ABSTRACT

This project covered (1) installation and commissioning of improvements for the Aerojet Rocketdyne (AR; formerly Pratt & Whitney Rocketdyne, PWR) compact gasifier, (2) commissioning of the Gas Technology Institute (GTI) pilot plant facility, (3) testing of this system on Illinois coal, and (4) data workup / post-testing analysis of the AR system at GTI. The objective of the AR system improvements was to address issues associated with (a) thermal management of the gasifier outlet and (b) chloride attack of gasifier components, which had been observed during testing on Illinois coal in the initial test AR program. AR funded the modifications to the gasifier equipment. AR also provided assistance to GTI during preparation and testing at the Advanced Gasification Test Facility (AGTF) and performed post-testing data and equipment analysis.

Preparations for this project, installation of the improved AR gasifier equipment, and system re-commissioning were accomplished in the second and third quarters of 2013. This included the purchase, pulverization / drying, and shipment of the Illinois No. 6 coal to the AGTF facilities, and installation of sorbent downstream of the gasifier (to meet IEPA permit requirements AGTF sulfur-emissions). Hot testing of the AR testing was then performed in September, 2013. A total of about fifty tons of Illinois No. 6 coal was gasified during sixty-six hours of gasification testing over a four-day period. The three planned data-analysis periods (DAPs, or steady-state testing period) were completed, with detailed analyses of the feed/product samples performed subsequent to the gasification testing. Rocketdyne completed work-up of the experimental results, as well as inspections on the gasifier equipment.

The Appendices to this report contain proprietary information, which is not meant for public distribution.
EXECUTIVE SUMMARY

There has been a name change for GTI’s partner in the development of advanced gasification/compact gasifier technology. The Rockedyne division of Pratt & Whitney (a division of United Technologies) was acquired by GenCorp, which merged Rocketdyne (in mid-June, 2013) with Aerojet to form Aerojet Rocketdyne. Therefore, the advanced gasifier system partners will now be referred to as Aerojet Rocketdyne (AR) instead of PWR.

AR is developing advanced gasification technology to reduce the cost of converting Illinois coal into power, chemicals, and fuels by approximately 25% relative to existing gasification technologies. The objective of this project was to perform follow-on testing of modifications to the pilot plant AR gasifier on Illinois coal to validate suitability of a redesigned gasifier outlet for reliable slag discharge and use of chloride-resistant materials. In combination with testing of the scaled-up AR gasification system in a China-based demonstration plant, the AR gasification technology will be ready for commercial use with Illinois coal.

The existing AR pilot plant gasifier at the Advanced Gasification Test Facility (AGTF) at the Gas Technology Institute (GTI) in Des Plaines, Illinois, has been modified to address thermal management and slag discharge issues identified in initial testing on Illinois coal. Another issue specific to Illinois coal was chloride attack on certain gasifier components. A modified injector design incorporating chloride-resistant materials (demonstrated in testing with simulated Illinois No.6 coal syngas) was fabricated. The testing on Illinois No.6 coal at the AGTF was expected (1) to demonstrate suitability of the modified liner outlet design for slag and operating conditions experienced with Illinois coal and (2) to demonstrate resistance to chloride attack of gasifier components for service with high chloride feedstocks such as Illinois coal. This testing, performed in existing facilities at GTI, made use of more than $25M that PWR / AR has invested in facilities to date to obtain hot-fire test results in a high-fidelity gasification environment.

The AR compact gasifier technology implements proprietary dense phase solid-fuel-feeding technology, rapid mix multi-element burners, and an Advanced Gasifier liner cooling approach to reduce gasifier reactor volume by 90%, increase gasifier efficiency due to reduced liner heat losses, and lower capital cost. The rapid-mix burner and advanced cooling approach are based on AR design experience derived from high performance, severe environment rocket engine applications. The technical and economic benefits of the AR technology were validated in extensive pilot plant testing on Illinois coal during 2010 and 2011.

Long-term benefits of the AR gasification technology extend to the coal mining, synfuels, and electric power industries. The AR gasifier is expected to change the economics of coal gasification. As Illinois and other coal-rich states have witnessed in recent years, coal gasification using existing gasification technologies has proven to be economically unsound, and thus often require state or ratepayer subsidies in order to proceed. The AR gasifier is different in that it will reduce the capital cost of gasification by 25 percent,
essentially changing the economics of every future project deploying this technology and leveling the playing field between gasification and conventional coal combustion technologies. Furthermore, it is estimated that the AR technology will make Illinois coal competitive with $6/MMBTU natural gas for chemicals production, as compared to $7.5/MMBTU or higher for other gasification technologies. With the AR technology, coal gasification becomes an economically viable option at Illinois and other Midwest electric utilities, renewing the possibility for carbon capture from Midwest coal plants. In addition, rapidly growing demand for coal in China and India is creating opportunities for coal producers throughout the world, including those in Illinois. With the expansion of the Panama Canal, currently underway, the AR gasifier can open new markets for Illinois coal throughout the Pacific rim.

Preparations for this project, installation of the improved AR gasifier equipment, and system re-commissioning were accomplished in the second and third quarters of 2013. This included the purchase, pulverization / drying, and shipment of the Illinois No. 6 coal to the AGTF facilities, and installation of sorbent downstream of the gasifier (to meet IEPA permit requirements AGTF sulfur-emissions).

