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ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

THE USE OF ECONOMIC CRITERIA IN PROVIDING A BASIS FOR SAFE REACTOR OPERATION

L'EMPLOI DE CRITERES ECONOMIQUES POUR L'ASSURANCE D'UNE BASE D'EXPLOITATION SURE DES REACTEURS

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THE USE OF ECONOMIC CRITERIA IN PROVIDING A BASIS FOR SAFE REACTOR OPERATION

John Graham

Prepared for the
International Atomic Energy Agency
Technical Committee
on the use of Probabilistic Criteria.

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RÉSUMÉ

Les critères probabilistes basés sur une mesure acceptable de protection de l'investissement des propriétaires de centrales nucléaires, peuvent compléter les divers critères probabilistes de conception qui existent entre ceux déterminés par la sécurité publique acceptable et ceux déterminés par la fiabilité acceptable d'exploitation de centrales.

Habituellement, du côté de la gamme de risques où les conséquences sont insignifiantes et la probabilité est forte($>10^{-2}$/an), un ordre convenable prévu d'exploitation et de maintenance conjugé à la redondance conçue pour permettre la maintenance préventive en direct, les essais périodiques appropriés et le contrôle de la qualité, assurent la conformité aux critères règlementaires de réduction des risques d'exploitation normale à des niveaux faibles.

D'autre part, du côté où les conséquences sont importantes et la probabilité est faible ($<10^{-4}$/an), plusieurs niveaux de protection, la redondance et diversité des systèmes de sûreté, le confinement, l'isolation et les procédures d'intervention d'urgence, permettent à l'installation de faire face à des évènements graves sans qu'il y ait de risques pour le public et l'environnement.

Entre ces deux côtés, dans la marge de probabilité de 10^{-2}/an à 10^{-4}/an, c'est la protection de l'investissement des propriétaires qui devrait conduire à la nécessité d'empêcher les longs arrêts de réacteurs et le remplacement d'éléments de centrales chers. On peut protéger l'investissement en prévoyant des marges de tolérance d'usure et de détérioration, une réduction de la puissance linéique du combustible pour assurer une marge de température et d'écoulement complémentaire dans les échangeurs de chaleur et générateurs de vapeur ainsi qu'une marge complémentaire dans l'appareillage principal. On peut exprimer les critères de conception nécessaires en critères probalilistes

Les critères qui intéressent la protection de l'investissement des propriétaires ont l'avantage de réduire les risques dans les zones de risque adjacentes en assurant une plus grande sûreté d'exploitation et moins de risques au public et à l'environnement.

On emploie actuellement ces critères de protection d'investissement pour prolonger la durée de vie des centrales mais on pourrait aussi les employer très avantageusement comme partie du processus de conception initial. Dans cette communication, on suggère des critères d'essai intéressant le risque d'arrêt prolongé de centrales et la nécessité consécutive d'acheter de l'électricité de remplacement et le risque de remplacement d'éléments de centrales chers. Il faut un investissement financier supplémentaire pour assurer qu'il y ait une bonne corrélation entre les mesures acceptables de protection de l'investissement des propriétaires et les niveaux de défense probabilistes suggérés mais on peut employer les critères d'essai proposés comme critères de conception pratiques importants.

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ABSTRACT

Probabilistic criteria based upon an acceptable measure of protection for owner investment can complete the range of design probabilistic criteria between those set by acceptable public safety and those set by acceptable reliability in plant operation.

Typically, at the low-consequence, high-probability (>10^{-2}/year) end of the risk spectrum, suitable planned operation and maintenance sequences coupled with designed redundancy to allow on-line preventative maintenance, suitable periodic testing and quality control, assure that regulatory criteria to reduce normal operating risk to low levels are met.

On the other hand, at the high-consequence, low-probability (<10^{-4}/year) end of the risk spectrum, multiple levels of protection, redundancy and diversity in safety systems, containment, isolation, and emergency procedures, enable the design to accommodate severe events without hazard to the public and the environment.

