In-Ground Operation of Geothermic Fuel Cells for Unconventional Oil and Gas Recovery

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Abstract

This paper presents operating and performance characteristics of a nine-stack solid-oxide fuel cell combined-heat-and-power system. Integrated with a natural-gas fuel processor, air compressor, reactant-gas preheater, and diagnostics and control equipment, the system is designed for use in unconventional oil-and-gas processing. Termed a “Geothermic Fuel Cell” (GFC), the heat liberated by the fuel cell during electricity generation is harnessed to process oil shale into high-quality crude oil and natural gas. The 1.5-kW_e SOFC stacks are packaged within three-stack GFC modules. Three GFC modules are mechanically and electrically coupled to a reactant-gas preheater and installed within the earth. During operation, significant heat is conducted from the Geothermic Fuel Cell to the surrounding geology. The complete system was continuously operated on hydrogen and natural-gas fuels for ~ 600 hours. A quasi-steady operating point was established to favor heat generation (29.1 kW_{th}) over electricity production (4.4 kW_e). Thermodynamic analysis reveals a combined-heat-and-power efficiency of 55% at this condition. Heat flux to the geology averaged 3.2 kW m⁻¹ across the 9-m length of the Geothermic Fuel Cell-preheater assembly. System performance is reviewed; some suggestions for improvement are proposed.

Keywords:

SOFC application, Geothermic Fuel Cell, Oil shale, In-situ oil shale processing, Unconventional oil and gas, SOFC-CHP

1. Introduction

This paper presents a pilot-scale demonstration of a novel combined-heat-and-power application of solid-oxide fuel cell (SOFC) technology. The heat generated by operating SOFCs while generating electricity is harnessed to process oil shale into oil and natural gas. This “Geothermic Fuel Cell” concept is shown in Figure 1. Solid-oxide fuel cells are placed hundreds of meters below the earth’s surface within the oil-shale geology and continuously operated over a period of years. The thermal energy released during fuel-cell operation is harnessed to heat the surrounding oil shale to temperatures near 400 °C. At these temperatures, the kerogen trapped within the oil shale is retorted to form liquid oil and natural gas. Once formed, the resources are withdrawn from the formation using conventional “collector” wells. The natural gas can be used to fuel the Geothermic Fuel Cells. Three valuable products are generated: electricity, natural gas, and most-importantly oil [1].

The demonstration presented in this paper involves a near-surface installation of nine (9) 1.5-kW_e fuel cell stacks into a clay formation at the Colorado School of Mines campus. Fueled by municipal natural gas, this Geothermic Fuel Cell is integrated with a natural-gas fuel processor, a reactive-gas preheater, and ancillary balance-of-plant and diagnostic components at an outdoor test site. The Geothermic Fuel Cell was continuously operated within the earth for a period of 25 days. This paper presents the results of this demonstration.

The U.S. Geological Survey estimates that over four trillion barrels of oil are trapped in the Piceance Basin of northwestern Colorado, the Uinta Basin of northeastern Utah, and the Greater Green River Basin of southwestern Wyoming [2, 3]. In contrast to liquid shale oil (or “tight oil”) trapped within porous geology [4], oil shale is a sedimentary rock that contains organic matter called kerogen [5]. When pyrolysed to ~ 350 °C [6], this kerogen decomposes into a mixture of oil, hydrocarbon gas and carbon-rich shale coke [7]. These oil-rich kerogen beds are buried below 250-600 m (800-1900 ft) of overburden, and can extend over 900 m (3,000 ft) below the surface at the center of the basins.

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The processing of oil shale into oil is well established [8]. Traditionally, the shale rock is mined from the earth and then retorted above ground. Significant oil-shale retorts have been in operation for decades in Estonia, China, Russia, and other sites. Conventional oil-shale processing is not cost competitive with Middle East sources. Environmental impacts - surface disturbance, water requirements, waste management - also present significant concerns [9]. Despite the enormity of this resource, its impact on the world energy portfolio remains modest [8].

Developers are turning to in-situ oil-shale processing to address these cost and environmental challenges. During in-situ processing, the oil-shale resource is retorted directly within the formation; this eliminates mining processes and minimizes surface operations [10]. Studies also show that in-situ processing leads to a significant increase in the energy yield, as greater volumes of oil shale can be processed at a time [11].

