DUAL-USE CONVERSION OF A HIGH MACH NUMBER JET ENGINE TEST CELL FOR INDUSTRIAL GAS TURBINE LOW-EMISSION COMBUSTOR DEVELOPMENT

P.W. Pillsbury and W.R. Ryan
Combustion Turbine Engineering
Westinghouse Electric Corporation
Orlando, Florida

J.R. Moore
AEDC Group
Sverdrup Technology, Inc.
Arnold Air Force Base, Tennessee

ABSTRACT
With the recent trend of reducing U.S. military expenditures, it has become desirable to develop dual use of certain Department of Defense facilities. These efforts have a commercial purpose, while still retaining a military benefit. The goals of these efforts are to make U.S. business more competitive in world markets, to develop the technology to solve pressing national problems, and to maintain intact the necessary talent pool and equipment for possible military needs. In a recent initiative described in this paper, test cell equipment at the Arnold Engineering Development Center, Arnold AFB, Tennessee, was modified and expanded to allow development by the Westinghouse Electric Corporation of low-emission combustors for heavy-duty gas turbines for commercial power generation.

INTRODUCTION
The Power Generation Business Unit of Westinghouse had been evaluating various sites where combustors for the new generation of large stationary gas turbines could be developed, at full pressure, temperature, and flow. A full-scale, high pressure combustor test facility is costly to operate, so combustor development at Westinghouse is split into at least four steps as shown in Table 1. Step 4 testing will be performed only on those combustors which have successfully come through the lower cost screening of Steps 1-3.

The combustors to be developed represent such a state-of-the-art change in form and function (in order to meet ultra-low NOx emission goals), that it is considered necessary to test them at full conditions in a single-combustor test rig before undertaking a field test in an operating power plant. What was needed was a site having a supply of 660K (725 °F) air at 14.2 atm, in a quantity of 22 kg/s (48 lb/s), and free of any combustion products (i.e., unvitiated), together with access to a high-pressure pipeline capable of furnishing 3800 Nm³/h (2350 SCFM) of natural gas, (Table 2). After considering many possibilities, both domestic and overseas in 1992-93, it was determined that a cooperative facility development with AEDC best met all criteria.

There is a test cell at AEDC, designated T-3, which is designed for testing small jet engines at simulated high flight Mach numbers. It is equipped with an unvitiated air supply having well in excess of the airflow, pressure, and temperature needed for one heavy duty gas turbine combustor. Test time is available at this cell, there is a large state-of-the-art control room, and extensive data acquisition hardware is in place. Furthermore, arrangements could be made to utilize the existing experienced technical staff to support much of the effort. Difficulties were encountered in attempting to adapt a jet engine test cell to combustor development, as described below, but the facility is now fully operational.

INSTALLATION CONSIDERATIONS
The large Westinghouse combustor test rig had to be installed without compromising the capability of the test cell to test jet engines. Figure 1 shows a conceptual view of Test Cell T-3 before installation of the Westinghouse combustor test rig. As built, the test cell contained a heavy thrust stand capable of retaining an operating jet engine, and recording its thrust using load cells. Surrounding the thrust stand was a heavy pressure-
TABLE 1: STEPS IN FULL SIZE COMBUSTOR DEVELOPMENT TESTING

