Final Technical Report

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Recipient: Rolls-Royce Fuel Cell Systems (US) Inc.

Title: "Evaluation of Reformer Produced Synthesis Gas for Emissions Reductions in Natural Gas Reciprocating Engines"

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Executive Summary

Rolls-Royce Fuel Cell Systems (US) Inc. (RRFCS) has developed a system that produces synthesis gas from air and natural gas. A near-term application being considered for this technology is synthesis gas injection into reciprocating engines for reducing NO_x emissions. A proof of concept study using bottled synthesis gas and a two-stroke reciprocating engine showed that injecting small amounts of high-flammables content synthesis gas significantly improved combustion stability and enabled leaner engine operation resulting in over 44% reduction in NO_x emissions. The actual NOx reduction that could be achieved in the field is expected to be engine specific, and in many cases may be even greater. RRFCS demonstrated that its synthesis gas generator could produce synthesis gas with the flammables content that was successfully used in the engine testing. An economic analysis of the synthesis gas approach estimates that its initial capital cost and yearly operating cost are less than half that of a competing NOx reduction technology, Selective Catalytic Reduction. The next step in developing the technology is an integrated test of the synthesis gas generator with an engine to obtain reliability data for system components and to confirm operating cost. RRFCS is actively pursuing opportunities to perform the integrated test. A successful integrated test would demonstrate the technology as a low-cost option to reduce NO_x emissions from approximately 6,000 existing two-stroke, natural gas-fired reciprocating engines used on natural gas pipelines in North America. NO_x emissions reduction made possible at a reasonable price by this synthesis gas technology, if implemented on 25% of these engines, would be on the order of 25,000 tons/year.

Comparison of Actual Accomplishments with Project Objectives

There were two main objectives of the projects. The first was to demonstrate the benefits of pre-conditioning a portion of the natural gas fuel to a reciprocating engine with the injection of a small amount of synthesis gas-namely extension of lean combustion limits to significantly reduce NO_x emissions. The second objective was to demonstrate that the synthesis gas could be produced by a reformer from natural gas and air. Success would allow RRFCS to engage an engine manufacturer or operator as a partner for a commercial demonstration. These objectives were achieved as NO_x emissions were significantly reduced when a high-flammables content synthesis gas was injected into a test engine at Colorado State University and when synthesis gas with high flammables content was produced by a prototype synthesis gas generator at RRFCS. RRFCS has held discussions with natural gas pipeline companies and representatives from the Pipeline Research Council International (PRCI) concerning an integrated field demonstration of the technology. Two natural gas pipeline companies have expressed interest in the field demonstration. RRFCS is seeking support for the integrated test and partners interested in applying this technology to other natural gas-fired engines.

Summarized Project Activities

Rolls-Royce Fuel Cell Systems (US) Inc. has developed compact systems that generate synthesis gas from hydrocarbon fuels. One application for synthesis

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gas may be injection into reciprocating engines to help reduce NO_x emissions. RRFCS investigated the use of synthesis gas in large-bore natural-gas (NG) two-stroke engines to reduce emissions. There are approximately 6,000 of these two-stroke engines used to compress and transport natural gas across long distance pipelines throughout North America. It is anticipated that future NO_x emissions regulatory requirements will require these engines to implement retrofit technologies to meet these regulatory requirements. The current NO_x emissions reduction technology under development in this project can be applied for this purpose.

A large number of the gas compression engines have Pre-combustion Chamber (PCC) technology to help achieve lower NO_x emissions. The PCC enables relatively fuel-lean (or air-rich) operation which yields relatively low NO_x emissions because lean conditions yield relatively cool combustion temperatures that inhibit NO_x formation. The PCC stabilizes combustion at lean operating limits that would otherwise be unstable if conventional spark ignition were applied. The PCC is a small spark-ignited chamber that burns a 1% to 2% slipstream of the natural gas feed to the engine. The PCC is a highly effective technique for reliably igniting the main combustion volume under relatively lean conditions because it provides energy that is one million times greater than a spark plug alone, while providing a highly turbulent jet of hot reactive gas into the main piston. This jet generates numerous ignition sites throughout the main combustion volume. Unfortunately, other non-NO_x emissions including carbon monoxide (CO), total hydrocarbons (THC), and volatile organic carbon (VOC) typically will increase as the engine is operated with increased excess air (i.e. more fuel lean) and decreased NO_x. The increase in non-NO_x emissions is acceptable as long as acceptable combustion stability is achieved. Emissions other than NO_x are more easily removed from the engine exhaust by using back-end, gas-clean-up technologies, whereas backend NO_x removal would require relatively costly and operationally complex Selective Catalytic Reduction (SCR) technology. Therefore, a front-end technology that trades off reduced NO_x emissions with increases in non-NO_x emissions is more valuable. Poor combustion stability limits how lean the engine can operate for reducing NO_x. Therefore, the lean operational limit which represents the minimum NO_x emission is dictated by an acceptable level of combustion stability typically referred to as the coefficient of variance of peak piston pressure (COVpp) as measured from cycle to cycle.

