The Probabilistic Assessment of Steam Generator Leakrate during a Secondary Side Accident

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1 INTRODUCTION

The tube bundle of Pressurized Water Reactor (PWR) Steam Generators (SG) has been affected by numerous corrosion damages, all over the world. One of the main problems is Primary Water Stress Corrosion Cracking (PWSCC) in the roll transition of Mill Annealed (MA) Inconel 600 tubes, mechanically expanded in the SG tube sheet. Multiple axial cracks are initiated from the primary side and grow rapidly through the tube wall ; they further grow in length and propagate outside of the roll transitions. This propagation could not been stopped by shot peening of the inside diameter of the roll transition area, as presently performed in most European and American plants.

The policy applied by several European countries, and presently proposed by the USA Utilities (EPRI Report, 1990), is to accept SG operation with axial Trough Wall Depth (TWD) cracks below a maximum length (called "plugging limit") which still provides adequate margins against tube bursting. Tubes reaching or exceeding the plugging limit must be either plugged or repaired (sleeving).

However another safety related limitation may result from the SG primary to secondary leak rate in case of a postulated large secondary side accident. Because of the larger associated differential pressure, the normal operation leak rate could be considerably increased and lead to an excessive radioactive release to the plant environment. This consideration may result in more tube plugging/repair than dictated by the structural plugging limit.

This paper describes the probabilistic methodology developed by LABORELEC to provide a direct assessment of SG leakrate under accident conditions.

2 PROBABILISTIC ASSESSMENT OF SG LEAK RATE UNDER ACCIDENT CONDITIONS

Operation of an SG with a large number of (close to) through-wall cracks raises a potential concern of leakage during :

- Normal operation.
- Accident conditions (the highest differential pressure being associated with a FeedWater Line Break - FWLB).

A simplified deterministic model for leakage from an axial crack in a pressurized tube is given by :

$$Q = KS\sqrt{2\ \Delta p/\rho}$$

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This illustrates the three sources of increased leakrate Q under accidental conditions

- . Differential pressure Δp increases from about 100 to 180 bar.
- . Leakage area S increases, both elastically and plastically, proportionally to the crack width which (depending on length) may grow from a few microns to a few tenths of a mm.
- . Flow discharge coefficient K, which under normal operating conditions is governed by the "tortuosity" of the intergranular leakage path, may increase from a low value of about 0.1 to a nominal value close to 0.6

The combined effect of the three parameters may result in a wide range for the ratio of accident to service leak rates.

In addition to this, other factors influence the service leak rate in an unpredictable way :

- . A large number of PWSCC cracks are very deep (> 80 % TWD) but not entirely through-wall. A thin remaining ligament (in the range of 5 to 10 %, depending on crack length) is likely to break under the increased differential pressure of accident conditions.
- . Some cracks are made up of aligned components which, even when TWD, leak very little if at all. Under accident conditions these ligaments are likely to fail, resulting in a single "long" crack with a large leakage area.
- . Some cracks, even when rather long and through-wall, may be prevented to leak by their outside environment (such as hard sludge) ; the loading imposed by accident conditions might break up these leak limiting barriers.
- . Tight PWSCC cracks (with TWD penetration) are easily clogged by cruds or precipitates and leak considerably less than under laboratory conditions; the substantial (elastic and plastic) widening of these cracks, under accident conditions, would restore a "clean" leakage path.

Based upon these considerations, it does not appear possible to establish a reliable ratio of accident to service leakage that could be further used by extrapolating the accident leak rate from the observed service leak rate.

Thus a probabilistic model was developed by LABORELEC to provide a direct assessment of SG leak rate under accident conditions.

The methodology consists in a stochastic combination of the statistical distributions assumed for each of the contributing parameters :

- . Mechanical properties (YS + UTS) at operating temperature.
- . Correlation coefficient between "flow stress" (FS) and mechanical properties K = FS/(YS + UTS).
- . Tube wall thickness.
- . Sizing uncertainty on crack length (based on RPC inspection methodology).
- . Expected crack lengths at the end of next (or current) cycle.

The four first distributions are approximated by Gaussian curves while the last one results from the "crack propagation prediction model" previously developped by LABORELEC (Hernalsteen P., SMIRT 10, 1989).