Between these ends of the risk spectrum, in the probability range of 10^{-2}/year to 10^{-4}/year, it is protection of owner investment which should drive the need to prevent extensive plant shutdowns and the replacement of expensive plant components. Protection of this investment can be accomplished by the provision of margins in wear and deterioration allowances, a reduction of fuel ratings to provide additional thermal and flow margins in heat exchanger and steam generation components, and added margins in structural units. Necessary design criteria can be expressed as probabilistic criteria.

Criteria which address the protection of owner investment have the benefit of lowering risk in adjacent risk regions by providing greater reliability in operation as well as less risk to the safety of the public and the environment.

Such investment protection criteria are currently being used to extend plant life but they could also be used very beneficially as part of the initial design process. In this paper trial criteria are suggested which address the risk of extended plant shutdown with the resultant necessity to purchase replacement power, and the risk of replacement of expensive plant components. Additional financial assessment is required to ensure that there is a proper correlation between acceptable measures of owner-investment protection and the levels of probabilistic defence suggested, but the trial criteria proposed can be used as important practical design criteria.

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INTRODUCTION

Probabilistic criteria based upon an acceptable measure of protection for owner investment can complete the range of design probabilistic criteria between those set by acceptable public safety and those set by acceptable reliability in plant operation.

Typically, at the low-consequence, high-probability ($>10^{-2}$/year) end of the risk spectrum, suitable planned operation and maintenance sequences coupled with designed redundancy to allow on-line preventative maintenance, suitable periodic testing and quality control, assure that regulatory criteria to reduce normal operating risk to low levels are met.

On the other hand, at the high-consequence, low-probability ($<10^{-4}$/year) end of the risk spectrum, multiple levels of protection, redundancy and diversity in safety systems, containment, isolation, and emergency procedures, enable the design to accommodate severe events without hazard to the public and the environment.

Between these ends of the risk spectrum, in the probability range of 10^{-2}/year to 10^{-4}/year, it is protection of owner investment which should drive the need to prevent extensive plant shut-downs and the replacement of expensive plant components. Protection of this investment can be accomplished by the provision of margins in wear and deterioration allowances, a reduction of fuel ratings to provide additional thermal and flow margins in heat exchanger and steam generation components, and added margins in structural units. Necessary design criteria can be expressed as probabilistic criteria.

BACKGROUND

Plant safety design requirements arise directly from the plant mission and operating requirements. Once the mission of the reactor plant has been set, many other, but not all, general safety requirements automatically ensue - they are implicit.

Table 1 lays out the correspondence between the requirements of the plant which lead to design requirements and hence to probabilistic criteria or limits for the entire spectrum of plant design conditions (steady state and transient).

1. Acceptable Operation

Acceptable operation of a base-load power reactor requires continued and uninterrupted reliable power production with a minimum number of outages. The plant design should therefore accommodate the whole duty cycle of transients, as well as the more probable of unplanned events, without damage to the plant, in a manner to maximize full-power days.

If, however, the reactor is an experimental reactor or an isotope producer, the operating cycle and the expected operating conditions are different. The listing of operating duty cycle events is different from that of a power reactor. Nevertheless, the design requirement is the same: that the design will accommodate planned and anticipated events without plant damage while maximizing mission time. In both cases, the transients that form part of the duty cycle have to be accommodated within the planned fuel lifetime and within the design accumulated strain allowances.

The probability of these different conditions ranges from those which are planned with a probability of better than unity per year, to those which are not planned but are anticipated with probabilities ranging to as low as once in the plant lifetime, for 30- to 40-year plants approximately 10^{-2} / year. These events would include spurious shut-downs, sticking valves, unavailable instrumentation, and the like.

The whole safety basis for acceptable operation is one of PLANNING (See Table 1), for a design which minimizes the number of events that challenge operation. Design analysis in the form of Failure Modes and Effects Analyses and Common Mode Failure Analyses reduce the number of unanticipated events to be accommodated within the design margins.

