Using the Second Law of Thermodynamics To Analyze Power Plant Performance

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ABSTRACT

The Second Law of Thermodynamics concerns thermodynamic losses in systems. PEPSE calculates Second Law of Thermodynamics Performance Parameters which can help identify and analyze problems and sources of inefficiencies. This paper discusses some of the uses of the Second Law parameters for components, streams and the system. At IELP, we are using the Second Law to help understand aspects of the operation of our plant and main turbine which vary from their design mode. There have been two main problems with which we have had to deal. One is the fact that we do not operate the second stage reheat of our MSR's, which is a significant deviation from our design heat balance. We have recalculated a new "design" heat balance reflecting our present plant configuration in order to have a benchmark by which to realistically gauge plant operation. Secondly, we measure turbine shell pressures which are approximately 20 psi lower than design values for turbine steam flows at or above design values. Part of our analysis of these problems has used the Second Law.

INTRODUCTION

At DAEC, we have been working to understand the differences between the operating configuration of our plant and the design heat balance supplied by GE. One of the factors that has provided a challenge in the analysis is the fact that DAEC is a Boiling Water Reactor (BWR) nuclear plant. This means that the steam cycle operates mainly in the wet steam region where a measurement of temperature and pressure do not uniquely define the state of the working fluid - steam.

Another factor is the fact that we deviate from our design heat balance configuration by not operating the second stage reheat portion of our moisture seperator reheaters (MSR's). Most of the steam that would have gone through the heating side of the MSR second stage now goes through the turbine. This means that the turbine steam flow is greater than the design heat Valves Wide Open (VWO) configuration. GE turbine analysis procedures would calculate higher turbine shell pressures in this case. However, in actual operation, we find lower pressures than in the design heat balance.

This puts us in the position of operating far from the "design point" of our design heat balance. We have had to calculate a new heat balance, without second stage reheat, in order to have a benchmark with which to make a meaningful comparison of our present plant operation. We have used the 2nd Law to confirm that our "new" heat balance is truly consistant with our "old" heat balance. We have also used it to understand those points at which our actual operation differs significantly from our expected or "heat balance" operation. We plan to use it to help monitor plant operation and spot inefficiencies as they develop. The 2nd Law "closes the loop" between the 1st Law of Thermodynamics and the procedures for calculating turbine performance from steam cycle conditions.

BASICS

The information supplied by PEPSE output consists of model geometry, thermodynamic properties, performance parameters, First Law of Thermodynamics performance analysis and Second Law of Thermodynamics performance analysis. For a steam cycle, the thermodynamic properties are flow, temperature, pressure, quality, enthalpy, entropy and specific volume of the steam and water in the streams connnecting the components of the model. The performance parameters are mainly the differences of the properties across components. The First Law performance table summarizes the energy drops across classes of components. It also calculates turbine and generator output, overal plant efficiency and heat rate. The Second Law performance tables are the thermodynamic availability and irreversibility for the components and streams of the model. This last area tends to be less straight forward than the rest of the output and is the main area in which I will concentrate.

There a few terms that need to be discussed/defined:

0th Law of Thermodynamics: You can tell a hot body from a cold body.
Also stated as: Two bodies in thermal equilibrium with a third body are in thermal equilibrium with each other.

1st Law of Thermodynamics: The *best* that you can do is break even.
Also stated as: The change in internal energy (dU) of a system is equal to the heat added (δQ) less the work done (δW), i.e.

$$dU = \delta Q - \delta W.$$

2nd Law of Thermodynamics: You can't break even.
Also stated as: It is impossible to construct a deivce that will operate in a cycle and produce no effect other than raising of a weight and the exhange of heat with a single reservoir. Equivallently, it is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat (Q) from a cooler body (at temperature T_C) to a hotter body (at temperature T_H). Or:

$$\Sigma(\delta Q/T) < \text{or} = 0 \quad \text{for a cycle.}$$

or: $$\text{Efficiency} = \eta = 1 - Q_C / Q_H < \text{or} = \eta_{\mathbf{Carnot}} = 1 - T_C / T_H.$$

Entropy: Where the energy went when you couldn't break even.
Entropy provides the connection between the statistical mechanics of the molecules which comprise the working fluid and the quantities which we can measure, e.g. pressure, temperature, energy, etc. It can be described as the energy transfer capability per degree absolute temperature (S) which is equal to Boltzmann's constant (k) times the logarithm of the number of possible molecular arrangements of a system (Ω) which will yield the same energy:

$$S = k \ln(\Omega).$$

Irreversibility: The energy you lost was transferred to the environment and you can't get it back.
It is related to the change in the number of choices of molecular arrangement of a system and the temperature (T_0) at which energy is lost from the system:

$$I = kT_0 \ln(\Omega_2/\Omega_1) = kT_0 \ln(\Omega_1) - kT_0 \ln(\Omega_2) = T_0(S_1 - S_2).$$

