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THE IMPLICATIONS OF USING "CONSEQUENCES" AS A CRITERION FOR REACTOR DESIGN.

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ABSTRACT

The influences which may necessitate closer consideration of reactor accident consequences, rather than reactor risk, as a criterion for design are examined briefly. Possible methods for reducing consequences are described and the advantages of inherent features for this purpose are discussed. The cost effectiveness of two possible methods of reducing consequences and risks is estimated.

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1. INTRODUCTION.

In virtually all of the developed countries which have a democratic form of government there is now considerable public opposition to nuclear power. This opposition is based on 3 main factors:

Fear of the consequences of an accident to a nuclear reactor.

Fear of long-term effects of the radionuclide wastes arising from a nuclear power programme.

Concern that the growth of nuclear power will increase the rate of proliferation of nuclear weapons.

The emphasis on each of these factors varies from time to time and from country to country. However, it seems likely that, if nuclear power is to gain general acceptance, the moderate majority of the public, who at present have no strong commitment either for or against nuclear power but who will eventually determine its rate of growth, will have to be satisfied about all three areas of concern. However, in this study we are concerned only with the first factor

During the past 25 years cost/benefit analysis has been used to an increasing extent by engineers and administrators to decide on the relative merits of alternative technological solutions to major problems (e.g. This approach has been used in flood control problems since 1960 (Ref. 1) and obviously the same techniques could be used with advantage to make decisions about nuclear power. However, in this case "cost" must include the penalties associated with possible accidents to nuclear plants. The expectation of loss [or "risk", as defined in WASH-1400 (Ref. 2)] can now be estimated with adequate accuracy for decision making purposes but it has also become apparent that the general public does not necessarily accept the use of the risk concept in such applications. For example, a study of the levels of fatality risks which have been accepted by the public in the UK, without further pressure for improvement, shows that these have ranged from 10^{-3} to 10^{-8} deaths per annum for perceivable risks (Ref. 3); recent studies in the US (Ref. 4) suggest that the risks of new technologies are greatly magnified in the public's mind, particularly if they are constantly brought to their attention. The very severe damage, to both health and property, which could conceivably be caused by an accident to a reactor was first revealed to the public in 1955 by Marley and Fry (Ref. 5) and again in 1957 by WASH-740 (Ref. 6) and subsequently by alarmist "popular" publications. The public concern arising from these conceivable effects has not been alleviated by the low risks demonstrated in WASH-1400 (Ref. 2). It is not surprising therefore that this concern continues to create resistance to the expansion of nuclear power.

In these circumstances it seems that a possible way to restore public confidence and to obtain acceptance, at least so far as reactor safety is concerned, would be to find ways of reducing the consequences of reactor accidents. In this paper some possible ways in which this might be done for LWRs and GCRs are considered and the cost effectiveness of possible changes is estimated.

2. POSSIBLE MEANS OF LIMITING CONSEQUENCES.

2.1 Accident Situations with Potentially High Consequences.

To cause any significant harm to the public a reactor accident would have to lead to the release of a substantial quantity of radio-active material to the environment. For example, in the Windscale accident of 1957 it is estimated that some 20,000 Ci of I-131, 600 Ci of Cs-137 and smaller quantities of other gaseous and volatile isotopes were released into the air but no measurable personal harm to members of the public was caused and the estimated property damage was less than $1m , mainly due to the contamination of milk supplies.

A power reactor could only give rise to a release of fission products to the atmosphere of the order of magnitude experienced at Windscale as a result of an accident which caused severe damage not only to the fuel but also to the pressure retaining boundary of the primary circuit and to the containment. Thus, it is not surprising that in the case of the LWRs, for example, the result of the WASH-1400 study (Ref. 2) show that significant consequences to the public would result only from accidents which lead to core meltdown. The same situation is encountered in other reactors (e.g. see Ref.7).

In this study, therefore, it is sufficient to limit our work to methods of preventing, or mitigating, the effects of accidents which lead to core meltdown or, in the case of HTGR,which has a more refractory type of fuel, to severe overheating of the core.

2.2 The Relationship Between Type of Consequence and Methods of Limitation.

The possible means of limiting the consequences of reactor accidents vary to some extent with the nature of consequence considered.

In this study 3 types of consequences have been considered, viz:

(a) Population dose (man-rem)

(b) Loss of life, based on early deaths and reduced expectation of life due to delayed effects

(c) Economic damage.

