Pratt & Whitney Rocketdyne/DOE Advanced Single-Stage Gasification Development Program

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Introduction

This paper describes the Advanced Gasification Systems Development (AGSD) program, a Cooperative Agreement between the Rocketdyne Propulsion and Power division of the Boeing Company and the Department of Energy (DOE). This paper describes the technical basis for the expected improvements in gasifier characteristics, provides an overview of AGSD program plans, and presents estimated commercial benefits of AGSD technology.

The Rocketdyne gasifier is an oxygen-blown, dry-feed, plug-flow entrained reactor able to achieve carbon conversions approaching 100 percent. The gasifier uses Rocketdyne rocket engine technology to enable a compact, long-life, efficient gasifier that increases performance and availability while decreasing capital costs. The injector design uses multi-element injection to rapidly mix the coal with hot steam and oxygen while rapidly dispersing the coal across the reactor's cross-section. Efficient cooling of the injector face plate enables injector life much greater than the two to six months typical of existing water-slurry gasifier injectors. The Ceramic Matrix Composite (CMC) liner is also actively cooled, resulting in a solid layer of slag on the gasifier side of the liner. This layer is expected to protect the refractory underneath, enabling an operational life much greater than the six to eighteen month life typically observed for non-cooled refractory brick in existing gasifiers. The dry feed system, rapid mix injector, and cooled refractory liner are expected to enable the gasifier to process all ranks of coal.

The current AGSD project is funded jointly by the DOE and Rocketdyne. The project objectives are to (1) demonstrate the applicability of the long life rapid-mix injector at a commercial scale, (2) test cooled refractory liner sections, and (3) perform a conceptual design and hardware definition of an 18 ton per day pilot plant gasifier demonstrating Rocketdyne technology.

Preliminary economic analysis has shown near term (2010) AGSD gasifier technology could reduce Cost of Electricity by 15% to 20% relative to current gasifier technologies, with >10% reduction in plant capital cost per kW and a 50% reduction in gasifier capital cost. Similar cost-of-product benefits (also based on a preliminary economic analysis) are anticipated for hydrogen production.

Advanced Gasification Systems Development (AGSD) Program

The AGSD program is a cooperative agreement between Rocketdyne and the Department of Energy's National Energy Technology Laboratory (NETL). The overall objective of the program is to improve the availability and efficiency of gasification-based power plants, and to reduce plant capital and operational costs. In the current phase of the program, these objectives are advanced by:

- Testing of cooled refractory liner coupons in an entrained flow gasifier environment.
- Demonstration of commercial scale multi-element dense-phase dry feed injectors in cold-flow testing.
- Conceptual design and hardware definition of a novel 18 tpd pilot plant that integrates a dense-phase dry feed system with a long-life, high-performance entrained flow gasifier.

Significant gasifier performance and life improvements result from incorporating dry feed, rapid-mixing and cooled components into the gasifier design. The impacts of these improvements are shown in Table 1, summarizing commercial gasifier targets.

Table 1. AGSD Goals for a Commercial-Scale Gasifier

Performance Parameter	Target
Carbon Conversion	>99%
Cold Gas Efficiency (HHV)	85%
Injector Life	>2 years
Gasifier Liner Life	>10 years

In addition to performance benefits, rapid mixing and dry feed enables high carbon conversion in short residence times. This reduces gasifier volume by approximately 90% relative to conventional gasifiers, and significantly reduces gasifier capital cost.

The Rocketdyne gasifier is expected to accommodate all ranks of coal, including lignite and petcoke. The dense phase feed system has been demonstrated previously with bituminous and sub-bituminous coals. Preliminary gasifier kinetics modeling indicates that >99% conversion can be attained for all ranks of coal with the basic gasifier configuration.

The current phase of the AGSD program will provide near-term data validating injector and liner life goals, and will define a pilot plant test program to demonstrate system performance as well as anchor life predictions. The current phase of the AGSD program consists of the following tasks:

<u>Task 1: Testing of Cooled Liner Sections</u>
This task evaluates the performance of multiple Ceramic Matrix Composite (CMC) sections for potential use in the gasifier liner through testing in an entrained flow gasifier at CANMET Energy Technology Centre - Ottawa. Testing will be completed in 2005,

and the results will support design of the pilot plant gasifier. Figure 1 shows a schematic of the spool segment that will contain the CMC sections, and indicates where the spool will be integrated into the existing CANMET gasifier.

