FIELD CONVERSION FROM SIMPLE CYCLE TO REGENERATIVE CYCLE OPERATION OF EXISTING GAS TURBINES

WINSTON A. JOHNSON, II
El Paso Natural Gas Company

INTRODUCTION

As the world becomes more industrialized, gas turbines are providing a larger percentage of the industrial horsepower. Industrial gas turbines are purchased and installed both with and without exhaust heat recovery systems in the form of regenerators or recuperators. Regenerative cycle gas turbines have a fuel savings of approximately thirty percent when compared to simple cycle gas turbines. The installed cost of the regenerative cycle turbine may run as much as 15% greater than simple cycle. The rapid increase in fuel costs and the decline in fuel availability have made the installation of new gas turbines with the regenerative cycle operation more economically attractive. The improvement of the fuel consumption of existing simple cycle gas turbines by conversion to regenerative cycle may also be economically desirable.

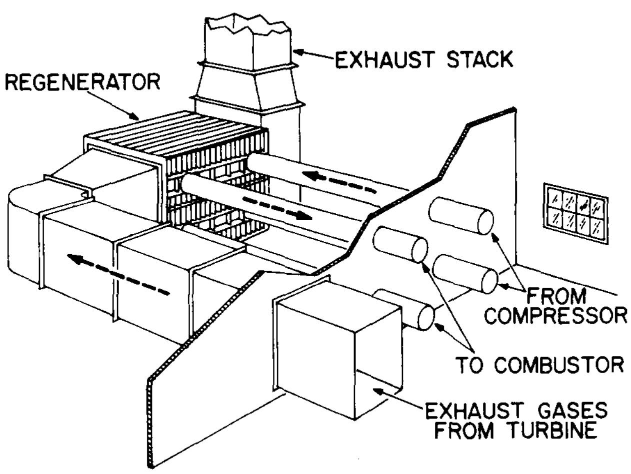

FIG. 1—TYPICAL REGENERATOR INSTALLATION (SIDE CONNECTION).
COURTESY OF GENERAL ELECTRIC

The compressed combustion air of the regenerative cycle turbine is routed to the regenerator before entering the combustion chambers. The air is heated in the regenerator by the gas turbine exhaust. An example of a typical regenerator installation is shown in Fig. 1. Figure 2 illustrates a typical mechanical flow diagram.

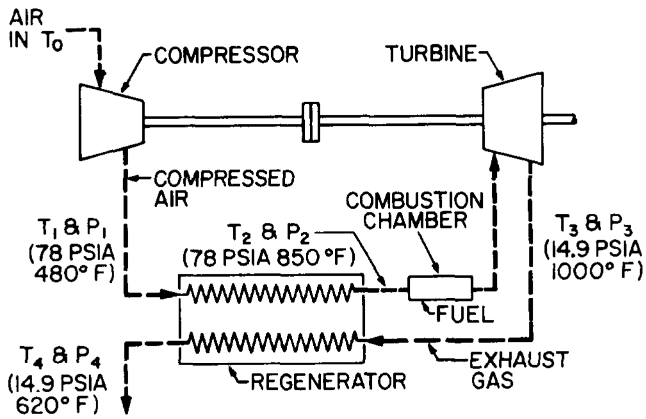

FIG. 2—FLOW DIAGRAM FOR REGENERATIVE CYCLE TURBINE.
COURTESY OF GENERAL ELECTRIC

In 1972, four existing simple cycle General Electric Model 3932 gas turbines were converted to the regenerative cycle and will be discussed in this paper. One of these four units illustrates the effect of the conversion. The site rating of the simple cycle gas turbine was 7900 brake horsepower (10,750 horsepower ISO). To improve the fuel consumption, this gas turbine was modified in the field to regenerative cycle at a total cost of $319,500. This modification increased the gas turbine thermal efficiency by 12 percentage points, reducing the fuel consumption by 31%. The decrease in fuel consumption justified the cost of the modification.

REGENERATOR DESIGN

The regenerators are large heat exchangers with an extended surface counterflow construction. They are constructed with air channels sandwiched between the exhaust gas channels. Figure 3 illustrates the construction of the sandwich of air and exhaust gas channels. The corrugated metal centers in the exhaust gas channels provide an added heat transfer capability. The construction of these regenerators allows for expansion and contraction in the flow dividers.