Clearly, all these types of consequence can be lowered by reducing the amount of fission products released. However, in the case of (a) and (b), if there were a delay in the release to atmosphere, giving time for evacuation, the consequences of a large release could, in principle, be reduced to insignificant proportions. In practice, evacuation is likely to be a more effective means of reducing the numbers of early deaths and acute illnesses, since the maximum distance to which these types of consequences can extend are much more limited than for delayed effects. A delay in the release would not be of substantial benefit in reducing the economic consequences at (c), although there are some cases (e.g. prevention of contamination of milk supplies) where a benefit can be visualised.

Similarly a policy of "remote siting" could reduce consequences measured in terms of early deaths and acute illnesses but would not be so effective for reducing delayed health effects or economic damage.

2.3 Certainty and Uncertainty in Consequence Limitation.

In any reactor system there are usually some inherent features, that contribute to safety, for which the underlying physical principles are well understood and have been verified experimentally on reactors as built (e.g. natural circulation). There are also likely to be other inherent features important to safety where the physical principles have not been so well verified and, as a result, the behaviour of the reactor in extreme fault conditions is less certain. If the proven features served to limit consequences, in all conceivable fault conditions, we should have approached the realization of a'low-consequence' reactor.

In addition to these inherent features there are also likely to be a number of engineering features whcih are important to safety (e.g. certain vital structures. such as the reactor pressure circuit, and "engineered safeguards", such as the emergency core cooling system of an LWR). For these engineered features there must always be some probability of failure and thus reactor systems in which safety depends mainly on engineering features are further from the goal of low consequences, even though they may present just as low a risk. It should be noted in this context that virtually all of the possible means of reducing consequences by the use of additional systems, such as those described below, suffer from this disadvantage. Even those obtained by the use of remote sites could be negated partially by unexpectedly adverse weather conditions.

To the rational administrator, faced with the problem of deciding whether to proceed with a large nuclear power programme as an alternative source of energy, the concept of evaluating the risks presented by the reactors* and comparing these with the benefits, is a useful one. By extending the concept to estimate the benefit, in terms of reduced risk, which could be secured by additional expenditure on safety the administrator could also arrive at a logical balance in the allocation of resources, e.g. in the UK it is now becoming very apparent that lack of resources for the National Health Service is leading to deaths which could be avoided, whereas the additional demand for resources to increase the safety of nuclear power stations contributes to the difficulty of increasing the resources that can be allocated to the NHS. In this situation, if energy requirements cannot be met without nuclear power, a decision must ultimately be made on the basis of "risk" rather than "consequence". However, some means is required for deciding how much additional cost should be incurred in reducing the consequences to a lower level, in order to placate public opinion, than would be reasonable on a strict risk/benefit basis.

In this context a reactor system in which safety is dependent mainly on inherent features, rather than on engineered safeguards, might be more acceptable to a public concerned more with "consequence" than with "risk".

It is unlikely that a completely satisfactory method for determination of the optimum relationship between additional cost and improved safety can be found in the near future. However, so far as long-term health effects are concerned, a possible measure is the absolute reduction of population dose (either whole body or to a specific organ) per unit of expenditure. This measure might be improved by attributing a specific cash value to each unit of population dose, e.g. in the U.S. the NRC have recently applied their "guide-line" value of $1,000 per man-rem (whole body dose) saved per year to reactor accident situations (Ref.8).

In the case of property damage, a "dollar-to-dollar" relationship is more readily established but even in

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* Note: In this context "risk" is defined as in WASH-1400 i.e.,

$$\sum_{\text{all } i} \text{probability } (i) \times \text{consequence } (i).$$

this case it is necessary to consider whether some substantial factor, varying with the magnitude of the damage, should be applied to allow for the public's aversion to risk. This would be analogous to the insurance industry's practice of increasing premiums in cases where the consequences of a single event could be exceptionally large.

3. THE USE OF ENGINEERED SAFEGUARDS TO REDUCE CONSEQUENCES.

In the previous Section some reservations concerning the uncertainties of engineered safeguards as a means of reducing consequences were expressed. Subject to these, it will be apparent that in a given reactor system the main purpose of the additional features would be to increase the capability of the "containment barriers", which could be the primary circuit envelope, and one or more containment systems, to prevent or to defer the release of active material to the environment.

Possible means of improving the containment of LWR have been discussed in several recent report (e.g. Ref. 9, 10, 11 and 12). All the authors have started from the standpoint that WASH-1400 shows that, given a core melt-down has occurred, there is a relatively high probability (about 0.3) that, in the designs analysed, the containment will fail due to over-pressurization. Thus, the main aim of the methods described has been to avoid the buildup of the over-pressure or to strengthen the containment.

