Analysis of Leakage Between HP and IP Turbines Using PEPSE

Marcus B. Caudill
Ronald D. Griebenow, P.E.

Santee Cooper

Analysis of Leakage Between HP and IP Turbines Using PEPSE

M. B. Caudill
Associate Engineer

R. D. Griebenow, P.E.
General Engineer

ABSTRACT

Accurate calculation of turbine efficiencies is the prime motivation behind performance testing. However, one area which has a substantial impact on calculated IP turbine efficiency is often neglected. This area is the internal leakage from HP to IP on opposed flow turbines, commonly referred to as "N2 Packing Leakage". Two methods to quantify N2 leakage were presented by Booth and Kautzman in the paper "Estimating the Leakage from HP to IP Turbine Sections." Our paper presents the practical application of the Booth and Kautzman methods in addition to an analysis of the effect that N2 leakage has on calculated IP and LP turbine efficiencies. By using the results of several N2 leakage tests to illustrate our testing and analysis procedures, we can help other performance engineers avoid the more common mistakes.

N2 PACKING LEAKAGE

Leakage from the high pressure to the intermediate pressure section of an opposed flow turbine through the number 2 packing (N2 packing) is not routinely measured during turbine performance tests. In test data analysis, a design packing flow coefficient is often used in the simplified Martin's formula (Reference 2) to predict the N2 leakage as a function of first stage pressure and specific volume. If the N2 packing has sustained no wear or damage, and is performing according to design specifications, the design flow coefficient will provide a good estimate of N2 leakage. However, if the packing has degraded, actual N2 flow can exceed design by more than three times. This increased leakage flow has significant effects on unit performance and calculated test results.

Effects of N2 Leakage

To understand the effects of N2 leakage, it is necessary to have an understanding of the N2 flow path in relation to the turbine main steam flow. Figure 1 is a schematic of the primary flow paths through the HP and IP turbines, including the N2 leakage flow path. N2 leakage affects test results in many areas of the turbine cycle. The most significant impact is on calculated values of IP turbine efficiency, LP turbine efficiency, and gross turbine heat rate.

First, increased N2 leakage decreases the mass flow through the HP turbine section downstream of the first stage. This causes a decrease in wheel power produced by the HP section. PEPSE's calculation of LP turbine efficiency uses measured generation, then subtracts HP and IP wheel power to calculate the generation produced in the LP. If an increase in N2 leakage is not accounted for, a higher than actual HP wheel power would be calculated. Therefore, a lower LP turbine wheel power would be required to produce the measured generation, which in turn would cause a lower than actual LP turbine efficiency to be calculated. Since pressures are an indication of the steam flow through the turbine stages downstream of the pressure measurement location, a large

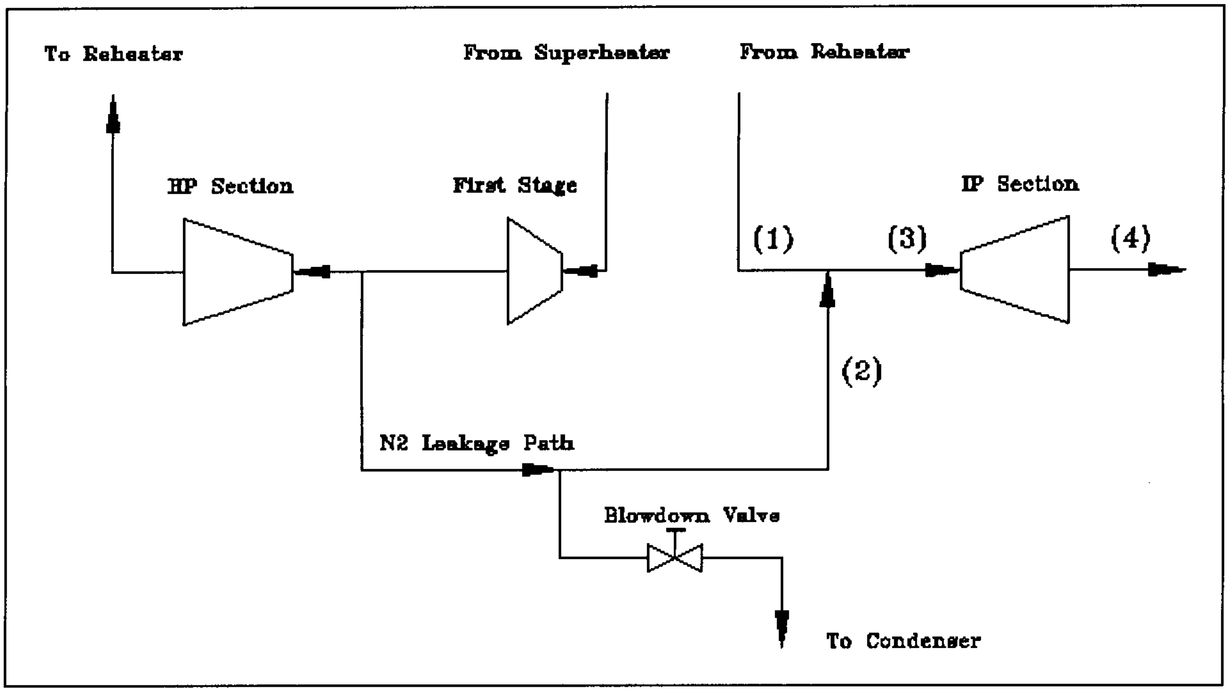

Figure 1 -- Leakage Flow Path

increase in N2 leakage could be indicated by a decrease in first stage pressure. Other measured turbine pressures would not change significantly because the N2 flow remixes with the primary steam flow prior to the first stage of the IP turbine.

