Rodney Fordham
http:\\homepage.ntlworld.com/rodney.fordham
>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
13 july 2005

1. A response by a retired nuclear safety consultant, Rodney Fordham, to the invitation by the Royal Society of Edinburgh's Inquiry Calls for Evidence in 'ISSUES FOR SCOTLAND'S ENERGY SUPPLY'

2. Societal risk is a central factor in addressing the costs and benefits of energy supply. This note opens with a qualitative discussion of a limited sub-set of the technicalities of the safety of reactor pressure vessels against disruptive explosion. This is followed by an evidenced discussion of the societal risk and the degree of control provided by the government in the nuclear power context. The theme follows the proposition that Society needs to be protected from the risk of explosion of the reactor pressure vessel of the Sizewell 'B' nuclear power station. The societal risk from Sizewell 'B' is not properly controlled. At the present time nuclear power is being either developed or is under active consideration for development more or less throughout the world. The pressurized water reactor system is the front runner of all of the nuclear power systems under consideration, and so the Royal Society of Edinburgh is likely to be confronted with proposals in that area. This note glimpses how the societal risk of nuclear power might fare under English Law.

3. CAVEAT. This document is not a review of the risks of nuclear power. It deals only with the risk of explosion during normal operation of the reactor pressure vessel of the Sizewell 'B' nuclear power station pressurized water reactor, caused by a defect or defects which may possibly occur in just one part of the slightly ductile steel fabric of that vessel. The following topics, all of which are additional possibilities, are not dealt with: failure whilst pressurized at low steel temperatures; reactor explosions; attack by molten reactor fuel; excessive operational pressure; water hammer; nearby explosions; deliberate sabotage; projectile impacts; aircraft impacts; earthquakes or subsidence; storm; or alterations to construction or operation; stress corrosion cracking; large scale corrosion by ignored leakage in service, although in some cases examples are mentioned.

4. The Sizewell 'B' reactor pressure vessel is very large by industrial standards. It is 482 cm in outer diameter, 1355 cm tall and 21.5 cm thick, or thereabouts, weighing about 450 tonnes.

The interior surface which is in contact with the reactor coolant is protected from corrosion by two fusion weld deposited layers of stainless steel with a minimum total thickness of a few millimetres. The vessel has been constructed by fusion welding forgings together. Forgings are made by forming large pieces of steel when it is hot enough to be relatively soft. Fusion welding is itself a known cause of unreliability and in addition it is known to be more vulnerable to degradation of the physical properties by neutron irradiation. For that reason a cylindrical section of the Sizewell 'B' vessel is made in one forged section only welded to the remainder of the vessel at top and bottom edges, away from the maximum neutron irradiation. In this review, only failure of this central cylindrical section of the vessel will be considered. The nuclear reactor in Sizewell 'B' is situated centrally within the cylindrical portion of the pressure vessel.

5. The following is a qualitative account of some of the details of the steel used to construct the Sizewell 'B' reactor pressure vessel, and how such steel behaves under extreme stress levels. This account is based upon published accounts of work in the field across the world, and over the years. It is neither exhaustive nor definitive. But it is food for thought.

6. The Sizewell 'B' reactor pressure vessel is made from "low alloy steel type A355B". Steel was invented in the nineteenth century by reducing and controlling the amount of carbon included within it. The strength of steel can be much increased by small additions of some other metals during manufacture.

7. A533B steel has density 7.83 grams per cubic centimetre, and nominal composition:-

Iron   97.02 atoms percent
Nickel   0.52 atoms percent
Manganese   1.31 atoms percent
Carbon   1.15 atoms percent

8. Some impurities present in steel can have adverse effects on the physical properties and need to be tightly controlled below maximum permissible values. These include hydrogen and copper. The effects of fusion welding, neutron irradiation, stress cycling, stress at high temperatures, and corrosion on steel are known to affect the composition and structure of steel adversely. Permanent deformation at low temperatures, known as 'cold work' also affects its properties.

