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Cleanliness Criteria to Improve Steam Generator Performance

T. Schwarz, R. Bouecke
Framatome-ANP GmbH
P.O. Box 3220
91050 Erlangen Germany
Thomas.Schwarz@Framatome-ANP.com
Reinhard.Bouecke@Framatome-ANP.com

S. Odar
Framatome-ANP GmbH
P.O. Box 3220
91050 Erlangen Germany
Suat.Odar@Framatome-ANP.com

ABSTRACT

High steam generator performance is a prerequisite for high plant availability and possible life time extension. The major opponent to that is corrosion and fouling of the heating tubes. Such steam generator degradation problems arise from the continuous ingress of non-volatile contaminants, i.e. corrosion products and salt impurities may accumulate in the steam generators. These impurities have their origin in the secondary side systems. The corrosion products generally accumulate in the steam generators and form deposits not only in the flow restricted areas, such as on top of tube sheet and tube support structure, but also build scales on the steam generator heating tubes. In addition, the tube scales in general affect the steam generator thermal performance, which ultimately causes a reduction of power output. The most effective ways of counteracting all these degradation problems, and thus of improving the steam generator performance is to keep them in clean conditions or, if judged necessary, to plan cleaning measures such as mechanical tube sheet lancing or chemical cleaning.

This paper presents a methodology how to assess the cleanliness condition of a steam generator by bringing together all available operational and inspection data such as thermal performance and water chemistry data. By means of this all-inclusive approach the cleanliness condition is quantified in terms of a fouling index. The fouling index allows to monitor the condition of a specific steam generator, compare it to other plants and, finally, to serve as criterion for cleaning measures such as chemical cleaning.

The application of the cleanliness criteria and the achieved field results with respect to improvements of steam generator performance will be presented.

1 INTRODUCTION

Steam generators (SG) of Pressurized Water Reactors (PWR) are key components. Their reliability affects greatly the overall plant performance and availability. World-wide experience shows that significant number of operating PWRs have corrosion or mechanical degradation problems in their SG's [1]. These SG problems often force unscheduled or extended outages for preventive and corrective maintenance, which are costly in terms of repair work, loss of power and personnel radiation exposure.

In addition to SG corrosion problems, which are experienced mainly on the secondary side, also deterioration of SG thermal performance is experienced in most of the plants, which is caused by growing SG tube scales affecting the primary to secondary side heat transfer. Based on field experience, corrosion product fouling in SGs has been identified as a major cause of heat transfer degradation in PWR plants, with the power output at some plants being decreased to as low as 80% of full power. The origin of these tube scales are the corrosion products generated in the secondary side of the plant and transported into SGs.

Figure 1 shows the SG being embedded in the steam/water (secondary side) cycle and shows the transport routes of impurities and corrosion product into the SG.

