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Development of a Coal-Fired Gas Turbine Cogeneration System - Status Report

Authors:
Wilkes, C.
Wenglarz, R.A.
Hart, P.J.
Thomas, W.H.
Rothrock, J.W.
Harris, C.N.
Bourke, R.C.

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Allison Gas Turbine Division
General Motors Corporation
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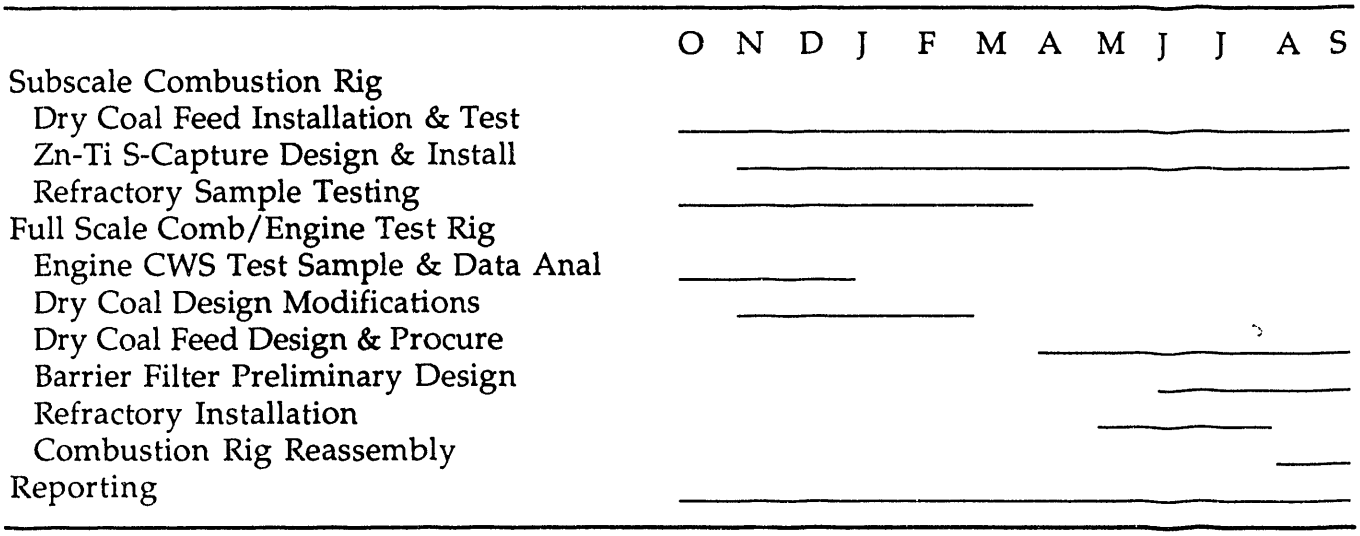
CONTRACT INFORMATION

Contract Number	DE-AC21-86MC23165
Contractor	Allison Gas Turbine Division General Motors Corporation P.O. Box 420 Indianapolis, Indiana 46206 (317) 230-2548
Contractor Project Manager	Colin Wilkes
Principal Investigators	Richard A. Wenglarz Peter J. Hart William H. Thomas John W. Rothrock Curtis N. Harris Richard C. Bourke
METC Project Manager	Leland E. Paulson
Period of Performance	July 1986 - October 1993

Schedule and Milestones

FY92 Program Schedule



OBJECTIVES

The primary objective of this program is the practical demonstration of the advanced coal-fueled technologies required for the future commercialization of direct coal-fueled turbines in cogeneration applications. The specific goals of Allison's Advanced Coal-Fueled Gas Turbine Program include the following objectives:

- assess the potential commercial applications/problems for coal-fueled gas turbines in cogeneration systems
- confirm the critical technology base for these direct coal-fueled gas turbines
- design and demonstrate full-scale proof-of-concept (POC) engine components
- demonstrate satisfactory operation of the POC coal-fueled engine system

BACKGROUND INFORMATION

This program is sponsored by the U.S. Department of Energy and addresses issues related to the future energy and environmental needs of the United States. These needs are being addressed in part by developing the technologies required to support the commercialization of a coal-fueled gas turbine system.

The Allison Advanced Coal-Fueled Turbine Program is now in the sixth year of a development effort that has led to a POC engine demonstration test on a Coal-Water-Slurry (CWS) fuel.

