MODELING OF THE SECONDARY LOOP AT TRILLO NPP, IN ECOSIMPRO

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Abstract – *In order to identify the causes of a small deterioration in the performance observed in the secondary loop at Trillo NPP, a very detailed model was developed of the heat balance of the plant. This model represents the individual equipment items of the three low-pressure trains, and the formulation was selected so as to allow analysis of both the nominal operating conditions and also cases of degraded operation due to wear and tear or equipment failure. The model was developed using EcosimPro, a simulation program developed by Empresarios Agrupados, and was connected to Excel in order to allow its use by process engineers who are not necessarily familiar with the program, and also to be able to display the results quickly and in an easy to understand format. The use of the model allowed us to unmistakably identify the cause of the degradation in performance: to this end a number of failures were assumed and an optimization algorithm was used to minimize the deviation between the variables measured in the cycle and the once calculated by the model changing the size of the failure. Logically, the most probable failure causing the degradation is the one that leads to a greater reduction of the deviations between the measured variables and calculated ones. Lastly, the cause of the degradation in performance predicted by the model was totally confirmed during the inspections carried out during the latest refuelling.*

1. INTRODUCTION

At Trillo NPP the electricity production figures indicated that a small loss of efficiency had occurred in the secondary loop of the plant. The equipment items suspected of being the cause of the loss of efficiency were the duplex heaters of two of the three condensate trains.

A duplex heater is an equipment item that combines LP Heaters 1 and 2 in a single space-saving module (see Figure 1).

While Train 3 continues to operate under conditions similar to the ones before the refuelling, LP Trains 1 and 2 had suffered deviations to their operating points, with respect to Train 3, as shown in Figure 2 below.