Next, increased N2 leakage has a dramatic effect on calculated IP turbine efficiency. Hot reheat pressure and temperature are measured at location (1) in Figure 1, upstream of where the N2 leakage remixes with the primary steam flow, allowing the calculation of the enthalpy at (1). The enthalpy at (2) is the same as first stage enthalpy, however, the enthalpy at (3) can only be calculated if the flows at (1) and (2) are also known. Location (4) is the crossover between the IP and LP turbine sections and this enthalpy is also calculated from direct pressure and temperature measurements. An accurate calculation of IP turbine efficiency depends on knowledge of the enthalpy at locations (3) and (4), therefore the flows at (1) and (2) must be obtained. Since these flows are interdependent, if either flow can be obtained, the second flow is easily calculated. The following example illustrates the importance of N2 leakage in the IP efficiency calculation. These calculations use valves wide open design pressures and temperatures to calculate IP turbine efficiency. The first calculation assumes 25000 lbm/hr of N2 leakage flow, while the second uses 50000 lbm/hr.

With 25000 lbm/hr Leakage:

T_1 = 1000°F
P_1 = 515.6 psia
h_1 = 1519.9 Btu/lbm
m_1 = 1687608 lbm/hr

h_2 = 1438.2 Btu/lbm
m_2 = 25000 lbm/hr

T_4 = 650.8°F
P_4 = 123.7 psia
h_4 = 1353.5 Btu/lbm
$m_4 = m_3$
h_{4s} = 1328.8 Btu/lbm

$m_3 = m_1 + m_2$

Calculate h_3: $h_3 = (m_1h_1 + m_2h_2)/(m_1 + m_2) = 1518.7$

$$\text{Efficiency} = \frac{1518.7 - 1353.5}{1518.7 - 1328.8} = 0.8699$$

With 50000 lbm/hr Leakage:

T_1 = 1000°F
P_1 = 515.6 psia
h_1 = 1519.9 Btu/lbm
m_1 = 1662654 lbm/hr

h_2 = 1438.2 Btu/lbm
m_2 = 50000 lbm/hr

T_4 = 650.8°F
P_4 = 123.7 psia
h_4 = 1353.5 Btu/lbm
$m_4 = m_3$
h_{4s} = 1325.7 Btu/lbm

$m_3 = m_1 + m_2$

Calculate h_3: $h_3 = (m_1h_1 + m_2h_2)/(m_1 + m_2) = 1517.5$

$$\text{Efficiency} = \frac{1517.5 - 1353.5}{1517.5 - 1325.7} = 0.8551$$

The resulting change in calculated IP turbine efficiency of 1.5 percent illustrates that unaccounted increases in N2 leakage could mask significant degradation in the IP turbine, or provide a false indication of improved IP turbine efficiency.

The masking effect on IP turbine efficiency also has an effect on calculated LP turbine efficiency. Because the IP efficiency is incorrect, the calculated IP wheel power is also incorrect, yielding a similar effect on LP efficiency as the flow error in the HP turbine section. The apparent increase in IP efficiency decreases the required output of the LP section and, therefore, reduces the calculated LP turbine efficiency.

Finally, an erroneous value of N2 leakage will increase the calculated uncertainty of IP efficiency, LP efficiency, and turbine heat rate results. The effects on turbine efficiency uncertainty can be clearly seen from the preceding discussions. The effect on heat rate is caused by the incorrect value of reheat flow. All of these errors make it essential to quantify N2 leakage flow.

METHODS TO QUANTIFY N2 LEAKAGE

Two methods, blowdown and temperature variation, are currently accepted for evaluation of N2 packing leakage using existing plant hardware. Each method has unique advantages and disadvantages, but both require the disruption of normal plant operation.

Blowdown Method

The blowdown method uses the emergency blowdown valve to divert the N2 leakage from the IP turbine inlet to the condenser. The emergency blowdown valve is a safety mechanism designed to prevent turbine overspeed by removing HP turbine leakage steam and passing it directly to the condenser, bypassing the entire IP and LP turbine sections. According to Booth (Reference 6), the flow passing capability of the blowdown valve should be more than sufficient to remove all of the N2 leakage from the turbine and route it to the condenser. This would make the energy at location (1) in Figure 1 equal to the energy at location (3). By eliminating all of the flow at location (2), the actual IP turbine efficiency can be calculated directly. The IP efficiency is then used with data collected when the blowdown valve is closed to calculate the N2 leakage flow.

Unit Set-up

According to GE, the blowdown test should be run below 50 percent load, with the blowdown valve open for no longer than 30 minutes. This allows approximately 15 minutes for the unit to stabilize and 15 minutes to collect data. The steps we follow for this test are:

(1) Bring unit to 50 percent load.

(2) Allow unit to stabilize at design throttle and hot reheat conditions.

(3) Begin data acquisition and collect 30 to 60 minutes of performance test data.

(4) After checking unit stability, begin data acquisition for blowdown test.

(5) Open blowdown valve.

(6) After data is collected for 30 minutes, close blowdown valve.

