# Calculation of Leakage Area and Leakage Rate for the Design of Leakage Detection Systems

G. BARTHOLOMÉ, W. KASTNER, E. KEIM
*Siemens AG, KWU, Erlangen, FGR*

ABSTRACT

For the design and the optimization of leakage detection systems it is necessary to know the leake-rate and the leakage area. The leakage area is computed with a fracture mechanics model using the integration of the crack opening along the crack front, considering plasticity and geometrical effects. The calculation of the leak rate from a through-wall crack in a component is based on a thermohydraulic model taking into account the effects of pressure, temperature, crack length, crack width, leakage area, crack depth (wall thickness), roughness and hydraulic coefficient of resistance. These analytical approaches, both fracture mechanics and thermohydraulics, are used to quantify the availability and safety margins of components in connection with plant life extension analyses.

## 1 INTRODUCTION

A leak detection system (LDS) is utilized successfully to guarantee the safety and availability of technical structures.

For pressure retaining components LDS can be applied in the case of Leak-before-Break (LBB) behaviour to ensure, as an independent redundancy, the detectability of leaks before growing to critical crack size. The calibration of a LDS is given.

## 2 LBB-BEHAVIOUR (Fig. 1)

- Definition of LBB: Generally, failures can be classified into break and leaks. Failures, which do not lead to a break are defined as LBB.

  There is LBB, if the crack length, which results in a leak after penetrating the wall thickness ($2c_{leak}$) is smaller than the critical through-wall crack length ($2c_{crit}$): $2c_{leak} < 2c_{crit}$.

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- Leakage Crack Length ($2c_{leak}$): The leakage crack length is a function of geometry and type of loading (membrane, bending or combinations).

- Critical Crack Length ($2c_{crit}$): The critical through-wall crack length is dependant on load, geometry and material properties.

- Leakage Area ($A_{leak}$): The main characteristic of LBB-Behaviour is the development of a small stable leak, which can be detected safely. This leakage reduces the load (internal pressure and external moment) and leads to a fail safe behaviour.

## 3 THEORETICAL AND EXPERIMENTAL DETERMINATION OF THE RELEVANT PARAMETERS AND APPLICATION TO A REALISTIC EXAMPLE

- Input data of the example: circumferential through-wall crack in a pipe:

| | | | |
|---|---|---|---|
| outer diameter | $d_o$ = 245 mm: | wall thickness | $t$ = 18 mm; |
| pressure | $p$ = 122.6 bar; | temperature | $T$ = 300 °C; |
| material | austenitic steel; | yield strength (300°C) | $R_p$ = 177 N/mm²; |
| ultimate strength (300°C) | $R_m$ = 373 N/mm² | external moment | $M$ = $4.4 \times 10^7$ mm; |

- Leakage Crack Length ($2c_{leak}$): The leakage crack length which produces a leak after penetrating the wall thickness, is calculated by fracture mechanics /1/. As an example, which is verified by experiments, the behaviour of a crack under tension is shown generally in Fig. 2 and for the example $2c_{leak}$ = 50 mm in Fig. 3.

- Critical Crack Length ($2c_{crit}$): The critical through-wall crack length is determined by fracture mechanics. The approaches are verified by the experimental results /2, 3, 4, 5/. The test results and the comparison with the theory (e.g. for tests with circumferential cracks under internal pressure /2, 3/, Fig. 4) are conservative, see also example: $2c_{crit}$ = 200 mm in Fig. 3.

- Leakage Area ($A_{leak}$): The leakage area is evaluated by fracture mechanics. A typical result of tests /2, 3/ (longitudinal crack), Fig. 5 proves that a subcritical through-wall crack produces a small stable leakage area in comparison to critical cracks.

  The leakage area depends on the crack length (2c) and the crack opening (b) (example: Nomogram 1, Fig. 6). Crack opening and leakage area are analysed using a modified Dugdale-model and are a function of geometry, crack length, plastic zone size, load and material tensile properties.

