MEMO

Dominion Engineering, Inc.

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To: Project File

From: Robert D. Varrin, Jr., Dominion Engineering, Inc.

Date: March 18, 2011

Subject: Independent Evaluation of Costs of Major Capital Items for High Temperature Gas Cooled Reactors

1 Background / Introduction

The Idaho National Laboratory (INL) is conducting both technical and economic evaluations in support of an anticipated design and construction of a high temperature gas cooled reactor (HTGR). The first plant that is being planned is known as the Next Generation Nuclear Plant (NGNP). Scheduled to be operational by about 2021, the NGNP will serve as a key demonstration of advanced gas cooled reactor technologies as well as help establish energy production costs prior to commercialization of this type of reactor. The NGNP is expected to have a thermal output of about 550 to 600 MWth and produce electricity as well as supply process heat (nominally high temperature gas) in support of chemical or petrochemical operations. High temperature steam supply to industrial processes is also a potential role for HTGRs that could be demonstrated by the NGNP.

Over the past 15 years, a number of potential US and international gas-cooled reactor vendors, the INL, the DOE and numerous international organizations have evaluated the economics of HTGRs. Overall, the inherent efficiency of producing electricity with a HTGR is expected to be higher than that achieved by conventional light water reactors. This is because HTGRs may operate with a reactor outlet temperature (ROT) of up to 950°C. LWRs typically operate at about 320°C. The Carnot efficiency of the HTGR would therefore be expected to be greater for the HTGR assuming the ultimate heat sink temperature is similar in the case of a conventional Rankine steam cycle.

As part of the overall development of the NGNP in specific and the HTGR technology as a whole, the INL is refining previous economic projections for the cost of designing, licensing and deploying HTGRs. As part of this work, INL asked Dominion Engineering, Inc. (DEI) to conduct an independent assessment of cost data (direct costs) for major capital equipment and infrastructure items.

The specific goal was to use cost estimates that had been generated by General Atomics (GA) in 2007 (Reference 1) and extrapolate them to various HTGR or NGNP deployment or design/operating condition scenarios. The GA estimates were developed for both the NGNP and a future multi-unit site with 4 reactors (so called "4-pack"). The NGNP costs were obviously for a "first of a kind" (FOAK) design and build, while the 4-pack costs are understood to represent an "nth of a kind" or NOAK deployment. GA did not provide estimates for a single unit NOAK nor the FOAK of a single unit commercial plant after NGNP.

It is understood that the GA cost estimates also assumed that NGNP would be designed with an ROT of 950°C while the reference 4-pack was based on earlier GA studies of a Modular Helium Reactor (MHR) operating with an ROT of 850°C (Reference 2).

The 11 most capital intensive HTGR items represent about 80% of the capital cost of the plant. These 11 items are summarized in Table 1. As such, extrapolating costs for only these items is a reasonable way of developing capital cost trends for the entire plant. The items of interest to INL as far as extrapolating the GA estimates were:

- ROT (750, 800, 850, 900 and 950°C)
- Use of 2-1/4Cr 1Mo, Mod P91 and SA508 Cl 3 as pressure vessel materials (reactor vessel, power conversion vessels, intermediate heat exchanger vessel, etc.)
- Rankine versus Brayton cycles for production of electricity
- Costs for NGNP, FOAK and NOAK plants
- 350 versus 600 MWth reactor output
- 4 pack versus single unit sites

Overall, the above variables correspond to more than 250 cases. Although costs for all cases were generated, the summary tables contained in this report were filtered in the sense that cases that were technically unrealistic were not reported (e.g., use of SA508 Cl3 for the reactor vessel with a reactor inlet temperature over 450°C).

Table 2 summarizes some of the HTGR design and operating variables for various proposed vendor designs. These designs were considered in determining which cases were technically unreasonable.