Availability: You can't use all of the energy you have.
Maximum reversible work that can be done by a system taking into account heat rejected to the environment:

$$\phi = (h - h_0) - T_0(s - s_0).$$

To discuss the use of the 2$^{\text{nd}}$ Law, I will use the governing turbine stage in a PEPSE model of DAEC as an example. Data from the PEPSE output is attached. I will try to use the same variable names or name types as are used and supplied by PEPSE.

IRREVERSIBILITY

Irreversibility is one of the Second Law parameters calculated by PEPSE for components and streams. PEPSE calculates it as the difference between the maximum potential power (P_{PM}) and actual power (P):

$$I = P_{PM} - P.$$

Engineering texts define it as the difference between reversible work (W_{rev}) and actual work (W) done:

$$I = W_{rev} - W.$$

Physics texts define it as the change in entropy (Δs) times the temperature of the reference reservoir (T_0) to which the heat is irreversibly lost:

$$I = T_0 \Delta s.$$

All three statements are equivalent.

The turbine stage we will look at is component 109 with inlet stream 108 and outlet stream 109:

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PEPSE CODE BY EI INTERNATIONAL, INC., IDAHO FALLS, ID.
VERSION 55I  CREATED 21 FEB 90     DATE 04/21/92.
DAEC version 7 - HEAT BALANCE

                         COMPONENT PROPERTIES

COMP   STREAM FLU  MASS                        SPEC.
        /PORT  ID   FLOW     TEMP   PRESS    QUALITY   ENTH    ENTRPY     VOLUME
                  (LBM/HR)   (F)    (PSIA)     ( - )   (B/LB)  (B/LB-F)  (FT3/LBM)

109 TNGS 108/I  0  6878029.  535.4  926.40    0.993    1191.5  1.39585   4.82E-01
         109/U  0  6878029.  505.1  712.99    0.959    1172.8  1.39867   6.18E-01
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PEPSE CODE BY EI INTERNATIONAL, INC., IDAHO FALLS, ID.
VERSION 551  CREATED 21 FEB 90    DATE 04/21/92.
DAEC version 7 - HEAT BALANCE

       SECOND LAW OF THERMODYNAMICS PERFORMANCE - COMPONENTS

                            AVAILABILITY      POTENTIAL                          EFFEC-
COMP  COMPONENT           ACTUAL   REL       FOR POWER     IRREVERSIBILITY  TIVE-
  NO. DESCRIPTION         CHANGE   CHANGE  MAXIMUM  REL  ACTUAL      REL    NESS
                          (BTU/HR)  ( - )  (BTU/HR) ( - ) (BTU/HR)   ( - )  ( - )

 109  NUCL. TURB. - GS  -1.387E+08  -.0559  1.387E+08 .0559 9.866E+06 .0212  .9289
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The irreversibility for the turbine stage can be calculated:

$$\text{IRRC}(109) = \text{WW}(108)*[\text{TTDEAD}+\text{XRT}(0)]*[\text{SS}(109)-\text{SS}(108)]$$

$$= 9.9 \times 10^{6} \text{ Btu/hr.}$$

This is essentially the same number found in the 2nd Law portion of the PEPSE output. This is the loss in potential work due to heat being transferred to a state in which the velocity of the working fluid is zero. This is called the "dead state" reservoir.

There are two columns under IRREVERSIBILITY in the 2nd Law table for components: ACTUAL and RELATIVE. ACTUAL we have just calculated for the turbine governing stage. RELATIVE is the fraction of the irreversibility of the entire system contributed by the one component. The irreversibility for the entire system is found by adding the irreversibility contributed by each componetnt. This total is found in the last table in the PEPSE output:

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PEPSE CODE BY EI INTERNATIONAL, INC., IDAHO FALLS, ID.
VERSION 55I   CREATED 21 FEB 90     DATE 04/21/92.
DAEC version 7 - HEAT BALANCE

        SECOND LAW OF THERMODYNAMICS PERFORMANCE - SYSTEM
                     (TTDEAD =  5.00000E+01 DEG F)

SUMMARY FOR CYCLE SUBSYSTEMS

                              POTENTIAL FOR POWER     IRREVERSIBILITY     EFFECT-
 SUBSYSTEM                    MAXIMUM    RELATIVE    ACTUAL    RELATIVE  IVENESS
                              (BTU/HR)     ( - )     (BTU/HR)    ( - )     ( - )