9. Iron melts around 1800 degrees centigrade and on solidification and cooling it has a system of allotropic forms. If the temperature is reduced very slowly to room temperature it is found to consist of tightly packed metallic grains each with a body centred cubic 'crystalline' structure, known as ferrite. When other elements are present the structure is more complicated. Carbon and iron tend to combine in different ways in different temperature ranges, and the changes involved in going from one stable form to another take time to occur, so that in addition to the chemical composition, the rate of temperature change is an important factor in determining the physical properties of the end product. For example rapid cooling from a temperature of 1000 degrees centigrade produces a hard brittle product with the structure which existed at the high temperature. This procedure is called quenching or hardening. Once in the hard state, the properties can be controlled by 'soaking' the steel at intermediate temperatures and subjecting it to cooling at carefully controlled rates of temperature reduction. The properties of the steel are measured by mechanical procedures which, because of the inhomogeneous nature of the product, give enormously variable results. For example, the shear strength of the steel can be calculated theoretically by reference to the known properties of the ferrite crystal atomic structure. However, the value measured in tests is only one thousandth of the theoretical value indicating the extent to which it is weakened by internal irregularities and disorder. The granular structure of the steel can be examined by the standard crystallographic polishing and etching techniques. Fusion welding thick steel sections together is achieved by filling a gap between the sections with 'passes' of deposited weld metal. For each 'pass' during which one strip of fusion weld metal is deposited, the adjacent parent metal is heated up to the melting point and down again. The Sizewell 'B' vessel cylindrical wall is 215 millimetres thick, necessitating about sixty passes to deposit the required amount of weld metal. The welding is performed in sequence from both the inside and the outside of the vessel, with the 'root' of the inside welds cut away before application of the outside weld. The parent steel in the vicinity of the weld is said to contain a 'heat affected zone', abbreviated to HAZ. The physical properties of the weld metal need to be controlled independently of the parent material in order to ensure so far as possible that failure of the weld does not occur preferentially. Uneven cooling of steel from high temperature causes variation in the crystal structure within the component. Local variations in density which result, mean that stress fields

exist within the component which, if they remain in service, will modify the actual stress distribution in service from that assumed in the design procedure. It is not unusual for quite large cracks to form during poorly conducted temperature control.

10. The added atoms present in low alloy steel complicate the matter still further, since their presence interferes with the formation of the ferrite crystals in that types of small hard crystals involving some of the additives form between the ferrite crystals, and some of the additive atoms become included within the ferrite structures. The sizes of the ferrite and hard crystals, and the distance between the hard crystals each have distributions which may be determined by measurement for a given specimen. These changes are directly responsible for the increase in the potential mechanical resistance of the steel to deformation under applied stress, thought of as improvement in its fitness for a structural purpose. The manner of deformation under load is affected by several mechanisms. Initially the deformation is elastic and almost fully recoverable up to the point called the elastic limit, where permanent deformation starts to occur. If the application and release of a substantial fraction of this stress takes place for a very large number of 'cycles', it is found that some of the irregularities within the steel start to increase in size, with each cycle producing a microscopic increase. This is called 'fatigue'. Defects below a certain size do not grow by fatigue; and for those of greater size that do grow, their rate of growth increases with their size, and also the larger the stress cycles, the smaller is the total number of cycles to cause eventual failure. At sufficiently high temperatures the application of stress within the elastic limit produces a very slow yielding, due to thermally induced migration of atoms within the steel, which takes place in three identifiable stages, collectively known as 'creep'. At lower design or working temperatures, and at stresses within the elastic limit, some chemical agents which may be present at the steel surface react with the surfaces of the metallic grains in the steel causing them no longer to be joined. This process is called 'stress corrosion cracking'. Where a component is significantly weakened by loss of thickness due to straightforward corrosion, a given load will cause an increased deflection. Beyond the elastic limit, permanent deformation starts to occur. For a brittle steel, cleavage fracture eventually occurs at the ultimate tensile stress in which the grains either break apart or separate cleanly. For thin or small ductile steel components under tensile stress, the poisson

effect or lateral contraction which accompanies the stretching means that compressive stresses are generated within the steel which act perpendicularly to each other. As the stress level is increased, thin layers of the steel move with respect to one another at an angle of 45 degrees to the direction of the contraction. The application of a brittle lacquer to the surface of a component can make the lines of slippage clearly visible. These very thin lines, only a few atoms wide are known as 'shear bands' or Luder's lines. This process is accompanied by thinning of the component perpendicular to the direction of the applied stress. As this process progresses, the true stress within the steel necessary to produce further deformation is observed to increase monotonically until eventual breakage. Some representative figures for A533B steel are:

True
strain
percent 0.5 1.0 1.5 4.5 5.5 6.5 7.5 8.5 9.5 10
20degC | | | | | | | | | | |
True 455 460 475 520 557 585 607 625 637 650
610 613
Stress
Mpa

