Fine Tuning and Detailed Testing of a New Heavy Duty G.T. in the Field

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Final field adjustments to optimize combustion and performance, as well as the comprehensive on site evaluation program performed on this gas turbine, are described in this paper. Included are a description of a series of minor combustion modifications which were easily possible due to the unique single-combustion-chamber design. Tests discussed included measurements of turbine blade operating temperatures and exhaust emissions.

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INTRODUCTION

Two important phases in the construction of any gas turbine power plant are the final start-up adjustments followed by a period of testing to evaluate and demonstrate unit performance. In the case of the four GT-55 machines at the Blue Lake Power Plant, these two tasks were of particular interest. The unique configuration of the Turbodyne heavy duty gas turbines provided considerable flexibility in the adjustments which could be made to optimize their operation. In addition, the testing phase was expanded into a thorough evaluation of overall unit performance.

HISTORY

The Northern States Power Company's Blue Lake Power Plant is located near Shakopee, Minnesota. The turnkey installation consists of four simply cycle gas turbines, Model GT-55 (Type 11) which were manufactured by Turbodyne in St. Cloud, Minnesota under a license agreement with Brown Boveri Company of Switzerland.

All four gas turbines went into commercial operation slightly ahead of the scheduled date of May 1, 1974.

Shipment and erection of the first gas turbine was scheduled sufficiently early to allow time for special adjustment and first unit testing as described in the following.

GAS TURBINE BACKGROUND

The GT-55 gas turbine is an uprated version of the Type 11, which was the first machine of a new family of gas turbines, and was introduced by Brown Boveri in 1970. The gas turbine is designed for 3600 rpm service and drives the electric generator directly through an intermediate block shaft.

A small version, the Type 9, operates at 4470 rpm with a step down gear for either 50 or 60 cycle power generation.

A larger 50 cycle version with 3000 rpm, the Type 13, has been introduced on the European Market in 1973. Designs of Type 9, 11, and 13 are very similar, and the majority of the components are simply scaled up or down from original Type 11 design. Operating experience is gained simultaneously on all three models and compared.

Table 1 shows technical data of the GT-55 gas turbine as installed in Blue Lake.

| TABLE 1 Technical Data GT-55 (Type 11, Blue Lake) |
| Generator Output at Terminals MW | 49.25 | 53.70 |
| Compressor Inlet Temperature °C | 0 | 15 |
| Compressor Inlet Pressure BAR | 1.013 | 1.013 |
| Speed rpm | 3600 | 3600 |
| Efficiency Net percent | 28.4 | 28.9 |
| Heat Rate Net BTU/kwh | 12018 | 11810 |

DESIGN CONCEPT

The thermal block of the gas turbine is conservatively designed for long life and an

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important design criteria has been the incorporation of maintenance convenience into the design.

The most important feature is probably the use of only one combustion chamber, with one burner and only one fuel nozzle. The combustion chamber (combustor) is located vertically beside the compressor and turbine section and connected by means of a 180 deg double walled air/gas duct (Fig. 1).

In the outer annulus, air from the compressor flows to the combustor while high temperature gas returns to the turbine through the inner lining.

Compressor discharge air coming to the combustor is split into three parts as shown in Fig. 2:

1. Primary air which enters the combustion zone through swirl vanes in the inner and outer swirlers
2. Secondary air which flows through six adjustable air flow vanes below the combustion tiles
3. Cooling air which flows between the inner liner and finned tiles entering combustion zone through clearances between tiles and through perforated section near the top of the combustor.

**AIR FLOW ADJUSTMENT**

The relationship of secondary air and primary air is adjustable by the secondary air valves. The direction of primary air flow into the combustion zone is adjustable by varying the vertical position of the outer swirler. In addition, vanes are installed at the upper combustion chamber flange to prevent a swirl in primary air before the air enters the combustion zone through inner and outer swirler.

Uniform distribution of the compressor air is achieved at the combustor — air/gas duct flange with control vanes which throttle the flow. For final adjustments of these vanes, 12 differential pressure probes are equally spaced on the circumference at the top of the combustor (Fig. 3).

**START UP ADJUSTMENTS**

Many system calibrations and adjustments are made during manufacturing and factory tested before shipment to site by system block testing. Combustion adjustments, however, and other settings which are influenced by local conditions as the type of fuel, etc., are made during the start up period in the field. These adjustments
include the fixed opening of the fuel nozzle for light off and rate of fuel nozzle opening to get the desired acceleration rate of the gas turbine.