Hot testing of the AR gasifier was then performed in September, 2013. Short-Duration (SD) testing was completed during two days in the first week of September, 2013, which confirmed the ability to light off the gasifier with the system improvements and to maintain steady-state operations. The gasifier was cooled and a thorough internal inspection was conducted. The gasifier injector section was changed out, in preparation for Long-Duration testing. Process data and analytical inspections were communicated to Rocketdyne, whose personnel performed the data work-up / process analysis, which can be summarized as follows:

- Excellent material and energy balances were obtained
- Results were consistent with prior coal testing
- Facility readiness for testing on Illinois No.6 coal was confirmed

Long-Duration (LD) hot testing was then completed in the second week of September, 2013. A total of about fifty tons of Illinois No. 6 coal was gasified during sixty-six hours of gasification testing over a four-day period. The three planned data-analysis periods (DAPs, or steady-state testing period) were completed, with detailed analyses of the feed / product samples performed subsequent to the gasification testing. Rocketdyne completed work-up of the experimental results, as well as inspections on the gasifier equipment. The results from the analysis by Rocketdyne can be summarized, as follows:

- Excellent material/energy balances were obtained with tests on Illinois No. 6
- Carbon conversion values were comparable to prior testing
- Performance of the new injector design, which incorporated commercially traceable design features, was comparable to the original injector design.
Sections of the gasifier were removed/sent to Rocketdyne for detailed inspection; the results from the analysis are the following:

-- Coated materials used in the gasifier testing experienced excessive corrosion, leading to the conclusion that this material was unsuitable for commercial application.

-- The new material used in the liner outlet, and at the ends of the original liner material, showed no apparent corrosion at the conclusion of testing.

-- Inspection of the original liner material, comprised of a superalloy offering high strength at temperature and good corrosion resistance, had shown excessive degradation in specific locations.

-- The corrosion of the original liner was most likely due to chloride attack, which is a challenge of specific importance to high chloride feedstocks such as Illinois coals.

The new material has been incorporated into new pilot plant gasifier injector and liner designs, and will be incorporated into the demonstration plant gasifier design to establish suitability of gasifier design for use with Illinois coals. Thermal data from the testing confirmed that the new material was suitable for use in gasifier environments.
OBJECTIVES

Specific Project Objectives: The principal objectives of the proposed research were as follows:

- Demonstrate efficacy of modified gasifier outlet in the thermal isolation of the liner outlet and the elimination of misdirected hot syngas flow at the gasifier outlet.
- Demonstrate suitability of chloride-resistant materials incorporated into a modified injector design (which also reflects a commercially traceable injector design) and the modified gasifier outlet.

Successful attainment of these objectives will validate the suitability of the AR gasifier design approach for long term use with high chloride feedstocks such as Illinois coal, and will mature these technologies to readiness for incorporation into the demonstration plant gasifier design.

Statement of Work: The project work was divided into four tasks:

Task 1 – Procurement and Planning Assistance: GTI shall assist AR in the re-activation of the AR Gasifier at the GTI AGTF for testing of coal fuels. These reactivation activities shall include the following:

(a) Stand-by/maintenance activities for key equipment in the AR facilities:
   a. Lubrication and periodic rotating of pumps, such as P-301 (CWS)
   b. “Dry-run” operation of the pulverized fuel pneumatic conveying system
   c. Purging of open vessels to minimize condensation from ambient air

(b) GTI will procure Illinois No.6 coal and have it transported to the CONSOL R&D facilities. AR shall enter a contract directly with CONSOL for the pulverization and drying of coal, and GTI will arrange for transportation to Des Plaines. GTI shall provide the following:
   a. Identify one or more suitable suppliers for the Illinois No.6 coal
   b. Provide bulk bags to CONSOL for packaging of the pulverized coal
   c. Arrange for storage of the bags of pulverized coal to the Chicago area
   d. Perform “full” (proximate, ultimate, HHV, MMOx) inspections on one or two samples of new pulverized coals

(c) GTI assistance to AR in the procurement of other consumables, such as ZnO sorbent for capture of hydrogen sulfide from gasification of pulverized solid fuels
Task 2 – Re-Activation: Advanced-Gasification Test Facility / AR Gasifier

(a) GTI development assistance for reactivation plans for Balance of Plant (BOP) equipment to include the following:

a. Process engineering will be provided by GTI for documentation updating and modifications to the PWR gasifier auxiliary systems, such as
   i. Coal feed un-bagging/transport system
   ii. Dense-phase feeding system for pulverized coal
   iii. Slag hoppering system

b. The process engineering will include the following:
   i. Update P&ID drawings, Instrument Index, etc
      1. Red-lined P&IDs to As-Modified status
      2. Add instrumentation adjustments for follow-on program
   ii. Update Operating Procedures
      1. Corrected to As-Tested status
      2. Implement modifications for any AR system upgrades
   iii. Review PWR plans for changes in CWS/CWR to the injector
      1. Reduction in overall CW flow to injector (and eventual reduction in CW circuits for third style of injector)
      2. Reduced CW flow rates through circuits in the gasifier-injector section/check suitability of current CW flow meters
   iv. Provide full set of updated P&ID drawings and Operating Procedures to AR. Assist PWR in developing Re-Commissioning Plan for gasifier and auxiliary systems
   v. Update spare-parts lists/inventories for fittings, small valves, etc
   vi. Verify operability of the control system (DCS) sequences and other parts of the control system, in the coal-gasification mode
   vii. Provide assistance in other areas, as requested by AR

c. Purchase ignition materials (TEB) for hot-fire testing

d. Develop scope of work and cost estimates to address modifications to the injector

e. Implement improvements to the slag-system
   i. Investigate/fabricate improved cleaning tools
   ii. Improved operation of everlasting lens valves

f. Determine sampling and analytical adjustments required for follow-on coal gasification testing, based on the assumption the sampling/analytical requirements will be similar to those in 2010-2011 long duration (LD) testing efforts
   i. Develop labeling scheme for improved identification of pulverized fuel supplies from CONSOL and/or other sources
ii. Improve sample labeling for products at AGTF; consider methods for pre-printed sample labels for cans

iii. Replace solids-sampling “thief”; investigate improved equipment for sampling high-moisture slag and fuel feed

iv. Procure improved display/recording system for infra-red camera system for vessel/piping inspections

v. Calibrate Rosemont process analyzer and micro-GC for syngas from coal gasification operations