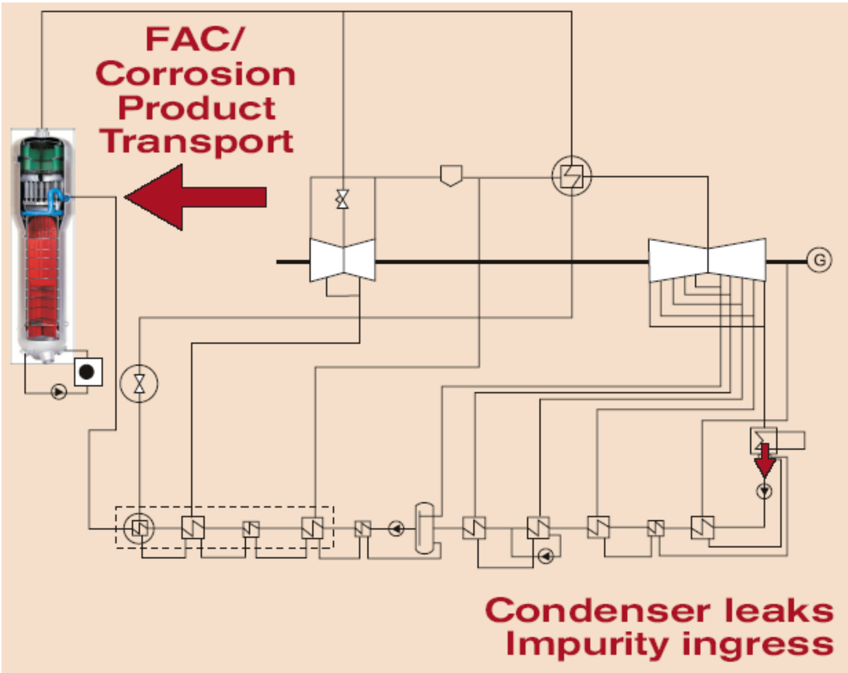

Figure 1**:** Impurity ingress into the steam generator

All these secondary side SG problems can be mitigated or even be prevented by adopting suitable secondary side water chemistry operation concepts or cleaning measures, if necessary.

The plant operators have to take decision whether corrective measures have to be planned. These decisions require an evaluation of the actual SG cleanliness condition. If the trend of the condition over the past operating years has been monitored, corrective measures can be planned more reliably and in due time before their implementation. A procedure for establishing cleanliness criteria is presented in the following.

2 PLANT DATA TO DETERMINE THE SG CONDITION

In order to gain a complete picture of each SG's cleanliness condition in a plant or its evolution all suitable plant operational and SG inspection data should be brought together. These data serve as "fouling indicators". Data may be categorized into "Heat Transfer Performance", "Water Chemistry Parameters" and "Inspection Results".

2.1 Heat Transfer Performance

The increase of tube scales (fouling) may deteriorate the primary- to secondary-side heat transfer, resulting in a steam pressure decrease and reduction of margins.

Only a few operational data need to be recorded in order to monitor the thermal performance, see Figure 2: the steam pressure (p_{st}), the feedwater flow rate and temperature (m_{fw}, T_{fw}), the blow down flow rate (m_{bd}) and the reactor coolant pressure and temperatures (p_{pri}, T_{in}, T_{out}). The most universal fouling indicator variable is the fouling factor, which can be considered as kind of additional heat transfer resistance appearing as a difference to the design condition. An example of the fouling factor evolution of a SG is shown in Figure 3.

Additionally, Figure 3 includes a curve of the accumulated iron in the SG. Both curves correlate well, which means that the Fe inventory is also an appropriate fouling indicator. The amount of the iron deposited in the SG can be obtained from an iron balance from measured concentrations and flow rates of feed water (ingress) and blow down (partial removal).

Moreover, the example of Figure 3 documents the effect of chemical cleaning. Both fouling factor and Fe inventory have drastically reduced after this cleaning measure.

