This TEV assumes familiarity with TEV-981; hence, detailed descriptions of the process models documented in TEV-981 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. The results presented in the following TEV are preliminary and subject to change, as the HTGR cost estimate currently is not a function of the ROT, power generation configuration, or heat generation type, i.e., generation of helium or steam. This TEV will be updated when the HTGR cost estimate update is complete.

2. CASES CONSIDERED

Seven cases 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.

ROT (°C)	Primary He Loop		Heat Production				Power Production
			Secondary He Loop		Steam Loop		
	IHX[b] Duty (MW_t)	Circulator Power (MW_e)	Delivery Temp. (°C)	Flow Rate (kg/s)	Delivery Temp. (°C)	Flow Rate (kg/s)	Generation Efficiency
650	618.8	18.8	625	321.9	540	272.4	43.2%
700	619.7	19.7	675	314.0	540	306.1	44.3%
750	620.5	20.5	725	306.5	540	360.8	45.2%
800	621.3	21.3	775	299.4	540	402.9	46.1%
850	622.0	22.0	825	292.6	540	403.4	46.8%
900	622.8	22.8	875	286.1	540	403.9	47.5%
950	623.4	23.4	925	279.8	540	404.3	48.2%

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

[b] Intermediate heat exchanger (IHX)

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 power associated with the primary helium loop was accounted for in the 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 at both the nominal and target HTGR cost. 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 presented below are preliminary and subject to change, as the HTGR cost estimate currently is not a function of the ROT, power generation configuration, or heat generation type, i.e., generation of helium or steam. This TEV will be updated when the HTGR cost estimate update is complete.

3.1 Capital Cost Estimation

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 program information. Cost estimates were generated for the power generation equipment and the HTGR. In some instances, several costs were averaged. The estimate presented is a Class 5 estimate and has a probable error of +50% and -30% (Association for the Advancement of Cost Engineering [AACE] 2005).

The installed capital costs presented for the power generation equipment are for inside the battery limits and exclude costs for administrative offices, storage areas, utilities, and other essential and nonessential auxiliary facilities. Fixed capital costs were estimated from literature estimates and scaled estimates (capacity, year, and material) from previous quotes. Capacity adjustments were based on the six-tenths factor rule:

$$C_2 = C_1 \left(\frac{q_2}{q_1}\right)^n \tag{1}$$

where C_1 is the cost of the equipment item at capacity q_1, C_2 is the cost of the equipment at capacity q_2, and n is the exponential factor, which typically has a value of 0.6 (Peters 2002). It was assumed that the number of trains did not have an impact on cost scaling. Cost indices were used to adjust equipment prices from previous years to 2009 using the Chemical Engineering Plant Cost Index (CEPCI) as depicted in Table 3. Costs for the HTGR were scaled directly based on capacity; the six-tenths factor rule was not used.

Table 3. CEPCI data.

Year	CEPCI	Year	CEPCI
1990	357.6	2000	394.1
1991	361.3	2001	394.3
1992	358.2	2002	395.6
1993	359.2	2003	402
1994	368.1	2004	444.2
1995	381.1	2005	468.2
1996	381.7	2006	499.6
1997	386.5	2007	525.4
1998	389.5	2008	575.4
1999	390.6	2009	521.9

For the HTGR, the estimates of capital costs and operating and maintenance (O&M) costs assumed the nuclear plant was an "n^{th} of a kind." In other words, the estimates were based on the costs expected after the HTGR technology is integrated into an industrial application more than ten times. The economic modeling calculations were based on two capital cost scenarios for the HTGR unit, which does not include the power cycle: a current best estimate of $1,708/kW$_t$ and a target of $1,196/kW$_t$ (Demick 2009) where kW$_t$ is the thermal rating of the plant. In comparison, light water nuclear reactor costs are approximately $1,333/kW$_t$ (NEI 2008). Based on the two capital cost scenarios for HTGR technology, the nominal capital cost for a 600-MW$_t$ HTGR would be $1.025 billion; the target capital cost would be $718 million.