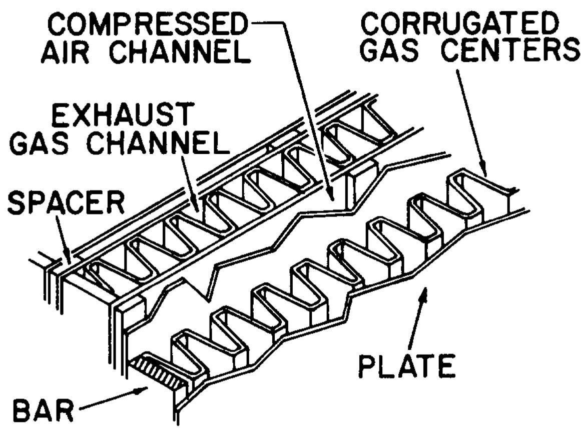

FIG. 3—TUBE CONSTRUCTION
COURTESY OF GENERAL ELECTRIC

ECONOMIC FACTORS

A comprehensive economic study was conducted to determine the desirability of converting the existing simple cycle turbines to regenerative cycle. The installation cost included the cost of the regenerator, gas turbine modification parts, labor, engineering expenditures, and other overhead. These estimates were based on the average cost of ten GE Model M 3932 gas turbines ranging from 4750 to 8700 simple cycle, site horsepower which were manufactured with external piping connections for the regenerator air piping. Thus the gas turbine modifications were not a major consideration in the total cost of conversion. The estimated cost for conversion of each gas turbine to regenerative cycle was $362,000 while the average actual cost for the four units converted in 1972 was $319,517. The actual installation cost and the breakeven cost of fuel for a regenerated unit is shown in Fig. 4. An annual estimated maintenance cost of $1800 has been included. The breakeven cost of fuel depends on the useful life of a regenerated unit and the expected load during the useful life. Based on these factors, each simple cycle gas turbine can be evaluated and a decision reached concerning the installation of a regenerator.

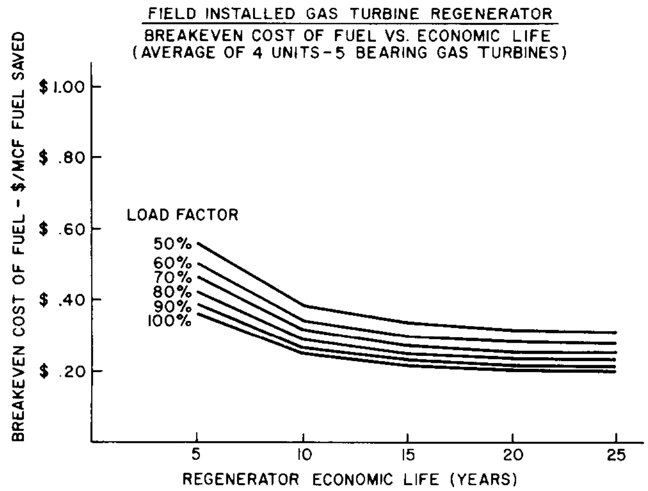

FIG. 4

In October 1973 one of the GE Model M3122 gas turbines was converted to regenerative cycle operation. The conversion of this unit cost approximately $465,000 which is substantially higher than the units previously modified. This additional cost is a result of the gas turbine being manufactured with internal air passages leading to the combustion section. Thus, there are no provisions for connecting the regenerator air piping to the gas turbine.

CONVERSION EFFECTS ON GAS TURBINES

At the time an existing gas turbine is converted in the field from simple cycle operation to regenerative cycle operation, certain performance characteristics will change. The four units converted in 1972 were predicted to have a loss in horsepower of 5 to 7% with no change in firing temperature. However, a portion of the predicted horsepower loss was regained by raising the firing temperature.

The firing temperature of a regenerative cycle gas turbine can be raised without affecting the parts life because a more even combustion temperature distribution is obtained, eliminating hot spots. The air entering the combustion chambers of a regenerated unit is approximately 400° higher than the temperature of a simple cycle unit. With this higher combustion air temperature, the temperature of the combusted gases leaving the combustion chambers is very uniform in comparison with the simple cycle gas turbine. The units converted in 1972 were predicted to have less than a 2% loss in horsepower with the increased firing temperature. Units which are not at the maximum rated horsepower prior to the conversion can be uprated to regain additional power.

A few minor changes in the gas turbine controls were required on each of the four units converted. The fuel control settings were readjusted for the new firing temperature and the new fuel nozzles. Other control changes may be desirable which will gradually load the gas turbine to reduce the effect of thermal shock on the regenerator. If the operation of a regenerated gas turbine requires starts with rapid loading, then expensive repairs to the regenerator can be expected. Starts with rapid loading may cause such a severe thermal shock to the regenerator that large cracks will occur, resulting in leakage that will reduce the performance of the gas turbine. The regenerator supplier has recommended warm-up procedures to help reduce the thermal shock. When the gas turbine has been down for less than 24 hours, 30 minutes of warm-up time should be allowed before full load is reached. For downtimes in excess of 24 hours a warm-up of one hour is recommended.