Task 3 – Commissioning of AR Facilities and Short-Duration Testing

(a) Final Preparations for Hot Fire Testing
   a. Conduct Facilities Readiness Review (FRR)
      i. Document implementation of HAZOP recommendations
      ii. Enumerate/identify equipment changes
      iii. Present commissioning plan

   b. Conduct commissioning on AR sections:
      i. Dense-phase feed system (DPhFd) for pulverized fuels
         1. Check/verify calibration of load cells: day bin, feed hopper, slag, and cyclone / filter drum scales
         2. Load one to three bags of pulverized coal from un-bagging station to low-pressure feed bin through Cyclonaire system
         3. Verify operation of pressurization sequence to feed hopper
         4. Calibrate fuel density meter for test feed stock
         5. Complete several batch tests of DPhFd system, to verify operability and to train new operations staff
         6. Reconfigure pulverized feeding from testing to gasification mode

      ii. Syngas sulfur removal
         1. Load ZnO sulfur sorbent into sorbent vessel(s) R-2002 and R-2003 to accommodate gasification tests with Illinois No.6 coal

      iii. Gasifier section
         1. DeltaV control system – Re-install/test EOR (May-2011) configuration
         2. Check alarm set points, hopper sequences, auxiliary system communications, etc.

      iv. Set-up one jumbo nitrogen tube trailer

     v. Rental compressor -- Procure/Install for commissioning tests

   c. Operating Procedures -- update
      i. Complete job safety analyses (JSA), as required
      ii. Implement improved labeling/storage system for pulverized fuel
      iii. Upgrade Log / Record sheets for slag/cyclone/Filter

   d. Finalize engineering documentation – PFD, P&IDs and other drawings
e. Carry out dry run / pressure testing of PWR complete system

f. Conduct Test Readiness Review (TRR)
   i. Completion of HAZOP recommendations
   ii. Commissioning results
   iii. Completion of other actions items
   iv. Review of AR test plan

(b) Short duration testing with Illinois No.6 Coal
a. GTI shall conduct initial hot fire testing, with the following objectives:
   i. Verifying overall facility functionality (sequences, data acquisition, sample acquisition, equipment operations),
   ii. Confirming process measurements, and
   iii. Familiarizing operations personnel with facility operations

b. Initial hot fire testing can be performed with the pulverized feedstock which is chosen to be most suitable, which may be the low sulfur feedstock (to minimize ZnO bed heat-up requirements)
   i. A total of 16 hours hot fire testing over a two week period. Eight coal/slag samples will be submitted for proximate, ultimate and HHV analysis
   ii. It is assumed that a two week downtime after this test is to be taken to complete any required maintenance and equipment adjustments before LD testing

Task 4 – Long-Duration Testing with Illinois No.6 Coal

(a). Preparation of gasifier facilities for long-duration tests with coal fuel
   a. Inspect gasification systems, as required after short-duration
   b. Remove injector utilized for commissioning and short-duration testing
   c. Install improved injector, and re-connect feed/auxiliary connections

(b). Long duration testing with Illinois No.6 Coal:
   a. GTI shall perform facility preparation activities, including equipment warm-up prior to hot firing for the initiation of long duration testing
   b. GTI will then perform greater than 50 hours of clock time testing on Illinois No.6 coal, in the format of “around the clock” operations.
   c. It is assumed 3 mass balance periods, 15 solids samples for proximate/ultimate/HHV analysis, and 4 samples for MMOX.

(c). Consolidation of samples and recovered solids (slag, cyclone, and filter)
   a. Provide materials to AR, as requested
   b. Provide disposal for excess feed and other materials from testing
(d). Completion of post-test clean-up activities at the conclusion of the overall long-duration test run
   a. Disposal of test residues (slag barrels, spent ZnO)
   b. Collection and transfer of testing information to AR
   c. Securing of FFTF / AGTF equipment, as required
INTRODUCTION AND BACKGROUND

The AR Compact Gasification System, as depicted in the following figure, is comprised of AR’s proprietary technologies in the Dry Solids Pump and the Compact Gasifier. Multiple independent reviews have confirmed the technical feasibility and expected economic and environmental benefits of these technologies.

![Schematic of Rocketdyne Advanced Gasification Process](image)

Feasibility of the AR gasifier technology was demonstrated in the initial phase of the pilot plant test program. The purpose of the pilot plant gasifier, shown in the pictures below, was to obtain gasifier test data (performance, environments, materials, operational, solids products) to establish the technical basis for a demonstration scale (400 to 800 TPD) gasification plant. Groundbreaking for the GTI facility and initiation of AR gasifier design was in July 2007, with completion of the test program in April 2011. A total of 764 hours of hot fire test time was accumulated on the gasifier, generating 53 unique detailed mass balance points with four feedstocks – primarily on Illinois No.6 coal, with limited testing on Alberta sub-bituminous coal, Alberta oil sands petroleum coke, and Joliet refinery petroleum coke.
Excellent mass balance was observed during testing, typically ranging between 95%-100% on an overall basis, as depicted in the following figure, which is a representative plot of overall mass balance over the duration of a pilot plant test.