In-situ oil-shale processing is being pursued through a number of novel technologies, including:

- The “In-Situ Conversion Process” (ICP) led by Royal Dutch Shell; resistive heaters are inserted within the formation and driven with electric current to supply heat to the oil shale [7];
- The “Electrofrac Process” led by Exxon-Mobil; hydraulic fractures created in the formation are filled with an electrically conductive material to form resistive heating elements that are then driven with electric current to heat the oil shale [12];
- The “Volumetric Heating” method developed by Illinois Institute of Technology; radio waves generated by electrode arrays heat the formation [13];
- The “In-Situ Vapor Extraction Technology” pursued by Mountain West Energy; methane gas is heated above ground and injected into the oil-shale formation. A similar process is being developed by Chevron with carbon dioxide serving as the working fluid [14].

Geothermic Fuel Cells differ from these approaches in that electricity is generated throughout in-situ processing. This presents a unique Combined Heat and Power (CHP) ap-

plication. In previous work, SOFC systems achieved CHP efficiencies approaching 85% [15, 16, 17, 18, 19, 20]. Unlike most CHP applications, in-situ oil-shale processing places higher value on down-hole thermal-energy release, at the expense of electricity generation. Addressing such operational tradeoffs and learning of the engineering challenges associated with underground SOFC operation motivate the current study.

2. Experiment

In this demonstration, a Geothermic Fuel Cell assembly was installed in the earth and continuously operated for ~ 600 hours. The GFC was fueled with natural gas that was passed through a fuel processor and converted into syngas. An extensive data set was acquired and used to quantify important performance metrics.

2.1. Geothermic Fuel Cell Modules

A schematic of a single Geothermic Fuel Cell module is shown in Figure 2. This assembly is centered on three 1.5-kW_e solid-oxide fuel cell stacks that are packaged and distributed within a cylindrical stainless steel housing. The housing is approximately 0.3 m (1 ft.) in diameter and 1.8 m (6 ft.) in height. Reactants are fed to the stacks in a parallel arrangement, while the stacks are connected in electrical series.

During operation, the fuel and air reactants fed to the stacks are electrochemically converted to products and electricity. Electrochemical oxidation occurs at $\sim 750^\circ\text{C}$ ($\pm 70^\circ\text{C}$) resulting in significant heat generation. This heat is liberated to the surrounding environment.

Prior to in-ground installation, Geothermic Fuel Cell prototypes were first tested in the Colorado Fuel Cell Center laboratory. These GFC modules included extensive instrumentation for monitoring GFC operation and performance. Indoor testing provided important insight to the unique operating characteristics of the GFC modules, and led to design modifications to improve performance and robustness.

For the in-ground demonstration, three GFC modules are joined using mechanical coupling. While the stacks within each module are connected in electrical series, the three

modules are connected in electrical parallel. The assembly contains a total of nine fuel cell stacks, extends 6 m in length, and has an electric power rating of 13.5 kW_e.

2.2. Outdoor Test Site Description

The in-ground Geothermic Fuel Cell architecture is shown in Figure 3. Key elements include:

1. Three mechanically and electrically coupled Geothermic Fuel Cell modules;
2. A reactive-gas preheater attached to the top of the GFCs to heat the reactant gases that feed the GFC assembly;
3. A fuel reformer that converts natural gas supplied from the local municipality into syngas;
4. Control systems and diagnostics.

The GFC modules and preheat assembly are placed within a 0.76 m-diameter (2.5 ft.) steel casing that separates the assembly from the surrounding geology. The casing sits within a 9.14 m-deep (30 ft) bore hole. The in-ground assembly hangs nine meters into the ground and is secured from above at the wellhead. A 1.2 m-tall (4 ft.) wellhead module secures the entire assembly to a 0.1 m-thick concrete pad from which the GFC-preheater assembly is suspended. The wellhead also serves as the interface for gas plumbing, the extensive diagnostic sensors, and electric power. As in the laboratory setting, the in-ground Geothermic Fuel Cell is fueled using a natural gas fuel reformer, with optional fueling using compressed hydrogen and nitrogen.

An illustration of the outdoor test site is provided in Figure 4 along with a photograph taken during GFC installation. The site consists of extensive materials and equipment for in-ground GFC operation and characterization including:

- Equipment trailer for housing of control and diagnostics hardware;
- Nearly 400 m³ (14,000 scf) of compressed hydrogen for use in startup operations;
- Liquid nitrogen dewar (1500-L) ;

- Air compressor, backup air compressor, and air-storage tank;
- 20-kW backup electric generator;
- 480-V, 208-V, and 120-V electrical circuits.

