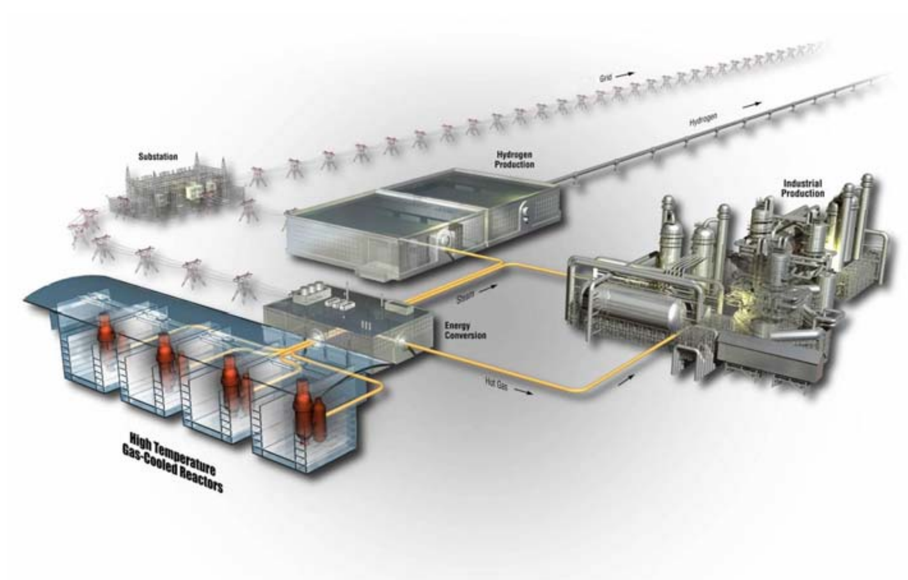
Document ID: TEV-1029
Revision ID: 0
Effective Date:11/18/10

Technical Evaluation Study

Project No. 23843

Integration of HTGRs to an In Situ Oil Shale Operation



The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

INTEGRATION OF HTGRS AND AN IN SITU OIL SHALE RETORT	Identifier: TEV-1029 Revision: 0 Effective Date: 11/18/10	Page: 1 of 31

NGNP Project	Technical Evaluation Study (TEV)		eCR Number: 584854

Signatures

Signature and Typed or Printed Name	Signature Code	Date (mm/dd/yyyy)	Organization/Discipline
Eric P. Robertson	P	11/12/2010	NGNP Engineering Support
Mike Patterson	C	11/18/2010	Project Manager NGNP Process Heat Applications
Phil Mills	A	11/18/10	Acting Director NGNP Engineering

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.

Note: Applicable QLD: REC-000101

REVISION LOG

Rev.	Date	Affected Pages	Revision Description
0	11/18/10	All	Newly issued document

CONTENTS

1. INTRODUCTION

This technical evaluation (TEV) addresses potential integration opportunities for single or multiple High Temperature Gas-cooled Reactor (HTGR) modules with production of oil from oil shale using an in situ retort process. It has been prepared as part of a study for the Next Generation Nuclear Plant (NGNP) Project to evaluate the integration of HTGR technology with conventional chemical processes. The NGNP Project functions under U.S. Department of Energy (DOE) direction to meet a national strategic need identified in the *Energy Policy Act* of 2005 to promote reliance on safe, clean, economic nuclear energy and to establish a greenhouse-gas-free technology for the production of hydrogen. The NGNP represents an integration of high-temperature reactor technology with advanced hydrogen, electricity, and process heat production capabilities, thereby meeting the mission need identified by 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.

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

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

The process of heating oil shale in an anoxic environment to pyrolyze the kerogen embedded within the oil shale and produce oil and gas is commonly called retorting. Kerogen is the organic portion of oil shale and is largely insoluble in organic solvents because of its very large molecular weight. If buried at sufficient depth, time, and concentration, kerogen will release oil and gas. Oil shale deposits rich in kerogen have not been buried at sufficient depths for oil and gas to form naturally. Retorting the oil shale is a method to convert the kerogen to oil and gas.

Shallow oil shale deposits may be mined and processed in a surface, or ex situ retort. Deeper oil shale deposits may be retorted in situ by conveying heat into the subsurface and producing the resulting oil and gas in a manner similar to conventional oil and gas production.

1.1 Integration of HTGRs with an in situ oil shale retort operation

This report describes how an HTGR could be integrated into an in situ oil shale production operation. A future report will provide a preliminary economic analysis comparing the HTGR-integrated process with the base concept of an in situ oil shale production process.

Two fluids, high temperature helium and steam, were considered as working fluids in the secondary flow loop that supplies heat to the in situ retort. Other heat transfer fluids are possible, but because this report relies on completed assessments by the NGNP working group, considering new heat transfer fluids is beyond the scope of this report. For this TEV, the HTGR module(s) is assumed to be physically located near the oil shale operation such that the heat lost during surface transport of the heating fluid is negligible. This TEV does not offer an assessment of the optimal siting of an HTGR with respect to an in situ oil shale retort operation facility. If an optimal siting assessment is desired, a separate study will be conducted that balances the distance between the two facilities to consider safety, heat loss, and licensing concerns.

1.2 Oil Shale Background

The oil resource within the Green River Formation oil shale deposits in Colorado, Utah, and Wyoming is 1.5 to 1.8 trillion barrels with two-thirds of the resource residing within the 1,200-square-mile Piceance Basin of western Colorado (Bartis et al. 2005). The total recoverable oil from this resource is estimated to be 0.5 to 0.8 trillion barrels (Bartis et al. 2005). By comparison, the remaining recoverable oil in the entire world is estimated to be 1.1 trillion barrels (Nashawi et al. 2010).

The basis for this evaluation is an in situ oil shale production project producing 50,000 bbl/day of shale oil, the product being ready for transport via pipeline to a local refinery. This analysis assumes that refining capacity exists in the region to accept the shale oil produced from the operation.

There are commercial ex situ oil shale operations internationally, but none in the United States. No commercial scale in situ oil shale operations exist anywhere in the world at this time. The current state of the in situ oil shale industry is the research, development, and demonstration (RD&D) phase, with a handful of RD&D leases being worked in western Colorado and eastern Utah. A large-scale, commercial in situ oil shale industry in the U.S. may emerge within the next 10 to 15 years. Even though there are no commercial in situ oil shale operations, numerous reports and analyses have been written and performed from which to draw the parameters necessary to perform an analysis of a hypothetical in situ oil shale production operation and its integration with an HTGR. Development and deployment of a commercial HTGR may also require 10 to 15 years. Thus, this conceptual study of integrating an HTGR with an in situ oil operation is timely.

Production from an in situ oil shale operation is assumed to be located in the Piceance Basin in northwestern Colorado from an oil shale zone below the nahcolite sealing zone, which separates the fresh water aquifer above and the highly saline water zone below (Day 2009). Contamination of fresh ground water during and after an in situ oil shale retort is not expected to occur because of the thickness of the low permeability nahcolite layer separating the fresh water aquifer and the deeper oil shale retort zone. No additional efforts to limit contamination of the shallower fresh water zones (e.g., development and maintenance of a freeze wall) are assumed to be required.

A schematic diagram of an in situ oil shale retort operation developed by American Shale Oil LLC is shown in Figure 1. Heat is supplied to the desired subsurface interval or zone to be retorted through a closed loop injection and return piping system. The circulating fluid does not directly contact the oil shale, but transfers its heat by conduction through the pipe wall.

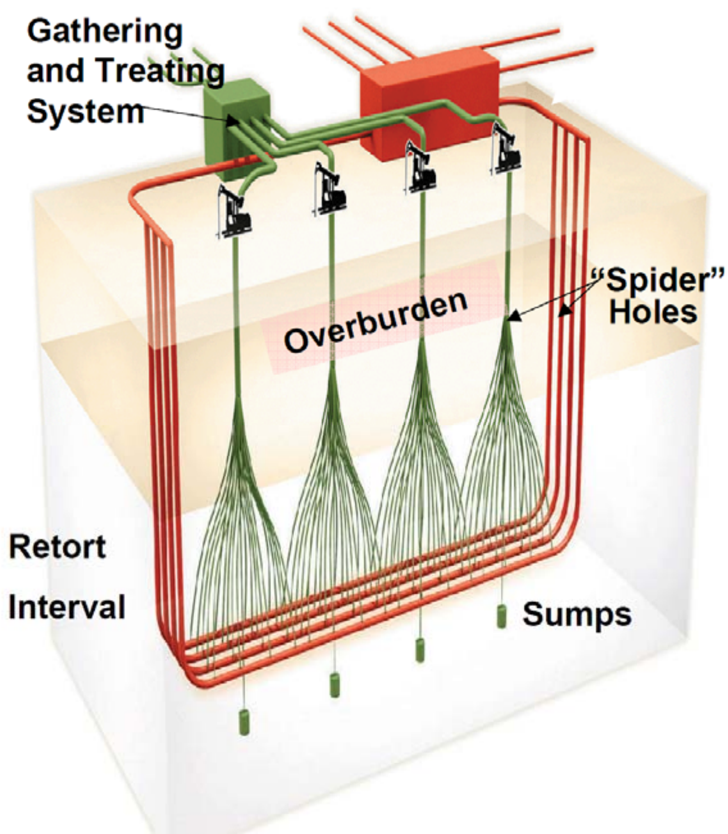


Figure 1. A schematic diagram of a possible configuration for the production of oil from an in situ oil shale retort operation. The closed loop piping system for the circulation of hot fluids is shown in red and the hydrocarbon fluids-gathering system is shown in green.