Table 1. Highest Direct Cost Items for NGNP/HTGRs

Reference Item	Description
1	Turbine Generator
2	Reactor Initial Core
3	Reactor Building
4	Reactor Vessel
5	Power Conversion Vessel
6	Core Refueling Equipment
7	Heat Rejection System
8	Reactor Metallic Internals
9	Intermediate Heat Exchanger (IHX)
10	Reactor Graphite Internals
11	Reactor Cavity Cooling System

Table 2. Summary of HTGR and NGNP Reference Conditions and Design Parameters used in Evaluation of Direct Costs

		GA PCDR 2007	AREVA '881	GA 545	GA 545
Reactor Type		Prismatic	Prismatic	NGNP	H2MHR
Power	MWth	600	565	600	600
N		1	1	1	4
Total Power	MWth	600	565	600	2400
RCS Pressure	Mpa	7	5	7	7
ROT	°C	950	900	950	950
RIT	°C	490	500	490	490
PCS Type	Type	Brayton	Rankine	Brayton	Brayton
Output	Mwe	300	241	300	300
Direct/Indirect	Type	Direct	Direct (SGs)	Direct	Direct
PCS Vessel	Matl	2-1/4 or P91	P91	P91	P91
PCS Weight	tons			1100	1100
IHX	MWth	10% Power	1 compact	65	
IHX Cost	Direct	Not specified	Not specified	$ 15,300,000	$ 10,815,000
(per plant)	Indirect	Not specified	Not specified	$ 16,900,000	$ 4,669,250
RV Cost (per)	Direct	Not specified	Not specified	$ 38,321,147	$ 38,321,147
	Indirect	Not specified	Not specified	$ 94,885,000	$ 65,317,429
RV Material	Matl	2-1/4 Cr- 1 Mo 31m H x 8.2 M D x 261 mm	SA508 Cl3 25m H x 7.5 m D	P91	P91
RV Weight	tons	891		891	891
Head Weight	tons	484		484	484
Cross Vessel Weight	tons	16		16	16
Vessel Supports	Matl	P91	Not Specified	P91	P91
RV Internal	Matl	Not specified	800H	800H	800H
Composite CEAS	Use	No	Yes	No	No

2 *Summary of Results*

Tables 3 through 6 summarize the results of the evaluation. Both 350 MWth and 600 MWth cases are provided. These are further divided as FOAK 1-pack, NOAK 4-pack and NOAK 1-pack. Example reference costs for a 600 MWth NGNP are shown in the 600 MWth tables. The results are then shown as a function of ROT.

Table 3. 600 MWth Brayton Cycle Results

			Brayton Direct Cycle															
			NGNP 1-Pack 600 MWt GA Vertical PCS Brayton (7 MPa)	FOAK 1-Pack					NOAK 4-Pack					NOAK 1-Pack				
Ref. Item	**Description**	**Scale Approach**	**950**	**750**	**800**	**850**	**900**	**950**	**750**	**800**	**850**	**900**	**950**	**750**	**800**	**850**	**900**	**950**
1	PCS Turbo Machinery	Exp	399.0	268.7	292.1	317.5	345.1	375.1	415.5	451.6	490.9	533.6	580.0	103.9	112.9	122.7	133.4	145.0
2	Reactor Initial Core	Linear	134.0	102.6	108.0	113.7	119.7	126.0	236.2	262.4	291.6	324.0	360.0	59.0	65.6	72.9	81.0	90.0
3	Reactor Building	Exp	254.0	186.9	198.8	211.5	225.0	239.4	333.0	339.8	346.7	353.8	361.0	117.2	119.6	122.1	124.6	127.1
4	Reactor Vessel	Detail	206.2	95.4	100.5	106.0	133.8	146.4	233.6	245.8	258.9	325.6	355.9	81.1	85.4	90.0	113.5	124.1
5	Power Conversion Vessel	Detail	154.8	71.5	75.4	79.5	100.4	109.9	174.5	183.7	193.6	243.9	266.7	60.7	64.0	67.4	85.1	93.2
6	Core Refueling Equipment	Equiv	98.7	92.8	92.8	92.8	92.8	92.8	162.0	162.0	162.0	162.0	162.0	57.0	57.0	57.0	57.0	57.0
7	Heat Rejection System	Exp	45.0	*42.3*	*42.3*	*42.3*	*42.3*	*42.3*	*161.0*	*161.0*	*161.0*	*161.0*	*161.0*	*40.3*	*40.3*	*40.3*	*40.3*	*40.3*
8	Reactor Metallic Internals	Detail	96.0	36.0	40.5	45.6	76.0	91.4	89.3	100.1	112.3	185.3	222.3	30.7	34.5	38.8	64.5	77.5
9	IHX	Detail	77.6	22.1	23.2	24.4	50.4	55.1	55.9	58.6	61.5	123.8	135.1	19.0	19.9	20.9	42.9	46.8
10	Reactor Graphite Internals	Exp	34.0	26.5	28.2	30.0	32.0	32.0	46.5	49.5	52.6	56.0	56.0	16.4	17.4	18.5	19.7	19.7
11	Reactor Cavity Cooling System	Exp	*31.0*	*29.1*	*29.1*	*29.1*	*29.1*	*29.1*	*50.8*	*50.8*	*50.8*	*50.8*	*50.8*	*12.7*	*12.7*	*12.7*	*12.7*	*12.7*
		Total per Unit	1530.3	974.1	1031.0	1092.4	1246.5	1339.4	489.6	516.4	545.5	630.0	677.7	598.1	629.4	663.4	774.7	833.5