2.2.1. Natural Gas Fuel Reformer

An autothermal fuel reformer supplied by Precision Combustion, Inc. (PCI, North Haven, CT, USA) is used to convert the natural gas supplied from the municipality into a hydrogen/carbon-monoxide syngas mixture. In addition to H_2 and CO , the reformat contains water vapor, carbon dioxide, nitrogen, and trace amounts of methane. The syngas generated by the reformer is used to fuel the GFCs.

Autothermal (ATR) reforming combines endothermic steam reforming (SR) and exothermic partial oxidation (POX) to create a near-thermoneutral chemical reaction. The natural gas is combined with air and water vapor oxidizers and passed over a catalyst at elevated temperature (800 °C); the oxygen-to-carbon and steam-to-carbon ratios can be altered to vary the reformat composition [21, 22]. Autothermal reforming reduces the need for an external heat source to drive the chemical reaction. Additionally, the reformer offers favorable start-up and response characteristics [23]. The range of operation for the PCI reformer is:

- 8-36 kW_{th} input energy based on the Lower Heating Value (LHV) and flow rate of natural gas;
- Variable oxygen-to-carbon (O/C) molar ratio: $0.8 \leq O/C \leq 1.2$ based on oxygen present in air supplied to the reformer;
- Constant steam-to-carbon (S/C) molar ratio: $S/C = 1.0$;
- Supplemental steam addition downstream of the reactor.

The supplemental steam addition enables modification of the reformat steam-to-carbon ratio and lower heating value. Measurement of reformat composition over a range of reformer operating conditions indicates that reformer chemistry is quite close to equilibrium predictions.

2.2.2. Reactive Gas Preheater

An integrated reactive-gas preheater and heat exchanger is used to heat the reactants upstream of the Geothermic Fuel Cell. An illustration of this preheater is shown in Figure 5. A counter-flow tube-in-shell architecture is utilized. This preheater/heat exchanger was designed by Saridea Inspired Engineering, LLC (Denver, CO, USA), and assembled by Deltech, Inc. (Denver, CO, USA).

Cool anode and cathode feed gases entering at the top of the preheat assembly are manifolded to a series of narrow, oval-shaped stainless-steel tubes that form an outer annulus. Heat is transferred to these cool reactants from hot exhaust gases exiting the preheat combustor and the GFC from the bottom. The natural-gas-fueled preheat combustor provides the bulk of the thermal power. A stainless steel inner shield forms the inner annulus of the preheat assembly. Fuel-cell electric power, sensor diagnostics, and combustor gas feeds are plumbed through this inner shield. The shield has fins welded to its outer diameter that extend into the exhaust channel. These fins induce mixing and promote heat transfer from the hot exhaust gases to the heat-exchanger tubing and cool reactant gases.

The burner operating conditions span:

- 8.3-16 kW_{th} input energy based on the LHV and flow rate of natural gas;
- Fuel flow rate 0.20-0.68 g s⁻¹;
- Air flow rate 5.5-17.6 g s⁻¹.

The preheater assembly is packaged within a stainless-steel housing (not shown) that is coupled to the top of the GFC modules within the bore-hole. The preheater is 3 m (10 ft) in length.

2.3. Testing Description

The Geothermic Fuel Cell system was operated during November and December of 2014. The average air temperature during the ~ 600 hours of operation was 1.1 °C (34 °F), with highs and lows of 17.8 and -7.2 °C (64 and 19 °C), respectively.

During startup, the SOFC stacks are brought to operating temperature using electric-resistance heaters contained within the Geothermic Fuel Cell modules. The electric heaters continuously provided 20 kW of thermal energy into the GFC during this start-up period. During heat up, a non-explosive hydrogen-nitrogen mixture (5% H₂ and 95% N₂) was fed to the nine GFC stacks.

After reaching a minimum stack operating temperature, the fuel composition was switched from the hydrogen-nitrogen mixture to reformat. Reformer performance was confirmed through measurement of reformat composition using a gas chromatograph. The reformat composition was: 23.7% H₂, 10.4% CO, 29% H₂O, 2.4% CO₂, 33.7% N₂, and 0.19% CH₄. This reformat composition was continuously monitored and found to remain constant for the duration of testing.