Earlier forecasts by CWS suppliers that suitable CWS fuels would be commercially available at an economic price have not been realized. A program replan has, therefore, been executed that incorporates the use of readily available dry pulverized coal. To support this program, technology issues relating to combustor performance and emission control, hot gas cleanup, and turbine deposition, erosion and corrosion (DEC) have been addressed. In addition, system assessment studies have been performed to evaluate the commercial prospects for small (<8 MWe) coal-fired industrial cogeneration systems and the application of the rich-quench-lean (RQL) coal-combustion technology to larger (> 100 MWe) utility-sized gas turbines. These results are reported by Wenglarz (1992). Combustor and engine tests on dry coal are now planned in preparation for a commercial demonstration that will follow the completion of this program.

PROJECT DESCRIPTION

This paper describes the program effort that has been directed towards the following technology development tasks:

- Engine Testing on CWS Fuel
- Dry Coal Feed System Conversion
- Refractory Materials Improvement

Coal Water Slurry Engine Testing

To demonstrate the feasibility of running a gas turbine on 100% coal, a production industrial Allison 501-K industrial engine was modified to accept an external coal combustion system. The engine center casing and production combustion hardware were replaced to allow for extraction of compressor discharge air and return of the hot combustion gases to the turbine section. Details of these modifications are discussed by Wilkes (1991).

Control of emissions is critical to the success of the program. To support this need, an RQL combustion system has been developed for use with CWS fuel that minimizes both the conversion of fuel nitrogen to NOx and the production of thermal NOx. Adaptation of the system to use dry coal fuel is now in progress.

Combustion tests reported in 1991 (Wilkes) were performed using Spring Creek (Montana) hot-water-dried subbituminous CWS produced by the University of North Dakota Energy and Environmental Research Center (UNDEERC). A similar fuel from the Wyoming Kemmerer seam was produced by UNDEERC for the POC engine test.

A comparison of the fuel properties is shown in Table 1.

Table 1. Bituminous and Sub-bituminous Coal-Water Slurry Properties

Fuel Type	S-Bit	S-Bit
Seam Name	Kemmerer	Spring Crk
Location	WY	MT
Supplier	UNDEERC	UNDEERC
Particle Size microns		
Median	15.8	15
Top	43.0	41
Ultimate Analysis (dry wt %)		
Carbon	72.31	71.38
Hydrogen	4.84	4.60
Nitrogen	1.45	1.20
Sulfur	0.44	0.41
Oxygen	18.16	18.01
Chlorine	0.08	0.01
Ash	2.72	4.39
MAFHHV Btu/lb	12800	12801

Engine tests on distillate No. 2 (DF#2) fuel were reported by Wilkes in 1991. Following these tests, a small quantity (less than 0.02% of the combustor refractory lining) of refractory material was found lodged against the first stage nozzle. To minimize the possibility of additional refractory material breaking loose during the engine test, the rig was blown-down with air for a period of several hours prior to the engine re-installation. A screen was placed at the combustor exit to catch any loose material for later inspection.

Following the completion of the rig blow-down, the engine was re-installed and prepared for CWS testing. Engine ignition, acceleration, and refractory warm-up were performed using distillate No. 2 fuel. The combustor was operated in the lean-quench-lean (LQL) mode with DF#2 injected into both the rich and lean combustor stages during this phase of the engine operation. After a warm-up period of approximately four hours, CWS was introduced into the rich zone while simultaneously reducing the DF#2 fuel flow rate in that zone to zero. Operation was maintained in this mode (LQL) for a period of one hour while instrumentation was checked and data were recorded. A change over to RQL mode was accomplished by reducing the lean zone DF#2 flow rate to zero and increasing the rich zone CWS flow. Following establishment of the RQL combustion mode, data were recorded for a period of three hours with the engine running on 100% CWS fuel.

Dry Coal Feed System Conversion

Both the subscale and full-scale test rigs are being converted to handle dry coal. To minimize delivery time, commercial systems were sought that were capable of delivering dry coal to a pressurized vessel operating at 165 psia. No manufacturer of coal conveying equipment was found that would guarantee the required mass flow stability of +/- 2% by weight measured over a period of a few seconds. Measurement of mass flow to this accuracy over short periods of time was also found to be difficult and subject to error.