Total project cost was approximately $37M, with $25M of that invested at GTI. The majority of the funds were from the joint development team (led by AR), with significant cost share from the Alberta Energy Research Institute (AERI, now known as Alberta Innovates: Energy and Environmental Solutions) and a grant from the Illinois DCEO.

All of the objectives for the test program were achieved, with satisfactory performance, environments and operational characteristics demonstrated on each of the tested feedstocks. Key overall findings from the test program were the following:

1. Gasifier performance was consistent with predictions and supports expectations of >99% carbon conversion in a ~0.5 sec residence time commercial scale gasifier
for all pilot plant feedstocks.

2. Peak heat fluxes were within the design basis and liner heat fluxes were consistent with predictions. Heat fluxes dictate design requirements for gasifier components.

3. Overall heat losses to the liner and injector were measured and were significantly lower than initial values used as the design basis. Heat losses partially determine oxygen input required to maintain target gasifier exit temperatures. Commercial scale predictions based on pilot plant data indicate a 3-4% cold gas efficiency gain relative to other entrained flow dry feed gasifiers, and ~9% gain relative to slurry-fed entrained flow gasifiers. Excellent agreement between measured outputs and inputs were achieved.

4. Based on thermal analysis and measured localized heat fluxes at gasifier components, PWR’s cooling approach is expected to keep injector and liner surface temperatures < 1000°F. At these temperatures, corrosion rates are acceptably slow. Combined with the observed deposition of protective slag coatings throughout the gasifier internal surfaces, this is supportive of gasifier component life targets and overall gasifier availability goals.

5. Slag from the gasifier is produced both as coarse and fine slag, with all of the slag demonstrated to be non-leachable.

6. Two issues were identified to be addressed in follow-on pilot plant testing.

Evidence of chloride attack was observed on some gasifier components. Chloride-resistant alternate materials have been identified for use in follow-on testing. Another finding was that misdirected flow of hot synthesis gas could cause adverse thermal environments to the pressure vessel of the gasifier. Minor gasifier modifications, along with analysis of test results, indicated that misdirected flow could be addressed by thermally isolating the gasifier outlet and by blocking off alternate flow paths. It was determined that both of these issues should be addressed at the pilot plant level to establish suitability of the PWR technology for use on Illinois basin coal.

The chloride attack issue was addressed by testing several candidate test coupons in a simulated Illinois coal syngas environment at gasifier process conditions. This was performed in the high temperature corrosion test apparatus at Oak Ridge National Laboratory (ORNL), shown in the following pictures.
Materials with excellent corrosion resistance were identified at ORNL and also in pilot plant gasifier testing. These materials were chosen to be incorporated into the modified gasifier liner (as shown below) outlet and new injector design in this study.
EXPERIMENTAL PROCEDURES

The testing of the AR pilot plant gasifier was done at the GTI Advanced Gasification Test Facility (AGTF), located in Des Plaines, Illinois, as shown in the following picture:

![Advanced-Gasification Test Facility (AGTF) at GTI, Des Plaines, Illinois](image)

All necessary infrastructure was in place for the proposed testing, which leveraged over $25M of investments to date that AR has made in the facility, along with existing GTI infrastructure investment. The effort was comprised of modifications to the gasifier and facility at GTI, fabrication of a new injector design with chloride-resistant materials, preparation of the facility for testing on Illinois coal, and a long duration test on Illinois coal to validate the efficacy of the planned modifications.

The initial phase of pilot plant testing, from December 2009 through April 2011, provided 764 hot fire test hours on four feedstocks, primarily Illinois No.6 coal, and provided 53 detailed mass balance periods for use in anchoring gasifier performance models. This testing validated the anticipated performance of the AR gasifier, confirmed operating environments were within design capability and consistent with predictions, established operating approaches, and identified issues with chloride attack and management of thermal environments at the gasifier outlet.

AR developed design approaches to manage the thermal environments at the outlet, fabricated and improved outlet configuration from materials resistant to chloride attack, and installed the liner at GTI in early 2012. AR completed design, and initiated fabrication of a new injector incorporating chloride-resistant materials identified in earlier
testing by AR at the ORNL. These improvements have been implemented specifically to enhance the technology for use with higher chloride feedstocks such as Illinois coal.

The FFTF at GTI has been described in other publications (such as Aderhold et al, 2011). The “blocks” from the FFTF which were utilized for this project are indicated in the following diagram:

![Block Flow Diagram](image)

Figure G: Block Flow Diagram for Rocketdyne Gasification of Illinois No. 6 Coal

When the coal-derived syngas was utilized for carbon-dioxide removal, the configuration was the following:

![Block Flow Diagram](image)

Figure H: Block Flow Diagram for Rocketdyne Gasification of Illinois No. 6 Coal With Carbon Dioxide Removal from Syngas
RESULTS AND DISCUSSION

Task 1 – Procurement and Planning Assistance (to AR)

For the gasification test fuel, seventy-five tons of Illinois No 6 coal, were procured from Peabody Gateway mine, near Coulterville, Illinois. This coal was transported to the R&D facilities of CONSOL Energy, near Pittsburgh, Pennsylvania, where the pulverization and drying were accomplished, to produce the test feedstock. GTI arranged for the purchase of bulk bags, which were delivered directly to Consol for bagging of the pulverized coal and delivery to Des Plaines, Illinois. Ninety-two bags were obtained and stored at Juno Logistics (Elk Grove Village, Illinois).

Task 2 – Reactivation: Advanced-Gasification Test Facility / AR Gasifier

Re-activation of the Rocketdyne advanced gasifier system was accomplished from a combination this ICCI-sponsored project and through an ARPA-E (DOE)-sponsored project, for testing the advanced system for partial oxidation of natural gas (as an initial step to producing liquid fuels from natural gas).