We shall take 455MPa as the yield stress and 613MPa as the ultimate tensile stress for thin sections, although these figures are reduced at working temperatures. In thick or large ductile steel components, the application of tensile stress beyond the elastic limit tends to generate internal 'tri-axial' stresses tending to tear the material apart. As the stress is increased, microscopic cavities form around some of the small hard crystallites. These 'microvoids' are irregular oblate ellipsoidal in shape with their long diameters parallel to the direction of the principal applied stress. As the stress increases these voids increase in size and are said to 'coalesce' as they join together (Refs.2 & 19).
If a large defect is present in a stressed thick ductile component, the stress not being carried by the material immediately adjacent to the defect is carried by other material in the vicinity. This is in addition to the load which that other material would have carried in the absence of the large defect. Thus it can be seen that as the applied stress is increased without limit, the size of the initial defect will increase progressively as the material in its vicinity carries the highest stress level and yields and fails preferentially. This process, if it occurs, is called 'stable tearing'. Some success has been achieved in mathematical simulation of this process using 'finite element modelling.'(Ref.19) It is imagined that as the size of the defect increases so this effect is

compounded until the all of the remaining material, known as the 'uncracked ligament' fails at or near to its ultimate stress. The total hoop stress in the cylindrical wall of the Sizewell 'B' pressure vessel is given by the product of the internal pressure and the inner radius, so that the thickness of the uncracked ligament for which this stress would be the ultimate load is less than 5.5 cm., only about a quarter of the wall thickness. Unfortunately, this means that the vessel is most unlikely to leak by this route, before failure occurs. The question of what is the maximum crack size which is safe against catastrophic failure is absolutely vital. The effect referred to above in which the stress in the vicinity of the edge or tip of a fatigue crack is increased above the stress at the same point in the absence of the crack is called 'stress concentration', and one experimentally based formula supposes that the load unsupported by the cracked material is carried by the nearby material within a fixed distance S cm. of the tip of the crack. As the crack grows this additional load increases until the total load on the material within the distance S cm. reaches the ultimate load, at which point catastrophic failure of a pressurized vessel ensues. No test of this hypothesis on a full size PWR vessel containing water at 325 degrees centigrade, and with a crack increasing in size by this mechanism, has been tried. The stable tearing theory postulates that at this point of instability, all that happens is that stable tearing begins and as the strength of the material increases by work hardening, further increase of the size of the crack is inhibited until either further growth occurs by another mechanism, or the applied pressure load is increased further. Measured values of S for thin-walled vessels are in the range of a few centimetres. Apart from the measurements of S, there have been no full size tests to destruction of pressurized ductile thick walled vessels. Simulated tests of spinning rotors have been used to explore crack growth under stress of a heated cylinder stressed both by rotational stress and by the simultaneous application of cold water to its inner surface whilst rotating. The crack sizes used in these tests were less than one quarter of the wall thickness. Apart from the crack size, the assessment of the safety of the Sizewell 'B' reactor pressure vessel against disruptive explosion relies upon innumerable tests of several types of small samples, combined with analytical methods of application. In some of these tests a slowly increasing force is applied by some kind of machine to a cracked component. The shape of the test sample and its prior treatment are specified, for example a pre machined crack may be 'sharpened' by stress cycling fatigue. The shape of the specimen component often includes features which are intended to maintain straightness of the line of the crack front within it. The slow rate of increase of the loading force in the actual test is often specified. Test specimen temperature is one of the independent variables. The magnitudes of the applied force and the deflection of the point of application are measured and recorded. Sometimes the angle or opening distance of the crack are measured and recorded. The electrical resistance of the specimen may be used to give an indication of any advance of the crack or other change in the dimensions of the test component. Fields of increasing stress and strain result within both the machine and the component. Amounts of mechanical energy are stored within the machine and the sample. Most tests are said to be using 'fixed grips', a descriptor implying that the mechanical energy stored in the loading machine is small as compared with the mechanical energy stored in the test specimen during the test, and all mechanical energy stored in the machine is disregarded. Thus test results of applied force and deflection show that as tests proceed beyond the elastic limit, a point of maximum applied force is reached after which the applied force decreases with further deflection. Observations made of advance of the crack tip during the test show that for A533B steel, about two millimetres of crack tip advance occur before the point of maximum applied force is reached. This is described as the 'stable tearing of a critical crack'.

11. In a real component, in which the loading force is applied by the pressure of water at 325 degrees centigrade, and a crack had advanced to the point of maximum strength, any further crack growth would lead to instability, for the force applied would not be reduced as it was by the non-availability of mechanical energy stored in the stressing system of the above described tests.