Dry Coal Supply. After studying options that included grinding coal on-site, a decision was made to purchase coal from companies that offer custom grinding services. The subscale rig burns coal at a rate of approximately 500 lb per hour while the full-scale rig burns coal at a rate of 5000 lb per hour, requiring two independent means of coal handling.

Companies were located that will custom grind small quantities of coal in the one to five ton range. Another company was found that produces and delivers ground coal commercially for electric utilities. The grind can be specified; a significant quantity is delivered at a mean of 30 microns that is used for low NOx PC-fired burners. Initial delivery of coal for the full-scale testing will be of this grind and from a Pittsburgh seam.

Subscale Coal Handling Facility. Coal for the subscale test rig is delivered in ground 64 cubic foot bags with sealed openings at the top and bottom. Each bag contains approximately two tons of ground coal. The filled bags are inerted with dry ice before delivery.

A continuous feed coal handling facility was designed and fabricated for the subscale rig. The facility is a partially enclosed tower designed to hoist the sacks of pulverized/micronized coal. Figure 1 shows a simplified schematic of the coal flow path. The coal is allowed to fall by gravity into one of two parallel, lock-hopper pressure vessels. Coal is supplied to the rig via the vessels which are alternatively pressurized and depressurized for recharging purposes. One 64 cubic foot bag provides sufficient coal for four hours of continuous running at simulated maximum power. The system is designed to permit coal supply bags to be changed without shutting down the rig and enables longer runs to be made if required.

Subscale Rig Delivery System. A dense-phase pneumatic feed system was selected for the subscale test rig after discussions were held with a number of suppliers and workers in the MHD field. Air boosters were included to introduce additional conveying air at frequent intervals along the transportation line. After difficulties were encountered during tests run with this system, modifications were made to convert the system to operate in the dilute

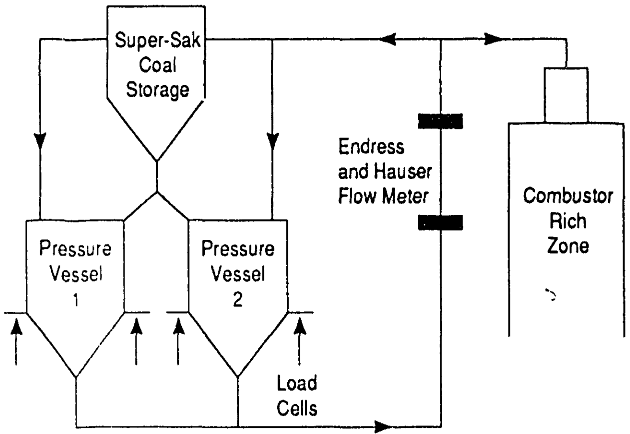


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Figure 1. Simplified Dry Coal Flow Schematic

phase regime. The air boosters were eliminated and a critical flow restriction was included in the pneumatic air supply line. The critical flow restriction permitted control of the conveying air mass flow rate independently of the variations in transport line pressure. Control of the coal flow rate is accomplished by adjusting the pressure drop from the transport vessel to the transport line.

Full-Scale Coal Handling Facility. The use of bags for the full-scale facility was rejected because the practical limitations of local bag storage and need to change bags at a rate of up to one every six minutes. The methods used to deliver pulverized coal to utilities was studied and adopted for the full-scale rig. A leased solid material haulage trailer with three hoppers has been refurbished and converted for use with coal. On-board inerting, O_2, and CO monitors have been installed to provide nitrogen blanketing capability during transportation or long-term storage. Coal is removed from the trailer via a pneumatic transport system and is received in a day-hopper. The hopper can be replenished without shutting the rig down, providing the capability for continuous operation.

Full-Scale Dry Coal Feed System. As a result of experience with cold-flow and combustion tests run on the subscale system, a pneumatic delivery system operating in dilute phase was ordered for the full-scale rig from a different supplier. Operation of the system is similar to the subscale rig. Two parallel lock-hopper vessels are used to alternatively supply pressurized coal and recharge with coal at atmospheric pressure.

Both feed systems are installed with programmable controllers to maintain flow rate and ensure correct sequencing of valves during normal operation. The full-scale control system is capable of being interfaced with the engine control system to permit fully automatic operation of fuel control.

