MPR ASSOCIATES INC. ENGINEERS

Enclosure 1 to
MPR Letter Dated
August 8, 2008

Number of HTGRs Hypothetically Required for Different Aspects of Current U.S. Hydrogen Production

Purpose

This evaluation estimates how many High Temperature Gas-cooled Reactors (HTGRs) would be needed to provide energy for different aspects of current U.S. hydrogen production. This study uses the method reported in Reference 1 to evaluate energy needs for U.S. merchant hydrogen.

Approach

The total annual U.S. hydrogen production in 2005 was estimated at 9 million tonnes (metric tons), which is equivalent to 3.74 trillion scf (standard cubic feet at 1 atmosphere pressure and 60°F) (Reference 2).

The production of U.S. merchant hydrogen, which is hydrogen that is produced for sale to another user as an industrial gas, was about 2.5 million tonnes or 1.05 trillion scf in 2007 (Reference 3). About 95% of it was made by the Steam Methane Reforming (SMR) method.

The sources of hydrogen production other than merchant hydrogen, and the production processes used are difficult to quantify because this hydrogen is not sold and recorded. This so-called captive hydrogen is used as a feedstock for one process at the same manufacturer where it was produced in another process. As an example, U.S. refinery production of captive hydrogen in 2007 was about 3.6 million tonnes (Reference 3), and this used many feedstocks such as napthas, napthenes, paraffins, still gas and natural gas, and included processes such as cyclization and dehydrogenation, as well as steam reforming.

For simplicity, this evaluation will consider two different production quantities. The first will be U.S. merchant hydrogen production. The second will be the total estimated U.S. hydrogen production. The following will be included in estimating the number of equivalent HTGRs:

- **Merchant Hydrogen Supply**: The fraction of the 1.05 trillion scf made by SMR (95%) will be evaluated. This equates to 1.00 trillion scf (2.4 million tonnes).
- **Total Hydrogen Supply**: For simplicity and as an upper bound, the total U.S. hydrogen production, estimated at 3.74 trillion scf (9 million tonnes), will be assumed to be made solely by the SMR process.

For each of the above cases, the following evaluations will be performed:

- Provide Energy Loads for SMR Process: Calculate the number of HTGRs to provide all energy loads needed to produce U.S. merchant plant hydrogen using SMR.
- Replace Lost Heat from Natural Gas Feedstock: Measure the amount of natural gas used as feedstock, based on its heating value, and calculate the number of HTGRs required to provide the same heating capability that is lost to feedstock.
- Eliminate All Use of Natural Gas for Hydrogen Production: If the hydrogen production was entirely made by HTGRs using water as a feedstock, with either Low Temperature Electrolysis (LTE) or High Temperature Electrolysis (HTE) as a process, calculate the required number of HTGRs. The temperatures for LTE are less than 200°C and the temperatures for HTE are around 900-950°C.

Methodology

To calculate the number of HTGRs required for hydrogen production, the following inputs are required:

- Production Method Used
- Total Annual Production, *P* (scf in a yr)
- Production Energy, *E* (Btu/scf)
- Conceptual HTGR Plant Size, *S* (MWt)
- Plant Capacity Factor, *C*

The number of HTGRs, *N*, required is given by:

$$N = \frac{P * E}{S * C * 2.99 * 10^{10}} \qquad \text{Equation 1}$$

Calculations

1. Merchant Plant Production via SMR

As previously noted, the merchant plant hydrogen produced by SMR is 1.00 x 10^{12} scf (2007).

a. Provide Energy Loads for SMR Process: The number of HTGRs that would be needed to supply the energy requirements for producing US merchant hydrogen made via the SMR process was estimated in Reference 1 on the following basis:

The production energy for hydrogen via SMR is calculated in Reference 4 using energy input values for a hypothetical 57 million scfd (scf per day) reference plant. This plant uses natural gas as a fuel and feedstock but also requires steam and electricity from an external source.