12. In an infinite area of thin sheet of infinitely strong homogeneous, perfectly elastic material, stressed in tension in one direction uniformly; the introduction of an infinitely thin straight crack of length 2a centimetres perpendicular to the direction of the stress field, disturbs the distribution of stress in its vicinity. Mathematical analysis of this idealised case enables the stress at any point to be determined. Along the line of the crack, within the uncracked material, the tension stress perpendicular to the direction of the crack is inversely proportional to the square root of the distance from the crack tip. Thus it can be seen that the stress at the crack tip in this theoretical example is infinite, and the stress

raising effect of cracks in real materials is explained qualitatively. For this case the 'constant' of proportionality is denoted by a quantity K1 divided by the square root of 2pi. In other cases the value of K1 depends upon the arrangement of the material, the stresses, the cracks, and the properties of the material. K1 is called the 'stress intensity factor'. In reality stressed steel fails progressively near to the tip of a sharp crack. In A533B steel the crack is observed to widen a little at the tip before tearing begins, a process called 'blunting'. In some tests the crack opens a little, and measurements are made of the angle of opening near to the crack tip, (Crack Opening Angle) or the width of the crack at a small standard distance from the crack tip (Crack Opening Displacement). The value of K1 for a given arrangement, at the point where stable tearing commences is called the critical value, denoted by K1c, and safety is said to be assured if this value is not exceeded. However, in the reality of crack growth in service, there would be no physical sign that this was so except for detection of the crack by periodic inspection and the subsequent withdrawal of the vessel from service. Repairs of such defects are an unknown quantity. Provision of new replacement vessels is a possibility. The more worrisome possibility is that operation with a 'stably' growing crack, if it continues for more than two millimetres, will eventually reach the stage at which the vessel wall starts to become weakened by the crack and no longer able to support the pressure load.

13. Historically, pressure vessels have been tested at the start of operation at a test pressure greater than the maximum pressure anticipated in service. It has been demonstrated that such a procedure confers a positive margin of safety between the maximum size of defect which could be present during the successful test without causing failure, and the size of defect which would cause failure during normal service. In the case of the Sizewell 'B' reactor pressure vessel the test pressure used is insufficient to provide any significant degree of such assurance.

14. If the stress applied to the material is not relieved by its failure then the defect is caused to increase in size at a fast speed which rapidly increases to the speed of compressive waves in the steel. This fast ductile failure continues until the supply of energy maintaining the applied stress becomes exhausted at which point 'crack arrest' is said to occur. The properties of the steel at places where permanent deformation or tearing are happening change continuously, its hardness increasing and its remaining ductility decreasing.

15. The phenomenon in which ductile steel pipes, pressurized by gas or vapour pressure, have ruptured by longitudinal through-wall crack propagation of fast ductile failure is far from unknown. (Ref.1) The mechanism of failure is that the speed of propagation of the crack along the pipe is greater than the velocity of sound in the fluid within the pipe, so that the stress applied to the pipe at the instantaneous location of the crack-tip is not relieved by escape of the pressure. Such failures have been arrested by changes in the structure of the pipe, e.g. at joints and flanges, and by change in the properties of the 'over-burden' within which the pipes had been buried. A critical, unstable crack at the belt-line of the Sizewell 'B' reactor pressure vessel, will commence to grow as a shear crack at 45 degrees to the surface, at a linear speed of 3.24 kilometres per second, and after the crack tip has travelled a short distance, the mode will change to cleavage, perpendicular to the vessel surface, and with a linear speed of 5.89 kilometres per second, which is the velocity of compressive waves in A533B steel. The velocity of sound in the reactor coolant at the inlet temperature of 225 is 1.2 kilometres per second. Once the crack has become unstable, and started to propagate in either ductile mode, then it will not stop running until the vessel has been effectively dismantled (Ref. 2). The time for the crack tip to traverse the circumference of the vessel at the belt-line is about 1.5 milliseconds. The mechanical energy absorbed by the creation of crack surfaces as the crack progressed once round the vessel is only about one percent of the energy available in the hot water. Once the structural strength has been removed by fast ductile crack propagation, the acceleration of the vessel fragments due the continuing exertion of the internal pressure is about one hundred times the acceleration due to gravity. The lateral gap between the pressure vessel and the concrete housing is only a few inches. The direction vertically upwards is virtually unrestrained. The mechanical energy equivalent stored in the hot water in the reactor pressure vessel, and which would be released before the pressure had fallen from 2000 to 100 psi, is about the same as four tonnes of TNT. If a one third part of the reactor vessel, weighing 150 tonnes, absorbed one third part of this pressure energy, then it would have sufficient upwards momentum to rise freely more then 300 metres above the point of projection. Loss of energy penetrating the containment building would not be significant. It is quite possible that such an event would be accompanied by a reactor power surge generating more than the usual heat output, as any control rods remaining attached to

the upper-vessel moved upwards with it. The Sizewell 'B' nuclear power station is provided with what the Nuclear Installations Inspectorate calls 'defence in depth', and 'multiple independent barriers' to prevent the escape of fission products from the reactor fuel into the environment. All of this is swept away and made absolutely ineffective by this event. The consequences would be Chernobyl transformed to Western Europe.