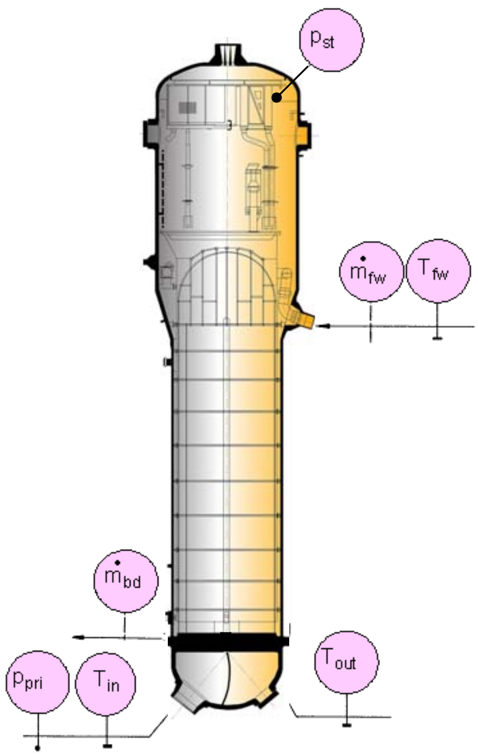

Figure 2**:** Operational data to be recorded for thermal performance monitoring

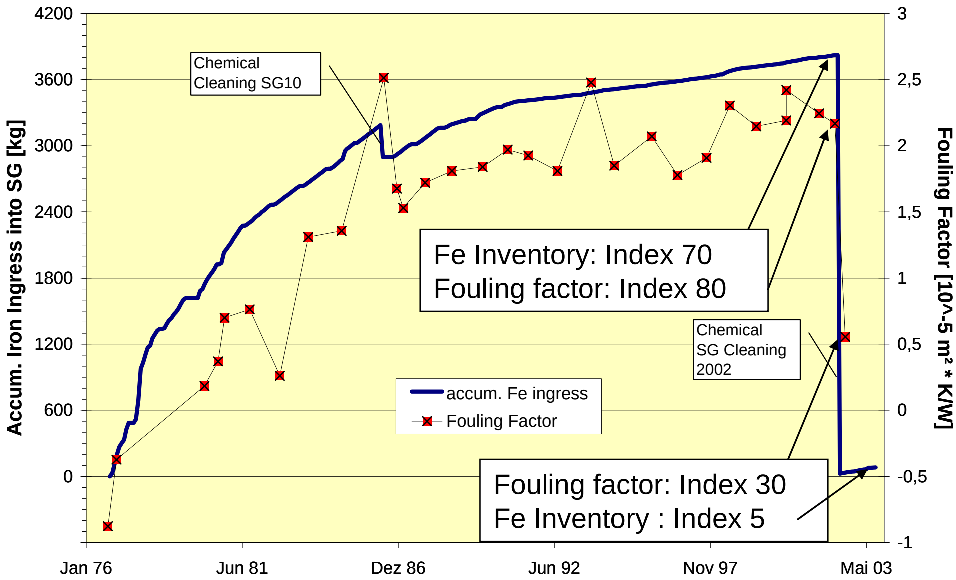

Figure 3**:** Fouling factor evolution vs. operating time correlated with Fe inventory. Effect of chemical cleaning. Index of fouling indicators before and after chemical cleaning

2.2 Water Chemistry Parameters

The change in SG condition usually is accompanied by a change of some SG operating chemistry parameters, which are indicative of the increased SG deposits:

One of the main chemistry parameters which can be used for this purpose is the change of SG and feed water (FW) hydrazine concentrations. The hydrazine concentration in SG is usually higher than in FW due to concentration increase by evaporation; but is limited because of volatility and thermal decomposition (SG temperature is higher than feed water temperature). Since the thermal decomposition of hydrazine is catalyzed by deposits, the decomposition rate will increase with increasing deposit amount. In other words, the hydrazine concentration ratio of SG to feed water, is expected to decrease with operating time of the plant. This is exactly what is experienced in many PWRs. In Figure 4 the behaviour of hydrazine concentration ratio is given as a function of 12 years of operating time for one PWR as a typical example. The purpose of using hydrazine is to maintain reducing conditions in SGs. Due to the increase of thermal decomposition of hydrazine in SG and limitation of feed water hydrazine concentration (because of environmental requirements), SG hydrazine concentration decreases with a operating time. In general, this, can lead to a situation where SG hydrazine concentration needed for maintaining the reducing conditions in SGs can no more be ensured; and accordingly a removal of the deposits may become necessary. Hence, the slope of SG/FW hydrazine concentration ratio decrease can be used as a fouling indicator variable to predict when SG cleaning will be needed.