The Geothermic Fuel Cell was continuously operated under natural gas reformat for ~ 190 hours. During the first 90 hours of reformat operation, the electric current drawn from the GFC was varied between 0 and 90 A. Following this series of intermittent tests, the current draw set to a constant value of 65 A for the remaining 100 hours of operation under reformat. While “steady-state”, time-invariant conditions were never achieved, quasi-steady operation was observed over 24 hours of reformat operation at the 65-A condition. The following section summarizes in-ground GFC system performance over this 24-hour period.

3. Results and Discussion

3.1. System Performance

A number of state points were explored over the 600 hours of in-ground Geothermic Fuel Cell operation. While this represents an important demonstration for the GFC technology, this time period is relatively brief, comprising less than 2% of the four-year operating duration for which the GFC is designed.

As expected, the high temperature of the solid-oxide fuel cell stacks and low temperature of the surrounding geology led to high transfer of heat from the GFC to its surroundings.

This places higher demands on the GFC for production of heat, rather than generation of electricity. As will be shown, the in-ground GFC was operated under conditions that maximize heat output in order to meet these thermal demands. While this led to considerable geological heating during the 600 hours of operation, the corresponding electricity generation and the resulting electrical efficiency were comparatively modest.

The in-ground GFC was operated at the 65-A condition for 100 hours. The 24 hours of quasi-steady operation at the 65-A condition provide a baseline operating point for GFC performance analysis.

Because of the series/parallel interconnection of the in-ground GFC stacks and modules, the 65 A of current is distributed across the three GFC modules, resulting in an average of 21.7 A per module, and 21.7 A per stack. It is important to note that the electrical architecture of the in-ground GFC is designed for higher-current operation, perhaps as high as 150 A. Therefore, far-higher electricity generation is possible with the in-ground GFC than was demonstrated during this 600-hour test.

Table 1 presents a performance summary for the in-ground Geothermal Fuel Cell at the 65-A condition. The values shown in this table are calculated using 24-hour averages of the temperatures and mass flow rates measured during operation. The sensible and chemical energies of the gas streams are calculated from the measured temperatures (T) and mass flow rates ($\dot{m}$):

$$\text{Sensible :} \quad \dot{Q}_s = \sum_i (\dot{m}_i c_{p,i}) \cdot T \quad (1)$$

$$\text{Chemical :} \quad \dot{Q}_{ch} = \sum_i \dot{m}_i \cdot LHV_i \quad (2)$$

where i denotes the individual gaseous species contained in each stream and $c_{p,i}$ is the specific heat capacity for species i .

The heat loss from the in-ground assembly to the surroundings ($\dot{Q}_{heat}$) is determined by evaluating the energy balance for a control volume around the components:

$$\left[\dot{Q}_s + \dot{Q}_{ch}\right]_{in} - \left[\dot{Q}_s + \dot{Q}_{ch}\right]_{out} - \dot{W}_{elec} = \dot{Q}_{heat} \quad (3)$$

where $\dot{W}_{elec}$ is the electric power generated by the solid-oxide fuel cell stacks.

At the 65-A condition, the complete GFC system was fed with 60.8 kW of chemical power. This chemical power comes from three inputs:

1. Natural gas fed to the fuel reformer;
2. Natural gas fed to the preheater combustor;
3. Supplemental hydrogen added to the reformat stream.

The chemical power was supplemented by 10.8 kW of heat supplied by the GFC's internal electrical-resistance heaters. This supplemental electric heating serves to maintain the target stack temperatures (680 - 820 °C) during operation. An additional 1.7 kW of thermal power is used to preheat the air that feeds the autothermal reformer. The total energy input to the in-ground Geothermic Fuel Cell system is 73.3 kW.

At the 65-A condition, 4.4 kW of electric power was continuously generated by the solid-oxide fuel cell stacks. As stated previously, this power draw is less than one third of the rated capacity of the GFC stacks. Operating conditions yielding higher electric power will be explored as our experience with GFC system operation grows. This results in a modest electrical efficiency of 7.2%. The low efficiency is primarily attributed to the low fuel utilization (25.9%) used for this series of tests.

