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Quantitative Risk Assessment ; the promised but not the sacred

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I. INTRODUCTION

To begin with I would like to point out that it is not my intention to analyse in great detail the quantitative data and methods used in WASH-1400. Such comments and recommendations for improvements have been made by various organizations in the USA and from abroad as well on the preliminary version of the report as on the final version. I think that all those that have advocated for some time a more quantitative approach in nuclear safety ought to be satisfied at the considerable effort made through the study and at the result.

Using an European expression, we may be "shooting at the man playing the piano", but in fact for a lot amongst us it is a hidden way of expressing our admiration and gratitude.

Also in presenting a number of data and expressing opinions I will not confine myself to the WASH-1400 but cover probabilistic methodology and risk assessment in general and also refer specifically to some other studies of similar nature.

The opinions expressed here do not necessarily reflect the views of the Commission of European Communities

II. THE PRESENT AND FUTURE APPLICATIONS OF QUANTITATIVE RISK ASSESSMENT - GENERAL

For quite a number of years, quantitative risk assessment has been a discussion point in connection with the safety and health problems inherent in nuclear energy. It is almost superfluous to recall the pioneering work which has been carried out in this field by R. FARMER since about 1967.

It is mainly in the past two years, however, that considerable attempts have been made to arrive at a still more quantitative assessment of the risks associated with the peaceful use of nuclear energy and at a comparison of these with other risks to which man is exposed in an industrially developed society.

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Studies of this nature, which are based largely on probabilistic methods, are sometimes concerned only with risks resulting from the occurrence of accidents in nuclear power stations (BWR and PWR): such is the case, for instance, with the WASH-1400 study (ref. 1, 2, 3) and the "Swedish Urban Siting Study" (ref. 4). At times they deal both with the risks resulting from normal operation and those resulting from accident conditions and embrace not only nuclear power stations but also certain parts of the fuel cycle: examples are the studies carried out in the Netherlands in 1975, such as the "Risicoanalyse van de splijtstofcyclus in Nederland (RASIN)" (Risk analysis of the fuel cycle in the Netherlands) (ref. 5) and the report on "Kerncentrales en Volksgezondheid" (Nuclear power stations and public health) (ref. 6).

Although these quantitative assessments provide interesting and valuable indications concerning the comparative risks, it is in my opinion also necessary to exercise great caution regarding the interpretations and applications of the quantitative data used and obtained. These methods of analysis offer a wide range of possibilities but also suffer from the many restrictions they impose.

It will no doubt be possible to determine in the short term the effects of the application of this kind of analysis and the results in the following areas:

a) optimization of the projects in respect of redundancy, separation and diversity of equipment (vital equipment, emergency equipment in particular) ;

b) optimization of the operating conditions, particularly regarding inspection and testing ;

c) improved appraisal of the importance of certain systems and components and the fixing of priorities in the field of safety research.

It is noteworthy that the initial purpose of WASH-1400, i.e. to provide the public with objective data on nuclear power risks has failed entirely: it has become a source book for controversy. The reason is that the approach has up to now not been understood by the public and perhaps never will be because of its level of technicality.

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In the medium and long term, the results of these studies will probably have their influence on the technical aspects of the licensing procedures, such as: the inclusion of revised requirements in the provisions governing the redundant design of equipment; the inclusion of revised requirements concerning quality assurance for certain vital or emergency equipment, etc. In this connection, an important question is whether and to which extent the results of these studies will influence site evaluation and criteria and emergency planning in the case of serious accidents. And this is a question to which I will address myself more in particular later.

Future, more sophisticated, studies of this kind will undoubtedly concentrate on the following difficult problems:

(i) the influence of the "human error" in design, manufacture, assembly, quality assurance and control, operation, maintenance and repair, inspection and periodic testing of the equipment;

(ii) the common mode failure of various components or systems due to a single cause of internal origin (e.g., fire, corrosion, common mode failure of a type of equipment) or of external origin (e.g., air crashes, explosions, sabotage).

Furthermore, if probabilistic studies are to be developed correctly they must be supplemented with improved statistical data on the failure of equipment, particularly mechanical and electro-mechanical components and structures of which there are limited examples in operation or which are made in limited amounts.

III. RESTRICTIONS AND POSSIBILITIES OF RISK ASSESSMENT

I would like to start off with summarizing in brief a first series of considerations which tend to mitigate the degree of applicability of risk assessment and risk comparisons ; in other words I am starting from a critical angle indicating generally what in my (and also others') view are some fundamental limitations and why such studies - or rather the interpretations to be made from them (their implications) - are not "sacred". Some specific examples of limitations are given in the latest part of the present paper.

1. The definition of risk, acceptable risk, benefit

The main fundamental difficulty lies in the definition of "RISK" and of what is an ACCEPTABLE (and ultimately ACCEPTED) RISK for instance if compared to a BENEFIT.

Various definitions of the term RISK have been used (e.g. ref. 7, 8, 9). In general they can be summarized sufficently by saying that

$$\text{RISK} = \frac{\text{PROBABILITY OF EVENT \& CONSEQUENCE}}{\text{SPECIFIED TIME INTERVAL}}$$

Contrary to what is the case in economics (losses, benefits), the RISK has here an inherent negative (damage) aspect. RISK can also be expressed as a DAMAGE FREQUENCY RATE ; it is a terminology sometimes used in assessment of conventional (e.g. chemical) industry risks, such as the Fatal accident frequency rate (F.A.F.R.) used by GIBSON (ref. 10).