The mass rate of steam required is:

$$\dot{M}_s = 1239 \frac{Mg}{day}$$

The amount of electrical energy required is:

$$\dot{E}_{elec} = 153{,}311 \frac{MJ}{day}$$

The mass rate of natural gas required for fuel is:

$$\dot{M}_{CH4\_fuel} = 43 \frac{Mg}{day}$$

The mass rate of natural gas required as a feedstock is:

$$\dot{M}_{CH4\_fs} = 392 \frac{Mg}{day}$$

The energy value of steam is assumed to be 1200 Btu/lb. Specific energies for natural gas are assumed to be 23,000 Btu/lb and 1030 Btu/scf. Finally, the thermal to electrical energy conversion efficiency is assumed to be 33% for SMR (not significant for SMR, see discussion about different efficiency values for electrolysis below).

The energy inputs per day for steam, electricity, and natural gas as a fuel are:

$$\dot{E}_s = \dot{M}_s \frac{2205 lb}{Mg} \frac{1200 Btu}{lb} \qquad \dot{E}_s = 3421 MMBtu/day$$

$$\dot{E}_{elec\_thermal} = \dot{E}_{elec} \frac{1}{0.33} \qquad \dot{E}_{elec\_thermal} = 436 MMBtu/day$$

$$\dot{E}_{CH4\_fuel} = \dot{M}_{CH4\_fuel} \frac{2205 lb}{Mg} \frac{23{,}000 Btu}{lb} \qquad \dot{E}_{CH4\_fuel} = 2181 MMBtu/day$$

The energy for the replacement of the steam, electricity, and fuel by an HTGR is therefore:

$$E_{SMR\_energy} = \frac{\dot{E}_s + \dot{E}_{elec\_thermal} + \dot{E}_{CH4\_fuel}}{57 * 10^6 \frac{scf}{day}} \qquad E_{SMR\_energy} = 106 \frac{Btu}{scf}$$

In Reference 1, a conceptual 500 MWt HTGR with a capacity factor of 0.85 is assumed.

$$S = 500 MWt \qquad C = 0.85$$

Therefore, from Equation 1, the number of HTGRs that can replace all energy sources in the SMR process for the production of merchant hydrogen is:

$$N_{SMR\_energy} = \frac{P_1 * E_{SMR\_energy}}{S * C * 2.99 * 10^{10}} \qquad N_{SMR\_energy} = 8$$

b. Replace Lost Energy from Natural Gas Feedstock: A way of comparing the amount of potential heating capability that is lost by using natural gas for the feedstock is to convert the feedstock into a number of HTGRs that could provide the same heating capability.

$$\dot{E}_{CH4\_fs} = \dot{M}_{CH4\_fs} \frac{2205 lb}{Mg} \frac{23{,}000 Btu}{lb} \qquad \dot{E}_{CH4\_fs} = 19{,}880 MMBtu / day$$

$$E_{SMR\_fs} = \frac{\dot{E}_{CH\_fs}}{57 * 10^6 \frac{scf}{day}} \qquad E_{SMR\_fs} = 349 \frac{Btu}{scf}$$

$$N_{SMR\_fs} = \frac{P_1 * E_{SMR\_fs}}{S * C * 2.99 * 10^{10}} \qquad N_{SMR\_fs} = 27$$

c. Eliminate All Use of Natural Gas for Hydrogen Production: The number of HTGRs it would take if no natural gas was used and all hydrogen was made by electrolysis with water as feedstock is shown below.