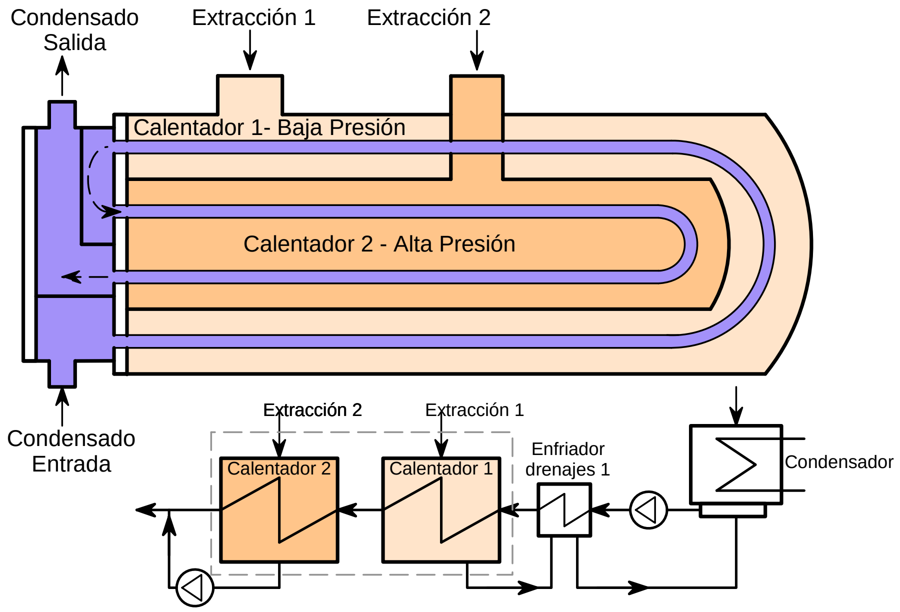


Figure 1. Duplex heater combining Heaters 1 and 2

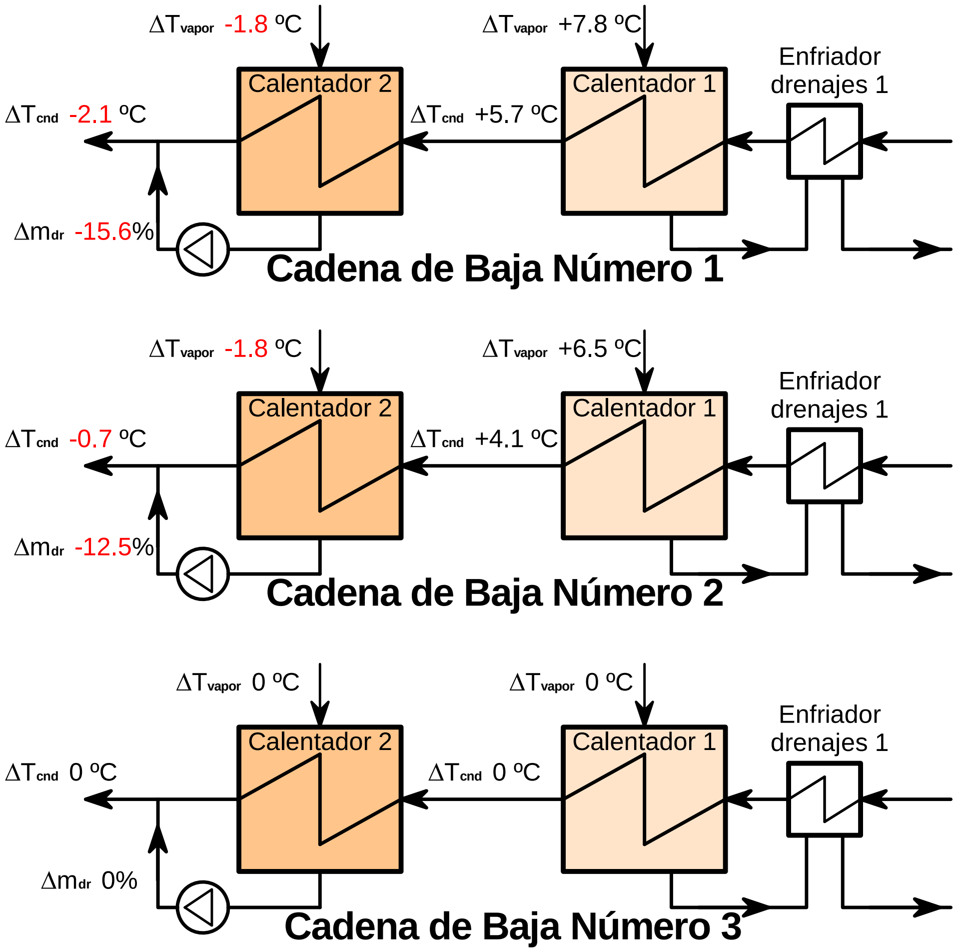


Figure 2. Deviations in Operating Points of LP Trains 1 and 2 with respect to Train 3

The main deviations that can be seen in Figure 2 are described below:

1. The drain mass flows from the HP side of Trains 1 and 2 had decreased with respect to Train 3. In the case of Train 1 the reduction was 15.6% and in the case of Train 2 it was 12.5%
2. The steam temperatures on the LP side of LP Trains 1 and 2 had increased very significantly with respect to the temperature in the LP side of LP Train 3. Said temperature increase was 77.8ºC in train 1 and 6.5ºC in Train 2.
3. The steam temperatures on the HP side also showed a clear asymmetry, but in the opposite direction to the asymmetry described above for the LP side. The steam temperature in the HP side of Trains 1 and 2 was 1.8ºC lower than in Train 3.
4. The condensate temperatures at the outlet of the heaters in Trains 1 and 2 were lower than that in Train 3. In the case of Train 1 it was 2.1ºC lower and in the case of Train 2 it was 0.7ºC lower.
5. The condensate temperatures at the outlet of the LP side also presented an asymmetry, but in the opposite direction to the asymmetry shown by the condensate at the outlet. The condensate at the outlet on the LP side was 5.7ºC higher in Train 1 than in Train 3, and it was 4.1ºC higher in Train 2 than it was in Train 3.

Even though it was known that the equipment items that were causing the loss of efficiency were probably the duplex heaters, the problem was far from being resolved as it had to be ascertained what failure had occurred in the said equipment so as to allow an inspection during the refuelling.

