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DETERMINING HP-IP TURBINE SEAL LEAKAGE

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ABSTRACT

This paper presents a new method for determining turbine shaft seal leakages. Specifically the seals are those which flow from the High Pressure (HP) turbine to the Intermediate Pressure (IP) turbine when these machines share the same cylinder. This work began with the well-known Booth/Kautzmann Method, also known as an "Influence Test". The work was instigated given that routine success of Booth/Kautzmann has not always been assured. This work promotes two major modifications. First, an improvement is advocated in which the contribution from seal flows is weighted based on source energies; i.e., use of a strictly defined thermodynamic boundary. This applies to isentropes and exergy differences. However, the use of weighted isentropes does not guarantee that Booth/Kautzmann will always work. Second, the use of a convergence parameter is advocated which normalizes the influence of differing Reheat flows. This convergence parameter leads to a consistently computed seal flow which is quite suitable for routine monitoring. The new technique has a remarkable ability to detect inconsistent data.

Four case studies are presented: two conventional North American designs in which the HP seal is placed between the Governing Stage shell and 2nd HP stage group (termed the "Dummy Seal" or "N2 Packing" leakage); and two European designs in which the HP seal is exposed to turbine inlet conditions. Although several of these studies produced sharp convergences using Booth/Kautzmann with weighted isentropes, this work places doubt on their reliability.

Comments are offered on the technique's use, data reduction procedures and on further development. A sample spreadsheet has been made available for use by power engineers. PAPER-79_Rev21.DOC

NOMENCLATURE

$a = h_{HRH} - h_{IP\text{-}X}$ $\quad d = g_{HRH} - g_{IP\text{-}X}$
$b = h_{LKG} - h_{IP\text{-}X}$ $\quad e = g_{LKG} - g_{IP\text{-}X}$
$c = h_{HRH} - h_{IP\text{-}ise}$ $\quad f = h_{LKG} - h_{LKG\text{-}ise}$
g_k = Exergy state at k (Btu/lbm or kJ/kg)
$= (h_k - h_{Ref}) - T_{Ref}(s_k - s_{Ref})$
g_{HRH} = Hot Reheat exergy of main IP steam
$g_{IP\text{-}X}$ = IP turbine exhaust exergy
g_{LKG} = Source exergy of HP-IP seal leakage
h_{HRH} = Hot Reheat enthalpy of main IP steam
$h_{IP\text{-}ise}$ = Enthalpy of IP turbine at IP bowl entropy and IP exhaust pressure
$h_{IP\text{-}X}$ = IP turbine exhaust enthalpy
h_{LKG} = Source enthalpy of HP-IP seal leakage
$h_{LKG\text{-}ise}$ = Enthalpy of HP-IP leakage at its source entropy and IP exhaust pressure
m_{HRH} = Mass flow of main IP steam flow, per run
$m_{HRH\text{-}AVG}$ = Average of main IP steam flow, all tests
m_{LKG} = Actual mass flow of HP-IP seal leakage
$m_{LKG\text{-}0}$ = Initial mass flow of HP-IP seal leakage
x = Real incremental correction term $(\xi - \xi_0)/\xi_0$
iy = Imaginary incremental corr. term $i(\xi - \xi_0)/\xi_0$
ϵ_{IP} = IP turbine exergy effectiveness
η_{IP} = IP turbine isentropic efficiency
ξ = Final mass ratio (m_{LKG}/m_{HRH})
ξ_0 = Initial mass ratio $(m_{LKG\text{-}0}/m_{HRH\text{-}AVG})$
$S_{\Gamma m}$ or $T_{\Gamma m}$ => Summation of m terms of a series which corrects the seal flow ξ_0; all series coefficients are assumed unity.

INTRODUCTION

This paper presents a new method for determining turbine shaft seal leakages. Specifically the seals in question are those which flow from the High Pressure (HP) turbine to the Intermediate Pressure (IP) turbine when sharing the same cylinder. The source of this sealing steam may derive from the shell of the Governing Stage (typical of North American designs), or from turbine inlet (throttle valve) conditions (commonly found in Europe). The routing of seal flows can be complex, they may derive from a single source, or combined flows may be employed. It is not uncommon with North American designs to combine seal flows from the Governing Stage shell (termed the "Dummy Seal" or "N2 Packing" leakages) with the high pressure side of HP turbine end-seals. Whatever the design details, when sharing the same cylinder, the HP to IP turbine shaft seals may significantly degrade over time. Such degradation has serious consequences for thermal performance. Seal flows have been observed to exceed design by a factor of 2 to 4; for the older machines a factor of 3 is not uncommon. When degraded, it is typical to observe a decrease in HP isentropic efficiency (i.e., reduced turbine path flow results in higher exhaust temperatures), accompanied by higher computed IP turbine efficiencies (IP exhaust being affected by high seal flow, as its enthalpy is lower than hot Reheat).

It has been the experience of the authors, and many of their colleagues, that use of the well-known Booth/Kautzmann Method (Booth & Kautzmann, 1984) may not be successful. This technique employs a series of assumed leakage flows, causing computed IP isentropic efficiencies to change which, through graphical resolution, leads actual seal flow. Classically three runs are executed (we recommend four runs/test) in which HP and IP inlet temperatures are varied, thus the impact of seal flow on IP efficiency is evidenced:

Throttle at 1000 F (537.8 C) with
Hot Reheat at 1000 F (537.8 C);
Throttle at 1010 F (543.3 C) with
Hot Reheat at 975 F (523.9 C);
Throttle at 975 F (523.9 C) with
Hot Reheat at 1010 F (543.3 C); etc.

Of course, such test patterns vary widely as maybe governed by: individual practices; the tolerance one may have for turbine vendor recommendations; imposed limitations on turbine cylinder differential temperatures given combined HP and IP enclosures); the magnitude of seal flows; design of labyrinth packings; etc.

Historically a graphing of computed IP isentropic efficiency versus seal flow may not always indicate clear solution. This lack of success may be rooted in the choice of temperature changes, and especially when considering turbine cylinder ΔT restrictions; or may be due to fundamental errors in analysis techniques. The authors are aware of a few practitioners who might deliberately exceed manufacture's casing ΔT limits; this might lead to "a convergence" (but a convergence which may be meaningless).

The following section presents introductory development leading to the use of flow-weighted seal energies. This discussion is followed by two sections on new analysis techniques for determining seal leakages. Results from four turbine tests are then presented.

BASE DEVELOPMENT AND FLOW-WEIGHTED SEAL FLOWS

Isentropic efficiency is defined as the ratio of the actual enthalpy drop (the **term "a"**), divided by the isentropic drop (the **term "c"**). Exergy effectiveness (also known as "rational efficiency") is defined as the ratio of this same actual enthalpy drop, divided by the exergy drop (the **term "d"**). The change in a turbine's exergy is the only true measure of its theoretical ability to produce power without violating the Second Law (Lang, 2002). When considering the source of the seal steam entering an IP turbine's shaft space, its effects on efficiency or effectiveness will be pronounced if its enthalpy or exergy content is greatly different from the turbine's inlet conditions. The actual enthalpy drop associated with the seal leakage is taken from its source condition less the actual exhaust (assuming complete mixing, the **term "b"**). The isentropic drop of the seal leakage is defined using its source entropy and actual IP exhaust pressure (the **term "f"**). The actual exhaust conditions define the boundary exergy (leading to the **term "e"**). Thus the isentropic efficiency and exergy effectiveness associated with an IP turbine, employing HP leakage steam is given by the following weightings of leakage flow (m_{LKG}) and main IP steam flow (m_{HRH}):

$$\eta_{IP} = (m_{HRH}\, a + m_{LKG}\, b) / (m_{HRH}\, c + m_{LKG}\, f) \qquad (1A)$$
$$\epsilon_{IP} = (m_{HRH}\, a + m_{LKG}\, b) / (m_{HRH}\, d + m_{LKG}\, e) \qquad (1B)$$

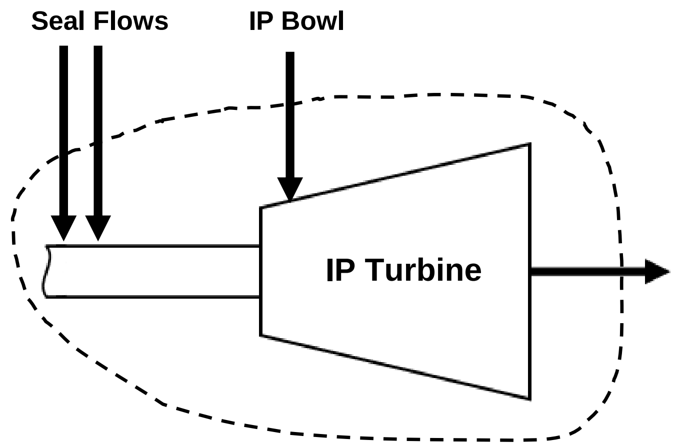
Dividing through by m_{HRH}, the ξ quantity becomes defined as the ratio of leakage steam to main steam flow:

$$\eta_{IP} = (a + b\xi) / (c + f\xi) \qquad (2A)$$
$$\epsilon_{IP} = (a + b\xi) / (d + e\xi) \qquad (2B)$$

It may be argued that an efficiency or effectiveness of an individual stage group should be weighted, allowing for a weighting sensitive to changes in extraction flow. This has not been traditional, the assumption being that the ratio of extraction flow to main steam flow is ≈constant over the range and period of testing. For this and other reasons, it is important that testing for seal flows be conducted over a short time span, at approximately the same load, using the same operational mode, and at steady state.

The following figure illustrates the assumed boundary which is applied for this work. We understand that use of source conditions for seal flows is arbitrary, but in practice we see greatly improved results.