Three sight glasses which allow flame observation are provided on the combustion chamber as important tools for start up and commissioning adjustments. Two sight glasses are directed to the flame center at the tip of the fuel nozzle and one sight glass which is horizontally located on the combustion side allows observation of the flame length.

Initial combustion adjustments for start up, no load operation, generator protection, and system check out at low loads were primarily in the vertical positioning of the outer swirler.

Further combustor adjustments at higher loads were made including setting of the air control vanes to get best uniform flow to the combustor and secondary air valve positioning. At high KW loads the initial unit exhibited unsatisfactory exhaust smoke levels. Also, unusual vibration readings were detected by the special instrumentation, provided for rotor dynamics testing. It was first discovered that the highest vibration levels were of a frequency of only 18 Hz and were found in axial as well as radial position on the turbine rotor and bearing cases. High response rate pressure transducers were installed to measure possible fluctuations in the control oil system, compressor discharge pressure, combustor pressure, fuel pressure, and fuel flow. All signals were recorded on tape during machine operation and afterwards played through a spectrum analyzer and plotted. The results showed very clearly that the exciting force for the low frequency was the combustion discharge pressure. Plots of fuel flow and control oil pressure showed no sign of 18 Hz frequency although compressor discharge pressure did show the low frequency at much reduced level.

It was decided to optimize the combustion further, on the first of the four turbines, by adjustments to the burner itself.

The combustion chamber design allows easy removal of burner and fuel nozzle by simply unbolting and lifting the combustion chamber cover plate. (A hot section turbine inspection with a visual inspection of first stage blading...
and hot inner liners can also be accomplished by removal of the cover plate. The time required for one burner adjustment including removal and reassembly of the cover plate plus test run and evaluation was approximately 1 day. Schematic details of burner configurations are shown in Figs. 4, 5, and 6. Fig. 4 shows the original burner configuration where 20 test holes were added as a temporary measure to confirm the theory that the flame needed additional primary air at the nozzle tip for flame stabilization.

Fig. 5 shows an inner swirler which provided a fixed amount of air through the air ring to the nozzle tip.

Also shown are two adjustments to the outer swirler which had very little effect on combustion stability and confirm that correction was only needed at the inner swirler. Fig. 6 shows the final burner configuration with a larger inner swirler and adjustable air orifice ring which allowed final combustion tuning.

The low frequency vibration at the turbine bearing was not detectable with the final burner configuration and exhaust smoke became invisible.

Fig. 6 Final burner configuration

TEST PROGRAM

Once the adjustments were completed and the machine was in its final configuration, the task of measuring its operating characteristics was begun. These units provided the initial opportunity for Turbdyne to gain in-the-field experience with heavy duty gas turbines manufactured in the USA. Therefore, a comprehensive evaluation program was carried out on the first of the four turbines, encompassing a variety of technical disciplines, including such diverse areas as rotor dynamics, exhaust emissions, and blade metal temperatures.

Only the scope of this testing is discussed herein, with those procedures and testing techniques of special interest covered in greater detail. Discussion of test results for one or more of these investigations is being considered for future papers.

INSTRUMENTATION EQUIPMENT

Faced with the problem of running an evaluation program of such diversity in a relatively short period of time, an instrumentation system was designed to allow for the simultaneous acquisition of data for several of the previously mentioned investigations.
Fig. 7 Data acquisition system

Fig. 8 Vibration and rotor dynamics instrument group

Utilizing an 8 x 30 ft trailer, a field instrumentation center was erected adjacent to the machine, inside the turbine building. This arrangement eliminated the necessity of exposing any instrumentation components to adverse weather conditions.

This instrumentation center housed three distinct but interconnected sets of instrumentation, the heart of which was the computerized Data Acquisition System (DAS), shown in Fig. 7. The computer, mounted in the center console, was addressed by means of the teletype mounted on top. This teletype also served as the print out mechanism. The magnetic tape and the pressure sensing scanning valves were located in the left console, while counters indicating oil flows can be seen on the right. The right cabinet also contained the multiplexer which read all of the electrical signals at a rate of eight inputs/sec. and fed them to the computer.

While allowing the acquisition of a large quantity of steady state data in a short time interval and with a minimum of manpower, the primary asset of the DAS was the capability of measuring complete transient engine characteristics. DAS vendor delivery problems made it necessary to assemble and check out the DAS at the Blue Lake site. For this reason, manual
backup instrumentation of key parameters was provided.

