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DEVELOPMENT AND FIELD VALIDATION OF A LARGE-FRAME GAS TURBINE POWER TRAIN FOR STEEL MILL GASES

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ABSTRACT

As of September 2009, GE Energy (GE) has successfully expanded its large-frame gas turbine product line to burn ultra-low calorific steel mill gas fuel blends, especially mixtures of Blast Furnace Gas (BFG) and Coke Oven Gas (COG). The first two GE frame 9E Gas Turbines in China with this capability have thus far accumulated more than 8000 hours operating on BFG/COG blends. The China site comprises two complete power trains, including GE 9E gas turbines, generators, fuel cleaning equipment, and fuel gas compressors. Since startup, combustion operating parameters have remained within design limits, consistent with the extensive full-scale lab testing GE conducted during the turbine's design development effort, and comparable to fleet experience on natural gas fired GE gas turbines. Based on this accumulated data set, especially the wide range of gas compositions tested in the combustion lab, similar process gases such as corex and finex gases, and air-blown synthetic gases are operable in this system. The GE 9E platform targets the 50Hz market. For 60Hz applications, a 7EA BFG product is available.

NOMENCLATURE

BFG	Blast Furnace Gas
COG	Coke Oven Gas
CCS	Carbon Capture and Sequestration
FFT	Fast Fourier Transform
FGC	Fuel-gas compressor
HRSG	Heat Recovery Steam Generator (in bottoming cycle)
LBO	Lean BlowOut, or combustor blowout
LDG	Linz-Donawitz furnace Gas
LHV	Lower Heating Value (kcal/Nm^3)
MNQC	Multi-Nozzle Quiet Combustor
MWI	Modified Wobbe Index in English Engineering Units (BTU scf^{-1} R^{-1})
NCM	Normal cubic meter at 0^oC 1 atmosphere, also Nm^3
S1N	First Stage turbine Nozzle (or stator)
S3B	Third Stage turbine Bucket (or rotor)
S3N	Third Stage turbine Nozzle
scf	Standard Cubic Foot at 15^oC (59^oF) and 1 atm
$T_{3.90}$	Combustion system exit temperature

INTRODUCTION

With the tremendous growth of the steel industry in recent years has also come a greater interest in increasing plant productivity and improving plant environmental performance. To help meet these goals, companies are exploring new ways to improve plant efficiency and effectiveness.

Blast Furnace Gas (BFG) is produced as a steel making byproduct during the combustion of coke in blast furnaces; it can be recovered and used, mixed with Coke Oven Gas (COG), another byproduct of manufacturing, as fuel for power and steam generation. Since the 1990s, GE Energy (GE) has worked with customers on ways to use BFG, to produce an internal, low-cost power and steam supply. This power can then either be sold or recycled back into the plant's process. At the same time, emissions can be reduced compared to flaring the gas. Building on the fuel flexibility and reliability of its 9E gas turbine [1-6], GE has developed an efficient, proven and flexible integrated solution to utilize BFG and COG for this industrial application.

The equipment configuration of GE's solution includes the 9E gas turbine, a generator and a fuel gas compressor, used in combined cycle operation. This power train has been developed to replace conventional boiler solutions in the steel-mill industry by burning low-calorific, low-pressure, low-cost fuel gases. It builds on considerable gas turbine experience in steel mills (e.g. five 9E turbines in Italy and China and ten 6B turbines in China) and syngas in refineries around the world. GE's fleet of gas turbines operating on steel mill gases produces a total of approximately 1000 MW of power [4]. The first two units of the new 9E BFG product were commissioned in 2009 at one of the largest steel producers in China. The system is flexible for syngas fuels with average Lower Heating Values (LHV) ranging from 1050 to 1400 kcal/Nm^3 with no additional pilot fuel required. Typical processes resulting in fuels in this range include BFG, COG, (and mixtures thereof), finex, corex and air-blown gasification of coal and other feedstock. Natural gas or distillate oil #2 can be used as startup/backup fuels.

OVERVIEW OF INDUSTRIAL PROCESS GASES

Blast Furnace Gas (BFG), Coke Oven Gas (COG) and Linz-Donawitz Furnace Gas (LDG) are off-gases (by-products) from the various furnaces used in the refining processes of industrial steel mills. Such furnaces require tremendous energy input, typically from coal feedstock. In the production of iron and steel, energy costs are a large fraction of plant operating costs.

Initially in the process, COG is produced by pyrolysis of bituminous coal in the coke oven. The function of the coke oven is to produce coke for the blast furnace. This high-temperature process extracts volatile components of the coal, such as water, tar, and gaseous hydrogen. Hence, the by-product gas contains high levels of H_2, typically 40-70% by volume, with some methane, and minimal inert content.

BFG is formed in the blast furnace, a large piece of capital equipment (see Fig. 1) in the steel mill. The blast furnace serves to reduce iron ore to metallic iron, in the presence of air and coke from the coke oven. Oxygen from the air partially oxidizes the ore, creating a gaseous mixture of H_2 and CO, typically with less than 5% H_2 in the mixture. Most of the heat in this gas is stored in the form of Carbon Monoxide (CO), ranging from 20-25% by volume. The balance of the gas is inert – CO_2 from the reaction, and N_2 from the air.

LDG is formed in the Linz-Donawitz Furnace, the place within an integrated steel mill where molten iron from the blast furnace is changed into liquid steel. The name Linz-Donawitz is taken from the names of two towns in Austria, near the Voest-Alpine Steelworks where the process was developed. Oxygen is blown into this furnace to partially oxidize the iron ore. The resulting gas is high in CO content, typically 60-80% by volume, with some inerts (CO_2, N_2) and small amounts of residual O_2. Because of the high CO content, this gas contains a significant amount of available energy, the conversion of which can greatly reduce the need for external power into the plant.

Corex gas is formed from a similar process wherein coal gasification is used in place of the coking process. The resulting gas resembles coal-gasification syngas in terms of H_2/CO content, but with higher levels of CO_2 and H_2O.

Other processes resulting in similar gases include air-blown coal gasification, finex gas, and some naturally occurring dilute mixtures of methane and CO_2.