Fig. A: Thermodynamic Boundary



For certain designs a secondary seal flow (as illustrated in Fig. A) may be employed. In addressing this, and complying with the proper weighting of effects, the following should be applied:

$$\eta_{IP} = (m_{HRH}\, a + m_{LKG1}\, b_1 + m_{LKG2}\, b_2) \,/\, (m_{HRH}\, c + m_{LKG1}\, f_1 + m_{LKG2}\, f_2) \qquad (3A)$$

$$\epsilon_{IP} = (m_{HRH}\, a + m_{LKG1}\, b_1 + m_{LKG2}\, b_2) \,/\, (m_{HRH}\, d + m_{LKG1}\, e_1 + m_{LKG2}\, e_2) \qquad (3B)$$

Again, dividing through by the main steam flow, a weighted seal flow and its energy may be developed; the ξ quantity then becomes defined as the ratio of the total leakage steam (m_{LKG1} + m_{LKG2}) to main steam flow. Therefore, for the case of two sources of seal steam:

$$b = (m_{LKG1}/m_{LKG})b_1 + (m_{LKG2}/m_{LKG})b_2 \qquad (4)$$
$$e = (m_{LKG1}/m_{LKG})e_1 + (m_{LKG2}/m_{LKG})e_2 \qquad (5)$$
$$\xi = (m_{LKG1} + m_{LKG2}) \,/\, m_{HRH} \qquad (6)$$

In the following discussion, when referring to data analyzed using the Booth/Kautzmann, what is meant is that it employs weighted isentropes, per Eqs.(2A) & (3A) as applicable; these results will be significantly different when compared to an application of Booth/ Kautzmann using un-weighted seal flows. In summary, seal flows are treated as separate streams through the IP.

SERIES SOLUTION TO SEAL FLOWS

Instead of assuming the ratio of seal leakage to main Reheat flow (ξ) is a simple constant, determined by graphical means by changing its value then computing η_{IP}, we choose to do the opposite. A fundamental concept is that ξ can be corrected using a series solution (remember we are dealing with a mathematical solution).

A series solution to ξ is fundamentally what any graphical approach is about. When one increments from an assumed flow, m_{LKG-0}, by some Δm_{LKG-0}, a series solution is being invoked. Thus a series representation of ξ may be viewed as a correction to an assumed (initial) leakage, ξ_0. Several points need to be made concerning a corrective series: 1) its terms need not be real, they may include imaginary components; 2) the summation of the series ($\mathbf{S}_{\Gamma m}$ or $\mathbf{T}_{\Gamma m}$) must be viewed as a multiplicative correction to ξ_0; 3) the value of ξ_0 may be higher, or lower, than the actual leakage ξ; and 4) any continuous series may apply (e.g., power, log or exponential).

It is the authors' experiences, based on numerous examinations of seal test data, that the chief reasons for inconsistent results lies with both faulty data collection and how the data is analyzed. How tests are performed matters greatly. We must test using the same operational mode (e.g., a boiler follow mode); and steady state is of course important to reduce changes in Reheat flow, seal densities, and so-forth. But the analysis dictates that the main flow delivered to the IP turbine is a function of an assumed (unknown) seal flow, which is generally non-linear. Whether Reheat flow effects are contributory to inconsistencies, or not, we simply choose to eliminate their effects by computing ξ as a function of either isentropic efficiency or exergy effectiveness; not the reverse. Note that the use of weighted seal quantities functionally isolates non-linear effects from main Reheat flow. To eliminate such effects, the following normalizations are employed:

$$\xi = (m_{HRH\text{-}AVG}/m_{HRH})(m_{LKG\text{-}0}/m_{HRH\text{-}AVG})\, \mathbf{S}_{\Gamma m} \qquad (7A)$$
$$= (m_{HRH\text{-}AVG}/m_{HRH})\, \xi_0\, \mathbf{S}_{\Gamma m} \qquad (7B)$$
$$= m_{LKG}/m_{HRH} \qquad (7C)$$

where, for j runs (i.e., all valid sets of test data):

$$m_{HRH\text{-}AVG} = \sum m_{HRH}/j$$
$$\xi_0 = m_{LKG\text{-}0}/m_{HRH\text{-}AVG}$$

In summary, we are defining an artifact ($\xi_0\, \mathbf{S}_{\Gamma m}$) normalized seal flow (a convergence parameter), which satisfies a global convergence of combined Eq.(2), Reheat and seal flows. Substituting Eq.(7B) into Eq.(2) and solving, the following are developed:

$(\xi_0 \mathbf{S}_{\Gamma\mathbf{m}}) = - (a - \eta_{IP}c) /[(m_{HRH\text{-}AVG} /m_{HRH})(b - \eta_{IP}f)]$ (8A)
$(\xi_0 \mathbf{S}_{\Gamma\mathbf{m}}) = - (a - \epsilon_{IP}d) /[(m_{HRH\text{-}AVG} /m_{HRH})(b - \epsilon_{IP}e)]$ (8B)

As more fully explained below, the quantity $(\xi_0 \mathbf{S}_{\Gamma\mathbf{m}})$ must be viewed - if a series correction to ξ is viable - as lying between the actual seal flow and mathematical limits associated with differences in non-converged efficiencies (η_{IP}) or effectivenesses (ϵ_{IP}). This is best illustrated in Fig. 2A2 when convergence is tight, or in Fig. 4A2 when not ideal. The parameter $(\xi_0 \mathbf{S}_{\Gamma\mathbf{m}})$, plotted as a function of η_{IP} or ϵ_{IP} for each run of a given test, will indicate convergence of both η_{IP} or ϵ_{IP} and an average seal flow (via $\xi_0 \mathbf{S}_{\Gamma\mathbf{m}}$) given an averaged Reheat flow. Such plots are termed "Preparatory Plots I".

It is the authors' experience that a significant number data sets associated with classical seal testing, which appear to be invalid, are, indeed, valid if analyzed using Eq.(8) in combination with weighted seal quantities. It also may be stated, that when using this technique, a truly invalid data set (one which does not add to a global convergence) will become most obvious. When this occurs, the data set should be discarded (the Results section offers examples).

DEVELOPING A SEAL FLOW

First, it is perhaps obvious that a Plot I, yielding a converged $(\xi_0 \mathbf{S}_{\Gamma\mathbf{m}})$, and using Eqs.(8) and (6) or (7), will produce an average seal flow:

$$m_{LKG} = m_{HRH\text{-}AVG} \; (\xi_0 \mathbf{S}_{\Gamma\mathbf{m}}) \qquad (9)$$

In practice, additional visual review is required to assure that all runs from a Plot I are, indeed, valid runs. To assess such validity the following procedure is recommended, leading to a "Preparatory Plot II".

By assuming that a resolving series may have either a real or imaginary solution, we can assume that, whereas $\mathbf{S}_{\Gamma\mathbf{m}}$ may sum a series of the likes of: $1.0 + x + x^2 + x^3 + \cdots$; an "imaginary" series of: $(iy\text{-}1) - (iy\text{-}1)^2/2 + \cdots$, may sum to $(\xi_0 \mathbf{T}_{\Gamma\mathbf{m}})$. Refer to Appendix A for further discussion. Thus Eq.(2) may be re-written as:

$$\eta_{IP} = (a + b\xi) / [c + f\, \xi_0(1.0 + \mathbf{T}_{\Gamma\mathbf{m}})] \qquad (10A)$$
$$\epsilon_{IP} = (a + b\xi) / [d + e\, \xi_0(1.0 + \mathbf{T}_{\Gamma\mathbf{m}})] \qquad (10B)$$

Solving for $(\xi_0 \mathbf{T}_{\Gamma\mathbf{m}})$:

$$(\xi_0 \mathbf{T}_{\Gamma\mathbf{m}}) = (a - \eta_{IP}c) /[(m_{HRH\text{-}AVG} /m_{HRH})(b - \eta_{IP}f)] + \xi_0 \qquad (11A)$$
$$(\xi_0 \mathbf{T}_{\Gamma\mathbf{m}}) = (a - \epsilon_{IP}d) /[(m_{HRH\text{-}AVG} /m_{HRH})(b - \epsilon_{IP}e)] + \xi_0 \qquad (11B)$$

A Plot II is prepared by assuming a series of η_{IP} or ϵ_{IP} values followed by computation of $(\xi_0 \mathbf{T}_{\Gamma\mathbf{m}})$. Although ξ_0 can be assumed, it will be noted that the algebra reduces to: $\xi_0 = (\xi_0 \mathbf{S}_{\Gamma\mathbf{m}}) + (\xi_0 \mathbf{T}_{\Gamma\mathbf{m}})$; thus at global convergence: $\xi_0 = 2(\xi_0 \mathbf{S}_{\Gamma\mathbf{m}})$. **To be sure, use of Eq.(11) is for visual acuity.** This said, the user will find Eq.(11) quite convenient for sorting data. In the first example presented, unit WOP, these procedures are presented in detail. In the supplied spreadsheet example, the user is encouraged to vary ξ_0, and to make deliberate errors in the data, thus to learn of the sensitivities.

But esoterics aside, a converged $(\xi_0 \mathbf{S}_{\Gamma\mathbf{m}})$ is repeatable and offers a vehicle for monitoring HP-IP seals over time. Differences in the computed seal flow of Eq.(9) represent differences in the actual:

$$\Delta m_{LKG} = f\, [\Delta m_{HRH\text{-}AVG}\, (\xi_0 \mathbf{S}_{\Gamma\mathbf{m}})]. \qquad (12)$$

The above development presents both an efficiency and effectiveness approach. Use of these techniques will produce identical $(\xi_0 \mathbf{S}_{\Gamma\mathbf{m}})$ values. However, a clear advantage lies with the effectiveness tool as illustrated below (Fig. 1A2, etc.); exergy is simply more sensitive.