Analysis of Blowdown Test Data

The first step in data analysis is the calculation of IP turbine efficiency with the blowdown valve open. Check data stability on the full 30 minutes and analyze the largest stable section. Then put the data into a PEPSE test data model and run it with N2 leakage flow set equal to zero. If all N2 leakage is diverted through the blowdown valve, this will yield an actual IP turbine efficiency. Next, the data set with the blowdown valve closed is used in conjunction with the blowdown open IP turbine efficiency. In this model, N2 leakage is controlled to yield the blowdown open IP efficiency.

Results of Blowdown Tests

We have run blowdown tests on three different units, with very consistent results. Unfortunantly, the blowdown results did not replicate the results of the temperature variation tests. In fact, the calculated leakages from the blowdown tests do not vary far from design, as can be seen from Table 1. It should be noted that the blowdown tests on Jefferies 3 and 4, which are identical units, calculate very similar leakage flows. This indicates that the blowdown valves are flow limiting. A calculation of the flow passing capability of the Winyah 1 blowdown valve at test boundary conditions resulted in a maximum calculated flow very near the 2.4 percent indicated by the test data analysis.

Table 1 -- Blowdown Test Results

UNIT	DESIGN LEAKAGE	BLOWDOWN RESULTS
Jefferies 3	2.2 %	1.29 %
Jefferies 4	2.2 %	1.24 %
Winyah 1	1.9 %	2.44 %

One advantage of the blowdown test is that a true IP turbine efficiency is calculated at the tested load, allowing N2 leakage to be calculated directly. In addition, only 60 minutes of test data is required at one load. However, these are only advantages if the blowdown system is capable of passing the entire N2 flow. Before attempting to run a blowdown test, the flow passing capability of the blowdown valve should be calculated.

Temperature Variation

The temperature variation method uses the difference between the enthalpy at the first stage of the HP turbine and the enthalpy at the IP turbine inlet to estimate N2 leakage. First, throttle temperature is depressed to achieve the maximum cooling effect of N2 leakage on the IP bowl conditions. The system response is measured and recorded, then hot reheat temperature is depressed to minimize the cooling effect of N2 leakage on IP bowl conditions. This varies the enthalpy difference between the first stage and the IP inlet and thus, the slope of a line relating an assumed N2 leakage and the resulting IP turbine efficiency. The intersection of these results provides a unique solution for both the N2 leakage and the true IP turbine efficiency. The temperature variation method accounts for N2 flow and other leakages between the HP and IP turbines, such as snout ring leakage and leakage through the turbine case. These latter leakages are rare, however they should be kept in mind.

To run a temperature variation test, the hot reheat and superheat temperatures are set to a temperature differential of approximately 75^{O}F. For example, set hot reheat to 1000^{O}F and superheat to 925^{O}F. Test data is collected and IP efficiency is calculated using assumed values of N2 leakage from 0 percent to 10 percent of first stage flow. The results of these calculations are plotted as an IP efficiency vs. leakage flow trend (Figure 2, Depressed SH Temp). Next, the unit is set up with reheat temperature at 925^{O}F and superheat temperature at 1000^{O}F. Another set of test data is collected and IP efficiencies are calculated, again using the same assumed range of N2 leakages. The results are plotted on the same graph (Figure 2, Depressed RH Temp). The intersection of these trends indicates the true HP to IP leakage and the true IP turbine efficiency.