Finally, an engineering fee of 10% and a project contingency of 18% were applied to the installed equipment costs to determine the TCI. However, the HTGR was excluded from engineering fees and contingencies, as the capital cost provided for the HTGR represents a complete and operable system; the total value represents all inside battery limits and outside battery limits elements as well as contingency and owner's costs.

The AACE International recognizes five classes of estimates. The level of project definition for this study was determined to be an AACE International Class 5 estimate. Although the baseline case is actually more in line with the AACE International Class 4 estimate, which is associated with equipment factoring, parametric modeling, historical relationship factors, and broad unit cost data, the

HTGR project definition falls under an AACE International Class 5 estimate, associated with less than two percent project definition, and based on preliminary design methodology (AACE 2005). Since the HTGR is a larger portion of the TCI, an overall Class 5 estimate was assumed.

Based on the AACE International contingency guidelines as presented in DOE/FETC-99/1100, the overall project contingency for the non-nuclear portion of the capital (power generation equipment) should be in the range of 30 to 50%, 30 to 40% for Class 4, and 50% for Class 5 (Parsons 1999). However, because the cost estimates were scaled based on estimated, quoted, and actual project costs, the overall non-nuclear project contingency should be more in the range of 15 to 20%. Eighteen percent was selected based on similar studies conducted by the National Energy Technology Laboratory (NETL) (2007). Again, contingency was not applied to the HTGR as project contingency was accounted for in the basis for the capital cost estimate.

Table 4 presents the capital cost estimate breakdown for the HTGR for heat production only. Table 5 and Figure 1 present the capital cost estimate breakdown for the HTGR for power generation. Varying only the cost of the nuclear facility was an adequate assumption, as the cost of the HTGR accounts for 80 to 100% of the capital cost. In addition, there is a greater level of uncertainty in the nuclear plant price given the nascency of HTGR development. Again, the results presented are preliminary and subject to change, as the HTGR cost estimate currently is not a function of the ROT, power generation configuration, or heat generation type, i.e., generation of helium or steam. This TEV will be updated when the HTGR cost estimate update is complete.

Table 4. Total capital investment, HTGR for heat generation, valid for all ROTs.

	Installed Cost	Engineering Fee	Contingency	Total Capital Cost
HTGR – Nominal Cost	$1,025,000,000			$1,025,000,000
HTGR – Target Cost	$717,500,000			$717,500,000
Total Capital Investment – Nominal HTGR Cost				**$1,025,000,000**
Total Capital Investment – Target HTGR Cost				**$717,500,000**

Table 5. Total capital investment, HTGR for power generation as a function of ROT.

	Installed Cost	Engineering Fee	Contingency	Total Capital Cost
HTGR – Nominal Cost	$1,025,000,000			$1,025,000,000
HTGR – Target Cost	$717,500,000			$717,500,000
Power Cycle – ROT 650°C	$155,373,761	$15,537,376	$30,764,005	$201,675,142
Power Cycle – ROT 700°C	$157,735,580	$15,773,558	$31,231,645	$204,740,783
Power Cycle – ROT 750°C	$159,650,577	$15,965,058	$31,610,814	$207,226,449
Power Cycle – ROT 800°C	$161,550,381	$16,155,038	$31,986,975	$209,692,395
Power Cycle – ROT 850°C	$163,017,768	$16,301,777	$32,277,518	$211,597,063
Power Cycle – ROT 900°C	$164,476,402	$16,447,640	$32,566,328	$213,490,370
Power Cycle – ROT 950°C	$165,926,463	$16,592,646	$32,853,440	$215,372,548
ROT of 650°C	**Total Capital Investment – Nominal HTGR Cost**			**$1,226,675,142**
	Total Capital Investment – Target HTGR Cost			**$919,175,142**
ROT of 700°C	**Total Capital Investment – Nominal HTGR Cost**			**$1,229,740,783**
	Total Capital Investment – Target HTGR Cost			**$922,240,783**
ROT of 750°C	**Total Capital Investment – Nominal HTGR Cost**			**$1,232,226,449**
	Total Capital Investment – Target HTGR Cost			**$924,726,449**
ROT of 800°C	**Total Capital Investment – Nominal HTGR Cost**			**$1,234,692,395**
	Total Capital Investment – Target HTGR Cost			**$927,192,395**
ROT of 850°C	**Total Capital Investment – Nominal HTGR Cost**			**$1,236,597,063**
	Total Capital Investment – Target HTGR Cost			**$929,097,063**
ROT of 900°C	**Total Capital Investment – Nominal HTGR Cost**			**$1,238,490,370**
	Total Capital Investment – Target HTGR Cost			**$930,990,370**
ROT of 950°C	**Total Capital Investment – Nominal HTGR Cost**			**$1,240,372,548**
	Total Capital Investment – Target HTGR Cost			**$932,872,548**