INSTALLATION

The field installation of the regenerators required each of the four gas turbines to be out of service for approximately two weeks. Prior to each shutdown, all the concrete foundations were completed. The inlet air filter was moved to provide the clearance necessary for the regenerator and air piping on two of the units prior to the shutdown for the regenerator installation. This was accomplished by installing a 13-ft elbow section of inlet air duct and moving the inlet air filter to a slightly offset position.

The exhaust stack was removed after the shutdown, and the upper portion was set aside to be remounted at the top of an adapter section which was attached to the regenerator. The regenerator itself was mounted on a combination of spring supports and rigid supports. Approximately seven spring supports were provided with adjustable load carrying capacities. The rigid supports consisted of one fixed point and two skid plate supports. This combination of supports allows the regenerator to expand and contract as the temperature varies. It was necessary to use extreme caution when setting the 50-ton regenerator on the support system. The bottom half of the regenerator did not weigh enough to compress the springs to permit the regenerator to be attached to the one fixed point. Once both halves were set in place, the final alignment and final spring support adjustments were completed. The air piping and exhaust duct system were then installed and the entire regenerator system insulated.

REGENERATOR PERFORMANCE

It is normal practice for a purchaser to require performance guarantees on new equipment. New gas turbines which are installed with regenerators have the regenerator performance included in the gas turbine performance guarantees of brake horsepower and fuel consumption, and the gas turbines and regenerators are tested as one unit.

With the field conversion of a gas turbine to regenerative cycle, the regenerator manufacturer has no control of the gas turbine condition at the time the regenerator is installed. Therefore, the performance guarantees for a field-installed regenerator must be as independent of the gas turbine as possible.

At the time the four regenerators installed in 1972 were purchased, effectiveness, pressure drop and leakage rate were selected as guarantees. Effectiveness is the ratio between the compressed air temperature rise and the temperature difference of the exhaust gas inlet and the compressed air inlet to the regenerator. The formula is shown below and the temperatures correspond to those shown in Fig. 2 and are in °F.

$$\text{Effectiveness} = \left[\frac{T_2 - T_1}{T_3 - T_1} \right] \times 100 \qquad (1)$$

During the performance testing of the four regenerators installed in 1972, the effectiveness was found to range from 73.0 to 76.5%. Once the effectiveness is determined on a particular unit, it is often used as a simple regenerator condition indicator.

The total pressure drop, calculated in percentage, is the second performance guarantee. The pressure drop of a regenerator is normally given as a percent total pressure drop. The sum of the actual pressure drops divided by the inlet pressure for the exhaust gas side and the inlet of the air side, respectively, is the total pressure drop in percent.

$$\% \Delta P_{total} = \% \Delta P_{air} + \Delta P_{exhaust} \quad (1)$$

$$= \left[\frac{(P_1 - P_2)}{P_1} + \frac{(P_3 - P_4)}{P_3}\right] \times 100$$

The pressures indicated in the equation are illustrated in Fig. 2 and are in psia. The field performance tests of these regenerators indicated the total pressure drop to vary from 3.9 to 4.77%.

The third guarantee is leakage rate. Leakage rate is calculated in percent of leakage based on the design air flow rate. There are at least two methods of calculating leakage rates. The first method requires that the manufacturer furnish a constant (c) for a given regenerator.

$$\% \text{ Leakage} = \frac{K(c)\left(\ln \frac{P_i}{P_f}\right)}{\Delta \Theta} \quad (1)$$

c = constant furnished by the regenerator manufacturer and based on design air flow rate, regenerator air side volume, and the design pressure and temperature.

P_i = The initial test pressure in the regenerator of approximately 60 psia.

P_f = The final test pressure in the regenerator at the end of the period. Normally determined during the test and approximately 15 psi less than P_i. This pressure is given in psia.

$\Delta\Theta$ = The time in seconds for pressure in the regenerator to drop from P_i to P_f.

$K = \sqrt{\frac{540}{T_t + 460}}$ The temperature correction factor for ambient conditions other than 80°F.

T_t = The ambient temperature during the test in °F.