The vibration and rotor dynamics instrument group, shown in Fig. 8, included a tachometer/phase meter, a real time spectrum analyzer, a two pen x-y plotter, an oscilloscope with camera, as well as its own magnetic tape recorder.

For the analysis of gaseous exhaust emissions, a portable emissions panel was designed and built. Fig. 9 shows the arrangement of the instruments while Fig. 10 presents them in schematic form. As can be seen, the parameters measured were: CO₂, CO, excess O₂, and NOx. The front face of the panel also included a hygrometer, which provided ambient temperature and relative humidity, and a dryer to remove moisture from the sample gas.

Both the vibration and emission instrument groups provided proportional voltage outputs which could be recorded and stored by the DAS.

PERFORMANCE TESTING

The parameters defining gas turbine performance serve as the means of correlation for most of the other forms of test data. For this reason, as well as providing the basis for the confirmation of the gas path design, it was the first task undertaken and continued throughout the program.

In order to determine the gas path component performance and operating conditions, signals from 304 measuring points, including 220 thermocouples and 63 pressure points, were fed to the DAS. Metal as well as gas temperatures were measured with the latter including combustor discharge and turbine inlet temperature rakes. Each test consisted of recording all of the previous data at loads ranging from Base (or Peak) to No Load. In this way, it was possible to test at various ambient temperatures and evaluate the ambient correction curves.

The transient testing consisted of recording selected groups of parameters at small intervals throughout starts and loadings as well as various types of unloadings and shut downs. One test of specific interest involved a series of consecutive starts, which revealed the change in starting profiles with increasing initial temperatures of the machine. Data recorded included 63 temperatures, compressor discharge pressure, fuel flow, generator power output, rotor speed, as well as starter motor information. The DAS allowed this data to be read every 15 sec.

INLET AND EXHAUST SYSTEM TESTING

Early studies of pressure loss data showed that improvements in the inlet and exhaust systems were possible. Pressure profile tests were run in both areas. In the case of the exhaust diffuser, five directional pressure sensing probes were used to develop pressure and velocity profiles at the entrance, center, and exit. As a result, flow straighteners at the diffuser entrance were added. Excess inlet pressure loss was detected and traced to a set of sound reflectors mounted in the air intake. Removal of these reflectors reduced the inlet loss to guarantee without a detectable increase in noise at ground level.

To accurately evaluate near and far field noise and to provide data on which present and future sound attenuation designs can be based it was decided to determine the source noise levels. This was accomplished by installing and analyzing the sound recorded by two microphones, one in the inlet duct and one in the exhaust stack. In the latter case, a special,
Fig. 12 Exhaust emissions sampling ports

Fig. 13 Water injection system for Blue Lake test

A water cooled microphone was utilized to withstand the exhaust gas temperatures.

VIBRATION AND ROTOR DYNAMICS TESTING

As previously mentioned, the monitoring of vibrations proved extremely useful in making final adjustments to the combustor. This was a side benefit to a program whose primary purpose had been to determine the synchronous and nonsynchronous lateral vibration characteristics of the rotor train. Individual component rotors (Gas Turbine, Intermediate Block, and Generator) are factory tested and balanced at speed. This investigation provided the opportunity to analyze the entire rotor train as installed and erected. A comparison of analytical analysis and test results showed excellent agreement and no field balancing was required.

BLADE TEMPERATURE TEST

The GT7As at Blue Lake included cooling of only the first stage turbine vanes. However, a future model calls for additional cooling. In order to obtain actual test data for comparison to design calculations, a test comparing the metal temperatures of corresponding cooled and uncooled blades and vanes was carried out. This was a sizable undertaking since it involved splitting the turbine twice to install and remove instrumented vanes and blades. The entire test was completed in the period of one month including the shipping of the rotor back to the factor for instrumenting and balancing during one of the two disassemblies.

Stator vanes were instrumented with precision thermocouples. In the case of the rotor blades, three methods which eliminated the use of thermocouples, with their need of slip rings to transmit their signals to the recording instruments, were evaluated. These consisted of temperature sensitive paint, thermal plugs, and the Method of Kryptonates. Temperature sensitive paints undergo unique changes in color when exposed to certain temperatures for short periods of time. Use of a variety of these, on each blade in question, provides an indication of the maximum temperature reached. This method requires visual inspection and/or photography following the test.

