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Assessment of pipeline integrity and associated hazards

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ABSTRACT: This paper outlines aspects of the procedures adopted within Nuclear Electric plc for the assessment of Leak before Break arguments and the consequences arising from leakage and/or pipe failure. Only new aspects are considered such as creep, leakage, temperature and over pressure assessments and pipewhip.

1. Introduction

Assessments relating to the integrity of pressurized pipelines can be divided into three broad categories. These are those where:

1. "double ended guillotine break" (DEGB) can be tolerated, it having been demonstrated that the consequences are acceptable;
2. a DEGB is not acceptable but some leakage can be tolerated and a Leak before Break (LbB) argument can be made;
3. a DEGB is not acceptable, neither can a LbB case be made and incredibility of failure arguments must be sustained.

This paper deals with recent developments in work areas contributing to the first two categories, and, in particular, those aspects that have now been incorporated into Nuclear Electric (NE) standard procedures. The paper will address aspects of the consequences of release from pressurized systems as contained in R3 (Fullard, 1994) the "Impact Assessment Procedure". In addition it will include a discussion of new features introduced into the LbB procedure for R6 (Ainsworth, 1994) "Assessment of the integrity of structures containing defects"

The discussion cannot simply follow the division of the first two categories identified since consequences have to be assessed when considering leakage in an LbB case. Therefore, the paper addresses various aspects of the consequences of a DEGB and leakage, preceded by discussions on some aspects of LbB.

2. Leak before Break

The underlying basis of a Leak before Break argument is that a through wall crack develops, and that the ensuing leakage can be detected before a DEGB occurs. A number of LbB procedures have been developed, some to suit specific systems, others to meet more wide ranging requirements. R6 contains a LbB procedure, and here attention is drawn to features that are new, and have recently been introduced into a revised version: specifically; fluid friction and its role in leak rate calculations; leak detection; and creep effects. It is worth noting that the R6 procedure is non prescriptive, that is it does not impose margins on any aspect, such as crack length, load, or leak rate. In particular it allows the leak detection system to be tailored to the calculated leakage, and gives advice on both of these aspects.

2.1 Fluid Friction and its Role in Leak Rate Calculations

The leak rate through a crack is dependant upon a number of geometric factors such as length, crack opening, path length and features influencing fluid friction. In this sub-section the role of fluid friction, only, is addressed.

Early work on the role of surface roughness on flow through cracks identified a correlation between the fluid friction factor, λ, and surface roughness as measured by its R_a value (Button et al, 1978). The relationship was similar in form to the classical pipe roughness correlation derived by Nikuradse (See eg Schlichting, 1968), but displaced to yield effectively higher friction levels. Internal work within NE has also been undertaken to assemble a database of R_a values for different types of crack surfaces.

The relationship derived between R_a and λ does not identify upper or lower bounds. However, a lower bound to λ as a function of Reynolds Number was found by Nikuradse and use of this relationship will yield a reasonable lower bound, and hence an over estimate of flow, for use in consequences assessments.

The calculation of an upper bound to λ (lower bound to flowrate) is more problematical, and the use of unrealistically high values of λ will reduce the calculated flow rate and may lead to difficulty in making an LbB case. The correlation derived by Button et al has only been validated up to $\lambda = 1$. Gardiner et al (1986) argue for an upper bound of $\lambda \leq 4$, and this was substantiated in large scale experiments (ie. large scale roughness, but geometrically similar to cracks) showing $\lambda \rightarrow 1$ and $\lambda \rightarrow 4$ in two separate experiments. However, the former was a geometry of more relevance to structural defects. More recently, the opportunity has been taken to measure flowrates through real cracks, and deduce friction factors. In these cases uncertainties arise about the basic crack geometries. Taking such aspects into consideration has yielded the following data: for a fatigue crack it was concluded that median and upperbound values for λ were 1.4 and 4, respectively; for conforming surfaces in a cracked weld the results showed $2 \leq \lambda \leq 4$. Overall, it is concluded that unless specific values of λ can be justified then the range $1 \leq \lambda \leq 4$ can be used in sensitivity studies.

2.2 Leak Detection

An essential part of any LbB case is that the leakage can be detected. There are a large number of techniques available for the detection of leaks. Structure-borne and airborne acoustic techniques offer considerable capability for the detection, location and quantification of leaks for both global and local applications, although development and validation work is required to achieve their full potential. The capabilities of all of the techniques available are highly application dependent and many of them, in addition to acoustic techniques, may merit consideration in support of LbB arguments for specific plant items.

All of the techniques monitor secondary effects, hence an adequately quantified correlation between leakage rate and the monitored parameter is required. Data on detection sensitivity, resistance to interference, and reliability are needed to provide confidence that defects of significance to a LbB argument will be detected.