Thermodynamic analyses reveal that the three Geothermic Fuel Cell modules liberated 18.8 kW of thermal power into the surrounding geology. In addition, the preheat unit drove 10.2 kW into the geology, increasing the total thermal power entering the geology to 29.1 kW. This resulted in a heat flux to the geology of 3.2 kW m⁻¹ across the 9-m length of GFC-preheater assembly. This is clearly well above the electric power generated by the stacks, as needed during initial startup conditions. The thermal efficiency for providing heat to the geology was 47.8%; the combined heat-and-power efficiency reached 55.0%.

Figure 6 depicts the relative distribution of energy across system outputs. The fraction of energy that represents the electrical power harnessed (4.4 kW) is small relative to the

heat lost to the geology (29.1 kW). This is due to the high heating demands placed on the GFC, as opposed to electricity generation, during initial operation. It is expected that as the geology grows warmer, more energy conversion can be directed towards electricity generation rather than heat liberation.

Significant thermal energy is also lost in the hot exhaust gases exiting the GFC-preheat assembly (8.4 kW). Such losses are significant in this near-surface demonstration, but will decrease as the Geothermic Fuel Cells are installed in deeper geological locations. Inefficiency in the autothermal reformer is also considerable (9.2 kW).

The energy lost due to unreacted reformat gases exiting the GFC is most significant (22.3 kW). While this unused fuel negatively impacts efficiency, the ability to pass reformat through the GFC without conversion is an important design feature, as it provides a measure of turndown in device operation. This enables a decrease in thermal and/or electrical output from the GFCs as the geology grows warmer, preventing overheating.

For this demonstration, the unreacted reformat was simply flared above ground. It is reasonable to consider that the unreacted fuel could be used in a number of ways to improve system performance. Unreacted reformat gases could be routed to the preheat combustor, reducing (perhaps even eliminating) the consumption of natural gas in this combustor. Thermodynamic calculations indicate that such a change would increase the CHP efficiency from 55.0% to 66.0% for the same conditions tested.

Alternatively, the anode exhaust could be “recycled” into the reformat fuel that feeds the GFC. Anode recycle has been shown to markedly improve system performance [24, 25, 26]. This change would necessitate use of a high-temperature anode-recycle blower. Such a blower would need to withstand the high temperatures of the anode exhaust gases (> 200 °C), and require power and control hardware for proper operation [27, 28]. However, these unreacted reformat gases exit the GFC at temperatures that are lower than those found in typical SOFC systems, perhaps reducing the cost of this balance-of-plant component.

3.2. Component Performance

This section presents the performance of the key components that comprise the Geothermic Fuel Cell System: the fuel reformer, the reactant preheater, and the Geothermic Fuel Cell modules.

The reformer is equipped with an air heater upstream of the reactor, and two “supplemental” steam generators that provide superheated steam to the reformat downstream of the reactor. The supplemental steam is provided in addition to the water that is injected with the air and natural gas into the catalytic reactor body. Operating conditions for the autothermal reformer were held constant throughout the 100 hours of operation at the 65-A condition:

- 36 kW_{th} chemical energy input;
- $1.0 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$ (60 slpm) natural gas flow rate;
- $3.1 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$ (183 slpm) air flow rate (1.16 O/C ratio);
- $8.1 \times 10^{-1} \text{ g s}^{-1}$ steam flow rate (1.0 S/C ratio);
- $7.1 \times 10^{-1} \text{ g s}^{-1}$ supplemental steam flow rate.

As listed previously, the measured reformat composition was very close to chemical-equilibrium predictions, with very little methane slip. The reformer efficiency (Eq.4) is evaluated based on the LHVs of the natural gas supply and the hydrogen product [21]:

$$\eta_{ATR} = \frac{(\dot{n}_{H_2} + \dot{n}_{CO}) \cdot LHV_{H_2}}{\dot{n}_{CH_4} \cdot LHV_{CH_4}} = 75.1\% \quad (4)$$

This definition assumes complete shifting of the carbon monoxide into CO₂ through the water-gas shift reaction, yielding one mole of H₂ for every mole of CO in the reformat:

Before the reformed natural gas is fed to the GFC, additional hydrogen (20 slpm) is injected to the fuel stream to increase its chemical power. This supplemental hydrogen is not included in the ATR efficiency calculation.

The flow of energy through the preheater is shown pictorially in Figure 7. The preheater is quite effective in increasing reactant-gas temperatures to SOFC-stack operating conditions. The air and reformat gases exit the preheater at 697 and 748 °C, respectively. These temperatures are quite well matched, and near the stack temperatures.