Both EVENT PROBABILITY or FREQUENCY and DAMAGE are usually accompanied by an uncertainty factor and this is taken account of e.g. in the more strict and general definition given by OTWAY (ref. 8) (see section III 3.2. 3° of present report).

The probability of events and the specified time intervals are straight forward notions which can be clearly defined (leaving aside the question of validity of the values used) ; however very often the consequence (damage) factor is insufficiently explored in detail.

For instance damage may refer to injury to human beings ; the injury in this case may vary from

- minor annoyances and discomfort
- to disabilities that cause reduction in normal activities (called morbidity by C. STARR)
- to loss of life (mortality or fatality).

Mostly damage to human beings is the main parameter in risk assessments for evident humanistic reasons. However if the goal is finally also to assess the benefits, then other objects of damage have to be included such as :

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- the insurance of the damaged human beings
- animal and plant-life
- buildings and pieces of art
- goods.

Also mortality is usu ally the most referred to parameter ; however C.STARR (ref. 7) also draws the attention to the fact that the less visible morbidity may be much more important in terms of humanistic, economic and social values. And this is an argument which highlights the need for risk assessments not only in the area of potential accident-conditions but also in the area of normal operation.

2. Factors of uncertainty

2.1. Public (or societal) risk versus individual risk

Although public (or societal) risk is the straight forward averaging of individual risk over a large group of population, the conversion from one to the other, in both directions, is sometimes a debatable exercise, like e.g. in the case of assessing genetic effects.

2.2. Averaged and predicted risks

The risks are expressed in average values or in expected (or predicted) values, depending whether the assessment stems from true statistical data or from predicted values. Predictions will always inherently have an error band. So if one accepts the saying "there are lies, damn lies and statistics", I wonder how predicted (i.e. non or partly- statistical) values might then be qualified.

2.3. Exposure time to risk

The "specified time interval"used for the risk analysis is mostly a year-period, probably because people understand more clearly, and because the exposure time often equals that period. Sometimes the specified risk is expressed per hour of true exposure time (e.g. ref. 9 and 10). The conversions from one to the other sometimes lead to misinterpretations.

2.4. Transition from risks to benefits

With regard to RISK/BENEFIT ANALYSIS, difficult points are :

- the non-random distribution of risks and benefits
- possible futur risks (e.g. genetic) where benefits are realized at the present moment.

(ref. 8)

3. ACCEPTABILITY OF RISK

3.1. What does it mean ?

RISK ASSESSMENT can be subdivided in RISK ESTIMATES and RISK EVALUATION (ref. 8).

So far I have spoken about RISK "ESTIMATES".

Most people using quantitative approaches such as those discussed here, will probably agree that this does not mean that these methods are fully objective. There always remains an element of human judgement in both the earlier mentioned factors (i.e. probality of event and consequence). Therefore rather than to speak about objective and subjective ways of appraising RISK, it is more appropriate to speak about formal and intuitive methods.

If we want to make the step to the ACCEPTABILITY and ACCEPTANCE of RISK, the RISK ESTIMATE must be complimented by a RISK EVALUATION and by a BENEFIT ANALYSIS. RISK EVALUATION means the determination of the meaning or value of the ESTIMATED RISK to those affected (individual, group, society). It is a process of ranking risks so that their total objective and subjective effects may be compared (ref. 8).

One may also call this RISK PERCEPTION.

I do not intent to deal much with this aspect because I feel that - if we have already numerous difficulties in RISK ESTIMATE exercises - we are with RISK EVALUATION (or PERCEPTION) entering in an even more complex area. Furthermore RISK EVALUATION should be connected to BENEFIT ANALYSIS (or ESTIMATION + EVALUATION) and how this is consequently bridged at the present moment is not at all clear to me.

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3.2. Influencing factors

Let me elaborate on some very difficult not fully resolved or even sometimes unresolved points in RISK EVALUATION (or PERCEPTION) therefore also in societal behaviour, risk acceptability and risk acceptance :

1° voluntary versus involuntary exposure

A typical voluntary risk is driving a car ; a typical non-voluntary risk is having a nuclear power plant near your home.

Inherently voluntary risks are better accepted than involuntary ; according to STARR (ref. 7) 1000 times better ; however this figure has been much argued about.

A rather involuntary risk is the statistical risk of death from disease ; STARR proposes it as a psychological yard-stick for establishing the level of acceptability and acceptance of other risks.

For instance an averaged involuntary risk can be considered as follows.

Excessive	if	$>$	disease mortality risk	$(= 10^{-2})$+)
High	if	$\simeq$	" " "	$(= 10^{-2})$
Moderate	if	$\simeq$	$\frac{\text{disease mortality risk}}{10 - 100}$	$(= 10^{-3} - 10^{-4})$
Low	if	$\simeq$	mortali y risk from natural causes	$(\simeq 10^{-6})$
Negligible	if	$<$	mortality risk from natural causes	$(< 10^{-6})$

It may also be recalled that "conventionally" an overall attitude of society to risk-conditions (voluntary or unvoluntary) is roughly as follows :

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+) individual annual risk

- an individual mortality-risk of 10^{-3}/year or more is generally considered unacceptable and systematic steps must be taken to try to reduce it (e.g. health organization, medical care, etc.)
- at a risk of 10^{-4}/year we are prepared to spend money (generally public money to eliminate the causes of accidents or mitigate their effects (e.g. traffic signals, publicity of police, fire precautions, etc.)
- at risks lower than 10^{-5}/year, the risks are generally of no concern any more ; they are considered on an individual basis and combatted by individual warnings (e.g. fire-arms, swimming, etc.)
- risks of the order of 10^{-6} or lower do not worry the populations ; they are accepted in a fatalistic way.