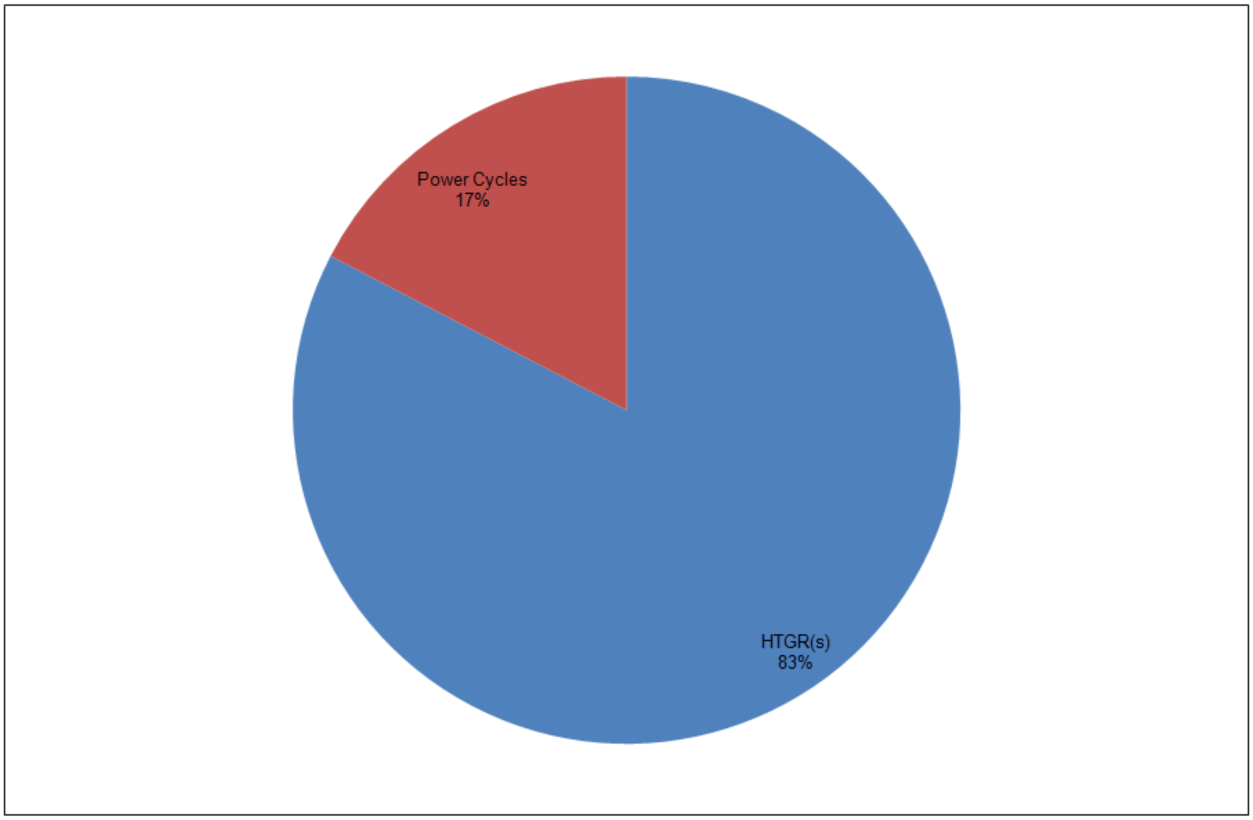

Figure 1. Total capital investment, HTGR for power generation at nominal HTGR cost, valid for all ROTs.