2. Acceptable Public Safety

At the other end of the probability scale, the design must recognize the need to protect the public and the environment in the face of some severe event. Even in the event of severe plant damage it is vital to ensure that the public is safe, and can see that it is safe, by the inclusion of mitigation features to reduce off-site exposures to very small values.

Thus the design will have levels of mitigation (barriers to the release of radioactivity) which are often dependent on whether it is possible for energy to be violently released. Containment barriers, remote siting, emergency procedures, are all elements of design which address this requirement. These protective features are more visible to the public than protection provided within the design for reliable operation.

The events against which this mitigation is provided have frequencies of the order of 10^{-4} to 10^{-6} / year or less. These figures arise from regulatory criteria which have been set, using good judgment, from a series of studies of what activities are acceptable to the general public.[1] Thus they accommodate risk aversion since a reactor system is not as acceptable as a freely chosen personal hazard (like smoking, down-hill skiing, or driving a car). This risk aversion is accommodated within the probability ranges and also by the visibility of the protection provided (for example, remoteness).

Unfortunately, the severe conditions considered generally cannot be reproduced and the design certainly cannot be tested against them. Thus the probability and consequences of these conditions are established by analysis which involves severe accident methodology, the study of conditions peculiar to the accident sequence, and an estimation of the probabilities of different events, conditions, and consequences. Fuel, of course, is not designed to withstand the thermal conditions that could arise in severe accidents.

The whole basis for acceptable public safety is one of JUDGEMENT (See Table 1) of what sequences of accidents are possible and how they might occur and proceed, and of the probabilities of those events.

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1 Chauncy Starr, "*Social Benefit versus Technological Risks*", Science, Vol. 65, September 1969 and "*Testimony on HR 14408 and S2534 Price Anderson Act*", presentation to the Joint Committee on Atomic Energy, Washington, D.C. May 16, 1974.

3. The Middle Range

Having dealt with the high-probability events within normal design through ensuring acceptable operation, and, having, provided overall protection against severe events through ensuring public safety, there is an uncovered middle ground in which bad, but not catastrophic, accidents and conditions fall. This is the frequency range from 10^{-2} to 10^{-4} / year.

In this range, the design is intended to accommodate a number of identified, but unanticipated, conditions that do not result in very major plant damage, of either fuel or component structures, but where continued operation may require re-evaluation and refurbishment.

The International Nuclear Safety Advisory Group (INSAG) recognizes this middle range as being composed of "design basis and complex operating events"[2] which require the protection provided by engineered safety features but which, in the worst cases, might lead to fuel damage, even severe fuel damage. INSAG's report is based on an assumption of the practices in current use. By their omission they recognize that no specific probabilistic criteria exist for events in this category beyond those that arise from their contributions as initiators to events beyond the design basis. These criteria lie within the realm of Acceptable Public Safety.

In terms of U.S. Nuclear Regulatory Commission regulations, the requirements of this middle range fall between those of 10 CFR 20[3] and those of 10 CFR 100[4]. There has always been some difficulty in the derivation of meaningful criteria to guide the design.

The U.S. Clinch River Breeder Reactor Project (CRBRP) did set meaningful fuel design criteria to complete this middle range.

TABLE 2 - CRBRP FUEL CRITERIA

DESIGN LIMIT	FUEL STRAIN	PROBABILITY LIMIT
Normal conditions	0.1%	1/year
Anticipated events	0.3%	$>3.10^{-2}$/year
Unanticipated events	0.7%	3.10^{-2} to 10^{-4}/year
Severe Accidents	coolable geometry	$<10^{-7}$/year

The fuel was designed to a limit of 0.1% accumulated strain during its operational life under normal conditions, and it had the capability of sustaining 0.3% accumulated strain in accommodating anticipated transients. Thus its operational duty cycle was established. These capabilities were confirmed by transient analysis and testing. At the other end of the scale, in severe accident conditions, evaluated to test acceptable public safety, fuel was

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2 *"Basic Safety Principles of Nuclear Power Plants "*- a Report by the International Nuclear Safety Advisory Group, Safety Series No. 75 - INSAG-3, IAEA, Vienna, 1988.