2. METHODOLOGY

With the aim of diagnosing the failure it was decided to develop a model of the plant heat balance capable of simulating degradations and equipment failures during steady state operation. Said model allowed the simulation of different scenarios with a high degree of approximation to the real response of the cycle, both during nominal operating conditions and also in case of degraded operation due to wear and tear or equipment malfunction.

Different degradations and failures of the equipment were postulated and for each degradation or failure an algorithm was applied to minimize the deviation between the variables measured at the plant and the variables calculated by the model, by changing the level of degradation or the size of the postulated failure. Logically, the most probable cause of the degradation would be the one that most reduced the deviation between the measured variables and the calculated ones, after application of the algorithm.

Following is a description of the model and of the optimization algorithm used for the search for the failure.

2.1. Modelling

First we identified some requirements on the simulation model for the plant heat balance, as identified below:

- Detailed modelling and representation of the 3 LP trains, as they were behaving in an asymmetric manner
- Ability to represent simulate the behaviour at a specified design point, and ability to extrapolate the behaviour of the components outside the design point

- Ability to represent degradations of the actuations of the equipment and also the ability to represent equipment failures. Apart from other myriad failures and degradations, the model shall also allow simulation of the following failures in the duplex heaters, that are considered as possible causes of the anomalous behaviour of the LP trains:
    1. Steam leaks on the LP side of Trains 1 and 2 to the condenser
    2. Steam leaks on the HP side of Trains 1 and 2 to the condenser
    3. Condensate bypass between waterboxes of Trains 1 and 2
    4. Steam leaks on the HP side to the LP side in Trains 1 and 2
    5. Condensate pipe rupture in Trains 1 and 2
- Connectable to optimization programs or sub-routines in order to be able to apply the above-mentioned failure detection algorithm
- Connectable to excel for immediate display of the results allow its use by personnel who do not know how to use the simulation program

Figure 3 shows the diagram of the EcosimPro model developed on the basis of the above-mentioned criteria with the purpose of investigating the loss of performance at Trillo NPP. The model represents the 3 LP trains in great detail (3 LP turbines, 3 condenser bodies and 3 LP heating trains).

A user interface with Excel was created in order to show the results of the balances calculated in EcosimPro in an easily understandable manner, and also to allow them to be used by personnel who do not know how to use the simulation program. The interface allows users to change the model data and to execute it; it then automatically displays the results over pre-defined diagrams. Figure 4 shows the global state of the plant in the Excel interface, and Figure 5 shows the details of the LP heating trains in the same interface.