When operating at the 65-A condition, the reactant gases pick up 19.0 kW of thermal power when passing through the preheater. There are two sources of this thermal energy: the high-temperature gases exiting the natural gas combustor, and the hot exhaust gases exiting the GFC modules. The combustor serves the primary heating role: 16.8 kW of thermal power are released through combustion, while 12.6 kW are liberated by the hot exhaust (8.0 kW from the air, 4.6 kW from the anode exhaust).

Much of the heat generated by the combustor and liberated by the GFC exhaust is transferred to the cool reactants (65%). However, heat transferred from the preheater to the surrounding geology is also substantial (10.4 kW).

A similar thermodynamic analysis of the three Geothermic Fuel Cell modules reveals that the GFCs drive 18.7 kW of thermal energy into the surrounding geology. The reactants bring nearly 52 kW of sensible and chemical energy into the GFC assemblies. The internal electric heaters generate 10.8 kW of heat within the GFC modules. The SOFCs electrochemically convert the chemical energy within the reactants into 4.4 kW of electricity, while 39.6 kW of sensible and chemical energy exit the GFCs through the exhaust. The remainder (18.7 kW) is released to the surrounding geology.

3.3. Geology Heating

Temperatures in the surrounding geology were periodically measured over the course of the in-ground Geothermic Fuel Cell testing. Figure 8a depicts the geology temperature as a function of depth from the surface on two consecutive days of 65-A operation. These measurements were taken within a bore hole located 1.2 m (3.9 ft.) from the GFC casing.

A substantial temperature difference is observed with depth below the surface; the highest temperatures are observed at 3.7 m from the surface, nearly adjacent to the top-most stack. The lowest temperatures and highest temperature gradients are found close to the surface.

At depths greater than 4 m, geology temperature gradually decreases with increasing depth into the earth. This reflects the higher volume of geology that must be heated at the bottom of the GFC. Heat transfer in the radial direction is dominant near the middle of the GFC-preheater assembly (depth of 4.5 m); axial heat transfer is also significant at the ends of the assembly. These fairly pronounced end effects result in the lower temperatures at the extreme positions. Overall, the geology temperature is found to increase by over 3 °C in the 24-hour period between the two series of measurements.

Geology temperature as a function of radial position from the GFC casing is shown in Figure 8b. This logarithmic temperature profile is consistent with the general solution for one-dimensional radial heat conduction into an infinite homogeneous medium [29]. Such a result may prove valuable for future modeling of the geology-heating process.

4. Conclusions

This paper reports on the design and performance of the world’s first Geothermic Fuel Cells. Three cylindrical GFC modules, each containing three 1.5 kWe solid-oxide fuel cell stacks, were mechanically and electrically coupled and joined to a gas-preheater/heat-exchanger assembly. The 9-m-long assembly was placed within the earth, integrated with extensive balance-of-plant components, controls, and diagnostics, then continuously operated over a period of 600 hours. An initial data set was gathered, and the effectiveness of the GFCs in heating the surrounding geology while simultaneously generating electricity was demonstrated.

In an effort to establish a steady operating point, the Geothermic Fuel Cell system was set at an electrical current output of 65 A while fueled with reformed natural gas. With the SOFC stacks within the GFC assembly operating at temperatures as high as 800 °C, and the surrounding geology at temperatures less than 100 °C, high heat transfer was observed from the GFC assembly to the surroundings. This necessitated a Geothermic Fuel Cell

operating condition that favored generation of thermal energy over generation of electricity. Key operating characteristics under this condition include:

- 4.4 kW of continuous electricity generation;
- 29.2 kW of heat transferred from the GFC-preheater assembly to the surrounding geology, with 18.8 kW liberated by the GFCs, and 10.3 kW provided by the preheater;
- 55% combined heat-and-power efficiency;
- 3.2 kW m^{-1} of heat flux transferred to the geology across the 9 m length of the GFC-preheater assembly.

The 22.4 kW of energy loss from the low fuel utilization and ensuing unreacted reformat exiting the GFC is the primary source of the relatively low system electrical efficiency (7.2%). Considerable performance increases could be realized by harnessing the chemical and thermal energy in the unreacted fuel exiting the GFC.