3 Code of Federal Regulations, Title 10, Part 20, *Standards for Protection against Radiation.*

4 Code of Federal Regulations, Title 10, Part 100, *Reactor Site Criteria.*

assumed to have failed at 0.7% accumulated strain, as shown in Table 2, but it was planned that coolable geometry would still be maintained[5].

However, in the middle range of probabilities, the fuel was specifically designed to retain its integrity, although it no longer had useful life. Integrity was marked by numerical criteria - principally by an accumulated 0.7% strain resulting from elevated centerline temperature values or the Critical Heat Flux (CHF), to address, in turn, high reactivity and low flow conditions.

These middle-range design criteria were not extended beyond the fuel to other components of the design. Nevertheless, the fuel strain criteria were very meaningful ones in the design of the stainless-steel-clad mixed-oxide fuel. They were set for reasons of fuel-life economy.

Similar design criteria for other plant components would be appropriate.

The greatest real financial risk for the operating plant occurs in this middle range of probable events.

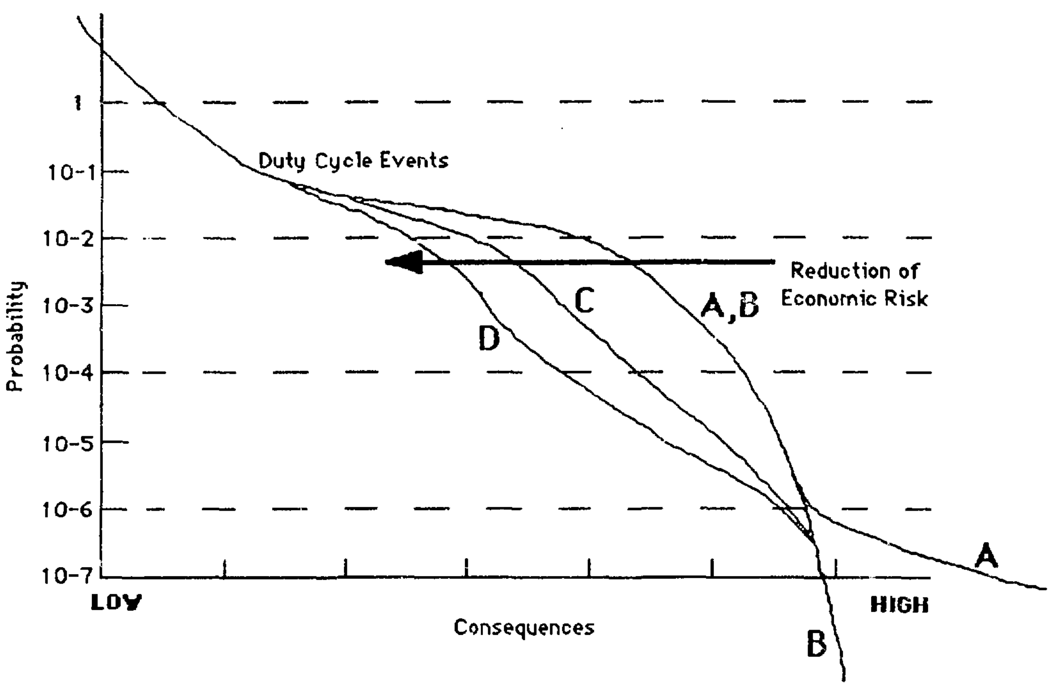

Figure 1 - Risk Curves for different Economic Criteria

Figure 1 shows postulated risk curves for a typical power plant. All are supposed to be

5 Graham, J., "*LMFBR Design Basis Accidents and their Accommodation*," Proceedings of the ANS Topical Meeting, *Nuclear Safety*, Tucson, Arizona, October 6-8, 1975.

