ON THE ELUSIVENESS OF LOW PROBABILITIES OF NUCLEAR PRESSURE VESSEL FAILURE

Gustaf Östberg, University of Lund, Sweden

ABSTRACT

Since the 1970s, the probability of catastrophic failure of the main pressure vessel of nuclear reactors of the light water type has been assessed on the basis of probabilistic fracture mechanics. Figures for the probabilities ranging from 10^{-8} to $6 \cdot 10^{-5}$ per reactor year have been calculated. No confidence limits or uncertainty ranges have been determined, and doubts have been voiced about their relevance from various point of view. While the figures in question are low, the consequences of a catastrophic failure are enormous, which implies that the associated risk is very large indeed and warrants serious consideration. The difficulties of dealing with this risk and its uncertainties with respect to psychological and philosophical aspects are reviewed with particular attention to societal decision-making. Suggestions are made for possible means of resolving at least parts of the present dilemmas, with particular emphasis on cognitive and organizational aspects.

THE TECHNICAL ISSUE

The main pressure vessel of the common types of light-water reactors, which contains the core with fuel elements, is a critical component with respect to accidents leading to massive release of radioactivity promptly and directly into the atmosphere. Therefore, the probability of a catastrophic of this vessel has been a subject of great concern in nuclear safety analyses and assessments.

In the early days of the development of light-water reactors, the assessment of the probability of pressure vessel failure was based on experience gained in non-nuclear pressure vessel technology. The same was true for the probability assessment in the Rasmussen study of 1975 [1]. At that time, however, the first calculations using probabilistic fracture mechanics had already been published in 1973 [2].

The reason for the introduction of the latter method was the fact that no disruptive failures of nuclear pressure vessels had occurred, which might otherwise have contributed to a base for regular frequentistic assessment of the probability. Instead, by means of probabilistic fracture mechanics information about the statistical distribution of the presence of cracks, mechanical stresses, and properties of the pressure vessel steel,could be utilized for failure probability calculations.

In the Rasmussen report, the numbers quoted for the probability are, in figures per reactor year, a median value of 10^{-7} with 10^{-6} as a lower bound [1]. In a subsequent review in 1977, these numbers were criticized for being based on an unconfirmed assumption that the failure probability for non-nuclear vessels should be divided by a factor 100 to be applied to nuclear vessels because of the higher standards of the latter with respect to design, fabrication testing and inspection [3]. According to this estimate, the probabilities in question should thus be 10^{-5} and 10^{-4} respectively, without making any allowance for an assumed higher quality.

In sum, the reported results of probabilistic fracture mechanical calculations of nuclear pressure vessel failure are as follows:

$2 \cdot 5 \cdot 10^{-8}$	[2]	(1973)
10^{-8} - 10^{-6}	[4]	(1976)
$1 \cdot 2 \cdot 10^{-7}$ - $6 \cdot 10^{-5}$	[5]	(1977)
$6 \cdot 10^{-7}$ and $9 \cdot 10^{-8}$	[6]	(1987)

At this point a caveat might be warranted about differences between pressurized and boiling water reactors, i.e. PWRs and BWRs respectively, concerning probabilities and consequences of pressure vessel failure. Of the probability figures referred to above, the first [2] does not relate to any specific type of reactors. The second and fourth [4] [6] are valid for PWR and the third [5] for BWR. As regards consequences, it is usually assumed that pressure vessel failure of a BR does not produce projectiles of a capacity sufficient to cause a break of the reactor containment. For PWRs a probability of 10% is postulated for the latter consequence that is to be considered in the following.

Although these figures are low, they are still to be considered important because of their implications for assessing the associated risk, taking into account the catastrophic consequences of extensive dispersal of radioactivity. Hence it is of general interest to examine the reported failure probabilities with respect to their validity for assessing the magnitude of the risk in question.

Admittedly, this survey of the literature commonly referred to on data for the probability of nuclear pressure vessel failure is somewhat schematic. For the sake of completeness it could therefore be warranted to mention that improvements have lately been made in the probabilistic fracture mechanics methodology [7] However, it appears to be impossible to draw any precise conclusions indicating that the justification of using the data in question for the present purpose might be doubted.