The use of Geothermic Fuel Cells in unconventional oil-and-gas recovery presents an exciting new application for solid-oxide fuel cell technology. For the present study, the primary resource to be accessed is the four-trillion barrels of oil trapped within U.S. oil-shale reserves. Other potential applications include down-hole steam generation for accessing tight oils and advanced conventional oil recovery.

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NOMENCLATURE

ATR	autothermal reforming
CHP	combined heat and power
GFC	Geothermic Fuel Cell
HX	heat exchanger
ICP	In-situ Conversion Process
LHV	lower heating value (kJ kmol^{-1})
NG	natural gas
O/C	oxygen to carbon ratio
PCI	Precision Combustion Inc.
POX	partial oxidation
S/C	steam to carbon ratio
SOFC	Solid Oxide Fuel Cell
SR	steam reforming
$c_{p,i}$	specific heat capacity ($\text{kJ Kg}^{-1}\text{K}^{-1}$)
$\dot{m}_i$	mass flow rate (Kg s^{-1})
$\dot{n}_i$	molar flow rate (kmol s^{-1})
$\dot{Q}_s$	sensible energy (kW)
$\dot{Q}_{\text{ch}}$	chemical energy (kW)
$\dot{Q}_{\text{heat}}$	heat loss to geology (kW)
T	temperature (K)
$\dot{W}_{\text{elec}}$	electric power (kW)
η_{ATR}	reformer efficiency (%)

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Table(s)

Total chemical power into system (kW)	60.8	(Power in NG to reformer) + (Power in NG into preheat combustor) + (Power in supplemental H ₂ to GFC)
Total heat into system (kW)	12.5	(Preheating of reactants at ATR) + (GFC internal electric heaters)
Stack electric power (kW)	4.4	(Electric current) * (GFC terminal voltage)
System electrical efficiency (%)	7.2	(Stack electric power) / (Total chemical power into system)
Fuel utilization (%)	25.8	(Moles of H ₂ consumed to produce electric current) / (Moles of [H ₂ + CO + 3*CH ₄] fed to GFC)
GFC heat loss to geology (kW)	18.8	[Total chemical and sensible energy in GFC inlet gases - Total energy in GFC exhaust gases] - GFC electric power
Preheater heat loss to geology (kW)	10.4	[Total (chemical and sensible) energy in the preheater inlet gas streams] - [Total energy in preheater outlet gas streams]
Total heat loss to geology (kW)	29.1	(Heat loss from GFC) + (Heat loss from pre-heat unit)
System heating efficiency (%)	47.8	(Total heat loss to surroundings) / (Total chemical power into system)
Combined heat and power efficiency (%)	55.0	(System electrical efficiency) + (System heating efficiency)
Heat loss per unit length of GFC (kW/m)	3.2	(Heat loss to geology) / (6 m GFC length + 3 m of Pre-Heater length)
Reformer efficiency (%)	75.1	(Chemical power in reformat) / (Chemical power in NG fuel)
Heat exchanger efficiency (%)	65.1	(Heat gained by GFC inlet gases) / [(Heat from NG combustion) + (Heat loss from GFC exhaust streams)]

Figure 2

Figure 5

Figure 8

LIST OF FIGURES

- Figure 1:** Illustration of the Geothermic Fuel Cell concept, solid-oxide fuel cells provide the thermal energy to heat the oil shale formation.
- Figure 2:** Schematic of a single Geothermic Fuel Cell module. Three such modules were joined and placed within the earth as part of this demonstration.
- Figure 3:** Geothermic Fuel Cell system architecture.
- Figure 4:** Layout of in-ground Geothermic Fuel Cell outdoor test site (left); photograph taken during GFC installation (right).
- Figure 5:** Saridea preheater/heat-exchanger assembly.
- Figure 6:** Distribution of energy across the Geothermic Fuel Cell system at the 65-A operating point.
- Figure 7:** Illustration of the heat and gas flows through the preheat assembly. The dashed red line represents the physical boundaries of the preheater. Line thicknesses reflect the magnitude of the heat and gas flows into and out of the preheater.
- Figure 8:** Geology temperature: a) as a function of vertical depth from the surface measured on consecutive days of testing; b) as a function of radial distance from the sidewall of the casing in which the Geothermic Fuel Cell assembly is placed. Measurements were taken at a vertical position of 4 m (13 ft.) below the surface.

LIST OF TABLES

- Table 1:** Performance of the in-ground Geothermic Fuel Cell system at the 65-A operating condition.