These by-products are often flared or burned in steam boilers. An alternative use chosen by some sites is combustion in a heavy-duty gas turbine, providing more efficient power for the plant, or for sale to the grid. Low-quality fuels, especially BFG, may be an attractive power source for the plant compared to the cost of natural gas or distillate oil. The higher-quality fuels (such as COG) may be better spent for other processes in the plant. Hence, gas turbines capable of operation with lower LHV fuels can add value to the process by reducing the demand for COG to the turbine (using more BFG instead). The "quality" of the fuel can be broadly gauged by the percent reactive species, both in terms of the commercial value, and the challenges for gas-turbine combustion. A related parameter is the fuel's lower heating value. However, the acceptability of a particular fuel for combustion operation is strongly dependent upon all fuel constituents and properties, which vary from site to site.

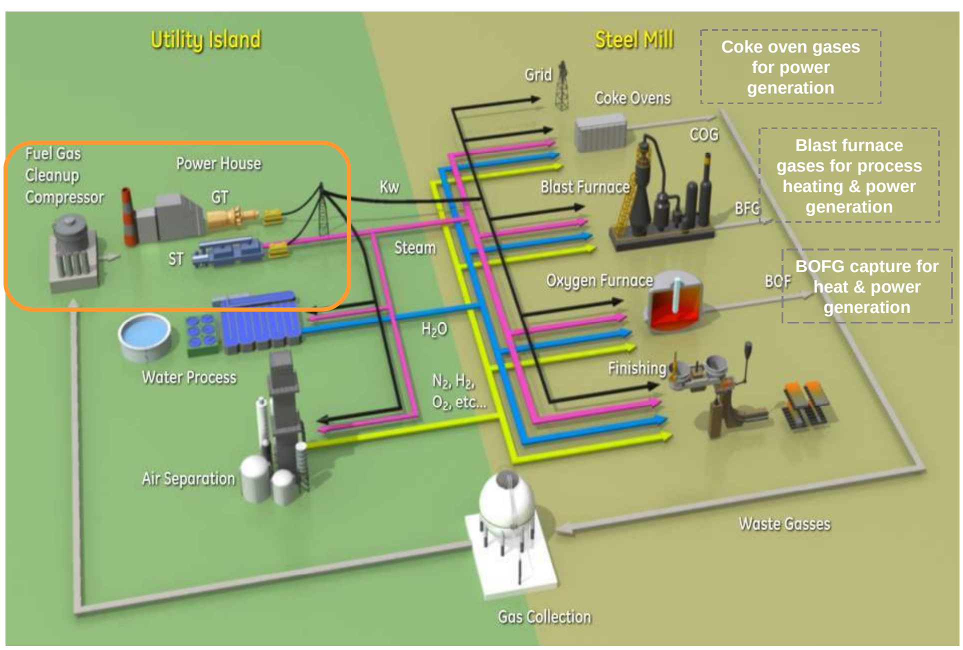

Fig. 1 Typical steel mill plant footprint, with coke oven and blast furnace. Iron ore is the principal material, and coal the original energy feedstock.

Fig. 2 Steel mill site in Italy, with three GE 9E gas turbines fired on BFG/COG blends, operational since 1996

Fig. 3 Steel mill site in China, with two GE 9E gas turbines fired on Corex gas, operational since 2007

PREVIOUS GE EXPERIENCE WITH STEEL MILL GASES

GE has three 9E gas turbines operating on steel mill gases in Italy (Fig. 2). Table 1 shows average gas compositions Table 2 shows availability of these engines. The average LHV when the three streams are blended together is approximately 1600 kcal/Nm^3. The new BFG product introduced herein targets 1050 kcal/Nm^3 with upgraded combustion technology.

Table 1 Average gas compositions at the steel mill site in Italy

Site average fuel compositions (% volume dry)	**BFG**	**COG**	**LDG**
H_2	2.5	60.3	1
CO	22.8	5	69.2
N_2	53.5	4.5	14.9
CH_4	0	25.3	0
CO_2	21.2	1.3	14.6
C_NH_{2N}	0	3.6	0.3
LHV, kcal/Nm^3	780±60	4500±290	2030±150

Table 2 Average availability at the steel mill site in Italy

Average % Availability since 1997	**Engine 1**	**Engine 2**	**Engine 3**
	94.2	93.9	91.7

NEW 9E BFG POWER TRAIN

For the 9E BFG application, GE has leveraged the Gas Turbine/Generator/Fuel Gas Compressor power train configuration originally developed in the 1990's, and fielded first in Italy and later in China, shown in Figs. 2 and 3, respectively. The heart of the power train is the frame 9E gas turbine, GE's 50-Hz industrial gas turbine workhorse with more than 430 operational units, 22 million operating hours, and typical rating of 126MW on traditional fuels [5]. Gas turbine modifications required to burn the ultra-low heating value fuel are limited to a few changes. The combustion system is a multi-nozzle quiet combustor (MNQC), a diffusion-flame configuration derived from decades of syngas experience and validated in GE's combustion lab. Details of the combustion development and validation are presented later. Modifications to pass the large volume of fuel through the gas turbine include an enlarged first-stage turbine nozzle (S1N). The gas turbine also makes use of up-rated third-stage turbine nozzle (S3N) and third-stage bucket (S3B) components that provide superior performance in high-flow conditions. The S3N and S3B airfoil design was previously enhanced to provide improved turbine efficiency relative to the historical baseline. The GE 9A5 generator is double-ended similar to the configuration fielded previously (Fig. 3) with rotor thrust modifications to handle the large compression loads associated with compressing ultra-low heating value fuel.