Other alternative configurations are being actively considered by industry, but none of the other designs can be directly integrated with heat supplied by an HTGR. Other options being considered by industry for heat delivery include injection of surface-generated hot fluids that directly contact the rock formation, creation of hot fluids by downhole combustion, and heating of the rock through electric heaters.

The option shown in Figure 1 is an early design of a commercial scale in situ oil shale operation developed by American Shale Oil LLC, which is actively advancing its technology on its in situ RD&D oil shale lease in the United States. American Shale Oil LLC has modified their design for its small-scale demonstration, but may revert to it for commercial operation.[a] Using electricity (as opposed to utilizing the HTGR heat directly) from an HTGR for heat generation via electric heaters is possible, but converting heat to electricity and then back to heat is an inefficient process and has high energy losses. The closed-loop production design in Figure 1 was selected as the base case for HTGR integration because it has the capacity to directly utilize and recycle the heat output from an HTGR.

Referring to Figure 1, hot fluids are injected vertically downward through cased, directionally drilled wells, then horizontally through the oil shale retort interval, and finally vertically upward to the surface where the fluids are reheated and re-injected through the U-shaped closed-loop piping system. The vertical sections of the closed loop are insulated to minimize heat loss, while the hot fluid in the horizontal section of the loop transfers its heat through the steel casing wall of the well by conduction and into the oil shale retort interval. Some convection of the hot pyrolyzed product within the retort zone may help distribute heat through the desired retort zone. Multiple, vertical, small-diameter, production wells drilled from a single surface borehole called “spider” holes are used to produce the hydrocarbon fluids resulting from the pyrolysis of the kerogen.

2. PROCESS MODELING OVERVIEW

Three oil shale production cases were identified for modeling:

1. A base case concept of in situ oil shale retort in which a subsurface retort interval is heated by circulating a hot fluid through a closed-loop piping system drilled through the retort interval. The heat transfer fluid for the base case is surface-heated steam with heat from a natural gas burner.

2. A steam HTGR-integrated case, which is the same as the base case except the steam is heated using heat generated from an HTGR.

---

[a] Personal communication with Alan Burnham, of American Shale Oil LLC (August 2010).

3. A helium HTGR-integrated case, which is the same as the base case except helium heated by an HTGR, instead of steam, is used as the fluid delivering heat to the oil shale retort interval.

A schematic block flow diagram of the base case concept of an in situ oil shale retort is shown in Figure 2.

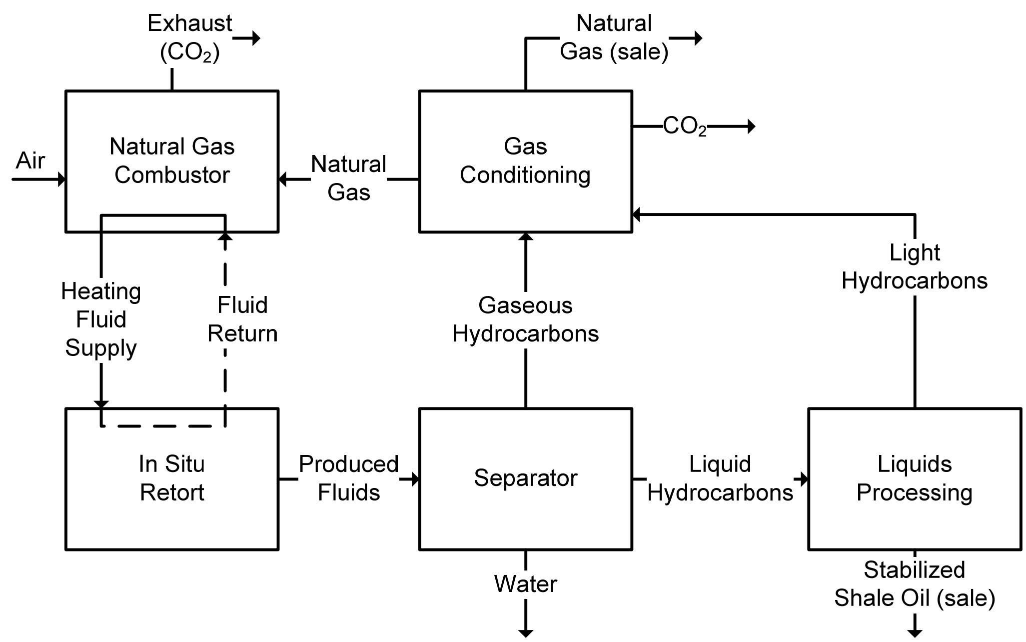


Figure 2. Block flow diagram for the base case concept of an in situ oil shale retort operation.

In an HTGR-integrated in situ oil shale retort operation, the natural gas combustor is replaced by an HTGR located nearby that supplies mainly heat to the oil shale operation. A power cycle is added to the return line going back into the HTGR in order to reduce the temperature of the returning heat transfer fluid to the HTGR maximum return temperature (see also Section 4.2.3). Figure 3 shows the block flow diagram for the HTGR-integrated, in situ oil shale retort case. In the HTGR-integrated case, produced natural gas is not used as fuel to produce the hot fluids used to pyrolyze the kerogen in the oil shale, thus eliminating the generation of flue gas, which contains a large portion of the CO_2 emitted from the base case in situ oil shale retort operation.

3. PROCESS ASSUMPTIONS

This section discusses and references inputs and assumptions necessary for the calculation of end products. An effort was made to make this assessment as generic as possible to broaden its applicability. However, depths to desirable zones and oil shale grade, for example, change areally; thus, site-specific considerations are important and should be used to analyze a specific location. The major portions of the operation include the natural gas burner, heat loss during circulation of the hot fluids, in situ conversion of kerogen to gaseous and liquid products, and surface separation of the produced fluids.

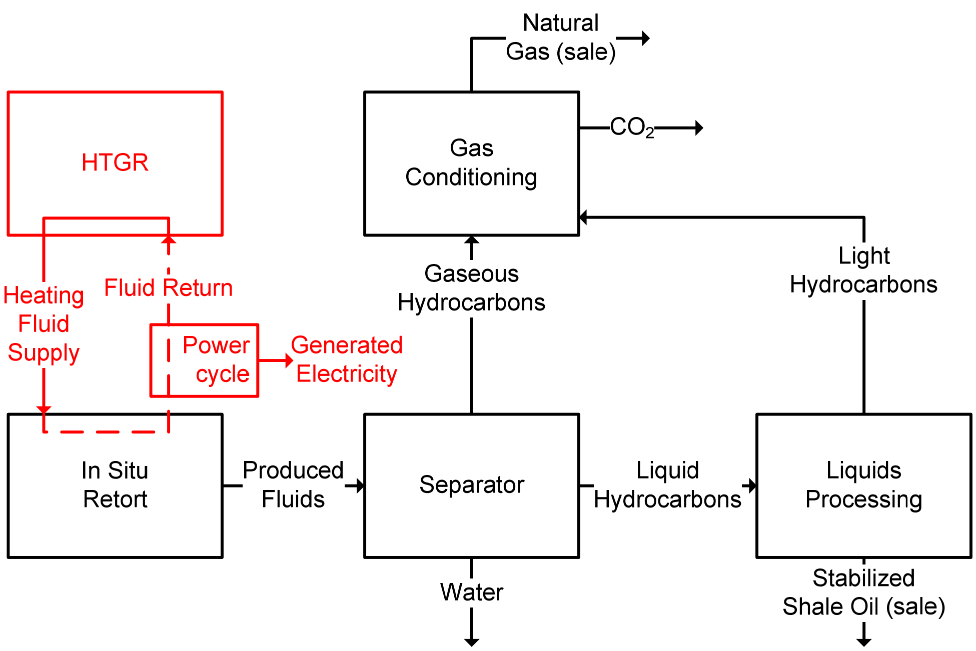


Figure 3. Block flow diagram for an HTGR-integrated in situ oil shale retort operation.

3.1 Natural Gas Burner

In the base case, flue gas containing CO_2 is generated during the combustion of natural gas to produce the heat necessary for the in situ retort. Air and natural gas are the inputs while heat and flue gas are the products. Flue gas is generated at a rate of 10.634 times the natural gas input on a volume basis (EGL 2006). Nine percent of the generated flue gas is CO_2 (EGL 2006). The electricity need for the natural gas burner is 0.147 W/scf-day (EGL 2006), which will be purchased from the local grid.

No natural gas burner is needed for the HTGR-integrated case. All heat requirements will be met by the production of hot gases from the HTGR. The natural gas that would have been used in the gas burner is available for sale. This case also eliminates all CO_2 emissions from flue gas.

3.2 Heat Requirements and Losses

The heat requirements for retorting oil shale were taken from Sohns et al. (1951). They present a table from which heat requirements of different grades of oil shale retorted at different temperatures can be obtained by interpolation between or from small extrapolations of their data, presented in graphical form in Figure 4.