3.1 Estimation of Revenue

Revenues were calculated to determine the necessary selling prices of heat and electricity for the HTGR to achieve a specific rate of return, 15%. Annual revenues presented at the IRR are for the HTGR at the nominal price. A stream factor of 92% is assumed for the heat and power generation scenarios. Table 6 presents the revenues for heat generation at the specified IRR and Table 7 presents the revenues for power generation at the specified IRR.

Table 6. Annual revenues, HTGR heat generation at nominal reactor price as a function of ROT at 15% IRR.

ROT	Product	Price		Generated		Annual Revenue
650°C	Heat – General	3.42	¢/kW_t-hr	618.8	MW_t	$170,402,959
	Heat – Helium	18.25	$/1000-kg	321.9	kg/s	
	Heat – Steam	21.56	$/1000-kg	272.4	kg/s	
700°C	Heat – General	3.42	¢/kW_t-hr	619.7	MW_t	$170,638,939
	Heat – Helium	18.73	$/1000-kg	314.0	kg/s	
	Heat – Steam	19.21	$/1000-kg	306.1	kg/s	
750°C	Heat – General	3.42	¢/kW_t-hr	620.5	MW_t	$170,863,905
	Heat – Helium	19.21	$/1000-kg	306.5	kg/s	
	Heat – Steam	16.32	$/1000-kg	360.8	kg/s	
800°C	Heat – General	3.42	¢/kW_t-hr	621.3	MW_t	$171,078,132
	Heat – Helium	19.69	$/1000-kg	299.4	kg/s	
	Heat – Steam	14.64	$/1000-kg	402.9	kg/s	
850°C	Heat – General	3.42	¢/kW_t-hr	622.0	MW_t	$171,282,997
	Heat – Helium	20.18	$/1000-kg	292.6	kg/s	
	Heat – Steam	14.63	$/1000-kg	403.4	kg/s	
900°C	Heat – General	3.42	¢/kW_t-hr	622.8	MW_t	$171,478,775
	Heat – Helium	20.66	$/1000-kg	286.1	kg/s	
	Heat – Steam	14.63	$/1000-kg	403.9	kg/s	
950°C	Heat – General	3.42	¢/kW_t-hr	623.4	MW_t	$171,666,017
	Heat – Helium	21.15	$/1000-kg	279.8	kg/s	
	Heat – Steam	14.63	$/1000-kg	404.3	kg/s	

Table 7. Annual revenues, HTGR power generation at nominal reactor price as a function of ROT at 15% IRR.

ROT	Product	Price		Generated		Annual Revenue
650°C	Power	8.79	¢/kW_e-hr	259.2	MW_e	$183,653,050
700°C	Power	8.63	¢/kW_e-hr	265.8	MW_e	$184,759,175
750°C	Power	8.46	¢/kW_e-hr	271.2	MW_e	$184,869,989
800°C	Power	8.29	¢/kW_e-hr	276.6	MW_e	$184,835,737
850°C	Power	8.17	¢/kW_e-hr	280.8	MW_e	$184,813,574
900°C	Power	8.08	¢/kW_e-hr	285.0	MW_e	$185,663,820
950°C	Power	7.96	¢/kW_e-hr	289.2	MW_e	$185,486,518

3.1 Estimation of Manufacturing Costs

Manufacturing costs for the nuclear plant were based on data from General Atomics for the gas-turbine modular high-temperature reactor published in 2002; these costs were inflated to 2009 dollars (GA 2002). HTGR manufacturing costs include O&M and fuel 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 cost by eliminating equipment associated with power production from the HTGR.

The manufacturing costs presented are preliminary, as the HTGR manufacturing costs are not a function of the ROT, power generation scheme, or heat generation type, i.e., generation of helium or steam. This TEV will be updated when the HTGR cost estimate update is complete.

Table 8 lists the manufacturing costs for the HTGR for heat and generation and Table 9 lists the manufacturing costs for the HTGR for power generation.

Table 8. Annual manufacturing costs, HTGR heat generation, as a function of ROT.

