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General Chairman: Asadour H. Hadjian, Bechtel Western Power Company, P.O. Box 60860 - Terminal Annex, Los Angeles, CA 90060, USA Phone: (213) 807-3817 • Telex: 677330 • Telefax: (213) 807-3444

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MR FRANCESCO ALICINO
[illegible]-SYSTEM ENGINEERING DEPARTMENT
ANSALDO S.P.A.
VIA D'ANNUNZIO, 113-
16129 GENOVA
ITALY

ID No.: 0191/0203
DIVISION: F

TITLE: CONCEPTUAL DESIGN AND COMPARISON OF ONCE-THROUGH TUBE BOILING STEAM GENERATORS FOR DIFFERENT ANNULAR BUNDLE CONFIGURATIONS

TITLE: ONCE-THROUGH STRAIGHT TUBE STEAM GENERATORS SUBJECT TO SEVERE THERMAL TRANSIENTS COMPENSATION SYSTEMS OPTIMIZATION

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Sincerely yours,

A. H. Hadjian
General & Scientific Chairman

# Fracture Mechanics Evaluation of Credible Breaks in Heavy Water Reactor Liquid and Steam Feeder Primary Lines

**Francesco Alicino, Stefano Chiocchio**
*ANSALDO SpA, Genova, Italy*

## INTRODUCTION

In designing Heavy Water Reactors, partial feeder pipe-line breaks, in both the liquid and the steam branches, have to be postulated for safety assessment purposes. If partial breaks, so wide as to give leakage rates greater than a critical value depending on the Plant features, should occur, stagnation of the primary coolant has to be postulated. In a very few cases, if stagnation can't be quickly removed, a very severe pressurized temperature growth can be imposed to the involved Pressure Tube (which contains the Nuclear Fuel). In such a case the metal temperature can reach so elevated values that temperature creep region for the material is entered (see, Alicino, 1986), thus highly increasing the potential of Pressure Tube failure. Furthermore, being the Pressure Tubes usually made in Zirconium based alloys, whose mechanical properties rapidly decrease as temperature grows, the allowable stress limits can be significantly overcome because of such an accident. Then, unless it can be proved that the occurence of this event can be neglected (in other words, that it has a very low probability to occur), the Pressure Tube failure should be faced as a consequence of such an accident.
This last consideration induced to adopt a deterministic Fracture Mechanics approach in order to estimate in the Design phase if cracks smaller than those giving unacceptable leakage rates can be safely detected by the plant leak detection system, bèfore instability be reached.

## METHODOLOGICAL BASES

### Detectable Leakage Rate Determination

The Plant leak detection system capability ($P_c$) is analyzed in order to be sure that it allows to detect leakage rates lesser than the critical ones for stagnation ($P_s$), with a suitable Safety Factor $SF_L$. A detectable leakage rate ($P_d$) that has to fall within the range:

$$P_c \times SF_C < P_d < P_s / SF_L.$$

can be then defined, which has to be greater than the system capability, $P_c$, times a Safety Factor $SF_C$.

### Detectable Flaw Size Determination

The size of through-wall cracks which under Normal Operating Conditions can open in such a way to provide the detectable $P_d$ leakage rate is determined. In a Design phase a criterion to select the pipe regions having the highest breaking potential is essential. This criterion is provided by the ANSI/ANS-58.2 Standard (1980). Cracks are thus to be postulated in the zones where the calculated Stress Intensity Range is greater than 2.4 $S_m$ and/or the Cumulative Usage Factor is greater than 0.1. Their orientation will depend on the pipe size and on the most significant loads.

The ANSI/ANS-58.2 (1980) standard establishes that only circumferential cracks be considered if the pipe nominal diameter is less than 4 in. Furthermore, when pipe-lines are prevalently subjected to stresses arising from bending moments, the integrity of the pipe is controlled only by the circumferential flaws. Otherwise, longitudinal flaws have to be analyzed as well as the circumferential ones.

By means of the Moody approach (1965), the leakage rate per unit of break area, $P_u$, is computed for each line under examination. From this value the minimum detectable flow area, $A_d$, is got as $A_d = P_d / P_u$.