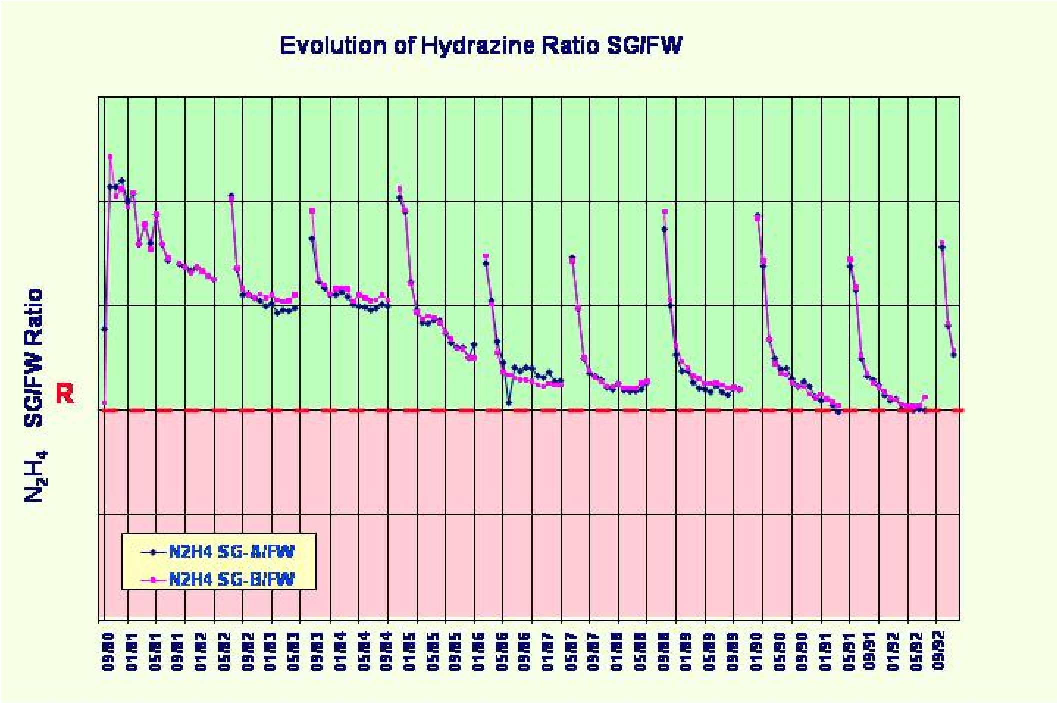

Figure 4**:** Typical evolution of hydrazine concentration ratio SG/FW in a PWR

Another set of chemistry parameters which can be used for cleanliness evaluation are the hide-out and hide-out return phenomena. Hide-out is the only mechanism in SGs, which may lead to impurity concentration up to corrosive levels; and therefore needs to be monitored and evaluated carefully. Increase of deposit levels increases the SG hide-out behaviour. When hide-out starts to be dominant for impurity control in SGs, it results in a high corrosion risk. This situation of SG hide-out behaviour can be monitored either by hide-out return tests during plant shut downs (release of impurities hidden-out during operation) or by hide-out tests (injection of Na-24 tracer into feed water).

During these tests, the constant SG Na-24 concentration (corrected by steam carry over, blow down and natural decay) is indicative for an insignificant SG hide-out behaviour. If Na-24 concentration decreases remarkably, this is due to significant hide-out. In Figure 5 an example of SG with significant hide-out is compared with the one without remarkable hide-out behavior.

The hide-out behavior of SGs changes also with the operating time; i.e. hide-out increases with increasing deposit loading. Thus, the hide-out increase rate can also be used as a fouling indicator variable.