RESULTS

Four HP-IP seal tests are presented. These units included two Fuji Electric turbines of 150 MWe (designated WOP) and 100 MWe (LRP), and two Westinghouse Electric turbines of 660 MWe (BR1) and 690 MWe (NC1). Figures 1A1, 2A1, 3A1 and 4A1 present Preparatory Plot I as based on Eq.(8). Figures 1A2, 2A2, 3A2 and 4A2 present Preparatory Plot II as based on Eqs.(8) & (11). The resolved seal leakage, the mass flow of Eq.(9), is plotted on Figures 1B, 2B, 3B and 4B as a function of IP exergy effectiveness (the preferred method). These flow plots also present Booth/ Kautzmann results using weighted isentropes.

WOP Results

The outcome from testing a 150 MWe Fuji machine represents an un-successful Booth/Kautzmann test, even when using weighted isentropes; four runs were attempted without clear indication. Using these same data sets, the new method achieved outstanding results.

It is of interest that this machine is a sister unit to the 100 MWe Fuji machine of the Fig. 2 series (LRP). They were installed at the same time and tested new within months of each other. Although success was achieved using $(\xi_0 \mathbf{S}_{\Gamma\mathbf{m}})$, as seen in Fig. 1A1, the 550C/570C run was clearly an outlying run. As seen in Fig. 1A2, sharp convergence was achieved. However, if such sharp convergence was not achieved, one could easily determine a min/max range by slightly alternating (ξ_0 **S** $_{\Gamma m}$), and thus ξ_0 and (ξ_0 **T** $_{\Gamma m}$) via Eq.(11). Applying such adjustment, one will find that the convergence of any two runs will begin to lie apart from global convergence. Such convergence for WOP was found at (ξ_0 **S** $_{\Gamma m}$) = 0.0578, with essentially no variance. The resultant average seal mass flow was determined at 6.035 kg/sec (47,900 lbm/hr) as shown in Fig. 1B. The design seal flow was 3.60 kg/sec (28,570 lbm/hr) at the as-tested throttle flow, indicating a 1.68 factor of design flow for a new machine.

Weighted vs. Un-Weighted Isentropes Using WOP

To demonstrate the importance of using weighted isentropes, Fig. 1B also presents a sensitivity study associated with weighted versus un-weighted isentropes. As seen, although the un-weighted data crosses somewhere about 13 kg/sec (off chart), it would appear as nonsense. Indeed, one of the test runs discarded using the (ξ_0 **S** $_{\Gamma m}$) technique, marked in red, actually "converges" (with one using yellow marks) when using the un-weighted. If BR1 and LRP data were analyzed using the un-weighted, as in Fig. 1B, they would also produce essentially parallel lines. If such non-convergence using our data is due to the modest cylinder ΔTs chosen (typically 10 to 20 ΔC), as opposed to the "success" achieved by others using 20 to 40 ΔC, then one must conclude that any approach using un-weighted isentropes cannot be correct. Methodology leading to viable convergences simply cannot be dependent on turbine cylinder ΔT.

LRP Results

The 100 MWe Fuji machine represents another series of successful tests, wherein sharp convergence was noted as seen in Fig. 2A1 using effectiveness. Fig. 2A2 clearly demonstrates that all runs converge well at a (ξ_0 **S** $_{\Gamma m}$) and effectiveness using Eqs.(8B) & (11B), but with an excellent convergence using isentropic efficiency via Eqs.(8A) & (11A). Note that: 1) both effectivenesses and efficiencies yield essentially the same answer; 2) the efficiency convergence appears exact using three runs; and 3) the effectiveness plots have a very slight non-convergence. Eliminating the run marked with red marks from the effectiveness plot produces perfect agreement with efficiency convergence. The lesson here is not that use of efficiency is a better technique, but rather that use of effectiveness provides heighten sensitivity for identifying inconsistent data (and that four runs per test should be considered a minimum). One will note that the mass flow shown in Fig. 2B, based on Eq.(9), is in slight disagreement with the convergent mass flow (also appearing in Fig. 1B); this is due to the use of a average Reheat flow, and its non-linear influence on (ξ_0 **S** $_{\Gamma m}$) convergence.

As plotted in Fig. 2B, the resolved seal mass flow using our methods was 5.976 kg/sec (47,430 lbm/hr). Although this machine was tested when new, its HP-IP seal flow was found to be high by a factor of 2.10 (versus the design at 2.850 kg/sec at the as-tested flow). This result is surprisingly similar to WOP results, although LRP is a 100 MWe machine. Given the clarity of (ξ_0 **S** $_{\Gamma m}$) convergence shown in Fig. 2A2, there can be little doubt as to conclusions. The question arises as to why two machines from the same vendor, built and tested at essentially the same time, but one 100 MWe (LRP) the other 150 MWe (WOP), produce the same very high HP leakage?

As seen in Fig. 2B, the converged Booth/ Kautzmann results, using weighted isentropes, indicated 5.580 kg/sec (44,290 lbm/hr). It will be observed that this result agrees with the effectiveness "line-cross" as seen in Fig. 2B. This agreement, although rare, most likely illustrates the impact of not using an average Reheat flow as employed in reaching a global (ξ_0 **S** $_{\Gamma m}$) convergence seen in Fig. 2A2.

The issue of differences between our technique using effectiveness and prior efforts (when convergence is achieved) is not fully understood. We only note that an isentropic enthalpy drop is a pretense of maximum specific power; maximum specific power can only be determined using a change in exergy.

BR1 Results

The Westinghouse machine associated with the Fig. 3 series (BR1) is considered pivotal as it represents limited convergence; convergence consisted of only two runs from two tests conducted on different days indicating a best estimate of seal flow. This is seen in Fig. 3A1. Note the plotted effectivenesses are offset such that (ξ_0 **S** $_{\Gamma m}$) convergences may be seen; for example, where a chosen $\epsilon_{IP\text{-}j}$ value was used to compute (ξ_0 **S** $_{\Gamma m}$)$_j$, the plotted point consisted of ($\epsilon_{IP\text{-}j}$ - 2.0) and (ξ_0 **S** $_{\Gamma m}$)$_j$, offset in this case by 2%. As would be expected if a global convergence is to be had, all data sets will yield the same (ξ_0 **S** $_{\Gamma m}$) value; they do exactly for the two tests run within one week. These data are further examined using Fig. 3A2. For the test conducted one month later, a higher (ξ_0 **S** $_{\Gamma m}$) value was observed; and was discarded as being bad data (?). Using Eq. (9), given (ξ_0 **S** $_{\Gamma m}$) = 0.0320, with an average as-tested Reheat flow of 3,629,530 K-lbm/hr (457.309 kg/sec), the seal leakage was determined at 116,145 lbm/hr (14.634 kg/sec), which is a factor exceeding 2 times design flow! Of course, the percent of seal flow relative to Reheat flow is the ($\xi_0 \mathbf{S}_{\Gamma \mathbf{m}}$) value; for this machine seals were 3.2% of main Reheat. It will also be noted that the Booth/Kautzmann analyses were not successful in producing any rational seal flows. Note all three tests were conducted over just one month. Since the time of this test the machine was upgraded.

NC1 Results

The Westinghouse Electric machine, of 690 MWe, is a most interesting example, a mixed example of data sets. One of the three tests produced extremely elevated flows; and although converged, overall test results leave some doubt. One test produced tight convergence using all three of its runs. A second test generally confirmed these results, but was based on only two runs. In summary, Fig. 4A1 indicates a ($\xi_0 \mathbf{S}_{\Gamma \mathbf{m}}$) convergence at 0.0275 using five runs (out of nine total).

However, it will be noted that the test considered bad, produced a ($\xi_0 \mathbf{S}_{\Gamma \mathbf{m}}$) convergence of 27.8% using two of its runs. This was confirmed from a second test (but again based on only two runs). This second convergence was conducted within a month of the first but <u>seven months before</u> the 2.75% convergence. Plant personnel reported no confirmatory indication of such an extreme HP leakage; the data was considered questionable, the second run of this test was considered a misinterpretation.

Closer inspection of results, using Fig. 4A2, indicated convergence at ($\xi_0 \mathbf{S}_{\Gamma \mathbf{m}}$) = 0.0275 using Test #3, but also a slight shift of ($\xi_0 \mathbf{S}_{\Gamma \mathbf{m}}$) = 0.0245 based on Test #2. Again there was seven months separation between these tests, thus they were analyzed using different averaged Reheat flows. As seen in Fig. 4A1, one run of Test #2 is clearly an outlier. The two converging runs appear reasonable, confirming Test #3 results at approximately 2.7% of Reheat flow. Fig. 4B presents both efficiency and exergy effectiveness plots; the computed HP-IP seal mass flow was 116,300 lbm/hr (14.65 kg/sec). Design flow for NC1 seals is 59,800 lbm/hr (7.53 kg/sec). Fig. 4B also indicates the disastrous results obtained using Booth/Kautzmann methods.

In summary, the analysis of NC1 was considered only moderately successful. Five runs of nine indicated the same percentage HP leakage. NC1 experience clearly speaks to the need for at least four runs per test, and the use of quality test instrumentation.

CONCLUSIONS

The technique presented, based on effectiveness, offers an ability to determine a consistent HP-IP turbine seal flow. It can be used to sort through often times confusing data sets, such that the parameter ($\xi_0 \mathbf{S}_{\Gamma \mathbf{m}}$) is resolved. Convergence using the ($\xi_0 \mathbf{S}_{\Gamma \mathbf{m}}$) concept will be definitive (or nothing); it will yield an indicative seal flow consistent with global convergence.