Means proposed for preventing the buildup of excessive over-pressure include the following:

> An increase in containment volume, either by a change in the design of the parent structure or by the provision of additional expansion volume in a separate structure ("compartment venting").
>
> By operating with the containment evacuated.
>
> The provision of a post accident filtration system (PAFS) for venting the containment safely to atmosphere.

Of these methods, the last one appears to be the most promising in terms of the potential reduction in consequence per unit of expenditure, but none of them would be effective in the event of a violent steam explosion accident, of the type visualized in WASH-1400. The only means of reducing consequences in that type of accident which has been specifically proposed as yet is the use of deep underground siting, allied with the provision of a large expansion volume, or filtered venting, in order to limit the loads on the various penetration closures to manageable levels (Refs.13 & 9).

Similarly, none of the methods proposed so far for preventing disruption of the containment by overpressurization would prevent penetration of the base of the containment by the molten core. WASH-1400 indicates that filtration by the ground beneath and around the containment should be sufficient to reduce the consequences to a relatively insignificant level. Nevertheless, some consideration is being given in the U.S., at least, to means of preventing this type of failure (Ref. 10).

All of the methods described above, which have been proposed in the context of improving the safety of LWRs could, in principle, be used to improve the safety of other current thermal reactor systems, or of fast reactors. A further proposal, specific to reactors which embody steel reactor pressure vessels has been suggested in the FRG; this proposal relates to the development of a "burst-proof" pressure vessel (Ref. 14). This proposal stems from the premise that, for reactors sited in densely populated areas, the public could not be convinced that the probability of vessel failure due to inherent defects could be made sufficiently low, thus, it would be necessary to retain the core in a coolable state after vessel failure, so that the consequences would still be acceptable.

It should be noted that in addition to the use of engineering features aimed at the direct reduction of consequences following core meltdown, it is also possible to envisage means of reducing the probability of meltdown occurring in the first place (e.g. see Ref. 10). However, for the purposes of this study it has been assumed that public anxiety would not be allayed by improvements of this type.

4. OTHER MEANS OF REDUCING CONSEQUENCES.

4.1 External Action as a Means of Reducing Consequences.

In addition to design features to reduce the release of activity to the evironment after core meltdown it is also possible to visualise methods for achieving the same objective by external action, taken after meltdown has occurred. Clearly, the time available between the initiating events which lead to core meltdown (or core heatup, in the case of HTGR) and the onset of severe leakage from the containment, due to overpressurization, is a vital factor, since it determines whether external action would be possible. Some estimates of the time available for particular reactor systems, in accident sequences with probabilities of order 10^{-5} per r.yr, or below, are as follows:

PWR	2 to 5 hours (for the more severe accident sequences)	Ref.WASH-1400
BWR	2 to 30 " " "	Ref.WASH-1400
AGR*	At least 10 hrs " "	Ref. 15
HTGR	About 150 " " "	Ref. 16

* Note: The CAGRs do not have a separate containment system of the type used for water reactors and fast reactors.

Allowing one hour for the operator to diagnose the situation and to decide what remedial action to take, there should be some opportunity for external action in each of the reactor systems listed above, though it would obviously be easiest, and less hazardous to the operator, in the case of HTGR. Considerable analysis is necessary to determine the nature and the full extent of the external action which would be worthwhile (e.g. see Ref. 13). However,it is likely that in any reactor system it would be advantageous to provide facilities for injecting cooling water, by means of self-powered mobile pumps, into essential water circuits which have been starved owing to the loss of all A.C. supplies. Similarly, providing that containment rupture could be prevented, the application of a sprayed plastic coating to reduce the leak rate might achieve a useful reduction in the overall consequence, in some accidents.

In addition to action centred on the reactor itself, the delay in the commencement of any large release would also facilitate the control of off-site aspects of the emergency, particularly in the case of the HTGR. In this case there would be time to evacuate very large numbers and to take prophylactic action such as the issue of potassium iodide tablets to reduce the effects of inhaling active iodine.

4.2 Remote Siting as a Means of Reducing Consequences.

It was shown in Ref.17 that at distances from a 1000MW(e) reactor of more than 3km; in average weather conditions, or about 12 km in adverse weather conditions (Pasquill stability Category "F") the probability of early deaths following a very large release falls off rapidly with distance; this is due to the distinct "threshold dose" required to cause such effects.

Thus,if power reactors in general could be sited at least 10 km from all centres of population from which evacuation at an hour's notice would not be possible, the total consequences attributable to acute health effects could be reduced greatly. However, in the case of AGR and HTGR, for which large scale evacuation is more feasible, the additional benefit obtained by remote siting would be small.

There would also be some reduction in the long-term health effects but in general, population distributions are such that the overall reduction in the population dose would be small.