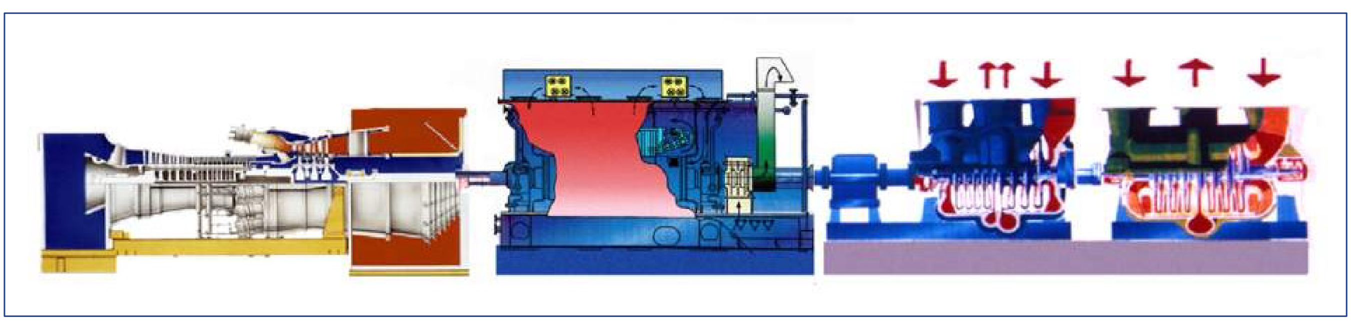

Fig. 4 Power train sub-systems

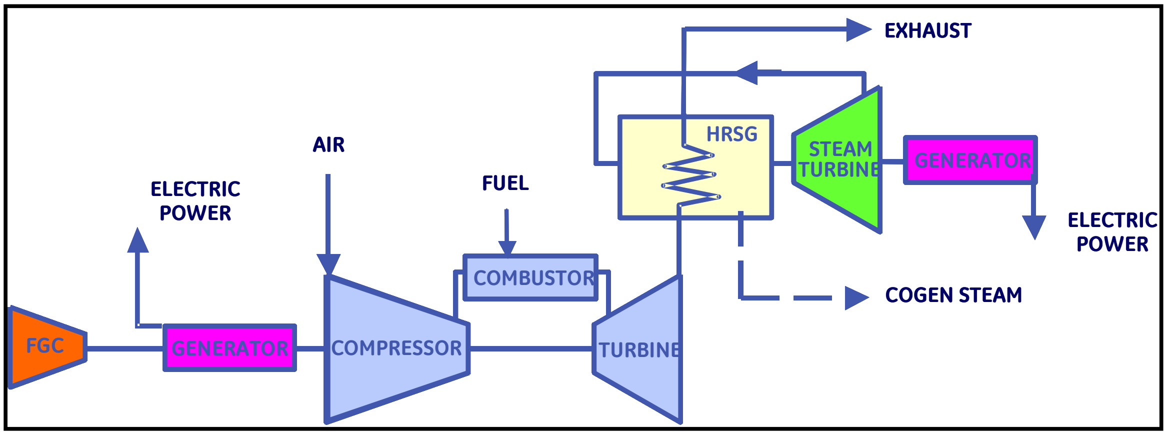

Fig. 5 Schematic of power train

Table 3: Typical, or representative gas compositions. Compositions are %mole. LHV is defined on a wet basis (i.e. H_2O content shown is included in the LHV.

fuel type	H_2	CO	CH_4	CO_2	N_2	H_2O	C_2H_6	LHV, kcal/NCM	LHV, BTU/scf	MWI
BFG	2	23	0	20	55			747	80	2.6
COG	55	10	25	5	4		1	4019	428	23.1
LDG	0	65	5	10	20			2394	255	8.7
BFG/COG blend	6	24	1.6	17	49	1.7	0.2	1050	112	3.8
Finex	15	29	2	44	9			1421	151	5.0
Corex	23	30	0.2	6	0.8	40		1518	162	6.8
Air-blown coal gasification	16	18	2	10	54	0.5		1120	119	4.4
Air-blown coal gasification w/ CCS	29	6	0.1	3	61	0.5		939	100	4.0
Dilute natural gas	0	0	45	45	8		2	4164	443	14.9
Natural gas	0	0	92	2	2.0		4	8500	905	39.8

The fuel-gas compressor features a 2-stage centrifugal compressor with one stage of inter-cooling. The centrifugal compressors offer the advantage of being extremely tolerant to impurities in the fuel and can expect to have much less degradation and longer intervals between maintenance when compared to axial compressors. Figure 4 shows the power train, with sub-systems from left to right as follows: gas turbine proper, generator, and fuel gas compressor (FGC). A thermodynamic schematic of the system is shown in Fig. 5 including FGC, generators, gas turbine proper, heat-recovery steam generator (HRSG), and steam turbine. For most steel mill applications, electric power is recycled back into the plant's process, although it can also be sold to the local grid.

COMBUSTION DESIGN AND DEVELOPMENT

Combustion Challenges

In the process of development of the BFG combustion system some important challenging operability issues had to be resolved. They included, among others, such problems as ability to operate at low heat content of the BFG fuel, stability of the flame within the combustor, ability to meet requirements of the turbine entry temperature profile, maximum temperature of the liner wall, emissions and dynamics. These challenges have been successfully addressed in the course of the development program.

Design for fuels with low heat content

Design of the combustion system architecture for steel mill applications is driven by the low LHV, or low Wobbe index (LHV normalized by the square root of the gas molecular weight) of the various gases. As shown by Richards et al. [7] the Wobbe Index relates several important design variables. They are, the heat required by the gas turbine Brayton cycle, the fuel's heating value, the injection orifice flow area, the engine operating pressure, and the fuel-nozzle pressure ratio. Richards et al. [7] show the basis of the Modified Wobbe Index (MWI), which includes the fuel temperature. The MWI used herein is defined as follows.

$$MWI = \frac{LHV(BTU/scf)}{\sqrt{\dfrac{\tilde{M}_{fuel}}{\tilde{M}_{dryAir}} T_{fuel,R}}}$$

where $\tilde{M}$ is the molecular weight (molar mass) of the gas fuel and dry air.

This parameter defines the required fuel nozzle flow area to maintain a constant fuel-nozzle pressure ratio (assuming a constant heat input and operating pressure for the engine.) Hence, as the LHV of the gas decreases, the MWI will, in general, decrease, and the required area increase. The increase in fuel flow results in a greater total mass flow rate through the turbine, however, because of the enlarged first stage turbine nozzle area (S1N) as discussed before, the equivalent combustor air flow function, $\dot{m}\sqrt{T}/P$, is consistent with GE field experience on the 9E frame. Table 3 shows some typical, or representative gas compositions for the various processes discussed herein. Compositions are given as % by mole, or volume. For the calculations in Table 3, a constant reference fuel temperature of 400°F (205°C) is assumed. Compositions shown in Table 3 are typical of that process; the actual composition will vary from site to site and from day to day at a given site.