acceptable on a regulatory basis. Curves A and B differ only for severe events, with very low probabilities - B being the more acceptable,since it has less residual risk by having no very severe events just beyond the bounds of "credibility", i.e., below 10^{-7} / year. Curve C differs from A and B in the middle range of probabilities by having much less risk, and Curve D shows even less. These curves are showing a reduction of severe economic risk to the owner. The division of probability into three ranges is arbitrary and the economic risk overlaps acceptable operation and acceptable public safety, but the greatest reductions in economic risk are likely to occur in the middle range. Notice that real improvements in this middle range tend also to improve operation and reduce risk to the public at the same time.

ACCEPTABLE ECONOMIC INVESTMENT

Having assured the protection of the public, the major concern for most plant owners in the event of serious accidents is protection of the plant and assurance against economic loss. A variety of losses can result and the loss of the plant itself has been a common factor for the more severe events (see Table 3). The loss of the plant would be a high proportion of the cost of building the plant, currently of the order of $3 to 5 billion (U.S.). Present criteria set the probability of this loss at approximately 10^{-5} to 10^{-6} per year. (The risk value for a 30-year plant lifetime would lie between 90,000 US$ and 1,500,000 US$) However, in addition to the loss of the plant, the cost of years of replacement power as well as other factors, have to be added.

TABLE 3 - ECONOMIC LOSSES OF SERIOUS ACCIDENTS

WINDSCALE	THREE MILE ISLAND	CHERNOBYL
Replacement Power	Replacement Power	Replacement Power
Plant	Plant	Plant
Clean up	Socioeconomic	Socioeconomic
	Damage analysis (R&D)	Clean up
	Decommissioning	Shutdown of other plants

For less serious events, from which the plant is expected to recover after refurbishment of the core and/or other components, the cost of replacement power is probably the largest economic loss. In the U.S., Philadelphia Electric Co. told its shareholders recently that the cost of replacement power for the Peach Bottom units in 1989 was of the order of $4 million (U.S.) per month per unit[6]. The utility was unable to earn any return on its investment in rates and this added a further $2.5 million per month while two units were shut down. Thus the cost of replacement power for a single unit is of the order of $5.25 million (U.S.) per month. Larger units could pay up to $1 million per day in replacement costs, or six times as much. The probability of a 3-month outage could be approximately 10^{-3}/year. (The risk value during a 30-year plant lifetime would lie between 472,500 US$ and 2,700,000 US$)

6 NUCLEONICS WEEK, Vol. 30, No.6, February 9, 1989.

Utility inhibitions against ordering new plants are probably not based on these risks, but on the risk of delays in bringing the plant into full-power operation while suffering the cost of borrowed money in the interim. Moreover, owners are also subject to risk aversion so that the potential for loss of a plant at $5 billion, at a probability of 10^{-6}/year, is not viewed as if it was the same risk as the certainty of paying $5,000 a year. However, the cost of reducing the probability of middle-range accidents by adding to structural margins, to fuel allowances, and in increasing operating margins, can be measured against the risk of losing part of the plant or its use. In particular, heat exchangers and steam generators operated to the very limits of their capacity and requiring refurbishment have been the cause of large replacement-power costs in several countries. Thus criteria to relate the probability of economic loss to design requirements are needed.

Electricité de France (EDF) have this year been studying whether a reduction of primary coolant temperature by 10°C in their 900 MW PWRs to preserve the lives of their steam generators is economically advisable. A reduction of temperature by that amount reduces the rate of growth of stress corrosion cracking by 50% while only reducing unit power output by less than 10%[7]. A reduction of the primary temperature by this amount before stress corrosion cracking had reached the present extent might have been indicated if economic probabilistic criteria had been available during the plant design process. While admittedly difficult, there should be a design criterion relating the steam generator lifetime to the cost of its replacement, and downtime power-replacement costs, by which its thermal operating limits could be set.

