

## The Influence of Testing Conditions on Burst Pressure Assessment for Inconel Tubing

P. HERNALSTEEN  
*Laborelec, Linkebeek, Belgium*

### 1 INTRODUCTION

Some countries are presently using Steam Generator (SG) plugging criteria based on the allowable length of a Through Wall Depth (TWD) flaw ; this requires a prior knowledge of the flawed tube residual strength. Various laboratories have conducted large experimental programs to measure the burst pressure of tubes with TWD flaws.

This paper will concentrate on the case of a single TWD axial flaw in the free span of a tube. The corresponding laboratory burst test measurements show large disagreements and special experiments are required to identify the reliable results.

### 2 BURST TESTING OF FLAWED TUBES

Laboratory testing of TWD flawed tubes is usually performed by pressurizing with a cold incompressible fluid (e.g. ref. 1). Various means of pressurizing are being used, either manual or motorized ; however no laboratory method allows to compensate for the leak rate through the flaw (up to the required bursting level). Thus a sealing system is used, usually an internal plastic bladder ; a local reinforcement is sometimes provided by a thin metal patch (copper, brass or stainless steel foil).

Flaws are fabricated by Electric Discharge Machining (EDM) or laser cutting ; in both case they are about 0.2 mm wide. This is apparently much different from the tight corrosion cracks to be simulated ; however as the tube fails in a purely ductile mode, it does not affect the burst strength.

When pressure approaches the burst condition, there is considerable plastic deformation (tube bulging, blunting of the flaw tips, widening of the flaw,...), without any stable crack growth. The test ends by gross leakage,

- . either by failure of the sealing system, without crack propagation,
- . or by an unstable crack propagation at both ends of the flaw (instantaneous crack length extension of several mm) ; crack propagation is arrested by the immediate pressure drop of the incompressible cold medium.

In both cases the maximum pressure is reported as the burst pressure.

As no standards are available, there are significant variations in the detailed testing procedures. The data produced by each particular laboratory have a reasonably small scatter but the situation is entirely different when comparing results from several independent laboratories.

### 3 INTERNATIONAL COMPARISON OF BURST DATA

In 1989/1990 the USA Electrical Power Research Institute (EPRI) assigned an international committee (made up of representatives from USA and foreign Utilities, NSSS vendors and EPRI consultants) to develop alternate plugging criteria for axial Primary Water Stress Corrosion Cracking (PWSCC) (ref. 2).

Within the work of this Committee, a comparison was made between burst data from various countries (Belgium, France, Great Britain and USA) ; this is illustrated by Fig. 1 which is a plot of the normalized burst pressure  $p^* = p/(S_u + S_y) R/t$  as a function of the normalized TWD axial crack length

$\lambda = a/\sqrt{Rt}$ , where :  $p$  = burst pressure  
 $S_u, S_y$  = ultimate, yield stress of material  
 $a$  = crack length  
 $R, t$  = average radius, wall thickness of tube

It can be seen that the US and British data bases are almost identical, while the Belgian and French data bases are both much higher than the previous one. Pending clarification of this large disagreement, the EPRI Committee took the conservative approach of using the indicated lower bound "Tube Rupture Equation".

The Belgian curve fits the prediction from the collapse load theory,  $p^* = 0.55/m$ , where  $m$  is the "bulging factor" defined by  $m = 0.614 + 0.385 \exp(-1.15 \lambda) + 0.436 \lambda$ .

The French curve is based on a similar law, with a slightly different expression of  $m$ , while the US/British curve is an empirical polynomial fit to the test data. As can be seen, the ratio between the upper and lower curves varies from 1.15 at  $\lambda = 3$  (corresponding to a length of 11 mm for 7/8" tube) to 1.8 at  $\lambda = 10$ .

The difference is still more impressive if expressed in terms of the plugging length. It also depends on whether the safety margin (3 for the nominal differential pressure of 100 bar) is taken on the load (as is the case in USA) or on the length (as is the case in Belgium) ; in the first case the allowable crack length is that corresponding to a pressure =  $3 \times 100 = 300$  bar while in the second case it is taken equal to 1/3 of the crack length corresponding to 100 bar.

For a  $\varnothing$  7/8" tube and a typical value of  $(S_u + S_y) = 950$  MPa, the allowable length varies from 12.5 to 10 mm, if the margin is taken on load, and from 16 to 9 mm, if the margin is taken on length.