	Price		Consumed		Annual Cost
Utilities					
Electricity - 650°C	6.96	¢/kW$_e$-hr	18.8	MW$_e$	$10,573,348
Electricity - 700°C	6.96	¢/kW$_e$-hr	19.7	MW$_e$	$11,050,130
Electricity - 750°C	6.96	¢/kW$_e$-hr	20.5	MW$_e$	$11,510,085
Electricity - 800°C	6.96	¢/kW$_e$-hr	21.3	MW$_e$	$11,947,603
Electricity - 850°C	6.96	¢/kW$_e$-hr	22.0	MW$_e$	$12,362,684
Electricity - 900°C	6.96	¢/kW$_e$-hr	22.8	MW$_e$	$12,760,937
Electricity - 950°C	6.96	¢/kW$_e$-hr	23.4	MW$_e$	$13,142,363
Nuclear Costs					
Fuel	4.19	$/MW$_t$-h	600	MW$_t$	$20,977,332
O&M	1.70	$/MW$_t$-h	600	MW$_t$	$8,504,324
Manufacturing Costs - 650°C					**$40,055,004**
Manufacturing Costs - 700°C					**$40,531,787**
Manufacturing Costs - 750°C					**$40,991,741**
Manufacturing Costs - 800°C					**$41,429,259**
Manufacturing Costs - 850°C					**$41,844,340**
Manufacturing Costs - 900°C					**$42,242,594**
Manufacturing Costs - 950°C					**$42,624,019**

Table 9. Annual manufacturing costs, HTGR power generation, valid for all ROTs.

	Price		Consumed		Annual Cost
Nuclear Costs					
Fuel	4.19	$/MW$_t$-h	600	MW$_t$	$20,977,332
O&M	1.70	$/MW$_t$-h	600	MW$_t$	$8,504,324
Manufacturing Costs					**$29,481,656**

3.2 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 power necessary for a return of 15% was calculated for all cases at the target and nominal HTGR cost. Table 10 lists the economic assumptions made for the analyses.

Table 10. Economic assumptions.

	HTGR
Plant Startup Year	2016
Construction Information	
Construction Period	5 years
Year Construction Begins	2011
Percent Capital Invested Each Year	20%
Plant Startup Information	
Startup Time	1 year
Percent Operating Costs During Startup	85%
Percent Revenues During Startup	60%
Economic Analysis Period	30 years
Availability	92%
Inflation Rate	3%
Debt to Equity Ratio	70%/30%
Loan Information	
Interest Rate on Debt	4.5%
Interest on Debt During Construction	4.5%
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	15%

3.2.1 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):

$$T_k = t(R_k - E_k - d_k) \quad (3)$$

Depreciation for the economic calculations was calculated using a standard Modified Accelerated Cost Recovery System (MARCS) depreciation method with a property class of 15 years. Depreciation was assumed for the TCI with the first charge occurring the year the plant comes online. Table 11 presents the recovery rates for a 15-year property class (Perry 2008).

Table 11. MARCS 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. The BTCF is defined as follows (Sullivan 2003):

$$BTCF_k = R_k - E_k - C_k \tag{4}$$

The ATCF can then be defined as:

$$ATCF_k = BTCF_k - T_k \tag{5}$$

3.2.2 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).

$$PW(i') = \sum_{k=0}^{N} ATCF_k (1 + i')^{-k} = 0 \tag{6}$$

Rather than solving for the IRR directly, the prices of heat and electricity necessary for an IRR of 15%, the assumed MARR, and a PW of zero were calculated for all cases. The heat and electricity prices required (for an IRR of 15%) were solved for using the Goal Seek function in Excel (Excel 2007).

4. ECONOMIC MODELING RESULTS AND OBSERVATIONS

The results presented below are preliminary and subject to change, as the HTGR cost estimate currently is not a function of the ROT, power generation configuration, or heat generation type, i.e., generation of helium or steam. This TEV will be updated when the HTGR cost estimate update is complete.

Table 12 presents the results for the HTGR heat generation as a function of the ROT and the HTGR price, listing the heat selling price required for a 15% IRR for general heat, i.e., thermal units; steam; and helium. Figure 2 depicts the results for heat generation, specifically the selling price as a function of ROT and HTGR price.

Table 12. HTGR heat generation results as a function of ROT.