In many countries it is difficult to find enough remote sites but, where other conditions, particularly depth of water, make the concept feasible, off-shore siting could provide an alternative means of reducing the acute health effects.

5. EVALUATION OF COST EFFECTIVENESS OF CHANGES TO REDUCE CONSEQUENCES.

In this study cost effectiveness can be judged by the reduction of consequences that would be achieved in the "worst" accident. The definition of "worst" presents some difficulty but initially this is taken to be the most severe of the accidents, or category of accidents, considered in the appropriate risk analysis, for which the change should be effective. Typically the estimated probabilities of the selected accident sequences have been estimated to be in the range 10^{-5} to 10^{-8} per r.yr. It could be argued that there are more severe accidents which should be considered; these are the so-called "ultimate accidents" (Ref. 18). This aspect of the problem is discussed further in Section 7, below.

If cost effectiveness is judged in terms of reduction in consequence, rather than in terms of reduction of risk, it is more appropriate to consider the reduction which would be achieved in the least favourable weather conditions and in terms of a specific site, with a specific population distribution, rather than in terms of a "mean consequence" averaged over a variety of weather conditions and sites. These factors can be taken into account by estimating the cost effectiveness in terms of the "average" consequences, which can be deduced from the data in WASH-1400 and the AIPA study (Ref.16) and by extimating separately the effects of population distribution and weather conditions, as follows:

(a) Population distribution. Ref. 19 provides an indication of the differences between the "average" and the "worst" sites in the U.S. This can be represented by a factors of 4, for both acute and late health effects. It is also a reasonable approximation for economic damage. In Europe this factor is about 10.

(b.) Weather conditions. The AIPA study (Ref. 16) indicates that the atmospheric dispersion factor could vary by a factor of about 20, as between the "average" and the "worst" cases. Due to the decrease in plume width in the "worst" case the variation in consequences is assumed to be a factor of 10. This is consistent with earlier work (Ref. 17). Thus, overall, the cost-effectiveness of a design change could be from 40 to 100 times greater on some sites than would be estimated from the reduction in the "average" consequences. In this study cost effectiveness has been estimated on the "worst case" conditions, assuming a factor of 40.

The following measures of cost-effectiveness have been used:

For population dose - Reduction in the total man-rem exposure giving a cost per man-rem saved. For simplicity an "equivalent whole body dose" has been derived from the estimated number of fatal latent cancers reported in Refs. 2 and 12.

For "loss of life" - Reduction in the number of acute deaths + 15 per cent reduction in latent fatal cancers, giving a cost per equivalent life saved.

Note: The 15 per cent of latent fatal cancers represents the reduction in life expectancy averaged over the whole population exposed.

For economic damage - Estimated cost in dollars of the damage avoided, based on the WASH-1400 model.

6. POSSIBLE DESIGN CHANGES TO REDUCE CONSEQUENCES IN SPECIFIC REACTOR SYSTEMS.

6.1 Inherent Features which Serve to Reduce Consequences.

Within the limited space allowed for this paper it is not possible to discuss the various power reactor systems in this respect. However, a recent study by Battelle, Colombus provides an objective survey which suggests that the safety of the molten salt reactor and of the HTGR is much less dependent on engineered safeguards than is the case in other current reactor systems. In the opinion of the present authors the current commercial, or near-commercial, thermal reactor systems can be ranked, in respect of inherent safety, in the following order:-

HTGR, AGR, Magnox, CANDU, LWRs.

As comprehensive, quantitative safety studies have been published for the LWRs and for HTGR (Refs. 2 and 16) it is convenient to use PWR and HTGR to illustrate the ways in which design changes might be made to reduce consequences.

6.2 PWR - Possible Design Changes to Reduce Consequences.

Overall, the safety of a PWR is dependent mainly on engineered safeguards; in LOCA, if these fail, the core meltdown would occur within a few minutes of the core becoming uncovered; in loss of flow faults, core meltdown would not occur for several hours; in ATWS faults core meltdown could occur within a few minutes.

It follows from the discussion in Section 3, above, that improvement of the containment by the provision of a PAFS is the most promising design change. This system could probably be designed to achieve a 100 fold reduction in consequences, except in those accidents in which it would be ineffective. The most important of these are the steam explosion sequences. Consequently, the uncertainty about the proportion of core meltdown accidents which lead to steam explosions, and the uncertainty about the destructive capability of these, may limit severely the extent of the benefit which can be claimed to result from this modification. There must also be some doubt as to the ability of the containment to survive a gross failure of the reactor vessel. Deep underground siting, together with compartment and/or filtered venting as part of the underground complex, could provide protection against steam explosions and also against reactor vessel failures due to other causes. Thus, this type of design could probably give a substantial reduction in consequences for all the types of accident which are usually considered.+ The question of more extreme accident sequences is discussed in Section 7, below. Until the uncertainties about steam explosions have been resolved it does not seem worthwhile to consider embodying the "burst-proof vessel" concept in PWR designs.