Dry Coal Flow Metering. Each pressurized transporter vessel is equipped with load cells that provide a loss-in-weight measurements. A rolling one minute average of the flow rate is determined from the load cell measurement. To provide an instantaneous measurement of flow, a single-loop coriolis meter was installed in the subscale coal flow line but was found to be unreliable due to plugging. A non-intrusive straight-through meter (Grannucor) made by Endress and Hauser was purchased and tested on the subscale facility. The meter consists of two capacitance sensors mounted on a straight section of pipe. A flow computer processes the signals from the sensors and provides measurements of bulk solids concentration, velocity, and mass flow rate. The meter is calibrated before use by flowing coal from one transporter vessel to the other and determining the flow rate from the loss-in-weight and gain-in-weight load cells. Figure 1 shows the simplified schematic for the coal flow path. After entering the transport line, the coal passes through the Grannucor meter and can be diverted back to the second transporter vessel or to the combustion chamber.

A second Grannucor meter was purchased for the full-scale test facility and is being used by the feed equipment supplier for test purposes. A flow system similar to that used on the bench scale system has been incorporated to enable a flow meter calibration and system check-out to be performed before each test.

Refractory Materials Improvement

During the engine tests reported in 1991 (Wilkes), some minor failure of the combustor refractory material was noted. A water-castable, high alumina material manufactured by A.P. Green, designated Greencast 94 was used for the inner wall lining. The general failure mode was the result of small local cracks being penetrated by molten ash, which caused small sections to eventually break loose after repeated thermal cycles.

Previous refractory improvement work (Wilkes, 1991) was aimed at protecting a low-cost substrate such as alumina with a plasma-sprayed coating of zirconia, aluminum titanate, and other ash resistant materials. Although promising, this approach has since been shelved in favor of using alumina-zirconia-silica (AZS) material. The material is available in at least two forms; a fused-cast product and a water-castable product made from ground fused-cast AZS. Both exhibit a high resistance to ash attack, thermal shock and erosion resistance. After extensive laboratory tests were run on samples of AZS with successful results, portions of the full-scale combustion rig were relined with both types of product. In addition, a cylindrical test piece for the subscale rig has been cast and is ready for test. The AZS material is being used as a test replacement for Greencast 94 and is a nominal 3 inches in thickness. The AZS insert is surrounded by a 3-inch layer of insulating Kast-o-lite 30 and two layers of 1/8-inch thick Jade paper.

RESULTS

CWS Engine Test Results

Change over to CWS and DF#2 fuel in the LQL mode was accomplished without incident. Operation was continued in the LQL mode for one hour, during which time some pressure and temperature instrumentation probes became unreliable due to the formation of ash deposits. Gaseous emission and particulate instrumentation probes were back-purged continuously, except when sampling, in order to maintain sample passages as free as possible of ash deposits. Conversion was made to the RQL combustion mode without incident.

Exhaust Stack Observation. Reliable smoke samples could not be recorded because of probe plugging. Repeated sightings were made of the exhaust stack, however, and no visible smoke emissions could be observed when operating on coal or DF#2 fuel.

NOx and CO Measurements. Measurements were made of NOx and CO emissions at the exit of the gas turbine when operating on CWS and are plotted on Figure 2. CO is shown as a function of NOx, both corrected to 15% exhaust oxygen by volume. Also included on this plot are data recorded from earlier subscale and full-scale tests.

NOx emissions resulting from oxidation of fuel-bound nitrogen (1.20% by weight) could be expected to exceed 500-600 ppmv with a conventional diffusion flame combustor. However, by adjusting combustion zone temperatures and water injection rate at a constant turbine inlet temperature, NOx could be controlled to less than 20 ppmv while simultaneously controlling

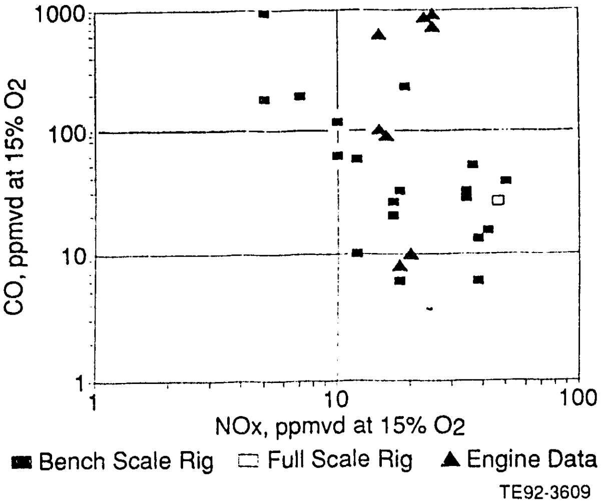

Figure 2. CO Versus NOx Results: Bench Scale, Full Scale, and Engine Test Rigs

CO emissions to less than 10 ppmv. The engine test results can be seen to be well within the range of data recorded in previous combustion tests. These results clearly demonstrate the effectiveness of the RQL combustion system in controlling NOx emissions from both thermal decomposition and fuel-bound sources.