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATMOSPHERIC, COLD FLOW</td>
<td>ATMOSPHERIC, COMBUSTION</td>
<td>MID-PRESSURE, COMBUSTION</td>
<td>FULL PRESSURE, COMBUSTION</td>
</tr>
<tr>
<td>Flow Visualization</td>
<td>Ignition</td>
<td>Emissions trends</td>
<td>Definitive emissions</td>
</tr>
<tr>
<td>Flow Distribution</td>
<td>Stability Trends</td>
<td>Stability Limits</td>
<td>Combustion Efficiency</td>
</tr>
<tr>
<td>Pressure Loss</td>
<td>Pressure Loss</td>
<td>Pressure Loss</td>
<td>Pressure Loss</td>
</tr>
<tr>
<td>Internal Velocities</td>
<td>NOx Propensity</td>
<td>Part Power Combustion</td>
<td>Wall Hot Spots</td>
</tr>
<tr>
<td>Fuel-Air Mixing Trends</td>
<td>Flashback Propensity</td>
<td>Wall Hot Spot Early</td>
<td>Turbine Inlet Pattern Factor</td>
</tr>
<tr>
<td>Verify CFD Cold Flow</td>
<td>Access for Laser Diagnostics</td>
<td>Gross Flashback Screening</td>
<td>Combustion-Driven Oscillations</td>
</tr>
<tr>
<td>Modeling</td>
<td>View Flame</td>
<td>Possibly View Flame</td>
<td>Define Flashback</td>
</tr>
</tbody>
</table>

TABLE 2: FACILITIES CAPABILITIES REQUIRED FOR COMBUSTOR TESTING

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Required Value, SI Units</th>
<th>Req’d. Value, US Customary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustor Inlet Pressure</td>
<td>1.2 atm to 14.3 atm.</td>
<td>18.0 to 210 psia</td>
</tr>
<tr>
<td>Combustor Inlet Air Temp.</td>
<td>310 K to 660 K</td>
<td>100°F. to 725°F.</td>
</tr>
<tr>
<td>Combustor Airflow</td>
<td>1.6 kg/s to 22 kg/s</td>
<td>3.6 lb/sec to 48 lb/sec</td>
</tr>
<tr>
<td>Combustor Outlet Temp.</td>
<td>310 K to 1811 K</td>
<td>100°F. to 2800°F.</td>
</tr>
<tr>
<td>Fuel Flow, No.2 Distillate Oil</td>
<td>3.2 l/m to 69.1 l/m</td>
<td>0.7 gpm to 15.2 gpm</td>
</tr>
<tr>
<td>Fuel Flow, Natural Gas</td>
<td>170 Nm³/h to 3800 Nm³/h</td>
<td>105 SCFM to 2350 SCFM</td>
</tr>
<tr>
<td>Steam Flow, (for injection)</td>
<td>0 to 5443 kg/h</td>
<td>0 to 12,000 lb/h</td>
</tr>
<tr>
<td>Gaseous Nitrogen (coolant)</td>
<td>0.6 kg/s</td>
<td>1.4 lb/s</td>
</tr>
<tr>
<td>Cooling Water</td>
<td>0 to 9200 l/m</td>
<td>0 to 2000 GPM</td>
</tr>
</tbody>
</table>

tight chamber, designed to be pressurized to simulate high Mach number, low altitude flight, or evacuated to simulate lower speeds and high altitudes. A heavy, air-tight cover opens at the top, to allow installing or removing jet engines. This feature is indicated in Figure 1.

Also indicated in Figure 1 is one of the two large air preheaters. It is a tube-type, indirect-fired heat exchanger. On its cold side, high pressure air from another building (not shown) is received. On the hot side, the heating medium is combustion products at approximately one atmosphere. This comes from natural gas burners. The burner-blower is indicated on the figure. Shown between the preheater and the test chamber is a blending section where air from the preheaters, and air direct from the compressors is mixed to
achieve the desired temperature. An air heater of the flow rate and pressure capability to supply a jet engine is extremely rare in combustor test facilities and it forms a very valuable part of the test apparatus. Figure 2 is included to show its scale.

A small jet engine on a thrust frame is depicted in the Figure 1. Unfortunately the combustor test rig more nearly resembles a large jet engine in size. The test rig is approximately 4 m (13 ft) long by 2.6 m (8.5 ft) at its widest point.