The high volumetric fuel flow required for the lower-quality fuels causes a variety of challenges for the design of the gas turbine combustion system. Perhaps most notable is blowout, which can occur even at full-load conditions due to a reduction in residence time compared to the low chemical reactivity. Due to the cost of importing hydrocarbon backup fuels such as natural gas, propane, distillate oil, etc. it is desirable to operate without any such back-up fuel. This large fuel volume creates large flames relative to combustion of traditional high-calorie fuels in a similar burner. Such flame can potentially lead to fuel and reaction near metal surfaces. Hence, metal temperatures could exceed what would be predicted for such traditional fuels based solely on the flame temperature, as this temperature is relatively low. As a result, cooling of the combustion liner has been improved to prevent cracking and maintain metal temperatures consistent with 9E experience. Reduced residence times and reaction rates, and high initial CO concentrations, may lead to challenges in CO burn-out. NO_X on the other hand is often less of a concern for similar reasons. In many cases nitrogen-bearing compounds in the fuel, such as ammonia (NH_3) are the leading source of NO_X emissions, as opposed to NO_X formed by thermal processes in the flame. For this reason, a diffusion-flame fuel injection approach is used here rather than lean pre-mixed combustion. These low-calorie fuels and the large fuel-nozzle area lead to piping challenges in providing suitable purge flows. Large volumetric flows of air are required for qualification tests during production, typically an order of magnitude greater than for natural gas applications.

Design for Flame Stability

The GE 9E BFG gas turbine power train includes a large system as described previously. One of the key challenges to fuel and operational flexibility with low-calorific process gases lies in achieving stable and complete combustion. Additionally, the reliability of the gas turbine requires that the products of combustion be well suited for entrance into the rotating machinery. This section outlines some of the design processes used to modify the design of combustion hardware for these requirements.

Static stability, in terms of flame-out, or lean blow-out (LBO) is a primary concern in the design of a low-H_2, low-LHV combustion system. High volumetric flows of fuel lead to reduced aerodynamic residence times, and low H_2 content and high inert content lead to reduced chemical reaction rates. As summarized by Glassman [8], empirical correlations of flame stability data can be generalized by a system Damköhler (Da) number, expressed as the ratio between some characteristic residence time scale and chemical time scale

The residence, or aerodynamics time scale is typically associated with a recirculation zone and the characteristic chemical time scale is typically associated with the time required to ignite the unburned fuel/air mixture. The chemical properties are governed primarily by the nature of the industrial process; design variables pertinent to the combustion system have a greater impact on the aerodynamic residence time.

Reacting-flow computational fluid dynamics (CFD) calculations have been used to design the primary combustion zone to achieve the desired flame stability.

Figure 6 shows a representative CFD image highlighting recirculation zones to quantify their size. Air flow is initially from right to left, with fuel flow from left to right, as indicated. This flow path is an integral part of GE's reverse flow combustion liner; in that air from the compressor discharge flows right to left (in the coordinates of this figure), before turning and entering the head end of the combustor. In Fig. 6, all velocity contours are negative relative to a left-to-right coordinate system. Geometry shown (wire mesh view) is a sector of the combustion chamber, with a single fuel nozzle, primary zone only. Key recirculation zones are indicated by the dotted lines.

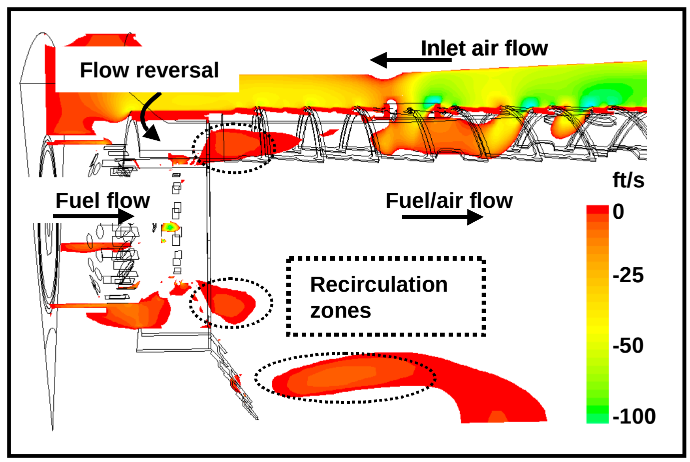

Fig. 6 Combustion flow field colored by axial velocity (ft/s); negative values are shown. Arrows indicate flow direction. Conditions correspond to Fig. 7.

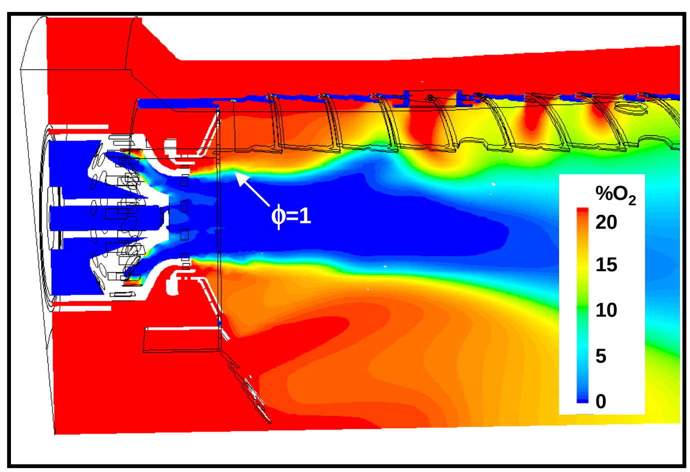

Fig. 7 Combustion primary zone colored by O_2 mole fraction. Blue is 100% fuel and red is air (21% O_2)