- Leak Rate ($\dot{V}$): The volumetric leakage rate is assessed according to the thermohydraulic parameters using approaches /6/, which are confirmed by experiments /6/, Fig. 7 (example: Nomogram 2, Fig. 8).

## 4 REQUIREMENTS FOR LDS

All the parameters which have to be taken into account now are known:

- crack length (2c), crack opening (b) and leakage area ($A_{leak}$) (Nomogram 1, Fig. 6) and
- crack length /2c) and leakage rate ($\dot{V}$) (Nomogram 2, Fig. 8).

These nomograms allow for the given example to calibrate the LDS, if safety margins are demanded, or to assess the safety margins of the component, if an LDS is installed or to estimate the influence of the parameters (geometry, load, material) on the scatter band of detectability or to optimize the LDS in respect to detectability, safety, availability and economy. The nomograms are only valid for the given example. They have to be worked out for each individual part (weld) of a system to establish the relevant requirements of the LDS.

## 5 LITERATURE


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/6/ V. Kefer, W. Kastner, F. Westphal, H. John, J. Reimann, L. Friedel: "Prediction Accurancy of Models for Leak Rate Calculations of Cracks in Pressure Retaining". DECHEMA-Monography, Vol. 111, VCH, Verlagsgesellschaft, 1988, pp. 123-148

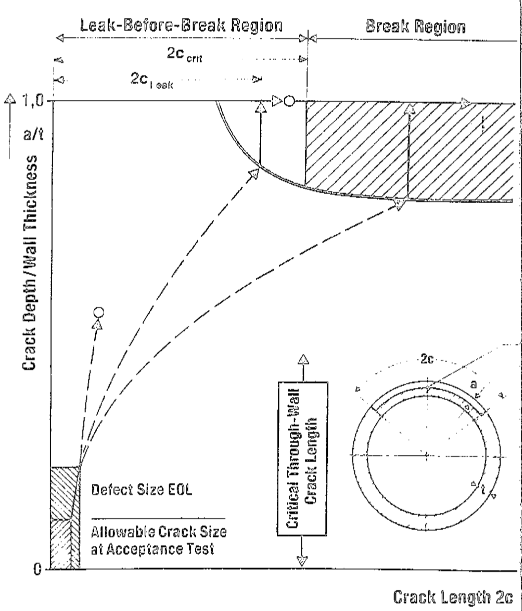
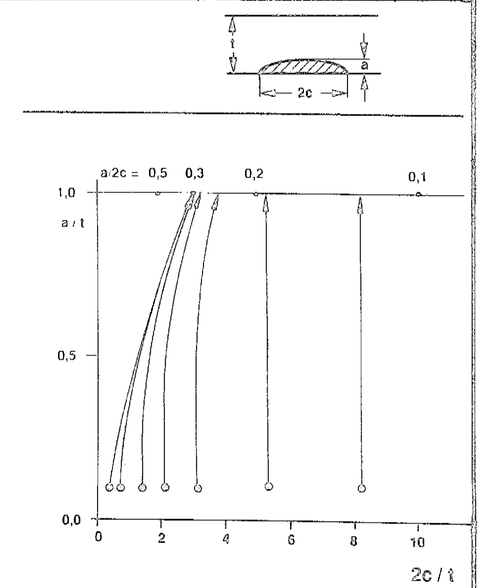



Fig. 1 Leak-Before-Break Diagram




Leakage Crack Length ($2c_{leak}$)