The thermal-to-hydrogen production efficiency of a given process is defined as the ratio of the lower heating value (LHV) of the hydrogen produced to the thermal energy required for production. The LHV of hydrogen is 290 Btu/scf (Reference 5). Studies from Reference 6 show that in a high temperature reactor (950°C outlet temperature) with a high power cycle efficiency (54.8%), the thermal-to-hydrogen production efficiencies of the LTE and HTE processes are:

$$\eta_{LTE} = 39\% \qquad \eta_{HTE} = 48\%$$

Determine the thermal energy required for electrolysis per scf of hydrogen:

$$E_{LTE} = 290 \frac{Btu}{scf} \frac{1}{\eta_{LTE}} = 744 \frac{Btu}{scf}$$

$$E_{HTE} = 290 \frac{Btu}{scf} \frac{1}{\eta_{HTE}} = 604 \frac{Btu}{scf}$$

The number of reactors needed to produce the 1.00 trillion scf of merchant hydrogen using LTE and HTE can be calculated:

$$N_{LTE} = \frac{P_{total} * E_{LTE}}{S * C * 2.99 * 10^{10}} \qquad N_{LTE} = 59$$

$$N_{HTE} = \frac{P_{total} * E_{HTE}}{S * C * 2.99 * 10^{10}} \qquad N_{HTE} = 48$$

The required number of HTGRs for LTE and HTE electrolysis methods can be compared to the combined 35 equivalent reactors for the SMR process in which the energy value of the SMR feedstock is expressed as equivalent reactors. The number of HTGRs required to produce 1.00 x 10^{12} scf of hydrogen using SMR, LTE and HTE methods are displayed graphically in Figure 1.

2. Total Hydrogen Demand

This section calculates the number of HTGRs required to produce the total U.S. hydrogen demand. using a single process. The use of SMR, LTE and HTE are compared, using the same techniques demonstrated above, including the assumption of a conceptual 500 MWt HTGR.

The total U.S. hydrogen demand in 2005 was 9 million tonnes, or in terms of scf:

$$P_{total} = 3.74 \times 10^{12}\ scf / yr$$

The number of HTGRs required for SMR is divided between replacement of energy (which is the steam, heat and electricity needed to run the SMR process) and the equivalent energy that is lost due to lost heating capacity of the feedstock (expressed as the number of HTGRs that would be required to replace the energy in the feedstock).

$$N_{SMR\_energy} = \frac{P_{total} * E_{SMR\_energy}}{S * C * 2.99 * 10^{10}} \qquad N_{SMR\_energy} = 31$$

$$N_{SMR\_fs} = \frac{P_{total} * E_{SMR\_fs}}{S * C * 2.99 * 10^{10}} \qquad N_{SMR\_fs} = 103$$

$$N_{LTE} = \frac{P_{total} * E_{LTE}}{S * C * 2.99 * 10^{10}} \qquad N_{LTE} = 219$$

$$N_{HTE} = \frac{P_{total} * E_{HTE}}{S * C * 2.99 * 10^{10}} \qquad N_{HTE} = 178$$

These values are graphically represented in Figure 2.