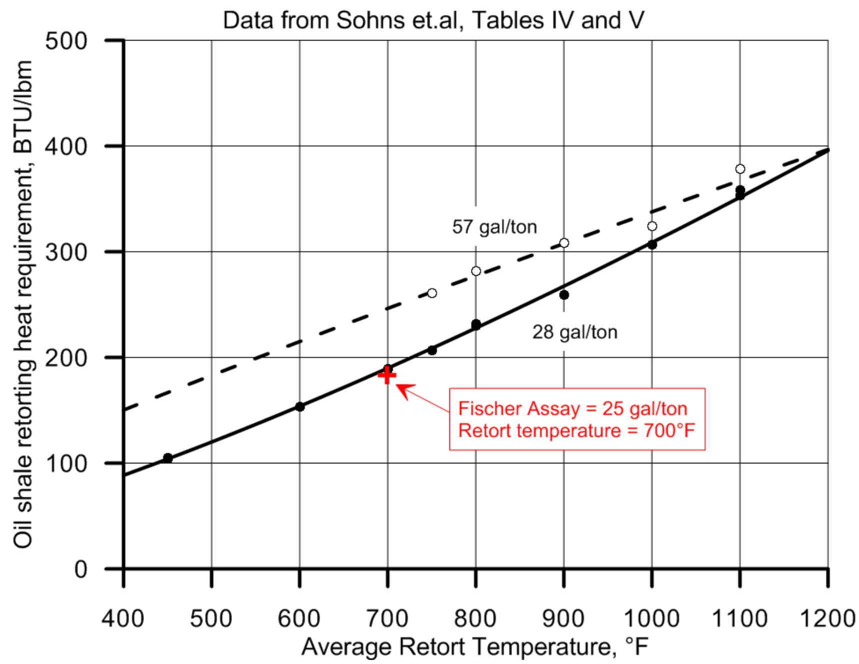


Figure 4. Retort heat requirements for different grades of oil shale as a function of retort temperature. Data taken from Tables IV and V of Sohns et al. (1951).

Assuming an average Fischer Assay grade for the oil shale of 25 gal/ton (Burnham et al. 2008b) and an average retort temperature of 370°C (BLM 2008), the heat requirement for retorting the oil shale is 184 Btu/lbm (see Figure 4).

It is assumed that the zone of interest lies below a low-permeability sealing strata sufficient to separate the fresh-water aquifer above from the saline waters below. The depth of this stratum is assumed to be 1,900 ft below ground level (Day 2009). Insulated tubing will be used in the vertical sections of the closed-loop, hot-fluid delivery system to minimize heat losses while the fluid is not in contact with the zone of interest. Nevertheless, some heat will be lost during transportation of the fluid through the insulated tubing and some will be lost to the cap and bottom rock out of the zone of interest. The overall in situ thermal efficiency is assumed to be 80% (EGL 2006).

3.3 In situ Pyrolysis of Kerogen and Production

The temperature of the oil shale is slowly increased at a rate of about 1.5°C per day to an average of 370°C. The size of a heated block is anticipated to be roughly 2,000 ft in length by 200 ft in height; its width will be expanded as production continues. The time required to retort a block of oil shale is expected to take about 2 years, which is followed by a production period of similar duration. To ensure that the temperature of all subsurface formations remain below the mineral decomposition temperature of about 650°C (Gersten et al. 2000), the temperature of the hot fluid as it is being injected is assumed to be 575°C.

The temperature of the fluid as it enters the retort interval is assumed to be 575°C, which is only slightly higher than the temperature assumed by Burnham et al. (2008a) of 520°C. The fluid is assumed to leave the retort zone at 350°C, or 20°C below the desired average retort temperature of 370°C.

Some of the pyrolyzed product will be unrecoverable and will remain in place underground. Typical hydrocarbon recovery efficiencies for conventional oil reservoirs range from 30 to 50%, and recovery efficiencies for gas reservoirs range from 70 to 85%. In an in situ oil shale retort, much of the pyrolyzed kerogen is in a gaseous state in situ at the high retorting temperatures and then condenses to liquids at the surface during processing. A recovery efficiency of 80% for the pyrolyzed hydrocarbon product is assumed (EGL 2006).

The hydrocarbon product resulting from the pyrolysis of kerogen in oil shale depends on heating rate, pressure, and the ultimate temperature (Vinegar 2006). Conversion efficiency of an oil shale retort is defined as the barrel-of-oil-equivalent (BOE) of hydrocarbon produced divided by the Fischer Assay oil amount. A conversion efficiency >1 is not uncommon for many retorting processes because the Fischer Assay accounts only for liquid oil production and neglects any gas production. Additionally, the Fischer Assay is not optimized to produce the greatest possible amount of liquid product. The conversion efficiency of in situ oil shale retorts is assumed to be 1.10 (Vinegar 2006).

The fraction of the hydrocarbon product from in situ retort tests, which is liquid (on a heating value basis) at standard conditions, has been reported to range from 0.66 to 0.84 (Burnham et al. 2008b; Vinegar 2006; Burnham and McConaghy 2006). The more recent data supports a liquid fraction in the lower end of the range; thus, a value of 0.68 is assumed for the liquids fraction, yielding a gas fraction of 0.32 on a heating value basis.

3.4 Surface Separation of Produced Fluids

Fluids are lifted from the subsurface retort zone to the surface using artificial lift technology (probably gas lift) employed by the petroleum industry. Produced fluids consist of water, liquid hydrocarbons, and gaseous hydrocarbons. Surface equipment commonly employed by the petroleum industry will be used to further separate and process the products as depicted by the Gas Conditioning and Liquids Processing blocks in Figure 2.

The liquid hydrocarbon stream resulting from an in situ retort is a light oil (45 degrees API gravity [Vinegar 2006]) that does not need further upgrading before transport to a refinery via pipeline. A small amount of CO_2 could be produced depending on the minerals present within the oil shale. Nahcolite is present in many, but not all, of the oil shale zones in the Piceance Basin. Nahcolite decomposes and releases CO_2 at about 150°C—well below the retort temperature of 371°C for the in situ process. Additionally, some CO_2 is released during the pyrolysis of the kerogen. Boak (2007) estimated that 168 scf of CO_2 will be produced per barrel of liquid shale oil produced because of the breakdown of minerals and from converted kerogen in an in situ process located in the Piceance Basin.

4. PROCESS CALCULATIONS

Equations and the calculation of values for various portions of the two cases under consideration are set forth in this section.

4.1 Production Rates

Total fluids production rate in BOE/day is a function of the specified liquids production rate, the fraction of the total fluid that is liquid (Btu basis), and the heat contents of the fluids:

$$q_t = \frac{q_l C_l}{f_l C_t}\ ; \qquad (1)$$

where q_t is the total hydrocarbon fluids production rate in BOE/day, q_l is the specified total hydrocarbon liquids production rate (50,000 bbl/day), C_l is the heat content of the produced liquids (5,900,000 Btu/bbl), f_l is the fraction of the total production stream that is liquid on a heat-content basis (0.68 Btu_{liquid}/Btu_{total}), and C_t is the heat content of the total hydrocarbon fluid stream (5,800,000 Btu/BOE). Total hydrocarbon fluids production rate is 74,797 BOE/day for a 50,000 bbl/day of shale oil output.

The natural gas fraction is based on the heat contents of the fluid streams, the total fluids production, and the gas fraction:

$$q_g = 1{,}000{,}000\,\frac{q_t f_g C_t}{C_g}\ ; \qquad (2)$$

where q_g is the natural gas production rate in scf/day, f_g is the fraction of the total hydrocarbon production stream that is gas on a heat-content basis (0.32 Btu_{gas}/Btu_{total}), C_t is the heat content of the total hydrocarbon fluid stream (5,800,000 Btu/BOE), and C_g is the heat content of the natural gas stream (1,000 Btu/scf). The natural gas production rate for both cases is calculated to be 138,824,000 scf/day.

4.2 Thermal Power Requirement

The thermal power requirement, P_{th} (Btu/day), to produce 50,000 bbl/day of shale oil from a mature, steady-state, in situ retorting process is calculated from the following equation:

$$P_{th} = 84{,}000 \frac{q_o H_r}{G_{FA} f_l \eta_{conv} \eta_{rec} \eta_{th}} \; ; \tag{3}$$

where H_r is the heat required to retort one pound of oil shale (184 Btu/lbm), q_o is the oil production rate (50,000 bbl/day), G_{FA} is the Fischer Assay grade of the oil shale (25 gal/ton), η_{conv} is the conversion efficiency (1.1 BOE/bbl), η_{rec} is the efficiency of the recovery process (0.80), η_{th} is the thermal efficiency of the process (0.80), and the 84,000 converts gallons to barrels and pounds to tons. Neglecting start-up power requirements, the thermal power (P_{th}) necessary to produce 50,000 bbl/day from a mature in situ oil shale operation is computed to be 64,669,000,000 Btu/day or 790 MWth.

4.2.1 Thermal Power for Base Project

In a mature base case project, natural gas will be combusted to provide the heat necessary to pyrolyze the kerogen in the oil shale. The amount of natural gas required as input into the gas burner, q_{gb}, to provide the necessary heat is a function of the thermal power requirement and the Btu content of the gas:

$$q_{gb} = \frac{P_{th}}{c_g} \, . \tag{4}$$

Assuming a thermal power requirement(P_{th}) of 64,669,000,000 Btu/day for the natural gas burner and the heat content of the gas (c_g) of 1000 Btu/scf, the feed requirement for the natural gas burner (q_{gb}) is computed to be 64,669,000 scf/day. Subtracting the gas feed rate for the natural gas burner from the total gas production rate leaves 74,154,000 scf/day of natural gas for sale.

4.2.2 Thermal Power for HTGR-integrated Project

In the HTGR-integrated case, the heat necessary for the in situ retort of the oil shale will come directly from an HTGR—not from the produced natural gas. Hence, the entire natural gas stream (138,824,000 scf/day) will be available for sale.