Fig. 2 under Tension loading

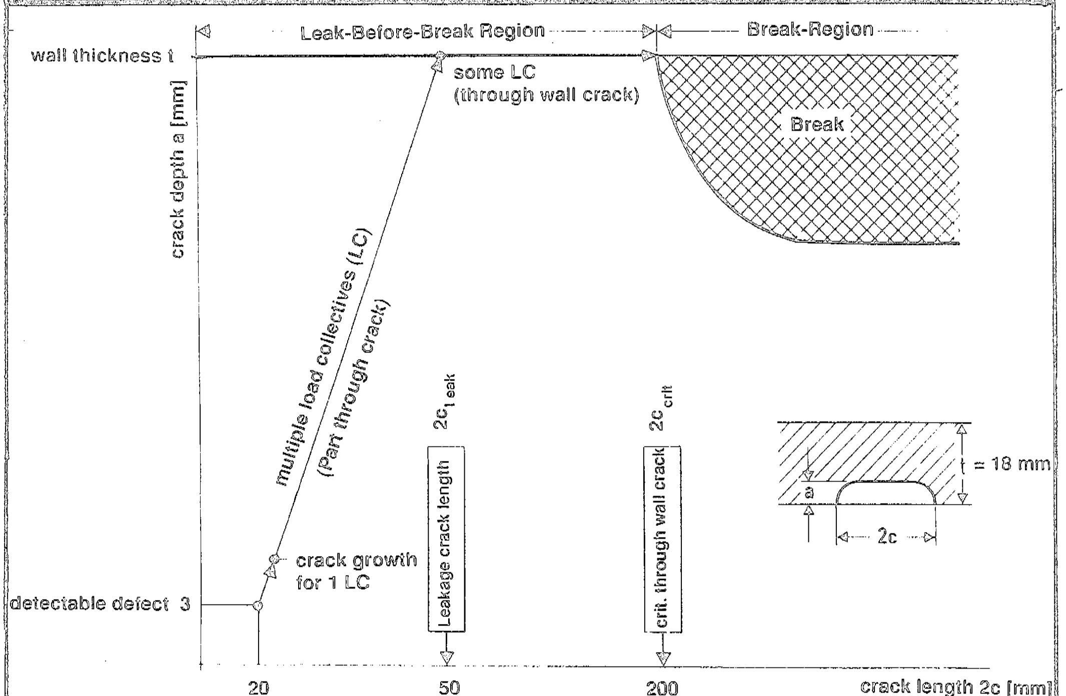



Fig. 3 Leak-Before-Break (Schematic), Plastic Limit Load, Circumferential Crack, Da x t = 245 x 18 mm

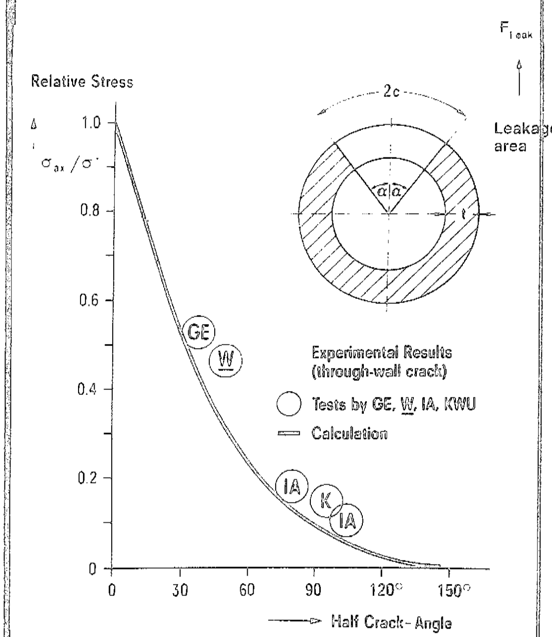



Fig. 4

Experiments (Circumferential, Through-Wall Crack)