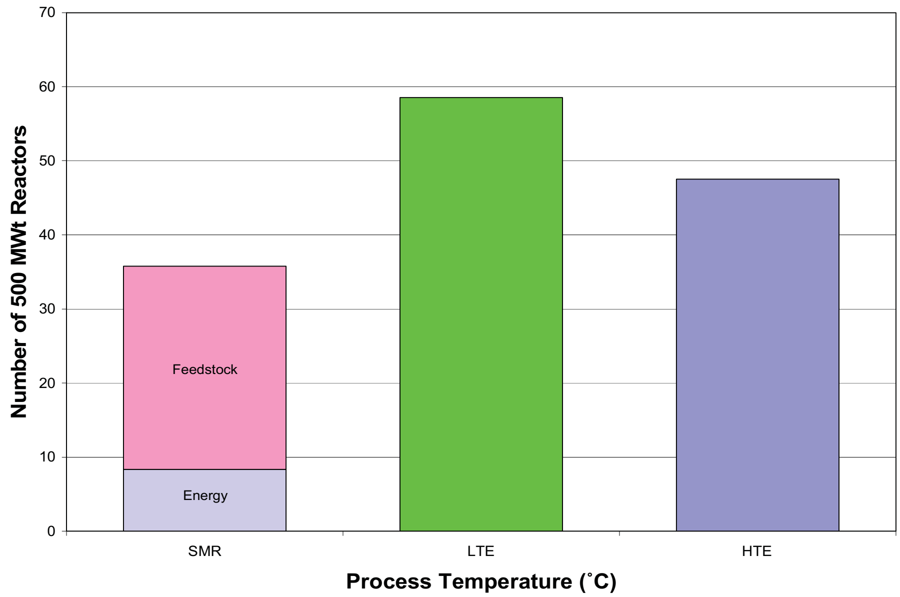

Figure 1. Number of HTGRs (950°C) to Meet 2.4 Million Tonnes U.S. Merchant Production Demand (1.00 x 10^{12} scf) by SMR*, LTE and HTE

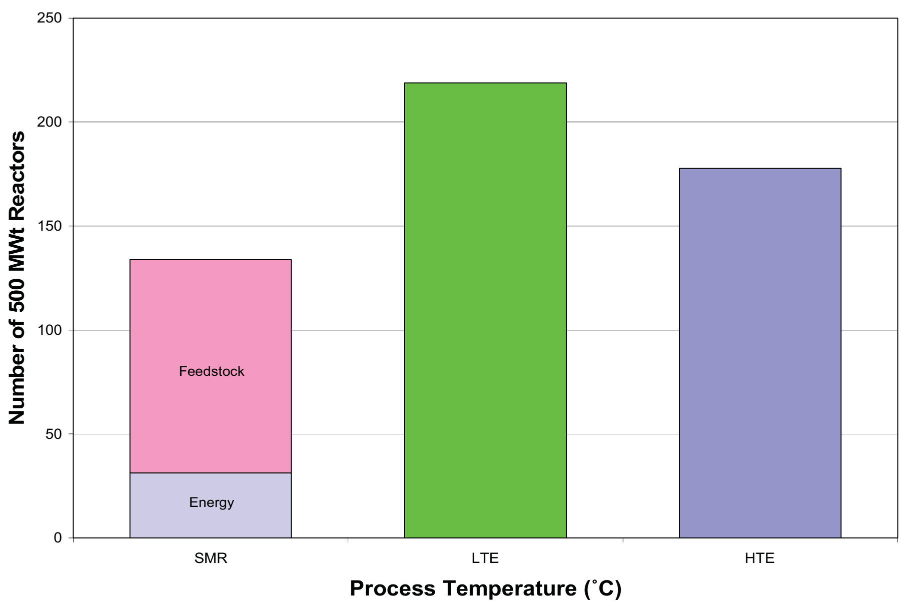

Figure 2. Number of HTGRs (950°C) to Meet 9 Million Tonnes U.S. Hydrogen Demand Assuming All is Produced by SMR*, LTE and HTE

Note: * If the SMR process is used, only the energy bar requires HTGRs. The Feedstock bar shows the amount of heat-making capacity lost due to use of natural gas as the feedstock. Thus, the total feedstock plus energy bar for the SMR process can be compared to the energy bars for the LTE and HTE processes.

References

1. Report MPR-3181, "Survey of HTGR Process Energy Applications," Revision 0.

2. U.S. DOE, "Today's Hydrogen Production Industry," www.fossil.energy.gov.

3. "2007 Hydrogen Production Data," Hydrogen Analysis Resource Center.

4. NREL/TP-570-27637, "Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming," Revised February 2001.

5. "Lower and Higher Heating Values of Fuels," Hydrogen Analysis Resource Center.

6. C. J. Steffen, Jr., M. G. McKellar, E. A. Harvego, and J. E. O'Brien, "The Effect of Electrolysis Temperature on Hydrogen Production Efficiency," ST-NH_2, ANS Conference, Boston, June 24-28, 2007.

Enclosure 2 to
MPR Letter Dated
August 8, 2008

Number of HTGRs Hypothetically Required for Future Canadian Oil Sands Needs

1. Purpose

The purpose of this evaluation is to show how many 500 MWt (conceptual size) High Temperature Gas Reactors (HTGRs) would be needed to provide for the process energy requirements associated with present and future Canadian oil sands extraction plant developments.