2° <u>Statistical versus individual risks</u>

Bowen (ref. 11) pointed at this problem while introducing also a proposal for risk-benefit assessment based on the "life-expectancy" concept.

The difference is shown by e.g. the effects of an accidental stack release of several hundred of curies of iodine leading perhaps to one or two cases of thyroid carcinoma amongst the several thousands affected (statistical risk) as opposed to a severe toxic gaz or large quantity (of the order of 10^4 - 10^5 curies), ground level radioactivity release affecting clearly the nearby population (individual+) risk).

According to Bowen risk acceptability criteria for severe accidents should be essentially based rather on "individual" than on "statistical" risks.

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+) bearing in mind that this risk still has statistical aspects.

3° Infrequent large consequence-events

a) Their significance, the types

A most difficult item in risk assessment is the potential of large-consequence but infrequent accidents (rare events).

To illustrate it bluntly with extreme hypotheses, an accident probability of 1/year with a consequence of 1 dead implies statistically the same risk as an accident probability of 10^{-6}/year with a consequence of 10^{6} dead.

That is also a reason why a strict and generally applicable definition of risk, as pointed out also by OTWAY (ref. 8), must be borne in mind ; i.e. RISK is a functional combination of :

- EVENT PROBABILITY and the UNCERTAINTY of the PROBABILITY
- the PROBABILITY of a specific CONSEQUENCE, assuming the EVENT has occurred, and the UNCERTAINTY of that PROBABILITY.

Furthermore there are different types of rare events.

There are those which are a rare combination of independent occurrences each with their own probability. These can be treated by usual risk analysis.

There are accident conditions which can be caused by one rare event. Such an event can be random, such as a meteor or an aircraft crashing on a nuclear plant ; such an event can also have a deterministic+) cause and course such as a pressure vessel rupture. If the first type of rare event can be handled in a probabilistic way, the second type must be treated with much precautions.

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+) influence of the history of design, manufacture, quality assurance, operation, inspection efficiency ; in other words all factors bearing the burden of human error and the difficulty of quantifying with sufficient precision probability connected to it.

b) Parameters for acceptability

A few years ago it was advocated that an individual yearly mortality-risk (additionnal) of 10^{-5} should be good enough (ref. 12). Now 10^{-7} is advocated and this value refers e.g. to the psychological acceptability and acceptance criterion referred to earlier (section 3.2. 1° of present report).

It has sometimes also been suggested (ref. 13) that a target criterion could be that the probability of an individual receiving an "emergency reference level" (E.R.L.) dose should be less than 10^{-7} per year. However this does not seem in conformity with the intent of such E.R.L.-doses as defined for instance by the British Medical Research Council. Remedial measures at or above such E.R.L.-levels have to be neighed against the prevailing situation at the site (e.g. risks due evacuation, mode of transport, etc.).

For accident conditions, it seems somewhat easier to discuss in terms of "frequency of events" than in terms of "mortality" or "bodily damage" (or morbidity)-risks. Let us therefore proceed further in that way.

It is generally considered unlikely that severe accidents which would result in a release of the order of $10^4 - 10^5$ curies of I-131 and associated volatiles would lead to one dead in the environs. The expense (decontaminations, etc.) would be high of course, but human damage still low.
Roughly speaking those of concern in this context here are essentially releases equivalent to $10^5 - 10^7$ curies of I-131, on an average (depending on the site conditions) leading to hundreds of dead over a 10 - 20 year period (ref. 12).
Such conditions are usually called "catastrophic". Should the acceptable frequency of such an occurrence be the same as that in the lower bound of "non-nuclear" major (catastrophic) accidents (e.g. dam ruptures, fires, chlorine releases) having

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similar consequences (i.e. also hundreds of dead) ? If this is the case a frequency of at least 10^{-3} events/year should be good enough. However looking at the future where as much as 10^{4} reactor-years may accumulate over the next decades, it is advocated to tend to a very much more stringent frequency value for the nuclear of 10^{-5} - 10^{-6} events/year.

Some (e.g. the USNRC) advocated earlier a target frequency value of 10^{-7} events/year arrived at as follows :

10^{-3} events/year averaged over all reactors assumed to be 1000 in number in the year 2000 in the USA

therefore : 10^{-6} events/reactor-year

safety margin 10^{-1} : 10^{-7} event/reactor-year.

I do not believe target value lower than 10^{-6} events/reactor-year are practical, nor are they necessary, taking account for instance of the severity with which the nuclear activities are handled.

Furthermore, as Bowen (ref. 11) has pointed out it is different to aim for a target of say 10^{-5} events/year or somewhat less at a 99 % confidence level or to aim for a 10^{-7} events/year without stating the confidence level. And in complex engineered systems - also subject to common mode failures and to the limitations which stem from the "deterministic" origin of the events - it is unlikely that such high confidence levels can be attained or maintained over the plant's life time.

Once more we connect up here with the strict and general definition of risk mentioned earlier (see section 3.2. 3°).

This is especially so for complex systems and components such as those applied in nuclear power plants.
For instance let us take 2 extreme accident initiating events and conditions for LWR's, respectively LOCA due to rupture of primary piping and LOCA due to pressure vessel rupture.