The heat will be delivered to the subsurface oil shale retort interval from an HTGR via insulated pipes assumed to be located near the oil shale operation such that heat losses through surface piping is negligible.

4.2.3 Integrating HTGR Output and In Situ Oil Shale Requirements

A process model developed using Hyprotech's HYSYS.Plant™ process modeling software[b] was developed to integrate HTGR modules with a 50,000 bbl/day in situ oil shale process with a goal to determine the thermal power output requirements from the HTGR heat source.

The HTGR-integrated cases are modeled by assuming two heat transfer loops connected by an intermediate heat exchanger (IHX). The primary loop is helium-filled and transfers heat from the HTGR to a secondary loop filled with either helium or steam, depending on the case. The secondary loop transfers its heat to the oil shaled retort zone.

The following conditions were used to model the integrated process cases:

- In the primary heat transfer loop, the HTGR inlet temperature is 322°C and the HTGR outlet temperature is 750°C. These conditions are set by the NGNP program for the 750°C HTGR
- In the secondary heat transfer loop, the temperature of the fluid as it enters the ground is 575°C and the temperature of the fluid as it exits the oil shale retort zone is 350°C (see discussion in Section 3.3)
- The temperature difference between the fluid in the secondary loop entering the IHX and the fluid in the primary loop exiting the IHX is 25°C
- Pressure drops in heat exchangers are 2% of the nominal pressure within the primary and secondary helium loops
- The helium circulators have adiabatic efficiencies of 80%
- Pumps have an adiabatic efficiency of 75%
- Power cycle efficiency was assumed to 35% as described in TEV-981(INL 2010a).

4.2.3.1 Helium HTGR-Integrated Case

The integrated process model for the helium HTGR-integrated case is shown in Figure 5. Temperatures at key

b. v2.2.2 (Build 3806).

points in the integrated process are shown. Values in red are given and fixed, while all others are calculated by the modeling software. The primary reactor loop is helium-filled and has a circulator, HTGR heat, and an intermediate heat exchanger. The secondary heat transfer loop is also helium-filled and extends below the ground surface to the oil shale retort interval. It is modeled with a circulator, heat loss to the retort zone, and incorporates heat losses in the 6,000 ft of piping as well. A power cycle was added to the secondary heat transfer loop in order to drop the return fluid temperature down to the maximum design inlet temperature for the HTGR of 322°C.

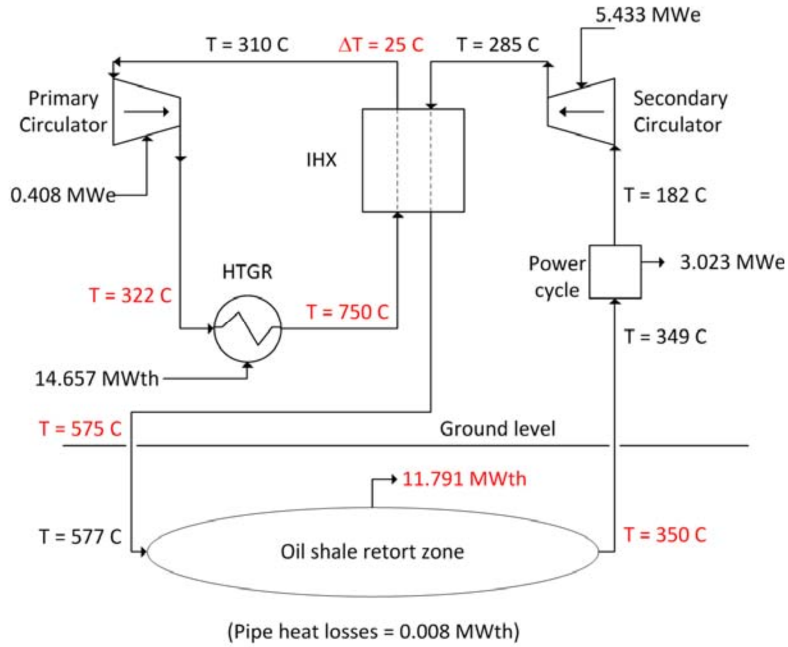


Figure 5. Process flow diagram for the helium HTGR-integrated oil shale process. Values shown are for one flow loop and do not represent the entire output from the HTGR.

In a fully developed in situ oil shale operation, the secondary heat transfer loop (the loop on the right) will be comprised of multiple heat transfer lines running through the retort interval (see Figure 1). The power generation and consumption values shown in Figure 5 are for a single pipe; values for the total project are much greater.

4.2.3.2 Steam HTGR-Integrated Case

The integrated process model for the steam HTGR-integrated case is shown in Figure 6. Values in red are given and fixed, while all others are calculated by the modeling software.

The primary reactor loop is helium-filled and has a circulator, HTGR heat, and a steam generator that acts as the intermediate heat exchanger. The secondary heat transfer loop is steam-filled and extends below the ground surface to the oil shale retort interval. It is modeled with a pump to circulate for fluid, heat loss to the retort zone, and incorporates heat losses in the 6,000 ft of piping. A power cycle was needed in the secondary heat transfer loop in order to drop the return fluid temperature down to the maximum design inlet temperature for the HTGR of 322°C in this case as well.

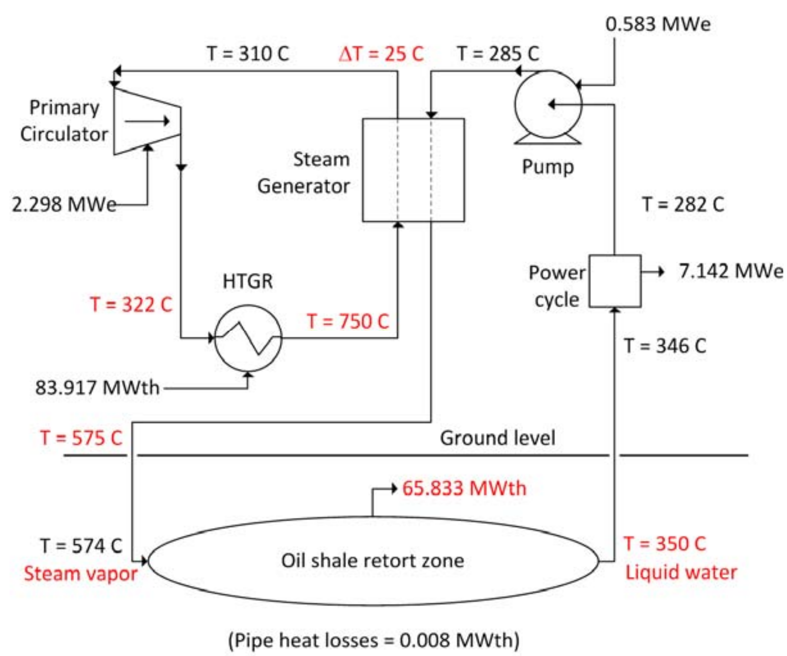


Figure 6. Process flow diagram for the steam HTGR-integrated oil shale process. Values shown are for one flow loop and do not represent the entire output from the HTGR.

4.2.4 Case Comparisons: Power Consumption and Generation

The flow loop for the base case is equivalent to the secondary loop for the steam HTGR-integrated case (Figure 6) except the power cycle is not added because there is no minimum temperature requirement for the natural gas burner as there is for the HTGR coolant return. HYSIS's pipe segment module was used to calculate pressure drops and heat losses in both the primary and secondary heat transfer loops. Eight-inch vacuum insulated pipes were assumed for the vertical sections in the secondary loop (Burnham et al. 2008a) and 8-inch uninsulated pipes were assumed through the oil shale retort section. To compare the output of each of the HTGR-integrated cases, the values in Figure 5 and Figure 6 were scaled up to match the 790 MWth necessary to produce 50,000 bbl/day from the oil shale operation. The heat and power material balances of the major components in the flow loops for the base case and both HTGR-integrated cases are shown in Table 1.

Table 1. Consumption and generation of thermal and electrical power for steam and helium HTGR-integrated cases for a 50,000 bbl/day in situ oil shale operation.

	Base	Helium	Steam
Thermal Power (MWth)			
Consumed in Retort Process	790	790	790
Generated in HTGR	—	982	1,007
Generated in Natural Gas Burner	790	—	—
Consumed as Pipe Losses	0.099	0.547	0.099
Electric Power (MWe)			
Generated in Secondary Loop	—	203	87
Consumed in Circulator 1	—	27	28
Consumed in Circulator 2 or Pump	7.1	365	7.1

In the helium HTGR-integrated case, the temperature of the helium in the return loop is 349°C, which is too high for the reactor inlet temperature of 322°C. The added power cycle was used to reduce the temperature and produce electricity. The need to reduce the temperature of the fluid returning to the HTGR results in a thermal output from the reactor (982 MWth) that is greater than the thermal power needed for retorting the oil shale (790 MWth). Appendix A contains the detailed output process flow sheets for a process model with helium in the secondary loop.

In the steam HTGR-integrated case, the pressure in the steam loop is established by ensuring that the water leaving the subsurface oil shale retort zone is a saturated liquid. The temperature of the condensed steam return line, however, is still above the 322°C maximum for the reactor inlet temperature and a power cycle is put in line to generate electricity and reduce the temperature of the return fluid to 322°C at the HTGR inlet. Less electric power is produced in the steam case than in the helium case. The addition of the power cycle for this case also increases the thermal power output from the HTGR (1007 MWth) to be above the thermal power needed for retorting the oil shale (790 MWth). Appendix B contains the detailed output process flow sheets for a process model with steam in the secondary loop.