ROT/ Heat Type	*TCI – Target HTGR*		*TCI – Nominal HTGR*	
	IRR	**Product Price**	**IRR**	**Product Price**
650°C	*$717,500,000*		*$1,025,000,000*	
General	15.0%	¢2.63/kW$_t$-hr	15.0%	¢3.42/kW$_t$-hr
Steam	15.0%	$16.57/1000-kg	15.0%	$21.56/1000-kg
Helium	15.0%	$14.02/1000-kg	15.0%	$18.25/1000-kg
700°C	*$717,500,000*		*$1,025,000,000*	
General	15.0%	¢2.63/kW$_t$-hr	15.0%	¢3.42/kW$_t$-hr
Steam	15.0%	$14.76/1000-kg	15.0%	$19.21/1000-kg
Helium	15.0%	$14.39/1000-kg	15.0%	$18.73/1000-kg
750°C	*$717,500,000*		*$1,025,000,000*	
General	15.0%	¢2.63/kW$_t$-hr	15.0%	¢3.42/kW$_t$-hr
Steam	15.0%	$12.54/1000-kg	15.0%	$16.32/1000-kg
Helium	15.0%	$14.76/1000-kg	15.0%	$19.21/1000-kg
800°C	*$717,500,000*		*$1,025,000,000*	
General	15.0%	¢2.67/kW$_t$-hr	15.0%	¢3.42/kW$_t$-hr
Steam	15.0%	$11.42/1000-kg	15.0%	$14.64/1000-kg
Helium	15.0%	$15.37/1000-kg	15.0%	$19.69/1000-kg
850°C	*$717,500,000*		*$1,025,000,000*	
General	15.0%	¢2.67/kW$_t$-hr	15.0%	¢3.42/kW$_t$-hr
Steam	15.0%	$11.42/1000-kg	15.0%	$14.63/1000-kg
Helium	15.0%	$15.75/1000-kg	15.0%	$20.18/1000-kg
900°C	*$717,500,000*		*$1,025,000,000*	
General	15.0%	¢2.67/kW$_t$-hr	15.0%	¢3.42/kW$_t$-hr
Steam	15.0%	$11.42/1000-kg	15.0%	$14.63/1000-kg
Helium	15.0%	$16.12/1000-kg	15.0%	$20.66/1000-kg
950°C	*$717,500,000*		*$1,025,000,000*	
General	15.0%	¢2.67/kW$_t$-hr	15.0%	¢3.42/kW$_t$-hr
Steam	15.0%	$11.42/1000-kg	15.0%	$14.63/1000-kg
Helium	15.0%	$16.50/1000-kg	15.0%	$21.15/1000-kg