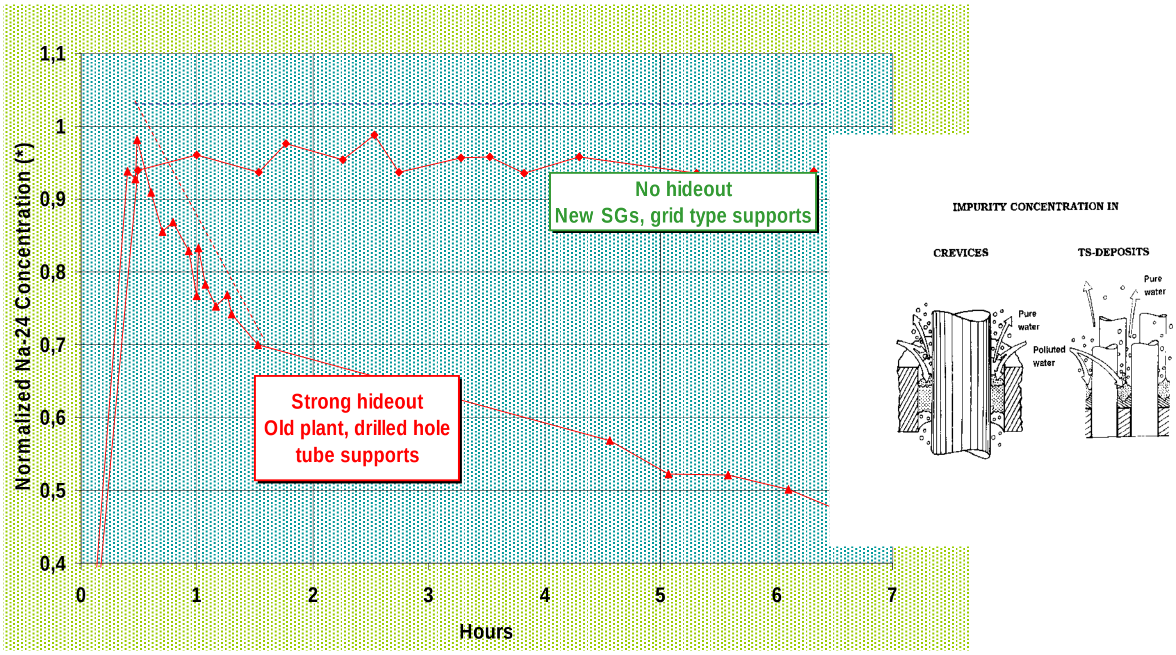

Figure 5**:** SGs with significant and negligible hide-out behavior

2.3 Inspection Results

Several outage inspection results can also be used as indicators for judging the cleanliness condition of the SG.

Heavy hard deposits are the locations for impurity concentration to corrosive levels. This can be confirmed by visual inspections: Different colours of deposits are direct indications for salt concentrations (see Figure 6). In cases where the deposits are uniformly black, only chemical analysis can help to assess their risk for tube corrosion.

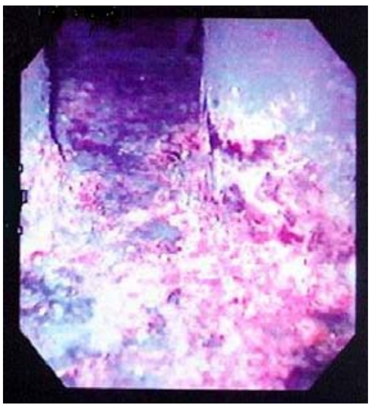

Figure 6**:** Colored SG deposits

Further useful inspection results can be gathered from

- measurements of sludge deposits on tube sheet (e.g. with endoscope visual testing or with tube eddy current testing)
- visual testing of the tube surfaces in the tube bend area (e.g. with floating cameras)
- tube scale thickness measurements

3 FOULING INDEX

In a next step of the cleanliness evaluation weighting factors are applied in order to normalize the fouling indicator variables and make them comparable among each other, see Table 1. Based on world wide field experience thermal performance has been found as the most important category. A weighting factor of 30% has been assigned to it. Likewise, water chemistry receives a weighting factor of 30 %. As per the definition, the sum of all weighting factors is 100%. Within each main category the indicator variables are individually weighted.