INDETERMINATE PROBABILITIES

One obvious feature of the probability figures reported above is the fact that they vary considerably. In principle, this can be assumed to be due to differences in data, models, and methods of calculation. Apparently, no comprehensive analysis of this aspect of the discrepancies has been made. On the other hand, it should be mentioned for the sake of completeness that general categorical objections have been raised against calculations of low probabilities [8][9]. Likewise, the evaluation of certain statistical data for crack propagation has been criticized [10][11][12]. Attention has also been called to the possible occurrence of non-homogeneities of the steel, which may affect the statistical distribution of its properties [13] [14] [15] .

However, such issues do not seem to require detailed considerations in the present review with its indicated aim. More important here is the scarcity of accounts of failure probabilities in terms of confidence or uncertainty ranges. There is only one case with an explicit notation of what is called error spread [1] and another one expressing the result as a range for the probability [4].

This default gives rise to two problems in the application of the reported probabilities for the assessment of the associated risk. In the event that it is deemed justified to use a more conservative probability value than the ones resulting from the probabilistic calculations, this would not give any guidance since it would lack more or less explicit notations of statistical confidences. Furthermore, this would also mean that no critical comparison can be performed between all the reported probabilities with respect to statistical confidence or uncertainty ranges.

Coupled to the differences in the results of the various calculations commented upon above, this deficiency with respect to confidence can, in a general sense, be expected to increase any conceivable uncertainty about their application for risk assessment. Clearly, this creates a particularly serious dilemma for those who have to consider this safety issue from a societal point of view in their capacity of decision-makers evaluating the use of nuclear power.

EXPERIENCES OF LOW PROBABILITIES

With the aim of enhancing our understanding of the nature of the prevailing uncertainty about the confidence and the reliability of low probabilities of nuclear pressure failure, an attempt has been made to search for analogies in other fields where frequentistic analyses might possibly be performed. It was assumed that there might be cases where probabilistic predictions of low probabilities may be compared with the actual outcome.

One example illustrating such an option was supposed to be experimental genetics, where large populations of drosophilia are used. To this end, an inquiry was made among several statistics specialists with extensive experience in various similar fields. Unfortunately, none of them could provide any cases at all.

Eventually, an expert on computer technology was approached on the assumption that the manufacture of circuits containing large numbers of chips and contacts may yield correlations between predicted failures due to defects comparable with those of concern in nuclear pressure vessels. It turned out that similar phenomena are indeed not uncommon. However, their occurrence does not seem to have received statistical consideration. They are simply remedied by application of special repair programs.

In this connection, a comment on a particular mode of reasoning about the predicted probabilities of nuclear pressure vessel failure may be warranted. It is sometimes argued that there is now sufficient experience in terms of time of operation of reactors to indicate that the probability numbers quoted are too conservative. Given, for instance, a probability of 10^{-4} per reactor year, an assumed experience of 10,000 years of operation without failure is enlisted to justify the conclusion that the probability in question is lower than 10^{-4}.

With a gross understatement it does not seem impertinent to say that such a statement is not compatible with common views of probability and hazard. Nevertheless, it is voiced surprisingly often, even by people whose position is such that they might be expected to know better.

PRAGMATIC DECISION-MAKING

When applied to practical cases in real life, calculations and evaluations of probabilities are connected with considerations of various implications, among other things in terms of the value of the associated risks. This aspect is, in fact, also recognized by safety experts when analysing current methods of dealing with such seemingly unequivocal issues as statistical distributions. One example of this is the following statement about such evaluations: "... if the question is motivated by safety considerations, greater weight would have to be given to the conservative, more pessimistic estimates [16]."

In principle, it should be justified to adopt this attitude to the probabilistic procedure as a whole. Thus the choice of a single particular number for the failure probability within an established confidence or uncertainty range would be made with due reference to the safety issue.