16. The design principle of the Sizewell 'B' reactor pressure vessel is that the pressure induced stress present within the pressure vessel wall is less than the yield stress, so that all of the ills that pressure vessels are prone to can be surely and safely controlled. The questions arise 'what defects have been found?' and 'How do we know that they are safe?'. The answers to these questions are, wrongly, kept secret from public knowledge.

17. During operation the Sizewell 'B' reactor pressure vessel temperature is sufficiently high to ensure ductile behaviour and the internal pressure is 15.5MPa - failure, even when pressurized, cold, does not constitute a long range hazard. Expensive though. Considerable resources have been expended on the avoidance of brittle fracture.

18. In the case of Sizewell 'B', it is said by the HSE that the probability of explosion is one in one million per year from all causes, with the reactor pressure vessel contributing just one tenth of that,(Ref.3). That is to say, one in ten million per year. Can this figure be substantiated?, and if it can be, is it safe enough?

19. The number of reactor pressure vessels in the world is about five hundred and they have been operating for about twenty years, making a total of experience of ten thousand vessel years; without a single catastrophic explosive failure so far. If we make the usual statistical assumption of ninety-five percent confidence, then this experience provides a reliable assurance that the catastrophic explosion rate is less than one in one thousand reactor years, or thereabouts. Not one in ten millions.

20. Government Special Case Procedure. The Sizewell 'B' nuclear power station is licensed by the Health and Safety Commission, Health and Safety Executive, Nuclear Safety Department, Nuclear Installations Inspectorate, (Ref.4). This organization has provided itself with Safety Assessment Principles (Ref.3) which it uses to

determine issues of large scale safety which it encounters during its licensing activities. For the most part these safety assessment principles are logical and well founded. However, when cases are encountered which can be neither justified nor denied, resort is made to a 'special case procedure'. The sense of the current version is as follows:-

"Special Case Procedure

A8.9 There are components in a nuclear installation whose safety is difficult to demonstrate in such a way as to readily satisfy the accident frequency requirements of the SAPs, the reactor pressure vessel of a pressurised water reactor being an example. This possibility is catered for in the SAPs by having a principle that allows for such items to be justified on a special case basis and this route has been used on a number of occasions.

A8.10 The two particularly important safety aspects to be addressed are that: the structure is as defect free as possible; and a demonstration that the structure is defect tolerant. In order to achieve this, several related but independent arguments must be used. For example, the arguments could include a demonstration that:

{ sound design concepts and proven design features have been incorporated;

{ potential failure modes have been analysed;

{ proven materials have been used;

Rev. 3 194

{ there has been a high standard of manufacturing;

{ a high standard of QA has been applied;

{ the component has been the subject of pre-service inspection, and will be the subject of in-service inspection, to detect defects at sizes below those which have the potential for causing or developing into a failure mode;

{ provision is made for in-service plant and material monitoring; and

{ a leak-before -break safety case has been made.

A8.11 Where the special case procedure is applied, or where any safety system is required to achieve a high reliability, the licensee has an independent assessment of the item carried out."

This means that the originating industry has done the best that can be expected of it, and that will have to do.

21. DUTY. The Health and Safety at Work Etcetera, Act, 1974, (Ref.5). Under "General duties":

"2. (1) It shall be the duty of every employer to ensure, so far as is reasonably practicable, the health, safety and welfare at work of all his employees."

And:

"3. (1) It shall be the duty of every employer to conduct his undertaking in such a way as to ensure, so far as is reasonably practicable, that persons not in his employment who may be affected thereby are not thereby exposed to risks to their health or safety."

Which leads us to:-

22. As Safe As Is Reasonably Practicable

In 1949, in Edwards v National Coal Board (Ref.6), which was an action for compensation for the death of a worker who was killed whilst at work, Lord Justice Asquith decided that:

"a computation must be made by the owner in which the QUANTUM of risk is placed on one scale and the sacrifice involved in the measures necessary for averting the risk (whether in money, time or trouble) is placed in the other, and that, if it be shown that there is a gross disproportion between them - the risk being insignificant in relation to the sacrifice - the defendants discharge the onus upon them. Moreover this computation falls to be made at a point in time anterior to the accident. The questions he has to answer are, firstly, what are the measures necessary and sufficient to prevent any breach, and secondly, are these measures reasonably practicable."

23. RISK. In the case of Regina vs Board of Trustees of the Science Museum, 1993, (Ref.7) the Court of Appeal ruled that as far as the use of risk in the Health and Safety at Work Etcetera Act, section 3 was concerned, this should be interpreted as conveying the 'idea of a possibility of danger'.