Table 4. 600 MWth Rankine Cycle Results

			Rankine Direct Cycle (7 MPa)															
			NGNP 1-Pack 565 MWt Areva NGNP Direct Steam Cycle (5 MPa)	FOAK 1-Pack					NOAK 4-Pack					NOAK 1-Pack				
Ref. Item	**Description**	**Scale Approach**	**900**	**750**	**800**	**850**	**900**	**950**	**750**	**800**	**850**	**900**	**950**	**750**	**800**	**850**	**900**	**950**
1	Steam Turbine Generator Plant	Exp	80% of Nuclear Heat Plant plus Power Conversion Plant Costs	161.6	175.7	190.9	207.6	225.6	481.4	523.3	568.8	618.2	672.0	120.4	130.8	142.2	154.6	168.0
2	Reactor Initial Core	Linear		102.6	108.0	113.7	119.7	126.0	236.2	262.4	291.6	324.0	360.0	59.0	65.6	72.9	81.0	90.0
3	Reactor Building	Exp		186.9	198.8	211.5	225.0	239.4	333.0	339.8	346.7	353.8	361.0	117.2	119.6	122.1	124.6	127.1
4	Reactor Vessel	Detail		93.8	98.8	104.1	131.4	143.8	229.6	241.6	254.5	320.0	349.7	79.7	83.9	88.4	111.5	122.0
5	Power Conversion Vessel	Detail		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
6	Core Refueling Equipment	Equiv		92.8	92.8	92.8	92.8	92.8	162.0	162.0	162.0	162.0	162.0	57.0	57.0	57.0	57.0	57.0
7	Heat Rejection System	Exp		*42.3*	*42.3*	*42.3*	*42.3*	*42.3*	*161.0*	*161.0*	*161.0*	*161.0*	*161.0*	*40.3*	*40.3*	*40.3*	*40.3*	*40.3*
8	Reactor Metallic Internals	Detail		36.0	40.5	45.6	76.0	91.4	89.3	100.1	112.3	185.3	222.3	30.7	34.5	38.8	64.5	77.5
9	IHX	Detail		22.1	23.2	24.4	50.4	55.1	55.9	58.6	61.5	123.8	135.1	19.0	19.9	20.9	42.9	46.8
10	Reactor Graphite Internals	Exp		26.5	28.2	30.0	32.0	32.0	46.5	49.5	52.6	56.0	56.0	16.4	17.4	18.5	19.7	19.7
11	Reactor Cavity Cooling System	Exp		*29.1*	*29.1*	*29.1*	*29.1*	*29.1*	*50.8*	*50.8*	*50.8*	*50.8*	*50.8*	*12.7*	*12.7*	*12.7*	*12.7*	*12.7*
		Total per Unit	744.0	793.8	837.5	884.5	1006.2	1077.4	461.4	487.3	515.4	588.7	632.5	552.4	581.8	613.9	708.7	761.2

