Fatigue crack propagation: Probabilistic models and experimental evidence

A.C.Lucia
Commission of the European Communities, Joint Research Centre, Ispra Establishment, Italy
G.Arman
Synthesis Srl., Milano, Italy
A.Jovanovic
Visiting Scientist at the CEC Joint Research Centre, Ispra, Italy

1 INTRODUCTION

The central aim of the LWR Primary Circuit Component Life Prediction Project, going on at JRC-Ispra, is to develop and check a "procedure" (encompassing monitoring and inspection, data collection and analysis, prediction) allowing the quantitative estimation of the accumulation of structural damage and of the residual lifetime, as described by Lucia (1982,1987).

The ongoing activity matches theoretical development and experimentation, the latter being at present essentially based on a test-rig for room-temperature fatigue cycling of 1:5 scaled models of pressure vessels.

The pressurization medium is water (controlled chemical composition), the pressure cycling frequency being 2 cpm.

2 THE RELIABILITY APPROACH

Our way to achieve a meaningful assessment of the reliability of a structure is based on a global procedure relying on a number of steps or partial assessments to be concatenated and merged: non-destructive testing, material characterization, analysis of loads, stress analysis, fracture mechanics analysis, fatigue crack growth analysis, failure mode analysis.

The flow diagram of Fig. 1 shows the reliability assessment procedure.

3 ANALYTICAL AND EXPERIMENTAL TOOLS

The basic part of the installation is the vessel model (Fig. 2). The vessel examined so far is the first of three scaled experimental vessels, planned to be used within the JRC-Ispra research program. The welds, with and without intentional fabrication defects, and the nozzle corners are the locations more thoroughly analyzed. Several techniques for continuous monitoring and periodic inspection are applied by JRC and other laboratories.

In order to obtain the relevant material properties (tensile properties, J-ΔA curves, fatigue characterization in dry and wet environments), a number of tests have been performed (for the three materials SA 533,