Although both isentropic efficiencies and exergy effectiveness techniques are presented, the authors strongly encourage use of only effectiveness. It is strongly recommended that the parameter ($\xi_0 \mathbf{S}_{\Gamma \mathbf{m}}$) be used to routinely monitor HP-IP seal flows over time. For the cases studied, the parameter ($\xi_0 \mathbf{S}_{\Gamma \mathbf{m}}$) in conjunction with effectiveness, appears quite robust. The following comments are offered regards use of the new technique (they are not listed in any order):

- The user is warned that use of un-weighted isentropes is not believed correct, results are meaningless.

- It is strongly recommended that 4 runs/test be conducted, with 2 HP and 2 IP temperature variations. This will assist in adjudicating data associated with any one bad run.

- Consideration of secondary and tertiary flows entering shaft seals may have surprising effects. One must understand all seal leakage paths and perform sensitivity studies for understanding effects.

- The user is warned to take care with spreadsheet mechanics. These analyses are tedious and are prone to error. One must organize the spreadsheet carefully (regards structure, use of consistent Steam Tables, consistently named cells, and the like).

- HP-IP seal testing demands steady state behavior. In searching data trends, the user should not be afraid of cherry-picking selected data sets which might be only 10 or 15 minutes in duration; one-hour trends might be conventional but not advised.

- The condition of the machine and how it is operated are of critical importance. When performing periodic testing, care must taken to use the same operational mode (the objective must be to maintain constant Reheat flow, constant spray flows, constant feedwater temperature profiles, etc.).

- The user is warned that determining HP-IP seal flows requires careful testing techniques. As examples of past concerns: misuse of ambient pressure correction has lead to inconsistencies; one cannot ignore T/C correction curves; IP turbine exhaust conditions should only be measured at the cross-over (exhaust conditions are troublesome); duplication of instruments is required; etc.

- The user should be aware this technique offers a viable over-check on the consistency of test data and should be used for that purpose. Many times errors made in manipulation of data will come to light through inconsistencies found in $(\xi_0 \mathbf{S}_{\ulcorner m})$ and $(\xi_0 \mathbf{T}_{\ulcorner m})$ convergences, and in η_{IP} or ϵ_{IP} results.

COMMENT TO THE READER

The presented technique requires assistance from the industry to assure that a well verified alternative to the Booth/Kautzmann Method can be established. To this end we are making available a sample Excel spreadsheet which may be used for patterning and analysis of test data; it can be found at [www.Exergetic Systems.com](www.ExergeticSystems.com). Excel Steam Table Add-Ins will have to be changed (they are marked); they can be obtained from Exergetic Systems or many other vendors. When using this example, or establishing your own, we would sincerely appreciate reports on the technique and improvements to be made; such reports will be posted on Exergetic Systems' web site as appropriate, and, of course, with full attribution. We need your help!

REFERENCES

Booth, JA and Kautzmann, DE, "Estimating the Leakage from HP to IP Turbine Sections", 1984 EPRI Power Plant Performance Monitoring Conference, Electric Power Research Institute, Palo Alto, California; also referenced as General Electric Co.'s GER-3469.

Lang, FD, "Fuel Consumption Index for Proper Monitoring of Power plants - Revisited", Am. Society of Mech. Engrs., IJPGC 2002-26097/CD.

APPENDIX A: COMMENTS ON DEVELOPMENT

The above has introduced a concept in which an unknown HP-IP leakage flow can be resolved by assuming a series solution, the summation of which is some $\mathbf{S}_{\ulcorner m}$ as used in Eq.(7B). We now offer a few comments pertaining to this concept and its further development. Although the following was the first to be applied in our search to improve the determination of HP-IP seal flows, we recommend the above techniques for their robustness (with use of effectiveness). This said, we present the following for those who desire to further develop, and to plant whatever inventive seeds might germinate. The original objective was the independent determination of ξ_0 and x.

Fundamentally any method which relies on a graphical solution - for example, altering a leakage flow to judge its thermodynamic influences on a downstream turbine - is assuming a series solution in which the functional value is unknown. Although any series could be assumed, allow a simple power series for study:

$$\xi = \xi_0 (1.0 + x + x^2 + x^3 + \cdots) \qquad \text{(A1)}$$

If we were to solve for an estimate of x, which is $\Delta\xi/\xi_0$, by using the first three terms of Eq.(A1), the following allows an approximation of $\mathbf{S}_{\ulcorner m}$ to then be obtained:

$$x = -0.5 \pm 0.5\{1.0 - 4[1.0 - (\xi_0 \mathbf{S}_{\ulcorner 3})/\xi_0]\}^{0.5} \qquad \text{(A2)}$$

For Eq.(A2) to produce a real solution (positive discriminant): $(\xi_0 \mathbf{S}_{\ulcorner 3})/\xi_0 > 0.75$ and thus $\mathbf{S}_{\ulcorner 3} > 0.75$, and given that $x = \mathbf{S}_{\ulcorner m} - 1.0$, then $x > -0.25$ and $\xi > 0.75\xi_0$. Thus we see that if a particular HP leakage flow to Reheat flow relationship is described by a power series, that the correction can be no lower than a certain value; the actual must be at least 75% of a relative $(\xi_0 \mathbf{S}_{\ulcorner m})$ if assuming an Eq.(A1) series.

Further, if $(\xi_0 \mathbf{S}_{\ulcorner 3})/\xi_0 < 0.75$ for a power series, the discriminant will be negative and solution will only be found on an imaginary plane by letting x = iy.

$$\xi = \xi_0 (1.0 + iy + i^2y^2 + i^3y^3 + \cdots) \qquad \text{(A3)}$$

If however $(\xi_0 \mathbf{S}_{\ulcorner 3})/\xi_0$ approaches unity, seals flows are either zero or fixed ($\xi = \xi_0$); and parallel lines will produce no convergence. The point here is that there is a mathematical basis for observing non-convergence.

What is suggested is that for a particular machine type, the number and nature of labyrinth packings, and the relationships between Eq.(2) or (10)'s variables, the quantities will acquire uniqueness. To this end, Table A-1 represents examples of the variations associated with different series; it is presented only to illustrate potential ranges, to provide a visceral understanding.

In summary, if a series solution can describe the problem being resolved, then the greater the correction needed to produce ξ, the greater the dependency on seal flows and, it is assumed, the sharper the convergence which should be method dependent, <u>and not dependent on the magnitude of temperature differences</u>.

Both real and imaginary approaches have been developed; several have demonstrated success (the first being the logarithmic of Table A-1), but none universally. The problem appears that when we attempt to assume that all turbines - given the vagaries of HP-IP seal flows, or, indeed, traditional HP-IP seal flows coupled with spurious HP leakage which might also influence the IP turbine - can be described with the same mathematical model we may be on a fool's errand. Again, its ultimate usefulness may lie with monitoring turbine performance over time, coupled with periodic testing; simply computing a consistent $(\xi_0\, \mathbf{S}_{\ulcorner m})$ quantity test-over-test.

Table A-1: Examples of Applied Mathematical Limits

Series	$(\xi_0\, \mathbf{S}_{\ulcorner m})$ or $(\xi_0\, \mathbf{T}_{\ulcorner m})$ Condition for a Real or Imaginary Solution	Limits on $\Delta\xi/\xi_0$
Logarithmic: $(iy-1) - (iy-1)^2/2 + \cdots$	$\mathbf{T}_{\ulcorner 2} < 0.50$, Imaginary	$iy < -0.50$
Exponential: $1.0 + x/1! + x^2/2! + \cdots$	$\mathbf{S}_{\ulcorner 3} > 0.50$, Real	$x > -0.50$
Power: $1.0 + x + x^2 + x^3 + \cdots$	$\mathbf{S}_{\ulcorner 3} > 0.75$, Real	$x > -0.25$
Cosine: $1.0 - x^2/2! + x^4/4! - \cdots$	$\mathbf{S}_{\ulcorner 3} > -0.50$, Real	$\approx 3.08 > x > -1.50$