2. Method

Reference 1 provided projections of oil recovery production developments in the Canadian oil sands region through 2050. The projections differentiate between open mining of near surface oil sands and "in-situ" recovery of bitumen extracted from deposits below the surface by various processes via drilled wells. Figure 1 predicts the production forecasts based on crash program scenarios (i.e., maximum rates of development).

The barrels per day (bbd) forecasted in Figure 1 were converted into a number of hypothetical reactors that could provide the necessary energy for bitumen recovery. The number of reactors was based on a conceptual 500 MWt HTGR with operational capacity factor of 0.85. This is the same basis that was used for the Reference 2 report which estimated the equivalent HTGRs for all industrial process energy needs. Based on the Reference 2 report, the following conversions were used for equating barrels per day (bbd) of bitumen recovery to required process energy in Megawatts-thermal (MWt):

- For Mining: 600 MWt will yield 100,000 bbd
- For In-Situ: 600 MWt will yield 50,000 bpd, based on a SAGD process (steam actuated gravity drain)

These conversions are rough estimates since the actual conversion rates are influenced by the quality of the oil sands and the steam to oil ratio (SOR) required for each well.

3. Summary

Table 1 shows the results of this evaluation. The prediction of 50 HTGRs for in-situ oil sands recovery in 2020, reported in Reference 2, is reflected by the underlined datum. Key conclusions from Table 1 are as follows:

a. Total annual thermal energy used for oil sands by 2050 is equivalent to 134 HTGRs.

b. Total annual thermal energy used only for in-situ applications by 2050 is equivalent to 127 HTGRs.

c. If the lifetimes of oil sands recovery plants are on the order of 30 years, most of the plants in support of mining will likely be in place by 2020. Further, the HTGR has unique capabilities for high temperature steam that is needed for in-situ applications. Therefore, the higher priority focus for HTGR should be toward in-situ plants.

By considering only the energy requirements for in-situ production starts after 2020, based on expected scheduled availability of HTGR plants, then up to 79 HTGRs could be applied by 2050 to oil sands development (see last column in Table 1).

Year	Mining Projection (M bpd)	*Number of 500 MWth Reactors for Mining*	In-Situ Projection (M bpd)	*Number of 500 MWth Reactors for In-Situ*	*Number of 500 MWt Reactors for all Energy*	*Number of Reactors for In-Situ Starting after 2020*
2005	***0.6***	***8***	***0.4***	***11***	***19***	***0***
2020	***2.3***	***32***	***1.7***	***48***	***80***	***0***
2030	***2.3***	***32***	***2.5***	***71***	***103***	***23***
2040	***2.3***	***32***	***3.5***	***99***	***131***	***51***
2050	***0.5***	***7***	***4.5***	***127***	***134***	***79***