'The starting point must be the ordinary meaning of the language of section 3(1). In our judgment the interpretation of the prosecution fits in best with the language of section 3(1). In the context the word 'risks' conveys the idea of the possibility of danger. Indeed, a degree of verbal manipulation is needed to introduce the idea of actual danger which the defendants put forward. The ordinary meaning of the word 'risks' therefore supports the prosecution's interpretation and there is nothing in the language of section 3 or indeed in the context of the Act, which supports a narrowing down of the ordinary meaning. On the contrary the preventive aim of sections 3, 20, 21 and 22 reinforces the construction put forward by the prosecution and adopted by the judge. The adoption of the restrictive interpretations argued for by the defence would make enforcement of section 3(1) and to some extent also of sections 20, 21 and 22 more difficult and would in our judgment result in a substantial emasculation of an essential part of the Act of 1974. The interpretation which renders those statutory provisions effective in their role of protecting public health and safety is to be preferred.

We have not lost sight of the defence submission that we ought to concentrate on the word 'exposed' rather than 'risks' in section 3(1). If the word 'risks' has the meaning which we consider it has, the point disappears. In that event exposure to a possibility of danger is sufficient. The word 'exposed' simply makes clear that the section is concerned with persons potentially affected by the risk… But the word 'exposed' cannot change the meaning of 'risks' from a possibility of danger to actual danger. On the principal points in this case the argument for the defence is really a red herring.'

24. INDIVIDUAL RISK. Individual risk is therefore the idea of the possibility of danger to the individual. Danger involves both the chance of harm and some measure of immediacy. We learn to perceive dangerous situations in everyday life, and we adjust our behaviour so as to control or avoid the risks which we know about. Danger is almost everywhere. In controlling risk from nuclear power stations the nuclear regulator concerns itself only with the fatal outcome to the individual. Bands of risk are defined in terms of values of the chance of an individual being killed.

25. MAXIMUM TOLERABLE RISKS. The Health and Safety Executive statement on the Tolerability of Risk (Ref.8 page 46) states that: "The maximum tolerable risk to workers should not exceed 1 in 1000 each year. The maximum tolerable risk to any member of the public from any large industrial plant should not exceed 1 in 10,000 each year but with a benchmark figure for any new nuclear installation of 1 in 100,000 each year. For accidental risks, the risks for both normal operation and accidents taken together, then the risk for most people in the vicinity of a nuclear installation would be at or near 1 in 1,000,000 each year." In the case of the Sizewell 'B' nuclear power station, no proof was provided that these rules had been, or were ever likely to be enforced.

26. NUCLEAR INSTALLATIONS ACT 1965 (NIA) (Ref.4) Liability of site operator Section 7 of the NIA imposes a basic obligation on every holder of a nuclear site licence. It requires the licensee to ensure that no occurrence on the site involving nuclear matter causes (a) injury to any person or (b) damage to any property except that of the licensee. The liability is absolute: a person who has suffered damage need not establish any fault or negligence on the part of the licensee.

27. The Chernobyl Reactor Explosion On the 12th April 2005 the United Nations News Service (Refs.9,10&11) reported that: "Nearly 8.4 million people in Belarus, Ukraine and Russia were exposed to radiation when the Chernobyl plant in Ukraine blew up. Beyond the cancers and chronic health problems, especially among children, some 150,000 kilometres - an area half the size of Italy - were contaminated, while agricultural areas covering nearly 52,000 square kilometres, more than the size of Denmark, were ruined."

28. The Cost of the Chernobyl Reactor Explosion: Estimates of the total costs of the Chernobyl accident range between £6 Billion and £200 Billion (Ref.12), which may be compared with the maximum total of compensation payable under United Kingdom legislation of three hundred million 'Special Drawing Rights' (a unit of account used by the International Monetary Fund worth about one euro) Even if this amount had been paid out in response to the minimum estimate of possible claims, there would have been a shortfall of more than ninety five percent. By comparison with the total of possible claims for the more realistic maximum, the compensation available would be almost negligible. Worse, a lawyer's opinion (Ref. 9) indicates that the proof of causality of ill health and death is notoriously difficult to establish in court. The extent of physical harm may not become apparent for decades and when cancers do appear they may be indistinguishable from cancers with other causes.