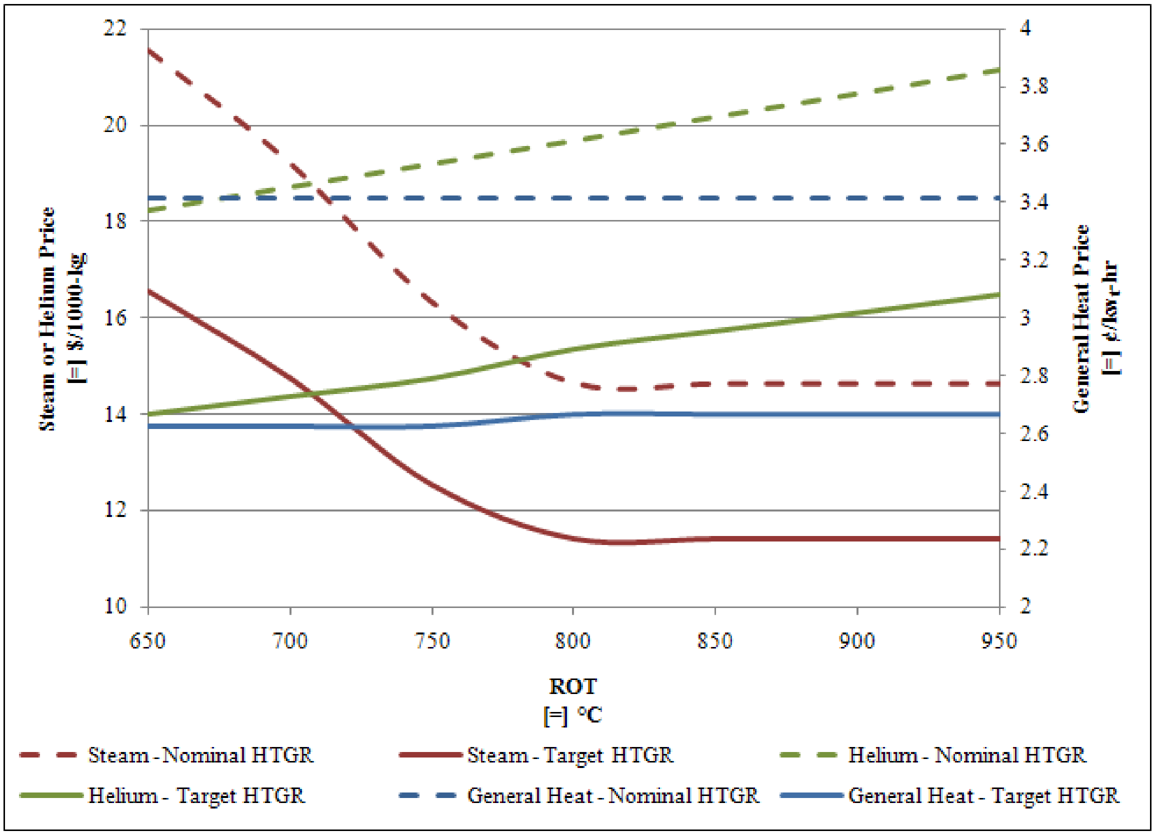

Figure 2. HTGR heat generation results as a function of ROT, 15% IRR.

The above results show that as the ROT is increased, the required selling price of heat remains constant when assessing the MW_t supplied from the HTGR. For helium, the price per 1000 kg increases as the ROT increases. This is because, although the same MWt of heat is transferred to the process, the temperature change between the reactor inlet and outlet temperature increases slightly as the ROT increases. As a result, in order for the same amount of heat to be transferred at the lower ROTs, the associated helium flow must increase. For steam, the price per 1000 kg appears to decrease as the ROT increases, then becomes constant at around 800°C. 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.

Table 13 presents the results for the HTGR power generation as a function of the ROT, listing the power selling price required for a 15% IRR. Figure 3 depicts the results for power generation, specifically the selling price as a function of ROT and HTGR price. In addition, Figure 3 presents the average U.S. electricity price, volume averaged for all sectors, as well as the average industrial, commercial, and residential electricity prices (EIA 2010).

Table 13. HTGR power generation results as a function of ROT.

ROT	*TCI – Target HTGR*		*TCI – Nominal HTGR*	
	IRR	**Product Price**	**IRR**	**Product Price**
650°C	*$919,175,142*		*$1,226,675,142*	
	15.0%	¢6.96/kW$_e$-hr	15.0%	¢8.79/kW$_e$-hr
700°C	*$922,240,783*		*$1,229,740,783*	
	15.0%	¢6.79/kW$_e$-hr	15.0%	¢8.63/kW$_e$-hr
750°C	*$924,726,449*		*$1,232,226,449*	
	15.0%	¢6.71/kW$_e$-hr	15.0	¢8.46/kW$_e$-hr
800°C	*$927,192,395*		*$1,234,692,395*	
	15.0%	¢6.58/kW$_e$-hr	15.0%	¢8.29/kW$_e$-hr
850°C	*$929,097,063*		*$1,236,597,063*	
	15.0%	¢6.50/kW$_e$-hr	15.0%	¢8.17/kW$_e$-hr
900°C	*$930,990,370*		*$1,238,490,370*	
	15.0%	¢6.42/kW$_e$-hr	15.0%	¢8.08/kW$_e$-hr
950°C	*$932,872,548*		*$1,240,372,548*	
	15.0%	¢6.33/kW$_e$-hr	15.0%	¢7.96/kW$_e$-hr

