THE PWR NUCLEAR POWER STATION RISK PROBLEM

INTRODUCTION

In a pressurized water nuclear reactor, nuclear heat from uranium oxide fuel elements heats water to 300 degrees centigrade. In order to localise the radioactivity, this 'primary' water is pumped through steel tubes so as to heat 'secondary' water in boilers so that steam is generated which drives turbines and makes electricity for the public supply. The nuclear reactor is about 6 metres tall and 3 metres in diameter and is situated inside a twenty five centimetre thick steel reactor pressure vessel (RPV) which is lined with stainless steel, and joined to pumps and the boilers by sets of large pipes. During operation an enormous amount of energy is stored in the 'primary' hot water. If the RPV ever became weakened sufficiently for it to burst while working then the most dreadful accident would ensue.

1. Steel is prone to cracking both in manufacture and throughout the working life of highly stressed steel components like the RPV. Recently all except one of the British 'hunter killer' nuclear submarines, which use pressurized water nuclear power for their propulsion, have been in the news because of the need for repairs of serious cracks in their pipework. The nuclear industry have gone to considerable trouble to avoid both any unexpected weakness in the RPV, and any unexpected overload. It is generally agreed that the consequences of sudden unexpected explosion of the RPV in operation are known to be so severe that the chance of it happening should be less than one in tens of millions. The only problem is that there is no known affordable way of demonstrating such high reliability. The nuclear industry and the Nuclear Installations Inspectorate, who are the guardians of the public safety against nuclear power station accidents have 'solved' this problem by declaring that when the nuclear industry have done as much as they can, then explosion of the RPV is 'deemed' (by them) to be incredible. That is the best that they have been able to do.

SAFETY AGAINST EXPLOSION

2. If the loading applied to any given structure increases without limit or if a loaded structure is continually weakened in some way, then eventually it will fail to withstand the load. The manner in which the failure occurs depends upon the design. A pressure vessel which starts to leak may release the applied internal pressure safely without explosion. The stranded steel cables supporting a passenger lift will not be seriously weakened by the breaking of many of their individual strands. But a rubber balloon explodes at a pin prick.

3. The PWR nuclear power station RPV would be weakened sufficient to burst at normal operating pressure by an axial/radial crack in the cylindrical wall, which extended about one third of the way through the steel. The nuclear industry claims that the occurrence of such a crack is incredible, but it is quite unlikely that if such a crack were to develop then the RPV would leak at all before it burst.

4. Many tests have been made in which steel pressure vessels with artificially

introduced cracks have been pressurized until they exploded. The results of these tests have indicated quite clearly that explosion occurs when the pressurization is by steam or compressed gas and the vessel wall stress no longer supported by the cracked material, overloads the nearby material to a certain distance beyond the crack tip, and which has been found to be quite predictable.

Unstable Fracture

5. A method of calculation called the Stress Concentration Method enables the critical combination of stress and crack size for failure to be calculated for any given instance. Initiation (crack criticality) is known to occur when the extent in distance beyond the tip of an existing crack, along the direction of the crack, of material stressed to the ultimate tensile stress (UTS) reaches a limiting value 'S'.

6. Values of 'S' have been determined by measurements performed by large numbers of tests including many test explosions of large pressure vessels together with the analysis of many failures of components in service, and the parameter has been both accurately determined and shown to depend on material properties, by co-workers W.H.Irvine and A.Quirk of the United Kingdom Atomic Energy Authority. Their research enabled the value of ' S ' to be evaluated from statistically significant measurements of the extension of tensile test specimens at failure together with measurements of notch ductility of test specimens, at the vessel operating temperature, for each of the materials in question.

7. The speed and extent of the post initiation cracking is reliably observed to depend upon the rate of change of gross area stress with the linear deformation (extension) of the structure. Pneumatic pressure causes explosion, cold hydraulic pressure does not.

8. Approximate theoretical analysis of the stress and strain in cracked steel plates enable Berry (ref. 1) to establish the importance of energy availability in the behaviour of critical cracks. If the rate of change of stress with structural deformation is less than the gradient of the Berry crack locus curve at the initiation point then the crack only extends a small distance before arresting otherwise complete unstable failure ensues. When the gradient of the fracture locus is positive then large crack extensions occur even when the rate of change of stress with structure deformation is infinite (constant strain case). In this case crack arrest occurs when the limited amount of energy stored in the elasticity of the structure and the pressurizing means has been converted into new cleavage crack surface. In particular when the gradient of the fracture locus is negative (ductile material on the "upper shelf" of the charpy energy vs material temperature graph) and the rate of change of stress with deformation of the structure is zero then complete failure immediately follows initiation.