29. And it is clear that: "The following losses were not covered by the Paris/Vienna Conventions or the Nuclear Installations Act 1965 at the time of Chernobyl and remain uncovered today:

- The costs of precautionary ,preventive or protective measures (e.g. evacuations,relocations, radiation monitoring, medical expenses, emergency service costs, food marketing and consumption restrictions, loss of agricultural goods;
- Economic losses consequent upon the occurrence but not consequent upon specific damage to claimant's property or person;
- The cost of damage to the wider unowned

environment;
· Economic loss or loss of profit as a result of contamination to the wider (unowned) environment (e.g. tourism);
· Decline in property prices;
· The cost of cleaning up contaminated land;
· Psychlogical damage.
Modernising the liability regime would involve:
· explicit provision for all these heads of damages including damage to the environment and natural resources;
· abolishing any time limit for bringing claims given the very long periods that can run before impacts manifest themselves;
· accepting mere exposure to a radiological hazard as the basis for statutory liability;
· defining clearly the level of contamination sufficient to constitute "damage";
· specifying clearly how in the event of insufficient funds, funds are to be distributed as between e.g. early and late claimants, those severely injured and those with property damaged;
· obtaining and retaining (claimants') access to appropriate lawyers, scientific experts, technologists over perhaps a period of fifteen years for a complex law suit;
· equipping courts to deal well with possibly thousands of claimants, as well as with complex scientific and technical evidence, and so as to avoid disagreement over claims."

30. It is quite clear that in the event of an explosion of the Sizewell 'B' reactor pressure vessel, the consequences would be on a comparable scale to those at Chernobyl and the persons affected would be massively disadvantaged. As is the case with those affected by the Chernobyl event.

31. THE UNITED KINGDOM GOVERNMENT'S WORDS ON RISK Her Majesty's Treasury - Green Book (Ref.13)
In recent years the United Kingdom government has required all government departments to apply managerial techniques to the control of all of the risks which may accompany their activities. In order to achieve this aim the government has caused the Treasury Department to provide a comprehensive guide to risk assessment and control, called 'The Green Book'. It says: "The purpose of the Green Book is to ensure that no policy, programme or project is adopted without first having the answer to these questions:

· Are there better ways to achieve this objective?

· Are there better uses for these resources?"

An example of the kind of measures imposed can be found at Annex 4, where Her Majesty's Government/Treasury requires the keeping by each Department of a RISK REGISTER or RISK LOG, as follows:

"BOX 4.1: RISK REGISTER (RISK LOG)

PURPOSE
A risk register lists all the identified risks and the results of their analysis and evaluation.

Information on the status of the risk is also included.The risk register should be continuously updated and reviewed throughout the course of a project.

CONTENT

A risk register is best presented as a table for ease of reference and should contain the following information:

.Risk number (unique within register);

.Risk type;

.Author (who raised it);

.Date identified;

.Date last updated;

.Description;

.Likelihood;

.Interdependencies with other sources of risk;

.Expected impact;

.Bearer of risk;

.Countermeasures; and

.Risk status and risk action status."

The entries made by the Health and Safety Commission in this log relating to the risk of explosion of the Sizewell 'B' reactor pressure vessel are as follows:

(Ref. 14) "No relevant records can be located"
Thus, it would appear that either the treasury directive is ignored in this respect, or the

entries are hidden from public view, like the cracks in the pressure vessel.

32. In a PWR, the reactor core fuel elements require to be renewed from time to time necessitating the removal and replacement of the top lid of the reactor pressure vessel. This lid is penetrated by a number of short steel tubes fitted into holes cut in the lid and sealed by welds on the inside of the lid. During operation the reactor control rod drive machines are fixed to flanges at the tops of these tubes. At a PWR in Ohio, USA (Refs.15,16&18) from time to time the tops of some tubes were found to be out of alignment and had to be 'bent' back into shape. This went on for several years until in 2003 one of these tubes 'fell over'. By this time the full thickness of the low alloy heat treated steel of the top dome had been corroded away, leaving just a few millimetres of internal stainless steel 'cladding' to carry the pressure load of the hot reactor water. Reactor coolant had been leaking continuously for several years, and the dissolved boric acid had corroded the full eight inch thickness of the steel lid away over an area of about thirty square inches. A subsequent assessment by the US nuclear regulators of the likelihood of failure in these circumstances (Refs.15&16) concluded reassuringly that the safety of that reactor vessel against explosion was not prejudiced. However, it is clear evidence that unless a leak of reactor coolant was so large that operation could not continue, then it has been ignored (Ref.17).

33. When it was realized that nuclear weapons tests in the atmosphere had produced measurable radioactive contamination of the entire atmosphere of the northern hemisphere, the decision was made to discontinue them. Weapons tests continued, of course, but underground. A kilometre or two down below the surface. And the resulting additional discharges of radioactive material into the atmosphere above ground were thereby very much reduced. So that, in the light of such knowledge, effective containment of a reactor pressure vessel explosion is quite clearly practicable, but is it reasonably practicable? And there are doubtless other practicable ways to contain the explosion of a reactor vessel effectively, which might be proven and evaluated?