It is important that the detection of the signal should be unambiguous, and knowledge of discrimination levels is necessary. For example to apply the structure borne acoustic technique requires the background noise levels to be known and due regard taken of likely extraneous influences. It is known that reactor power load will change background noise levels, as will changes in operational mode. It must be demonstrated that the margins between the possible range of background noise levels and the expected leakage signal levels are sufficient to ensure that adequate detection is possible whilst avoiding false alarms.

Attenuation rate data are necessary to enable structure borne acoustic systems to be optimally designed to provide adequate coverage whilst minimising cost. Ideally this should be specific to the plant items to be monitored. However, based on NE data for both ferritic and austenitic steel steam pipework, a far field value of 1.8dB/metre may be pessimistically assumed.

There is sufficient evidence available from NE work to justify deployment of the technique for the detection of steam leaks of a magnitude expected to exceed some 10 g/s. This is in agreement with Jax (1992) where a detection level of between 8 and 70 g/s is claimed.

The airborne acoustic technique has been developed within NE for global application and there is operational experience in its use on stream pipework. Although simple to apply retrospectively, it requires the leak to have an acoustic path through any lagging to ensure detection. This may require lagging and cladding to be disrupted to provide an adequate acoustic path to the detection microphones. An alternative is to retain airborne acoustic detection but with resultant lower sensitivity. Experiments have shown that damage to insulation in the neighbourhood of a leak results in acoustic energy being released from the outside of the cladding. However, energy levels will be very dependent upon design details and generalisations are not possible.

Airborne acoustic monitoring is also susceptible to interference from background noise such as steam leaks from other plant (eg. valve stems). Thus successful use of the technique is dependent on the disruptive and acoustic properties of the leak. The present evidence from plant indicates that leakages of less than 10 g/s could be detected by the careful targeting of microphones on lagged pipes.

Manual inspection for leaks is widely used on steam raising plant. Where the surveyor is relying only on his own perceptions it is not possible to quantify detection limits. When the survey is undertaken using a hand held ultrasonic leak detector then preliminary surveys using the instrument are necessary to determine background noise levels. Signals emanating from leaks will attenuate with distance and must generate energy levels that are significantly higher than the background levels at the detector. Leaks of less than 10 g/s have been detected in moderately noisy environments at distances of some 7m. However, in the presence of high background noise levels the leak detection limit may be several hundred grams per second.

2.3 Creep Effects

The LbB procedure first incorporated into R6 only addressed the assessment of plant operating outside of the creep regime. However, there are numerous instances where pressurised plant operates at temperatures where creep needs to be considered, and where the ability to use LbB arguments in safety cases would be of value. Hence the new R6 LbB procedure includes an assessment of high temperature phenomena. The NE "Assessment procedure for the high temperature response of structures" (R5, Ainsworth, 1994) considers high temperature phenomena and their impact on structural integrity. The incorporation of specific aspects of creep into an LbB procedure is now discussed. These relate largely to fracture aspects rather than the leakage and detection aspects considered in sub-sections 2.1 and 2.2.

For cracked components operating within the creep range two aspects need to be assessed: creep crack growth and creep rupture due to continuum damage mechanisms. Both of these need to be considered before and following defect breakthrough and the procedures used within NE for their assessment are discussed below.

For calculating creep crack growth of a defect prior to through-wall breakthrough, it is assumed that the shape of the surface breaking flaw at the start of high-temperature service has been characterised as semi-elliptical. The instantaneous crack growth rates at the surface and the deepest point are then calculated using reference stress methods together with an appropriate best-estimate creep crack growth law. In the absence of specific crack growth rate data on the material, methods are given in R5 for estimating crack growth rates in terms of rupture or creep ductility data only. The growing flaw is then continuously re-characterised as a semi-elliptical surface crack until break-through occurs with ligament failure of the growing crack, and the defect length at breakthrough characterized using standard R6 methods.

Welding residual stresses need to be taken into account in the crack growth calculations, although the magnitude of these stresses reduces with time due to creep straining and any ductile tearing of the ligament which may occur as a result of time-independent loading. The effect of residual stresses on creep crack growth rates is addressed in R5. Estimates are also given which enable the timescales over which these stresses relax to be quantified. It may then be possible to justify considering only part of, or none of, the initial residual stresses when considering further crack growth.

For high temperature applications the crack opening area, COA, in general changes with time due to creep. In primarily membrane loading situations, the COA increases and hence it is conservative to use the calculated opening in the absence of creep, as this leads to an underestimate of leak rate and hence to both a predicted greater detection time and to lower margins in a leak-before-break case. However more accurate assessments can be made involving the creep strain rate, which will be a function of time. This requires the resulting COA equation to be integrated as a function of time, in conjunction with the defect growth rate.

The time for the leaking defect to grow to the limiting crack length is obtained by integrating a creep crack growth law between the crack length at breakthrough, and the limiting length. As for the semi-elliptical flaw prior to breakthrough, the extent of creep crack growth is estimated using reference stress methods but now these require the stress intensity factor K for fully-penetrating flaws. These solutions generally correspond to an averaged K through the wall thickness. Where the through-wall variation of K is obtained for particular loading cases, an averaged value should then be computed. This crack growth rate is applied at the mid-wall position and the defect is then assumed to grow uniformly through the thickness.