Fig. 1A1: WOP Testing for HP-IP Seal Flows, Preparatory Plot I

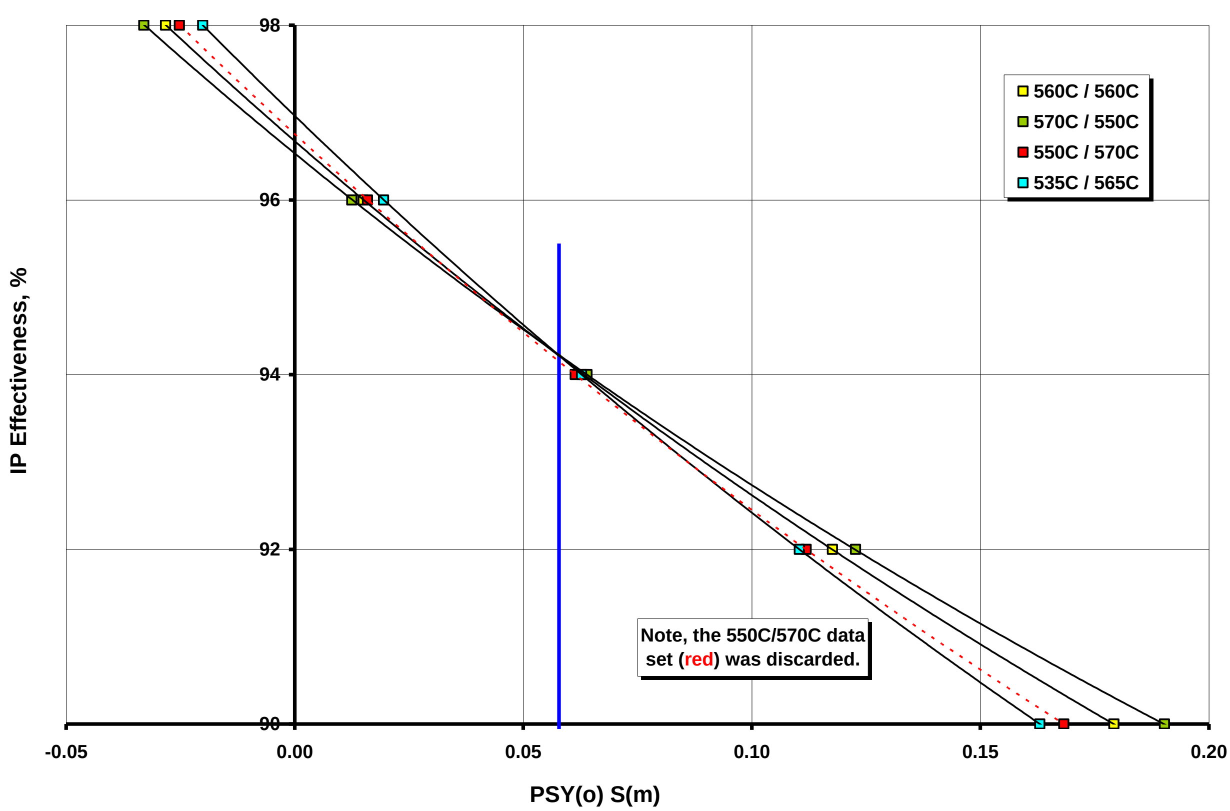


Fig. 1A2: WOP Testing for HP-IP Seal Flows, Preparatory Plot II

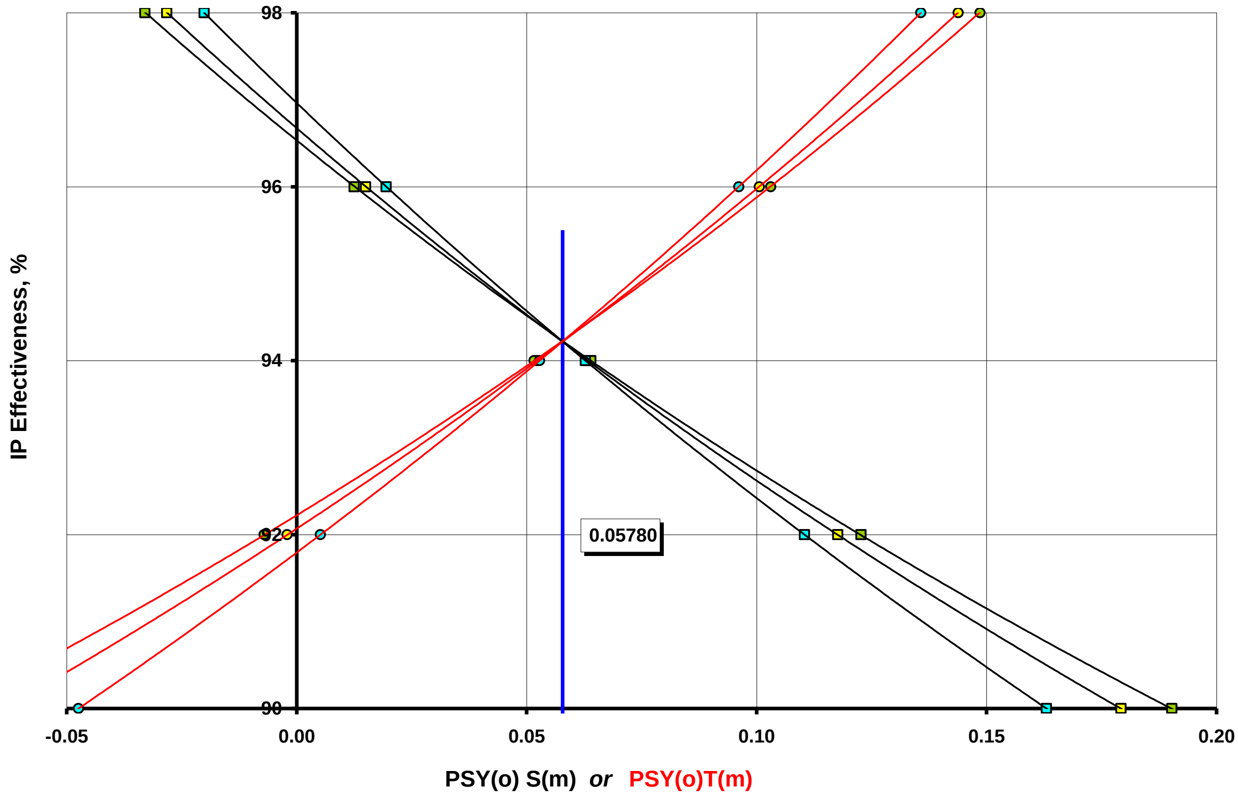


Figure 1B: WOP Testing for HP-IP Seal Flows

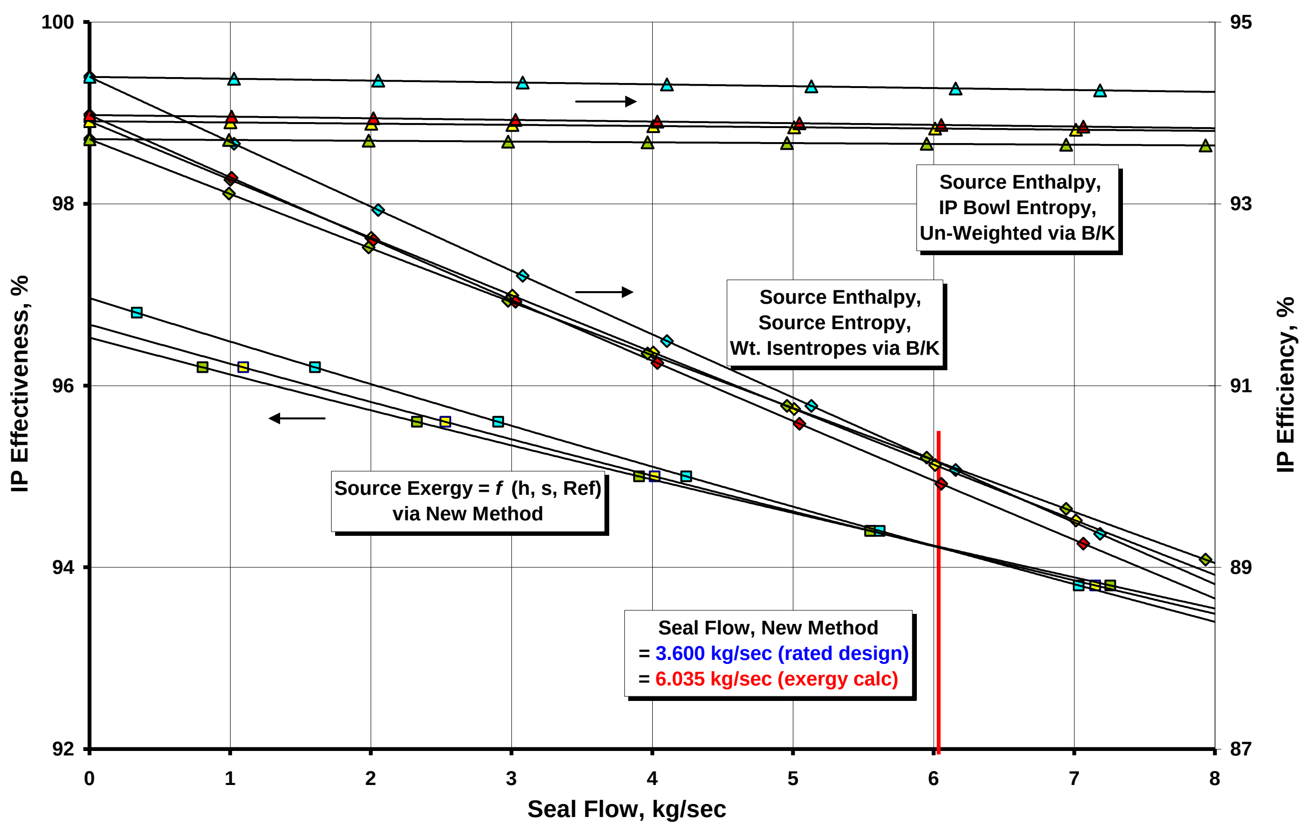