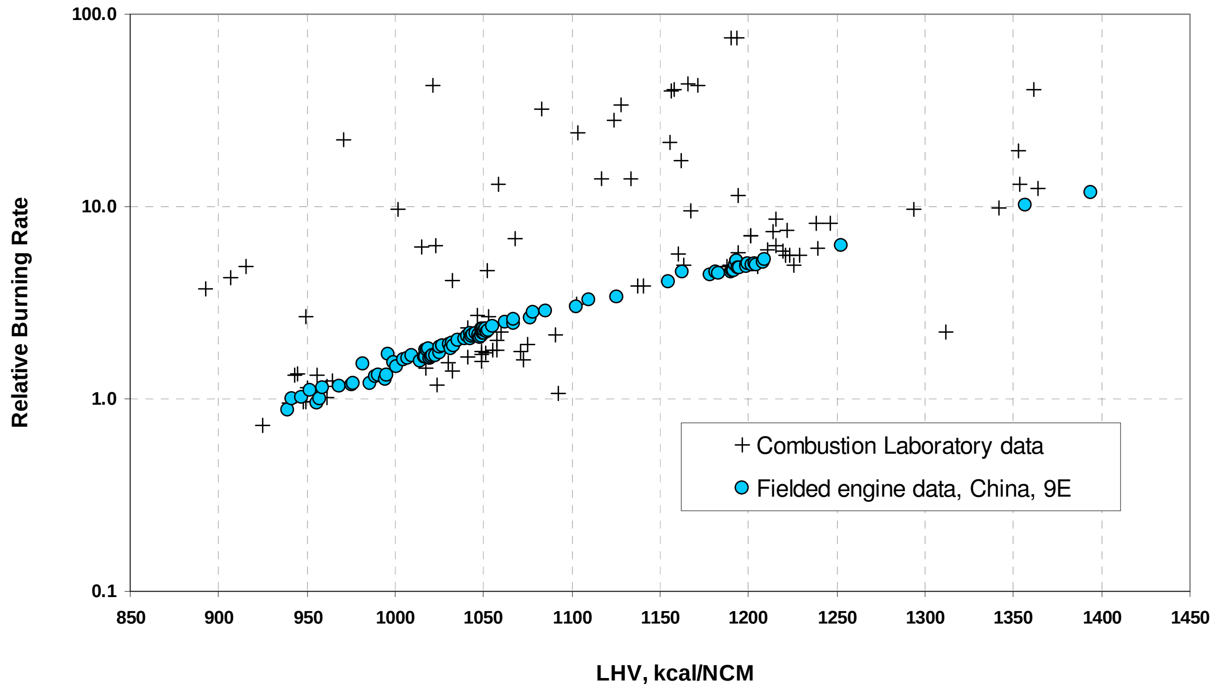

Fig. 8 Chemical burning rate, normalized to burning rate at high-H_2 conditions.

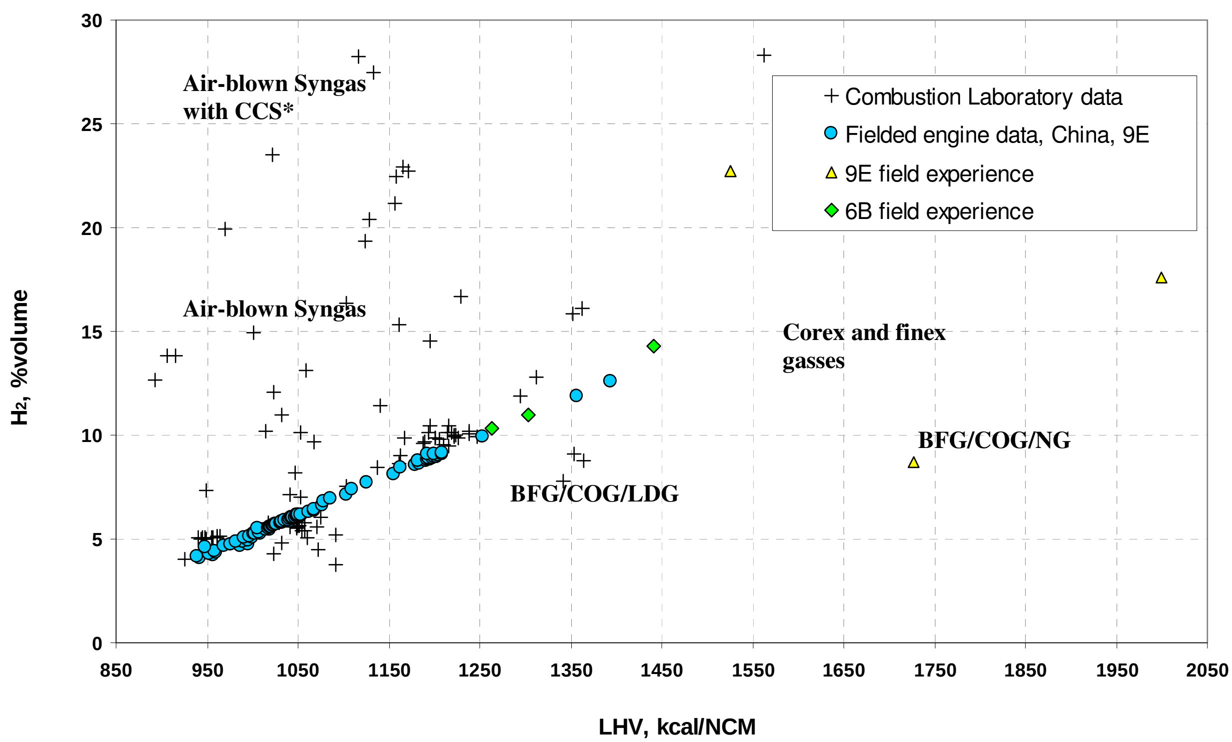

Fig. 9 H_2/LHV range covered in laboratory and engine testing. Typical ranges for industrial process gases are indicated. *CCS is pre-combustion Carbon Capture and Sequestration, which results in higher H_2 content at similarly low LHV. NG is natural gas. Points marked as "Fielded Engine data" refer to the new 9E BFG described herein. Other field experience (9E and 6B) are at other sites as described in the introduction section.

The CFD study used a steady Fluent version 6.3.26 and double precision solver with a realizable k-epsilon turbulence model and conjugate heat transfer enabled. No radiation transfer was needed for this analysis because it focused on aerodynamic features of the flow field and absolute temperatures were not required. Species transport was modeled with non-reacting mixing among 6 species.

Contours of O_2 mole fraction, shown in Fig. 7, further illustrate the flow field. In Fig. 7, blue shading indicates zero O_2 (pure fuel) and red indicates 21% O_2 (pure air). For the conditions analyzed, ϕ=1 occurs at 9.9% O_2, where ϕ is the fuel/air equivalence ratio. Co-location of the stoichiometric contours with regions of low or negative velocity is a key feature for flame stability, as this condition maximizes the Damköhler number. This is based on two assumptions. The first being that regions of negative axial velocity indicate recirculation and increased residence time, and the second that, for diffusion flames, temperatures and reaction rates tend toward a maximum at or near equivalence ratios of one.