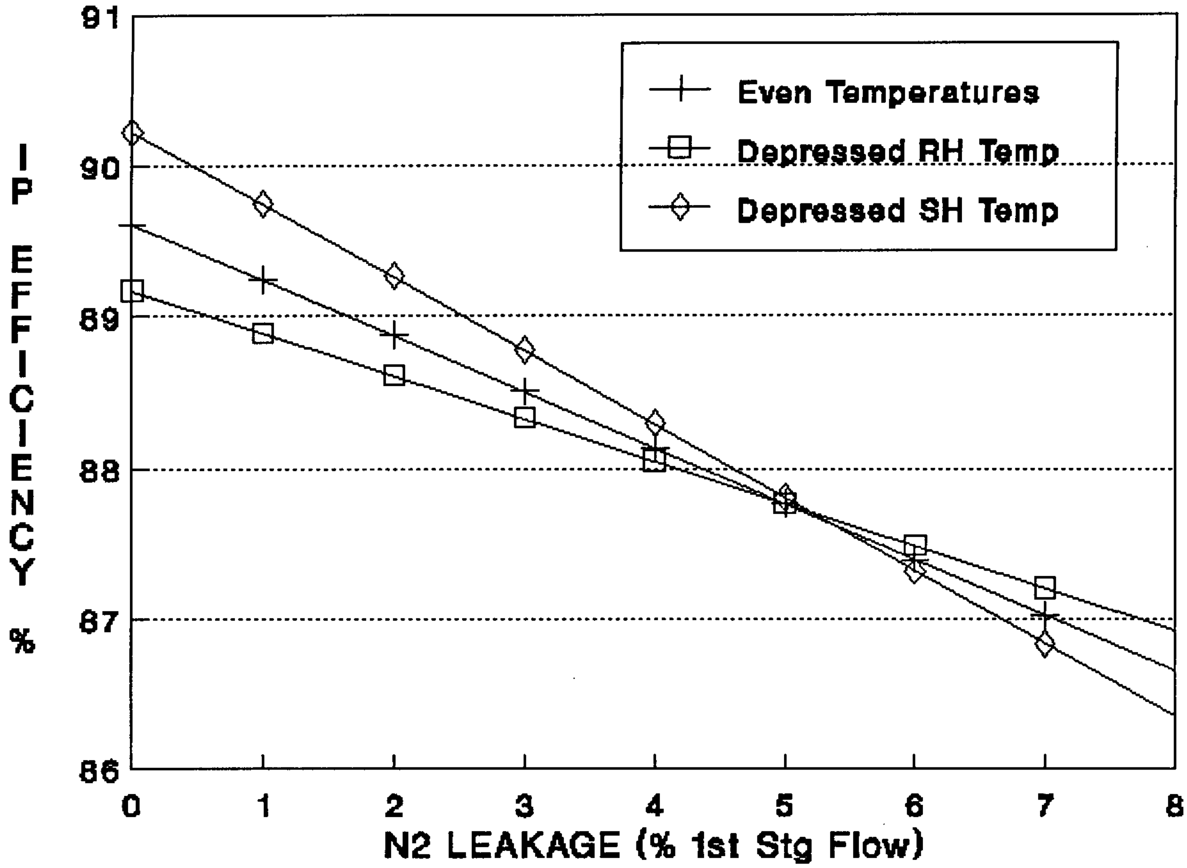

Figure 2 -- Assumed N2 Leakage vs. IP Efficiency

Results of Temperature Variation Tests

We have successfully run temperature variation tests on four units since beginning to analyze N2 leakage. Our studies indicate the results of the tests are sensitive to several items. Initially, there were concerns about sensitivity of the results to superheat sprays, throttle valve position, make up flow, continuous blowdown, unit stability, and first stage temperature. Studies based on PEPSE test data models indicate that unit set up has no significant effects, as seen in Figure 3. However, unit stability and the method used to determine first stage temperature do have a dramatic effect on calculated results.

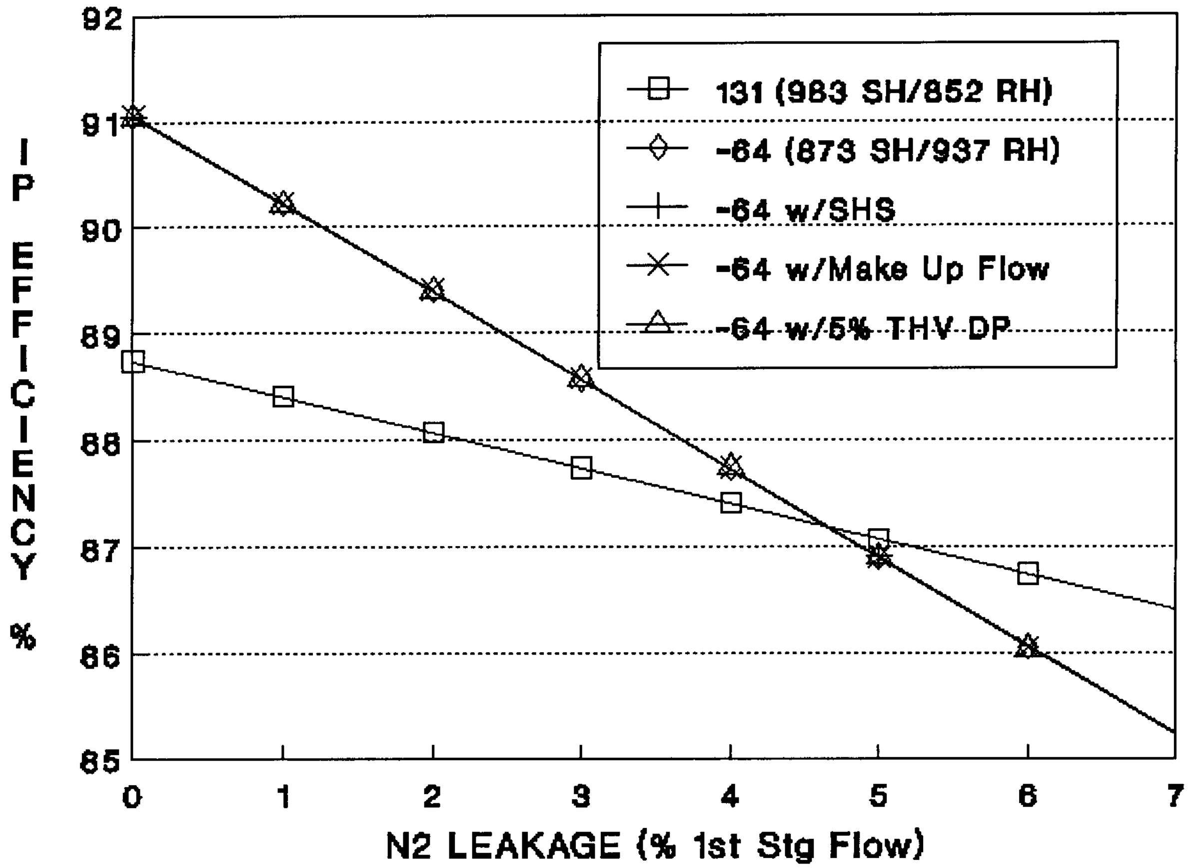

Figure 3 -- Unit Set Up Sensitivity - 150 Mw

Figure 4 is a graph of throttle temperature, throttle pressure and hot reheat temperature vs. time for one of the tests run at 220 Mw. Throttle temperature is stable for the entire 60 minutes, but throttle pressure and hot reheat temperature stabilize between 20 and 30 minutes. By breaking the data represented by this graph into two 30 minute segments, we can analyze the sensitivity to unit stability. In Figure 5, Test 1 corresponds to the first 30 minutes and Test 2 represents the second 30 minutes. Test 5 is a stable, depressed throttle temperature test at the same valve point. In this case, the difference between stable and unstable test results is about 0.5 percent in efficiency and 0.5 percent in leakage. As leakage increases, the sensitivity to test stability also increases.