Fig. 2A1: LRP Testing for HP-IP Seal Flows, Preparatory Plot I

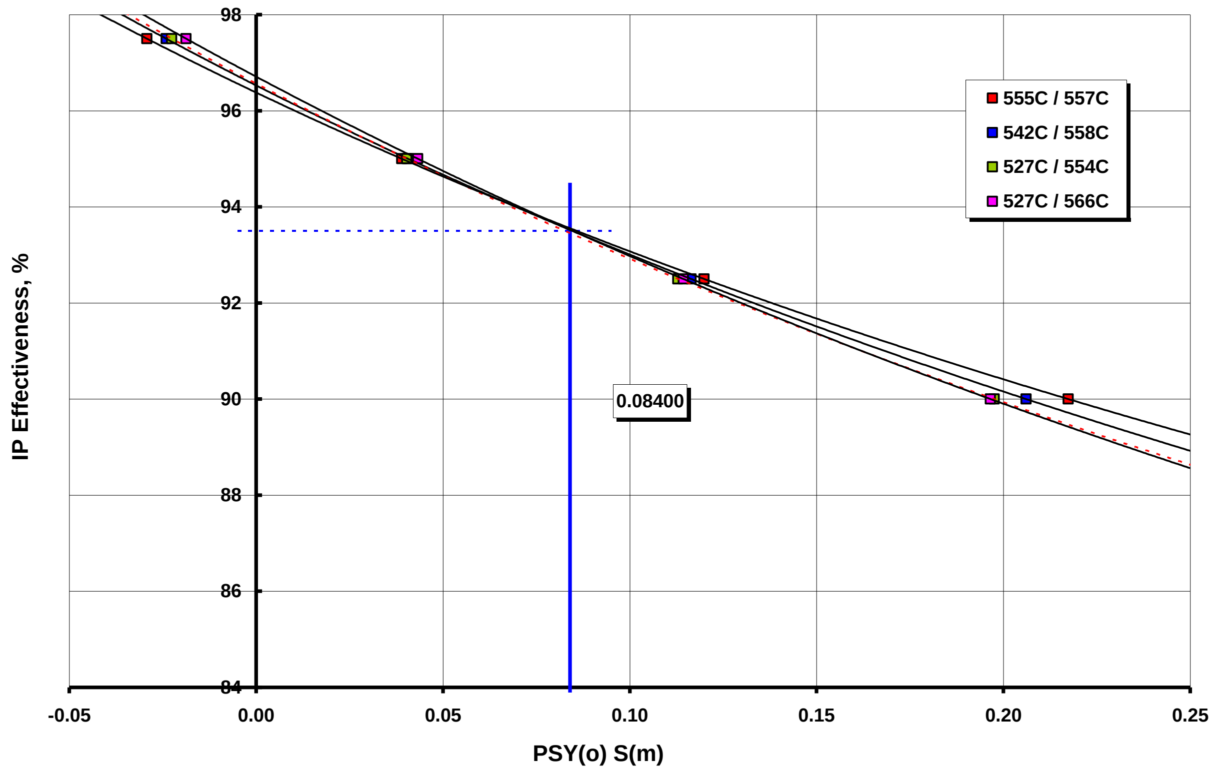


Fig. 2A2: LRP Testing for HP-IP Seal Flows, Preparatory Plot II

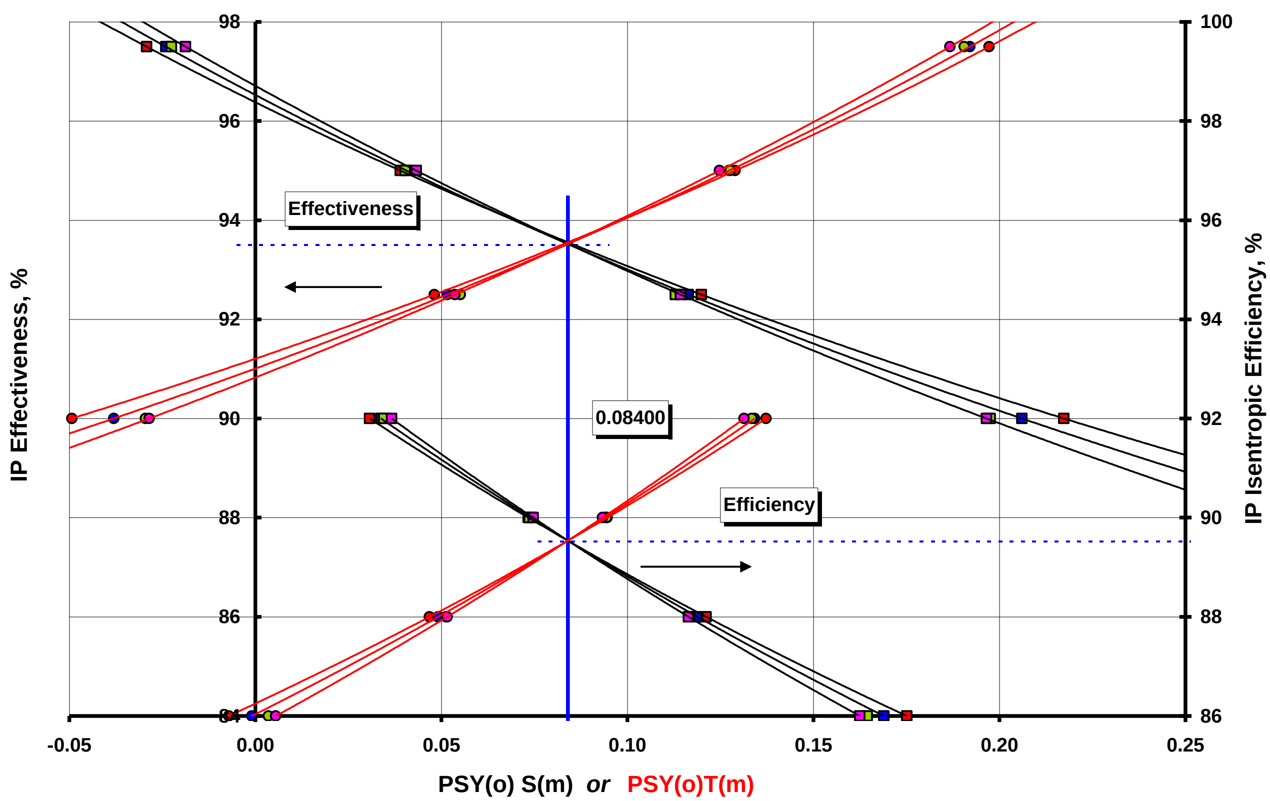


Figure 2B: LRP Testing for HP-IP Seal Flows

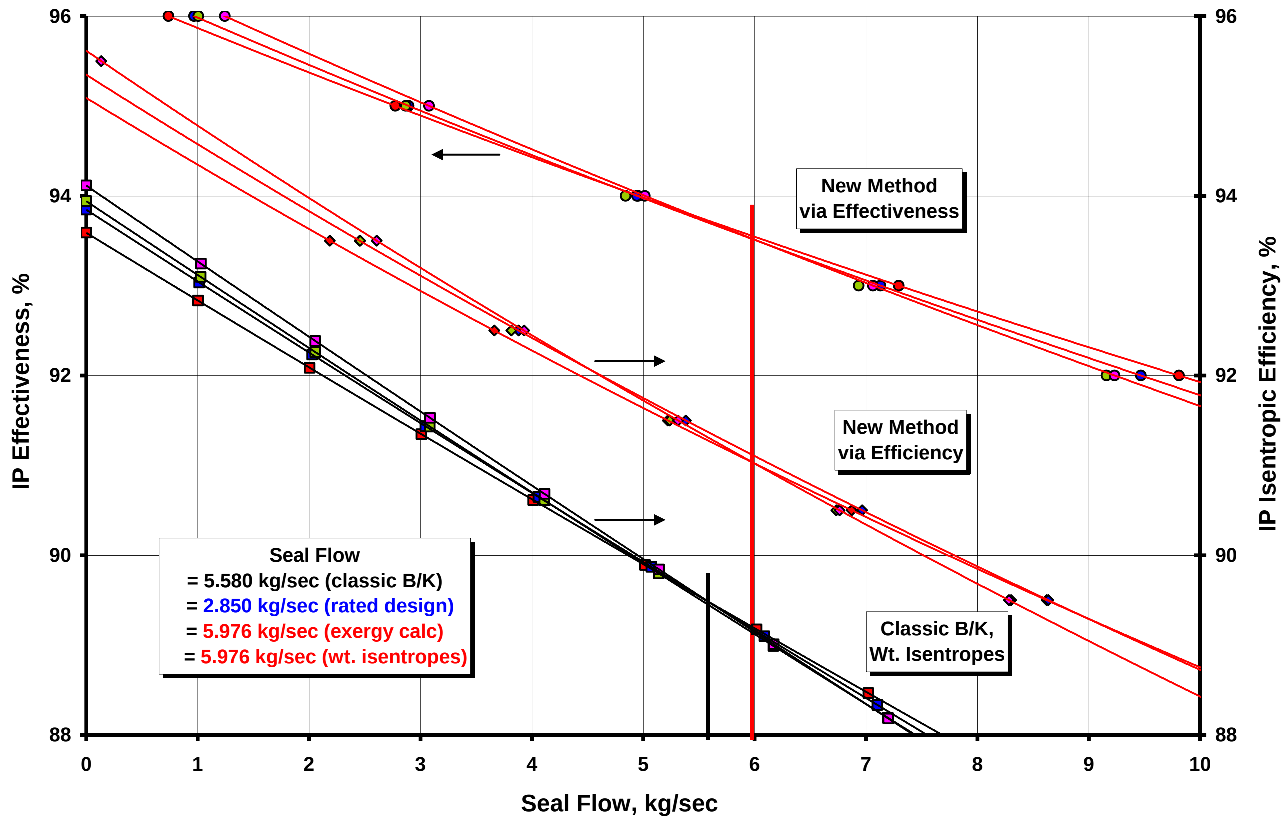