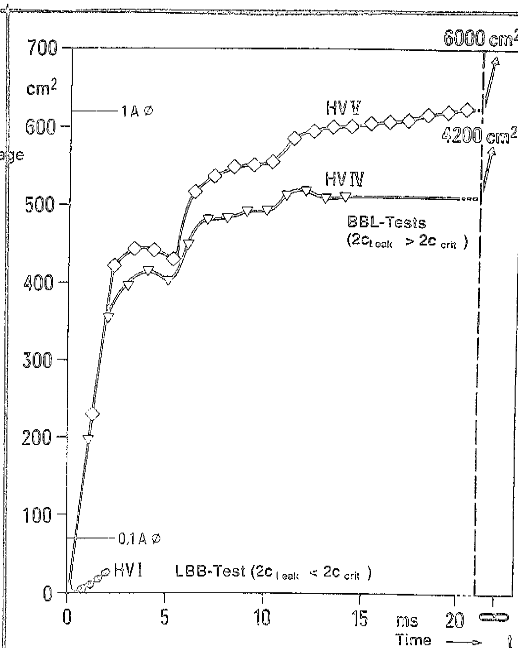



Fig. 5 Experimental Leakage Area

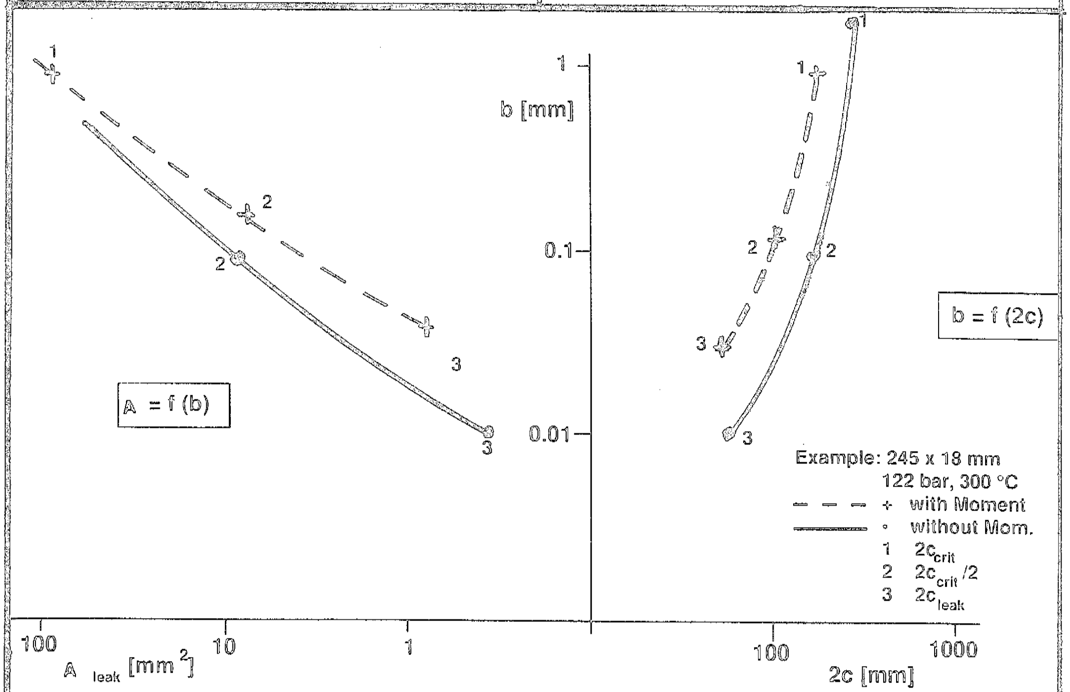
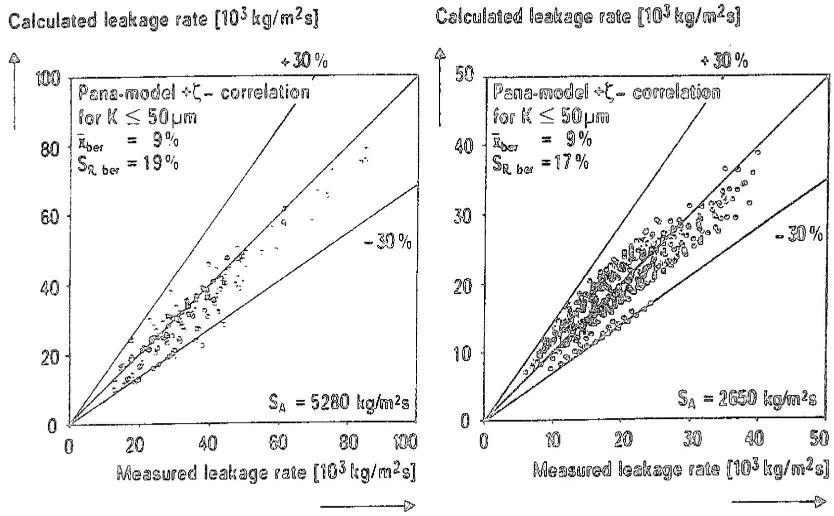