Provision of simple additional facilities to make external action feasible, if time permits, would seem to be worthwhile, as the cost should be negligible.

The cost effectiveness of these methods is discussed in Section 6.4, below.

+ Note: It is assumed that the probability of the "interfacing systems LOCA" (Ref. 2) will be made insignificant by re-design or better in-service inspection.

6.3 HTGR - Possible Design Changes to Reduce Consequences.

The AIPA study (Ref. 16) has shown that the 1100 MW(e) HTGR design analysed presents a much lower risk, for a comparable range of faults, than any other reactor system which has been subjected to a detailed reliability analysis, e.g. there are some two orders of magnitude difference in the overall risks presented by the HTGR and by the two LWRs analysed in WASH-1400. More detailed examination of the data presented in Ref. 16 shows that this estimated reduction is due mainly to reduced consequences in the severe accidents sequences which lead to core heatup, rather than to greater reliability of individual safety systems, although the greater time available for "repair" tends to improve reliability. The reduction in consequences stems mainly from the inherent features of the system.
In most severe accident conditions the only engineered safeguard necessary to limit consequences to a very low level is the containment building (i.e., a passive feature).

It is claimed in Ref. 16 that, because of the nature of its possible failure modes, complete integrity of the containment is not as important to HTGR as to a PWR. Moreover, the inevitable uncertainties associated with this aspect of the analysis could be offset by the provision of a filtered venting system for the containment to prevent failure by over-pressurization. The range of accidents for which consequences would be kept at a low level could be increased by this means, or by simple modifications to make it easier for the operator to take remedial measures on the plant, or to take external action, during the long period (about 150 hours) available for this purpose.

The benefit which would be secured by these measures is discussed in Section 6.4, below.

6.4 Cost Effectiveness of Possible Improvements.

6.4.1 Method of estimating cost effectiveness.

The methods used are described in Appendix 1; the results obtained for PWR are shown in Tables 1 and 2 and those for HTGR are shown in Table 3.

In order to appreciate the significance of these results it should be noted that:

i) The cost effectiveness measured in terms of a reduction in consequences is based on severe accidents (defined in Appendix 1) occurring in the most unfavourable weather conditions and on the least favourable site. An overall factor of 40, as compared with the average, has been assumed (see Section 5, above).

ii) The cost effectiveness measured in terms of a reduction in risk is based on the summated risk for the life of the station (30 years), since this represents the total "expectation of loss" against which the additional protection should be effective.

6.4.2 Cost Effectiveness in Terms of Reduction in Population Dose.

The NRC's "guide-line" figure of $1000 per man-rem (per year) is for a recurring benefit for the life of an installation. Thus, assuming a station life of 30 years, a more appropriate "guide-line" figure for situations where the improvement would be obtained once only would be $30 per man rem.

It will be seen from Table 2 that, for PWR, the addition of a PAFS or deep undergrounding could be readily justified in terms of cost-effectiveness measured in terms of this type of consequence, since the costs are trivial compared with the guide-line value.

However, on a risk basis both a PAFS and deep undergrounding would cost considerably more than the guideline value.

From the risk point of view, a decision to use either method of improvement could be interpreted as the adoption of a specific "risk aversion factor" (RAF). The value of the RAF for a PAFS and for deep undergrounding are 70 and 1 x 10^4 respectively. A possible method of interpreting risk aversion factors is discussed in Section 8, below.

In the case of HTGR the consequences and risks, in terms of population dose, attributable to the "unimproved" design are considerably lower than for PWR (about 2 orders). Assuming the same costs for a PAFS and for deep undergrounding as in the case of PWR, a decision to provide a PAFS, based on the reduction of consequences, could be justified but the case for deep undergrounding would be marginal. However, in terms of risk reduction neither would be reasonable unless very large risk aversion factors (2 x 10^4 and 3 x 10^6 respectively) were considered to be appropriate.

6.4.3 Cost Effectiveness in Terms of Lives Saved and of Property Damage.

Recent legal cases in prosperous countries such as the U.S. suggest that a minimum "guide-line" value is about $300,000 per life saved. This is a factor of ~10 lower than can be deduced from the NRC's guide-line value of $1000 per man rem (per year) for population dose. Nevertheless reference to Table 2 shows that, in terms of consequence reduction, both the use of a PAFS or of deep undergrounding would still be highly cost-effective. However, in terms of risk, a decision to use these improvements for PWR would imply adoption of RAF values of 70 and 2×10^4 respectively.