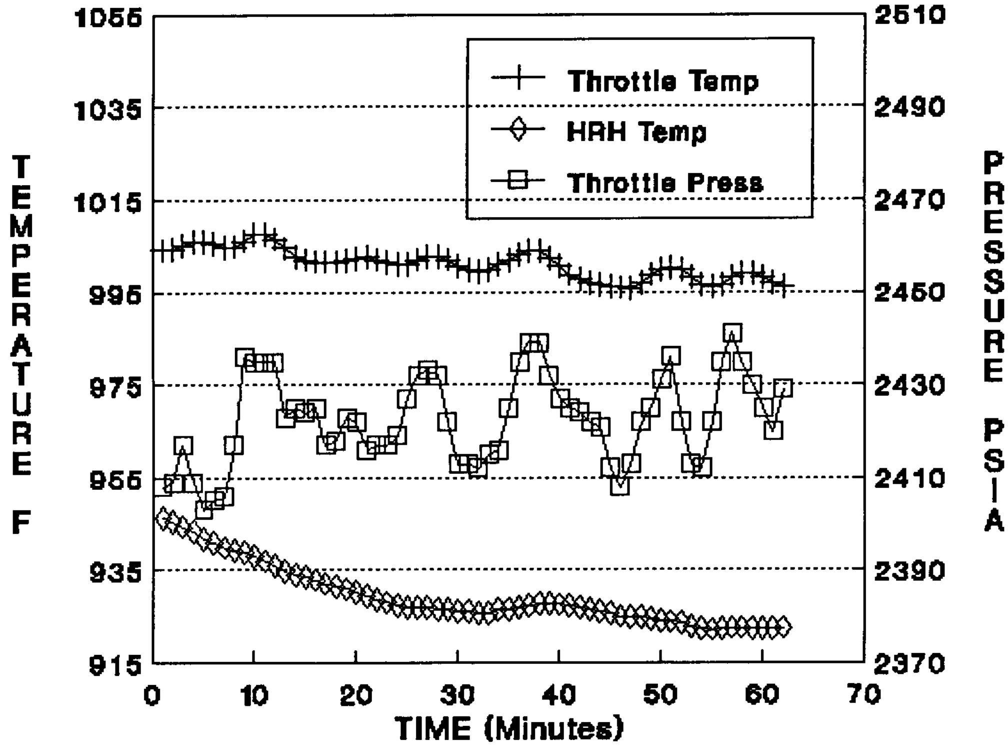

Figure 4 -- Test Stability - 220 Mw

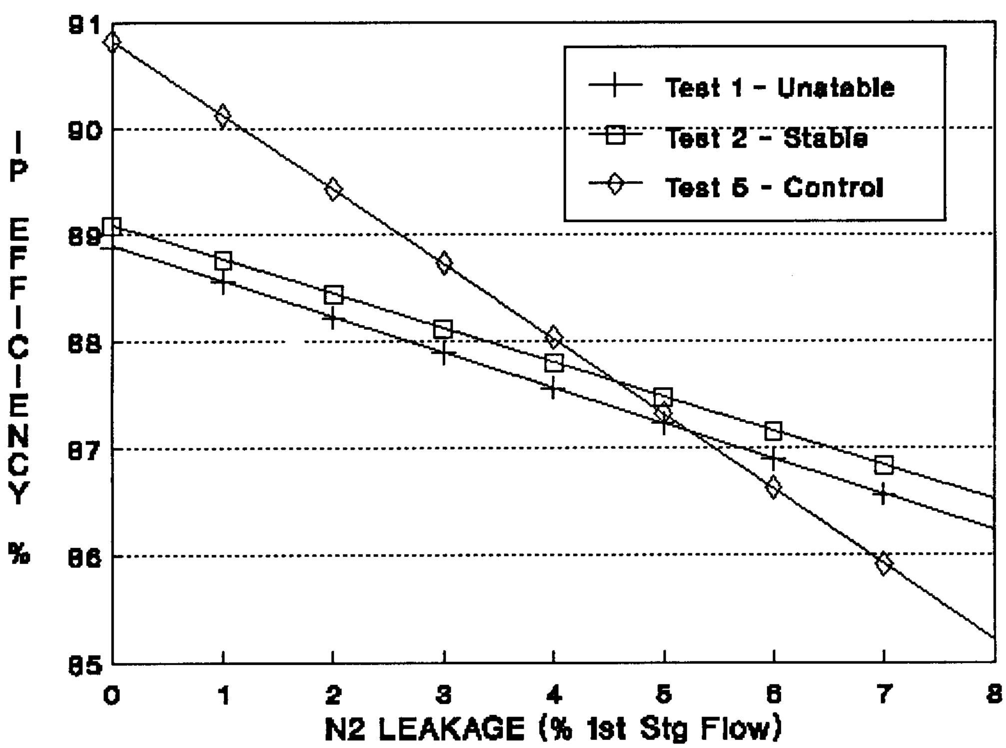

Figure 5 -- Test Stability Sensitivity - 220 Mw

Determining first stage conditions can be a difficult proposition because most turbines have no provisions for measuring first stage temperature. Using the measured first stage pressure, a number of methods are available to estimate first stage enthalpy. With a Type 8 turbine model, design first stage efficiency and measured pressure will yield one enthalpy, while a straight expansion line from HP bowl to cold reheat and the measured pressure yield a slightly different enthalpy. Figure 6 depicts the difference between results using the straight expansion line and design first stage efficiency. Note that although the IP efficiency shifts about 0.25 percent between the two different methods, the associated