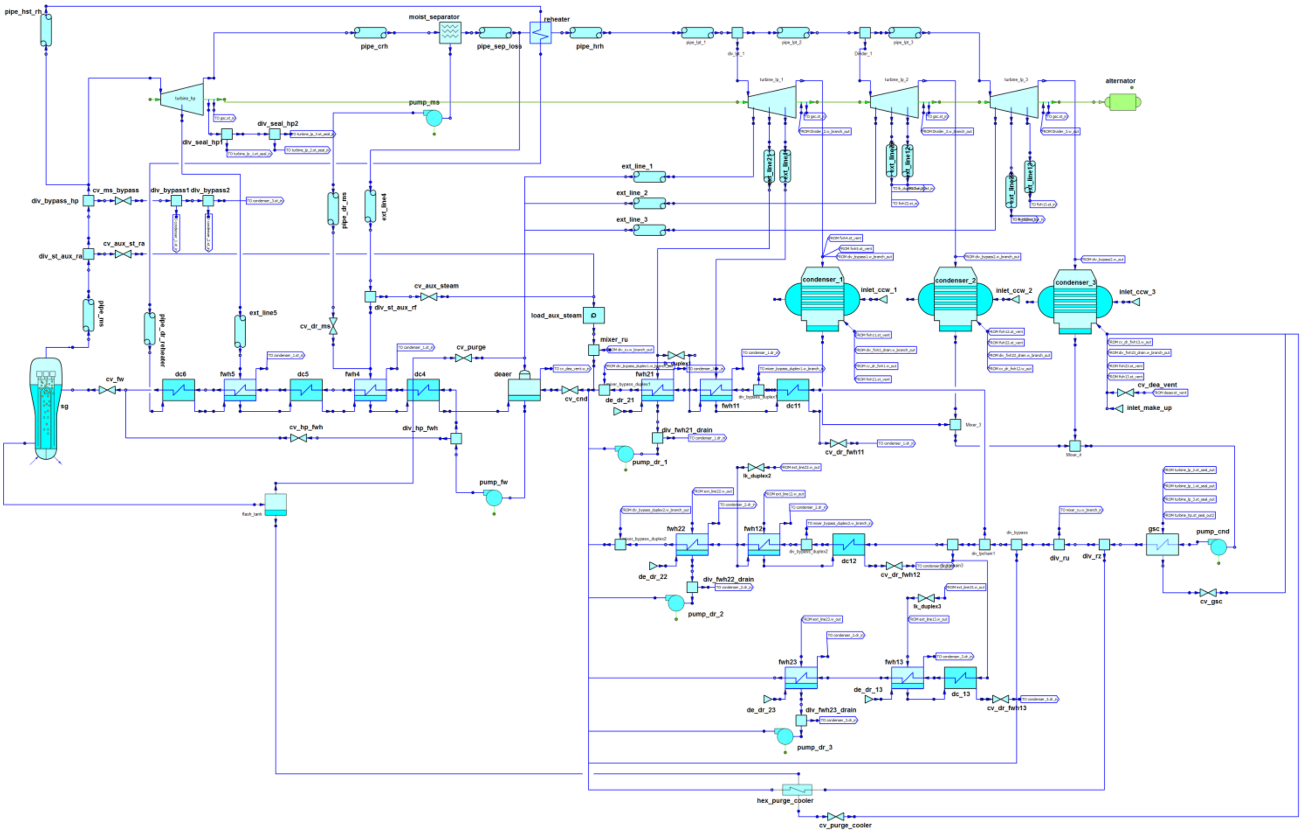


Figure 3. Model of the Heat Balance at Trillo NPP

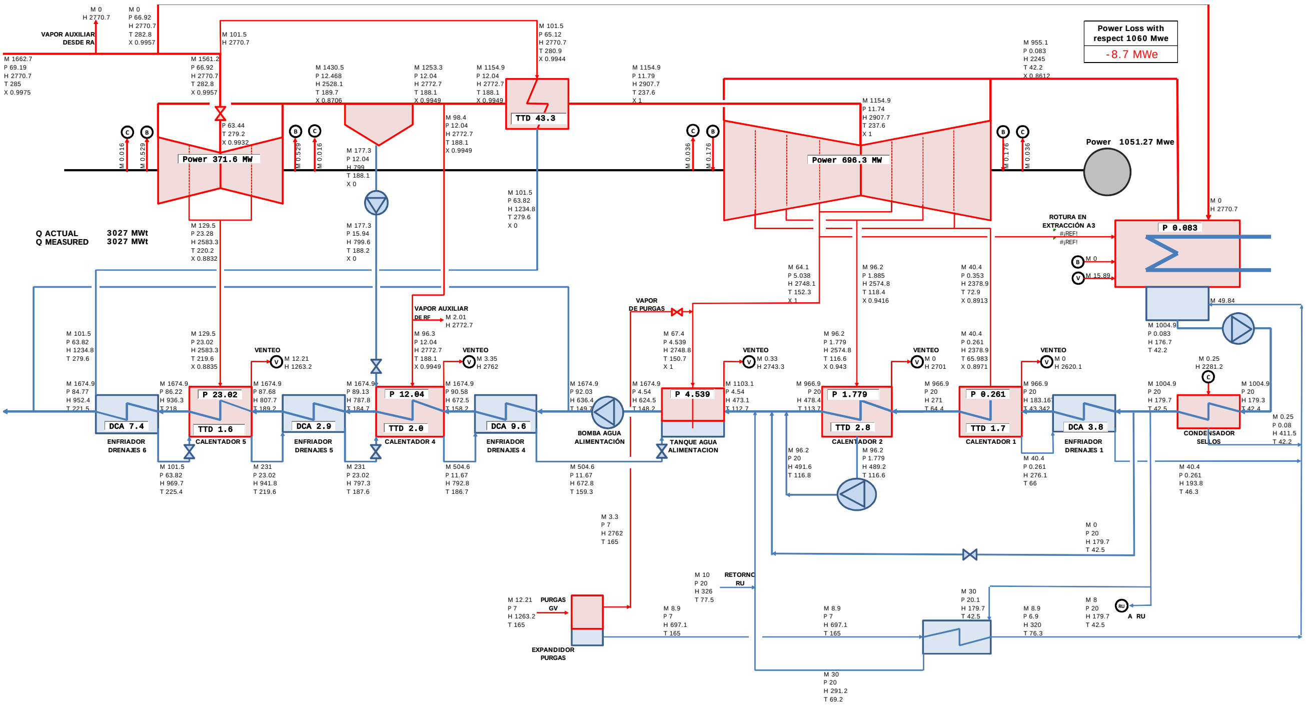


Figure 4. Diagram of the global state of the plant, in Excel the interface

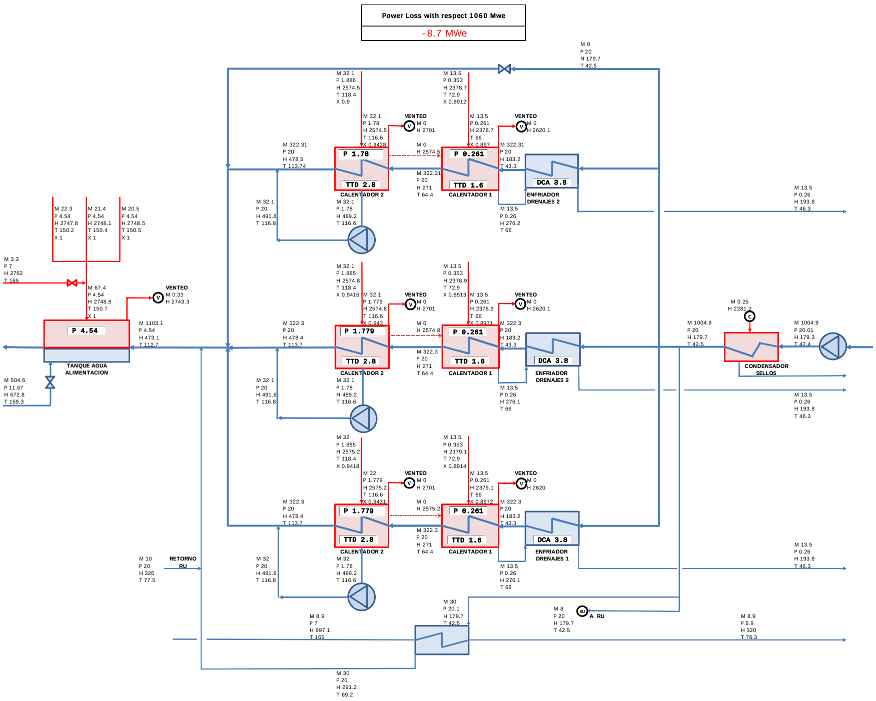


Figure 5. Diagram of the LP heating trains in the Excel interface

2.2. Definition of the Optimization Problem

Resolving an optimization problem requires the definition of the cost function to be minimized. In this study the cost function was defined as the quadratic sum of the errors between the measured variables and calculated variables in the LP train area.

$$CF = \sqrt{\sum_{i=1}^{i=Nmf}\left(\frac{m_{i,\ calc} - m_{i,\ meas}}{\sigma_{mass\ flow}}\right)^2 + \sum_{j=1}^{j=NTemp}\left(\frac{T_{j,\ calc} - T_{j,\ meas}}{\sigma_{Temp}}\right)^2}$$

where:

Cost function

CF

Number of mass flows used in the cost function = 3

Nmf

Number of temperatures used in the cost function = 21

$NTemp$

Mass flow calculated at Point i

$m_{i,\ calc}$

Mass flow measured at Point i

$m_{i,\ meas}$ Temperature calculated at Point j

$T_{j,\ calc}$ Temperature measured at Point j

$T_{j,\ meas}$ Typical deviation of the temperature measurement; assuming = 1 ºC

σ_{Temp} Typical deviation of the flowmeters; assuming 2% of the 100% flow

$\sigma_{mass\ flow}$

As the failure was located in the LP trains, the variables considered in the cost function were exclusively those that described the state of the LP heating trains, as listed in Table 1 below:

Table 1. Measured and calculated variables used in the coast function

Tag	Variable	System	Place or Position	LP Train
M1	Mass Flow	Drains	Heater 2	1
M2	Mass Flow	Drains	Heater 2	2
M3	Mass Flow	Drains	Heater 2	3
T1	Temperature	Extraction Steam	Heater 2	1
T2	Temperature	Extraction Steam	Heater 2	2
T3	Temperature	Extraction Steam	Heater 2	3
T4	Temperature	Drains	Heater 2	1
T5	Temperature	Drains	Heater 2	2
T6	Temperature	Drains	Heater 2	3
T7	Temperature	Extraction Steam	Heater 1	1
T8	Temperature	Extraction Steam	Heater 1	2
T9	Temperature	Extraction Steam	Heater 1	3
T10	Temperature	Drains	Heater 1	1
T11	Temperature	Drains	Heater 1	2
T12	Temperature	Drains	Heater 1	3
T13	Temperature	Condensate	Drain cooler outlet	1
T14	Temperature	Condensate	Drain cooler outlet	2
T15	Temperature	Condensate	Drain cooler outlet	3
T16	Temperature	Condensate	Heater 1 outlet	1
T17	Temperature	Condensate	Heater 1 outlet	2
T18	Temperature	Condensate	Heater 1 outlet	3
T19	Temperature	Condensate	Heater 2 outlet	1
T20	Temperature	Condensate	Heater 2 outlet	2
T21	Temperature	Condensate	Heater 2 outlet	3

With regard to the variables calculated using the optimization algorithm to minimize the cost function, we included the ones that defined the size or scope of the failure. However, given the type of failure to be analyzed, the real pressure at the inlet of the last stage of the LP turbine and the pressure drop in the extraction lines of the heaters could also have a significant impact on the results. In order to estimate the real pressures at the inlet of the last stage of the LP turbine, and the pressure drop in the extraction lines on the LP side of the duplex heaters as accurately as possible, we decided to include the flow factor of the last step of the LP turbine and a multiplier of the pressure drops in the extraction lines on the LP side of the duplex heaters, in the variables of the optimization problem. Table 2 below shows the optimization variables used in each failure case.