As a part of this project, engineering evaluations were first conducted for the process areas which needed to be re-activated for the coal-gasification experiments:

-- Feed un-bagging / transport system
-- Dense-phase fuel feeding system
-- Slag-hoppering system

The Piping & Instrumentation Drawings (P&ID’s), the equipment list, and the instrument index were updated, to reflect modifications required for new injector. A review was done of the prior advanced-gasifier HAZOP studies, and an implementation plan was developed for the open recommendations.

With assistance from AR, the new injector was installed on the top of the AR advanced gasifier vessel. In order to accomplish this, a scope of work had to be developed for installation of the process and utility (cooling-water) piping to the modified injector. A mechanical contractor was selected, and they completed the injector installation.

Likewise, the sampling and analytical instrumentation / equipment was inspected, and upgrading requirements were determined. The required supplies and materials for re-activation were procured and installed.

Task 3 – Commissioning of AR Facilities and short-duration Testing

A detailed advanced-gasifier commissioning plan was developed to cover both the ICCI-sponsored requirements and those which were conducted subsequently through other AR-related programs.
The initial commissioning activities included preparation and validation of the coal-feeding system for the Advanced Gasifier. Specifically, a “dry” test was carried out (without pulverized material) for the dense-phase feeding system, by stepping through the sequence for pressurization of coal feed and ultra-dense coal feeding to AR gasifier. Then, one bag of pulverized Illinois No. 6 coal was loaded into the un-bagging hopper and transported through the pneumatic conveying system (Cyclonaire) into the coal-fuel day bin, to clean out the system and to confirm operability. Upon completion of this cleaning, this pulverized coal was removed from the system. Another bag of pulverized coal was then loaded into the Day Bin and passed through the lock hopper into the coal / fuel feed hopper. Two cycles of dense-phase feeding out of fuel feed hopper, were then accomplished in the “recycle” mode.

Several other AGTF systems were prepared for gasification testing. Sulfur sorbent (ZnO, which is required for capture of hydrogen-sulfide from the syngas before routing to the flare during the testing of high-sulfur fuels) was installed in the two sulfur-sorbent drums. Inspections/operability checks were performed for the slag-hoppering system. Materials, supplies, and services for the testing phase were also procured, including the following:

- The TEB igniter was ordered and received
- Contacts were established with suppliers for bulk-nitrogen trailers, the rental air compressor, and other needs for the testing phase

As part of the separate DOE- / ARPA-E-sponsored AR project, the Rocketdyne gasifier in the advanced-gasification test facilities (AGTF) was utilized to conduct a series of experiments on the partial oxidation of natural gas; thus, many sections of the Rocketdyne system were re-commissioned under that program rather than under this ICCI-sponsored project. The remaining systems, which were required for coal-gasification testing in the AGTF, were then re-commissioned in the second half of August, 2013, such as the slag-hoppering (removal) system and the secondary syngas cyclone hoppering (removal) system.

A combined Facility Readiness Review (FRR) / Test Readiness Review (TRR) was then conducted at GTI on 28-August, with the following highlights:

- Both GTI and Rocketdyne personnel participated
- Updated process documentation was presented
- Implementation of the HAZOP-review recommendations was verified
- Operating procedures and start-up/shut-down sequences were reviewed
- Personal-protection equipment and safety systems were covered
- Testing plans were presented and discussed by Rocketdyne

Short-duration (SD) testing was performed on the AR advanced-gasifier system, during the first week of September, 2013, with Rocketdyne personnel on-site in Des Plaines. As planned, PRB coal was employed for SD testing, in order to conserve the Illinois No. 6 coal and the ZnO sorbent for the Long-Duration testing sequence. The primary objective for the SD testing was hot firing for short periods on Rocketdyne’s gasifier. Light-off
with the TEB/igniter system was confirmed in several brief tests. Then, a one-day (multi-shift) hot test was then completed on 4-September, 2013, after AGTF heat up was completed. One Data-Analysis Period (DAP) was accomplished during this continuous testing, as had been planned. This DAP was labeled as “TR-032”, and the specific timing was from 15:32 to 19:32 on 4-September-2013. Samples from the product-solid streams were collected and submitted to the GTI Lab to form the necessary composites and to perform analyses (ultimate, Proximate, HHV, MMOx inspections). The results from these post-testing analyses are included as Appendix 4. Plots of key process variables for several segments during the Short-Duration testing are included as Appendix 3.

The gasifier was cooled and a thorough internal inspection was conducted. The gasifier injector section was changed out, in preparation for Long-Duration testing. Process data and analytical inspections was communicated to Rocketdyne, whose personnel performed the data work-up / process analysis, which can be summarized as follows:

-- Excellent material and energy balances were obtained
-- Results were consistent with prior coal testing
-- Facility readiness for testing on Illinois No.6 coal was confirmed

Task 4 – Long-Duration Testing with Illinois No.6 Coal

The planned Long- Duration (LD) test series with Illinois No. 6 coal was then conducted, with Rocketdyne personnel also on site during the LD series. More than sixty-five hours of hot, gasification testing was completed with the Illinois No. 6 coal by mid-day on 14-September, 2013 which greatly exceeded the planned (minimum) fifty-plus hours of hot testing.

The initial light-off for the LD test occurred late on 10-September, 2013. During preliminary procedures, some problems occurred with auxiliary equipment and an unexpected problem was discovered with the Advance Gasifier (AG) unit’s coal injector tube. A repair was made and the AG unit light-off was achieved at 11:00 pm on 10-September, 2013.