The thermal power produced by the HTGR is very similar for both of the integrated cases, with the helium case requiring slightly less reactor heat. However, a major difference between the two HTGR cases is the electric power consumed and generated in the secondary heat transfer loops. The helium case required 67 process loops to deliver the necessary heat (790 MWth) to the retort zone, whereas the steam case required only 12 process loops. The larger number of process loops and the associated pressure losses is the cause for larger electrical power requirement for the helium case compared to the steam case.

The heating of the oil shale retort zone is a long-term process and is designed to require two or more years to reach maturity. The flow of heat into the subsurface retort zone will be interrupted from time to time during regularly scheduled reactor shutdowns for servicing/refueling. However, such short-term interruptions in this long-term process are not expected to cause any problems with the oil production operations and no allowances were incorporated into the analysis for times when the reactor modules are out of service.

4.3 Electricity Usage and Generation

Electricity usage, generation, and net production for each case are discussed in the following sections.

4.3.1 Electricity Usage

Compression and/or pumping of the heat transfer medium for the HTGR-integrated cases require 392 MWe for the helium case and 35 MWe for the steam case (see Table 1). Additional electricity needs for miscellaneous HTGR uses is estimated to be 10 MWe (INL 2008b)

Electrical usage for compression/pumping for the base case is assumed to be equal to the secondary loop of the steam HTGR-integrated case or 7.1 MWe. Additionally, the base case requires 0.147 W/(scf/day) for operation of the natural gas burner (EGL 2006) or 9.5 MWe, which brings the total electricity needs for heat generation and fluid circulation to 16.6 MWe. The required electricity usage for surface processes associated with processing natural gas and the shale oil is assumed to be equal to that for a similarly sized in situ Canadian oil sands operation, which was estimated to be 123 W/bbl-D (INL 2010b) or 6.15 MWe total for a 50,000 bbl/day operation. This requirement is the same for the base case as well as each of the HTGR-integrated cases.

The total electricity needs for a 50,000 bbl/day base case operation sum to 22.75 MWe. For a helium HTGR-integrated operation, the electricity needs sum to 408.15 MWe. For a steam HTGR-integrated operation, the electricity needs sum to 51.15 MWe.

4.3.2 Electricity Output

No electricity is generated in the base in situ oil shale retort case. However, for the helium HTGR-integrated case, 203 MWe is generated from power cycle in the secondary flow loop put in place to reduce the temperature of the flow stream as required by the HTGR. For the steam HTGR-integrated case, 87.4 MWe is generated in the secondary flow loop.

4.3.3 Net Electricity Usage or Output

Table 2 summarizes the electricity requirements, electricity generated, and the net electricity input or output.

Table 2. Summary of electricity inputs, outputs, and net usage or generation.

	Electricity (MWe)		
In Situ Retort Case	**Generated**	**Consumed**	**Net**
Base	—	-22.8	-22.8
Helium HTGR-Integrated	+203.0	-408.2	-205.2
Steam HTGR-Integrated	+87.4	-51.2	+36.2

The base case requires 22.8 MWe for operation, which is purchased from the local grid. The helium HTGR-integrated case requires 205.2 MWe for operation, mainly because of the compression requirements for moving the large amount of helium. However, the steam HTGR-integrated case actually generates 36.2 MWe, which is assumed to be exported to the local grid.

4.4 CO_2 Emitted

The CO_2 production rate resulting from the decomposition of kerogen and nahcolite, $CO2_m$, is calculated from the following equation:

$$CO2_m = 720.2 \frac{CO2_k q_l}{G_{FA}} \; ; \qquad (5)$$

where $CO2_k$ is the CO_2 produced per gram of oil shale (6.4 mg/g of oil shale from Boak [2007] and Burnham and Carrol [2008]) and the 720.2 coefficient is a conversion factor with units of (1,000 gal-scf/ton-bbl) and results in 9,219,000 scf/day of CO_2 from mineral decomposition for a 50,000 bbl/day operation.

For the base case, the majority of the CO_2 emitted results from burning natural gas to produce the heat necessary for retorting the oil shale. CO_2 in the flue gas, $CO2_f$, is calculated from the following equation:

$$CO2_f = q_{gb} q_f f_{CO2} \; ; \qquad (6)$$

where q_{gb} is the flow rate of gas to the boiler (64,669,000 scf/day), q_f is the volume of flue gas generated per volume of natural gas input (10.634 scf/scf), and f_{CO2} is the CO_2 fraction in the flue gas (0.09 scf/scf). The CO_2 emitted in the flue gas stream is calculated to be 61,892,000 scf/day from the above equation.

The total amount of CO_2 emitted is the sum of the CO_2 emitted in the flue gas stream and the CO_2 emitted as a result of the decomposition of kerogen and minerals. Table 3 shows the total CO_2 emitted for the base case and the two HTGR integrated cases.

Table 3. Total CO_2 emitted from a 50,000 bbl/day in situ oil shale operation for the cases described in this document.

Case	Total CO_2 Emitted (scf/day)
Base Case	71,111,000
HTGR-Integrated Cases	9,219,000

5. SUMMARY OF PROCESS RESULTS

An in situ oil shale retort operation with output of 50,000 bbl/day of refinery-ready shale oil was modeled for three different cases. Each case uses a closed-loop piping system through which a heat transfer fluid delivers heat to the in situ retort operation. The three cases are described below.

Case	Case Name	Heat Source	Heat Transfer Fluid
1	Base with steam	Natural gas burner	Steam
2	Steam HTGR-Integrated	HTGR	Steam
3	Helium HTGR-Integrated	HTGR	Helium

The Fischer Assay grade of the oil shale ore was assumed to be 25 gal/ton with an average retort temperature of 700°F. Results for each of the cases are summarized in Figure 7 showing inputs and outputs for each case.

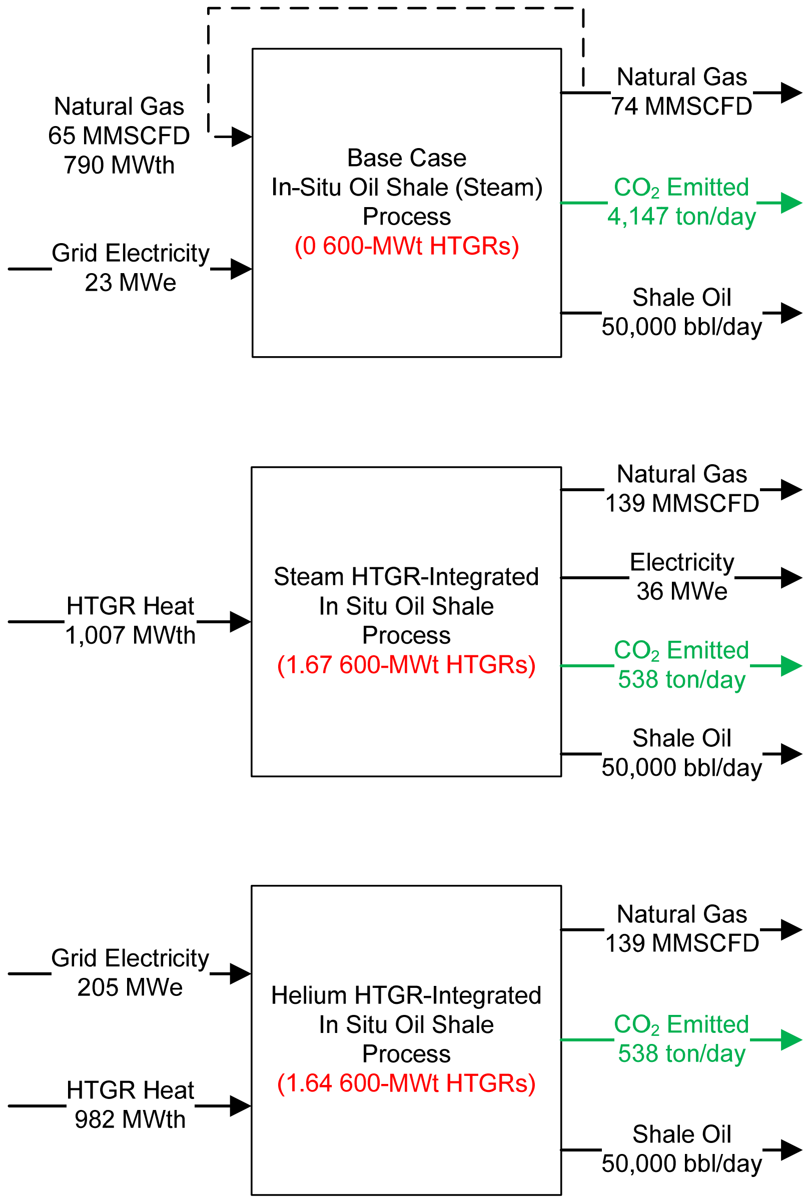


Figure 7. Summary results showing inputs and outputs of the three cases analyzed for oil production from an in situ oil shale retort operation.

Natural gas is produced in all three cases during the pyrolysis of the kerogen in the oil shale. In the figure for the base case, the dashed line represents natural gas that is taken from the production stream and combusted to provide the heat necessary for the retort operation. Almost one-half of the produced gas is used to generate the heat needed for the retort process; while in both the HTGR-integrated cases, the full natural gas stream is available for sale as a revenue stream.

CO_2 is produced from all three cases, but the base case produces about eight times more CO_2 than the HTGR-integrated cases, which may become an important issue if future CO_2 emissions are restricted either by governmental controls or through penalties.