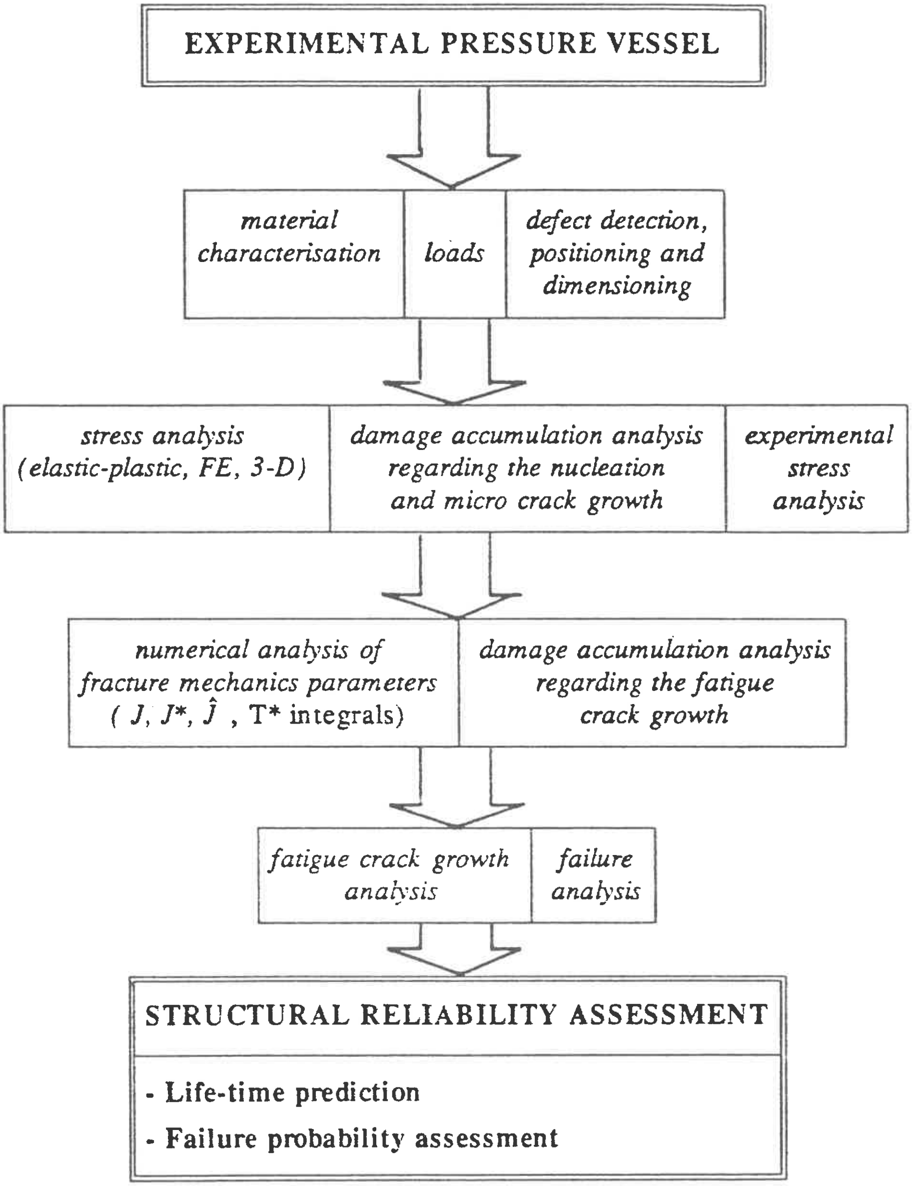


Fig. 1 Applied structural reliability assessment procedure.

SA 508, AISI 347) on specimens cut from the same ingots of the vessels. The complete stress analysis has been made for the unflawed and flawed vessel case by means of 3D, elastic-plastic, ADINA, STRUDL and ABAQUS codes. At the pressure of about 180 bar the first significant plastic zone (in the cladding) appears, at the non-cracked nozzle corner. The first appearance of the plastic zone in the base material occurs at the level of 220 bar and over, but only in a very restricted zone (some points only).

These facts lead to the conclusion that:

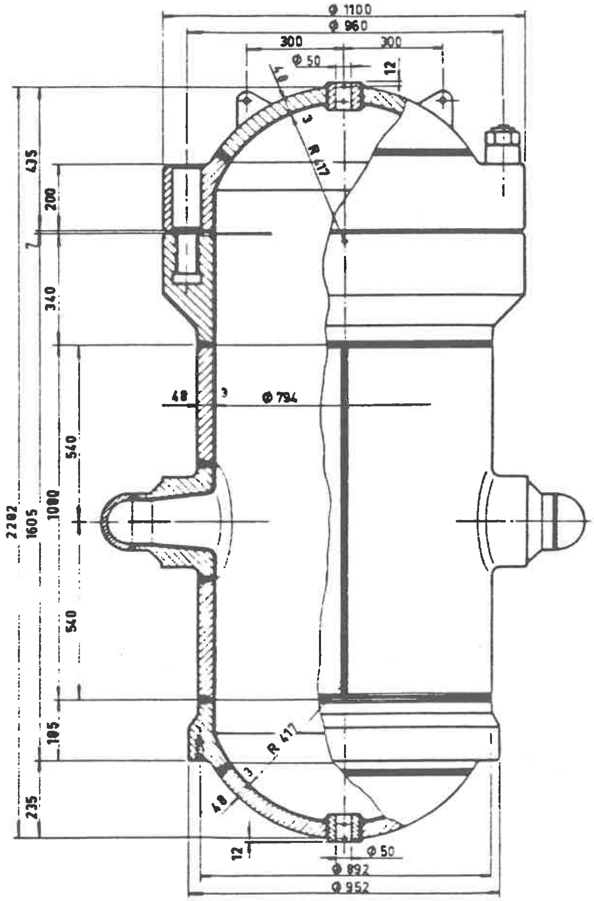


Fig. 2 JRC-Ispra experimental pressure vessel - dimensions and materials (SA 533 - plates; SA 508 - forgings; AISI 347 - cladding (in stripes, one layer)).

a) irreversible damage accumulation process should be expected at the nozzle corner;
b) accumulated (equivalent) plastic strain should be a dominant parameter for the process (a);
c) the structural reliability analysis, regarding the nozzle corner, should consider and include both the problem of fatigue crack nucleation and the problem of fatigue crack growth.

Particularly accurate was, consequently, the stress and strain analysis at pressures over 180 bar. Fig. 3 shows the behaviour of the elastic-plastic stress intensity factor at nozzle corner crack. Details are presented by Jovanovic, Lucia and Sedmak (1987) and Jovanovic, Lucia et al. (1987).

4 THE LOADING HISTORY AND THE FATIGUE CRACK GROWTH ANALYSIS

After a pre-service hydrotest (180 bar), the vessel was loaded according to Table 1, the loads with $R = 0.5$ being made for marking purposes.