Correlations between the Flaw Opening Area (depending on the state of stress) and the Flaw Size (in terms of angular dimension) can be determined making use of the approach described by Paris (1983), which gives the Flaw Opening Area, $A_f$, as the superposition of a bending ($A_b$) and a pressure ($A_p$) contribution:

$$A_f = A_b + A_p \qquad (1)$$

being:

$$A_b = \sigma_b R^2 I_b(\theta) / E \qquad (2)$$

$$A_p = \sigma (2 \pi R t) G_p(\lambda) / E \qquad (3)$$

where: 1) $\sigma$, is the longitudinal membrane pressure stress when flaw is neglected (= pR/2t); 2) $\sigma_b$, is the maximum bending stress neglecting the flaw; 3) E, is the Young's Modulus; 4) R, is the pipe mean-wall radius; 5) t, is the pipe wall thickness; 6) $I_b(\theta)$, is a function depending on the angular dimension $\theta$ of the flaw; 7) $G_p(\lambda)$, is a function of the crack parameter $\lambda = a/\sqrt{(Rt)}$; 8) a, is the crack semi-length. The complete formulas for $I_b(\theta)$ and $G_p(\lambda)$ are given by Paris and Tada (1983).

By using of the above relationships and the Normal Operating state of stress, curves $A_f$ = funct($\theta$) can be calculated (see, Figure 1). Entering the abscissas of these curves with the $A_d$ value, the semi-angular dimension of the Detectable Flaw is got at each selected location.

## Detectable Flaw Stability Analysis

The stability of the detectable flaws has to be studied under the severest loadings anticipated for the component (Faulted Condition, as usual). Both the Local (Tearing Instability) and the Global (Net Section Collapse) stability are to be controlled. A suitable further Safety Factor shall be used in stability analysis ($SF_s$).

### Global Stability

Global Stability should be checked from two complementary points of view:

1) Evaluation of the Limiting Loading Combination which can integrally plasticize the section where the detectable flaw is postulated;
2) Evaluation of the critical size that a through-wall crack should have for the section be integrally plasticized under the severest anticipated loading combination.

The latter one is in general the controlling approach.

To evaluate the Plastic Beding Moment the relation given by Paris (1983) and Tada (1979) can be used:

$$M_p = 4 \sigma_f R^2 t f(\theta, a_0, p_0) \qquad (4)$$

where: 1) $M_p$, is the Plastic Bending Moment; 2) $\sigma_f$, is the Flow Stress [ $=(\sigma_y+\sigma_u) / 2$ ]; 3) R, is the pipe mean-wall radius; 4) t, is the pipe thickness; 5) $f(\theta,a_0,p_0) = (1-a_0)(\cos\alpha - 0.5\sin\theta) + 0.5\pi p_0 \sin\alpha$; 6) $\theta$, is the semi-angular dimension of the through-wall crack; 7) $a_0$, is the relative depth of the no-through-wall portion of the crack (=a/t); 8) $p_0 = p/(2\pi R t)\sigma_f$.

The above equation is based on the crack geometry shown in Figure 2 (see, Paris, 1983) and on the hypothesis of elastic-perfect plastic material.

Figure 3 shows a typical curve of the Plastic Bending Moment, $M_p$, vs. the semi-angle $\theta$ .

**Local Stability**

From the Local Stability standpoint the conditions to be met in order to prove that unstable propagation of a postulated flaw can't occur are (see, Paris, 1983, ASME Section XI Task Group, 1986, and Kumar, 1981):

1) Condition for a crack can't propagate: $J_{app} < J_{Ic}$;
2) Condition for a propagating crack has a stable growth (when $J_{app} > J_{Ic}$): $T_{app} < T_{mat}$.

Local instability can occur before or after the occurrence of the flawed section overall plasticization. In either of these two cases the above conditions hold (see, Paris, 1977). If it can be shown that the Global Instability is reached before the Local one for not plasticized sections, then only the latter mechanism can occur.