As a difference of 1 mm in the plugging limit may translate in several tens of tubes to plug (or repair) at each plant outage, this highlights the technical/economical impact of the observed difference in laboratory test data.

### 4 INFLUENCE OF TESTING CONDITIONS

When comparing the laboratory testing conditions with the SG accident conditions (such as a Feed Water Line Break), 3 main differences are identified (Fig. 2).

- Burst definition.

Premature failure of the leaktight bladder, without instable crack propagation, results in an underestimation of the field burst pressure.

- Load time history.

During a SG accident, the differential pressure rises monotonically from about 100 bar to about 180 bar (in more than 10 s). Under laboratory conditions, the pressure rise gradient and shape (load fluctuations) is not normalized, not always monitored and rarely reported.

- Sealing system.

When comparing the behaviour of the crack area under testing and accidental conditions, 2 significant effects are apparent (Fig. 3).

. the local metal reinforcement (when used), raising the burst pressure through additional friction/tearing resistance, but also modifying the local pressure distribution with unpredictable results.

. the thickness of the plastic bladder which may act in two ways

- pressure resistance of the plastic tube,

- wedge effect of the plastic bladder protruding through the crack lips.

In fact all of these effects may be strongly interrelated ; for instance, for avoiding premature bladder failure without metal reinforcement, there is an incentive to both increase the plastic membrane thickness and to increase the pressure gradient (to reduce plastic creep through the crack).

## 5 PARAMETRIC TEST PROGRAM

In 1990, Laborelec conducted a program to quantify the effect of various testing conditions. However all tests were aiming at an unstable burst condition ; the case of unreinforced thin bladder was not included as it can obviously lead to very low "burst" values by allowing seal extrusion as soon as gross yielding is reached i.e. when  $\sigma > \sigma_y/m$

The investigated effects were

- the loading rate (10 ms to 100 s)

- the sealing system (various metal and plastic thicknesses)

- the pressurizing test rig and procedure

For the latter point, an air driven pressure multiplier, as illustrated by Fig. 4, was used in 2 ways :

. either with no axial loading in the test specimen (illustrated case)

. or with axial loading (modified case where the test specimen, provided with end fittings, is connected by a flexible hose to the pressure generator).

Alternatively, a reciprocating manual pump was also utilized ; this implies a less controlled average pressure gradient and the superposition of pressure pulses generated by the pump strokes.

29 tests specimens provided with a 16 mm laser cut TWD axial flaw were burst tested ; Fig. 5 illustrates a typical pressure record.

The following conclusions were drawn :

- The only 2 cases where unstable crack propagation could not be reached involved a relatively thin membrane thickness (2 mm), without local reinforcement and at a slow loading rate (10 to 20 s). The maximum pressure was but 5 % lower than the burst value reached by repressurizing with a thicker membrane ;
- The metal reinforcement increased the burst pressure by 10 to 15 % with respect to unreinforced thick bladder.
- The loading rate increased the burst pressure by about 15 % when reducing the pressurizing time from 10 s to 10 ms. When increasing the loading time from 10 to 100 s, the burst pressure was somewhat reduced (5 % ?) but this is believed to be a plastic creep effect (easing up through wall extrusion) rather than a metal strain-rate effect.

- Without axial stress, the burst pressure is apparently reduced ( $\approx 5\%$ ); this might be explained by the overall specimen bending (in plane of the flaw) not being counteracted by the end axial loads.

When the full range of burst data is considered, a total variation of 38% (190 to 280 bar) was observed, larger than the difference (at  $\lambda = 4.4$ ) between the 2 sets of curves from the international comparison.

Taking into consideration that reasonable load rates were used (even when not documented) by all experimentators, it was concluded that the upper curves may be under conservative because of using local metal reinforcement while the lower curves may be overconservative because using unreinforced plastic membrane resulted in premature leakage failure; the latter effect also explains the increased difference for the longer flaw lengths.

No conclusion could be reached as to representativeness with respect to the true SG conditions.

## 6 TEST PROGRAM WITHOUT SEALING SYSTEM

To settle the question, an additional test program was conducted by Laborelec with a high pressure (280 bar), high leakrate (100 m<sup>3</sup>/h) facility, using the main feedwater pump of a Belgian fossil fueled power production plant (Schelle); this allowed quasi static pressurization of TWD test specimens ( $\varnothing$  3/4" and 7/8", with axial flaw lengths from 12 to 50 mm) up to unstable bursting, without any sealing provision.