1) Primary piping rupture

Estimated frequency of

- pipe rupture	10^{-3} (till 10^{-5})
- non availability of ECCS	10^{-2} (till 10^{-4})
- consecutive failure (probably slow) of containment	10^{-3} (till 10^{-4})

Note : a) these estimations (ref. 14) concur in their highest values roughly with the analysis of WASH-1400 ;

b) I will conservatively refer to the highest values only.

This leads to a total sequence probability of events leading to "catastrophic" conditions of about 10^{-8} events/reactor-year; however there is in my view much uncertainty under those circumstances about the final effectiveness of containment ; so the probability of failure could there also equal 1 (being very pessimistic) which leads to a value of 10^{-5} events/reactor year.

2) Pressure vessel rupture

Estimated frequency of

- pressure vessel rupture	10^{-6} $\pm$ a factor 10 +)
- non-availability of ECCS	1
- consecutive (probably rapid) failure of containment	10^{-3} till 1

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+) Based for instance on pressure vessel reliability data put forward in

1) the report on the integrity of reactor vessels for LWR's - ACRS

2) technical report on analysis of pressure vessel statistics from fossil fuelled plants service, and assessment of reactor vessel reliability on nuclear plant service ; Regulatory Staff USAEC

3) the role of inservice inspection in the enhancement of primary boundary reliability ; by S. BUSH and W.C.HAM Battelle PNL ; paper presented ANS topical meeting Nuclear Safety 1975 October 5-8, Tucson.

This results in a total sequence probability of events leading to "catastrophic" conditions which varies from the very pessimistic to the very optimistic between 10^{-5} till 10^{-10} events/reactor-year ; but I would say the more reasonable range would lie between 10^{-5} till 10^{-7} events/reactor-year.

This is also the reason why structured protections against severe external accident initiating events (such as, for most sites, "commercial" aircraft random crashes) may be considered exaggerated, from the moment the probability of the event is much smaller than say 10^{-6}/year. Besides there is the fact that such a crash would not necessarily create a "catastrophic" release of radioactivity.

If one sticks to the conservative criterion of 10^{-6} events/reactor-year, than it seems justified that in some large areas especially in Western Europe military aircraft-activity (or - depending on the site - possibly commercial aircraft) is considered more seriously and protected against.

Finally still unresolved questions are :

- should money better be spent on higher frequency - less consequence accidents or on these low frequency - high consequence accidents ?
- Should non-nuclear activities with similar potential of severe consequence (e.g. chemical industry) be protected with the same stringent measures as the nuclear ? In my view - according to logic - yes. It is likely that the recently issued report by the Health and Safety Commission's Advisory Committee on major hazards in the UK (B. HARVEY-report) will be illustrative to that point (report not available to the authors at the present time). But of course then the question could be raised whether the nations really would have the ressources to raise the standard of non-nuclear hazardous activities to the same level as the nuclear (ref. 15).

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- Using Prof. WILSON's allegory (ref. 16), will the public continue to (and afford to) refuse an event-probability between 10^{-6} to 10^{-4} per year of running into a dinosaur in the Amazone-forest, and drown around Cape Horn ?

IV. APPLICABILITY OF WASH-1400 TYPE STUDIES IN THE FUEL CYCLE

It has been suggested already at some occasions to apply WASH-1400 type studies to the fuel cycle operations (outside the reactor).

My personal considerations and comments to this are :

1) the operations involved in the fuel cycle are much less automatied than in the case of reactors (operator decisions and interventions during the performance of operations). This will emphasize the uncertainties surrounding the probability factors affecting the event-frequency (or failure frequency) and the consequences and therefore the overall risk-estimates. The human error influence is even greater here than in the case of reactors.

2) Data banks from which informations can be drawn on failures of equipment (systems and components) similar to that used in the nuclear fuel cycle operations are few. To the best of my knowledge, the only existing data are those on the operation of conventional chemical works. With regard to accidents during transport, some probabilistic studies have been carried out on the frequency (actual and forecast) of accidents during transport of conventional (and sometimes nuclear) consignments in the US and the Federal Republic of Germany (e.g. ref. 17, 18).

3) Up to now, the input-data for studies of this kind have largely failed to satisfy the fundamental requirement that both the probabilities of disturbances of internal or external origin and their consequences should be quantified with sufficient precision (or not too large a margin of error). On the other hand, determination analyses of the consequences of postulated accident conditions have since long been carried out for the various stages of the fuel cycle.

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From this can be concluded as follows :

1° at the present stage of development, a study of the fuel cycle on the fuel cycle operations in the lines of the WASH 1400 report would be reasonably valid only if it confined itself to either the reprocessing operations or specific transport operations (excluding e.g. waste treatment operations).

2° With regard to reprocessing, it would have to relate to a specific plant. Owing to the non-standardization of much of the equipment and the various processes used, its extrapolation to other plants would raise much more serious difficulties than the extrapolation with respect to nuclear power stations as done in WASH-1400.

3° With regard to transport, it would first be necessary to examine further the data on frequencies of road, rail and air accidents (actual and forecasts).

4° A step-wise approach is therefore advocated by applying :

a) a comparative analysis of the consequence-factor for the various phases in the fuel cycle introducing to the extent possible data that would be available on the probability of abnormal events.

b) In the first step, examination of the products-hazards as opposed to operations-hazards such as fuel fabrication, reprocessing, waste treatment and transports.

It is significant and natural that first studies of this type were aimed at risk-estimates for transport operations (e.g. ref. 17, 18).