leakage is virtually identical. This indicates that for this particular case, calculated N2 leakage is not very sensitive to first stage efficiency. However, as in the case of unit stability, the higher the N2 leakage, the more sensitive the results are to the method used in determining first stage conditions.

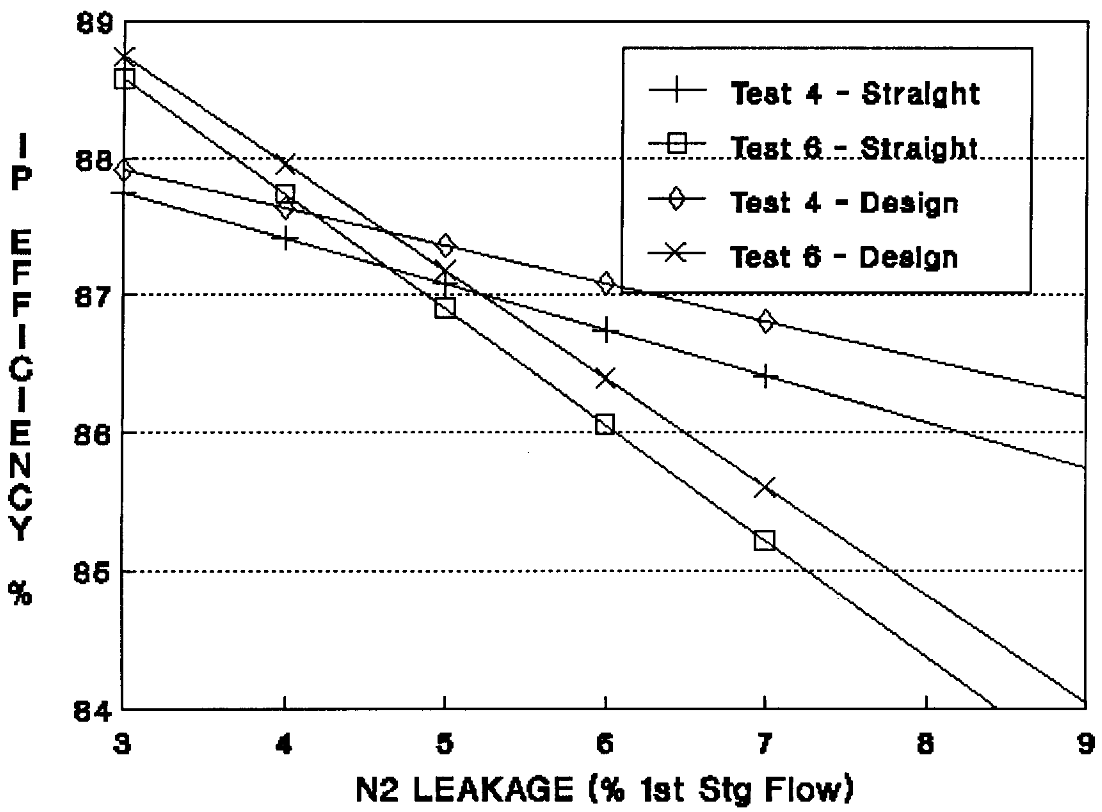

Figure 6 -- 1st Stage Efficiency Sensitivity

Figures 7, 8 and 9 present the results of our most recent series of N2 leakage tests run on Winyah Unit 2. Three hours of temperature variation data were collected on each of three different days, with very consistent results. All three loads indicate slightly less than five percent N2 leakage. The results of temperature variation tests on four Santee Cooper units are presented in Table 2. In the case of Jefferies 3, the calculated N2 leakage is almost five times design.