The concept under development has the potential to significantly reduce NO_x emissions with conventional PCC technology by further extending the engines lean operating limit at constant combustion stability as measured by COVpp. The standard PCC approach was modified by replacing a significant fraction of the natural gas feed stream to the PCC with synthesis gas rich in hydrogen (H_2) and CO. Synthesis gas is highly combustible relative to natural gas. Its high combustibility is caused by the high flame velocity of H_2 relative to natural gas, and the relatively wide envelope of flammable air / fuel mixtures under which H_2 and CO burn relative to natural gas. The nature of the PCC gas jet that results from the H_2/CO mixture can also enhance the effectiveness of the PCC.

Experimentally, the synthesis gas feed mixture was shown to yield high combustion stability during tests conducted at Colorado Sate University's (CSU's) Engines and Energy Conversion Laboratory. Bottled-gas blends were used to

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simulate synthesis gas / natural gas feed blends to the PCC of a large-bore Cooper Bessemer GMV-4TF laboratory natural gas reciprocating engine. The engine had an output of 440 horsepower (hp) and represents a typical model used for natural gas transport through long-distance pipelines in North America. This testing defined the synthesis gas composition and feed conditions required to significantly extend the lean operating limit of the engine at constant combustion stability (COVpp). It also demonstrated the fuel feed system required to deliver the synthesis gas at PCC conditions.

Table 1 summarizes the most significant engine test results that illustrate the impact of synthesis gas on combustion stability and emissions at several boost levels. The term engine boost is used to describe the quantity of air feeding the engine as a result of turbo-charging. It is measured as the inlet air pressure entering the pistons and is typically reported with the units of inches of mercury (Hg). Synthesis gas injection into the PCC enabled stable engine operation at a higher inlet air pressure compared to natural gas only operation. For example stable engine operation with synthesis gas was extended to an inlet air pressure of 22 inches of Hg while maintaining combustion stability (COVpp equal to about 6 pounds per square inch, psi) similar to 100% natural gas firing at only 18 inches of Hg. The higher inlet air pressure resulted in a NO_x reduction in excess of 44% (from 0.52 to 0.29 grams per brake horsepower hour, g/bhp-hr). The NO_x reduction was even more pronounced at an elevated level of combustion stability. For example at COVpp equal to about 5 psi, only a relatively low engine boost (8.5 inches of Hg) could be used with natural gas. However for the same COVpp the synthesis gas extended the lean limit to 18 inches of Hg. This yielded a large reduction (87%) in NO_x emissions (from 3.83 to 0.49 g/bhp-hr) as shown in the Table.

Table 1 - Results from Engine Tests

Impact of Syngas Injection:				**Holding Combustion Stability Constant:**			
PCC Fuel	NG		Syngas	PCC Fuel	NG		Syngas
Inlet air pressure	18" HG		18" HG	Inlet air pressure	18" HG		22" HG
COV-pp psi	6.38	⇨	5.01	COV-pp psi	6.38	=	6.11
Nox g/bhp-hr	0.52	21% Improvement	0.49	Nox g/bhp-hr	0.52	⇨	0.29
CO g/bhp-hr	1.71	in Combustion	2.08	CO g/bhp-hr	1.71		3.01
CH2O g/bhp-hr	0.29	Stability	0.28	CH2O g/bhp-hr	0.29	44% Reduction	0.37
VOC g/bhp-hr	1.51		1.15	VOC g/bhp-hr	1.51	in NOx	1.48
THC g/bhp-hr	5.85		5.40	THC g/bhp-hr	5.85		8.09
Constant Inlet Air Pressure:				**High Degree of Combustion Stability:**			
PCC Fuel	Syngas		NG	PCC Fuel	Syngas		NG
Inlet air pressure	22" HG	=	22" HG	Inlet air pressure	18" HG		8.5" HG
COV-pp psi	6.11	⇨	7.26	COV-pp psi	5.01	=	5.23
Nox g/bhp-hr	0.29		0.30	Nox g/bhp-hr	0.49	⇦	3.83
CO g/bhp-hr	3.01	Poor Combustion	2.74	CO g/bhp-hr	2.08		0.62
CH2O g/bhp-hr	0.37	Stability	0.36	CH2O g/bhp-hr	0.28	87% Reduction	0.18
VOC g/bhp-hr	1.48		2.03	VOC g/bhp-hr	1.15	in NOx	0.88
THC g/bhp-hr	8.09		8.59	THC g/bhp-hr	5.40		3.33