V. NUCLEAR RISKS IN NORMAL OPERATING CONDITIONS

This subject should be dealt with in a paper on its own. Besides it is not directly connected to the considerations of WASH-1400. Nevertheless it is to be considered also in the overall risk estimation of nuclear power, especially if one wishes to proceed quantitatively.

Let it suffice in this instance to summarize in a very crude (orders of magnitude) way the essentials of the situation deducted from recent analyses (ref. 19, 20 and 21).

It should be noted that in this area also still a lot of discussion is going on, which personally I find for a large part too academic because of the margins of safety mostly on hand especially with regard to the general public (not necessarily with regard to the professionally exposed).

Arguments which are not fully cleared for instance are :

- is it better to compare to global (overall)+) back-ground (radiation, somatic and genetic incidence) or is it feasible to compare validly to conventional pollutions (e.g. SO_2, NO_2, dust, etc.) where unknowns also subsist ?
- is the linear dose-effect relationship extrapolation to low-doses, really conservative e.g. with regard to the somatic effects ?

In the brief summary given here, comparisons refer essentially to the natural and global (overall) back-ground and the linear relationship is applied.

Also conservatively is referred to the population in the immediate environs of nuclear plants.

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+) The term "global" is preferred to "natural" here because I refer e.g. also to radiations from buildings, medical radiations, abnormalities from other causes than radiations.

TABLE 1

A. Populations (in the immediate environs of nuclear plant)

1. Genetic effects

Global existing risk of deviations	5.10^{-3}	in first generation
Risk due to natural back-ground (100 mrem/year)	10^{-5}	in " "
Additional risk due to 5mrem/year	5.10^{-7}	in " "
Gross margin with present global risk	10^{4}	

2. Somatic effects

Global existing risk of death due to cancer	2.10^{-3}	individual per year
Risk due to natural back-ground (100 mrem/year)	2.10^{-5}	" " "
Additional risk due to 5 mrem/year	10^{-6}	" " "
Gross margin with present global risk	$\sim 10^{3}$	

B. Professionally exposed

N.B. Assuming radiation limits of the order as recommended by ICRP e.g.

1. Genetic effects

Global existing risk of deviations	5.10^{-3}	in first generation
Risk due to natural back-ground	10^{-5}	" " "
10000 man-rem	10^{-4}	" " " (with uncertainty of factor 10)
Gross margin with present global risk	$\sim$between 5 and 500	

2. Somatic effects

Global existing risk of death due to cancer	2.10^{-3}	individual per year
Risk due to natural back-ground	2.10^{-5}	" " "
Risk due to death from leucemia (global back-ground)	5.10^{-5}	" " "
Risk due to death from other malicious tumour (global back-ground)	5.10^{-4}	" " "
Additional risk from 10 rem-dose		
- leucemia	10^{-5}	" " "
- other tumour	6.10-5	" " "
Gross margins with present global risks	between 5 and 10 ; equivalent to natural back-ground risk.	

Other comparative presentations have been made (e.g. ref. 9) but very crudely it can be noted e.g. that for normal operation of nuclear plants the yearly individual additional total risk of illness from malicious tumours is approximately 2.10^{-6} and that of leucemia 6.10^{-7}. These values can be put in perspective if one compares to mortality risks from our daily usual (non-nuclear) environment.

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TABLE 2

(partly ref. 9)

Origin	Yearly individual mortality risk
Professional activities	5.10^{-4} - 4.10^{-5}
Ground-traffic	about $3,5.10^{-4}$
House and free-time activities	2.10^{-4}
Serious illness	$2,5.10^{-3}$ - $8,7.10^{-6}$
All illness	5.10^{-3}
Smoking (smokers only)	5.10^{-4}

On the basis of preceding considerations can be noted :

1) the individual risk values lie for the population as a whole well in the range of low or negligible risks (see section III 3.2. 1° of present report).

2) For the professionally exposed they lie in the moderate or low range of risks.

3) The individual risk for the population as a whole is in normal operation about a factor 10000 higher than the risk from accidents (see section VI-1 of present report) ; however one should not be misled by this "apparently" surprising conclusion : it is typical of the extreme relationships between probability of event (e.g. very low, very high) and consequence (e.g. very low, very high) ; this problem has been hinted at in section III 3.2. 3° of the present report.

The opinion can therefore also be expressed :

1° that more emphasis should be placed upon the protection of the professionally exposed ; operational practice (e.g. ref. 22) demonstrates that this is an important item for improvements.

2° That integrated doses (the man-rem concept) will have to be applied more and more as a means of assessment and possibly requirement which is complimentary to individual doses.

3° That medium or long-term developments which are presently advocated in order to protect the population (typical examples are the retention of Tritium and Kr-85) should more carefully be weighed against the risks of not doing it and the benefits (and costs) of doing it.

I for my part tend to argue :

- that even on a long-term forecast basis it is not (contrary to the present belief) the global universal effects of these long-life isotopes which can justify their retention ; perhaps the respect of dose-limits in the immediate vicinity of nuclear plants (especially high capacity reprocessing plants), yes ;

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- that the associated additional risks to the public by releasing them appears rather trivial ;
- that the additional risk to the professionally exposed and to the public by retaining them may finally become greater than by releasing due to e.g. necessity of treatment, storage, transport ; disposal of the corresponding solid waste-filter equipment ;
- that the relative costs should be considered according to OTWAY (ref. 8) reducing the Tritium releases by 50 %, using current technology would cost about $ 170.000 per man-rem ; the equivalent figure for Kr-85 retention would be $ 10 per man-rem ; a reasonable figure of $ 200 per man-rem is put forward as criterion in the mentioned reference.