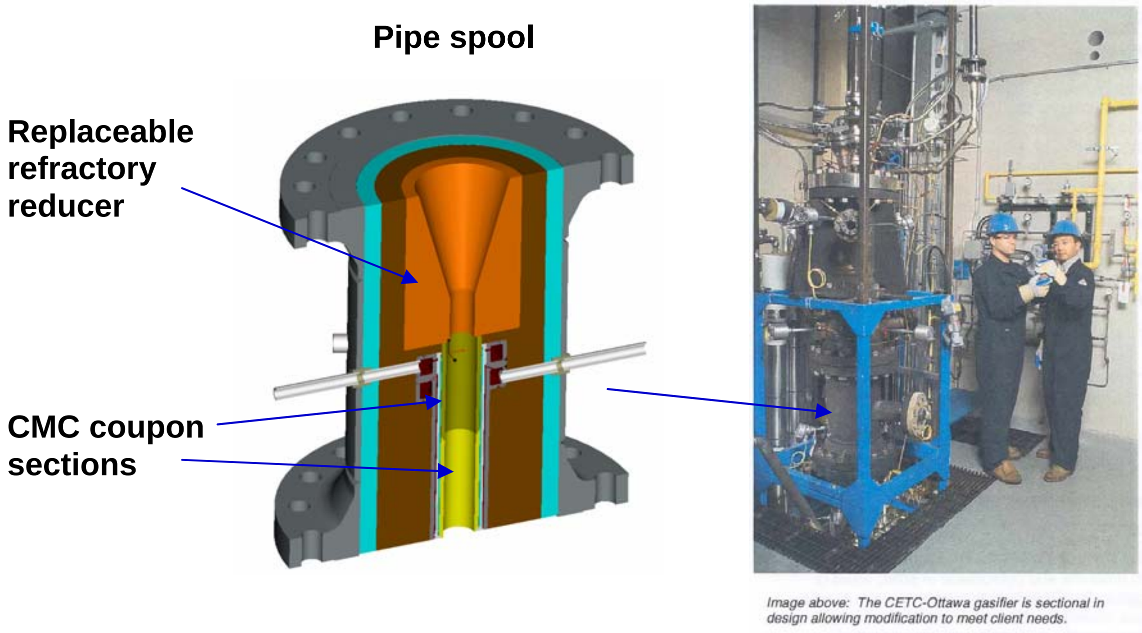

Figure 1. CMC spool section and CANMET gasifier.

Task 2: Injector Cold Flow Testing

Injector cold flow testing will flow 400 tpd of coal through commercial scale injector elements by way of a dense-phase dry feed system, as illustrated in Figure 2. In the initial phase, as part of the current effort, a lockhopper will introduce pulverized coal at 1,300 psia into the high pressure discharge tank. The coal will flow by dense-phase transport from the discharge tank to a flow splitter that will evenly distribute the dense-phase feed among multiple injector elements. This task will demonstrate the uniformity of plug-free dense-phase feed splitting at large scale with pulverized coal under operational feed system conditions. A follow-on effort is planned that would incorporate a dry pump feed system and demonstrate injector element life with long-duration testing.