Based on the recirculation zone size determined from CFD and the Da number criteria defined by Glassman [8], a static stability limit can be defined, above which stable combustion of the low-LHV gas will be possible. The remaining parameter then is the chemical time scale, taken here as the chemical burning rate. This property is shown in Fig. 8. For comparison, a wide range of stable Combustion Laboratory data are shown, with recent engine data as well. The same laboratory data points are shown in Figs. 8 and 9. In Fig. 9 relative burning rate has been replaced with %H_2, which gives a suitable representation of chemical reactivity for typical steel mill gases. This approach has the advantage of being formulated in terms more readily obtained from a gas analysis, and it can be seen that numerous steel mill gases lie within the tested range.

Design for Turbine Entry Profile

It is important to ensure that the proven reliability of the GE 9E turbine is preserved, even as it operates with fuel flows an order of magnitude greater than for natural gas or distillate fuel oil. To this end, the combustion hardware was modified during the development phase to produce a uniform temperature profile at the turbine inlet (combustion outlet).

The initial design phase used the jet-penetration correlations of Holdemann and Walker [9], to determine hole placement, diameter, and count for injection of dilution air within the combustion liner. Total dilution area was fixed to minimize CO emissions and flame stability, based on the bulk-average combustion temperature upstream of the dilution injection plane. The axial location of the dilution air injection plane was set by the same considerations.

In application of the two-dimensional (2-D) correlations of Holdemann and Walker [9], the key parameter is the center-line trajectory of the dilution-air jet, Y_{CL}. The equation of this center-line penetration depth is as follows.

$$\frac{Y_{CL}(X)}{D_j} = 0.539 J^{0.25} \left(\frac{S}{D_j}\right)^{0.14} \left(\frac{H}{D_j}\right)^{0.38} \left(\frac{X}{D_j}\right)^{0.17} e^{-b}$$

where

$$b = \left[0.091 \left(\frac{X}{H}\right)^2 \left(\frac{H}{S} - \frac{\sqrt{J}}{3.5}\right)\right]$$

X	axial position within liner channel
S	spacing between centerlines of adjacent orifices
D_j	dilution-jet diameter
H	duct height or liner diameter
J	momentum ratio, jet to free stream

For a given combustor geometry, the primary design variables are the jet diameter, D_j, and the count, which sets the spacing, S.

The 2-D correlations of Holdemann and Walker [9] give penetration profile of the jet centerline for a jet in cross flow, discharging into a confined duct area. With options defined in this manner, CFD predictions of exit temperature distribution were used to complete definition of the dilution air injection pattern. Two such calculations are shown in Figs. 10 and 11. The computational approach described earlier was used for this analysis as well. Figure 10 represents the baseline pattern, with the new design shown in Fig. 11. Temperature scales are defined relative to the maximum temperature in the flow field (given a value of 0^oC).

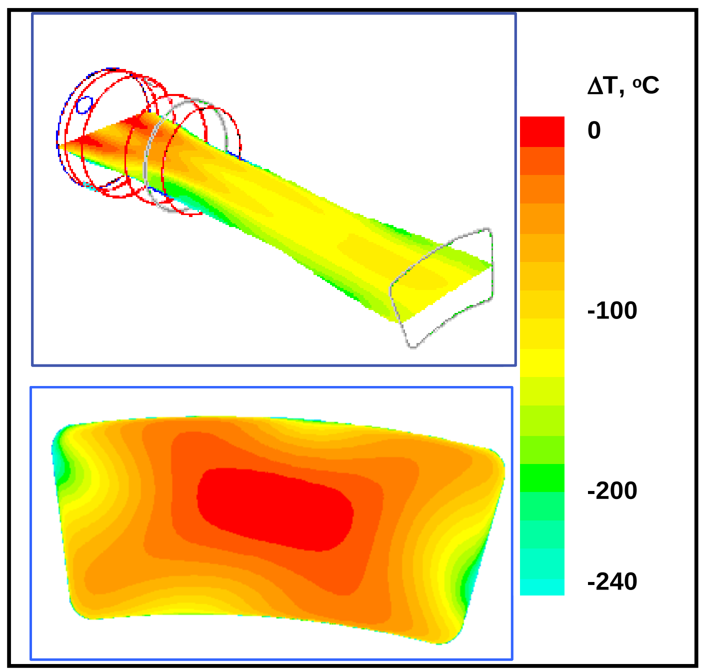

Fig. 10 Baseline turbine inlet (combustor exit) temperature profile

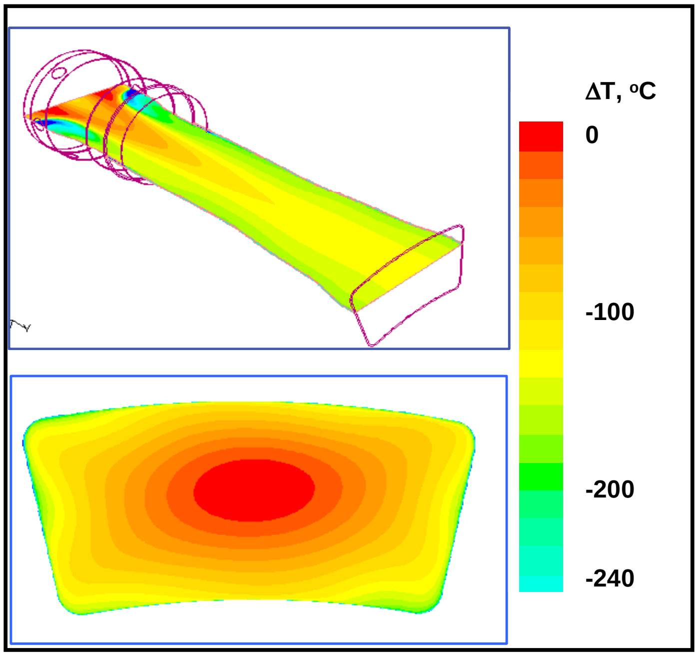

Fig. 11 Improved turbine inlet (combustor exit) temperature profile

As can be seen from Fig. 11, the improved combustion system configuration, especially liner and transition piece assemblies, provide a more uniform and symmetric temperature distribution, consistent with the cooling pattern and life requirements of the downstream turbo machinery.