Seperately from the crack growth calculations, the times to continuum damage failure of the cracked component should be calculated. For conservatism, lower-bound rupture data should be used as these lead to reduced estimates of rupture time and hence lower margins in a leak-before-break case. It is also conservative to assume that the through-wall defect has existed from the start of high temperature operation. Advice is given in R5 for calculating improved estimates of time to failure which account for the flaw growth stage; these calculations need to be performed simultaneously with the crack growth calculations described above. In cases where a high-temperature leak-before-break case cannot be made due to creep rupture prior to leak detection, it may be possible to increase the predicted rupture times by following this route.

3. Consequences

We now move away from LbB to consider some of the consequences arising from fluid leakage, whether from a through wall crack or a DEGB. The consequences of fluid release can be divided into two broad categories, thermal and mechanical. Here discussion will be restricted to thermal consequences arising from leakage or failure of a pipe, and pipewhip.

3.1. Thermal Consequences.

A jet emerging from a crack, or a broken pipe, may impinge upon a structure, giving rise to jet forces and a temperature rise of the component. In addition, there will be the more global consequence of temperature and pressure rise within the building containing the leak. The R3 assessment procedure includes advice on all of these aspects, but here, jet forces will not be discussed.

For evaluating the temperature rise it is conservative to assume that the target on which a jet impinges is at the stagnation temperature of the fluid. However, new modelling is now available for gases, or superheated steam, which takes into account jet cooling arising from entrainment as a function of distance. This work is based on experimental data, and gives considerable alleviation on target temperature compared to the simple constant temperature assumption.

With regard to global consequences; it is necessary to evaluate the pressure transient in order to determine if a wall of the building will fail, and the temperature transient in order to determine whether critical equipment is damaged. Alternatively given limiting pressures and temperatures it is possible to evaluate the maximum release that can be tolerated, and the ventilation requirement.

Mass transfer is an important process in steam release studies. Condensation onto surfaces and into the atmosphere affect the temperature of the atmosphere and equipment, in addition, the presence of a moisture film may be detrimental for electrical equipment.

Ventilation processes are also important. Forced ventilation is usually by extract or inlet fans. Failure of these fans in a high temperature environment must be considered as the fan motor is frequently in the hub of the fan, adjacent to any hot gas. Inlet fans will be more secure than extract ones.

Natural ventilation is usually required and if vents are placed at different heights buoyancy forces will help to purge released gas from the building.

These various physical processes act in parallel. Whilst the response of the building atmosphere and low thermal inertia components is usually rapid, the time-constants of the heat and mass transfer processes between atmosphere and heavy components are long, so that analytic steady state solutions are inappropriate.

The fluid release promotes good mixing within the room, in general, allowing the use of relatively simple "lumped parameter" computer models rather than sophisticated computational fluid dynamics codes for the majority of problems. HOTJET is a code written using lumped parameter concepts. This code solves the mass, energy and momentum equations for a room or series of rooms, vented to atmosphere.

It should be noted that lumped parameter modelling is only valid if there is instantaneous mixing. This criteria will become invalid if the momentum of the gas jet is low and buoyancy forces dominate. Criteria are included within the R3 procedure to define the validity of HOTJET.

3.2 Pipewhip Consequences

In the event of a DEGB a thrust will be applied to both open ends of the pipe, and, depending upon the geometry, may well result in pipewhip of one or both, severed ends. The consequences of whip, i.e. impact with a third body, are not considered here. Only the "zone of influence" and attendant velocities will be discussed. A simple approach is to consider a "sphere of influence" centred on the identification of a pivot point and of radius extending to the break. This is very conservative. Extensive experimentation has shown that pipes whip in well defined planes that are clearly identified by pipeline geometry and the thrust. In addition, as the free end of the pipe accelerates a plastic hinge, or hinges, can develop to further restrict the zone of influence. For pipes whipping in a single plane a theory has been developed to predict behaviour. The model assumes rigid-plastic behaviour with the onset of plasticity defined by a flow stress. Strain rate effects can also be accommodated, but appropriate data are not always available.

Historically, detailed modelling of pipewhip behaviour has been generally restricted to small deflections or complicated computer simulation. A pipewhip specific code, WHIPPIT, has been written to provide a simple and fast route for calculating pipe motion for straight pipes and single bend pipes where the tip force is normal to the pipe and in the plane of any bend present. This code has been validated against experiment and good correlation is shown. In its present form, the code does not represent ovalisation at a bend, or the elastic response of the pipe. The former is seen in thin walled pipes, whilst the latter may be significant in thick walled pipes. Elastic effects on the swept zone can be assessed separately and added to the computed deflections.

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