Carbon Burn Out. Quench zone particulate samples and cyclone exit ash samples were taken and analyzed for carbon content. Table 1 shows the results including particle size distribution.

Although only limited data were obtained from the quench zone due to probe plugging, the carbon burnout results agree reasonably well with those calculated from the cyclone ash samples. The average burnout of both sets of data approaches 99%.

Turbine Deposition. Throughout the test on CWS, the compressor discharge pressure was monitored to determine the compressor surge margin. As the test proceeded, the discharge pressure was observed to increase progressively, indicating turbine ash deposition was taking place. Following the test, the engine was removed, disassembled, and inspected. Significant deposits of friable ash were present on the hot gas surface of the transition duct and the turbine section.

From the data recorded, the first stage nozzle effective area was calculated assuming choked flow conditions at the throat. The result of these calculations is shown in Figure 3 as a function of time. Clearly shown is the effect of ash deposit formation on first stage nozzle area. From this data, the first stage nozzle blockage rate of 0.026 in^2/lb of ash passing was determined. The relatively high rate of blockage was later found to be caused by poor cyclone separation efficiency, which averaged 49% for two cyclones in parallel. The poor separation efficiency is the result of the relatively small particle size distribution entering the cyclone (8.3 microns average, see Table 2, quench zone exit) and partial blockage of one cyclone exit. The reduced cyclone efficiency and increased fuel ash level above the original 0.8% baseline fuel resulted in a turbine inlet ash concentration 56 times the original POC engine design value.

The deposit rate data confirms the need for hot gas clean-up equipment in addition to cyclones. From this data it is conservatively estimated that, with a 10% ash coal, a ceramic barrier filter will extend the permitted running time between turbine washing to 350-500 hours, or approximately once every two to four weeks of continuous operation. Further testing is required with a barrier filter to evaluate the effects of particle size on deposition rate in addition to

Table 2. Sample Ash Content and Particle Size

Sample Description	Ash Content % wt	Carbon Burn Out %	D50 Microns	Dtop Microns
Starting Coal	4.39	--	15.0	41
Quench Zone (1)	74.08	98.4	7.6	26
Quench Zone (2)	76.00	98.6	9.1	28
Cyclone Exit	86.39	99.3	13.0	40
Lean Zone Exit	99.92	99.99	8.8	29

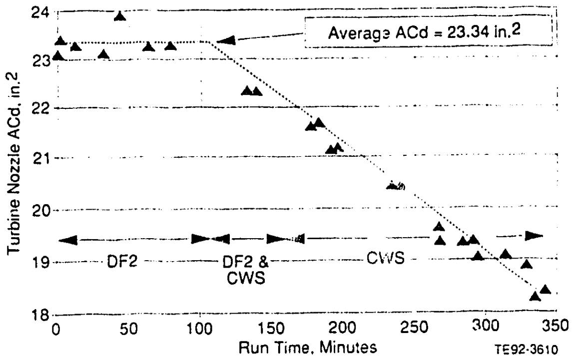

Figure 3. Calculated First Stage Nozzle Flow Area Distillate No. 2 and CWS Fuel

particle concentration. The smaller particles that may pass through the filter are less likely to adhere to the exposed surfaces and are more likely to follow the flow path, extending the time between cleaning.

Deposit Removal. The deposits collected on the turbine section were found to be friable and could be removed by mechanical means. Figure 4 shows a typical second stage vane segment following the CWS test. Leading edge and pressure side deposits are shown. The nature of the deposit is indicated by the missing ash on the left side of the vane segment, which was accidently removed during disassembly. A variety of cleaning methods were tested, including walnut shelling and water washing. Water washing was found to be the most effective method of removing the deposit. Figure 5 shows the effects of water washing the same vane segment shown in Figure 4. Complete removal of the ash was possible by this means. Other vane segments with deposits were heated in an oven to 1400, 1600, and 1800° F and water washed with the same results. No strongly-adhering deposits were found on any of the metal surfaces.