Figure 3A1: BR1 Testing for HP-IP Seal Flows, Preparatory Plot I

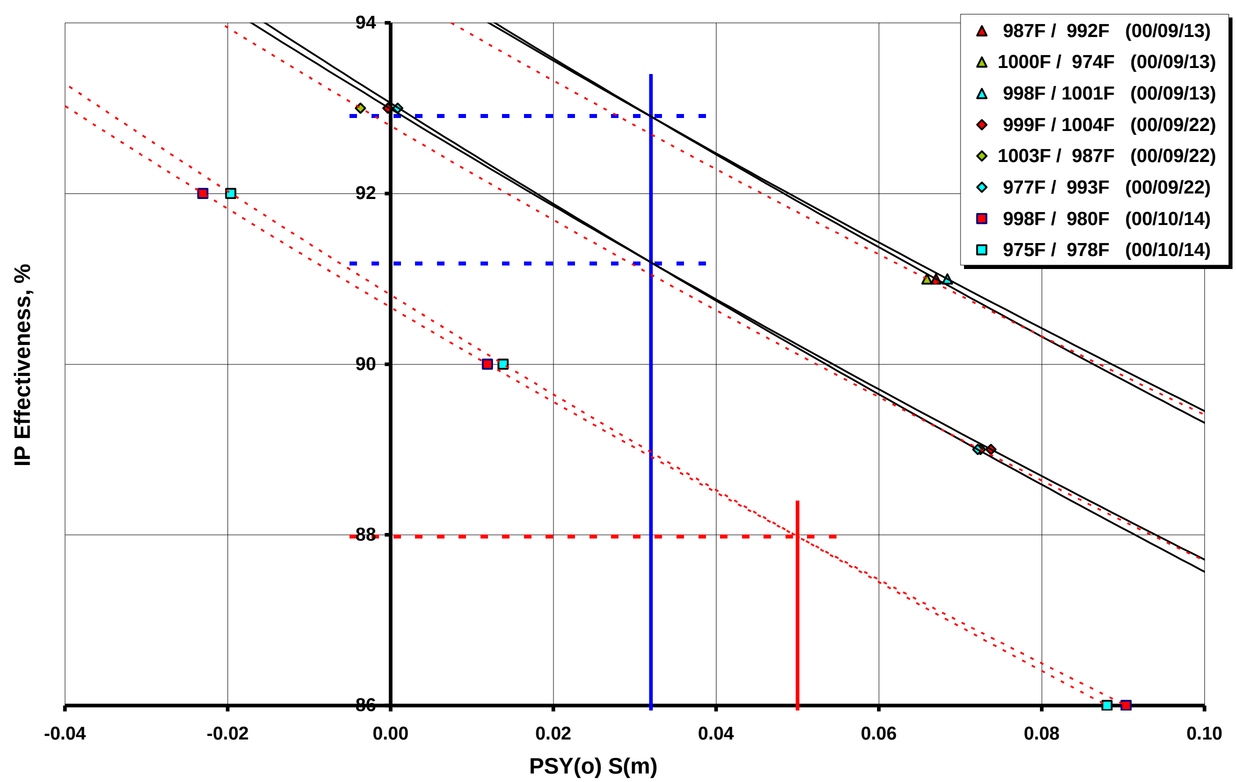


Figure 3A2: BR1 Testing for HP-IP Seal Flows, Preparatory Plot II

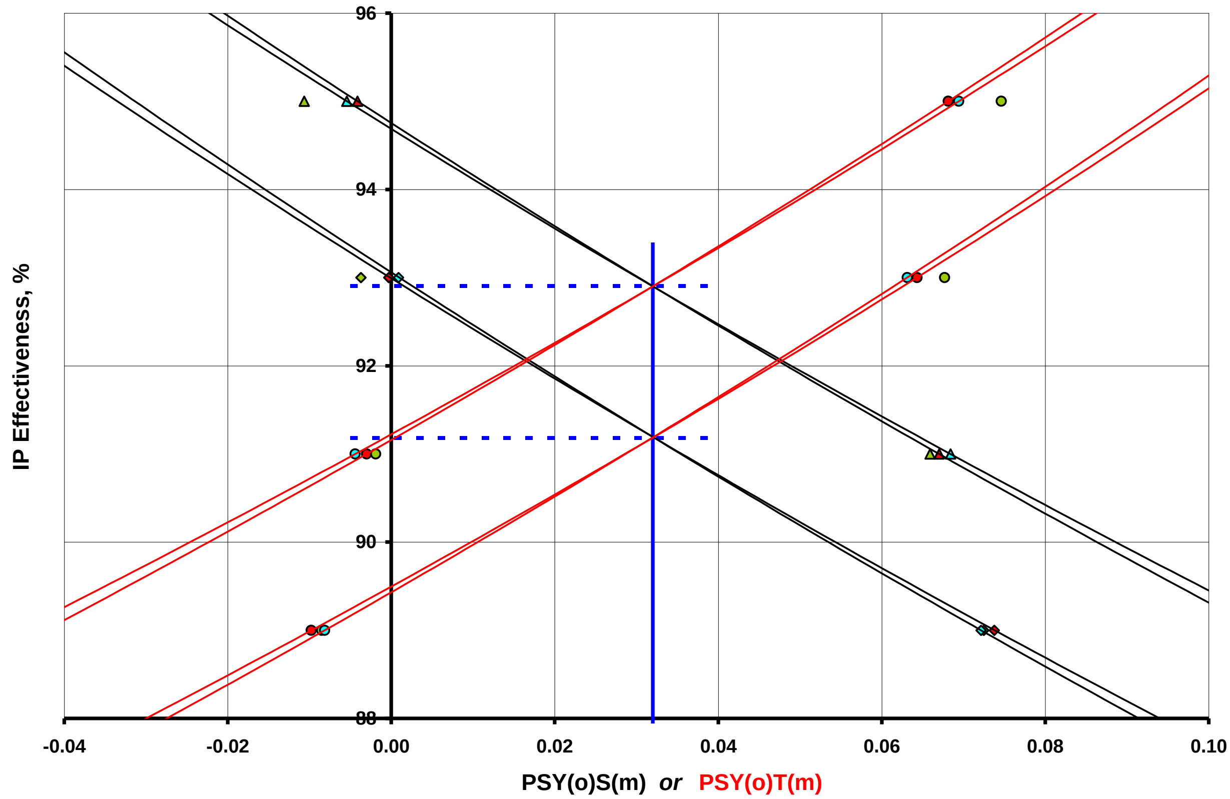


Figure 3B: BR1 Testing for HP-IP Seal Flows, Final (00/09/13 & 22)