Table 2. Optimization variables for different failure cases

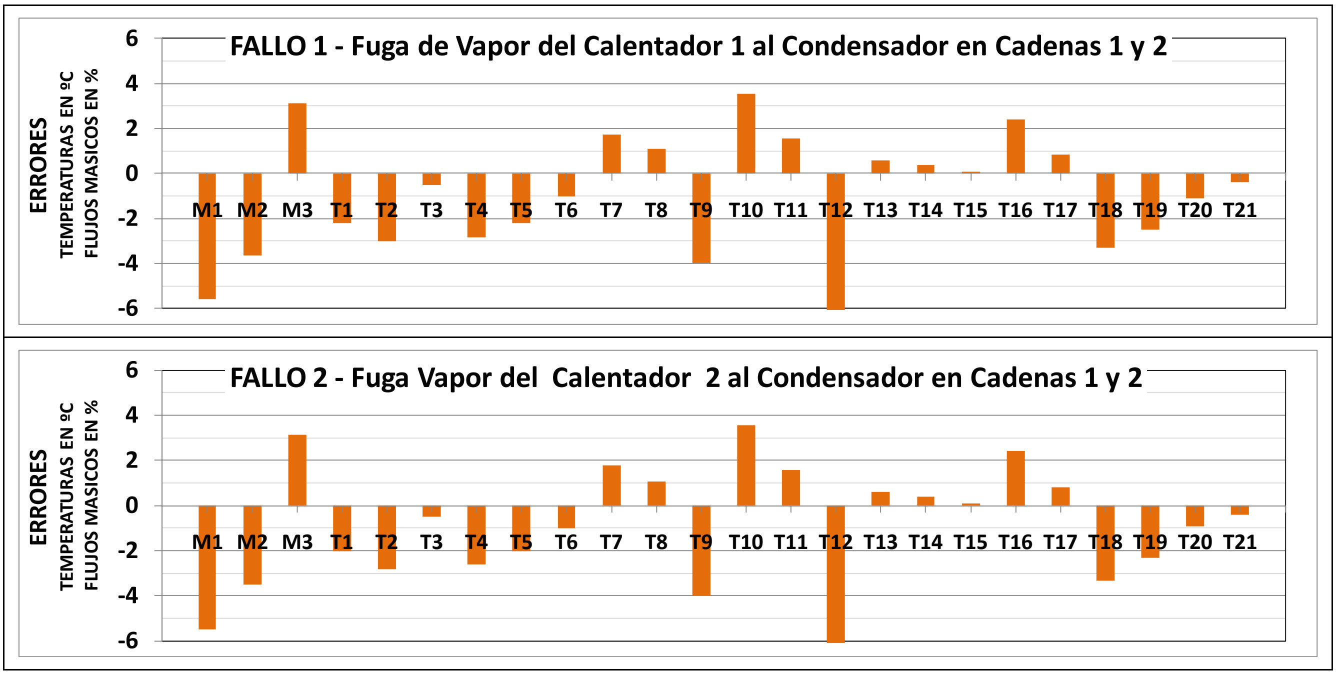
Failure	**Description**	**Optimization Variables**
1	Leak on the LP side of the duplex heater (heater 1) to the condenser in trains 1 and 2	4 **variables for optimization:** 1. Flow of leaks from heater 1 in train 1 2. Flow of leaks from heater 1 in train 2 3. Flow factor of the last step of the LP turbine 4. Multiplier of pressure drops in extraction 1
2	Leak on the HP side of the duplex heater (heater 1) to the condenser in trains 1 and 2	4 **variables for optimization:** 1. Flow of leaks from heater 1 in train 1 2. Flow of leaks from heater 1 in train 2 5. Flow factor of the last step of the LP turbine 3. Multiplier of pressure drops in extraction 1
3	Bypasses in duplex heater water boxes	**6 variables for optimisation:** 1. Fraction of bypass in heater 1 of train 1 2. Fraction of bypass in heater 2 of train 1 3. Fraction of total bypass in duplex heater of train 1 4. Fraction of bypass in heater 2 of train 1 5. Fraction of bypass in heater 2 of train 2 6. Fraction of total bypass in duplex heater of train 2 7. Flow factor of the last step of the LP turbine 8. Multiplier of pressure drops in extraction 1

Failure	Description	Optimization Variables
4	Lean from the HP side to the LP side in duplex heaters in trains 1 and 2	**4 variables for optimization:** 1. Flow of leaks in duplex heater of train 1 2. Flow of leaks in duplex heater of train 2 3. Flow factor of the last step of the LP turbine 4. Multiplier of pressure drops in extraction 1

3. RESULTS

Figure 4 shows bar charts with the deviation between variables as measured and as calculated for the four postulated failures in the duplex heaters after optimization of the size of the failure. It shows clearly that failure number 4, steam leaks in duplex heaters in trains 1 and 2 from the high pressure side (heater 2) to the low pressure side (heater 1) is the one that best matches the measurements taken on site. It should be noted that failure 3, despite using a double number of optimization variables, gives a much worse match.

After the work was done, the equipment was inspected during the refueling outage in 2015. Initial inspection found no leakage area between the high and low pressure sides of the duplex heaters in trains 1 and 2 at points easy to inspect. Nevertheless, the results of the analysis featured herein were so conclusive that the decision was made to carry out a test that revealed the leak, but that test is written up in a separate paper [1].