For property damage an upper limit guide-line value is clearly $1 spent for $1 worth of damage saved. On this basis both types of improvement could be justified for PWR in terms of a reduction in consequence but in terms of risk a large value of RAF would be implied (1×10^3) in the case of deep under-grounding. However, the provision of a PAFS (RAF of 6) would seem to be justifiable (see Section 8, below).

In the case of HTGR the position is similar to that found for population dose; in this case, in terms of consequence reduction, the use of a PAFS could be justified but deep under-grounding would be marginal. However, in terms of risk reduction very large RAF values would have to be adopted in both cases (ranging from 1×10^3 to 3×10^6).

7. ULTIMATE ACCIDENTS.

Recently, increased attention has been given in FRG to "ultimate accidents", in order to establish the behaviour of reactor systems in the event of fault sequences which should be much less probable than those considered in WASH-1400 and in the AIPA study. One of the objectives of this work is to determine the minimum time available for evacuation (Ref. 18).

Since some of the fault sequences for PWR already considered in WASH-1400 lead to the release to atmosphere of 40 per cent or more of the gaseous and volatile fission products within about 3 hours of the onset of the fault, more extreme fault sequences could not lead to a substantial increase in consequences, unless they were to cause partial vaporization of the fuel; this would require a large power excursion. A cause for this is difficult to visualize; however, if such an event were to occur then, as in the case of steam explosions, it is doubtful whether a PAFS would be of any value. Nevertheless, deep under-grounding could still be effective.

In the case of HTGR a large power excursion, combined with earlier failure of the containment, could also lead to more severe consequences and less time for evacuation. However, the large thermal capacity of the fuel and moderator, together with the large negative reactivity temperature coefficient, should prevent a rapid release of large quantities of fission products from the PCRV and the rapid buildup of pressure within the containment. Thus, even in the most extreme faults, a PAFS should still provide additional protection to an HTGR. Alternatively, there should still be time to take external action before the containment failed.

8. CONCLUSIONS.

This brief study is sufficient to show that, if the "worst case" potential consequences of accidents were adopted as a criterion for reactor design, improvements such as the addition of a post-accident filtration system (PAFS) for venting the containment, or deep undergrounding, would appear to be cost effective for any thermal reactor system.

However, if the cost effectiveness of such improvements were judged on the basis of risk reduction, they could be justified only by the adopting of the risk aversion factors greater than one. The size of this factor varies greatly from one thermal reactor system to another and, to a lesser degree, with the type of risk considered. The overall range is from order 10^1 to order 10^6.

It is not within the scope of this paper to discuss at length what value of risk aversion factor should be acceptable. However, it should be noted that whereas, in view of the uncertainties in the analysis, a value of 10 would seem reasonable, large factors (100 or more) are indicative of a possible waste of resources. On this basis the provision of a PAFS for PWR, for example, would seem to be reasonable but this would not be so in the case of HTGR. This difference is due mainly to the inherent features of the HTGR. Deep under-grounding would appear to be difficult to justify for either of these systems, or for any other thermal reactor system.

It seems unlikely that a different view would be reached by consideration of "ultimate" accidents, rather than the "worst-consequence" accidents assumed in this analysis.

In all thermal reactor systems it is likely that there would be some time available to take external action to mitigate the consequences of a severe accident. When, as in the case of HTGR, for example, this time may be of order 100 hours, further investigation of the possibilities of external action by the reactor operator might indicate more economical means of reducing the consequences than have been considered hitherto.

TABLE 1. PWR - Reduction in Consequences and Risk by Filtered, Vented Containment and by Deep Under-grounding (Average Site and Conditions).

Type of Consequence	Reduction in Consequences		Reduction in Annual Risk	
	Filtered, vented Containment	Deep Undergroundings	Filtered, vented Containment	Deep Undergrounding
Population Dose, Man rem(e.w.b)	8×10^6	14×10^6	14	16
Loss of Life over 30 years	80	220	1.4×10^{-3}	1.6×10^{-3}
Property Damage $	8×10^8	11×10^8	6×10^3	7×10^3

TABLE 2. PWR - Cost Effectiveness of Filtered, Vented Containment and of Deep Undergrounding as Means of Reducing Consequences and Risk.