The 2-D and 3-D approaches described above are compared in Fig. 12. Here, a quarter sector of the combustion liner is shown at an axial distance approximately 2.5 cm downstream of the dilution jet plane. Selection of this axial plane is arbitrary, and is taken as 2.5 cm (1 in) for the purpose of comparison. Conditions are the same as those of Figs. 10 and 11, and the plots are colored by temperature, relative to the maximum temperature in the flow field. A value of 0°C is assigned to the maximum. The blue-green circular patterns show dilution jet penetration for 4, 6, and 8 hole patterns. The inserted points are the predictions of the center-line penetration depth from the wall, using the 2-D correlation. Hence, it can be seen that the 2-D and 3-D approaches give consistent results both qualitatively and quantitatively.

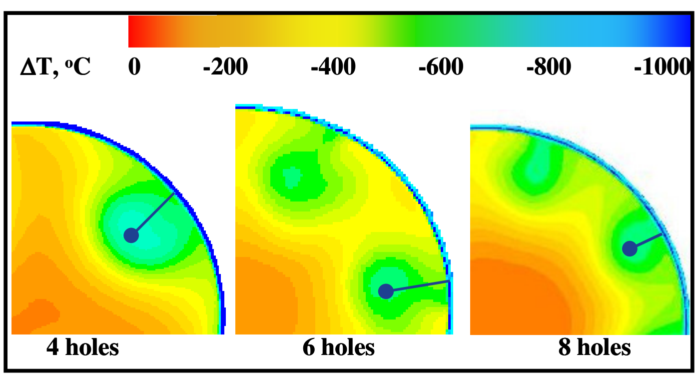

Fig. 12 comparison of 2-D and 3-D predictions. CFD results are colored by temperature, and the inserted points are the predicted centerline penetration depth (Y_{CL})

Combustion Laboratory Configuration

The development effort for the current GE 9E BFG product included extensive combustion lab testing to produce and validate a combustion system capable of operating with low-LHV fuels. The Gas Turbine Technology Laboratory is located in Greenville, South Carolina, U.S.A., and houses multiple test cells, each capable of delivering the full range of pressure, temperature, fuel and air flow encountered in the engine, to a full-scale single-chamber combustion rig. For low-calorie gas fuels, additional header pipes are standard in the facility, and all major components of typical steel mill gases can be blended to specification, and varied during the course of a lab test. Although not required for most steel mill gases, the facility also has the ability to blend heavier hydrocarbon fuels as well.

The following figures show the experimental apparatus and equipment used in the combustion development. In Fig. 13, the main control center of the combustion laboratory is shown during a typical test. Numerous screens are available to monitor all flows in real-time, along with dynamic pressure oscillations (post FFT), hardware metal temperatures, emissions and exhaust products (NO_X, CO, UHC, CO_2, O_2, H_2O).
Combustor exit gas temperatures, and other measures of combustion performance and durability, including visual imaging of the flame itself are available. Details of the combustion laboratory and testing procedure can be found in Myers et al. [10] section VI.

Fig. 13 Gas Turbine Technology Center Combustion Laboratory: main control center

Figure 14 shows a partially built rig for a test with BFG and similar fuels. In this case, a large header pipe is required for the high volume of fuel flow, approximately one order of magnitude greater than would be required for natural gas fuel flow for the 9E turbine. Additional connections are present for distillate fuel oil. Large header pipes upstream of the connection shown are adequately sized for even the highest flow rates of low-calorie gases.

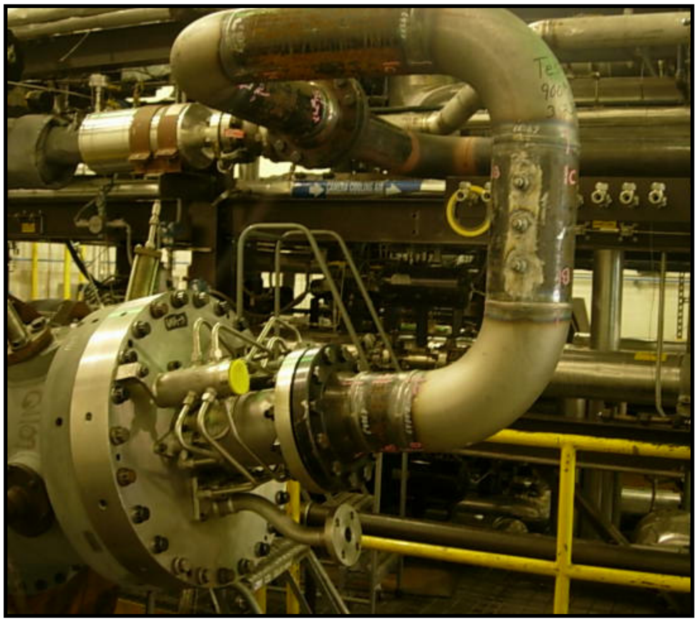

Fig. 14 BFG test stand prior to testing

Figure 15 shows a typical low-calorie (syngas) combustion test apparatus after full assembly. Fuel flow is from right to left in the view shown, with heated air entering through the duct at the bottom of the image. This arrangement replicates the engine environment in geometry and fluid flow, for a single can.

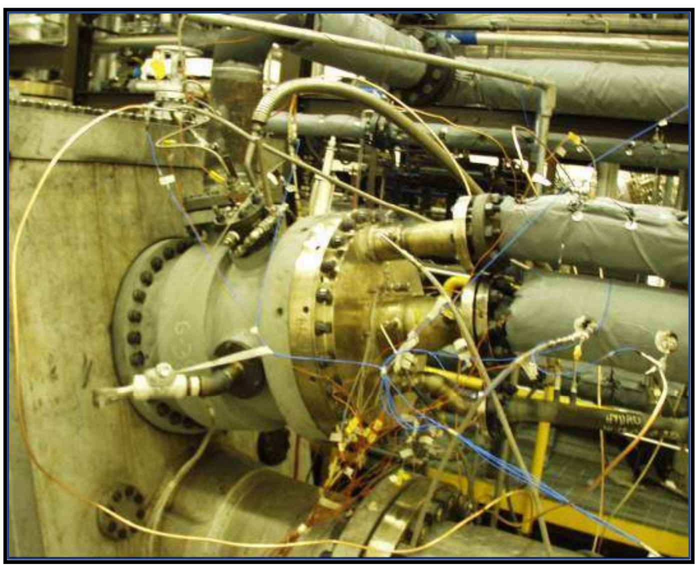

Fig. 15 Low-calorie combustion test apparatus with sensors, piping, etc. installed

LABORATORY AND FIELD TEST RESULTS

The results of numerous combustion laboratory tests for the 9E BFG development project were shown before, in Figs. 8 and 9. As can be seen from the labels in Fig. 9, many process gases fall in the range of H_2 and LHV tested, not just BFG. Other processes for which the system has been tested include air-blown synthetic gases, both with and without carbon capture, from a variety of feedstock, and corex and finex gases.