The results for  $\varnothing$  7/8" are given in table 1 and illustrated by Fig. 6 and 7 for the 2 specimens with a 12 mm long flaw; both were pressurized at 278 bar (the highest value achievable with the pump) which was sufficient to initiate rupture in one specimen while leaving the other in a just precritical status. Fig. 6 shows the pressure/flow rate diagram while Fig. 7 is a photograph of the 2 specimens after testing. This dramatically illustrates what "unstable propagation" means!

When the burst data are plotted against the original Belgian laboratory curve (taken from Fig. 1), an almost perfect fit is obtained, as shown by Fig. 8. This validates the upper curves of the international comparison.

## 7 CONCLUSIONS

Because of the lack of normalization for burst testing of tubes with TWD flaws, large divergences are observed between laboratory results. This could result in either unsafe or unduly penalizing consequences.

Testing flawed tubes under representative conditions (high leak rate without any sealing provision) yielded results matching previous laboratory data that were obtained with a locally reinforced bladder. This should not be construed to validate any similar laboratory technique, as the particular combination of materials (plastic and metal) strength and thickness, together with other testing details (such as load rate) may affect the results.

## REFERENCES

- (1) P. Hernalsteen, "Evaluation of critical lengths for through thickness axial cracks in SG tubing", SMIRT 6, paper F 7/6, Paris, 1981.
- (2) "PWR Steam Generator Plugging Limits - Technical Support Document for Expansion Zone PWSCC", EPRI report NP 6864, December 1990.

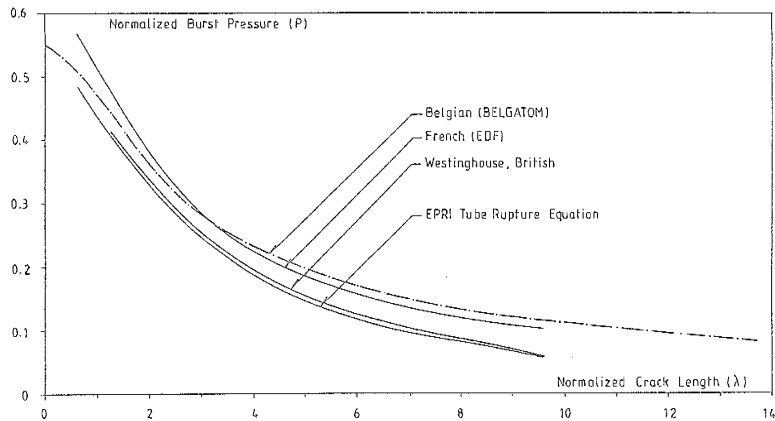


Fig. 1  
 Comparison of international test data ( from ref. 2 )