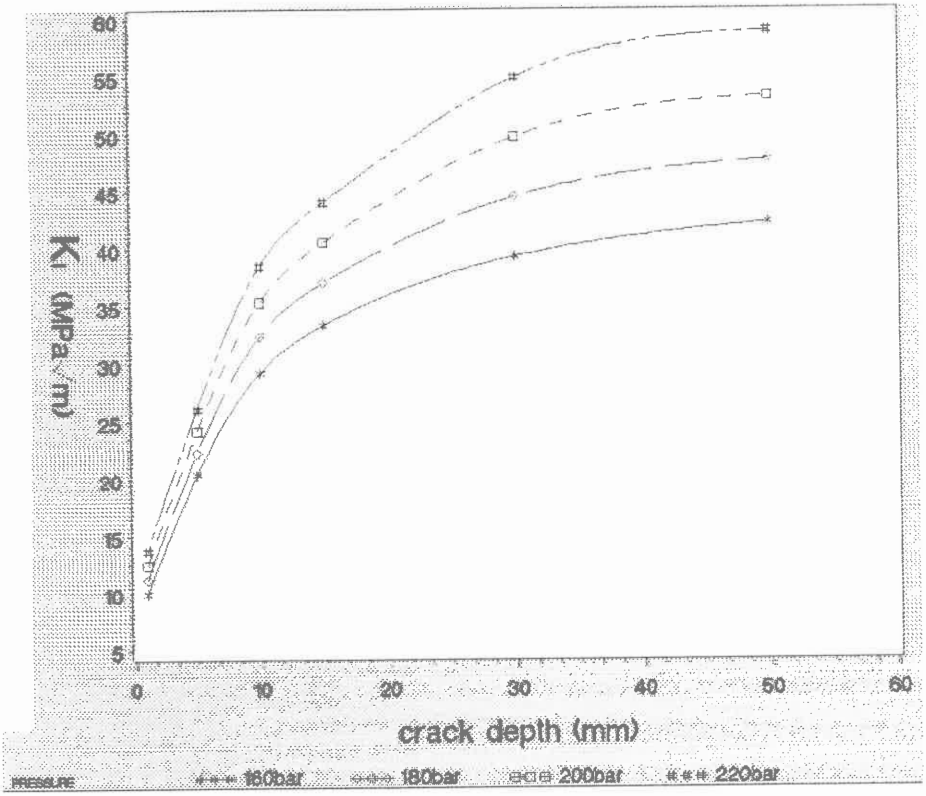


Fig. 3 Stress intensity factor calculated by the virtual crack extension method for the nozzle corner cracks on the 1:5 scale JRC vessel.

This first phase of testing ended after 339,545 cycles, when a leak appeared at the upper corner of one of the two nozzles. The behaviour of the nozzle corner region during the cycling of the vessel can be divided into two principal phases: the one of void nucleation and growth, and the one of macro-crack growth.

To the phases correspond the two "states of the structure": crack-free structure at the beginning of the first phase, and structure with an initial crack (size) at the beginning of the second phase. So the issue of the "initial crack size" becomes a very important one, having a major influence on the results of the analysis. Unfortunately, the present state of NDE methods does not allow a very precise and reliable detection and dimensioning of the nozzle corner cracks. Therefore, the FCG analysis has to be based on some assumptions.

The assumptions adopted in this case have been the following ones:

a) The "nucleation assumption": the analysis will start from the "zero" state, i.e. it will include the phase of the void nucleation and growth, and on the basis of these results, continue with the macro-crack FCG analysis.
b) The "in-service inspection and monitoring assumption": the analysis will start with the data provided by the continuous monitoring and periodic inspection techniques.
c) The "backwards analysis": the analysis will start from the final

TABLE 1

Pressure min. - max. (bar)	Number of cycles (-)	R (-)	f (cpm)	Total number of cycles (-)
16-160	25000	0.1	1	25,000
16-160	27547	0.1	2	52,547
18-180	11691	0.1	2	64,238
19-190	21930	0.1	2	86,168
95-190	1698	0.5	2	87,866
20-200	19571	0.1	2	107,437
100-200	4378	0.5	4	111,815
20-200	34535	0.1	2	146,350
100-200	6000	0.5	4	152,350
20-200	10285	0.1	2	162,635
20-220	26650	0.1	4	189,285
110-220	5020	0.5	4	194,305
20-220	23725	0.1	4	218,030
110-220	5230	0.5	4	223,260
20-220	15700	0.1	4	238,960
110-220	6900	0.5	8	245,860
20-220	19045	0.1	1-4	264,905
110-220	4603	0.5	3	269,508
20-220	20001	0.1	3	289,503
110-220	4996	0.5	8	294,505
20-220	20460	0.1	2-4	314,965
110-220	5980	0.5	8	320,945
20-220	18600	0.1	2	339,545

state, i.e. from the through crack at the nozzle corner, and going backwards, analyse the process of the FCG.