Measure of Cost Effectiveness	"Guide-line" Value	Cost Effectiveness (Worst Consequences)		Cost Effectiveness (Summated Risk)		Risk Aversion Factor	
		PAFS	Deep U/G	PAFS	Deep U/G	PAFS	Deep U/G
$ Spent per unit of population dose saved (man, rem, e.w.b)	$30	3×10^{-3}	0.3	2000	4×10^5	70	1×10^4
$ Spent per Equiv. Life Saved	300,000	300	3×10^4	2×10^7	5×10^9	70	2×10^4
$ Spent per $ of property damage saved	1	3×10^{-5}	5×10^{-3}	6	1×10^3	6	1×10^3

TABLE 3. HTGR - Cost Effectiveness of Filtered, Vented Containment and of Deep Undergrounding, as a Means of Reducing Consequences and Risk.

Measure of Cost Effectiveness	"Guide-line Value	Cost Effectiveness (Worst Consequences)		Cost Effectiveness (Summated Risk)		Risk Aversion Factor	
		PAFS	Deep U/G	PAFS	Deep U/G	PAFS	Deep U/G
$ Spent per unit of population dose saved.$ per man rem(e.w.b)	30	0.3	60	6×10^5	1×10^8	2×10^4	3×10^6
$ Spent per Equiv. Life Saved	300,000	30,000	6×10^6	6×10^9	1×10^{12}	2×10^4	3×10^6
$ Spent per $ of Property damage saved	1	3×10^{-3}	0.6	1×10^3	2×10^5	1×10^3	2×10^5

APPENDIX 1. Estimate of Cost Effectiveness of Changes to Reduce Consequences and Risk.

A.1 Method of Estimating the Reduction of Consequence and Risk which could be Achieved in PWR.

It is assumed that the results presented in WASH-1400 are a good estimate of the consequences and risks associated with typical PWRs.

The most severe type of accident which could be mitigated by a PAFS is that designated as "Category 2" in WASH-1400, in this type of accident the containment is assumed to fail owing to over-pressurization due to hydrogen burning or lack of cooling. A PAFS would mitigate the hazards from all accidents which lead to disruptive failure of the containment, except those due to steam explosions (Note - It has been assumed in this study that the special case of containment by-passing by failure at the Low Pressure Injection System interface has been eliminated by design changes). Thus, although the improvement in terms of consequence is measured by consideration of Category 2 alone, the improvement in terms of risk can be measured by summation over Category 2 through 5, since these include no significant sequences in which the PAFS would be ineffective.
It is assumed that the deep-undergrounding solution would mitigate the hazards from virtually all accidents. In this case therefore the improvement, in consequences and in risk are measured by the improvements in Categories 1 through 9, respectively.

The consequences and risks for each Category, in terms of the parameters listed in Section 2.2, of the main text, can be derived from the results given in Ref.22. It is assumed that an improvement factor of 100 can be obtained by both PAFS (see Ref. 11) and by deep undergrounding (Ref. 13). With these assumptions the estimated improvements in consequences, for averaged site and weather conditions are as shown in Table 1 of the main text. The estimated annual risks are also shown.

A.2 Method of Estimating the Cost-Effectiveness of Consequence and Risk Reduction in PWR.

The cost of PAFS is estimated to be about $1m (see Ref.11) and that of deep under-grounding to be about $200m (20 to 25 per cent of the cost of the same PWR on a surface site, as estimated in several studies). Using these estimates the cost effectiveness for the two methods of improvement can be estimated. As noted in Section 5 of the main text, in the case of consequence it is more appropriate to consider the worst combination of site and weather, rather than the averaged conditions. The consequences shown in Table 1 have therefore been increased by a factor of 40 for this reason in completing Table 2 of the main text. As the improvements should provide protection against the annual risk (assumed constant) for the life of the station, which is taken to be 30 years, the risk has been summated over this period, in estimating the cost effectiveness of the improvements in terms of reduction of risk.

A.3 Consequence and Risk Reduction in HTGR Due to Use of a PAFS or to Deep Under-Grounding.

In the case of the HTGR the most severe accidents of those considered in the AIPA study (Ref.16) in which a PAFS could mitigate the consequences would be those in Category "CH2". These are core heat-up accidents in which the containment is assumed to have failed partially at 140 hours after the initiating event and in which the plate-out within the PCVR and containment had been poor, i.e. at the lower end of the uncertainty range. These combined probability is estimated to be about 2 x 10^{-8} per r. yr.