The initial plan was to place the combustor test rig inside the test cell on the thrust frame. Figure 3 shows this arrangement drawn to scale. In some respects it appears desirable, in that the ability of the test cell to receive jet engines is in no way disturbed. However, as is shown later in Figure 7, changing combustors for testing through the port in the forward bulkhead of the combustor test rig, would be impossible in this arrangement, because the port would be so close to the head-end of the altitude chamber.

Figure 1 makes it appear that the altitude test cell is surrounded on both sides by ample space, but in actuality there was inadequate space in the T-3 Test Cell building to locate the combustor test rig. The decision was made to locate it in the area between the building housing T-3 and the adjoining larger building on the south. The addition of a new concrete foundation underneath, and a sturdy rain/sun shield and steel support frame above, together with the existing building walls on two sides provides all the shelter that is needed.

Figure 4 shows the final arrangement of the hot-air/cold-air mixer, the original T-3 altitude chamber, and the combustor test rig. When combustor tests are to be conducted, a blank-off plate is placed in the large flange at the inlet end of the altitude test chamber. This diverts air out the side of the hot/cold air mixer through the two small flanges shown in Figure 4, and then through a tee into approximately 20 m (65 ft) of 25.2 cm (10 in) diameter pipe. Valves provide controllability over a wide range of airflows. When jet engine tests are run, blank-off plates are installed at the mixing plenum flange and the large blank-off plate is removed from the head end of the altitude chamber. Downstream of the Westinghouse test rig, there is a deluge section, consisting of approximately 2.75 m (9 ft) of 50.8 cm (20 in) pipe, fitted with 15 water spray nozzles. This section has been very effective in reducing stack noise to an acceptable level, and eliminating any hot spots (in excess of 477 K [400°F]) in the pipe or the back-pressure valve.

**CONTROLLING THE HEATED COMBUSTION AIR SUPPLY**

Large air heaters, such as the one used here, resist rapid temperature changes needed for testing. For example, proper evaluation of an industrial gas turbine combustor in a test rig requires moving expeditiously through a series of conditions such as those shown in Table 3. Rapid setting of test conditions is accomplished in this facility by a system of air-blending valves, (Figure 5) rather than adjusting the gas burners. Air for the combustor comes to the heater from a large air compression system located in an adjacent test facility, labeled "VKF". After filtering and pressure regulation by valves, it enters the cold side of the heater through a 25.4 cm (10 in) pipe, and leaves in a 30.5 cm (12 in) line. Process air for turbine engines in T-3 or in this case the Westinghouse combustor, passes through flow control valves, with excess hot air vented to atmosphere through alternate valves. Large and small valves are installed in pairs to cover a wide range of airflows. Fortunately this was done when T-3 was originally developed for turbojet testing, for this permits it to supply the proper airflow for the Westinghouse rig, which requires only a third of that for which the cell was designed. Similarly, the provision to vent hot air is vital, because at many of the combustor test rig conditions, there would not be enough through-flow in the air heater to prevent its tubes from overheating. Downstream of the hot valves, FV9 and FV10, the hot air enters a cylindrical mixing chamber, just upstream of the original T-3 altitude cell. Cold air bypasses the heater, and goes directly through flow control valves FV3 and FV4 to the mixer. Excellent mixing is achieved by routing the cold air into a ring manifold surrounding the mixing cylinder, and then feeding the cold stream into the hot, in 34 equally-spaced jets. Combustion air temperature, pressure, and airflow rate to the combustor test rig can be rapidly set or changed by simultaneously opening or closing of the hot and cold flow control valves. All control valves are automatically controlled by a computer system called the Test Environmental Controller (TEC) in order to provide both stable operation and rapid response in changing test conditions.