NO_x reduction at constant combustion stability is dependent on the value of excess air and is indicative of the fact that NO_x emissions will decrease exponentially with excess air. Many engines that are currently operating at lower boost levels have turbo-charging capacity to go to yet higher excess air levels.

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Therefore very significant NO_x reductions that would meet anticipated regulatory NO_x emission levels are certainly feasible through this approach. However, stores of bottled gas are not a practical or cost-effective means of supplying synthesis gas to the engines. Therefore, a cost-effective technology is required to supply the synthesis gas. RRFCS is currently developing a synthesis gas generator (SGG) and its testing was the focus of this project.

The SGG under development generates the required synthesis gas mixture composition by applying a modified catalytic partial oxidation (CPOX) approach. The catalytic partial oxidation of natural gas typically uses air as the oxidant. RRFCS had previously developed several applications for air-driven CPOX. The current approach uses an oxygen-enriched air stream. This project performed proof-of-concept testing on a modified CPOX process that successfully produced enriched synthesis gas with flammables concentrations in excess of 65%.

The prototype SGG is shown in Figure 1. Its major components included the reactant preheater, the reactor vessel, the synthesis gas cooler and the reactant flow control devices. The SGG was able to produce synthesis gas with the composition and production rate that matched those used by CSU in the engine tests for achieving the most significant NO_x emission reduction results. Figure 2 shows SGG operational data for catalyst temperatures, synthesis gas product rate, synthesis gas percent flammables (sum H_2 + CO) content and methane content. The observed Methane levels (~1% by volume) were near the expected thermodynamic equilibrium value. Based on the test results it was concluded that a slightly larger CPOX catalyst compared to the tested catalyst would ensure a close approach to equilibrium conversion of natural gas to synthesis gas at the production rate required for the 440 hp test engine. A single commercial of-the-shelf catalyst can easily supply synthesis gas to meet the required capacity at the smaller compression stations (up to 5,000 hp). Therefore, larger compression stations would require multiple SGG units unless a customized catalyst is produced. However, 5,000 hp SGG units would provide significant economies of scale for compression stations of any size.

The operating cost of the SGG depends in part on the operating life or the durability of the catalyst. Catalyst durability refers to its resistance to a decline in methane conversion over time due to deactivation. Deactivation therefore is characterized by increasing methane slip. Catalyst durability was thought to be a concern at the more severe catalyst operating conditions required by the SGG to produce synthesis gas with the high-flammables content necessary to achieve the desired engine performance. The more severe operating conditions are more susceptible to carbon formation and may yield significantly higher catalyst temperature that could shorten catalyst life. After 100 hours of SGG operation at the supposed severe operating conditions the catalyst did not show any signs of accelerated degradation compared to historical data for a catalyst with the same formulation that was tested previously for 1,000 hours. Figure 3 depicts the performance of the current test catalyst in the red symbol. It is overlaid on historical performance data that demonstrates durability at the same operating conditions. The current catalyst showed no excessive deactivation. The initial projections for

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catalyst life in the SGG are one year and should meet the initial performance target of a yearly SGG maintenance cycle.

Product Development

The pipeline industry in North America has over 2,500 Cooper Bessemer model GMV engines in operation and a total of approximately 6,000 two-stroke engines from all manufactures. A significant portion of these engines are equipped with PCC. NO_x emissions reduction made possible by the synthesis gas technology, if implemented on 25% of these engines, would be on the order of 25,000 tons/year. Firing the PCC with synthesis gas instead of natural gas would require a relatively small SGG. An economic analysis of the SGG approach estimates that its initial cost and yearly operating cost are less than half that of the competing NO_x reduction technology exhaust after treatment using Selective Catalytic Reduction (SCR). Figure 4 shows a projection of the costs for each technology. Significant NO_x emissions reduction may be made possible at a reasonable price by the synthesis gas technology.