In order to ensure the uniformity of treatment between PWR and HTGR in the comparison of consequences (for each of the selected parameters), these have been estimated for HTGR from the data given in Ref.20, as described below. With the exception of the rare gases, the estimated release fractions for each of the isotopes are lower by a factor of at least 140 than the corresponding fractions for PWR Categories 1 and 2 of WASH-1400. For the rare gases the release fraction is reduced by a factor of only about 1 per cent of the consequences, both for health effects and for property damage, the overall reduction in consequences must be at least two orders of magnitude. i.e. the consequences to be expected from the worst accident (at the 10^{-8} per yr. probability level) considered for HTGR are about the same as would be expected from a PWR provided with a PAFS which is 99 per cent effective in Category 2 accidents. Assuming that the cost of a PAFS, or of deep under-grounding, would be the same as for the PWR, their cost effectiveness can be estimated, on the basis that the consequences without them are smaller than in PWR by a factor of 100. The cost effectiveness for each type of consequence is shown in Table 3.

In order to estimate the cost effectiveness of these improvements in terms of risk the summated risk of Categories CH1 thro CH6, of Ref.16, in terms of release fractions of individual isotopes, can be compared with those for, say, PWR Category 2. It is found that the summated release-fraction risks for HTGR are, with the exception of the rare gases, smaller by a factor of at least 300 than for PWR Category 2. In this instance the rare gas release is smaller by a factor of 10. The summated risks, for each of the parameters considered, can then be derived from the results shown for PWR2 in Table 10 of Ref.20, on the assumption that they are smaller by a factor of at least 250. The maximum cost effectiveness of a PAFS or of deep under-grounding, in terms of each of the three selected parameters can then be estimated. These are shown in Table 3.

REFERENCES

1. MAASS, A. et al. "Design of Water Resources Systems". Harvard University Press. 1962.

2. USAEC "An Assessment of Accidental Risks in US Commercial Nuclear Power Plants". WASH-1400

3. POLLUTION PREVENTION (CONSULTANTS) LTD. "Equating Nuclear and Non-Nuclear Risk". In course of publication for EEC.

4. HERBERT, J.A. "An Analysis of Public Perception of Risk in Nuclear Power". Proceedings of ANS Topical Meeting on Thermal Reactor Safety (Vol.1) Sun Valley, Idaho, August 1977.

5. MASLEY, W.G. and FRY, T.M. "Radiation Hazards from an Escape of Fission Products". Proc.Int.Conf.PUAE Energy Vol.13,p.102 (1955)

6. BECK, C. "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plant" USAEC, WASH-740,Mar.'57

7. CAVE, L. "The Principal Safety Aspects of the AGR System". Tech.Mtg. No.10. "Nuclex 66". Basle 1966.

8. US NUCLEAR REGULATORY COMMISSION. "Anticipated Transients Without Scram". Nureg 0460, p.90.

9. CARLSON, D., HICKMAN, J.W. et al "WASH-1400 Insights Utilised in Assessing Alternative Containment Design". Proc.of "ANS Topical Mtg."Probabalistic Analysis of Nuclear Reactor Safety" Newport Beach, May 1978. Vol.3.

10. US NUCLEAR REGULATORY COMM. "Safety Rsearch for LWRs". 1978.

11. GOSSETT, B., CAVE, L. et al. "Post Accident Filtration as a Means of Improving Containment Effectiveness". Ibid (Ref.4).

12. CYBULSKIS, P. et al. "Alternative Containment Systems for LWRs". Battelle Memorial Inst. Report BM12002 (Nurey CR-0138)

13. FINLAYSON, F.C. et al. "Alternatives to Underground Nuclear Power Plant Siting". Aerospace Corpn.Rep.ATR-77(7652)-1.

14. FREWER, H. "Experience with Nuclear Power Plant Siting and Safety Criteria in the FRG. BNES Jnl.14, 3, p.191.

15. Private Communication. I WARD (NPC) - L.CAVE. Sept.1978.

16. GENERAL ATOMIC CO. "HTGR Accident Initiation and Progression Analysis ("AIPA Study") Vol.9.

17. CAVE, L. and HALLIDAY, P. "Suitability of Gas Cooled Reactors for Fully Urban Sites". BNES Symposium on "Safety and Siting" London March 1969.

18. KASPER, K. and REDONDO, J.A. "Systemverhaltensmodelle zur Analyse Hypothetischer Storfallsequezen Bein HTR". Reactortagen 1977. Mannheim, March 1978.

19. USAEC "An Assessment of Accidental Risks in US Commercial Nuclear Power Plants. WASH-1900. First Draft 1973.

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REFERENCES Continued....

20. WALL, I.B., YANIV, S.S. et al. "Overview of the Reactor Safety Study Consequence Models". Proc. of International Conf. on Nuclear Systems Reliability Eng. and Risk Assessment. Gattenburg, Tennessee. June 1977 (Nureg - 0340).