VI. NUCLEAR RISKS IN ACCIDENT SITUATIONS IN COMPARISON WITH OTHER ACTIVITIES

1. Risk estimation in accident conditions

What are the risks in accident conditions in nuclear power stations (in the case of the LWR type, including "catastrophic" conditions), account being taken of the present situation in the United States ? (ref. WASH-1400, 1,2,3).

w are these risks to be compared with other risks which result from other human activities or from natural phenomena to which society is exposed ?

This is now well known and reported in WASH-1400 as revised. The following data are essentially a brief "digested" extract from WASH-1400.

TABLE 3

Average risk of fatality by various causes (United States); Ref. 2 (statistics for 1969)

Accident type	Individual risk per year		
Motor vehicle	$2{,}5 \cdot 10^{-4}$	1 in	4 000
Falls	10^{-4}	1 in	10 000
Fires and hot substances	$4 \cdot 10^{-5}$	1 in	25 000
Drowning	$3{,}3 \cdot 10^{-5}$	1 in	30 000
Firearms	10^{-5}	1 in	100 000
Poisoning+)			
(a) by solids and liquids	10^{-5}	1 in	100 000
(b) by gases and vapours	$8 \cdot 10^{-6}$	1 in	125 000
Air travel	10^{-5}	1 in	100 000
Falling objects	$6 \cdot 10^{-6}$	1 in	160 000
Electrocution	$6 \cdot 10^{-6}$	1 in	160 000
Lightning	$8 \cdot 10^{-7}$	1 in	1 200 000
Tornados	$4 \cdot 10^{-7}$	1 in	2 500 000
Hurricanes	$4 \cdot 10^{-7}$	1 in	2 500 000
All accidents	$6 \cdot 10^{-4}$	1 in	1 600
Nuclear reactor accidents (100 stations)	$2 \cdot 10^{-10}$	1 in	5 000 000 000
	(NB 1 in 300 000 000 = $3 \cdot 10^{-9}$ in the first version of WASH-1400)		

+) Ref. 8.

It is necessary to make the following comments on the figures quoted:

1. Whereas the figures concerning conventional risks are based on statistical data, the figures concerning the nuclear risk are derived from the above-mentioned predictive probabilistic study (owing to a lack of statistical data on accidents);

2. The figure of $2 \cdot 10^{-10}$ in respect of nuclear reactors embraces the population of the United States in the vicinity of 100 stations on 68 sites the operation of which is planned for 1980 (this population being about 15 million);

3. In the first version of the WASH-1400 report the individual immediate risk of fatality was evaluated at $3 \cdot 10^{-9}$ and was calculated on the above-mentioned 15 million people. The difference results from the more sophisticated approach in the new analysis. (It is merely a coincidence that the individual risk expressed for the entire population of the US (200 million) in this case also yields the same figure, i.e., $2 \cdot 10^{-10}$).

TABLE 4

Approximate average risk per year from potential nuclear station accidents (100 stations in the US) (Ref. 3)

Effect	Societal	Individual
Early fatalities (a)	$3 \cdot 10^{-3}$	$2 \cdot 10^{-10}$
Early illness (a)	$2 \cdot 10^{-1}$	10^{-8}
Latent cancer (b)	$7 \cdot 10^{-2}$ 2 in total +)	$3 \cdot 10^{-10}$
Thyroid illness (b)	$7 \cdot 10^{-1}$ 20 in total	$3 \cdot 10^{-9}$
Genetic effects (c)	10^{-2}	$7 \cdot 10^{-11}$

+) assumed occurrence over thirty years.

NB: the individual risk is equal to the risk for the society in question divided by:

(a) the 15 million inhabitants in the immediate vicinity of the power stations

(b) the 200 million inhabitants of the US over a period of thirty years after the potential accident

(c) the 200 million inhabitants of the US over the first generation.

4. There is an element of uncertainty attached to these figures, with regard to both probability of event and consequence (see section III. 3.2.3º of the present report). These uncertainty factors in respect of the nuclear figures are in the order of 1/4 to 4 for the consequences and 1/5 to 5 for the probability.

5. Latent cancers do not necessarily cause death; thyroid illness can be medically treated and in 90% of the cases is benign.

6. The comparison applies only to the effects with fatal consequences. The individual overall risk of injuries or diseases as a result of conventional accidents is in the order of magnitude of $2 \cdot 10^{-2}$ per year.

7. The number of extra cases of delayed effects of cancer and genetic effects is likely to be hidden by the number of these cases which would normally occur.