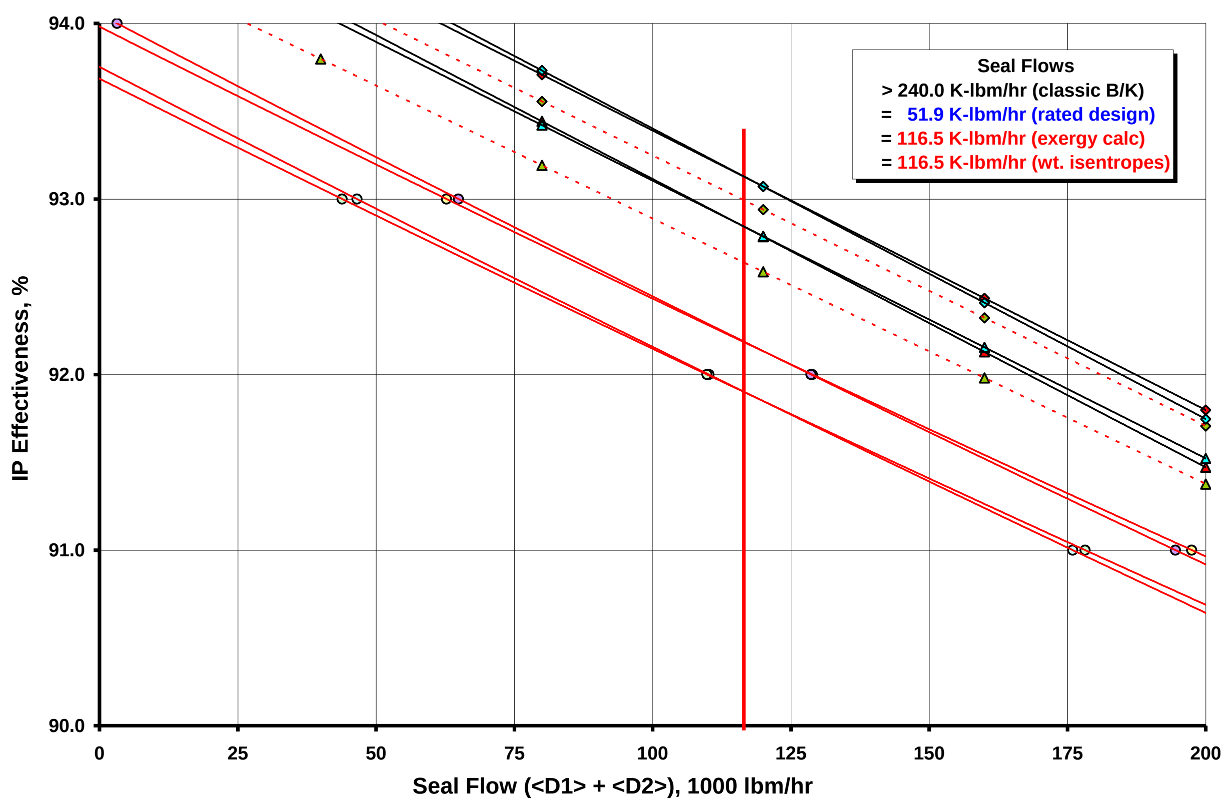


Fig. 4A1: NC1 Testing for HP-IP Seal Flows, Preparatory Plot I

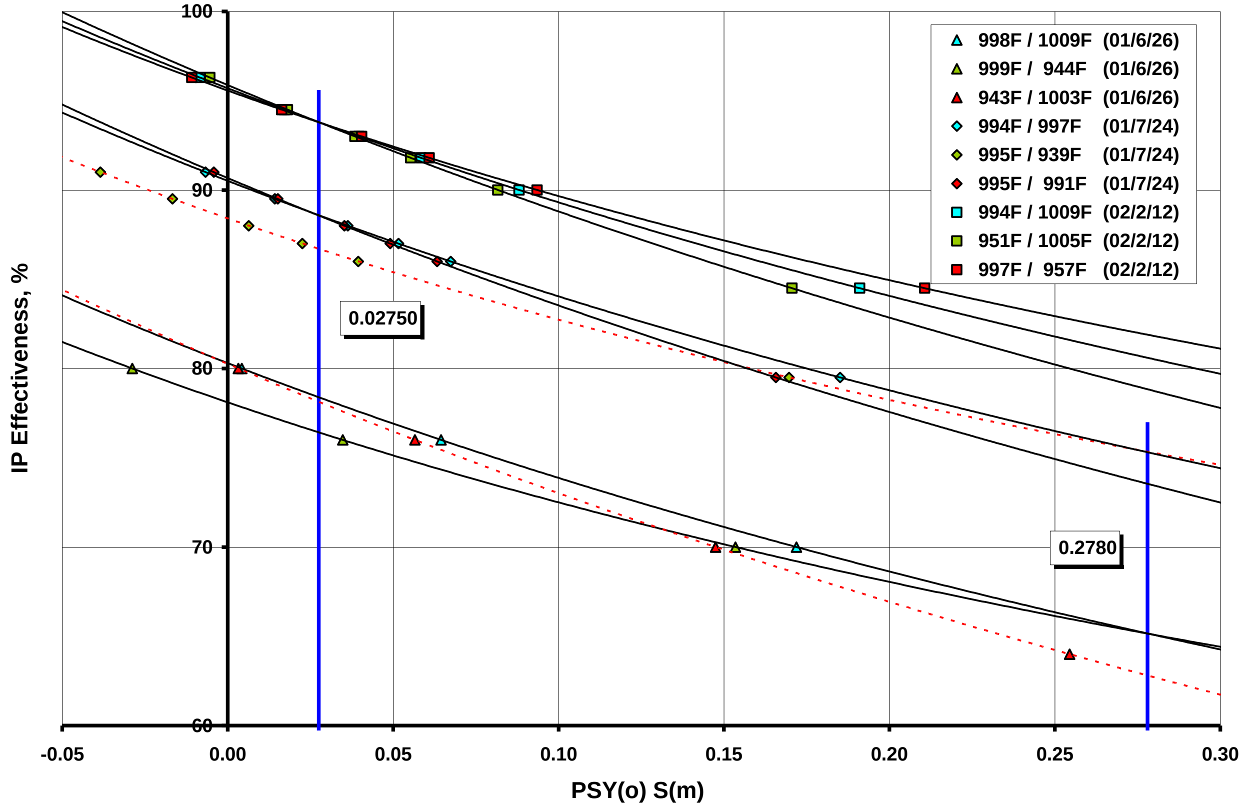
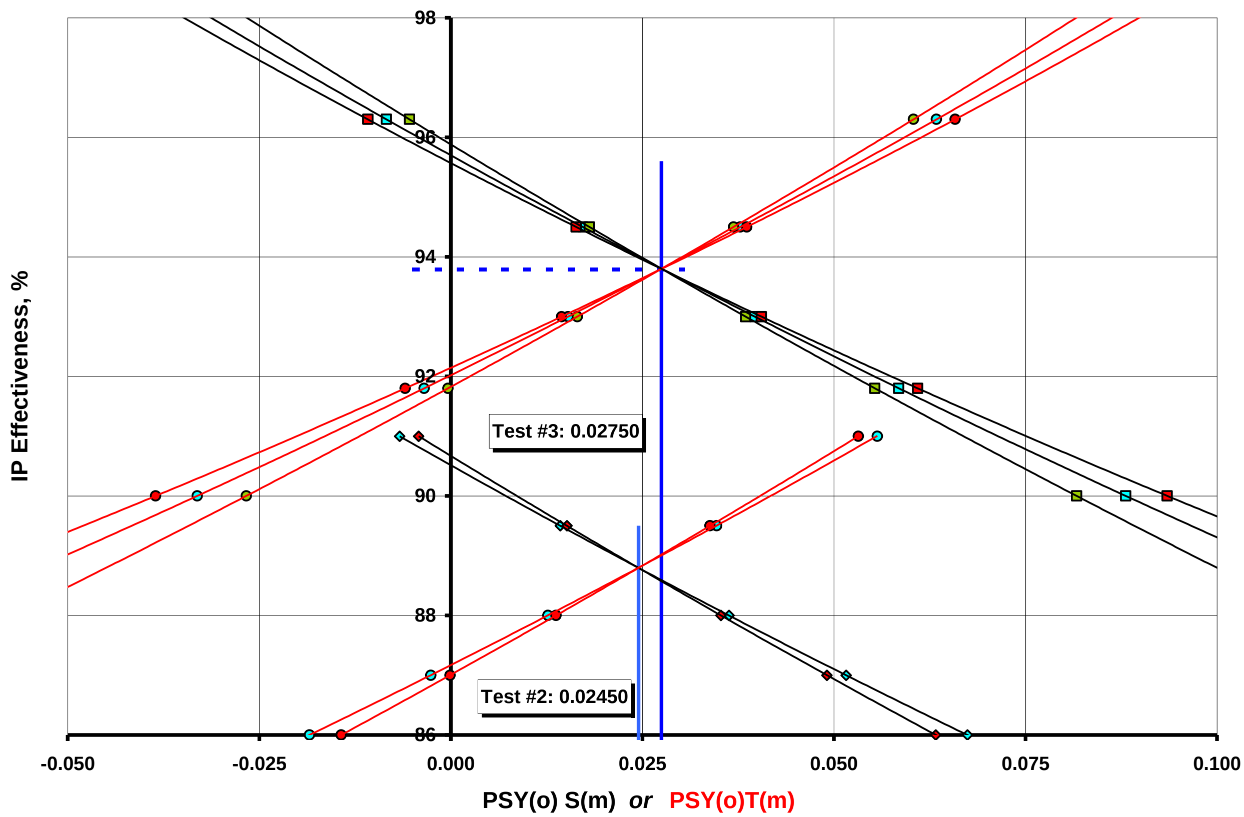


Fig. 4A2: NC1 Testing for HP-IP Seal Flows, Preparatory Plot II



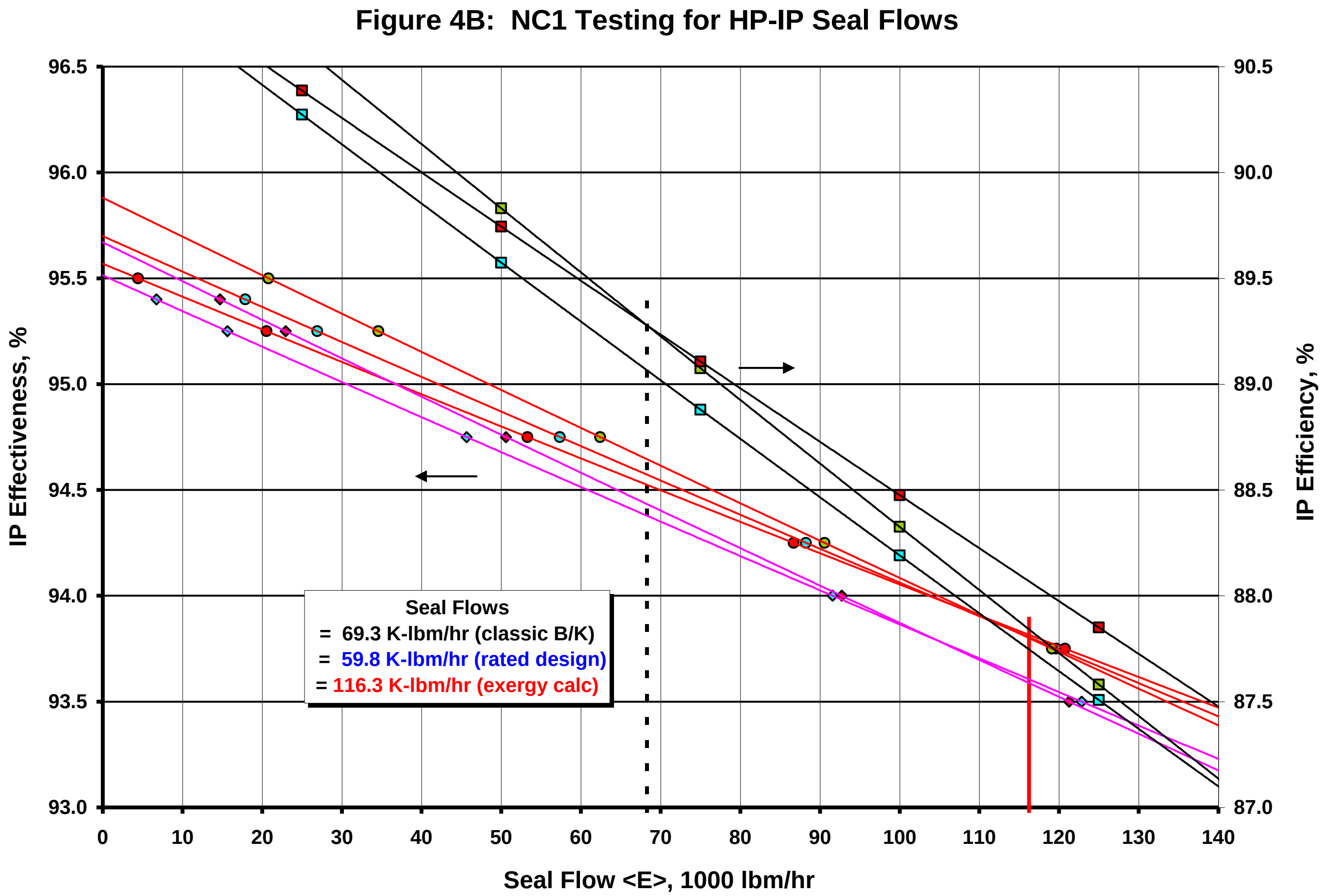


Figure 4B: NC1 Testing for HP-IP Seal Flows
IP Effectiveness, %
IP Efficiency, %
Seal Flow <E>, 1000 lbm/hr
Seal Flows
= 69.3 K-lbm/hr (classic B/K)
= 59.8 K-lbm/hr (rated design)
= 116.3 K-lbm/hr (exergy calc)
96.5
96.0
95.5
95.0
94.5
94.0
93.5
93.0
90.5
90.0
89.5
89.0
88.5
88.0
87.5
87.0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140