The first period of hot-test operation was then a continuous twenty-hour span, during which two steady state Data-Analysis Periods (DAP’s) were conducted. Coal feed to the gasifier was established and maintained steady at a rate of approximately 1,500 pounds per hour. Gasifier pressure was controlled at 385 psig, and gasifier syngas outlet temperature was quenched and controlled at about 600-650 °F. Continuous operation stopped at 19:15 on 11-September, 2013, due to a safety trip which monitors several temperatures throughout the AG unit.

Overview trends of some key process parameters and other information, such Data Analysis Periods (DAP’s), are given in the Figure 1 below:
The following notes clarify the data displayed on Figure 1:

- This plot covers a forty-eight hour period, from noon on 10-September through noon on 12-September, 2013.
- Each point is a one-hour average value, from the listed starting time.
- The blue diamonds (PI-3103) represent the gasifier pressure, which is typically 385 psig during gasification operations.
- There are several variables presented, which are related to fuel /coal feed rate:
  - Instruments at the outlet of the feed hopper provide on-line indication of solid-fuel velocity (blue X’s) and density (green triangles), which are combined to provide an on-line solid-fuel feed rate (orange open squares).
  - The differential pressure between the feed hopper and the advanced gasifier (PDI-3170, blue solid squares) is also directly related to fuel feed rate.
- The oxygen feed rate to the advanced gasifier (FI-3327) is given by purple squares.
- The temperature of the syngas out of the gasifier is indicated by the quench outlet (TI-3763-A, purple filled triangles).
- Start/end times for data analysis periods are given by vertical dashed orange lines.
For the first two DAP periods, the following observations can be noted:

- for both DAP-201 and DAP-202, gasifier pressure was constant, as well as syngas outlet temperature and oxygen feed (which was increased for DAP-202)
- for DAP-201, all indicators of fuel feed rate were also very constant
- for DAP-202, the differential pressure (PDI-3170) indicated steady feed rate, as well as the solid velocity (SI-3152); the indicated solid-feed density (DI-3152) seems to have drifted, which caused a drift in FI-3152

Hot test operation resumed at 20:30 on 11-September, 2013 and another nine hours of hot-test operation was logged. The third DAP was accomplished. Gasifier pressure and outlet syngas temperature were controlled at the same set points as the first two DAP’s. Gasifier coal fuel feed rate was slightly reduced, at about 1,425 pounds per hour. This hot test segment was stopped early on 12-September, 2013 when the AG unit again experienced a shutdown from a flame detector safety trip.

Examination of the trips by Rocketdyne and GTI personnel concluded these were spurious events and confirmed the AG unit was ready to resume operation. (Past experience running the AG unit had seen these trips before; with most occurrences attributed to a spurious event due to fouling of the flame detector window and/or misalignment of flame detector optical path.) Efforts with commercial designs are looking at making this measurement more robust. Gasification was re-started, and, in the following Figure 2, the time scale has been extended through 14-September, 2013 to include the cumulative gasification operations on Illinois No. 6 coal.

![Figure 2 -- Gasification of Illinois No. 6 Coal on AR Gasifier -- 2013-Sept-10-14](image-url)
The next hot test operation was delayed somewhat due to a problem with the AG unit light-off system; a plug in a tube interconnection was found and fixed. Gasifier light-off proceeding again and hot testing was re-started at 1500 hours on the 12-September, 2013. During this operating period, a brief two hour interruption occurred as a result of a facility safety issue; this outage was between 7:30 to 9:30 pm on the 13-September, 2013. GTI operators cleared the issue and hot testing resumed and an additional twenty-nine and a half hours of continuous gasification hot operation was then logged. Gasifier pressure and gasifier outlet syngas temperature control set points were unchanged and gasifier coal feed rate was at 1,400 lb/hr.

After completion of the three DAP periods, which were planned for this ICCI-sponsored project, testing of carbon-dioxide removal from the coal-derived syngas was carried out on the Acid-Gas Removal (AGR) section of the GTI Flex-Fuel Test Facility (FFTF) for almost thirty hours. Specifically, the particulate free syngas from the AR gasifier was routed to the Direct Cooler to reduce the syngas temperature close to ambient (and remove the bulk of the water content). Then, the syngas was compressed to about 1000 Psig for absorption of carbon dioxide in the AGR section.

Hot testing was next stopped because a cooling water leak within the AG gasifier vessel was detected, when only a few hours of Illinois No. 6 coal fuel remained. The Injector section for the advanced gasifier was removed. Visual inspection determined that significant damaged had occurred, so that a replacement injector was installed. The few remaining bulk bags of the Illinois No. 6 coal was loaded into AG fuel feed lock hopper, and it was estimated that approximately three to four hours of further gasification operations with the Illinois fuel. The coal fuel for subsequent hot gasification testing (which was supported by separate funding from Rocketdyne) was then loaded into the AG fuel-feeding system, “on top of” the Illinois No. 6 coal. Thus, an “on-line” or “live” transition from Illinois coal to the second test coal fuel was planned.

The final hot-testing period with Illinois No. 6 coal thus started on 14-September, 2013 at about 14:00. This hot testing period logged thirty-seven hours of continuous gasification operation, with the first four hours consuming the Illinois No. 6 pulverized fuel. Upon consumption of the available inventory of pulverized coal, hot gasification testing on the Advance Gasifier was stopped voluntarily. In summary, there were five periods of continuous gasification: from five hours to thirty hours each. The cumulative hot-testing time on Illinois No. 6 coal was approximately 80 hours.