In the steam HTGR-integrated case, excess electricity is generated and can be sold as revenue. In contrast, the base case and the helium HTGR-integrated case are both net consumers of electricity. The electricity necessary to circulate the low density helium as the heat transfer fluid in the helium HTGR-integrated case is quite high compared to that needed to circulate the steam in the other two cases.

The required heat output from the two HTGR-integrated cases is roughly equivalent, with the steam HTGR-integrated case delivering slightly more heat than the helium-integrated case. The small difference between the two cases is to the result of differences in the fluid properties of steam and helium.

Using steam in the secondary heat transfer loop to deliver heat to the in situ oil shale retort process appears to be a much better option than using helium based on the material balances shown in Figure 7. Note that this report considered only steam and helium, and the process may not be optimized as other heat transfer fluids may perform better than steam. However, optimizing the heat transfer fluid is beyond the scope of this evaluation.

6. FUTURE WORK AND RECOMMENDATIONS

Future work will consist of incorporating an economic analysis to the cases considered in this document.

Steam and helium were evaluated as heat transport fluids in this report and it is recommended that additional heat transport fluids be evaluated, as productivity gains may be possible with other fluids.

7. REFERENCES

Bartis, J. T., T. LaTourrette, L. Dixon, D. J. Peterson, and G. Cecchine, 2005, *Oil Shale Development in the United States*, Prepared by Rand Corporation for the National Energy Technology Laboratory of the U.S. Department of Energy.

BLM, 2008. *Proposed Oil Shale and Tar Sands Resource Management Plan Amendments to Address Land Use Allocations in Colorado, Utah, and Wyoming and*

Final Programmatic Environmental Impact Statement, Appendix A, FES 08-32, September 2008.

Boak, J., 2007, "CO_2 Release from In-Situ Production of Shale Oil from the Green River Formation," *27th Oil Shale Symposium, Golden, Colorado (17 October).*

Burnham and Carroll, 2008, CO_2 Sequestration in Spent Oil Shale Retorts. 28th Oil Shale Symposium (13–15 October).

Burnham, A. K., and J. R. McConaghy, 2006, "Comparison of the Acceptability of Various Oil Shale Processes," *26th Oil Shale Symposium, Golden, Colorado, October 16–18, 2006.*

Burnham, A. K., R. L. Day, and P. H. Wallman, 2008a, "Overview of American Shale Oil LLC Progress and Plans," *28th Oil Shale Symposium, Golden Colorado, October 13–15, 2008.*

Burnham, A. K., T. Ruble, M. Machus, and M. Herron, 2008b, "Characteristics of Illite-Rich Oil Shale from the Piceance Basin, Colorado," Poster number 20-15, *28th Oil Shale Symposium, Golden, Colorado, October 13–15, 2008.*

Day, R. L., 2009, "AMSO's Colorado Oil Shale RD&D Lease Tract: Progress and Plans," Presented at the *29th Oil Shale Symposium, Golden, Colorado, October 20, 2009.*

EGL, 2006, *Plan of Operations*, E.G.L. Resources, Inc., for Oil Shale Research, Development and Demonstration (R,D/D) Tract. Submitted to Bureau of Land Management, White River Field Office, Meeker, Colorado. Available on line at http://www.blm.gov/pgdata/etc/medialib/blm/co/field_offices/white_river_field/oil_shale.Par.62160.File.dat/PlanofOperation.pdf (accessed on August 3, 2010).

Gersten, J., V. Fainberg, G. Hetsroni, and Y. Shindler, 2000, "Kinetic Study of Thermal Decomposition of Polypropylene, Oil Shale, and their Mixture," *Fuel,* Vol. 79, pp. 1679–1686.

INL, 2010a, "An Analysis of the Effect of Reactor Outlet Temperature of a High Temperature Reactor on Electric Power Generation, Hydrogen Production, and Process Heat," Technical Evaluation Study, TEV-981, September 13, 2010.

INL, 2010b, "Nuclear-Integrated Oil Sands Recovery via Steam-Assisted Gravity Drainage," Technical Evaluation Study, TEV-704, May 15, 2010.

Nashawi, I. S., A. Malalla, and M. Al-Bisharah, 2010, "Forecasting World Crude Oil Production Using Multicyclic Hubbert Model," *Energy Fuels*, Vol. 24, pp.1788–1800.

Sohns, H. W., L. E. Mitchell, R. J. Cox, W. I. Barnet, and W. I. R. Murphy, 1951, "Heat Requirements for Retorting Oil Shale," *Industrial and Engineering Chemistry*, Vol. 43, No. 1, pp. 33–36.

Vinegar, H., 2006, "Shell's In-situ Conversion Process," *26th Oil Shale Symposium, Golden, Colorado, October 16–18, 2006.*

8. APPENDIXES

Appendix A, Process Flow Sheets for Process Model with Helium Secondary Loop

Appendix B, Process Flow Sheets for Process Model with Steam Secondary Loop

Appendix A
Process Flow Sheets for Process Model with Helium Secondary Loop

HYPROTECH

INL
Calgary, Alberta
CANADA

Case Name:	C:\Documents and Settings\mgq\Desktop\NGNP\Vary ROT\Heat Trans
Unit Set:	NGNP
Date/Time:	Mon Oct 11 15:23:35 2010

Workbook: Case (Main)

Streams

Name		Circ Inlet	Circ Outlet	Cold Leg	Down Leg Heat Loss	Electric Power Out
Vapour Fraction		1.0000	1.0000	1.0000	---	---
Temperature	(C)	182.08	285.23	310.23 *	---	---
Pressure	(MPa)	6.0016	9.1000 *	8.9180	---	---
Molar Flow	(kgmole/s)	2.4981	2.4981	1.6450	---	---
Mass Flow	(kg/s)	10.000	10.000	6.5851	---	---
Liquid Volume Flow	(m3/h)	290.2	290.2	191.1	---	---
Heat Flow	(kW)	8320	1.375e+004	9907	5.112	3023
Molar Enthalpy	(kJ/kgmole)	3331	5505	6022	---	---
Name		**HTGR Heat**	**Into Heat Leg**	**Into Shale**	**Oil Shale Heat**	**Out of Heat Leg**
Vapour Fraction		---	1.0000	1.0000	---	1.0000
Temperature	(C)	---	576.66	575.00 *	---	350.00 *
Pressure	(MPa)	---	7.5652	8.9180	---	7.4152
Molar Flow	(kgmole/s)	---	2.4981	2.4981	---	2.4981
Mass Flow	(kg/s)	---	10.000	10.000 *	---	10.000
Liquid Volume Flow	(m3/h)	---	290.2	290.2	---	290.2
Heat Flow	(kW)	1.462e+004	2.884e+004	2.878e+004	1.177e+004	1.707e+004
Molar Enthalpy	(kJ/kgmole)	---	1.154e+004	1.152e+004	---	6833
Name		**Out of Shale**	**Primary Circulator Pc**	**Reactor Inlet**	**Ql-2**	**Reactor Outlet**
Vapour Fraction		1.0000	---	1.0000	---	1.0000
Temperature	(C)	349.31	---	322.00	---	750.00 *
Pressure	(MPa)	6.3416	---	9.2820	---	9.1000 *
Molar Flow	(kgmole/s)	2.4981	---	1.6450	---	1.6450
Mass Flow	(kg/s)	10.000	---	6.5851	---	6.5851
Liquid Volume Flow	(m3/h)	290.2	---	191.1	---	191.1
Heat Flow	(kW)	1.701e+004	408.2	1.032e+004	5664	2.494e+004
Molar Enthalpy	(kJ/kgmole)	6808	---	6271	---	1.516e+004
Name		**RIT Goal**	**Secondary Circulator**	**Up Leg Heat Loss**		
Vapour Fraction		---	---	---		
Temperature	(C)	---	---	---		
Pressure	(MPa)	---	---	---		
Molar Flow	(kgmole/s)	---	---	---		
Mass Flow	(kg/s)	---	---	---		
Liquid Volume Flow	(m3/h)	---	---	---		
Heat Flow	(kW)	---	5433	3.047		
Molar Enthalpy	(kJ/kgmole)	---	---	---		

Composition

Name	Circ Inlet	Circ Outlet	Cold Leg	Into Heat Leg	Into Shale
Comp Mole Frac (Hydrogen)	0.00000	0.00000	0.00000	0.00000	0.00000 *
Comp Mole Frac (H2O)	0.00000	0.00000	0.00000	0.00000	0.00000 *
Comp Mole Frac (Oxygen)	0.00000	0.00000	0.00000	0.00000	0.00000 *
Comp Mole Frac (Nitrogen)	0.00000	0.00000	0.00000	0.00000	0.00000 *
Comp Mole Frac (CO2)	0.00000	0.00000	0.00000	0.00000	0.00000 *
Comp Mole Frac (Argon)	0.00000	0.00000	0.00000	0.00000	0.00000 *
Comp Mole Frac (Helium)	1.00000	1.00000	1.00000	1.00000	1.00000 *
Comp Mole Frac (Methane)	0.00000	0.00000	0.00000	0.00000	0.00000 *
Comp Mole Frac (CO)	0.00000	0.00000	0.00000	0.00000	0.00000 *
Comp Mole Frac (NO)	0.00000	0.00000	0.00000	0.00000	0.00000 *
Comp Mole Frac (NO2)	0.00000	0.00000	0.00000	0.00000	0.00000 *
Comp Mole Frac (N2O)	0.00000	0.00000	0.00000	0.00000	0.00000 *
Comp Mole Frac (N2O4)	0.00000	0.00000	0.00000	0.00000	0.00000 *

Hyprotech Ltd. HYSYS.Plant v2.2.2 (Build 3806) Page 1 of 4

Licensed to: INL

* Specified by user.