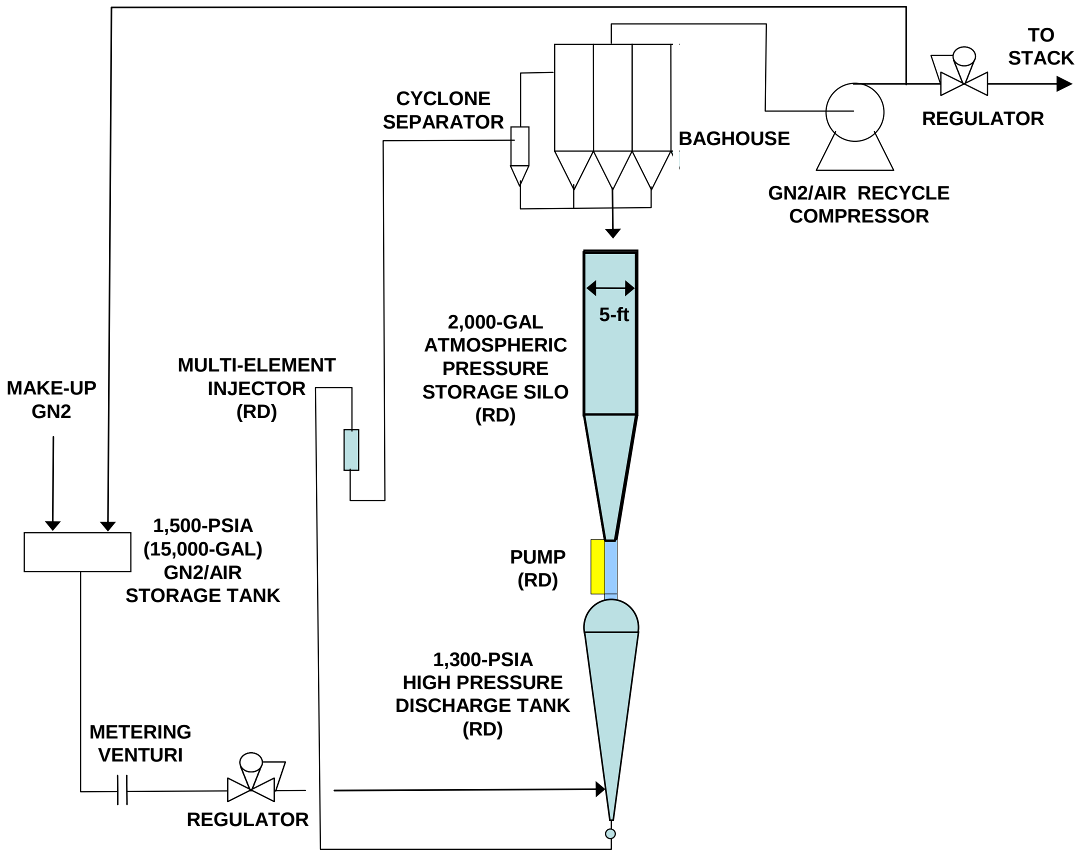

Figure 2. Commercial-scale, multi-element injector demonstration facility schematic.

<u>Task 3: Pilot Plant Definition and Planning</u>

This task defines a pilot plant demonstrating the integration of a dense-phase dry feed systemwith the advanced gasifier at a scale of 18 tpd, incorporating all key technologies for the commercial system. The pilot plant dense-phase feed system will include a STAMET Posimetric pump for continuous feed of pulverized coal from ambient pressure to >500 psia. STAMET pump performance at this discharge pressure was demonstrated earlier in 2005 as part of another NETL program. The integrated system will be installed at the Gas Technology Institute (GTI) Flex-Fuel Test Facility in Des Plaines, Illinois, shown in Figure 3. Existing state-of-the-art facilities at GTI will be used as-is or slightly modified for cost-effective demonstration of the advanced gasifier system. Pilot plant definition and planning will be completed in September 2005. Planned start date for the pilot plant gasifier detailed design, fab and test program is April 2006. The goal of the pilot plant test program is to demonstrate integrated operation of the advanced gasification systems, experimentally verify gasifier performance parameters, obtain experimental data anchoring injector and CMC liner design life predictions, and demonstrate operations with bituminous and sub-bituminous coal. Findings from this program will be used to validate projected commercial benefits of the gasifier technology, and to refine commercial-scale gasifier designs.

Figure 3. GTI's Flex-Fuel facility will be the site for the advanced gasifier pilot plant.

Rocketdyne Gasifier Technology

The advanced gasifier design integrates proven Rocketdyne technologies in the areas of rocket engines and gasification to achieve high performance and long life.

Previous gasification experience at Rocketdyne includes demonstration of compact gasifiers with actively-cooled rapid mix injectors, short residence times, high pressure (up to 1,500 psia) operation, high flame temperatures (up to 5,000ºF), and the use of cooled refractory liners. Rocketdyne has also demonstrated dense-phase dry feed systems as well as slurry-feed systems. Rocket engine technologies incorporated into the advanced gasifier include CMC liner and advanced injector technologies that promote long component life under the expected operating conditions.

Design features of the advanced gasifier, and the advantages relative to existing gasifier technology, are:

- Compact plug flow gasifier: 90% gasifier volume reduction enables factory fabrication (vs. field fabrication), low capital cost, and short Mean Time To Repair (MTTR).
- Rapid-mix injector with dense-phase dry feed system: Eliminates gasification kinetic suppression and Cold Gas Efficiency (CGE) penalty associated with water-slurry feed systems, enabling rapid and complete (~99%) conversion

with high (82-85%) cold gas efficiency (depending on rank of coal) and reduced GOX/coal ratio (~20% less than slurry-fed single stage gasifier).