Table 1: Weighting of Fouling Indicators

i	Indicator Variables	Weighting Factors
	Heat transfer performance	**30 %**
1	Fouling factor	…
2	Heat transfer margins	…
3	Growth rate	…
…	…	…
	Water chemistry parameters	**30 %**
	N_2H_4-ratio	…
	Fe inventory	…
	Hide-out behaviour	…
	Hide-out-return behaviour	…
	…	…
	Sludge on tube sheet	**15 %**
	Number of tubes affected	…
	Height of sludge	…
	Colours of tube scale	…
	…	…
	Last TS lancing	**15 %**
	Quantity removed	…
	Density of sludge	…
	Composition of sludge	…
	…	…
	Tube scale measurements	**10 %**
	Scale thickness	…
	Appearance, colours	…
n	…	…
		100% Sum

From the sum of the weighted individual indicator variables an overall fouling index of the SG is obtained which, as per the above definitions, is between 0 and 100, where 0 stands for “clean” and 100 stands for “fouled”

$$\text{overall fouling index} = \sum_{i=1}^{n} (\text{fouling index} \cdot \text{weighting factor})_{\text{indicator } i}$$

4 CLEANING RECOMMENDATIONS

The overall fouling index can be used as a basic indicator to judge whether counter measures are necessary or not. Three zones are defined::

- “Green”, index 0 to 50: No cleaning actions have to be foreseen
- “Orange”, index 50 to 80: An optimization of the chemistry program shall be considered (corrosion product control, oxygen control etc.) and cleaning measures shall be planned in the long term

- "Red", index 80 to 100: cleaning actions have to be initiated as soon as possible.
  Possible cleaning actions are mechanical tube sheet lancing with high pressure water jets or, ultimately, chemical cleaning of the whole tube bundle (e.g. with Framatome ANP's high temperature cleaning process, [3 - 6])

Of course, the overall index is not a strict number for the measures. The final decision will also be based on the individual fouling indicators which are judged in the course of the expertise.

For example, chemical cleaning of SGs in German NPP performed in 2002 was planned in long term. The fouling indicators "Fouling Factor" and "Fe Inventory" had been indexed by 80 respectively 70 before chemical cleaning and 30 respectively 5 after chemical cleaning (see Figure 3). Taking into account all available indicators, this measure has decreased the overall fouling index from 62 to 34.

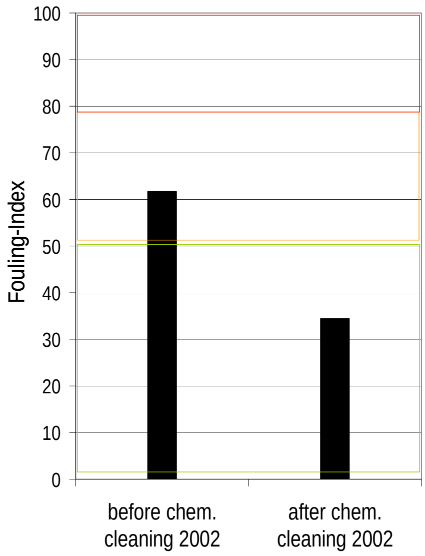

Figure 7**:** Example: Overall fouling index before and after chemical cleaning

5 SUMMARY

A procedure for an expertise is presented which evaluates the cleanliness condition of a steam generator and gives a firm basis to the plant operators, i.e. for a decision on cleaning measures (see Figure 8).