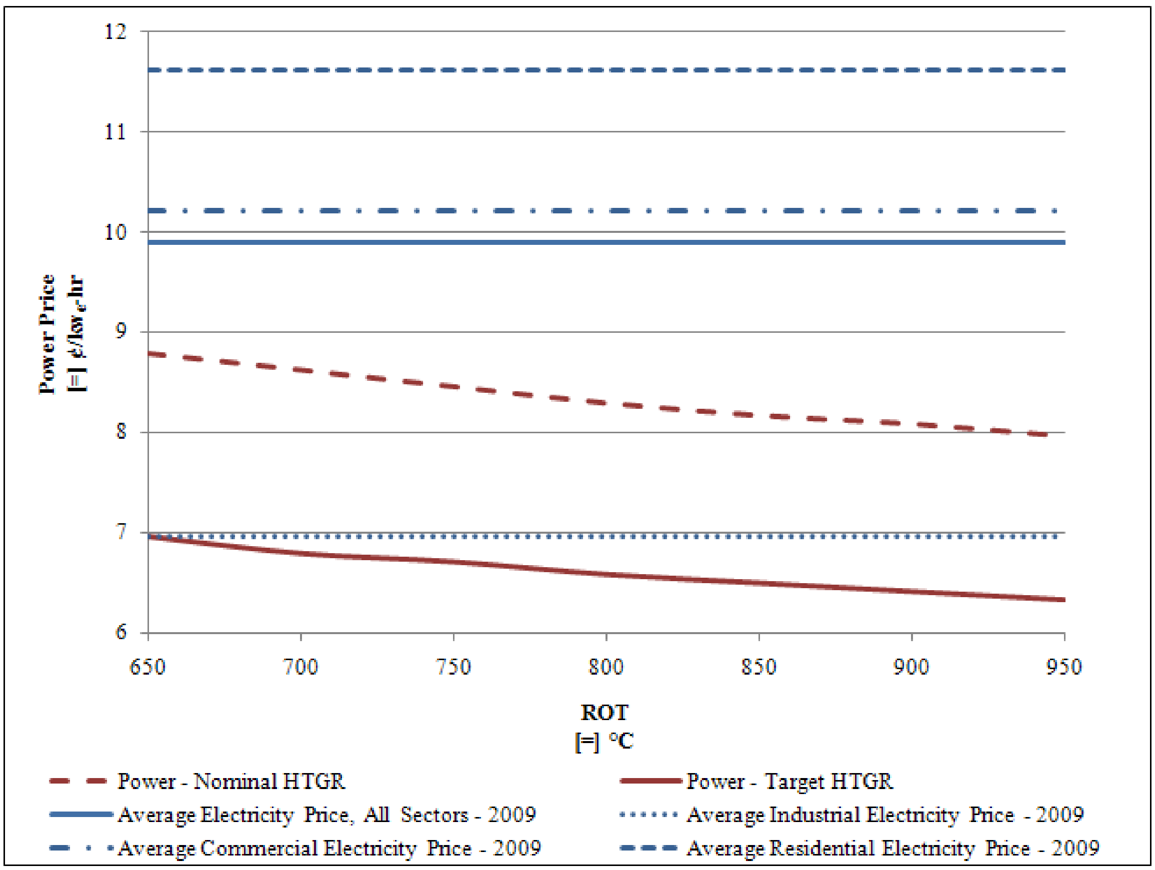

Figure 3. HTGR power generation power price results as a function of ROT, 15% IRR.

The above results show that as the ROT is increased, the required selling price of power to achieve a 15% IRR decreases. Furthermore, the required selling price decreases when the selling price of the HTGR is decreased from the nominal to the target price. When compared to the average U.S. electricity price, the HTGR generates power competitively when the HTGR is at the target price or the nominal price. When compared to average end user prices, the HTGR does not produce power at a price less than the industrial selling price at the nominal price; only the target price produces power at the industrial selling price for at least a 15% IRR.

5. FUTURE WORK AND RECOMMENDATIONS

Based on the results of this study, the following activity is recommended before comprehensive conclusions can be made:

- Refined estimates of the HTGR capital cost, annual fuel costs, and annual operation and maintenance costs should be developed, including sensitivity to reactor outlet temperature, power generation configuration, and heat generation type, i.e., generation of helium or steam.

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