- Long-life components (cooled refractory liner and injector): Long life (Mean Time Between Failure, or MTBF) coupled with short MTTR enables 99% gasifier availability without redundant units.
- Fuel flexibility: The dry feed system and cooled chamber wall with solid slag barrier layer allows gasification of all ranks of coal, and other carbonaceous solids. Adaptable for biomass, resid, other fuels.
- Product flexibility: High pressure operation enables cost competitive production of hydrogen, synfuels, and chemicals as well as electricity.

These design features are illustrated in Figure 4. The plug flow configuration minimizes recirculation, which tends to slow down gasification kinetics by reducing the temperature in the reaction zone. This minimizes the amount of oxygen required per unit of fuel to sustain the desired gasifier operating temperature. Rapid mixing of the oxygen and fuel using techniques derived from rocket engine technology (which places a premium on rapid conversion in very short residence times) minimizes mass transfer limitations to gasification reactions. Use of the dry feed system eliminates the combustion lag time due to evaporation of water associated with the fuel, and enables higher temperatures near the fuel particles, significantly enhancing overall gasification kinetics. The combined influence of this design approach reduces the residence time required for fuel conversion by 90% relative to conventional gasifiers, thus enabling a low cost, compact gasifier design.

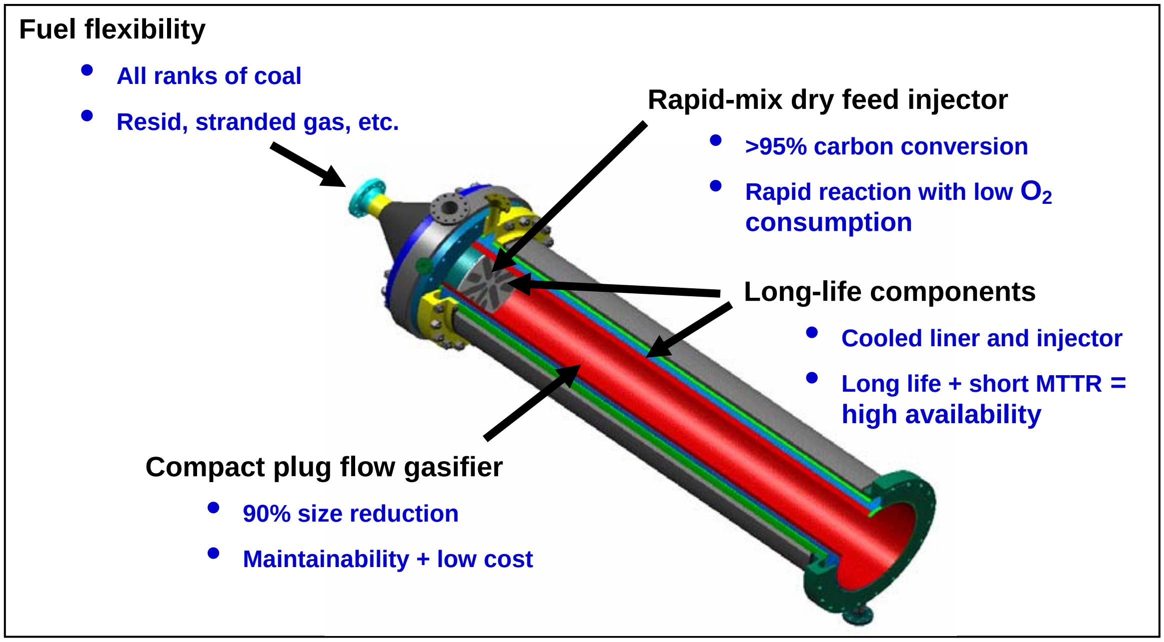

Figure 4. Key design features of the Rocketdyne advanced gasifier.

Use of a dry feed system also greatly reduces the cold gas efficiency penalty associated with evaporating and heating large quantities of water while maintaining slagging temperatures. Dry feed systems enable ~20% lower oxygen to fuel ratios at a given gasifier temperature, resulting in a larger fraction of the fuel heating value being converted into syngas (i.e, higher CGE). This also reduces gasification plant capital costs for a given syngas production rate by decreasing equipment capcity requirements for coal preparation, air separation unit (ASU), syngas cleaning, and sulfur recovery.