These three assumptions could correspond, respectively, to the three types of the pressure vessel safety analysis, namely: the pre-service analysis, the in-service analysis and the post-accidental analysis. The data necessary for all of the three types of analysis being available, all the three have been performed, as reported by Jovanovic, Lucia et al. (1987).

A probabilistic model of nucleation, based on the accumulation of the effective plastic strain and the assumed growth of sulphuric voids is under development. It allowed a nucleation prediction which, at least, did not disagree with experimental evidence: more details are presented by Jovanovic and Lucia (1987).

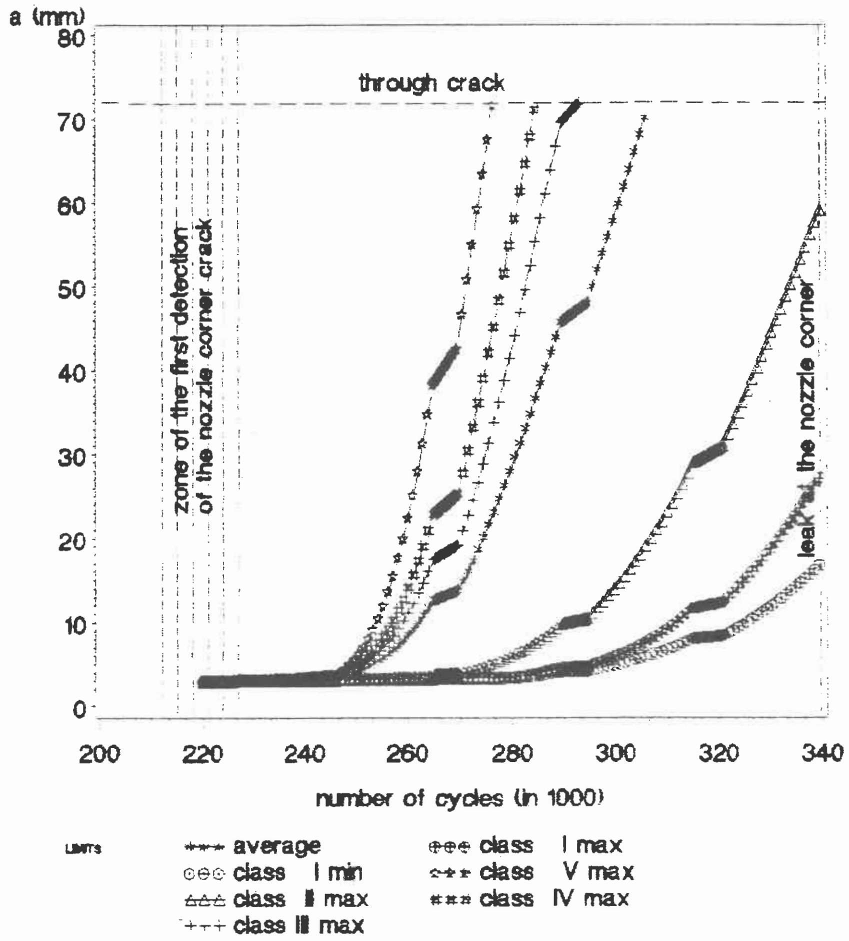
The backward analysis being in this case of little interest, we will briefly describe the in-service prediction.

5 PREDICTION AND EXPERIMENTAL EVIDENCE

Two main analytical tools have been developed at JRC for FCG prediction and failure probability estimation.

The first is the code COVASTOL, implemented at the end of a large study on pressure vessel failure probability, performed by Dufresne, Lucia et al. (1983). It is essentially based on probabilistic fracture mechanics and on the randomization of the Paris law for FCG. The failure probability is estimated as the probability of crossing of random processes (load carrying capacity and demand).

The second tool is the code RELIEF, developed by Arman and Lucia (1985) and based on the assumption that the fatigue damage accumulation