CLASS 0 - TURBINES           2.280154E+09  0.9191   2.359805E+08  0.5072   0.8965

CLASS 1 - FW HEATERS         1.622800E+08  0.0654   1.622800E+08  0.3488   0.8494

CLASS 2 - HEAT EXCHANGERS    2.602005E+07  0.0105   2.602005E+07  0.0559   0.8675

CLASS 3 - VALVES ONLY        1.485703E+07  0.0060   1.485703E+07  0.0319

CLASS 4 - PUMPS             -2.681659E+07 -0.0108   1.695073E+06  0.0036

CLASS 5 - MIXERS             5.678278E+06  0.0023   5.678278E+06  0.0122

CLASS 6 - SPLITTERS          2.883329E+06  0.0012   2.883329E+06  0.0062

CLASS 7 - MISC COMPONENTS    0.000000E+00  0.0000   0.000000E+00  0.0000

STREAMS                      1.584646E+07  0.0064   1.584646E+07  0.0341

 TOTALS                      2.480903E+09  1.0000   4.652406E+08  1.0000

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In this case, the turbine governing stage contributed 2.12% of the total irreversibility of the entire system.

We can find more relationships if we look at the turbine expansion on a Mollier diagram, as on Figure 1.

An isentropic expansion would take us from an enthalpy of h_1= HH(108) to h_X=HHISEN(109). The efficiency of the turbine governing stage component is:

$$\eta = \mathrm{EFFTRE}(109) = (h_1 - h_2) / (h_1 - h_X) = 1 - (h_2 - h_X) / (h_1 - h_X)$$

$$= [\mathrm{HH}(108) - \mathrm{HH}(109))] / [\mathrm{HH}(108) - \mathrm{HHISEN}(109)]$$

$$=1-[\mathrm{HH}(109) - \mathrm{HHISEN}(109))] / [\mathrm{HH}(108) - \mathrm{HHISEN}(109)].$$

A change in irreversibility will have the efffect of moving the point corresponding to h_2=HH(109) along the constant pressure line for p_2=PP(109), which is also the constant temperature line for T_2=TT(109). An increase in irreversibility increases h_2=HH(109) and decreases η=EFFTRE(109). If, in the calculation of irreversibility, we use the temperature at the end point of expansion for the stage, T_2=TT(109), rather than the Dead State reservoir temperature, T_0=TTDEAD, then we get an expression for a transfer of heat out of the system at a temperature of T_2=TT(109) rather than T_0=TTDEAD. The quantity obtained exactly equals

$$T_2(s_2 - s_1) = h_2 - h_x = \mathrm{HH(109) - HHISEN(109)}$$

This reinforces the interpretation of irreversibility as lost work and also shows the explicit connection between efficiency and irreversibility.

AVAILABILITY

The other 2^{nd} Law parameter that PEPSE calculates is availability. This is the maximum *theoretical* power availlable from a component or the system. For a stream, the availability is the theoretical work that could be extracted from the stream when brought to some standard state. The availibility function is:

$$\phi = \psi - \psi_{ss,0} = (h - T_0 s + V^2/2g_c + Z\, g/g_c) - (h_{ss,0} - T_0 s_{ss,0} + Z_0\, g/g_c).$$

The standard state is not the same as the dead state. The dead state is $T_0 = 50^oF$ and $p_0 = 14.696$ psia. The standard is at $T_{ss,0} = 77^oF$ and $p_{ss,0} = 14.696$ psia. PEPSE ignores velocity and differences in elevation in its calculation of availability. The standard state availability function is the same as that for saturated liquid at 77°F:

$$\psi_{ss,0} = (h_{ss,0} - T_0\, s_{ss,0}) = \psi_{f,77} = (\, h_{f,77} - T_0\, s_{f,77}) = 0.3689 \text{ Btu/lb}_m.$$

In practice, PEPSE references its avalilbility calculation to saturated steam at 77°F so that:

$$\psi_{ss} = \psi_{g,77} = \psi_{fg,77} + \psi_{f,77} = (h_{fg} - T_0\, s_{fg}) + \psi_{ss,0}$$

$$= 52.8287 + 0.3689 = 53.1976 \text{ Btu/lb}_m.$$

The availability which PEPSE calculates is the mass flow times the availibility function.