In the case of a catastrophic failure of the main pressure vessel of a nuclear reactor, the most severe consequence is, of course, the effects on people subjected to the massive dispersal and fallout of radioactivity following the failure of the vessel. The consequences include not only fatalities,' but also injuries and various kinds of long-term health impairments.

The losses of property and invested capital in material goods and establishments are more accessible for quantification. Such estimates have been made for a number of cases in various countries, using different assumptions, methods of calculation and principles of predicting depreciation of worth. In the present review, it might suffice to cite one study focused on what has been called the "worst case scenario" for the Biblis nuclear power plant in Germany. The result of this estimate was a predicted loss of the order of USD 6,800 milliard (USD$\cdot 10^9$) [17].

As could be expected, the publication of this estimate has given rise to a debate about the relevance of its magnitude. It could be added that certain amendments have later been made of the methodology of dealing with issues related to risk aversion with respect to external costs of a nuclear accident [18]. However, the present considerations are more narrowly defined that in these studies. Hence the figure referred to above is only an indication of the scale of the economic consequences of the worst catastrophe involving a light-water reactor.

In particular, this point is made in order to call the attention to a tendency in some quarters to dismiss risks with a low probability, disregarding their consequences. Apparently, this attitude is an application of the "de minimis" principle, implying that there is a limit below which no concern is warranted [19]. However, it seems that in the present case it is only the probability aspect of the risk that is taken into account and not the consequences.

Inversely, there is another criterion that can be used as an argument against the acceptance of the risk in question, namely that its consequence is such that it must be completely avoided by simply closing down the reactor, disregarding all the costs involved. Actually, this is the position sometimes taken by political decision-makers when they consider pressure vessel failure from the point of view of consequence rather than probability.

In decision-making about risk, there is also another alternative principle that may be applied, namely that of "cost-benefit". This means that a proposal is accepted if its assumed advantages exceed the anticipated disadvantages. In the present context, this would be the benefit of avoiding the risks involved in operating a reactor by closing it down before the end of its life expectancy as compared to the loss of the investments in the installation as utilities may claim.

Let us assume, for the sake of the argument, that the costs in terms of property values as a consequence of a catastrophe caused by a disruptive failure of a reactor pressure vessel are of the order mentioned above, i.e. USD 6,800 milliard. For the failure probability, the highest single number reported, $6\cdot 10^{-5}$, will be chosen with no allowance for any uncertainty range but with a 10 % reduction in order to take the probability of a break of the reactor containment, as a consequence of a pressure vessel failure, into account, i.e. $6\cdot 10^{-6}$. For the remaining years of reactor operation, a figure of 35 will be used.

Based on these admittedly eclectic assumptions, the worth of the risk in question is calculated by multiplying the indicated data, resulting in an estimate of the order of USD 1,4 milliard. This figure is within the range of the loss estimated for the capital invested in the first reactor closed at the Barsebäck nuclear power plant in Sweden, namely between USD 1 and 3 milliard. Obviously, the "cost-benefit" criterion for closing down one reactor at Barsebäck would be satisfied.

Finally, it should be pointed out that the benefit and the cost belong to different financial domains and budgets, which makes it complicated to compare them from the societal points of view.

It is, of course, even more relevant for society to take other kinds of risks and consequences of a reactor catastrophe into account. Among other things, the closing down of a reactor results in the risk of a serious shortage of electricity if no replacement is provided.

Hence, in the end it appears that an intellectually irresolvable conflict between the various parties involved is inevitable with respect to all the different aspects of a catastrophic pressure vessel failure. Consequently, in this situation it should be of interest to examine the common ways and means of coping with this kind of decision-making problems.

COGNITIVE CONDITIONING

Obviously, the issue of low-probability nuclear pressure vessel failure is not limited to the statistical, technical and economic aspects considered so far in this review. There are also conceptual and mental problems in dealing with risks that render decision-making difficult.