Table 1 Number of HTGRs Needed to Provide Energy for Oil Sands Development

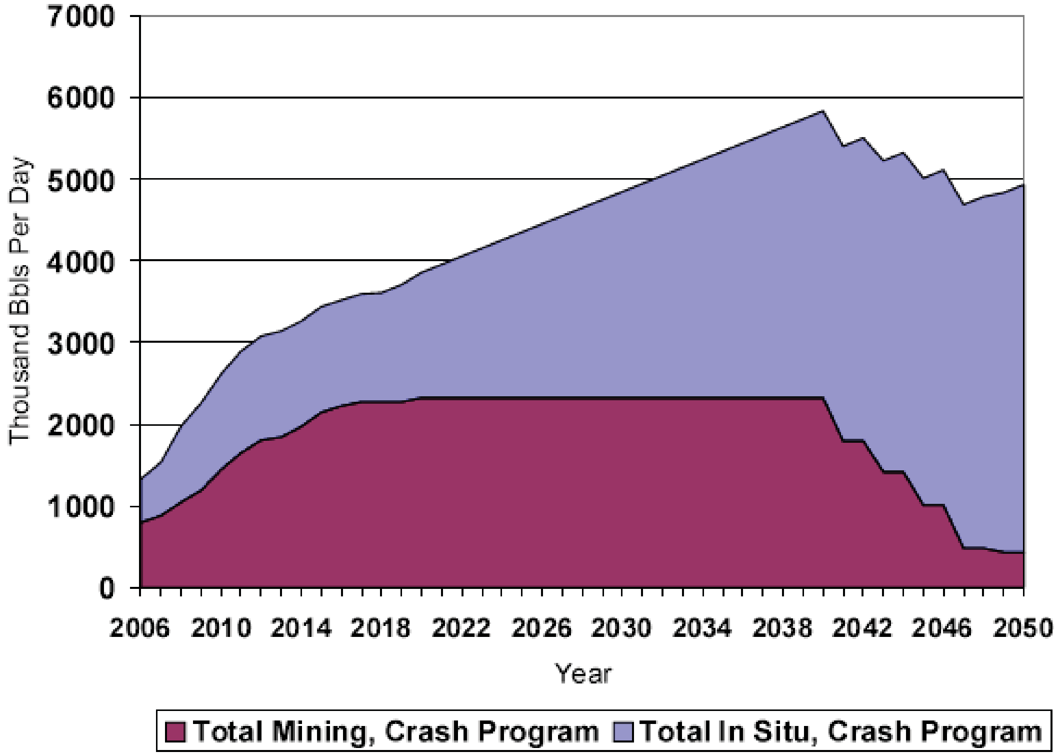

Figure 1: Long Term Oil Sands Crash Program Production Forecast [1]

4. References:

1. B. Söderbergh, F. Robelius and K. Aleklett, "A Crash Program Scenario for the Canadian Oil Sands Industry," June 8, 2006, http://www.peakoil.net/uhdsg/20060608EPOSArticlePdf.pdf

2. Report MPR-3181, "Survey of HTGR Process Energy Applications," Revision 0, May 2, 2008

NEXT GENERATION NUCLEAR PLANT PROJECT INFORMATION INPUT SHEET

1. Document Information

Document ID:	MPR Letter Report	Revision ID:	
		Project Number:	23843
Document Title/Description:	Number of High Temperature Gas-cooled Reactors that Could Hypothetically be Applied to U.S. Hydrogen Production and to Canadian Oil Sands Recovery, Prepared by MPR Associates	Sub-Project No.:	
		Date of Record:	08/08/08
Document Author/Creator:	MPR Associates	OR	
Document Owner:	Phil Mills	Date Range:	
Originating Organization:	INL	From:	To:

2. Records Management Requirements

Category: ☒ General Record ☐ Quality Assurance ☐ Controlled Document

If QA, Record, QA Classification: ☐ Lifetime ☐ Non-Permanent

Uniform Filing Code: 8201 Disposition Authority: A17-31-a-1 Retention Period: Until dismantlement or disposal of facility, equipment, system, or process; or when superseded or obsolete, whichever is earlier.

Keywords:

Medium: ☒ Hard Copy ☐ CD/Disk (each CD/Disk must have an attached index) ☐ Other:

Total Number of Pages (including transmittal sheet): 12 File Index Code: 8201.1.2

Folder: Engineering

Type: Reports

Special Instructions:

3. Signatures

SENDER:

Print/Type Sender Name	Sender Signature	Sender S Number	Date
Phil Mills	[signature]	085841	3/03/10

QA RECORD VALIDATOR:

Print/Type Authenticator Name	Authenticator Signature	Authenticator S Number	Date

ACCEPTANCE/RECEIPT:

Print/Type Receiver Name	Receiver Signature	Receiver S Number	Date
Tammy Albrethsen	Tammy Albrethsen	105429	3/8/10

4. Records Processing Information
For Document Control and Records Management Use Only

☐ Image ☐ Vault Page: Import: Index: QC:

NOTE: This transmittal to be used in accordance with PLN-1485. Instructions for completion can be found on Form 435.77A.