**COMBUSTOR TEST RIG AND INSTRUMENTATION**

The test rig, as installed, is shown in Figure 6. This test rig was used in the 1970's and 1980's by Westinghouse for full-size combustor development (Hendry and Pillsbury, 1987), and was reactivated and overhauled for this program. Prominent in the foreground are four hoses. These hoses carry natural gas to each of four zones in an experimental dry low NOx combustor, and are rated well in excess of the 2069 kPa (300 psi) needed for this application. Below the fuel hoses is the rig combustion air inlet. The flange for this inlet is heavily insulated for personnel protection, since the inlet air averages 658 K (725°F). The test rig itself, being completely water-jacketed, remains cool to the touch during all phases of combustion. The combustor to be tested is installed and removed via the cover just above the air inlet.

A better idea of how the test rig works can be seen from Figure 7. A conventional, rather than a staged dry low NOx combustor, is shown. Note that the combustion air enters at the bottom, passes through a simulated diffuser, turns 180 degrees, and flows back to the head end of the combustor. This
FIGURE 1. ARTIST'S CONCEPT OF T-3 TEST CELL BEFORE INSTALLATION OF WESTINGHOUSE RIG

FIGURE 2. PHOTO OF PREHEATER FOR T-3 TEST CELL COMBUSTION AIR
FIGURE 3. CONCEPTUAL LAYOUT OF WESTINGHOUSE TEST RIG INSTALLED IN T-3 ALTITUDE CHAMBER

FIGURE 4. LAYOUT OF T-3 AREA SHOWING FINAL POSITION OF WESTINGHOUSE TEST RIG
TABLE 3: CONDITIONS A SINGLE-COMBUSTOR RIG MUST PRODUCE IN ORDER TO DUPLICATE AN ENGINE

<table>
<thead>
<tr>
<th></th>
<th>Cold Flow</th>
<th>Ignition</th>
<th>0% Load</th>
<th>25% Load</th>
<th>50% Load</th>
<th>75% Load</th>
<th>100% Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Press., kPa (psia)</td>
<td>124 (18)</td>
<td>124 (18)</td>
<td>1034 (150)</td>
<td>1138 (165)</td>
<td>1241 (180)</td>
<td>1345 (195)</td>
<td>1448 (210)</td>
</tr>
<tr>
<td>Inlet Temp., K (°F.)</td>
<td>311 (100)</td>
<td>311 (100)</td>
<td>611 (640)</td>
<td>622 (660)</td>
<td>633 (680)</td>
<td>644 (700)</td>
<td>658 (725)</td>
</tr>
<tr>
<td>Combustion Airflow, kg/s (lb/s)</td>
<td>1.6 (3.6)</td>
<td>1.6 (3.6)</td>
<td>21.8 (48)</td>
<td>21.8 (48)</td>
<td>21.8 (48)</td>
<td>21.8 (48)</td>
<td>21.8 (48)</td>
</tr>
<tr>
<td>Fuel Flow, kg/s (lb/s)</td>
<td>— (0.08)</td>
<td>0.04 (0.40)</td>
<td>0.18 (0.46)</td>
<td>0.30 (0.66)</td>
<td>0.40 (0.88)</td>
<td>0.54 (1.20)</td>
<td>0.68 (1.50)</td>
</tr>
<tr>
<td>Steam Flow; kg/h* (lb/h)</td>
<td>— (2000)</td>
<td>— (3200)</td>
<td>907 (2000)</td>
<td>1451 (3200)</td>
<td>3175 (7000)</td>
<td>4535 (10,000)</td>
<td></td>
</tr>
</tbody>
</table>

* Non-dry low NOx combustors, only
FIGURE 5. SCHEMATIC OF VALVING FOR QUICK-RESPONSE CHANGES OF COMBUSTION AIR TEMPERATURE