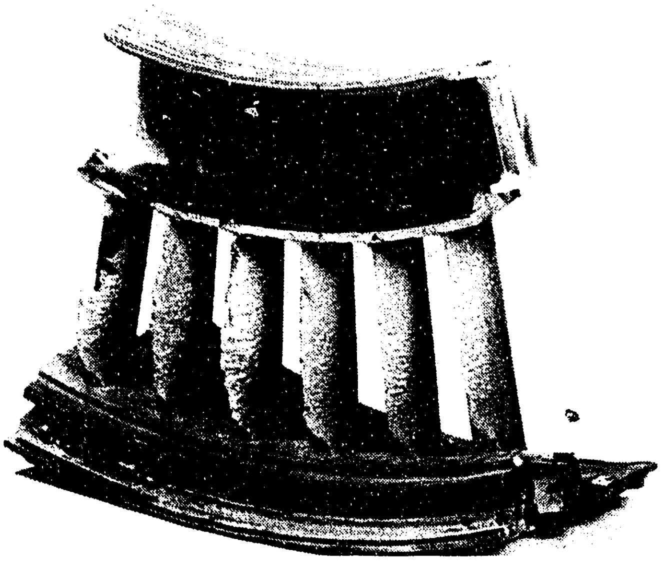

Figure 4. Second Stage Vane Segment After Testing on CWS

Figure 5. Second Stage Vane Segment After Water Washing

Dry Coal Flow Testing

Results from the subscale test facility are shown in Figure 6. Mass flow rate of coal is shown as a function of time determined from the Grannucor signal and load cells during an early checkout test. The coal flow rate was found to be difficult to control and slow to respond. Load cell output indicated close to +/-2% variation in flow rate over a rolling one minute average, but the instantaneous readings from the Grannucor indicated significantly larger fluctuations, of the order of +/-15%. Improvements in short term fluctuations to approximately +/-5% were made by decreasing the coal/transport air ratio from 5:1 to 1:1, as shown by the Grannucor output on Figure 7. Long term flow stability, however, was