Table 5. 350 MWth Brayton Cycle Results

Brayton Direct Cycle			NGNP 1-Pack Rough Estimate	FOAK 1-Pack					NOAK 4-Pack					NOAK 1-Pack				
Ref. Item	Description	Scale Approach	950	750	800	850	900	950	750	800	850	900	950	750	800	850	900	950
1	PCS Turbo Machinery	Exp	296.6	199.8	217.1	236.0	256.5	278.8	308.9	335.8	365.0	396.7	431.2	77.2	83.9	91.2	99.2	107.8
2	Reactor Initial Core	Linear	86.7	66.4	69.9	73.6	77.4	81.5	152.8	169.8	188.7	209.6	232.9	38.2	42.5	47.2	52.4	58.2
3	Reactor Building	Exp	194.0	142.8	151.9	161.6	171.9	182.8	254.3	259.5	264.8	270.2	275.7	89.5	91.4	93.2	95.1	97.1
4	Reactor Vessel	Detail	142.3	65.9	69.4	73.2	92.4	101.1	161.5	169.9	178.9	224.9	245.8	56.0	59.0	62.2	78.4	85.7
5	Power Conversion Vessel	Detail	106.2	49.1	51.7	54.5	68.9	75.4	119.8	126.1	132.8	167.3	182.9	41.7	43.9	46.3	58.4	63.9
6	Core Refueling Equipment	Equiv	74.0	69.6	69.6	69.6	69.6	69.6	121.5	121.5	121.5	121.5	121.5	42.8	42.8	42.8	42.8	42.8
7	Heat Rejection System	Exp	34.4	*32.3*	*32.3*	*32.3*	*32.3*	*32.3*	*84.8*	*84.8*	*84.8*	*84.8*	*84.8*	*21.2*	*21.2*	*21.2*	*21.2*	*21.2*
8	Reactor Metallic Internals	Detail	91.4	25.4	28.6	32.2	53.7	64.6	63.1	70.7	79.3	130.9	157.0	21.7	24.4	27.4	45.6	54.8
9	IHX	Detail	54.8	15.6	16.4	17.3	35.6	38.9	39.5	41.4	43.5	87.5	95.4	13.4	14.1	14.8	30.3	33.1
10	Reactor Graphite Internals	Exp	34.0	21.2	22.6	24.0	25.6	25.6	26.6	28.3	30.1	32.0	32.0	9.4	10.0	10.6	11.3	11.3
11	Reactor Cavity Cooling System	Exp	*23.6*	*22.2*	*22.2*	*22.2*	*22.2*	*22.2*	*38.8*	*38.8*	*38.8*	*38.8*	*38.8*	*9.7*	*9.7*	*9.7*	*9.7*	*9.7*
		Total per Unit	1138.2	710.3	751.8	796.4	906.0	972.8	342.9	361.6	382.0	441.1	474.5	420.8	442.7	466.5	544.3	585.5

Table 6. 350 MWth Rankine Cycle Results

			Rankine Direct Cycle (7 MPa)															
			NGNP 1-Pack	FOAK 1-Pack					NOAK 4-Pack					NOAK 1-Pack				
Ref. Item	**Description**	**Scale Approach**		**750**	**800**	**850**	**900**	**950**	**750**	**800**	**850**	**900**	**950**	**750**	**800**	**850**	**900**	**950**
1	Steam Turbine Generator Plant	Exp	No 350 MWt NGNP Cost Estimates	123.4	134.2	145.8	158.5	172.3	367.7	399.7	434.4	472.2	513.2	91.9	99.9	108.6	118.0	128.3
2	Reactor Initial Core	Linear		66.4	69.9	73.6	77.4	81.5	152.8	169.8	188.7	209.6	232.9	38.2	42.5	47.2	52.4	58.2
3	Reactor Building	Exp		142.8	151.9	161.6	171.9	182.8	254.3	259.5	264.8	270.2	275.7	89.5	91.4	93.2	95.1	97.1
4	Reactor Vessel	Detail		65.1	68.5	72.3	91.2	99.8	159.5	167.8	176.7	222.1	242.8	55.3	58.2	61.4	77.4	84.6
5	Power Conversion Vessel	Detail		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
6	Core Refueling Equipment	Equiv		69.6	69.6	69.6	69.6	69.6	121.5	121.5	121.5	121.5	121.5	42.8	42.8	42.8	42.8	42.8
7	Heat Rejection System	Exp		*32.3*	*32.3*	*32.3*	*32.3*	*32.3*	*84.8*	*84.8*	*84.8*	*84.8*	*84.8*	*21.2*	*21.2*	*21.2*	*21.2*	*21.2*
8	Reactor Metallic Internals	Detail		25.4	28.6	32.2	53.7	64.6	63.1	70.7	79.3	130.9	157.0	21.7	24.4	27.4	45.6	54.8
9	IHX	Detail		15.6	16.4	17.3	35.6	38.9	39.5	41.4	43.5	87.5	95.4	13.4	14.1	14.8	30.3	33.1
10	Reactor Graphite Internals	Exp		21.2	22.6	24.0	25.6	25.6	26.6	28.3	30.1	32.0	32.0	9.4	10.0	10.6	11.3	11.3
11	Reactor Cavity Cooling System	Exp		*22.2*	*22.2*	*22.2*	*22.2*	*22.2*	*38.8*	*38.8*	*38.8*	*38.8*	*38.8*	*9.7*	*9.7*	*9.7*	*9.7*	*9.7*
		Total per Unit		584.1	616.2	650.8	738.0	789.6	327.2	345.6	365.6	417.4	448.5	393.1	414.1	436.9	503.8	541.1

The cells in the above tables shown in grey were not evaluated (there is no 350 MWth NGNP reference cost data for the Rankine Cycle, nor is there a PCS in the Rankine cycles). Items in italics were not scaled by temperature because it was not clear that the direct costs would be drastically affected by changes in ROT (although a simple cost-factor exponential relationship could be used if detailed information on the sizes of sub-components was known).