Deterministic algorithms and discrete values are further used for :

- . The tubesheet reinforcing effect (TSR).
- . The crack shape factor SF = OD length/ID length, on the basis of an assumed linear relationship between the OD and ID crack lengths.
- . The plugging limit PL.
- . Dependence of the flow discharge coefficient on the average crack width.

3 THE LABOLEAK SOFTWARE PROGRAM

The methodology described hereabove has been built into a software program, using a Monte-Carlo type method, written in APL language and implemented on a personal computer. The program is called LABOLEAK, after LABOrelec LEAKrate (Hernalsteen P., Laborelec Report MOO-90-023/R-PH, 1990).

As illustrated by Fig. 1, the program calculates resulting probability distribution functions for :

- Flow stress (FS).
- Crack critical length, with and without the tubesheet effect (cl, CL).
- The expected crack population at the end of the current operating cycle (with and without the effect of ECT uncertainty (ml, ML) ; this is based on beginning of cycle (BOC) inspection data and the previously referenced prediction model, or a direct assumption of end of cycle (EOC) inspection data.
- The outer diameter (OD) crack length resulting from the assumed shape factor SF (ML2).

The program then establishes the crack average width, for any combination of actual (ML, ML2) and critical (CL) lengths, and the corresponding flow discharge coefficient (K) matrix. The final calculation step produces the distribution of tube leak rates ; consideration of the number of cracks then yields the desired distribution curve of SG leak rate.

4 LABOLEAK PROGRAM VALIDATION

Apart from routine analytical verification of the computer algorithms, the validation process was centered on the following sensitive parameters (Hernalsteen P., Laborelec Report MOO-90-024/R-PH, 1990) :

- Leakage area.
  While the elastic component is well defined by available analytical studies, the plastic component needed to be established by an experimental test program ; this allowed the leakage area to be expressed as a non-linear function of the ratio of actual to critical length of the crack.
- "Flow stress" coefficient.
  This coefficient is derived from experimental burst tests of flawed tubes, as a function of the flaw length.
  International comparison of test results from various programs (Belgium, France, UK, USA, ...) indicated a very large scatter ; this was shown to result from the experimental conditions and, mainly, from the sealing arrangement needed to allow pressurization of the test specimens with TWD flaws. Recent tests performed by LABORELEC without any seal (with a high pressure pump allowing a flow rate in excess of 20 m^3/h) allowed to identify the reliable results.
- "Flow discharge" coefficient K.
  The K dependence on crack width has been modeled in a way to simulate the relatively scarce leak rate field data (or laboratory data, when performed under representative conditions) ; further refinement may be needed and is currently under investigation.

5 LABOLEAK PROGRAM USES

The program is currently used to perform parametric and sensitivity studies of the degraded SG under accident conditions.

Results are typically printed out as illustrated by Fig. 2 combining :

- A summary of all input data.
- A plot of the leak rate distribution among the various crack length categories, with indication of the total leak rate.
- A comparison plot between the expected crack length distribution (at end of cycle) and the critical crack length distribution, with indication of the resulting probability of having a SG Tube Rupture, in case of a FWLB.
- The plot of the total SG leak rate distribution, allowing to select a design value for any predefined confidence level.

The available results confirm that, for a SG significantly affected by PWSCC, the "best estimate leak rate" is higher than the value originally expected.

6 CONCLUSIONS

On the basis of the statistical analysis of a large amount of accurate inspection data, complemented by extensive field and laboratory experience, a computer program (LABOLEAK) has been developed for the probabilistic assessment of SG leakrate under accident conditions.

This tool is used to perform safety evaluations, to verify the adequacy of the tube plugging limit and to support the long term repair/replacement strategy of steam generators affected by PWSCC in the tube roll transitions.

This methodology has drawn international interest and in, particular, has been adopted by the Mechanism Specific Defect Management (MSDM) Committee, conducted by the U.S.A. Electrical Power Research Institute (EPRI) to support a Utilities proposal for alternate tube plugging criteria (EPRI Report, 1990) ; within the latter context EPRI has taken a licence of the LABOLEAK program to make it available to all U.S. Utilities operating PWR plants.