One can make a rough extrapolation of the most recent results of the WASH-1400 study to the foreseeable situation in a specific country, e.g. in Belgium in 1985. This yields the following results:

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TABLE 5

United States (Ref. WASH-1400 - revision)

No of stations: 100

Population : 15 million in general vicinity of nuclear power stations out of a total population of 200 million

Overall risk (per year) of fatal consequences (i.e., whether immediate or delayed, assuming that all delayed effects result in death)

$= 3 \,.\, 10^{-3} + 7 \,.\, 10^{-2} = 7 \,.\, 10^{-2}$

Thyroid illness (without medication)

$= 7 \,.\, 10^{-1}$

Genetic effects $= 10^{-2}$

Belgium Number of power stations: 10

Population : about 10 million (in the vicinity of nuclear power stations, and total)

Overall risk (per year) of fatal consequences

= about $7 \,.\, 10^{-3}$ (individual $= 7 \,.\, 10^{-10}$)

Thyroid illness

$= 7 \,.\, 10^{-2}$ (individual $= 7 \,.\, 10^{-9}$)

Genetic effects $= 10^{-3}$ (individual $= 3 \,.\, 10^{-10}$)

From the foregoing we may conclude (which is already widely known)

1. The overall risk of an accident with fatal consequences (i.e., whether immediate or delayed) is less by a factor of 10 000 to 100 000 than the risk of an accident with immediate fatal consequences resulting from a number of conventional man-made activities (e.g., air travel, motor vehicle traffic).
2. The order of magnitude of these individual risks is by far less than 10^{-6} (individual risk per year), at which there is, generally speaking, no particular reason for worry (see section III. 3.2.1° of present report).

By way of illustration, these reflections can once more be considered from a somewhat different angle and be compared roughly with the results of similar studies carried out in the Netherlands (for an installed capacity of 3 500 Mwe or five power stations) (Refs. 5 and 6).

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TABLE 6

Probability of a reactor accident involving core melt (most serious hypothesis) (probability of event per reactor year)	WASH-1400	Studies carried out in the Netherlands
1. Resulting in < 1 acute death in the general vicinity	$5 . 10^{-5}$	$1 . 5 \times 10^{-5}$
2. Resulting in > 10 acute deaths in the general vicinity	$3 . 10^{-7}$	$10^{-6} - 10^{-5}$
3. Resulting in > 100 acute deaths in the general vicinity	10^{-7}	$10^{-7} - 10^{-6}$
4. Resulting in > 1 000 acute deaths in the general vicinity	10^{-8}	$10^{-7} - 10^{-6}$

It must be pointed out that the studies carried out in the Netherlands envisage a limited evacuation within a radius of 1.5 km around the power station (at least in the study by the Health Council), whereas the American study envisages a larger-scale evacuation.

Expressed in terms of about 10 power stations (forecasts in Belgium), the situation is roughly as follows:

TABLE 7

Probability of a reactor accident involving core melt (probability of event per reactor year)	
- Resulting in > 10 immediate deaths in the general vicinity	$10^{-5} - 10^{-4}$
- Resulting in > 100 immediate deaths in the general vicinity	$10^{-6} - 10^{-5}$
- Resulting in > 1 000 immediate deaths in the general vicinity	about 10^{-7}

These figures can also be compared (Ref: studies carried out in the Netherlands) with certain conventional dangerous occurrences:

TABLE 8

Probability of a rupture of a chlorine tank resulting in > 100 immediate deaths	$1.5 \cdot 10^{-2}$ per year
Probability of an aircraft crash on a crowd resulting in > 100 immediate deaths	$1.2 \cdot 10^{-2}$ per year
Possibility of flood disasters after the Delta works have been completed (several hundred deaths)	$1\text{-}2.5 \cdot 10^{-4}$ per year

2. VARIOUS RISK-CATEGORIES IN POTENTIAL RADIATION BURDEN ON THE ENVIRONMENT DUE TO ACCIDENTS

Most of you are aware of the report of the Commissie Reactorveiligheid (Reactor Safety Committee) in the Netherlands.

It will suffice here to adduce only one of its most important conclusive data derived through WASH-1400.

TABLE 9

Radioactivity released in the event of an accident, in function of the probability of occurrence (frequency)					
Releases of activity into the atmosphere (x 1 000 Ci)	frequency in 10^{-6} per year (1st line)				
	core melt			no melt	
	1 X	15 X	60 X	100 X	400 X
Noble gases	250 000	120 000	900	110	30
Iodine	250 000	15 000	5	0.15	0.012
Caesium, rubidium	5 500	400	0.1	-	-
Tellurium	60 000	5 600	2	-	-
Strontium, barium	19 000	1 300	0.3	-	-
Ruthenium	10 000	1 300	0.3	-	-
Others	5 000	700	0.3	-	-

The Committee concluded that the results of the Rasmussen study concerning a reactor core melt, which it considers to be an extreme type of accident, can be summarized in three representative discharge categories, each with its own probability of occurrence. As regards the reliability uncertainty of the data presented, it is stated that the possibility of occurrence may deviate by a factor of three. The given quantities of discharged noble gases and iodine are the most reliable; these quantities may vary by at least a factor two for other nuclides.

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VII. CURRENT PRACTICE APPLIED IN ACCIDENT EVALUATION - TECHNICAL IMPLICATIONS ON EMERGENCY PLANNING

Hitherto, it has been customary to adopt a so-called deterministic approach to analyses of accident situations.

A series of reasonably conceivable accidents are analysed. The theoretically calculated consequences of the most serious accidents are then used as input for the planning of emergency measures.

Generally speaking, in Western countries - with a few possible variations - the practices which are summarized in Appendix E to the USNRC's 10 CFR 50 are adhered to for intervention in case of an accident. I may mention that these were implemented further at the end of 1975 in "Regulatory Guide (Div. 1 No 101) for Emergency Planning".

Let me take as specific example of analysis as applied in Belgium. The analysis carried out on this basis of the various conceivable accidents for a pressurized water reactor showed that two of these accidents are determining as to the external consequences, namely, rupture of the primary circuit and an accident in the course of fuel handling (it is to be noted that with German designs the latter accident condition would not be a determining accident condition for the environs).