Fig. 6

Nomogram 1:
Crack Length (2c), Crack opening (b) and Leakage Area ($A_{leak}$)




Experiments with parameters as follows:

| | | | |
|---|---|---|---|
| Pressure | $20 \le p_0 \le 160$ bar | Leakage area | $5.9 \le A \le 51.2$ mm² |
| Subcooling | $0 \le \Delta T_0 \le 70$ K | Crack depth ("wall thickness") | $10 \le t \le 46$ mm |
| Crack length | $19 \le 2c \le 108$ mm | Roughness | $5 \le K \le 240$ μm |
| Crack width | $0.1 \le b \le 0.64$ mm | Hydraulic coefficient of resistance | $1 \le \xi \le 85$ |

Fig. 7 Comparison between Measured and Calculated Leakage Rates

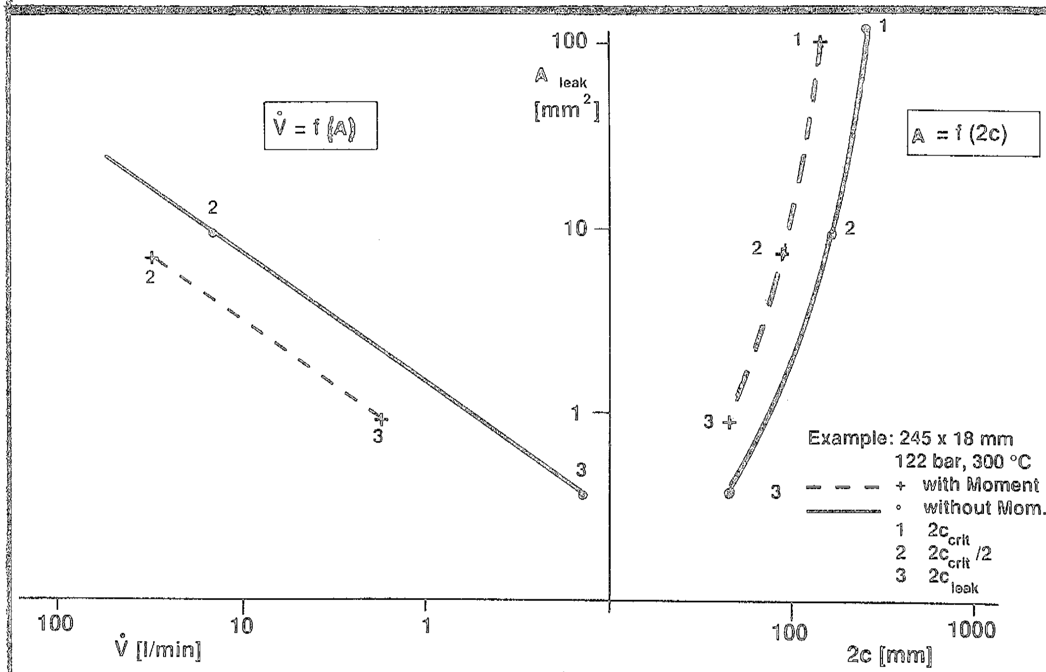



Fig. 8 Nomogram 2: Crack Length (2c), Leakage Area ($A_{leak}$), Leak Rate ($\mathring{V}$)