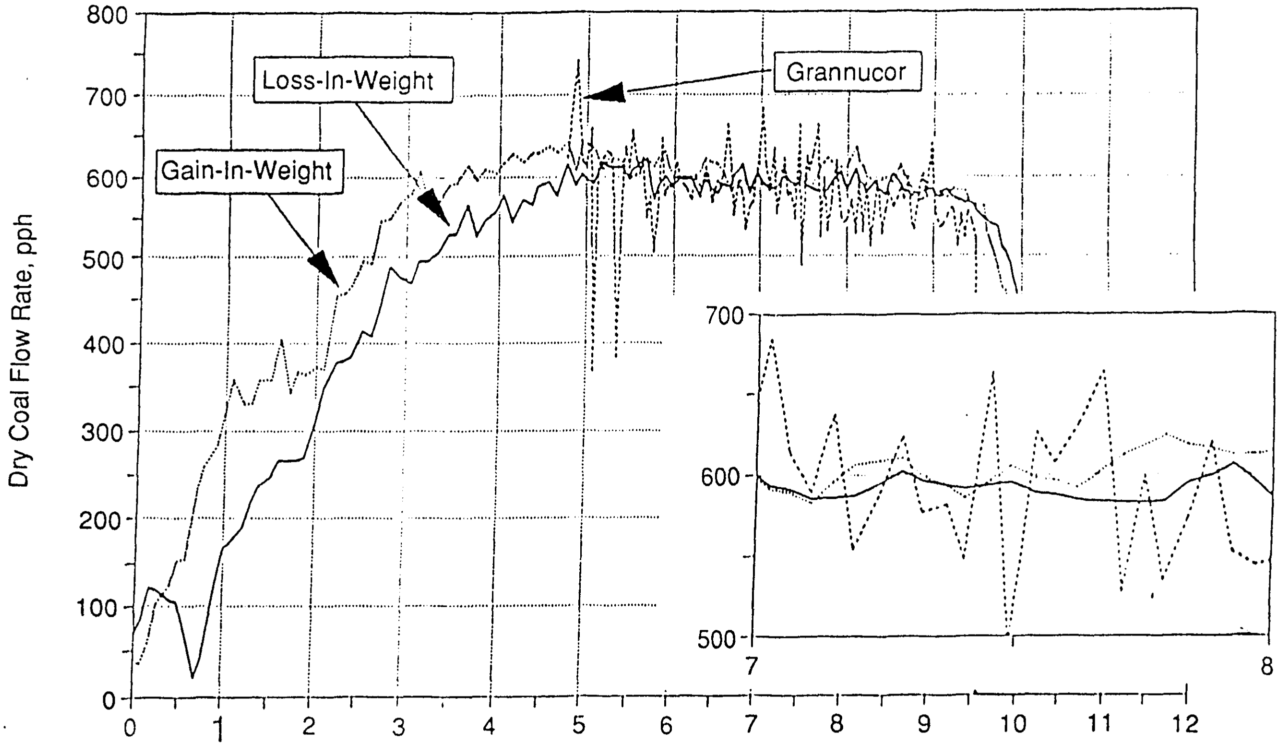

Figure 6. Dry Coal Flow Rate Vesus Time: Load Cells 1 &2 and Grannucor

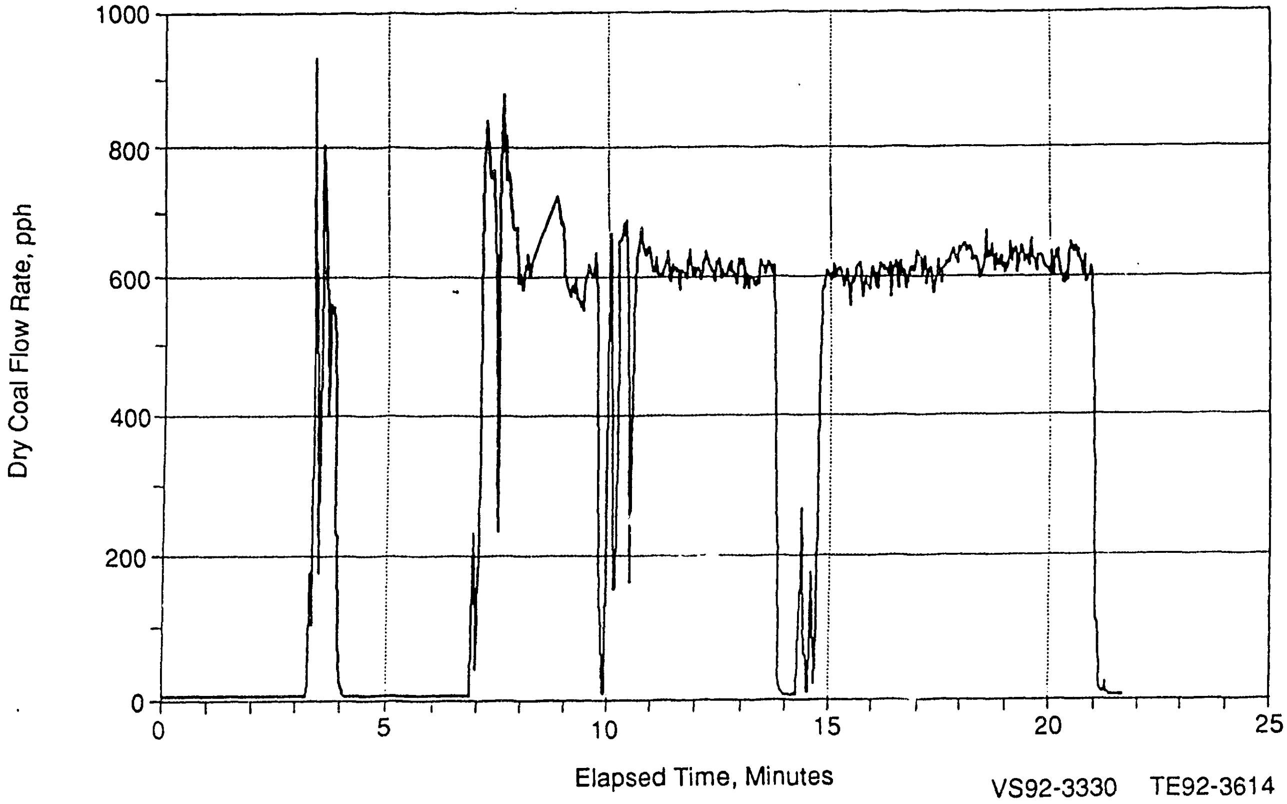

Figure 7. Dry Coal Flow Rate Measured with Grannucor

not achieved as indicated by the flow interruptions. These interruptions are caused mainly by flow instability in the pressurized transporter vessel. Both bridging and rat-holing problems have been observed and are due to difficulties in handling the coal at the relatively low flow rate of 500 pph and the requirement to transition from the hopper exit to the transport line diameter of 0.625 inches.