Thus the costs resulting from accommodating accidents or conditions in the middle range of probability could provide boundaries of acceptability of risk, just as acceptable operation and acceptable public safety requirements do at the high- and low- probability ranges respectively, when the probability of expensive accidents is compared to other voluntary financial activities of owners.

Three recommendations for economic criteria are made by Dinnie[8]. Firstly, he suggests that to limit the on-site **risk of loss on return of investment** to an acceptable level of the order of $1 million (Canadian)/ reactor year (where 'acceptable' is defined as below 1% of annual generation costs), the accident frequency should be 10^{-4} / year or lower. This is based on the assumption that the return on investment has been estimated to be in the range of $1 billion to $10 billion on an Ontario Hydro multi-unit station. Secondly, he suggests a criterion aimed at preventing **off-site economic penalties arising from the effects of a release of radioactivity,** which could give clean-up costs in the same range ($1 to $10 billion (Canadian) in 1981 terms). To meet an acceptable level of risk set by premiums under the Nuclear Liability Act ($100,000 / year) the frequency of such an accident would need to be kept less than 10^{-5} / year. Finally, Dinnie suggests a criterion to address **loss of livelihood** from a large release. He acknowledges the difficulty of defining both the meaning of "loss of livelihood' and the size of the release which would result in such an

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7 Lucien Berton, Executive Vice-President of Nuclear and Fossil Generating Group, Electricité de France, quoted in NUCLEONICS WEEK, Vol. 30, No.9, March 2, 1989.

8 Keith Dinnie, "*A Review of Quantitative Criteria for Demonstrating Nuclear Power Plant Design Adequacy*," Technical Note, CNS Bulletin, Vol. 10, No. 1, Canadian Nuclear Society, January / February 1989.

effect, as well as the problem of correlating this to an acceptable frequency for initiating events. On the basis of a reactor program involving 20 reactors, each with a 40-year life and a target of a 95% chance that no such accident occurs, he calculates that the predicted frequency for such accidents should be 10^{-6} / year or less. Dinnie then translates these considerations into stringent criteria to prevent fuel and core damage which could be precursors of these conditions.

The last two areas of Dinnie's concern apply to events which border on the lower-probability end of the middle range of probable reactor conditions, whereas this paper is more concerned with the higher-probability end, where damage to the plant could occur before significant release to the public takes place. Dinnie's criterion to prevent loss on return of investment is similar to the first of the economic criteria suggested in the next section, which addresses protection from payment of replacement-power costs. It results in approximately the same probabilistic guideline.

The acceptability of economic loss varies according to the owners' and the plant's requirements. It must vary for different utility financial structures and it must vary for different countries. It is different for small-scale heating reactors and research reactors, and for large-scale power reactors. Neverthless, it should provide meaningful probabilistic criteria by a comparison against other risks which are acceptable to the owner.

RECOMMENDATIONS

The primary factor in economic loss is the loss of the plant, a common factor in severe accident losses (see Table 3). Irretrievable costs could include, first, the replacement-power costs followed by the cost of replacement (if possible) of plant components. These consist of, firstly, the Nuclear Steam Supply System (NSSS); secondly, the secondary systems, steam-plant and turbine; and lastly, the civil work and containment. The principal component, the NSSS, consists of the reactor vessels, the reactor vessel internals and fuel, and the heat transport system with pumps, valves, and heat exchangers or steam generators.

The acceptability of public risk is measured by comparing the reactor risk against the risk of other activities which the public finds acceptable (making due allowance for risk aversion)[1]. Similarly, the acceptability of economic loss could perhaps be measured by comparing the risk of plant loss against that of other activities into which the owner (the utility) enters, such as the payment of nuclear liability insurance payments as suggested by Dinnie, or the cost of accepting limited-life plant components. Clearly, owners such as EDF are taking actions to reduce the risk of such failures. U.S. utilities are taking actions to improve the reliability of operating systems to obviate the costs of extended shutdowns[9].