In summary, the advanced gasifier design approach results in a compact, low-cost, long life, highly efficient gasifier with substantial payoffs in improved plant efficiency, higher overall availability, and reduced capital costs.

Commercial Benefits

As an initial assessment of Rocketdyne advanced gasifier benefits to the commercial market, the advanced gasifier was assessed relative to a single-stage quench gasifier based on detailed stream data and overall plant economics modeling described in NETL report PED-IGCC-98-001, issued in June 2000. Modifications were made to integrate the Rocketdyne gasifier into a similar flowsheet, and to scale equipment based on relative loading. Plant modeling assumptions not related to the gasifiers (i.e., turbine efficiencies, Heat Recovery Steam Generator (HRSG) parameters, etc.) were kept consistent in these comparisons. This assessment was performed internally at Rocketdyne. An independent assessment by NETL is in progress.

Comparative data for the Integrated Gasification Combined Cycle (IGCC) case are shown in Table 2, for an Illinois #6 coal at $1.5/MMBTU fuel cost. Further details for process equipment capital cost impacts are provided in Table 3. Capital cost reductions are realized for the ASU and sulfur recovery unit (SRU), in addition to the gasifier, resulting in an estimated overall capital cost reduction of 14.5%. Higher cold gas efficiency, coupled with a reduction in ASU compression demand, provides an estimated gain of 3.3% points overall plant efficiency. A substantial improvement in availability is anticipated based on life and MTTR assessments for the advanced gasifier versus typical availability in recent IGCC demonstrations. In total, these benefits are estimated to reduce the cost of electricity by 18.5%.

Table 2. Comparison of Rocketdyne Advanced Gasifier with an Existing Single Stage Quench Gasifier for Single Train IGCC Application

Application	Existing Gasifier	Rocketdyne Gasifier	Improvement
Plant Capital Cost ($/kWe)	1517	1297	14.5%
Cost of Electricity ($/MWh)	49.3	40.2	18.5%
Plant Efficiency (HHV, %)	39.8%	43.1%	3.3 pts
Plant Availability (%)	85%	94%	9 pts

Table 3. IGCC Process Equipment Capital Cost Reductions Due to Rocketdyne Advanced Gasifier

Equipment Item	% Change ($/kWe)	Changes vs. IGCC with Single Stage, Slurry Fed Quench Gasifier
Air Sep'n Unit	-13.9%	• 22% decrease on GOX demand
Coal Prep + Gasifier	-44.5%	• 10% reduction in coal feed • Dry pulverization system • 90% reduction in gasifier volume • Dry slag/flyash removal
Syngas Cooling + Sulfur Recovery	-4.7%	• 50% reduction in volumetric syngas flow rate • 10% reduction in sulfur • Eliminated syngas saturator
Gas Turbine + HRSG + Steam Turbines	+0.1%	• 7% reduction in steam turbine power output
Balance of Plant	-14.5%	• Factored from major equipment
TOTAL	**-14.5%**	• **Cumulative Plant Capital Cost Reduction**

Figure 5 presents a comparison of Rocketdyne dry feed gasifier cold gas efficiency and IGCC Total Capital Requirement (TCR) with results from a series of studies performed by NETL in June 2000 (PED-IGCC-98-001 for GE/Texaco; PED-IGCC-98-002 for Shell, and PED-IGCC-98-003 for ConocoPhillips/Destec). The NETL results illustrate the trade-off between performance and capital cost for existing commercial gasifiers. Through the combination of the dry feed system, rapid mixing, and cooled components, the Rocketdyne gasifier offers high performance and reduced plant capital cost.