INL
Calgary, Alberta
CANADA

Case Name:	C:\Documents and Settings\mgq\Desktop\NGNP\Vary ROT\Heat Trans
Unit Set:	NGNP
Date/Time:	Mon Oct 11 15:23:35 2010

Workbook: Case (Main) (continued)

Composition (continued)

Name	Out of Heat Leg	Out of Shale	Reactor Inlet	Reactor Outlet	RIT Goal
Comp Mole Frac (Hydrogen)	0.00000	0.00000	0.00000	0.00000 *	---
Comp Mole Frac (H2O)	0.00000	0.00000	0.00000	0.00000 *	---
Comp Mole Frac (Oxygen)	0.00000	0.00000	0.00000	0.00000 *	---
Comp Mole Frac (Nitrogen)	0.00000	0.00000	0.00000	0.00000 *	---
Comp Mole Frac (CO2)	0.00000	0.00000	0.00000	0.00000 *	---
Comp Mole Frac (Argon)	0.00000	0.00000	0.00000	0.00000 *	---
Comp Mole Frac (Helium)	1.00000	1.00000	1.00000	1.00000 *	---
Comp Mole Frac (Methane)	0.00000	0.00000	0.00000	0.00000 *	---
Comp Mole Frac (CO)	0.00000	0.00000	0.00000	0.00000 *	---
Comp Mole Frac (NO)	0.00000	0.00000	0.00000	0.00000 *	---
Comp Mole Frac (NO2)	0.00000	0.00000	0.00000	0.00000 *	---
Comp Mole Frac (N2O)	0.00000	0.00000	0.00000	0.00000 *	---
Comp Mole Frac (N2O4)	0.00000	0.00000	0.00000	0.00000 *	---

Coolers

Name		Oil Shale
Duty	(kW)	1.177e+004
Feed Temperature	(C)	576.7
Product Temperature	(C)	350.0 *

Heaters

Name		HTGR
Duty	(kW)	1.462e+004
Feed Temperature	(C)	322.0
Product Temperature	(C)	750.0 *

LNGs

Name		IHX
UA (Calculated)	(W/C)	1.950e+005
LMTD	(C)	77.09 *
Exchanger Cold Duty	(kW)	1.503e+004
Minimum Approach	(C)	25.00

Compressors

Name		Primary Circulator	Secondary Circulator
Feed Pressure	(MPa)	8.918	6.002
Product Pressure	(MPa)	9.282	9.100 *
Molar Flow	(kgmole/s)	1.645	2.498
Energy	(kW)	408.2	5433
Adiabatic Efficiency		80 *	80 *
Polytropic Efficiency		80	82

Hyprotech Ltd. HYSYS.Plant v2.2.2 (Build 3806) Page 2 of 4

Licensed to: INL * Specified by user.

INL
Calgary, Alberta
CANADA

Case Name:	C:\Documents and Settings\mgq\Desktop\NGNP\Vary ROT\Heat Trans
Unit Set:	NGNP
Date/Time:	Mon Oct 11 15:23:35 2010

Workbook: Case (Main) (continued)

Pipe Segments

Name		Down Leg	Up Leg			
Inside Diameter(1)	(mm)	173.1	173.1			
Outside Diameter(1)	(mm)	219.1	219.1			
Pipe Length(1)	(m)	609.6 *	609.6 *			
Elevation(1)	(m)	-609.6 *	609.6 *			
Heat Loss	(kW)	5.112	3.047			
Insulation Thickness	(m)	2.540e-002 *	2.540e-002 *			
Roughness(1)	(m)	4.572e-005 *	4.572e-005 *			
Heat Transfer Coefficient (kJ/s-m2-C)		2.174e-005	2.174e-005			
Material Type(1)		Mild Steel *	Mild Steel *			
Ambient Temperature	(C)	15.556 *	15.556 *			
Insulation Conductivity	(W/m-K)	5.000e-004 *	5.000e-004 *			
Insulation Type		Evacuated Annulus *	Evacuated Annulus *			
Ground Type		Moist Sand *	Moist Sand *			

Unit Ops

Operation Name	Operation Type	Feeds	Products	Ignored	Calc. Level
Power Cycle	Standard Sub-Flowsheet	Out of Shale	Circ Inlet Electric Power Out QI-2	No	2500 *
SPRDSHT-2	Spreadsheet			No	500.0 *
HTGR	Heater	Reactor Inlet HTGR Heat	Reactor Outlet	No	500.0 *
Primary Circulator	Compressor	Cold Leg Primary Circulator Power	Reactor Inlet	No	500.0 *
Secondary Circulator	Compressor	Circ Inlet Secondary Circulator Power	Circ Outlet	No	500.0 *
Oil Shale	Cooler	Into Heat Leg	Out of Heat Leg Oil Shale Heat	No	500.0 *
IHX	LNG	Circ Outlet Reactor Outlet	Into Shale Cold Leg	No	500.0 *
ADJ-2	Adjust			No	3500 *
Down Leg	Pipe Segment	Into Shale	Into Heat Leg Down Leg Heat Loss	No	500.0 *
Up Leg	Pipe Segment	Out of Heat Leg	Out of Shale Up Leg Heat Loss	No	500.0 *

Workbook: Power Cycle (TPL1)

Material Streams

Name		1 @TPL1	4 @TPL1			
Vapour Fraction		1.0000	1.0000			
Temperature	(C)	349.31	182.08			
Pressure	(MPa)	6.3416	6.0016			
Molar Flow	(kgmole/s)	2.4981	2.4981			
Mass Flow	(kg/s)	10.000	10.000			
Liquid Volume Flow	(m3/h)	290.2	290.2			
Heat Flow	(kW)	1.701e+004	8320			

Compositions

Name	1 @TPL1	4 @TPL1			
Comp Mole Frac (H2O)	0.00000	0.00000			
Comp Mole Frac (Helium)	1.00000	1.00000			

INL Calgary, Alberta CANADA	Case Name:	C:\Documents and Settings\mgq\Desktop\NGNP\Vary ROT\Heat Trans
	Unit Set:	NGNP
	Date/Time:	Mon Oct 11 15:23:35 2010

Workbook: Power Cycle (TPL1) (continued)

Energy Streams

Name		Qh @TPL1	Electric Power Out @	Ql @TPL1		
Heat Flow	(kW)	8688	3023	5664		

Unit Ops

Operation Name	Operation Type	Feeds	Products	Ignored	Calc. Level
HX @TPL1	Cooler	1 @TPL1	4 @TPL1 Qh @TPL1	No	500.0 *
SPRDSHT-1 @TPL1	Spreadsheet			No	500.0 *

Hyprotech Ltd. HYSYS.Plant v2.2.2 (Build 3806) Page 4 of 4

Licensed to: INL * Specified by user.

Appendix B
Process Flow Sheets for Process Model With Steam Secondary Loop

	INL Calgary, Alberta CANADA	Case Name:	C:\Documents and Settings\mgq\Desktop\NGNP\Vary ROT\Heat Trans
		Unit Set:	NGNP
		Date/Time:	Mon Oct 11 15:31:17 2010

Workbook: Case (Main)

Streams

Name		Cold Leg	Down Leg Heat Loss	Electric Power Out	HTGR Heat	Into Heat Leg
Vapour Fraction		1.0000	---	---	---	1.0000
Temperature	(C)	310.23 *	---	---	---	574.45
Pressure	(MPa)	8.9180	---	---	---	22.845
Molar Flow	(kgmole/s)	9.2603	---	---	---	2.2204
Mass Flow	(kg/s)	37.069	---	---	---	40.000
Liquid Volume Flow	(m3/h)	1076	---	---	---	144.3
Heat Flow	(kW)	5.577e+004	5.100	7142	8.231e+004	-5.007e+005
Molar Enthalpy	(kJ/kgmole)	6022	---	---	---	-2.255e+005
Name		**Into Shale**	**Oil Shale Heat**	**Out of Heat Leg**	**Out of Shale**	**Primary Circulator Po**
Vapour Fraction		1.0000	---	0.0000	0.0000	---
Temperature	(C)	575.00 *	---	350.00 *	345.55	---
Pressure	(MPa)	23.520	---	19.650 *	15.815	---
Molar Flow	(kgmole/s)	2.2204	---	2.2204	2.2204	---
Mass Flow	(kg/s)	40.000 *	---	40.000	40.000	---
Liquid Volume Flow	(m3/h)	144.3	---	144.3	144.3	---
Heat Flow	(kW)	-5.009e+005	6.455e+004	-5.652e+005	-5.655e+005	2298
Molar Enthalpy	(kJ/kgmole)	-2.256e+005	---	-2.546e+005	-2.547e+005	---
Name		**Pump Inlet**	**Pump Outlet**	**Pump Power**	**QI-2**	**Reactor Inlet**
Vapour Fraction		0.0000	0.0000	---	---	1.0000
Temperature	(C)	281.50	285.23	---	---	322.00
Pressure	(MPa)	15.475	24.000 *	---	---	9.2820
Molar Flow	(kgmole/s)	2.2204	2.2204	---	---	9.2603
Mass Flow	(kg/s)	40.000	40.000	---	---	37.069
Liquid Volume Flow	(m3/h)	144.3	144.3	---	---	1076
Heat Flow	(kW)	-5.861e+005	-5.855e+005	582.9	1.349e+004	5.807e+004
Molar Enthalpy	(kJ/kgmole)	-2.640e+005	-2.637e+005	---	---	6271
Name		**Reactor Outlet**	**Up Leg Heat Loss**			
Vapour Fraction		1.0000	---			
Temperature	(C)	750.00 *	---			
Pressure	(MPa)	9.1000 *	---			
Molar Flow	(kgmole/s)	9.2603	---			
Mass Flow	(kg/s)	37.069	---			
Liquid Volume Flow	(m3/h)	1076	---			
Heat Flow	(kW)	1.404e+005	3.026			
Molar Enthalpy	(kJ/kgmole)	1.516e+004	---			