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 VERSION 551   CREATED 21 FEB 90      DATE 04/21/92.
 DAEC version 7 - HEAT BALANCE

          SECOND LAW OF THERMODYNAMICS PERFORMANCE - STREAMS

              AVAILABILITY  AVAILABILITY
    STREAM      FUNCTION      FUNCTION                        RELATIVE
    NUMBER         IN            OUT       IRREVERSIBILITY     IRREV.
                (BTU/HR)      (BTU/HR)        (BTU/HR)          ( - )

     108       2.935992E+09  2.935992E+09   0.000000E+00       0.0000

     109       2.797263E+09  2.797263E+09   0.000000E+00       0.0000
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 VERSION 551   CREATED 21 FEB 90      DATE 04/21/92.
 DAEC version 7 - HEAT BALANCE

          SECOND LAW OF THERMODYNAMICS PERFORMANCE - COMPONENTS

                               AVAILABILITY       POTENTIAL                     EFFEC-
 COMP  COMPONENT            ACTUAL     REL        FOR POWER     IRREVERSIBILITY  TIVE-
  NO.  DESCRIPTION          CHANGE    CHANGE   MAXIMUM    REL    ACTUAL    REL    NESS
                           (BTU/HR)   ( - )   (BTU/HR)   ( - )  (BTU/HR)  ( - )  ( - )

 109  NUCL. TURB. - GS    -1.387E+08  -.0559   1.387E+08  .0559  9.866E+06 .0212  .9289
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For the example, in the model we are using, the availability of the inlet stream for the turbine governing stage is:

$$\Phi_{108} = \mathrm{AVSTRU}(108) = 2.936 \times 10^9 \text{ Btu/hr.}$$

The availability of the outlet stream is:

$$\Phi_{109} = \mathrm{AVSTRI}(109) = 2.797 \times 10^9 \text{ Btu/hr.}$$

The availability difference for the turbine governing stage is:

$$\Delta\Phi = -\mathrm{DAVCMP}(109) = \mathrm{AVSTRI}(109) - \mathrm{AVSTRU}(108)$$

$$= 1.39 \times 10^8 \text{ Btu/hr.}$$

The potential for maximum power is:

$$P_{MP} = \Delta\Phi = 1.39 \times 108 \text{ Btu/hr.}$$

The effectiveness (ξ) is the actual power produced (P) compared to the potential power (P_{MP}):

$$\xi = EFFC(109) = (P_{MP} - I) / P_{MP}$$

$$= P/P_{MP} = .9289.$$

This is similar to efficiency (η) since it conpares actual power out to some potential maximum. In this case, the efficiency of the turbine governing stage is:

$$\eta = EFFTRE(109) = 0.87346.$$

For both efficiency and effectiveness, the potential power is what would be achieved if there were no change in entropy. For efficiency, the end point pressure is kept constant:

$$\eta = [h(p_1,s_1) - h(p_2,s_2)] / [h(p_1,s_1) - h(p_2,s_1)] = [h_1 - h_2] / [h_1 - h_X].$$

For the case of effectiveness, the end point enthalpy is kept constant:

$$\xi = [h(p_1,s_1) - h(p_2,s_2)] / [h(p_1,s_1) - h(p_2,s_2) - T_0(s_1-s_2)] =$$

$$= [h_1 - h_2] / [h_1 - h_2 - T_0(s_1-s_2)].$$

As efficiency increases and approaches η=1, the power out increases. As effectiveness increases and approaches ξ=1, the power out remains constant.

AVAILABLE ENERGY

The term *available energy* is sometime confused with *availability* and vice versa. The two are related but not the same. Available energy, E_A, is the energy available from an isentropic expansion of the steam from the bowl pressure of the turbine stage to the shell pressure:

$$E_A = h_1 - h_X.$$

It is calculated from the steam velocity, V_0, for which the turbine blade velocity would be equal to its Ideal Blade Speed:

$$E_A = V_0^2 / 2g.$$

The blade speed, V_B, for the governing stage is calculated from the pitch diameter, PD, and the turbine rotational speed, ω:

$$V_B = \pi \, PD \, \omega.$$

If this is to be the Ideal Blade Speed, then:

$$V_0 = 2V_B \text{ for a governing stage with a single row of blades; and}$$

$$= 4V_B \text{ for a governing stage with a double row of blades.}$$

It turns out that the difference between availibility and available energy is:

$$\Delta\phi - E_A = (T_0 - T_2)(s_2 - s_0).$$

This is an area on a T-s diagram which represents the net amount of work done by a Carnot cylcle operating between temperatures T_0 and T_2 and is shown on Figure 2. This represents the amount of energy left after the expansion through this one stage which is available for the expansion through succeeding stages. It also shows the expected relationship that the energy actually available to do work is less than that potentially available.