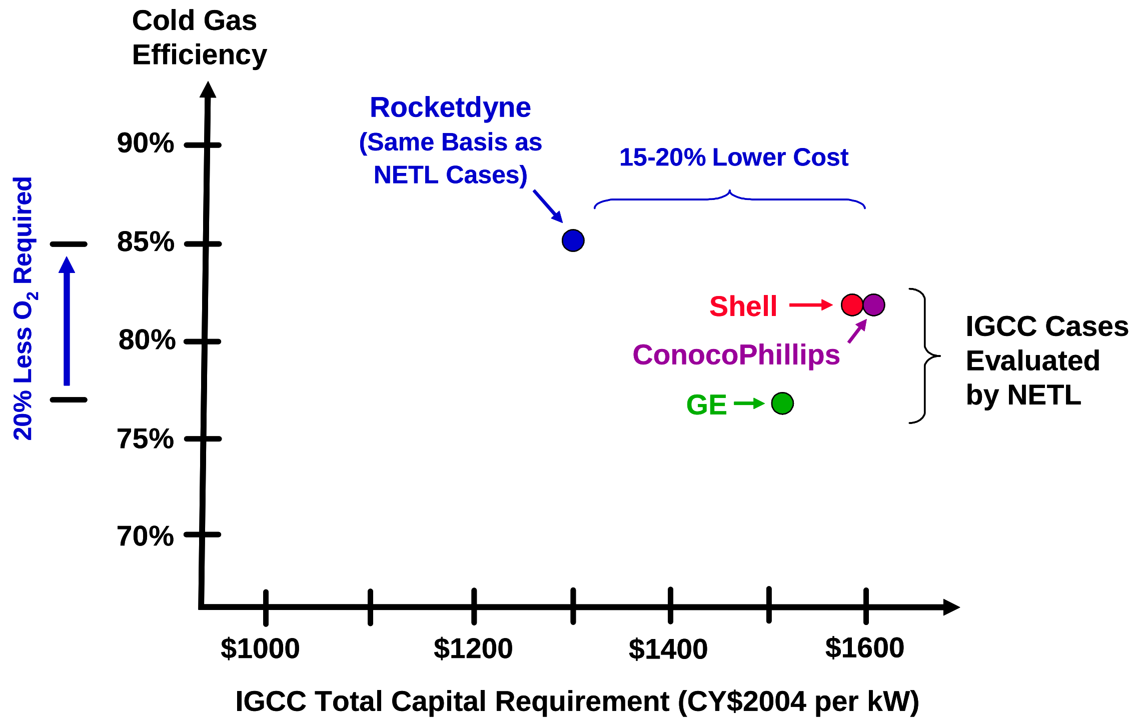

Figure 5. Comparison of CGE and IGCC Total Capital Requirement for the Rocketdyne gasifier and existing commercial gasifiers.

Comparative data for hydrogen production are shown in Figure 6, again for an Illinois #6 coal with variable fuel cost. Capital cost reduction, efficiency and availability improvements similar to the IGCC case are expected, resulting in a reduction of H_2 product cost of $0.5/MSCF relative to an existing single stage quench gasifier. Figure 6 also shows typical H_2 product costs via Steam Methane Reformer (SMR) with natural gas at $3, $4 and $5 per MMBTU. This figure shows that, for a given fuel cost, a hydrogen plant based on the Rocketdyne gasifier will be competitive relative to an SMR at natural gas prices $1/MMBTU less than the point at which an existing slurry-fed, single-stage gasifier is. For example, at a fuel cost of $0.25/MMBTU (such as petcoke), the Rocketdyne gasifier is competitive at natural gas prices slightly less than $3/MMBTU, while the existing gasifier will require natural gas greater than $4/MMBTU to be competitive.