FIGURE 6. PHOTO OF TEST RIG
airflow pattern duplicates the reverse flow of the heavy-duty machines designed in the U.S. (Scalzo, et al, 1994). A curving transition piece receives hot combustion gases from the burner, and conveys them to the simulated turbine plane. Instead of a turbine cascade, however, the hot gases pass through an array of 14 cooled probes: 7 temperature probes, followed by 7 pressure/emission probes. At today’s firing temperatures, these probes must be cooled by a very substantial flow of 0.63 kg/s (1.4 lb/s) of gaseous nitrogen, (GN2). AEDC has a high capacity GN2 supply, another illustration of the advantages of dual-use conversion projects at a facility such as this. The 14 probes range in diameter from 1.9 to 2.5 cm (0.75 to 1.0 in) and create a substantial pressure drop, which works together with the back-pressure valve farther downstream, to hold the maximum required pressure of 14 atmospheres in the test chamber. Figure 8 displays the system which protects the probe rakes from elevated burner outlet temperatures, and cools the emission sample on its way to the emission measurement instruments. The first row of probes, the three supervisory thermocouples, are located in the boundary layer, and this location, together with heavy-duty construction, preserves them. These thermocouples provide a full-time, but somewhat slow and approximate indication of combustion temperature. The next row contains 7 equally-spaced thermocouple probes which span the entire transition exit height, and being fixed in position, must withstand the full total temperature of the burner discharge gases. These are continuously purged with GN2 except for intervals of approximately 15 seconds when a reading is desired. The readings are extrapolated in real time by the AEDC data system to give a steady-state burner outlet temperature value, using the pulsed thermocouple method (Gabriel, et al, 1982). During the brief interval when the thermocouple probes are taking a reading, hot gases flow into the probe bodies, over the thermocouple junctions, and then out to the stack. The cycling on and off of the purge and the aspiration of hot gas is controlled by solenoid valves as shown in Figure 8. To protect the valve to the stack, TCCV2, the hot gases go through a cooler, as shown.

The final row contains 7 pressure/emissions probes, which also are fixed in position, and span the entire height of the passage. They are designed with three concentric passages. The outermost passage is continuously purged with GN2, which is discharged downstream into the combustor exhaust. The second passage is purged until an emission reading is desired. Then, the solenoid valves depicted cycle, cutting off the purge, sending the sample to the three coolers shown and then to the emissions measurement line. Transport times, in the emissions probes and associated lines are kept low by dumping most of the sample to the stack downstream of Valve PTCV3. Only the sample actually needed for the instruments is tapped off through the hand valve shown, and sent through the final cooler to the instruments. The innermost passage in the pressure/emissions probes is for total pressure measurement, and since it is a non-flow passage, leading to a transducer, it is not purged.

All instrumentation systems, measurement lines, and probes used for measurement during this testing comply with SAE ARP 1256. Smoke measurements during testing with fuel oil comply with SAE ARP 1179. Currently, the emissions measurement instruments used include the following: 2 Thermo Electron Model 10AR chemiluminescent analyzers, for NO and NOx; 3 Beckman Model 865 NDIR analyzers; 2 for CO, and one for CO2; one Beckman Model 404 flame ionization detector for total hydrocarbons; and one Beckman Model 755 paramagnetic oxygen analyzer.

FUEL SUPPLY CONSIDERATIONS

As an aeropropulsion test facility, AEDC is primarily equipped to supply volatile liquid hydrocarbon fuels to the test cells. However, current industrial gas turbines are predominantly fueled on natural gas; most are sold with back-up distillate oil operating capability also. Natural gas in sufficient quantities for the 63 Nm3/min (2350 SCFM) flowrate required for the test rig was available in the vicinity of Test Cell T-3. However the available line pressure of 621 kPa (90 psi) was lower than the required test rig operating pressure of 2758 kPa (400 psi). To meet this requirement, a Dresser-Rand Model 2KOA-1 compressor, packaged with a 198 kW (265 hp) Caterpillar Model G342TA natural gas-fueled drive engine was supplied by Westinghouse, and installed near the test cell. It draws its fuel from the same pipeline which supplies the gas it compresses, and represented one of the largest items purchased for the test stand conversion. It is an example of how dual-use conversion enhances the capability of a facility.