This comparison of economic losses and probabilistic criteria would have the benefit of making real the costs and economic benefits of adding margins to the plant, or of running a plant at slightly less than full rating in return for a reduced probability of events which result in major downtime, or loss of plant components.

As an illustration, the following criteria, derived here judgementally, address these considerations:

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9 Alan Marie, Philadelphia Electric Co., Private Communication. March 1989.

- The plant design shall ensure that the probability of all events which could result in a repair and refurbishment unplanned shutdown of 3 months or longer will be less than 10^{-4} per year.
- The plant design shall ensure that the probability of all events which would result in major plant-component replacement will be less than 10^{-6} per year.

These criteria require a critical review of those events and sequences which, while of low probability, have been experienced in plants across the world. Firm economic criteria provide good motivation for this review by the owner, with additional safety across the board. This is because such criteria derived from a protection of owner investment are expected to, first, reduce the middle range of the risk curves (Figure 1), second, increase the reliability of normal operation against high-probability minor events, third, decrease the risk to the public, and, although this is beyond the scope of the present thesis, pay dividends in extending the life of the plant. Economic studies are required to confirm these assertions.

REFERENCES

1 Chauncy Starr, "*Social Benefit versus Technological Risks*", Science, Vol. 65, September 1969 and "*Testimony on HR 14408 and S2534 Price Anderson Act*", presentation to the Joint Committee on Atomic Energy, Washington, D.C. May 16, 1974.

2 "*Basic Safety Principles of Nuclear Power Plants* "- a Report by the International Nuclear Safety Advisory Group, Safety Series No. 75 - INSAG-3, IAEA, Vienna, 1988.

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5 Graham, J., "*LMFBR Design Basis Accidents and their Accommodation,*" Proceedings of the ANS Topical Meeting, *Nuclear Safety*, Tucson, Arizona, October 6-8, 1975.

6 NUCLEONICS WEEK, Vol. 30, No.6, February 9, 1989.

7 Lucien Berton, Executive Vice President of Nuclear and Fossil Generating Group, Electricité de France, quoted in NUCLEONICS WEEK, Vol. 30, No.9, March 2, 1989.

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9 Alan Marie, Philadelphia Electric Co., Private Communication, March 1989.

TABLE I - PLANT DESIGN CRITERIA

	ORIGIN OF CRITERIA	DESIGN REQUIREMENTS	DESIGN CONDITIONS	PROBABILISTIC RANGES
PLANNING	**ACCEPTABLE OPERATION** • allowable planned operations • refuelling outages • maintenance periods • test periods • allowable failed fuel operation • QA	Design accommodates a range of planned and anticipated conditions within normal design margins and continued operation is possible without damage to the plant	**Conditions which are planned** • normal design conditions (operational transients only) **Conditions which are anticipated** • minor part failures subject to correction in maintenance	**1/year and more** value established by planning and pre-determination **less than 10^{-2}/ year** (once in the plant life) established by design analysis (FMEA)
MARKET	**ACCEPTABLE INVESTMENT** • structural margins • wear and deterioration allowances • fuel margins in heat ratings • thermal margins in the primary heat transport system	Design accommodates a range of identified but unanticipated conditions without major plant damage. Continued operation is possible after refurbishment.	**Conditions which are unanticipated** • fuel life impaired • possible design limits are exceeded requiring re-evaluation before continued operation	**10^{-2} to 10^{-4}/year** established by testing protective systems • shut-down mechanisms • heat transport system components
JUDGEMENT	**ACCEPTABLE PUBLIC SAFETY (enhanced to include risk aversion)** • levels of protection • containment barriers • operator emergency training • isolation / siting • emergency procedures	Design accommodates a range of identified severe events without damage to the health and safety of the public.	**Severe conditions** • plant damage • fuel damage • out of normal range thermal conditions	**10^{-4} to 10^{-6}/year** established by analysis • involves severe accident methodology and probability estimation of component sequences of the event

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