The next step in developing the Syngas generator is an integrated test with an engine to obtain reliability data for system components (catalyst, heat exchangers, compressors, etc.) and to confirm operating cost. A successful integrated test would demonstrate the approach as a low-cost option to reduce NO_x emissions for existing two-stroke, natural gas-fired reciprocating engines used on natural gas pipelines in North America. Once an integrated test is successfully completed, the technology would be ready for a long-term field demonstration. Two natural gas pipeline companies have expressed interest in a field demonstration through the Pipeline Research Council International (PRCI).

Publications

1. M. Ruter, D. Olsen, M Scotto and M Perna, "Performance of A Large Bore Natural Gas Engine with Reformed Natural Gas Prechamber Fueling", ASME 2010 Internal Combustion Engine Division, Fall Technical Conference, San Antonio, Texas, 2010.

Collaborations Fostered

This program was carried out with funding provided from a 2008 U.S. Department of Energy award. In 2009 RRFCS executed a subcontract with CSU's Engine and Energy Conversion Laboratory to conduct the bottled synthesis-gas feasibility tests on a full size engine. During the execution of the subcontract a very good working relationship developed between CSU and RRFCS. The two organizations co-authored a paper to the 2010 ASME Internal Combustion Engine Division, Fall Technical Conference and are pursuing follow-on development opportunities to advance the synthesis gas technology to the demonstration stage. Additionally RRFCS and CSU have interacted with the Pipeline Research Council International (PRCI) concerning follow-on development and a possible field demonstration of the technology. Two natural gas pipeline companies have held discussions with RRFCS and CSU and expressed interest in a field demonstration.

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Patent Application

RRFCS is pursuing a continuation patent on patent application that includes the engineering process that was developed under this project, and also summarizes methods of control for this process. The engineering process pertains to several variations on a general arrangement of equipment used for the generation of synthesis gas that is highly concentrated in flammable species, the largest component of which is hydrogen. Various control schemes for the process are presented. The majority of equipment is procured as commercially available; however, the CPOX reactor is an internally designed component that is the heart of the technology. Some of the functions performed by the commercially-available equipment may eventually undergo customized development to reduce the process footprint and cost.