3 Summary Description of Evaluation

The evaluation and extrapolation of the cost estimates provided in 2007 by GA was performed as follows:

- The GA cost data was summarized for NGNP at ROT of 950°C and a 4-pack design based on MHR at an ROT of 850°C. No change was made to account for 2010 dollars versus 2007 (so the results should be interpreted as 2007 dollar equivalent).
- Each of the 11 items was then grouped by scaling methodologies: (1) exponential scaling laws (similar to those used in petrochemical industry - exponentials ranged from 0.32 to almost 1.00 with an average of about 0.6), (2) linear scaling by reactor size, (3) equivalent cost regardless of selected parameters such as core size (e.g. refueling equipment), (4) more rigorous or “detailed” evaluations based on first principles and material property behavior as function of temperature, or (5) no scaling due to uncertainties in savings that might be achieved by changes such as reducing temperature.
- A limited amount of literature data on gas cooled reactor costs such as that available from the GEN-IV program (G4 ECONS Models) was considered.
- For the detailed evaluations, spreadsheets were developed that used the following inputs:
    - Cost of SA508 pressure vessel steel from the LWR industry.
    - The percent of the component that would be subjected to elevated temperature design (ETD) rules (hence cost of the component would be higher relative to lower temperature components).
    - Relative costs of candidate materials of construction.
    - Relative fabrication costs for various materials of construction.
    - A Code-allowable stress for temperatures below ETD limits (lower strength materials require thicker sections).

- A general placeholder for an activation energy for temperature dependent degradation mechanisms such as general corrosion – this can be set to zero by the user (currently set to 18 kcal/mol).

- A user defined breakout of direct costs in terms of raw materials, forming and fabrication, final fabrication, pre-service inspection and transportation.

- Any components subject to creep were cost-adjusted using a correlation between allowable stress at 100,000 hours creep rupture life and increased in size to lower stresses as needed as a function of temperature. This is a somewhat suspect method of addressing costs associated with creep, as increasing the size of components is not necessarily the best approach.

- Cost scaling from the GA estimates was based on a top-down approach as opposed to a detailed bottom-up method.

- RD&D, design, construction, commissioning, operations, fueling and decommissioning costs were not factored into the evaluation.

- Field fabrication versus shop fabrication was only considered to the extent a transportation factor was used in discriminating between the 600 MWth and 350 MWth RV and PCS vessel costs.

- Rankine turbine generator costs were developed independently using publically available data on supercritical fossil plants.

- NOAK versus FOAK costs were based on published “learning factors’ used in the LWR industry – 0.94 for equipment and 0.90 for materials (e.g. each doubling of site size reduces direct cost by 16%).

- Contingencies were not explicitly included in the cost extrapolations – this was largely because it was not clear if sub-supplier contingencies had already been included in the GA costs.

- No credit for modularization or factory production was taken, although this might be expected to actually increase the costs until a production of some number of units was completed (on the order of 20).

- The cost estimates in the “detailed evaluations” did consider a heavy burden for nuclear grade components versus industrial grade.

- Rankine cycle steam turbine scaling factors were taken from the literature (0.5).
- Gas turbine scaling factors were taken from the literature (0.48 to 0.55).
- Reactor graphite internals costs were not scaled upward in increasing ROT from 900°C to 950°C (800H assumed in both cases). They were lowered below 900°C.
- Reactor Inlet Temperatures (RITs) were assumed to vary as follows (based on overall trends in various vendors' proposed NGNP designs):

ROT (°C)	RIT (°C)
750	350
800	375
850	400
900	425
950	450

4 References

1. "NGNP and Commercial H2-MHR Cost Information", PC-000545, prepared by General Atomics for the Battelle Energy Alliance, LLC, July 2007 (Proprietary).
2. "NGNP and Hydrogen Production Preconceptual Design Studies Report", General Atomics Report 911107, July 2007.

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