The planned three Data Analysis Periods (DAPs) were accomplished, with the specific timing, figures with process-variable trends, and material / energy balances presented below.
### DAP-201 Overall Mass Balance

<table>
<thead>
<tr>
<th>Stream Name</th>
<th>lb/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1341</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1175</td>
</tr>
<tr>
<td>Steam</td>
<td>150</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>406</td>
</tr>
<tr>
<td>Quench Water</td>
<td>2493</td>
</tr>
<tr>
<td><strong>Total Input</strong></td>
<td><strong>5565</strong></td>
</tr>
<tr>
<td>Syngas at G8</td>
<td>5345</td>
</tr>
<tr>
<td>Slag Solids</td>
<td>294</td>
</tr>
<tr>
<td>Cyclone Solids</td>
<td>79</td>
</tr>
<tr>
<td>Filter Solids</td>
<td>13</td>
</tr>
<tr>
<td><strong>Total Output</strong></td>
<td><strong>5731</strong></td>
</tr>
<tr>
<td><strong>% Error</strong></td>
<td><strong>103.0%</strong></td>
</tr>
</tbody>
</table>

### DAP 201 Overall Enthalpy Balance

<table>
<thead>
<tr>
<th>Stream Name</th>
<th>Enthalpy MMBTU/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Coal</td>
<td>17.08</td>
</tr>
<tr>
<td>Moisture in Coal</td>
<td>0.00</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.07</td>
</tr>
<tr>
<td>Steam</td>
<td>0.18</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.00</td>
</tr>
<tr>
<td>Quench Water</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>TOTAL INPUT</strong></td>
<td><strong>17.34</strong></td>
</tr>
<tr>
<td>Dry Syngas</td>
<td>11.63</td>
</tr>
<tr>
<td>Steam in Syngas</td>
<td>3.22</td>
</tr>
<tr>
<td>Solids</td>
<td>1.81</td>
</tr>
<tr>
<td>Moisture in Solids</td>
<td>0.05</td>
</tr>
<tr>
<td>Injector Heat Load</td>
<td>0.01</td>
</tr>
<tr>
<td>Liner Heat Load</td>
<td>1.06</td>
</tr>
<tr>
<td>Heat Loss to Surrounding</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>TOTAL OUTPUT</strong></td>
<td><strong>17.83</strong></td>
</tr>
<tr>
<td><strong>% Enthalpy Balance</strong></td>
<td><strong>102.9%</strong></td>
</tr>
</tbody>
</table>
DAP-202
Start: 12:30 – 11-Sept
End: 18:30 – 11-Sept

### DAP 202 Overall Mass Balance

<table>
<thead>
<tr>
<th>Stream Name</th>
<th>lb/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1327</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1275</td>
</tr>
<tr>
<td>Steam</td>
<td>150</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>406</td>
</tr>
<tr>
<td>Quench Water</td>
<td>2852</td>
</tr>
<tr>
<td><strong>Total Input</strong></td>
<td><strong>6010</strong></td>
</tr>
<tr>
<td>Syngas at G8</td>
<td>5916</td>
</tr>
<tr>
<td>Slag Solids</td>
<td>249</td>
</tr>
<tr>
<td>Cyclone Solids</td>
<td>55</td>
</tr>
<tr>
<td>Filter Solids</td>
<td>19</td>
</tr>
<tr>
<td><strong>Total Output</strong></td>
<td><strong>6239</strong></td>
</tr>
<tr>
<td><strong>% Mass Balance</strong></td>
<td><strong>103.8%</strong></td>
</tr>
</tbody>
</table>

### DAP 202 Overall Enthalpy Balance

<table>
<thead>
<tr>
<th>Stream Name</th>
<th>Enthalpy MMBTU/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Coal</td>
<td>16.90</td>
</tr>
<tr>
<td>Moisture in Coal</td>
<td>0.00</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.08</td>
</tr>
<tr>
<td>Steam</td>
<td>0.18</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.00</td>
</tr>
<tr>
<td>Quench Water</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>TOTAL INPUT</strong></td>
<td><strong>17.17</strong></td>
</tr>
<tr>
<td>Dry Syngas</td>
<td>11.07</td>
</tr>
<tr>
<td>Steam in Syngas</td>
<td>3.80</td>
</tr>
<tr>
<td>Solids</td>
<td>1.12</td>
</tr>
<tr>
<td>Moisture in Solids</td>
<td>0.05</td>
</tr>
<tr>
<td>Injector Heat Load</td>
<td>0.01</td>
</tr>
<tr>
<td>Liner Heat Load</td>
<td>1.26</td>
</tr>
<tr>
<td>Heat Loss to Surrounding</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>TOTAL OUTPUT</strong></td>
<td><strong>17.35</strong></td>
</tr>
<tr>
<td><strong>% Enthalpy Balance</strong></td>
<td><strong>101.1%</strong></td>
</tr>
</tbody>
</table>
DAP-203
Start: 00:00 – 12-Sept
End: 05:21 – 12-Sept

### DAP 203 Overall Mass Balance

<table>
<thead>
<tr>
<th>Stream Name</th>
<th>lb/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1354</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1175</td>
</tr>
<tr>
<td>Steam</td>
<td>150</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>406</td>
</tr>
<tr>
<td>Quench Water</td>
<td>2564</td>
</tr>
<tr>
<td><strong>Total Input</strong></td>
<td><strong>5648</strong></td>
</tr>
<tr>
<td>Syngas at G8</td>
<td>5073</td>
</tr>
<tr>
<td>Slag Solids</td>
<td>322</td>
</tr>
<tr>
<td>Cyclone Solids</td>
<td>62</td>
</tr>
<tr>
<td>Filter Solids</td>
<td>14</td>
</tr>
<tr>
<td><strong>Total Output</strong></td>
<td><strong>5471</strong></td>
</tr>
<tr>
<td>% Mass Balance</td>
<td><strong>96.9%</strong></td>
</tr>
</tbody>
</table>