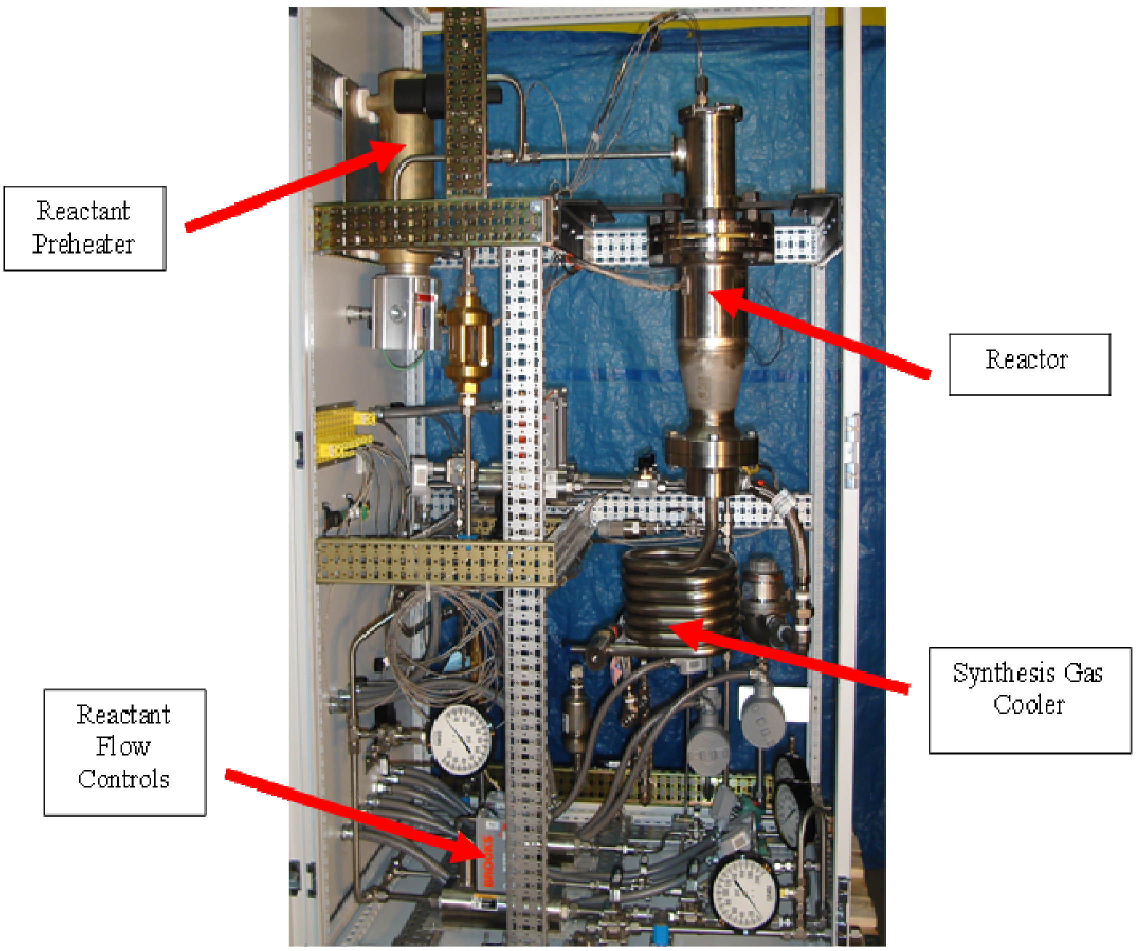

Figure 1: Synthesis Gas Generator (SGG)

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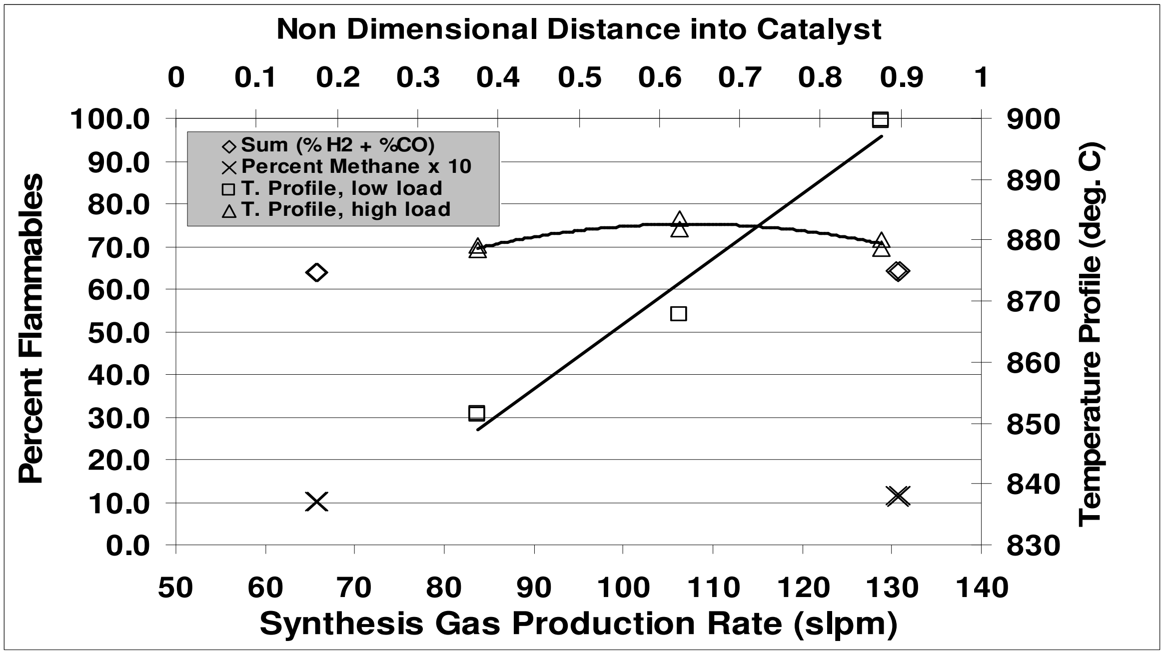