PLANT RESULTS

Irreversibility also relates to the change in stagnation conditions of the working fluid. The change in stagnation pressure for an ideal gas is:

$$p_{02}/p_{01} = e^{\Delta S/R}$$

We expect a certain pressure drop across a turbine stage since that is how the steam accelerates through the diaphram nozzle blades in order to impinge on the buckets on the rotating wheel and do work on them. Usually, a larger pressure drop across a stage means more work out. However, if a larger pressure drop does *not* result in more work out, then we should expect to find increased irreversibility due to some additional loss mechanisms.

This was our experience at DAEC. First stage turbine design pressure is 713 psia for a turbine steam flow of about 6.9 Mlb_m/hr.

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 DAEC version 7 - HEAT BALANCE

                DETAILED TURBINE PERFORMANCE TABLE B

                              PRESSURE      ENTHALPY      ENTROPY                 SHELL   EXTR
COMPONENT  STG GROUP          AT LOAD       AT LOAD       AT LOAD        PRESS    FLOW    PRESS
           BOWL FLOW       BOWL  SHELL    BOWL  SHELL   BOWL  SHELL     RATIO    COEFF   DROP
           (LBM/HR)           (PSIA)        (BTU/LBM)     (BTU/LB-F)      (-)      (*)     (-)

109/N-GS   6878029         926.40  712.99  1191.5  1172.8  1.396  1.399    1.30    201641.  N.A.
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Without second stage reheat in operation, the turbine steam flow is increased to about 7.2 Mlb_m/hr.

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PEPSE CODE BY EI INTERNATIONAL, INC., IDAHO FALLS, ID.
VERSION 55I  CREATED 21 FEB 90     DATE 04/22/92.
BENCHMARK w/o 2nd STAGE REHEAT STEAM

          DETAILED TURBINE PERFORMANCE TABLE B

                            PRESSURE      ENTHALPY       ENTROPY                SHELL   EXTR
COMPONENT   STG GROUP       AT LOAD       AT LOAD        AT LOAD       PRESS    FLOW    PRESS
            BOWL FLOW     BOWL  SHELL   BOWL  SHELL    BOWL  SHELL     RATIO    COEFF   DROP
            (LBM/HR)        (PSIA)       (BTU/LBM)     (BTU/LB-F)       (-)      (*)     (-)

109/N-GS     7163474.    926.40  743.33  1191.5  1175.3   1.396  1.398    1.25    201641.  N.A.
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At this flow, by GE turbine procedures, we should expect a shell pressure of about 743 psia rather than the 693 psia which we do measure. This lower than expected shell pressure along with no increase in power output led us to suspect damage within the high pressure section of the turbine. On top of this was PEPSE's calculation of increased irreversibility and availibiity change when actual plant pressures were put into the model:

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VERSION 55I  CREATED 21 FEB 90     DATE 04/21/92.
DAEC version 7 - HEAT BALANCE

                        COMPONENT PROPERTIES

COMP    STREAM  FLU   MASS                          SPEC.
         /PORT   ID    FLOW    TEMP   PRESS   QUALITY   ENTH    ENTRPY     VOLUME
                     (LBM/HR)   (F)   (PSIA)    ( - )   (B/LB)  (B/LB-F)   (FT3/LBM)

109 TNGS  108/I   0   6878029.  535.4  926.40   0.993    1191.5  1.39585    4.82E-01
          109/U   0   6878029.  505.1  712.99   0.959    1172.8  1.39867    6.18E-01

          SECOND LAW OF THERMODYNAMICS PERFORMANCE - COMPONENTS

                           AVAILABILITY        POTENTIAL                            EFFEC-
COMP  COMPONENT          ACTUAL     REL       FOR POWER       IRREVERSIBILITY   TIVE-
  NO. DESCRIPTION        CHANGE    CHANGE    MAXIMUM   REL    ACTUAL     REL     NESS
                         (BTU/HR)   ( - )    (BTU/HR)  ( - )  (BTU/HR)   ( - )   ( - )

109  NUCL. TURB. - GS  -1.387E+08  -.0559   1.387E+08  .0559  9.866E+06  .0212   .9289
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PEPSE CODE BY EI INTERNATIONAL, INC., IDAHO FALLS, ID.
VERSION 551   CREATED 21 FEB 90      DATE 04/22/92.
REDUCED HP TURBINE SHELL PRESSURES

                              COMPONENT PROPERTIES

 COMP    STREAM  FLU  MASS                              SPEC.
          /PORT   ID   FLOW    TEMP   PRESS  QUALITY  ENTH    ENTRPY    VOLUME
                      (LBM/HR)  (F)   (PSIA)    (-)     (B/LB)  (B/LB-F)  (FT3/LBM)