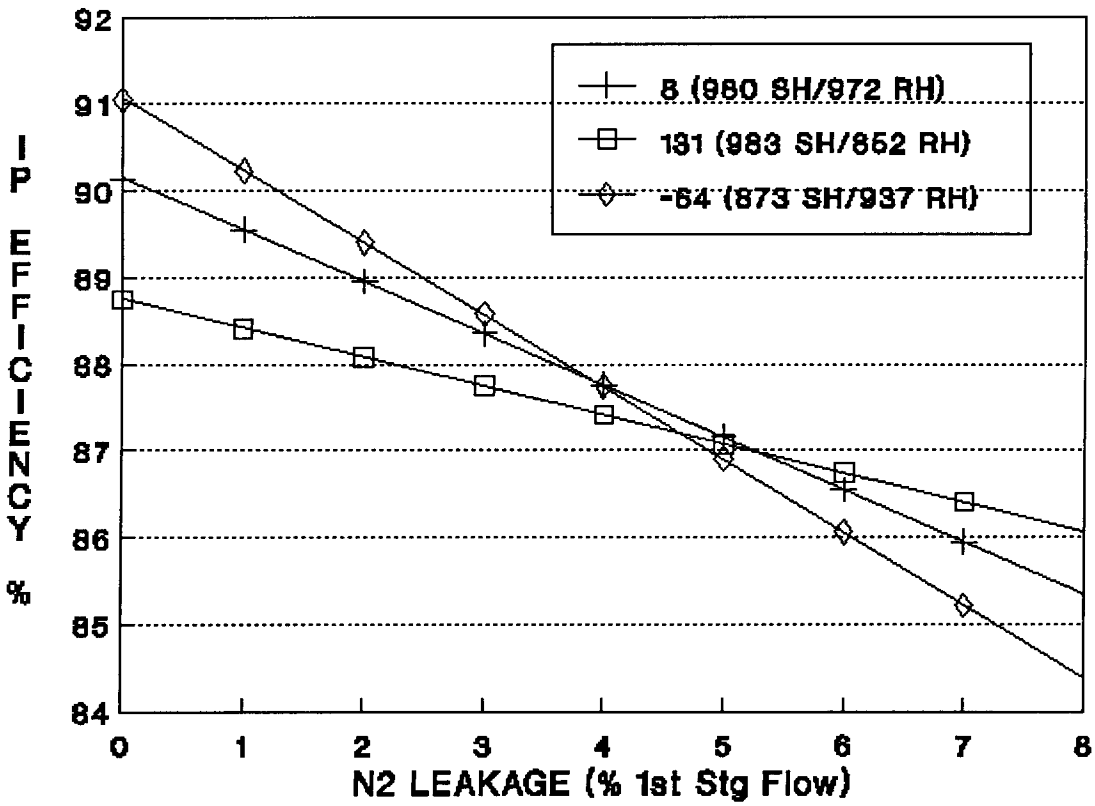

Figure 7 -- Winyah 2 N2 Leakage - 150 Mw

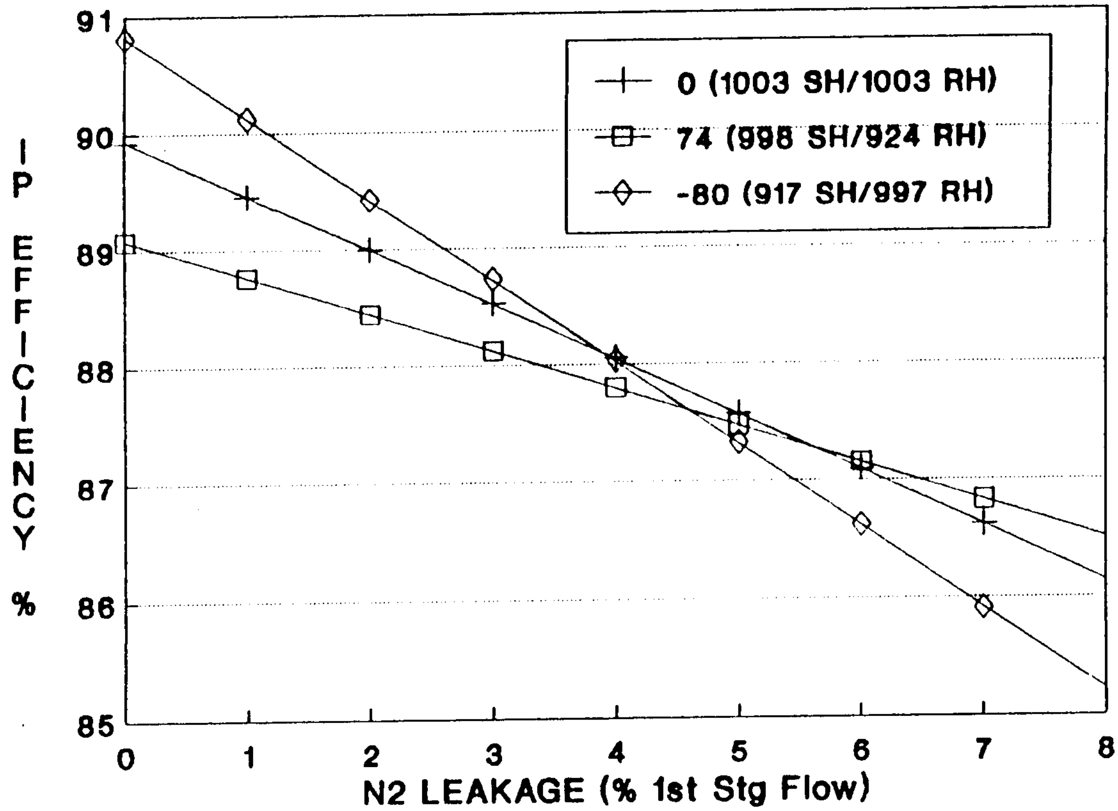

Figure 8 -- Winyah 2 N2 Leakage - 220 Mw

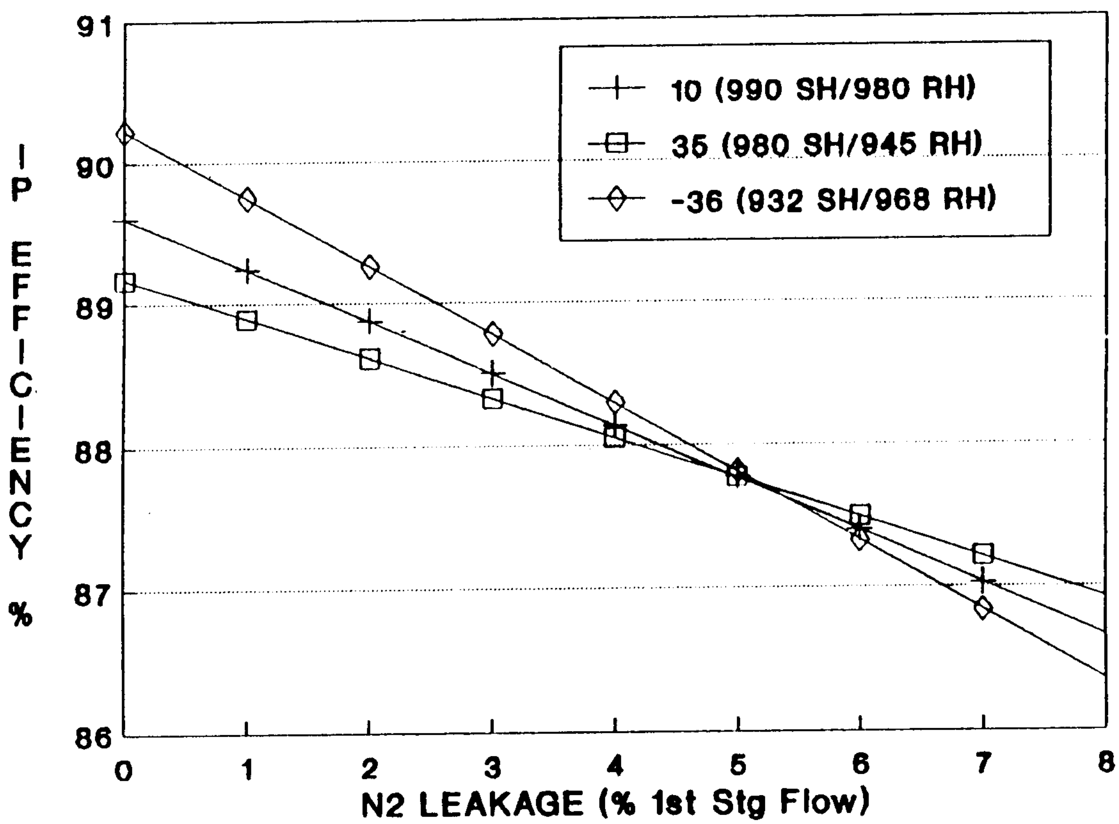

Figure 9 -- Winyah 2 N2 Leakage - 285 Mw

CONCLUSION

To date, the blowdown method has not been successful for measuring N2 leakage on any Santee Cooper unit. If the blowdown valve has sufficient flow passing capability to pass all of the N2 leakage flow, this test would be the easiest method to determine the true IP turbine efficiency.

Temperature variation provides a consistent and repeatable method for estimation of N2 leakage and IP efficiency. Proper care must be taken to obtain good unit stability and, a reliable, consistent method of obtaining first stage enthalpy should be employed. Temperature variation tests requires an extensive amount of time for adequate testing and analysis, however the resulting increase in performance test accuracy is worth the effort.

Table 2 -- Temperature Variation Results

UNIT	DESIGN LEAKAGE (%)	TESTED LEAKAGE (%)	IP EFFIC W/DESIGN LEAKAGE (%)	IP EFFIC W/TESTED LEAKAGE (%)
Jefferies 3	2.2	10	86.6	84.4
Jefferies 4	2.2	8	87.7	86.3