REFERENCES

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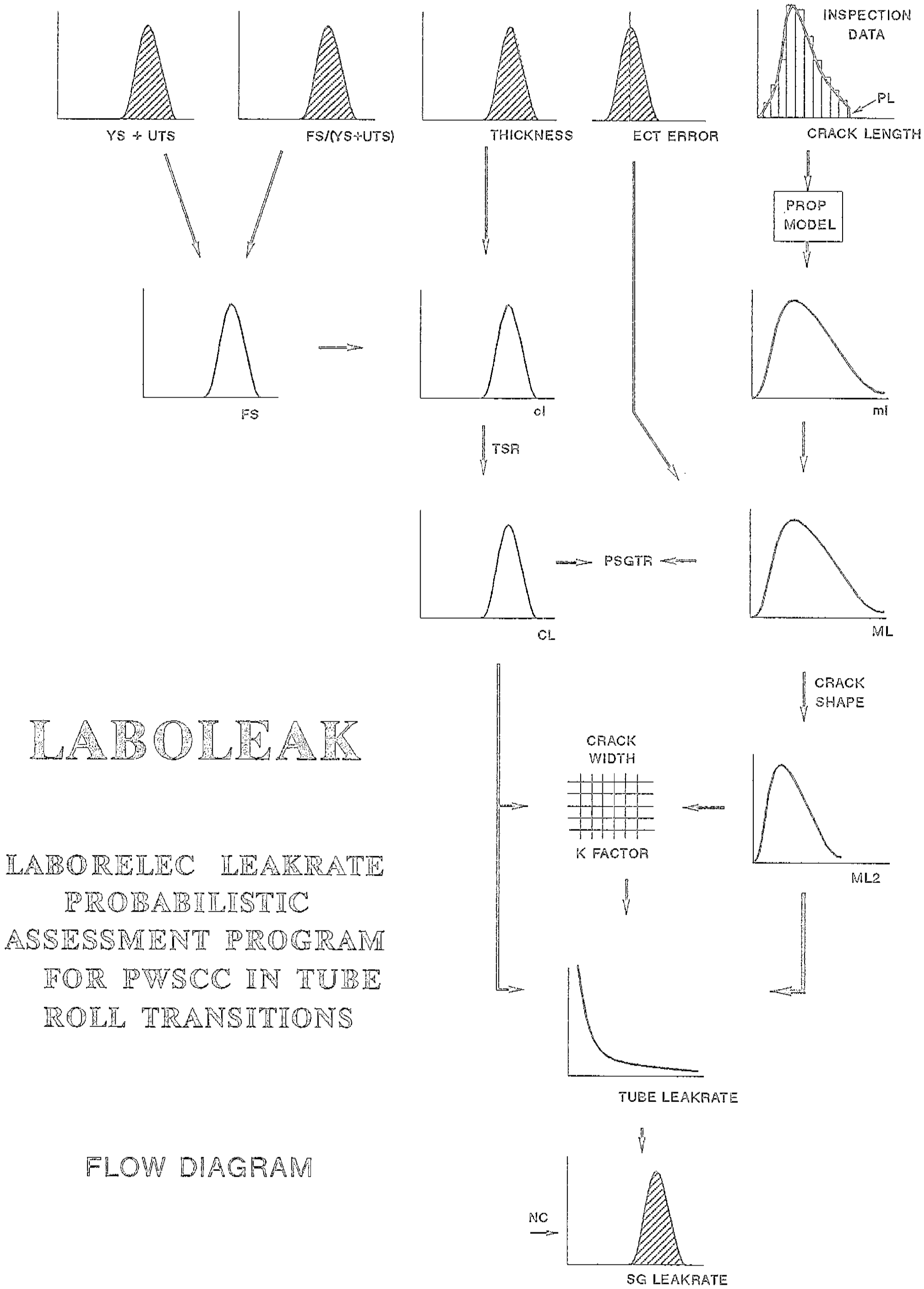
INSPECTION DATA
PL
YS + UTS
FS/(YS+UTS)
THICKNESS
ECT ERROR
CRACK LENGTH
PROP MODEL
FS
cl
ml
TSR
PSGTR
CL
ML
CRACK SHAPE
LABOLEAK
CRACK WIDTH
K FACTOR
ML2
LABORELEC LEAKRATE PROBABILISTIC ASSESSMENT PROGRAM FOR PWSCC IN TUBE ROLL TRANSITIONS
TUBE LEAKRATE
FLOW DIAGRAM
NC
SG LEAKRATE