109 TNGS  108/I    0  7104928.  535.4  926.40   0.993    1191.5  1.39585   4.82E-01
          109/U    0  7104928.  502.0  693.00   0.961    1174.8  1.40324   6.38E-01

          SECOND LAW OF THERMODYNAMICS PERFORMANCE - COMPONENTS

                          AVAILABILITY        POTENTIAL                            EFFEC-
COMP  COMPONENT          ACTUAL    REL        FOR POWER       IRREVERSIBILITY      TIVE-
  NO. DESCRIPTION        CHANGE    CHANGE   MAXIMUM    REL   ACTUAL      REL       NESS
                         (BTU/HR)   (-)     (BTU/HR)   (-)   (BTU/HR)    (-)       (-)

109  NUCL. TURB. - GS   -1.451E+08  -.0586   1.451E+08 .0586 2.674E+07   .0541     .8157
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This increase in irreversibility reinforced our suspicion that some type of throttling was occuring in side the turbine. Inspection of the high pressure turbine during DAEC's 11th Refueling Outage in the spring of 1992 revealed significant damage to the diaphram between the 1st and 2nd stages of the high pressure turbine and is shown in Figure 3. The effect of this damage was to cause internal throttling of the steam so that an increase in entropy occured without any work being done.

CONCLUSION

This has been a brief examination of the information available from PEPSE's Second Law of Thermodynamics performance parameters and an example of how we used them at DAEC. We have found the Second Law parameters add a useful dimension and perspective to analysis of plant performance