In absence of an overall plasticization of the flawed section, the applied value of the J-Integral can be obtained by the the EPRI Engineering Approach (see, Kumar, 1981):

$$J_{app} = J_{el} + J_{pl} \qquad (5)$$

where:

a) $J_{el} = K_I^2 / E$ (6)
being, $K_I = \sigma_b \sqrt{(\pi R \theta)}\, F_b(\theta)$ (7)
(as defined by Paris, 1983);

b) $J_{pl} = \alpha\, \sigma_0\, \varepsilon_0\, c\, (a/b)\, h_1\, (M/M_0)^{n+1}$ (8)

and: 1) $\sigma_b = M / \pi R^2 t$ is the bending stress; 2) $F_b(\theta)$ is a no-dimensional function of the crack semi-angle $\theta$; 3) $\alpha$, n, $\sigma_0$, $\varepsilon_0$ are the Ramberg-Osgood equation parameters; 4) 2c, is the circumferential ength of the no-flawed portion of the section; 5) a/b, is the flaw length normalized with respect to the circumference length; 6) $M_0$, is the bending moment related to $\sigma_0$ stress; 7) M, is the applied bending moment; 8) $h_1$, is a function of the type of the applied load (see, Kumar, 1981).

In the case it has been proved that the mechanism controlling flaw instability is the Net Section Collapse, the Local Stability approach for integrally plasticized section is followed only to ascertain if further margins can exist against unstable flaw propagation. Local Stability for integrally plasticized sections is essentially governed by the pipe-line compliance and it can be expressed in terms of equivalent critical pipe length (see, Paris, 1983).

## APPLICATION OF THE METHODOLOGY TO THE CIRENE PLANT

### Basic data

The Italian CIRENE Heavy Water Reactor has the Pressure Tubes made up of Zircalloy-2. For this Plant, it has been proved that the critical leakage rate for stagnation, Ps, is around 2500 g/s. Also, it has been shown that temperatures following a partial feeder pipe-line break event which causes stagnation can reach values as high as 550°C, which is a value very close to the lower boundary of the critical region for the Pressure Tube (see, Alicino, 1986).

Two types of feeder pipe-lines have been foreseen in the CIRENE Nuclear Plant: a) primary steam feeder lines; and, b) primary liquid water feeder lines.

Both these pipe-lines are made up in SA-106 Gr. B steel, whose mechanical properties are given in Table 1 (see, Ranganath, 1981).

The primary steam feeder pipelines have a 1" nominal diameter and a 0.11" wall thickness. The primary liquid water feeder pipelines have a 2" nominal diameter and a 0.554"÷1.246" wall thickness.

In this study only the primary liquid feeder lines have been treated.

Two leak detection systems are provided for the CIRENE feeder lines:

a) a system based on acoustic emission whose sensitivity is of 30 g/s;
b) a humidity collection wells system which has a sensitivity of 60 g/s.

Based on these data and assuming a Safety Factor 2 with respect to the system capability (SFC = 2), the Detectable Leakage Rate is set in $P_d$ = 120 g/s.

Since the thermal-hydraulic analyses showed that the minimum leakage rate that can cause stagnation is $P_s$ = 2500 g/s (which is given by a flow area equal to 20% of the feeder pipe cross-section flow area), the Safety Factor with respect to stagnation is SF = ~ 21.

## Results

1) The plant Leak Detection System allows to detect leakage rates of 120 g/s, with a safety factor 2, well less than the critical leakage rate for stagnation (2500 g/s);
2) A through-wall circumferential crack should have an angular dimension of 59° through 87° to give a detectable leakage rate, when subject to the Normal Operating Loads (see, Table 2);
3) The stability for through-wall cracks is controlled by the Net Section Collapse criterion, with Safety Margins of 47.5 through 78.0 %, with respect to the applied loads, and of 27.0 through 42.0 %, with respect to the critical flaw size;
4) If a through-wall crack should reach the critical size, it would leak during Normal Operating Conditions with a rate of nearly 250 g/s which is easily detectable (with a Safety Factor 4) and is well below the critical value for stagnation (with a Safety Factor 10);
5) The highest calculated $T_{App}$ value for the flawed section not overall plasticized was 50.3, which is lesser than $T_{MAT}$ = 385 (see, Table 1);
6) A through-wall crack that should reach the critical size never can furtherly propagate unstably under tha severest loading conditions, because of the compliance of the lines. The minimum length, $L_{min}$, necessary to have unstable propagation of the detectable flaws is nearby 18000 mm, while the effective pipe length is actually well less than this value (~ 6000 mm). Thus a critical leakage rate for stagnation can never be expected.