The second method of calculating the regenerator leakage rate is as follows:

Leakage rate at test conditions:

$$L_t = 2.7 \frac{\Delta P}{T} \frac{1}{\Delta\Theta} = \text{lb air loss/sec}$$

Leakage rate at operating conditions:

$$L_o = L_t\left(\frac{T}{T_m}\right)^{1/2}\left(\frac{P_o}{P_t - \Delta P}\right) = \text{lb air loss/sec}$$

Percent leakage at operating conditions:

$$\% \text{ Leakage} = \frac{L_o}{Q} \times 100 = \% \text{ by weight flow} \quad (2)$$

V = Regenerator air side volume (ft^3)

P_t = Initial regenerator test pressure (psia).

P_o = Regenerator operating pressure (psia).

ΔP = Regenerator pressure drop during test (psia).

T = Air test temperature (°R).

T_m = Mean air side operating temperature (°R).

$\Delta\Theta$ = The time in seconds for the test pressure drop (ΔP) to occur.

The performance tests on the four regenerators indicated that the leakage rate ranged from 0.001 to 0.73%.

During these tests the necessary data was taken to determine the brake horsepower developed, fuel consumption, and turbine efficiency. The gas turbine brake horsepower developed during these tests met or exceeded that predicted by the manufacturer. The turbine efficiency ranged from 30.5 to 32.6 at full load conditions. The fuel consumption on these units ranged from 96 to 98% of that predicted by the manufacturer. Thus the results of these tests showed that a fuel savings of approximately 30% has been realized with the installation of regenerators on the four gas turbines in 1972.

Another effect of the installation of a regenerator is the reduction of noise emitted from the exhaust stack. Sound level readings were taken at one of the installation sites prior to and following the addition of the regenerator. The sound level approximately 600 ft from the unit was reduced from 72 dbA to 61 dbA. The sound level at other points closer to the building housing the gas turbine was reduced generally by 10 dbA. This particular gas turbine did not have any exhaust silencing prior to the regenerator installation.

REGENERATOR TESTING

The leakage rate tests were completed prior to the installation of the regenerator air piping by placing blind flanges over the regenerator air piping flanges. A one-inch air line from an air compressor was attached to one of the blind flanges to supply the pressurizing air, and a thermowell with a test thermometer was inserted into the air chamber of the regenerator. A barometer, stop watch, and a test gauge, incremented in 0.2 lb, were also used during the leakage rate test. The regenerator was pressurized with air to slightly over 50 psig and then the air supply was shut off. The elapse time required for the air pressure in the regenerator to drop from 50 to 35 psig was recorded. This elapse time, the pressures, and temperature was the data necessary for the leakage test. Each regenerator half was tested at least twice in this manner.

This leakage test could be accomplished with the regenerator piping installed by placing 1/4-in. blind plates between the piping flanges at the regenerator. In this manner this test could be run on existing regenerators during repair work. It could be used to determine when sufficient repair work has been accomplished.

The effectiveness and pressure drop test data was taken with the gas turbine at full load or the maximum horsepower capability for the test conditions. The temperature measurements required to compute the regenerator effectiveness were made with thermocouples and a potentiometer. Four thermocouples were located in the regenerator air piping of the regenerator piping flanges. Eight other thermocouples were located at the exhaust gas inlet to the regenerator. The pressure measurements for the pressure drop test were made with two water manometers, a test gauge, and a barometer. The regenerator air side differential pressure was measured with a 50-in. manometer, and the exhaust side pressure drop was measured with a 10-in. manometer. The regenerator air side inlet pressure was measured with a 0.2 psi incremented test gauge, and an aneroid barometer indicated the barometric pressure.

Prior to taking the data for each effectiveness and pressure drop test point, the gas turbine exhaust temperature and gas producer speed were checked to ensure that maximum turbine horsepower was being developed. The data of several test points was taken to compute the effectiveness and pressure drop.

Tests performed as described above were completed on the four units installed in 1972. But as a result of discussions with the regenerator manufacturer, additional tests were performed in the fall of 1973. Flows were measured, and a heat balance was calculated for the regenerator. The additional tests determined that a more elaborate test was needed and that different types of guarantee parameters were needed.

CONCLUSIONS

The installation of regenerators on existing gas turbines has become more economically attractive as fuel costs continue to increase. A fuel savings resulting from increased turbine efficiency, and possibly, a slight reduction in horsepower, are the characteristics which evolve with the conversion to regenerative cycle. The experience gained with the field installation of four regenerators in 1972 has lead to a decision to continue the regenerator installation program on other existing gas turbines. The installation economics and the relative ease of installation have been found to be favorable.

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