The mathematical expression of risk as the product of probability and consequence is obviously simple as such but mentally, risk is apparently difficult to apprehend as a unified concept. Interviews with professional decision-makers about low-probability risks with large consequences have shown that it is only rarely that their thinking takes both probabilities and consequences into account at the same time [20].

A similar effect influencing the thinking on risk is so-called "thought style". This psychological and philosophical conditioning determines in what manner certain problems may and should be dealt with in particular contexts by parties representing different scientific ideologies, as it were [21].

These mental and conceptual determinants for dealing with risk in general also influence the consideration of the mentioned uncertainties of both the fracture mechanical calculations of probabilities and the assessment of the associated consequences of a catastrophic nuclear pressure vessel failure. Most of these uncertainties are likely to defy clarification in a statistical sense. Therefore, decision-makers concerned with reactor safety have to accept the present state of knowledge about the risk in question.

In principle, the knowledge thus available is accessible to everybody. However, according to cognitive psychology, each individual is selective in the attention he or she pays to various parts of it. In psychological terminology this phenomenon is dealt with in terms of "perspective". In philosophy, the corresponding concept is "perspectivism" [20].

The principle of perspectivism claims that people's world views are determined by their respective perspectives. That individualization is complemented with the personal values attached to what is included within the perspectives.

Clearly, all these cognitive conditions are applicable to the apprehension of the risk of catastrophic failure of nuclear pressure vessels. Therefore, in particular in view of its non-technical associations, a wide variety of individually different opinions and standpoints have to be taken into account. This calls for considerations of possible means for dealing with such a diversity in a social context.

MODES OF SOCIETAL RISK HANDLING

Studies of different cases of dealing with nuclear risks on a national level in a number of countries have shown that a definition of the issues in question at an early stage is a prerequisite for a successful process [22]. Mutual recognition between parties of different opinions is necessary for avoiding a stale-mate whereby opponents limit themselves to arguing in terms of their respective negative and positive opinions only.

Furthermore, crucial for progress in balancing the different views is a certain flexibility of the organizations involved. Experience of reconciliation of the interests of opposite parties engaged in environmental conflicts has proved that such an adaptation might be possible to achieve. What is required is a willingness and ability to relax from the usual strictness and stiffness in attitudes [23]. The term "clumsy organizations" has been coined for this behaviour.

In political contexts it has turned out that so-called "muddling through" is a successful means of avoiding more or less violent confrontation between extreme parties [24]. Per definition, this is naturally the opposite of dialectics and contrary to a revolutionist approach. In principle, it is a way of attaining one's ends by not referring in the first place to one's own interests in an obvious manner but instead meeting opponents at a point somewhere in the middle between the extremes.

This is illustrated by the difference between countries that have been successful in stifling major internal conflicts and those that have not, for instance New Zealand and Australia as opposed to Argentina and Uruguay. One conspicuous feature of "muddling through" in such cases is the ritualization of adversity or latent conflicts in order to prevent fighting to the bitter end, as it were. This might possibly be feasible also in dealing with such issues as nuclear safety.

CONCLUSION

The fracture mechanical calculations of the probability of a catastrophic nuclear pressure vessel failure suffer from uncertainties that make the results debatable as a basis for assessing the associated risk. This dilemma is serious in view of the enormous consequences of a failure.

Against this background, the estimated risk is an appropriate subject of critical considerations in a wide perspective by both individuals and decision-makers. In order to take into account the interests of those affected by a failure, there is a need to regard the technicalities in a societal context. In such an evaluation it is necessary for all parties involved to be aware of the fact that their points of view are interrelated.

This means, among other things, that isolating a certain aspect for separate examination in a reductionist sense may eliminate essential characteristics due to the loss of coherence with otherwise connected parts of the comprehensive perspective. Accordingly, the different partial perspectives should not be separated from each other but regarded as parts of a whole.

It would then appear that a holistic appreciation of the complex in question might be achieved by applying a kind of systems concept. However, there are certain cognitive structural features of the phenomenon to be considered that are likely to make such an approach illusory [25]. Therefore, it must be concluded that low probabilities are elusive in the present context.

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