Fig. 1

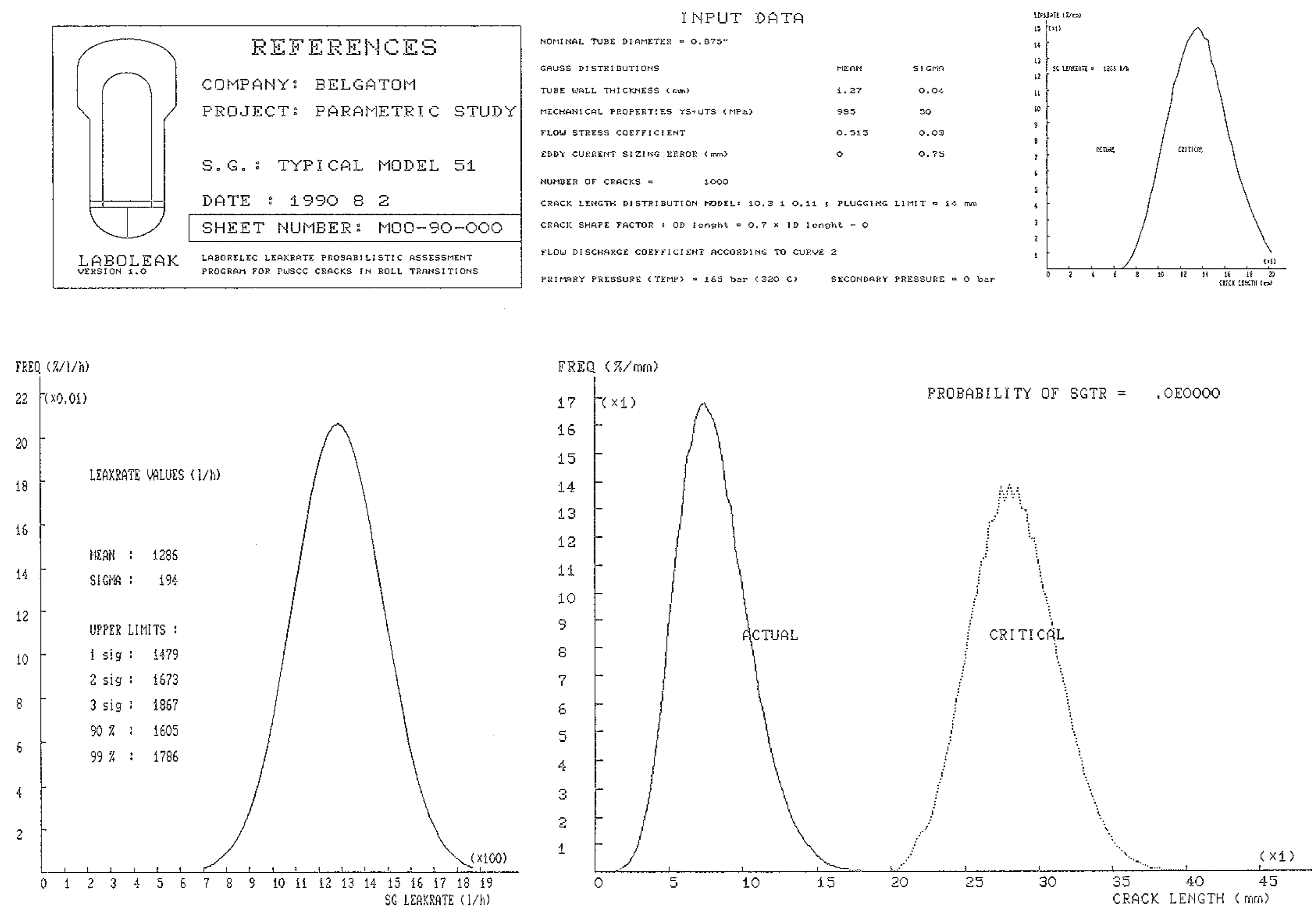

Fig. 2 - LABOLEAK program : typical print out of results