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TABLE 1

SA-106 Gr. B Mechanical Properties

| | | | |
|---|---|---|---|
| Yielding Stress, | $\sigma_y$ | 241. | MPa |
| Ultimate Stress, | $\sigma_u$ | 414. | MPa |
| Flow Stress, | $\sigma_f$ (1) | 328. | MPa |
| Fracture Toughness, | $J_{Ic}$ | 263. | N/mm |
| J-R Curve Slope, | dJ/da | 207. | MPa |
| Material Tearing, | $T_{mat}$ | 385. | |
| Ramberg-Osgood Equation Parametrs $\varepsilon/\varepsilon_0 = (\sigma/\sigma_0) + \alpha(\sigma/\sigma_0)^n$ | | | |
| Reference Stress, | $\sigma_0$ | 186.3 | MPa |
| Reference Strain, | $\varepsilon_0$ | 0.0009 | |
| Strain-hardening Exponent, | n | 6.98 | |
| Strength Coefficient, | $\alpha$ | 1.08 | |

(1) $\sigma_f = (\sigma_y + \sigma_u) / 2$

TABLE 2

Global Stability Analysis Safety Margins

| | $a_0 = 0.2$ | $a_0 = 0.0$ | Margin |
|---|---|---|---|
| Global Stability controlled by the applied load | 47.5 % | 78.0 % | $S.M. = \frac{M_{lim}}{M_{app}} - 1$ |
| Global Stability controlled by the critical flaw | 27.0 % | 42.0 % | $S.M. = \frac{rcrit}{rdete} - 1$ |

FIGURE 1

Curve of the Flaw Opening Area $A_f$ vs. the Angular Extension of a Postulated Circumferential Flaw

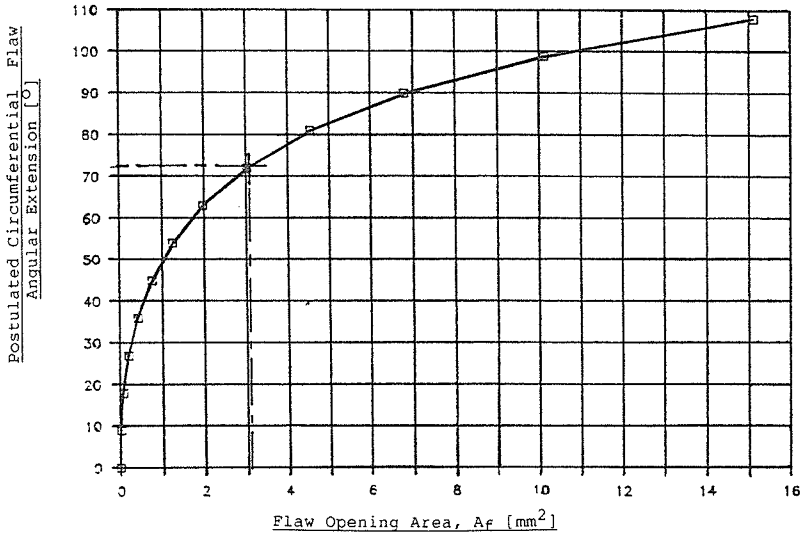


FIGURE 2

Schematic of the Crack Geometry

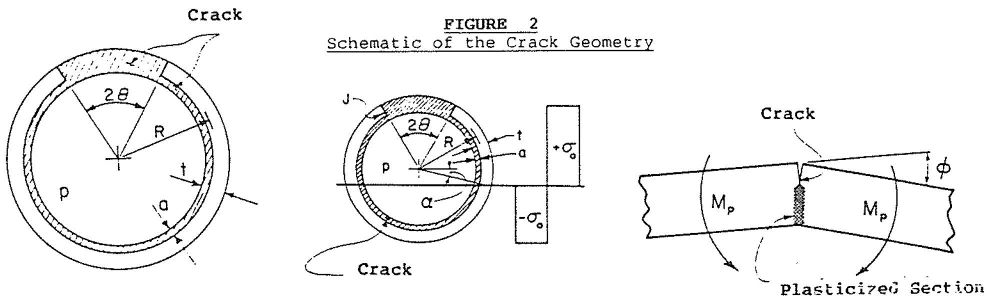


FIGURE 3

Plastic Moment vs. Semi-Angular Extension of a Through-Wall Crack for Various Relative Depths of the No-Through-Wall Portion of the Crack