9. In the context of the stress concentration method, stable crack growth refers to the growth of cracks before initiation and while they are sub critical, the growth occurring by processes possibly including fatigue, stress corrosion, creep, wear, and other mechanisms. The slow extension of sub critical cracks by slow tearing

under increasing stress to any significant extent is not accounted for in the stress concentration method except in the case in which the the gradient of the fracture locus is negative and constant structural deformation is applied.

10. The reliability (probability of catastrophic failure per year of service time) of metal structures which are stressed in tension has not been shown to be less than one in one hundred thousands with fifty percent confidence. In the case of statistically insignificant numbers of stressed metal components for which the required reliability is ten or more times greater than this value, past experience does not provide any direct basis upon which to proceed.

11. **The need for high reliability**.

12. The Sizewell 'B' PWR pressure vessel wall is ten inches (254 millimetres) thick and during operation contains water at a temperature above 300 degrees centigrade and a pressure of one ton per square inch (15 meganewtons per square metre.) In an accident involving the discharge of radioactive material from the reactor fuel, it is the longer lived radioactivity which contributes a major part of the risk to peoples lives. The fuel in a nuclear power station contains many times as much longer lived radioactive material as an H-bomb. When the testing of nuclear weapons in the atmosphere was banned by international agreement, nevertheless, for a time weapons testing continued underground. It may readily be seen that when the need justifies it, safe protection against powerful explosions involving huge quantities of radioactivity can be engineered. At the Sizewell 'B' public inquiry it was admitted by the designers that the reactor containment building was not known to be able to withstand the 'challenge' (their term) by explosion of the RPV.

13. Serious accidents to nuclear power reactors are potentially of such severity that the nuclear industry needs to be able to argue that their probability of occurrence is quite negligible. One per million years was claimed at the Sizewell 'B' inquiry. Faced with this dilemma the nuclear industry defined technological areas in which advances might be claimed.

14. A deficiency of Irvine and Quirk's stress concentration method of assessing critical crack size is that it is easy to understand and simple to apply, and when its use is combined with the statistics of pressure vessel failure observations then it becomes 'difficult' to prove the safety of PWR power stations. New ways had to be devised both to distract attention from the stress concentration method and to replace it by something more 'successful'. The condition of stressed crack criticality was redefined as being the first increase in crack length under applied load. This change enabled the argument that crack growth before actual catastrophic instability was 'the stable growth of a critical crack'. Pre-critical crack growth was re-defined to be Post-critical crack growth. Everything has a breaking point. True instability occurs when the applied force exceeds the maximum strength of the structure, and this necessarily occurs when either the crack has just exceeded its maximum stable length or the stress has reached its maximum stable value. Thus in a constant load type of tensile test true instability occurs at a point of maximum load. A ductile test piece may tear or stretch before breaking.

15. The increase in the test stress supported between the start of deformation and eventual fracture was postulated to be due to some 'fracture resistance' claimed to be a material property.

16. The main contributor to catastrophic instability in practical cases is the energy stored in the pressurizing means. Where this is gas at 130 atmospheres or water at 300 degrees centigrade, this energy is a very significant factor. This inconvenient consideration was glossed over by disregarding its role in promoting crack instability. Furthermore the physical analysis of the behaviour of cracked material was complicated by the adoption of concepts like crack resistance and a 'path independent line integral' to define the onset of stable crack growth renamed criticality. The role of pressure energy stored in the pressurizing medium was completely ignored.

17. The ' S ' limitation of uncracked material beyond the crack tip and stressed to the ultimate tensile strength was assumed to be increased above the value given by Irvine and Quirk so that it extended entirely through the uncracked material to the far side of the component thickness before the onset of unstable crack extension. This enabled the calculated strength of the structure to be increased substantially, and enabled the claim to be made that the vessel would be likely to leak safely without explosion.

18. A new and additional criterion was devised in which the value stress intensity in the uncracked structure is compared with the stress intensity in the structure when cracked right through, called the critical stress intensity. In the case of the Sizewell 'B' pressurized water reactor pressure vessel (RPV) which is such a metal component, a new method of assessment was contrived by the old Central Electricity Generating Board in order to utilize these new concepts and overcome any possible objections.