Full-scale dry coal feed system testing at full pressure is now underway at the vendor's manufacturing facility. A pressurized receiving tank is connected to the coal transport line discharge to simulate the combustor. Initial results indicate that no problems have occurred with bridging or rat-holing in the coal feed hoppers and that most flow control problems have been eliminated. Flow fluctuations have been reduced to about +/- 5% as measured by the Grannucor meter. Further tests are being conducted with the goal of decreasing the amplitude of the flow fluctuations.

Combustion Test

A subscale rig combustion test was run at full pressure in the rich-lean mode. Rich zone gas temperature was limited to 2700° F for control purposes but was capable of being raised to the design value of 3000° F. Fluctuations in temperature of +/-100° F were observed together with brief periodic stoppages in coal flow rate. Similar or larger fluctuations of the lean zone gas temperature were also observed. The test was terminated after adjustments to the pneumatic transport system pressures failed to stabilize coal flow rate. No reliable emissions data were recorded due to the unsteadiness of the operating conditions.

Refractory Materials

Ash and calcium resistance tests have been performed in both oxidizing and reducing atmospheres at 3000° F. Samples of AZS were tested together with sections of alumina brick that were used as a reference material. The alumina brick samples were penetrated by the ash and also reacted with the calcium in a manner similar to that reported previously (Wilkes 1991). Subsequent thermal cycling has shown that failures of the structure will occur due to differential thermal expansion between the alumina brick and the ash/frozen slag. The AZS samples, however, showed complete resistance to chemical attack from either ash or calcium with no penetration of the surface being observed. To further explore resistance to alkali attack, an ash sample was doped with up to 10% sodium by weight and the test repeated at 3000° F with the same results.

Thermal shock screening tests were run by exposing the sample surface to an oxygen/propane flame at 3000° F for one minute followed by a 70° F air jet for one minute. The test is intended to screen for materials that have high thermal shock resistance, but is not necessarily representative of the conditions experienced in the combustion system. Alumina bricks typically survive for 10 to 15 cycles before major fracturing and failure of the material is apparent. AZS samples have survived for between 70 and over 140 cycles, depending on the manufacturing process employed. Some evidence of silica extrusion on the surface has been noted at 3000° F, but is eliminated if the peak temperature is reduced to 2900° F.

Based on these promising results, both fused-cast AZS and a water-castable AZS material have been installed in the full scale rig for testing and further evaluation under combustion conditions.

FUTURE WORK

Dry coal feed rate fluctuations must be reduced before combustion tests can begin. A variable-speed screw-feeder has been ordered for the subscale rig that is designed to promote steady flow and eliminate the bridging and rat-holing problems. Following a successful check-out of the system, testing will commence with an exploration of dry coal combustion emission characteristics while operating in the RQL mode. Tests are also planned for a zinc-titanate sulfur removal system and a ceramic candle barrier filter system. Both the barrier filter and sulfur capture systems are installed and ready for testing.

Full-scale combustion testing will begin after delivery and installation of the dry coal delivery system. Design of a full-scale barrier filter will be completed and engine tests will be run after installation of the filter.

REFERENCES

Wenglarz, R. A., Wilkes, C. 1992. Commercialization of Coal-Fueled Gas Turbine Systems. In *Proceedings of the Ninth Annual Coal-Fueled Heat Engines, Ad-*

vanced Pressurized Fluidized Bed Combustion and Gas Stream Cleanup Systems Contractors Review Meeting, to be published.

Wilkes, C., Thomas, W. H, De Julio E. R., Garrison, C. A., Hillstrom, T. L., and Bourke, R. C. 1991. Proof-of-Concept Testing of a Coal-Fueled Industrial Gas Turbine System. In *Proceedings of the Eighth Annual Coal-Fueled Heat Engines and Gas Stream Cleanup Systems Contractors Review Meeting*, 138-146. DOE/METC-91/6122. NTIS/DE91002091 Springfield, Va National Technical Information Service.

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