### DAP 203 Overall Enthalpy Balance

<table>
<thead>
<tr>
<th>Stream Name</th>
<th>Enthalpy MMBTU/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Coal</td>
<td>17.24</td>
</tr>
<tr>
<td>Moisture in Coal</td>
<td>0.00</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.07</td>
</tr>
<tr>
<td>Steam</td>
<td>0.18</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.00</td>
</tr>
<tr>
<td>Quench Water</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>TOTAL INPUT</strong></td>
<td><strong>17.50</strong></td>
</tr>
<tr>
<td>Dry Syngas</td>
<td>10.54</td>
</tr>
<tr>
<td>Steam in Syngas</td>
<td>3.01</td>
</tr>
<tr>
<td>Solids</td>
<td>1.36</td>
</tr>
<tr>
<td>Moisture in Solids</td>
<td>0.06</td>
</tr>
<tr>
<td>Injector Heat Load</td>
<td>0.02</td>
</tr>
<tr>
<td>Liner Heat Load</td>
<td>1.06</td>
</tr>
<tr>
<td>Heat Loss to Surrounding</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>TOTAL OUTPUT</strong></td>
<td><strong>16.09</strong></td>
</tr>
<tr>
<td>% Enthalpy Balance</td>
<td><strong>91.9%</strong></td>
</tr>
</tbody>
</table>
Samples from the product-solid streams were collected and submitted to the GTI Lab to form the necessary composites and to perform analyses (Ultimate, Proximate, HHV, MMOx inspections). The results from these tests are included as Appendix 5.

Process data and analytical inspections were communicated to Rocketdyne, whose personnel performed the data work-up / process analysis. The results from the analysis by Rocketdyne can be summarized, as follows:

- Excellent material/energy balances were obtained on Illinois No.6 Coal tests
- Carbon conversion values were comparable to prior testing
- Performance of the new injector design, which incorporated commercially traceable design features, was comparable to the original injector design

As the Rocketdyne compact gasifier was dis-assembled and inspected, several samples were obtained of the accumulated solids. The GTI Analytical Laboratory performed the required inspections, and this information (which is included as Appendix 6) was communicated to Rocketdyne. The results from the analysis by Rocketdyne can be summarized, as follows:

- An accumulation of char and slag was observed within the quench vessel beneath the gasifier outlet at the conclusion of testing
- Major/minor oxides analysis of the inerts within the material confirmed that this was a direct product of the feedstocks tested

Sections of the gasifier were removed/sent to Rocketdyne for detailed inspection; the results from the analysis are the following:

- Coated materials used in the gasifier testing experienced excessive corrosion, leading to the conclusion that this material was unsuitable for commercial applications.
- The new material used in the liner outlet, and at the ends of the original liner material, showed no apparent corrosion at the conclusion of testing.
- The new outlet design prevented misdirected flow of hot syngas under all test conditions, and showed no signs of slag accumulation within the outlet.
- Inspection of the original liner material, comprised of a superalloy offering high strength at temperature and good corrosion resistance, had shown excessive degradation in specific locations.
- The corrosion of the original liner was most likely due to chloride attack, which is a challenge of specific importance to high chloride feedstocks, such as Illinois coal.

The new material will be incorporated into the demonstration plant gasifier design to establish suitability of gasifier design for use with Illinois coals. Thermal data from the testing confirmed that the new material was suitable for use in gasifier environments.
Safe disposal of excess materials (coal feed, gasifier product solids, and spent sulfur sorbent) was completed. The hot syngas filter and other down-stream equipment were opened for inspections and cleaning.

The GTI Flex-Fuel Test Facility (FFTF) was re-configured from the Rocketdyne advanced-gasifier mode to that required for fluid-bed gasifier mode. Routine AR maintenance was performed, as well as repair of those items which experienced problems during the testing phases: (a) an emergency dump valve on the AR cooling-water system was removed and repaired and (b) the relief valve for the oxygen feed system (which was also found to be leaking) was removed and repaired.
CONCLUSIONS AND RECOMMENDATIONS

The GTI and AR teams were able to complete the re-activation of the advanced gasifier (AG) at the AGTF section of the Flex-Fuel Testing Facilities (FFTF) in Des Plaines, Illinois. The new gasifier equipment, which was designed and fabricated by AR was installed.

Commissioning and Short-Duration (SD) hot testing demonstrated that these facilities were ready for testing with Illinois No. 6 coal, as the solid-fuel for operations.

The planned Long-Duration (LD) hot tests were completed, including three Data Analysis Periods (DAP’s). The data work-up / process analysis can be summarized, as follows:

- Excellent material/energy balances were obtained on Illinois No.6 Coal tests;
- Carbon conversion values were comparable to prior testing;
- Performance of the new injector design, which incorporated commercially traceable design features, was comparable to the original injector design.

Sections of the gasifier were removed and the results from the analysis are the following:

- Coated materials used in the gasifier testing experienced excessive corrosion, leading to the conclusion that this material was unsuitable for commercial application.
- The new material used in the liner outlet, and at the ends of the original liner material, showed no apparent corrosion at the conclusion of testing.
- Inspection of the original liner material, comprised of a superalloy offering high strength at temperature and good corrosion resistance, had shown excessive degradation in specific locations.
- The corrosion of the original liner was most likely due to chloride attack, which is a challenge of specific importance to high chloride feedstocks such as Illinois coals.
REFERENCES


DISCLAIMER STATEMENT

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