REFERENCES

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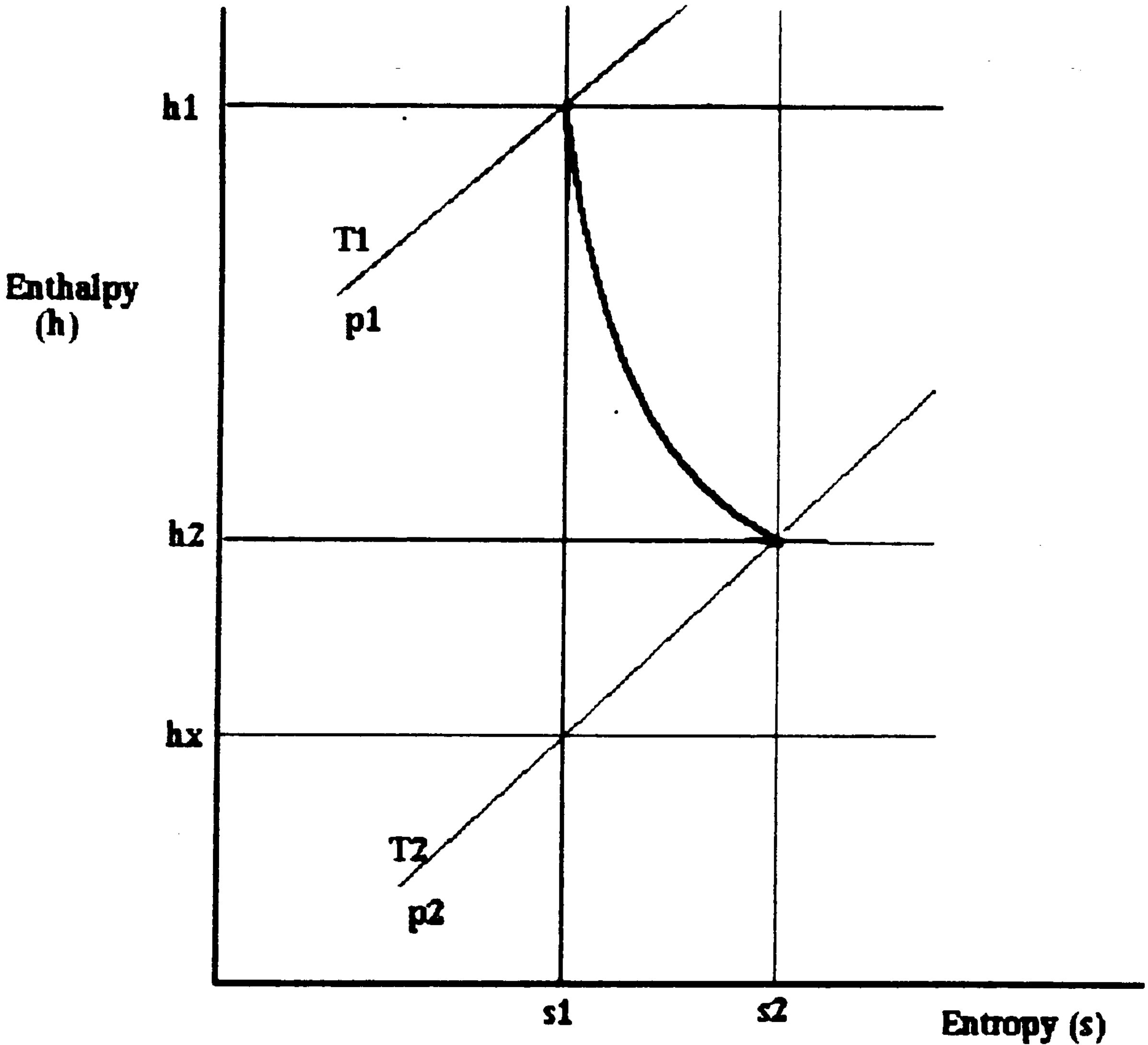
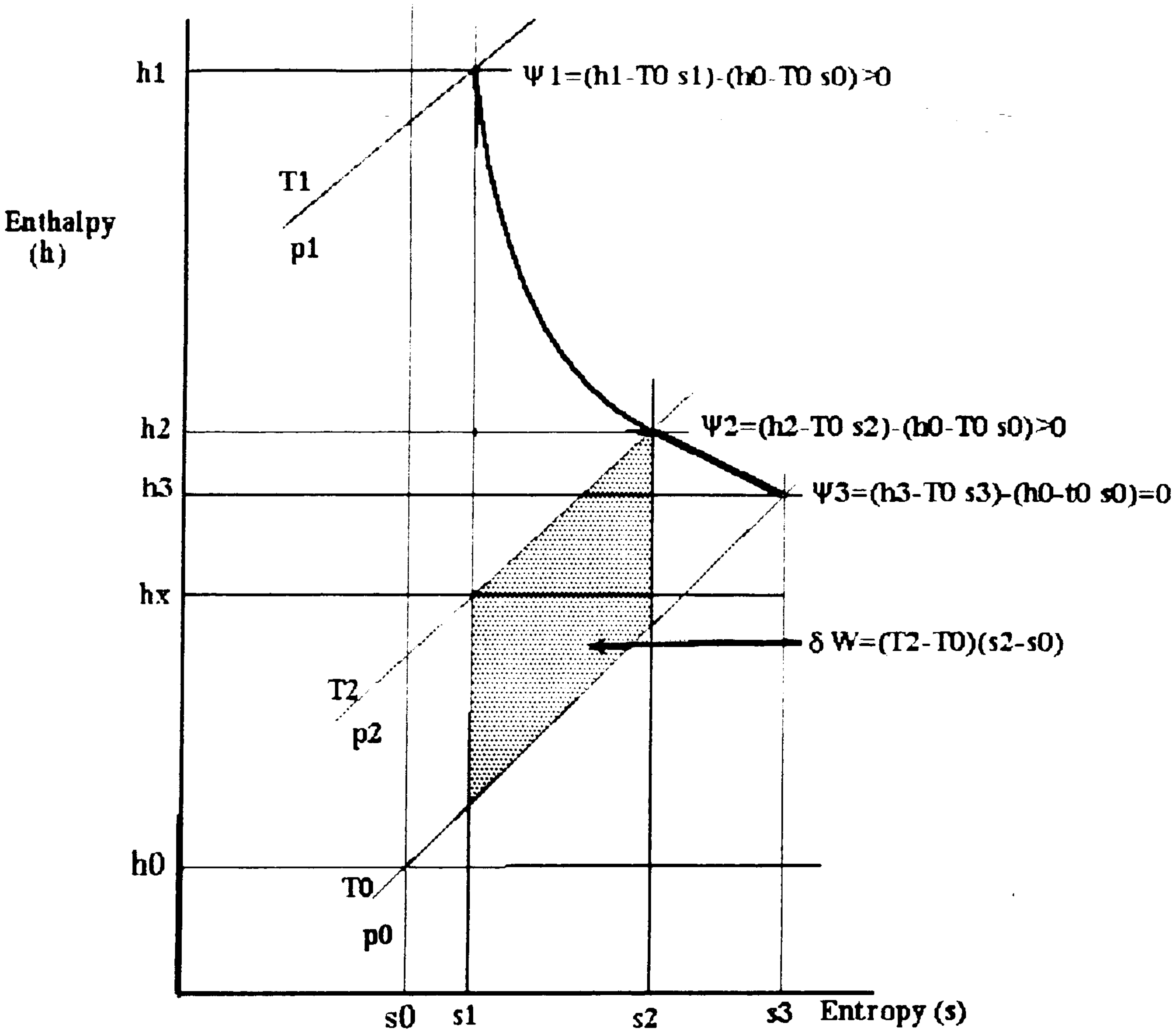
Van Wylen, G. J. and R. E. Sonntag, Fundamentals of Classical Thermodynamics, Wiley, 1973