Combustion System Metal Temperatures

A comparison of combustion liner metal temperatures between field and laboratory testing is shown in Fig. 16. Thermocouples were placed strategically throughout the hardware; maximum value is shown. For comparison, results are normalized to the maximum field result. From the plot, a general trend can be seen of increasing metal temperatures with fuel LHV, however, there is notable scatter in these coordinates. The fundamental reason for this behavior has to do with the variation in individual species fractions at a given LHV. Detailed data analysis was able to produce a multi-variable correlation, relating metal temperature to fuel properties and engine cycle properties, including fuel reactivity, fuel-jet momentum, peak flame temperature, and hot-side and cold-side metal temperatures.

The data in Fig. 16 show that the fielded configuration is operating within the expected range of metal temperatures and always cooler than the maximum levels measured and analyzed under the development program.

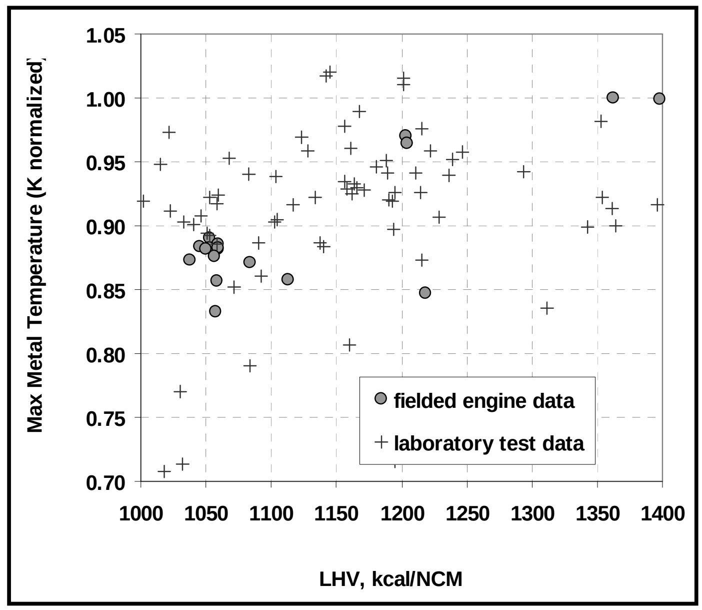

Fig. 16 Laboratory and field data, normalized maximum combustion liner metal temperatures. (All sets of data are below allowable design limits for all points.)

Emissions and Dynamics

Emissions of carbon monoxide (CO) provide a useful indication of flame stability and degree of complete combustion, and can be used to assess the repeatability of laboratory results in the engine environment. A comparison of laboratory and fielded CO emissions is shown in Fig. 17, with CO plotted as a function of combustor exit temperature, $T_{3.90}$. This temperature is the adiabatic flame temperature based on bulk fuel and air flows and is plotted as a delta relative to the full load temperature, that is, the X-axis coordinate = $T_{3.90} - T_{3.90,\text{full load}}$. CO is reported on a dry volumetric basis with reference to 15% exhaust O_2 Exponential curve fits to the engine data are shown for ease of comparison; the dashed line is an extrapolation to lower temperatures. The engine operates consistently and predictably, with CO > 25 ppm reached for temperatures 150^{o}C below the full-load value.

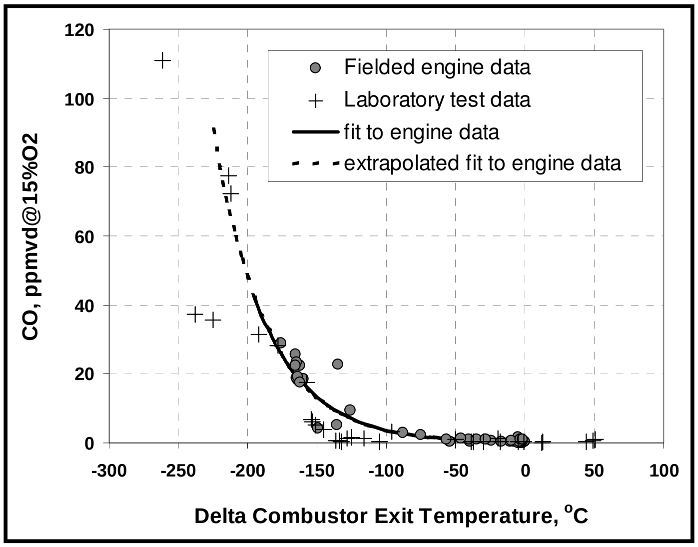

Fig. 17 Laboratory and field data, CO emissions. Combustor exit temperature is defined relative to full-load (see text), and CO emissions are shown with reference to 15% exhaust O_2.

Combustor pressure instabilities, or "combustion dynamics", were very quiet during syngas operation. All frequencies were well below their design limits for a range of gas heating values, both in laboratory and field testing. Starting reliability was proven over the course of one year, with seasonal variations from approximately 0-40°C.

CONCLUSIONS

The large-frame 9E BFG Gas Turbine power train developed by GE has been extended to operate with process gas fuels ranging from 1050 to 1400 kcal/Nm^3 (average design value). This approach provides a higher efficiency, greater output, and lower emissions when compared to traditional boiler technology for steel mills. It can generate additional revenue via sales to the grid with low-cost fuel (1 to 2 USD/MBTU), with lower emission and smaller plant footprint. In many cases, the emissions benefit can help bring the plant into compliance with local pollution regulations and create eligibility for carbon monetization. GE can effectively support end-users to add substantial value to their projects.

Extensive fuel-space mapping in the Combustion Laboratory, followed by field validation, has shown the system to be operable for a variety of process gases. A similar product is available for the 7EA frame for 60Hz applications [11].

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