Winyah 1	1.9	8	90.3	88.3
Winyah 2	1.9	5	89.0	87.8

REFERENCES

The following references were used during the course of the analysis and in the preparation of this paper.

1 - PEPSE Computer Code, Energy Inc., PO Box 736, Idaho Falls, Idaho, Version 54P; 1988.

2 - PEPSE Manual: Volume I, User Input Description, Energy Inc., PO Box 736, Idaho Falls, Idaho, Revision 14; 1988.

3 - 1967 ASME Steam Tables, Second Edition, United Engineering Center, 345 East 47th Street, New York, N.Y.; 1968.

4 - ASME PTC 6, Steam Turbines, United Engineering Center, 345 East 47th Street, New York, N.Y. 10017; 1976.

5 - "Steam Turbine Performance Seminar Lecture Notes"; Cotton, K.C.; Encotech, Inc., P.O. Box 714, Schenectady, NY.; 1989.

6 - "Estimating the Leakage From HP to IP Turbine Sections"; Booth,J.A., Kautzmann,D.E.; EPRI Power Plant Performance Monitoring Conference/Workshop; 1984

7 - Jefferies Steam Electric Generating Station, Maintenance and Operations Manual Volume II-A; Steam Turbine and Electric Generator; GEI-84614

8 - Winyah Unit No. 1 Steam Turbine-Generator Thermal Performance Data, Heat Balance No. 371 HB 833, General Electric Company, Schenectady, NY