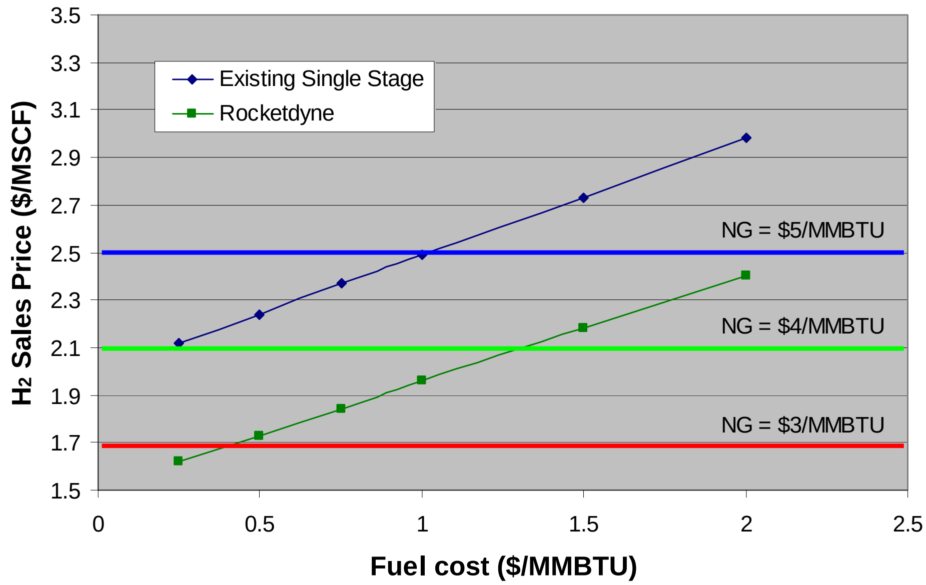

Figure 6. Rocketdyne advanced gasifier is projected to offer $0.5/MSCF benefit relative to an existing slurry-fed single-stage quench gasifier for hydrogen production.

Development Roadmap

The overall development roadmap for Rocketdyne advanced gasifier technologies is illustrated in Figure 7. Near term development activities consist of the joint DOE-Rocketdyne AGSD program, with the follow-on pilot plant program anticipated start date of April 2006, and initial pilot plant testing at GTI in the 2nd half of 2007. The pilot plant will demonstrate integrated operation of dry feed and gasifier hardware incorporating all of the key design characteristics upon which predicted advanced gasifier advantages are based. This will provide near term validation of Rocketdyne gasifier technology commercial benefits, as well as additional design data to reduce the risk of proceeding with commercial scale demonstration plants. Current plans are to begin definition of potential commercial demonstration plants in 2006, commence fabrication and construction in 2008-2009, and begin operations in 2010.

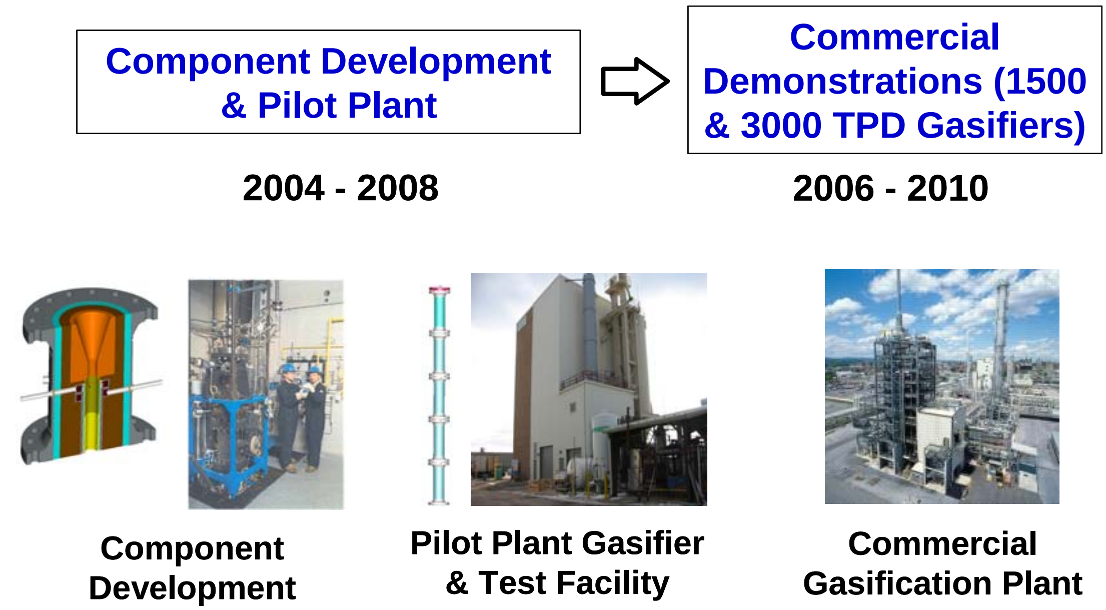

Figure 7. Advanced gasifier technology development roadmap will culminate in commercial-scale demonstration in 2010.

Summary

DOE and Rocketdyne are cooperatively developing advanced dry-feed gasification technologies that significantly reduce capital cost and increase efficiency, while enhancing overall plant availability. The result of this cooperative effort will be a long-life, high performance gasifier that incorporates proven technologies in the areas of rapid mixing and thermal management. The pilot plant team, including GTI and STAMET, is in place and defining an affordable program that will demonstrate the integrated dry-feed gasification system in 2007. This will enable commercial scale gasifier preliminary and detailed design to begin in 2007, fabrication and construction in 2008-2009 and initial demonstration of commercial scale operations in 2010.

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