Thermal plugs are metal pieces, recessed into the blade, which undergo predictable hardness changes as a function of temperature. A material for the temperature range in question must be selected. The hardness versus temperature relationship can be determined in the laboratory using material from the same batch used to make the plugs.

The Method of Kryptonates involves exposing portions of blades to krypton gas and heating the sample. This makes the blade radioactive. The kryptonated part is then installed into the engine and exposed to the operating condition for approximately an hour. During this period some of the krypton gas trapped in the metal is released, resulting in a new, stable and lower krypton level. This level will not be further reduced, unless the equilibrium temperature is exceeded.

The blades are then removed and the measurement is made by reheating the sample in successive, known steps. Following each step the sample is removed from the reheat furnace and the level of radioactivity measured with a registered trademark of Panametrics, Inc.
a geiger counter. The level of activity will remain constant until the reheat temperature exceeds the unknown temperature, which can then be determined from the intersection of the two lines as shown in Fig. 11.

The test was run in two parts, the first of which exposed the measuring points to operating temperature for 10 min. After the machine was sufficiently cool the turbine was entered by means of the combustion chamber for the purpose of visual and photographic inspection of the temperature sensitive paints. The engine was then restarted and operated at temperature for 50 additional minutes before removing the instrumented blades and vanes for analysis.

EXHAUST EMISSION TESTING

The most detailed testing was done in the area of determining exhaust emission levels. Due to the scope of this test, as well as the fact that emission levels will be of interest at future sites, the decision to develop an emission panel was made. In addition to a cost savings this provided the flexibility in scheduling not present when working with an independent test laboratory.

Fig. 12 shows the locations of the 30 sampling ports. These six probes, each equipped with five ports, were used to determine both the radial and circumferential profiles, with NOx being of particular interest. The data acquired at three load levels, provided the basis for the selection of two representative ports, which were then equipped with remotely operated solenoid valves to facilitate sampling.

The next step was to determine the load profiles of all emission levels. In addition to defining the characteristics of the Blue Lake machines, it provided a baseline curve for the investigations to follow, during which the combustion process would be altered. The first of these changes was to reconfigure the combustion chamber by installing an outer swirler with a smaller flow area. This diverted more air through the inner swirler resulting in a leaner mixture in the primary combustion zone. An increase in emission levels as well as smoke was found and the original outer swirler was reinstalled.

The fuel burned at Blue Lake was a No. 2 home heating oil with a low nitrogen content. To simulate a lower grade oil, a nitrogen additive was mixed with the fuel in the tank truck to obtain the desired nitrogen concentration. Mixtures, with up to 5000 ppm of nitrogen, were tested to determine the conversion of fuel bound nitrogen to NOx.

Since several future installations require the use of water or steam injection, a temporary water injection system was set up at Blue Lake. A schematic of this system is shown in Fig. 13. The components, internal to the combustion chamber, consisted of a circular manifold which fed 12 nozzles. These passed through the outer swirler to a plane just below the tip of the fuel nozzle. Despite the fact that the injection system was not a permanent part of the Blue Lake units, the appropriate protection devices were installed. A pressure switch, shown downstream of the final check valve, prevented overheating the turbine in case of water system malfunction by tripping the gas turbine. In addition, the water system was tied into the #7 trip relay to prevent quenching of turbine parts in case of an emergency trip.

Again, the accessibility of burner ports allowed several configuration changes in the injection nozzles and in so doing permitted an exploratory search for the optimum injection pattern, both from a standpoint of NOx reduction and combustion stability. By varying nozzle diameter, the effect of injection velocity was investigated. The change of injection direction revealed that the optimum configuration was achieved when the water jets barely made contact with the flame cone.

The primary result was the determination of NOx reduction factor as a function of water flow rate (at water to fuel mass ratios of up to 2.8), while achieving stable combustion throughout this range.

CONCLUSION

Successful optimization of the combustion process of the first unit demonstrated the advantages of the single burner/combustion design. The knowledge, that inner swirler configuration and vertical position of the outer swirler are primarily factors influencing combustion performance, will be incorporated into future burner designs.

In looking back at the Blue Lake test program, it is apparent that the wealth of technical information gained was not limited to test data. Future test programs will benefit greatly from the experiences in instrumentation design, use of the computerized DAE, operation of an emission panel and test procedures, in general.