Dry low NOx combustors for developmental industrial gas turbines often must be fuel-staged in order to meet stringent low emissions requirements or standards. T-3 was therefore equipped with five-zone fuel supply systems for both natural gas and distillate oil fuel. Figure 9 shows a schematic of the natural gas portion of the fuel system: the distillate oil system is similar. Downstream of the natural gas compressor the line splits into 5 branches, each with its own turbine-type flowmeter and throttle valve. Zones 1A and 1B are shown connected together, since it was contemplated that they would feed a conventional diffusion-flame pilot in an otherwise premixing-type combustor. Such diffusion flame pilots may have to go from very low to very high fuel flows, and so two parallel flowmeters and valves were specified to cover the range. Zones 1A and 1B can also be operated as separate zones by removing the tee. Control of the fuel systems was programmed in the Westinghouse Distributed Processing Unit available in the T-3 control room and used for control of all test cell functions.
FIGURE 7. CUTAWAY VIEW OF TEST RIG

FIGURE 8. PROBE RAKE PURGE/READ SYSTEM
INITIAL OPERATING EXPERIENCE

Conversion of T-3 Cell was sufficiently complete by late April, 1994, so that combustion testing could begin. Initial test experience immediately showed areas where improvements were needed, and several modifications have been made. For example:

- Local pneumatic accumulators were added to speed up operation of the back-pressure valve.
- A readout of the natural gas compressor RPM was added to a control room screen so that gas pressure could be controlled more precisely.
- An analog display of supervisory thermocouple temperature outputs was added to the control panel (this was found much quicker to follow than digital numerals on screens, especially during lighting attempts).
- Six water spray nozzles were added to the original nine in the duct downstream of the rig to eliminate duct wall and back-pressure valve hot spots.

- Combustion air temperature and mass flow rate control were made automatic, rather than manual.
- Air-fuel ratios in the five zones of pre-mix type combustors were taken out of the large data displays, and put on a dedicated, rapidly-updating screen, to assist operator control.

Figure 10 is a close-up photo of a full-size experimental combustor being installed in the test rig. Here the combustor itself is already inside the rig, and the cover plate is being tightened. In Westinghouse practice, the experimental combustors are mounted to cover plates, the fuel injectors installed, and the whole assembly instrumented with sealed leads, before they are brought to the test area. The combustor shown has five zones, each with its own fuel connection, which, together with the instrumentation leads, explains the complexity of the cover plate in the photo.

CONCLUSIONS

A dual-use modification of jet engine Test Cell T-3 at Arnold Engineering Development Center has been completed, and it is
now in use as part of the on-going development testing of new type dry-low NOx combustors for industrial gas turbines. Relative to engine testing, use of the facility is saving time and expense. Other positive results for the industrial participant, and for the Air Force are summarized below:

- Development of a successful cooperative effort with benefits for both Westinghouse and AEDC.
- Reduced uncertainty for Westinghouse when new-design combustors are first introduced into power plant gas turbines.
- An opportunity for staff at an Air Force facility to gain skills in component development in addition to turbine engine testing.
- A ground power plant development capability at AEDC to supplement the existing aeropropulsion capabilities.
- Assistance in keeping the AEDC technical team together by supplementing the military workload.
- A center where U.S. manufacturers can hone their skills in the areas of emissions reduction and energy efficiency to better compete in world markets.

ACKNOWLEDGMENTS
The authors wish to acknowledge the very significant help of Mr. T.D. Garretson of the U.S. Air Force in bringing about the development of a high-pressure combustor test facility at Arnold Engineering Development Center, as well as the efforts of Sverdrup Technology, Inc. personnel at Arnold, especially L.R. Bahor, W.C. Gobbell, C.A. Leach III, J.E. Reavis, D.G. Gardner, C.L. Walters, W.L. Bonson and many others; and, from L.P.G. Industries, Mr. F. K. Gabriel.

REFERENCES