Figure 2: SGG Operational Data

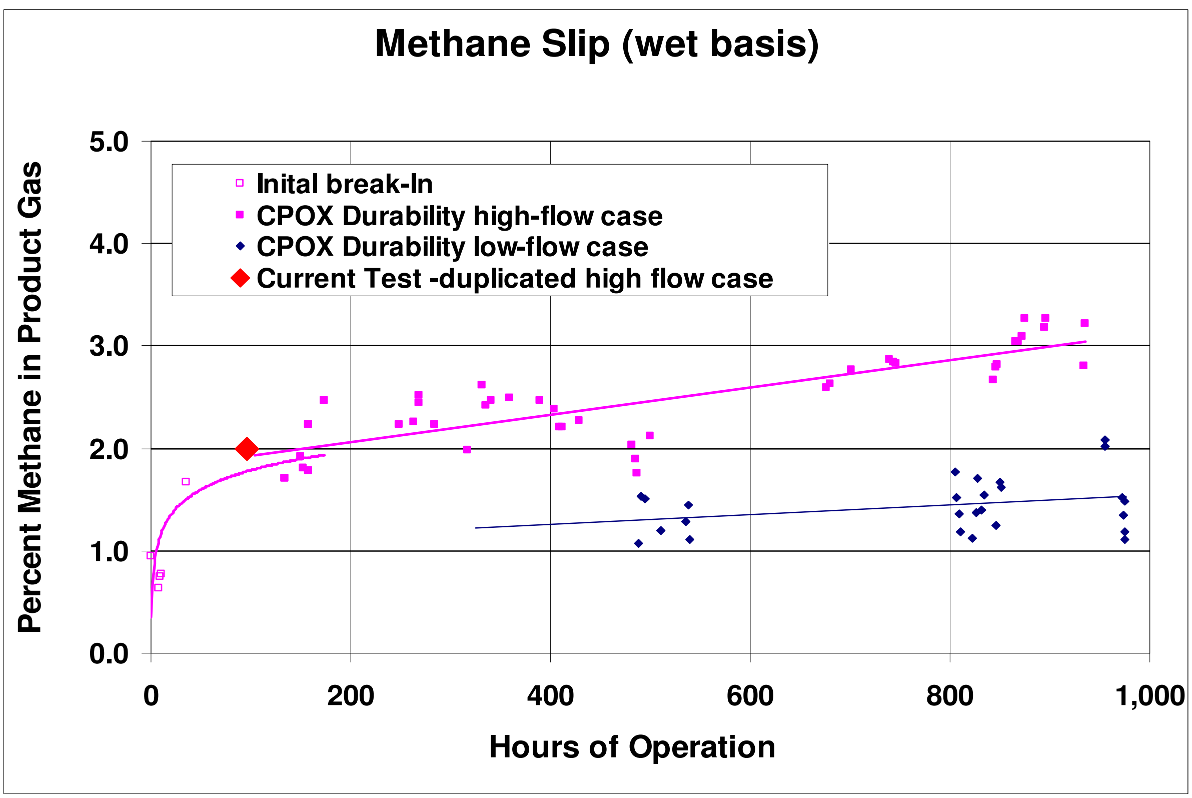

Figure 3: Current Catalyst Performance and Historical Data for Durability

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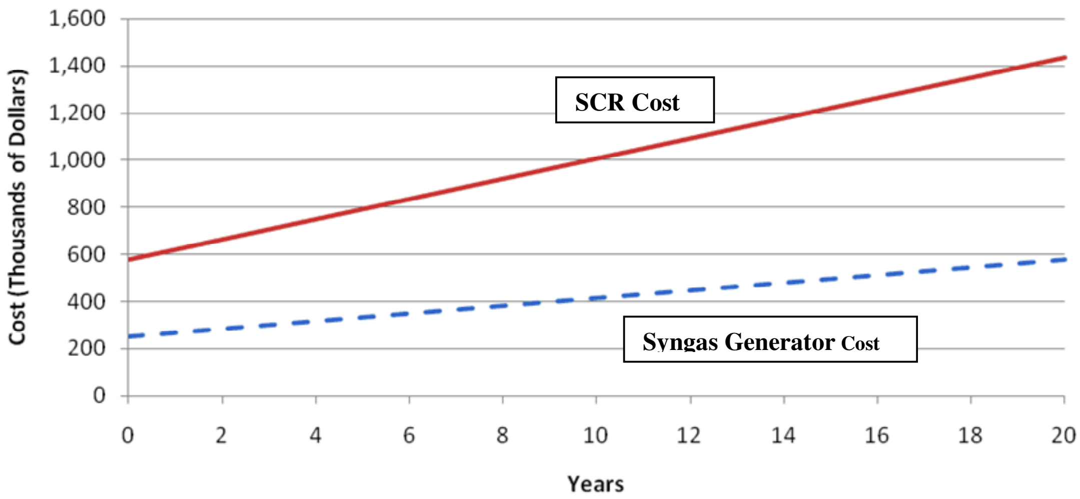

Figure 4- Cost Comparison for Synthesis Gas PCC Fueling vs. SCR

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