Composition

Name	Cold Leg	Into Heat Leg	Into Shale	Out of Heat Leg	Out of Shale
Comp Mole Frac (Hydrogen)	0.00000	0.00000	0.00000 *	0.00000	0.00000
Comp Mole Frac (H2O)	0.00000	1.00000	1.00000 *	1.00000	1.00000
Comp Mole Frac (Oxygen)	0.00000	0.00000	0.00000 *	0.00000	0.00000
Comp Mole Frac (Nitrogen)	0.00000	0.00000	0.00000 *	0.00000	0.00000
Comp Mole Frac (CO2)	0.00000	0.00000	0.00000 *	0.00000	0.00000
Comp Mole Frac (Argon)	0.00000	0.00000	0.00000 *	0.00000	0.00000
Comp Mole Frac (Helium)	1.00000	0.00000	0.00000 *	0.00000	0.00000
Comp Mole Frac (Methane)	0.00000	0.00000	0.00000 *	0.00000	0.00000
Comp Mole Frac (CO)	0.00000	0.00000	0.00000 *	0.00000	0.00000
Comp Mole Frac (NO)	0.00000	0.00000	0.00000 *	0.00000	0.00000
Comp Mole Frac (NO2)	0.00000	0.00000	0.00000 *	0.00000	0.00000
Comp Mole Frac (N2O)	0.00000	0.00000	0.00000 *	0.00000	0.00000
Comp Mole Frac (N2O4)	0.00000	0.00000	0.00000 *	0.00000	0.00000

Hyprotech Ltd. HYSYS.Plant v2.2.2 (Build 3806) Page 1 of 4

Licensed to: INL * Specified by user.

HYPROTECH

INL
Calgary, Alberta
CANADA

Case Name:	C:\Documents and Settings\mgq\Desktop\NGNP\Vary ROT\Heat Trans
Unit Set:	NGNP
Date/Time:	Mon Oct 11 15:31:17 2010

Workbook: Case (Main) (continued)

Composition (continued)

Name	Pump Inlet	Pump Outlet	Reactor Inlet	Reactor Outlet	
Comp Mole Frac (Hydrogen)	0.00000	0.00000	0.00000	0.00000 *	
Comp Mole Frac (H2O)	1.00000	1.00000	0.00000	0.00000 *	
Comp Mole Frac (Oxygen)	0.00000	0.00000	0.00000	0.00000 *	
Comp Mole Frac (Nitrogen)	0.00000	0.00000	0.00000	0.00000 *	
Comp Mole Frac (CO2)	0.00000	0.00000	0.00000	0.00000 *	
Comp Mole Frac (Argon)	0.00000	0.00000	0.00000	0.00000 *	
Comp Mole Frac (Helium)	0.00000	0.00000	1.00000	1.00000 *	
Comp Mole Frac (Methane)	0.00000	0.00000	0.00000	0.00000 *	
Comp Mole Frac (CO)	0.00000	0.00000	0.00000	0.00000 *	
Comp Mole Frac (NO)	0.00000	0.00000	0.00000	0.00000 *	
Comp Mole Frac (NO2)	0.00000	0.00000	0.00000	0.00000 *	
Comp Mole Frac (N2O)	0.00000	0.00000	0.00000	0.00000 *	
Comp Mole Frac (N2O4)	0.00000	0.00000	0.00000	0.00000 *	

Coolers

Name		Oil Shale
Duty	(kW)	6.455e+004
Feed Temperature	(C)	574.4
Product Temperature	(C)	350.0 *

Heaters

Name		HTGR
Duty	(kW)	8.231e+004
Feed Temperature	(C)	322.0
Product Temperature	(C)	750.0 *

LNGs

Name		Steam Generator
UA (Calculated)	(W/C)	9.797e+005
LMTD	(C)	86.36 *
Exchanger Cold Duty	(kW)	8.461e+004
Minimum Approach	(C)	25.00

Compressors

Name		Primary Circulator
Feed Pressure	(MPa)	8.918
Product Pressure	(MPa)	9.282
Molar Flow	(kgmole/s)	9.260
Energy	(kW)	2298
Adiabatic Efficiency		80 *
Polytropic Efficiency		80

Pumps

Name		Pump
Delta P	(MPa)	8.525
Energy	(kW)	582.9
Feed Pressure	(MPa)	15.47
Product Pressure	(MPa)	24.00 *
Molar Flow	(kgmole/s)	2.220
Adiabatic Efficiency	(%)	75.00 *

Hyprotech Ltd. HYSYS.Plant v2.2.2 (Build 3806) Page 2 of 4

Licensed to: INL * Specified by user.

INL
Calgary, Alberta
CANADA

Case Name:	C:\Documents and Settings\mgq\Desktop\NGNP\Vary ROT\Heat Trans
Unit Set:	NGNP
Date/Time:	Mon Oct 11 15:31:17 2010

Workbook: Case (Main) (continued)

Pipe Segments

Name		Down Leg	Up Leg			
Inside Diameter(1)	(mm)	173.1	173.1			
Outside Diameter(1)	(mm)	219.1	219.1			
Pipe Length(1)	(m)	609.6 *	609.6 *			
Elevation(1)	(m)	-609.6 *	609.6 *			
Pressure Drop	(MPa)	0.6748	3.835			
Heat Loss	(kW)	5.100	3.026			
Elevation(1)	(m)	-609.6 *	609.6 *			
Insulation Thickness	(m)	2.540e-002 *	2.540e-002 *			
Roughness(1)	(m)	4.572e-005 *	4.572e-005 *			
Ambient Temperature	(C)	15.556 *	15.556 *			
Heat Transfer Coefficient	(kJ/s-m2-C)	2.174e-005	2.174e-005			
Ground Type		Moist Sand *	Moist Sand *			
Material Type(1)		Mild Steel *	Mild Steel *			
Insulation Type		Evacuated Annulus *	Evacuated Annulus *			

Unit Ops

Operation Name	Operation Type	Feeds	Products	Ignored	Calc. Level
Power Cycle	Standard Sub-Flowsheet	Out of Shale	Pump Inlet Electric Power Out QI-2	No	2500 *
SPRDSHT-2	Spreadsheet			No	500.0 *
HTGR	Heater	Reactor Inlet HTGR Heat	Reactor Outlet	No	500.0 *
Primary Circulator	Compressor	Cold Leg Primary Circulator Power	Reactor Inlet	No	500.0 *
Oil Shale	Cooler	Into Heat Leg	Out of Heat Leg Oil Shale Heat	No	500.0 *
Steam Generator	LNG	Pump Outlet Reactor Outlet	Into Shale Cold Leg	No	500.0 *
Pump	Pump	Pump Inlet Pump Power	Pump Outlet	No	500.0 *
Down Leg	Pipe Segment	Into Shale	Into Heat Leg Down Leg Heat Loss	No	500.0 *
Up Leg	Pipe Segment	Out of Heat Leg	Out of Shale Up Leg Heat Loss	No	500.0 *

Workbook: Power Cycle (TPL1)

Material Streams

Name		1 @TPL1	4 @TPL1			
Vapour Fraction		0.0000	0.0000			
Temperature	(C)	345.55	281.50			
Pressure	(MPa)	15.815	15.475			
Molar Flow	(kgmole/s)	2.2204	2.2204			
Mass Flow	(kg/s)	40.000	40.000			
Liquid Volume Flow	(m3/h)	144.3	144.3			
Heat Flow	(kW)	-5.655e+005	-5.861e+005			

Compositions

Name	1 @TPL1	4 @TPL1			
Comp Mole Frac (H2O)	1.00000	1.00000			
Comp Mole Frac (Helium)	0.00000	0.00000			

Hyprotech Ltd. HYSYS.Plant v2.2.2 (Build 3806) Page 3 of 4

Licensed to: INL

* Specified by user.

INL
Calgary, Alberta
CANADA

Case Name:	C:\Documents and Settings\mgq\Desktop\NGNP\Vary ROT\Heat Trans
Unit Set:	NGNP
Date/Time:	Mon Oct 11 15:31:17 2010

Workbook: Power Cycle (TPL1) (continued)

Energy Streams

Name		Qh @TPL1	Electric Power Out @	Ql @TPL1		
Heat Flow	(kW)	2.064e+004	7142	1.349e+004		

Unit Ops

Operation Name	Operation Type	Feeds	Products	Ignored	Calc. Level
HX @TPL1	Cooler	1 @TPL1	4 @TPL1 Qh @TPL1	No	500.0 *
SPRDSHT-1 @TPL1	Spreadsheet			No	500.0 *

Hyprotech Ltd. HYSYS.Plant v2.2.2 (Build 3806) Page 4 of 4

Licensed to: INL

* Specified by user.