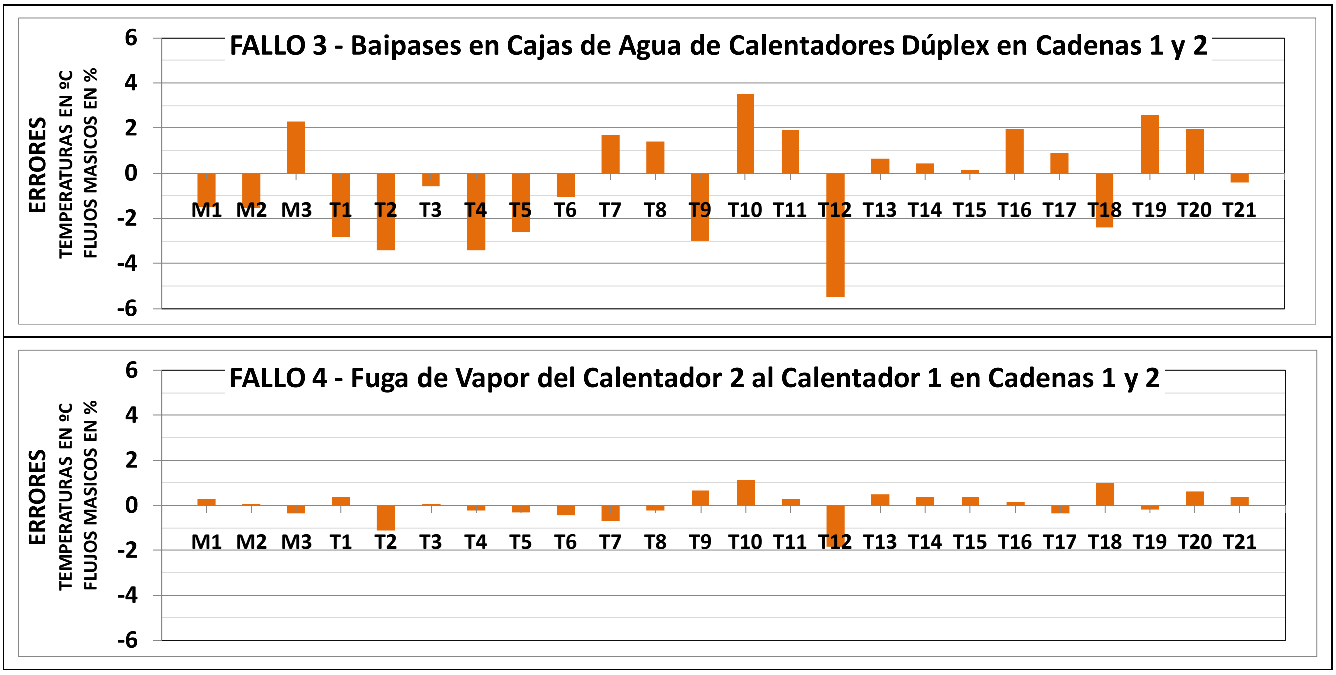


Figure 6. Deviations between Measured and Calculated Variables for the Four Postulated Failures

4. CONCLUSIONS

A detailed model of the secondary of a nuclear power plant can be used to depict equipment breakdowns and malfunctions. If an equipment item is suspected to be malfunctioning, the detailed model can help identify the failure or breakdown unmistakably by using the optimization technique used in this paper, provided that the following conditions are met:

- The model must portray the parallel trains separately and individually. A model that groups together parallel branches that operate symmetrically in case of normal operation without any malfunctions is suitable for predicting the output of the cycle, but is not suitable for identifying equipment failures, since the malfunctions cannot be expected to appear simultaneously in all the parallel branches.
- The potential failures of the equipment must be depicted in the model. As obvious as it may sound, a failure cannot be identified if it is not represented anywhere in the model. Representation of equipment failures requires a firm understanding of the equipment and its architecture.
- The proposed technique (optimization to identify the type of failure as well as the size of the defect or wear) has made it possible to identify a breakdown in non-inspectable areas that would not be detectable by other means.

REFERENCES

[1] Alejandro López Hernández "*Análisis de las Pruebas de Rendimiento del Secundario de C.N. Trillo*", 41 Reunión Anual de la Sociedad Nuclear Española, Sesión 15 – Operación.