Zemansky, M. W., Heat and Thermodynamics, McGraw-Hill, New York, 1968



$\eta = (h1 - h2) / (h1 - hx)$

Fig. 1 Turbine Expansion



$$\xi = \frac{h1 - h2}{h1 - h2 - T0\,(s2 - s1)}$$

Fig. 2 Available Work After Expansion Through One Stage

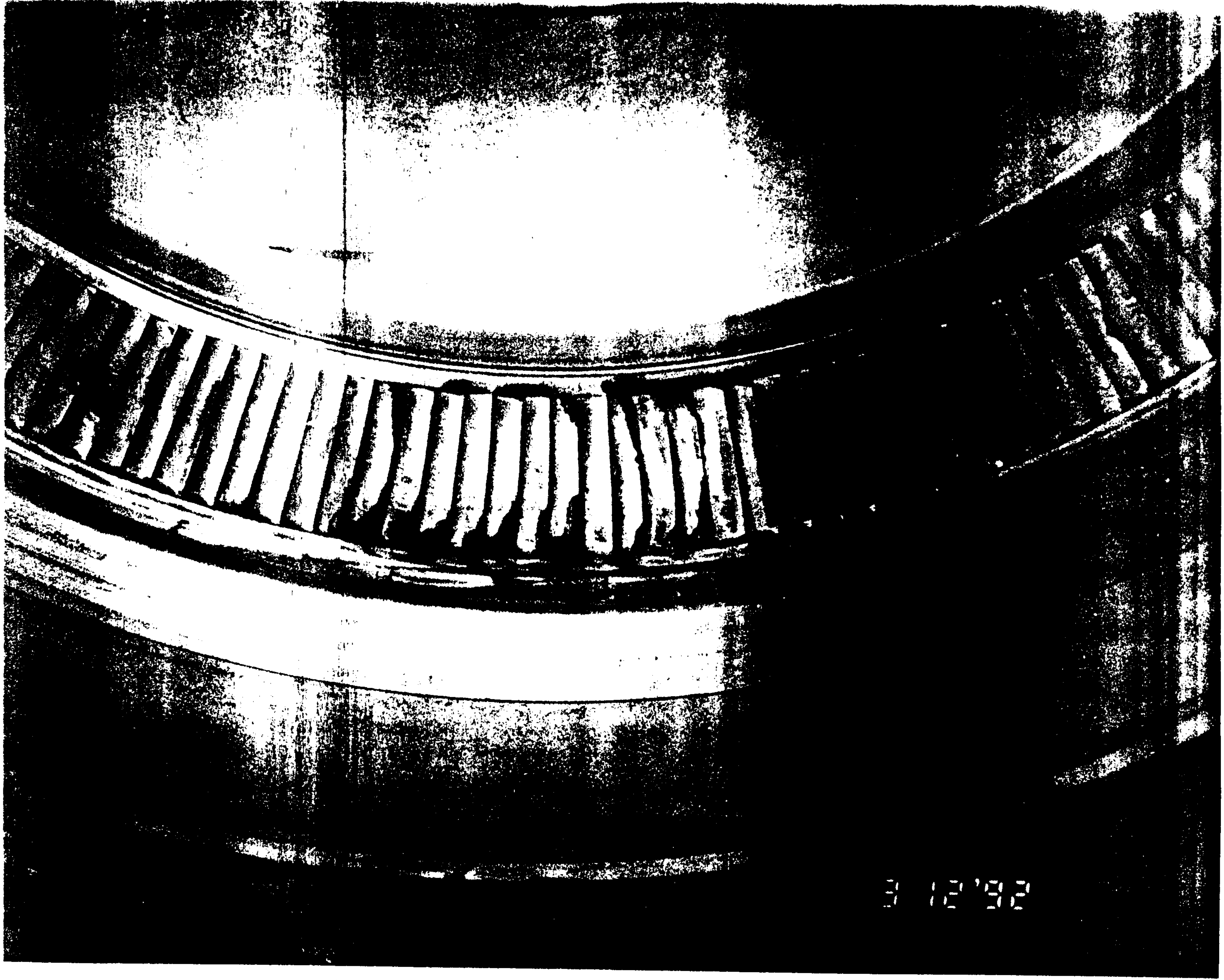


FIGURE 3: DAMAGE TO HP TURBINE 2nd STAGE DIAPHRAM