The R6 Method

19. The R6 Method (Assessment of the Integrity of Structures Containing Defects - .Central Electricity Generating Board - August 1976) for the assessment of the safety of the Sizewell ' B ' reactor pressure vessel predicts instability delayed until the extent in distance beyond the tip of an existing crack, along the direction of the crack, of material stressed to a 'collapse load' has extended entirely through the cracked member to the limit of the uncracked material before failure occurs. This ultimate condition of snap through is named 'plastic collapse', a term with more anodyne connotations then stress rupture. It is postulated that as the distance beyond the tip of an existing crack, along the direction of the crack, of material stressed to the ultimate tensile stress increases, so the material at the crack tip tears slowly. This postulated phenomenon is called 'slow stable tearing of a critical crack'.

20. Tensile tests using machines with a constant structure-deformation characteristic and pressure vessel tests using low vapour pressure hydraulic pressurization (also having a constant structure-deformation characteristic) have shown that between

the onset of yield and ultimate failure by the extent of crack elongation, a proportion of the tests exhibited 'slow stable tearing'. These were tests in which the rate of change of stress with structure deformation is less than the (negative) gradient of the Berry fracture locus curve at the initiation point so that the crack only extended a small distance before arresting. in these tests it was observed that a small amount of the observed 'slow stable tearing' in some instances did occur while the applied load borne by the structure was increasing. this phenomenon was called 'crack resistance' and was claimed to be a property of the material rather than of the testing method.

21. Using the first version of the R6 Method the safety of a given crack size and position within a stressed structure is assessed by evaluating the ratio of the gross area stress to somewhere near to the UTS; and the ratio of the stress intensity to the critical stress intensity and plotting these ratios on an assessment diagram on which, essentially, both if both ratios can be seen to be less than unity then the structure can be assumed to be safe.

22. In R6 - Revision 2, the stress beyond the crack tip is evaluated as the average of the point two five percent yield stress and the UTS, called the 'flow stress'. In R6 - Revision 3, this stress is evaluated as the point two five percent yield stress. Thus the R6 Method was made a little more conservative with the passage of time, but still far more permissive than Irvine and Quirk's Stress Concentration Method.

23. In the R6 Method the energy necessary for creating both the new crack surface and the stretching of the material in the vicinity of a crack extending under stress, are assumed to be derived from the energy stored only within the elasticity of the structural material itself. That is the consequence of the 'J-integral' and the stress intensity ratio procedure. The possibility that more energy might be fed in rapidly from the stressing mechanism during the actual crack growth and on a time scale short compared with that of unstable crack growth is not referred to anywhere in the vast volumes of reports on the subject, except in the works of W.H.Irvine and A.Quirk, carried out before 1980. This work is not referred to anywhere in the R6 Method.

24. At the Sizewell ' B ' Public Inquiry the old CEGB argued for the virtual absolute certainty of "two millimetres of stable crack growth of a critical crack before catastrophic failure can occur" the objective of this being that a crack of critical size would not cause disruptive failure before being certain to be detected by periodic non destructive examination and the power station taken out of service safely.

25. At the Sizewell ' B ' public inquiry the only evidence submitted on the effect of varying stored energy on crack stability (Vassilaros et al) did not demonstrate any vestige of stable crack growth anywhere. Supporting evidence of bursting tests on thick steel pressure vessels and thick flat plates (Heavy Section Steel Tests) were all carried out with no significant amount energy stored in the stressing means, that is to say significant in the explosion context.

26. Inspector Frank Layfield at the Sizewell ' B ' public inquiry, who was a planning

lawyer, accepted that the weight of opinion as argued by the world authorities was strongly in favour of the incredibility of explosion of the reactor pressure vessel. The Government Health and Safety Commission declared their acceptance and agreement.

27. At the Hinkley Point ' C ' public inquiry, I adduced these same arguments and in addition I pointed out the fundamental difference between the instability of axial/radial cracks in the cylindrical pressure vessel wall as compared with inside and outside, the outside being more unstable through bulging tending to open the crack rather than close it.

28. My requests for the numbers, locations, orientations and sizes of the cracks found by inspection in the Sizewell 'B' reactor pressure vessel to be disclosed to be are refused. I hereby repeat my request for those disclosures.

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