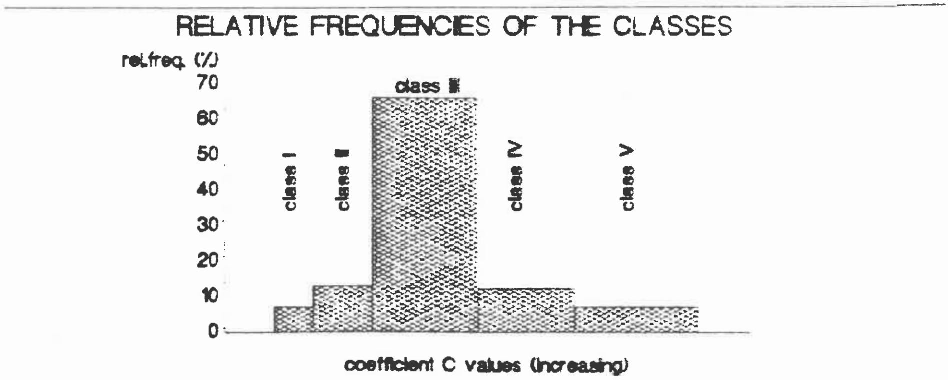


Fig. 4 Fatigue crack growth - nozzle corner crack on the JRC 1:5 scale vessel (COVASTOL-FCG-PLOT results).

process is a semi-Markovian process. The present predictions have been made by the code COVASTOL.

The code RELIEF, in fact, is being improved with the introduction of time history dependence and, furthermore, the data so far produced for material characterization is not enough to guarantee a correct application of the code. In fact, because it does not entail any assumption on the physics of damage processes, its application needs a wider data bank than COVASTOL, based on a phenomenological representation of fatigue crack growth process.

In the prediction procedure based on continuous monitoring and periodic inspection data, initial crack dimensions have been taken according to the results of the ultrasonic continuous monitoring (Jovanovic, Lucia et al., 1986). The results have been resumed in the statement that "a 3 to 4 mm wide crack in the base metal has been detected around 220,000 cycles". Starting from these assumptions, the probabilistic FCG analysis has been performed leading to the results shown in Fig. 4.

The results allow to make the following conclusions:

a) there is a good general agreement between the FCG curves and the experienced leak at the nozzle corner;
b) for the 3•6 mm initial crack, the leakage point is in accordance with the propagation as predicted by the most probable class (class III), having the relative frequency of about 65%.

The results of acoustic emission monitoring (Caretta and co-workers, 1986) cannot be quantified as those of the ultrasonics, but they, however, show a qualitative agreement with the latter.

It is of interest to remember that acoustic emission measurements made by Beesley, Bentley and Scruby (1985) during the first hydrotest, detected the existence of a source (not detectable by XR and UT) in the nozzle region where the crack developed: this might have been due to some undercladding microcrack.

6 CONCLUSIONS AND PERSPECTIVES

During Phase I of fatigue testing of vessel R2, different pieces of information coming from material characterization, non-destructive inspection, continuous monitoring, stress analysis, have been merged and used to infere the future behaviour of the structure.

The prediction of residual lifetime (cycles to failure), based on the outcomes of the ultrasonic continuous monitoring and made by means of the COVASTOL code, was in quite good agreement with experimental evidence.

Next steps of the activity are:

- benchmark exercise on lifetime prediction of the scaled vessel;
- fatigue cycling to obtain propagation of fabrication defects (in the weld);
- start of test on a new test rig for thermal shocks and thermal transients.

7 REFERENCES

Arman, G. & A.C. Lucia 1985. Estimation of the residual life of structural components under cyclic loading, Proc. of the 8th SMiRT Conf., Brussels.

Beesley, M.J., P.G. Bentley, C.B. Scruby & K.O. Stacey 1985. Acoustic

emission measurements during the first hydrotest of a 1/5 scale PWR pressure vessel, UKAEA, Risley, ND-R-1231(R).
Caretta, A., M. Galli & A.C. Lucia 1986. Acoustic emission monitoring of fatigue crack growth in pressure vessel welds, Proc. of the 2nd Int. Conf. on On-line Surveillance and Monitoring, Venice.
Dufresne, J., A.C. Lucia, J. Grandemange & A. Pellissier-Tanon 1983. Etude probabiliste de la rupture de cuves de réacteurs à eau sous pression, EUR Report No. 8682 Fr.
Jovanovic, A., A.C. Lucia & S. Sedmek 1987. Application of the J integral approach to the safety and reliability assessment of pressure vessels with a nozzle corner crack, Proc. of the 5th Int. Conf. on Mechanic Behaviour of Material, Beijing.
Jovanovic, A., A.C. Lucia, R. Brunnhuber, J. Elbaz & U. Schwarz 1987. Behaviour of the nozzle corner region during the first phase of the fatigue test on scaled models of pressure vessels, EUR Report, Ispra, in press.
Lucia, A.C. 1982. An experimental and theoretical study for evaluation of the residual life of the primary circuit components of LWRs, Proc. of the ANS-ENS Int. Conf., Chicago.
Lucia, A.C. 1987. LWR primary circuit component lifetime prediction, in Reactor Safety Programme Progress Report: 1986, EUR Report, Ispra, in press.