Advantages are:

- the expertise systematically makes use of all suitable plant data (check list)
- where appropriate, it recommends additional highly informative tests such as sludge chemical analysis
- the fouling trend vs. operating time of the SG under consideration is reliably evaluated if the same measurement locations and techniques are used
- the standardization via the indexing of the variables allows a cross comparison among different plants
- the expertise allows establishment of SG status oriented maintenance strategy

- the success of cleaning measures can be verified
- SG cleanliness offers the perspective for plant life time extension

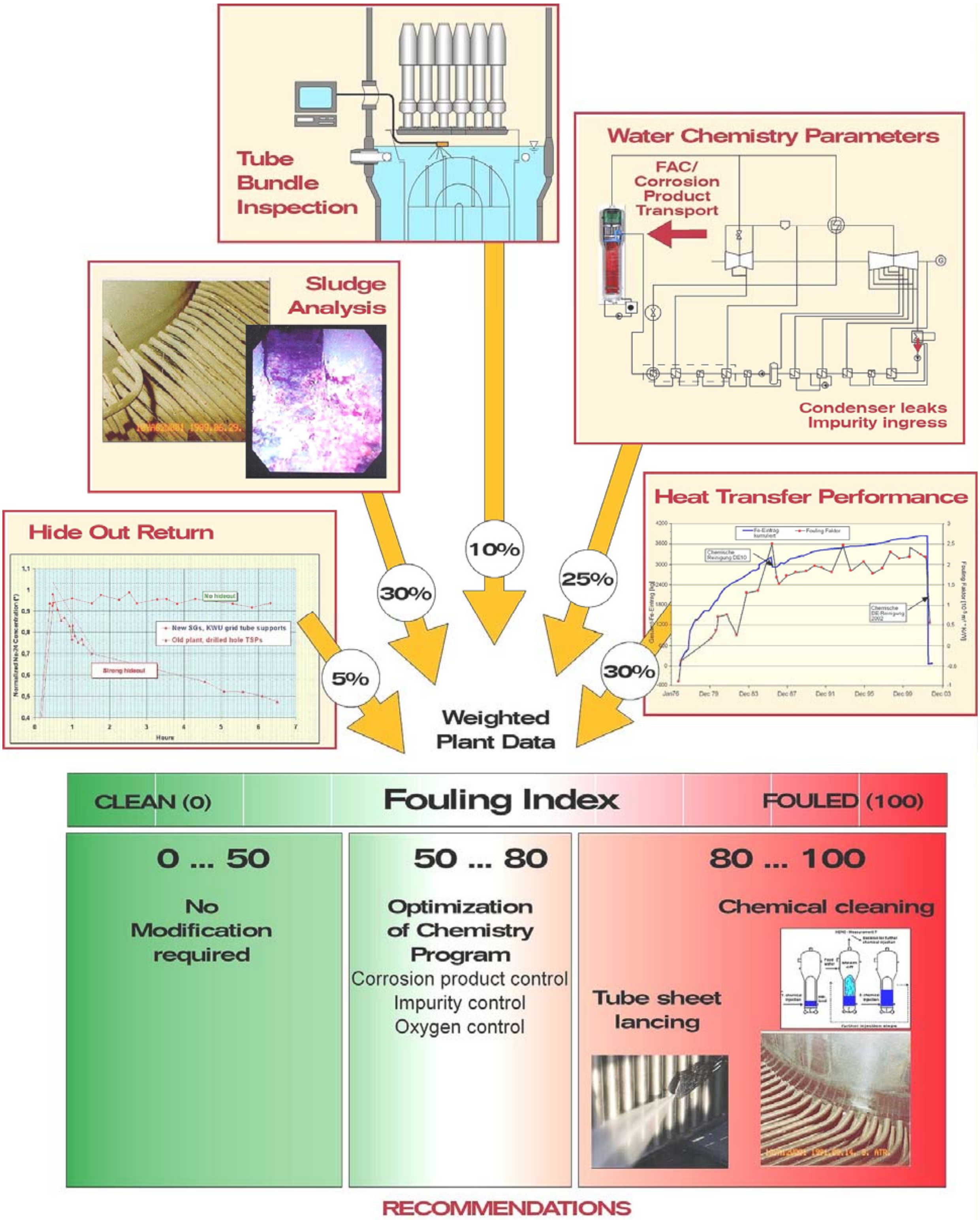

Figure 8**:** Summary: fouling index and derived cleaning recommendations

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