34. SOCIETAL RISK: The effective containment of the reactor pressure vessel explosion is clearly a "measure for averting the risk", and the costs of that sacrifice can be ascertained. The QUANTUM of risk is now the total sum value of lives lost or foreshortened; disabilities and incapacitations; property denied, livelihoods

lost; a myriad of irreversible consequential losses. Can we be sure that the undoubted and generally accepted possibility of explosion of the Sizewell 'B' reactor pressure vessel is a risk to which the Health and Safety at Work Etcetera Act 1974 applies?

35. The risk of the Sizewell 'B' reactor pressure vessel explosion is clearly that same kind of risk, as was referred to by Lord Justice Asquith, and quoted above. That risk must include all of the consequences, and not just the effects on a single imaginary individual. We are all exposed to the risk of Sizewell 'B' exploding, no matter what causes it.

36. In the Sizewell 'B' Inquiry Transcript Day 65, page 48, at G, when asked if the CEGB had included in their cost evaluation of the UKPWR nuclear power station, any element representing the contribution anticipated from reactor accidents, Mr J W Baker replied "No".

37. It seems inconceivable that the cost of a nuclear power station would even be doubled by the cost of a demonstrably effective explosion containment. The additional sacrifice seems trivial in comparison with the quantum of risk that we have recognized in the other scale pan. Indeed, for it to be shown that there is a gross disproportion between them - the risk being insignificant in relation to the sacrifice - a huge margin of additional cost yet remains. And this is not guesswork. In terms of scale, the accident has happened; and even if the upper estimate mentioned above is reduced one thousand fold (and it cannot be that far wrong!) this is still true. During the Sizewell 'B' public inquiry, I heard it said by a leading protagonist that "We cannot possibly accommodate as safe as reasonably practicable." And so it came to pass.

List of References

1. B.N.Leis & R.J.Eiber, Fracture Propagation Control in On shore Transmission Pipelines, Onshore Pipeline Technology Conference, Istanbul, December 1998, pp. 2.1 - 2.35

2. B. Banerjee, Material Point Method Simulations of Fragmenting Cylinders. 17th ASCE Engineering Mechanics Conference, June 13-16, 2004, University of Delaware, Newark, DE. EM2004

3. Health and Safety Commission; Health and Safety Executive; Nuclear Safety Department; Nuclear Installations Inspectorate; Safety Assessment Principles for Nuclear Plants 2000.

4. Nuclear Installations Act 1965

5. Health and Safety at Work Etcetera Act, 1974.

6. Edwards v National Coal Board 1949

7. Regina v Board of Trustees of the Science Museum 1993

8. Health and Safety Executive, Reducing Risks, Protecting People - HSE's Decision Making Process. December 2001.

9. the United Nations News Service 12th April 2005

10. UNSCEAR Exposures and Effects of the Chernobyl Accident, ANNEX J, Report to the UN General Assembly

11. Economics Institute of the Belorussian Academy of Sciences, April 24th, 2002, Reported by Financial Times April 24th, 2002.

12. J.K. Woolley. Report on the Legal Liabilities for Civil Plutonium Accidents. Oxford Research Group, June 2000.

13. H.M.Treasury, The Green Book, Appraisal and Evaluation in Central Government, 2003.

14. letter from HSE

15. P.T.Williams & B.R.Bass, Structural Assessment of a Corrosion Degraded Reactor Pressure Vessel Head. Paper # D03-5, Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (SmiRT 17), Prague, Czech Republic, August 17-22, 2003.

16. W.H.Cullen, NRC Response to the Davis-Besse Head Degradation Event. 2004

17. Materials and Metallurgy Sub Committee, USNRC, 11545 Rockville Pike, Room T2-B3, Thursday September 21, 2000, Unedited Transcripts of Recorded Discussion.

18. H.Werdine, Pro-Active Safety Management Strategies Related With The Operating Experience Process, IAEA, Beijing, 18-22 September 2004.

19. L.Xia, C.F.Shih, J.W.Hutchinson, A Computational Approach to Ductile Crack Growth Under Large Scale Yielding Conditions. J. Mech. Phys. Solids. Vol.43, No.3, pp.389-414. 1995.

 Mark Wallaceâ€™s recovery of the bird-God of the Bible signals a deep grounding of faith in the natural world. The moral implications of nature-based Christianity are profound. All life is deserving of humansâ€™ care and protection insofar as the world is envisioned as alive with sacred animals, plants, and landscapes.