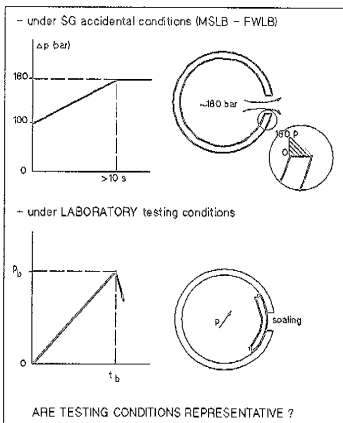


Fig. 2  
 Tube burst : comparison of actual and testing conditions

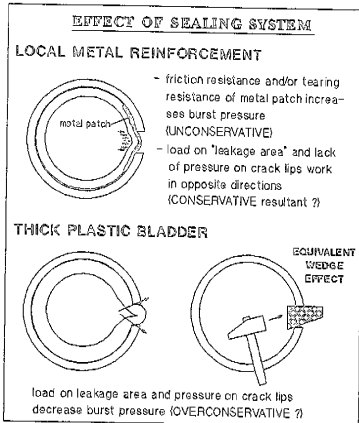


Fig. 3  
 Evaluation of the biases introduced by the sealing system

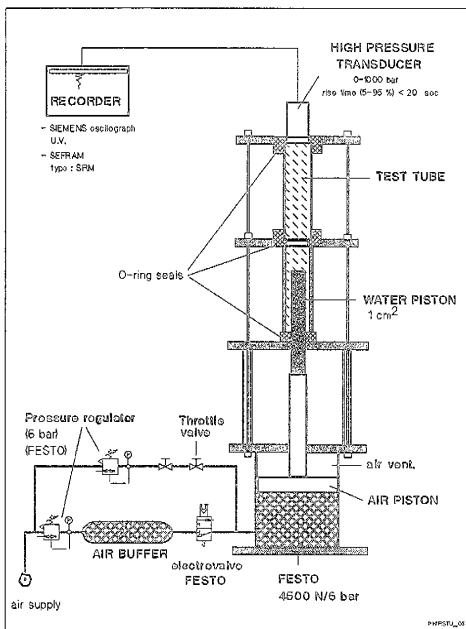


Fig. 4  
 Pressure generator and test assembly

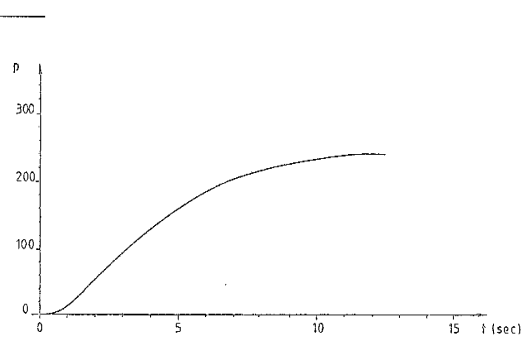


Fig. 5  
 Typical pressure loading curve

a (mm)	m	p (bar)	$\lambda$	$\bar{p}$	K	COMMENT
16	2.51	207	4.38	0.195	0.460	test performed 17/3/90
16	2.51	232	4.38	0.218	0.515	TESTS performed on 16/4/90
16	2.51	245	4.38	0.230	0.545	
20	2.99	198	5.47	0.186	0.525	
20	2.99	196	5.47	0.184	0.515	
12	2.05	278	3.29	0.261	0.505	
12	2.05	>278	3.29	>0.261	>0.505	
30	4.17	128	8.2	0.12	0.47	TESTS performed on 11/8/90
40	5.36	102	11	0.096	0.48	
50	6.55	78	13.7	0.073	0.45	
average value					>0.50	
standard deviation					0.03	

Table 1

Burst test results ( without sealing system )  
 K defined as  $\frac{m \sigma}{S_u + S_y}$  is verified to be constant, as expected from the collapse load theory

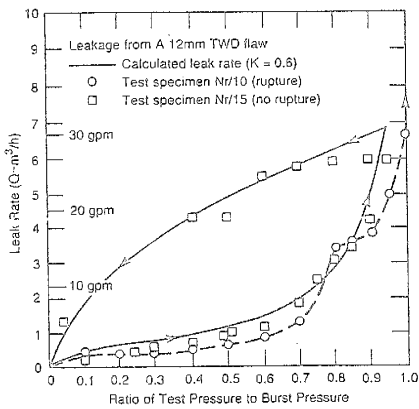


Fig. 6

Leak rate as a function of pressure for 2 identical test specimens



Fig. 7

Unstable crack propagation ( the two identical test specimens were pressurized at 278 bar )

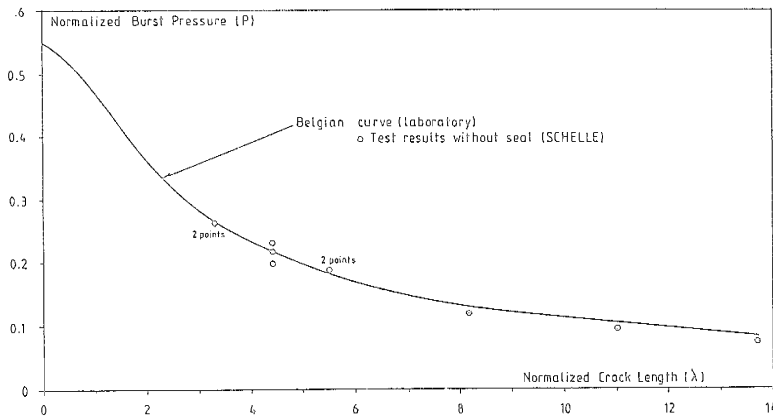


Fig. 8

Comparison of the Schelle data points with the prior laboratory curve