The analyses of this accident situation may differ somewhat from one reactor plant to another (depending, for instance, on some specific features of the secondary safety containment) but roughly speaking they are all of the same order of magnitude.

Below are the data assumed for Doel 1 and 2 (Ref. 23).

1) For rupture of primary circuit and loss of coolant

Two hypotheses are usually assumed

(a) realistic hypothesis

Because of the efficiency of the emergency cooling system, the release of fission products into the safety containment is confined to the gap release (between fuel and clad) of 100 % of the fuel elements.

(b) pessimistic hypothesis

This hypothesis considers the melt of the complete fuel charge without impairment of the integrity of the containment (again with the realistic and pessimistic parameters regarding efficiency in the case of release into the environment).

The realistic and pessimistic parameters are given in Table 10 below.

TABLE 10

	Pessimistic hypothesis	Realistic hypothesis
Fraction of core activity released into containment		
- noble gases	total	pellet-clad gap
- iodine	25 %	1/2 pellet-clad gap
Abundance of forms of iodine for calculation of inhalation doses		
- inorganic	90 %	90 %
- organic	10 %	10 %
for calculation of milk ingestion doses		
- inorganic	100 %	100 %
Leakage rate		
- primary containment	0.25%/day	0.10%/day
- secondary containment	10%/day	10%/day
Efficiency of iodine filters in intermediate gap		
- inorganic	90%	90%
- organic	10%	10%

In view of the retention effect of the secondary containment and on account of the ventilation filters, the short-lived solids and the halogens, with the exception of iodine, can be ignored, leaving only the isotopes of iodine, xenon and krypton to be taken into consideration.

The following calculations were made for the release of activity into the atmosphere:

	Pessimistic hypothesis	Realistic hypothesis
noble gases (Xe-133 equivalent)	606 000 Ci	17 500 Ci
iodine (I-131 equivalent)		
(a) inhalation	216 Ci	8.6 Ci
(b) uptake	156 Ci	6.7 Ci

On the basis of these activities and taking account of pessimistic and realistic meteorological coefficients, the following individual doses were calculated for the immediate vicinity:

	Pessimistic hypothesis	Realistic hypothesis
Whole-body	0.10 rem	2.8 10^{-3} rem
thyroid nodules (child)		
(a) inhalation	0.5 rem	0.02 rem
(b) uptake in milk	83 rem	3.6 rem

The figures for the thyroid nodules assume that, in the case of excessive contamination, milk would not be confiscated, and this, of course, is a hardly conceivable hypothesis.

2) <u>For an accident in the course of fuel handling</u>

The accident hypothesis considers the drop of an irradiated fuel element into the spent-fuel which is located outside the containment; it is assumed that all element rods break. Again the pessimistic and realistic hypotheses are assumed; these are presented in the following table.

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TABLE 11

	Pessimistic hypothesis	Realistic hypothesis
Fraction of rods destroyed	100%	100%
Time-lag after reactor shutdown	100h	100h
Fraction of assembly's activity in pellet-clad gap		
- noble gases	10%	5%
- iodine	10%	6%
Fraction of assembly's activity released into water		
- noble gases	10%	5%
- iodine, of which:	10%	1.2%
- inorganic	99.75%	99.75%
- organic	0.25%	0.25%
Water retention factor		
- noble gases	1	1
- inorganic iodine	133	760
- organic iodine	1	2
Fraction retained in iodine filters		
- inorganic	90%	90%
- organic	70%	70%

The following activity is released into the atmosphere:

	Pessimistic hypothesis	Realistic hypothesis
Xe-133 equivalent	48 000 Ci	24 000 Ci
I-131 equivalent		
(a) inhalation	37.5 Ci	1.5 Ci
(b) uptake	18.7 Ci	0.4 Ci

This yields the following doses:

	Pessimistic hypothesis	Realistic hypothesis
whole-body	0.07 rem	0.03 rem
thyroid nodules (child)		
(a) inhalation	0.8 rem	0.03 rem
(b) uptake in milk	870 rem	1.5 rem

It is again assumed that there is no check on milk consumption.

The foregoing calculations were carried out according to the American model with the exception of the meteorological data; the uptake from milk contamination is usually not taken into consideration in the American calculations.

It is obvious from a comparison of the accident situation involving a rupture in the primary circuit with the data contained in Table 9 (Committee on Reactor Safety in the Netherlands) that the pessimistic accident parameters referred to here more or less correspond to the case of a core-melt accident, having a probability of occurrence (frequency) of about $6 \cdot 10^{-5}$ per reactor year. The realistic accident parameters used above correspond to the accident situation having a probability of about $4 \cdot 10^{-4}$ per reactor year (without core melt); in other words, these are the most probable parameters for both cases (with and without core-melt).

In any event, accidents of this nature (with relatively reduced consequences) with probabilities of occurrence of this order of magnitude do not necessitate evacuation measures; it is sufficient for a check to be made on the milk consumption.

VIII. COMPARISON OF POTENTIAL CONSEQUENCES OF "THE MOST SERIOUS" (CATASTROPHIC-TYPE) ACCIDENT IN A PWR AS PRESENTED IN RECENT STUDIES - IMPLICATIONS FOR SITING AND EMERGENCY PLANNING

1. Comparative data

Table 2 below presents some comparative data. In addition to the studies mentioned above (Refs. 1, 2, 3, 5, 6 and 8), account is taken of the Swedish Urban Siting Study (SUSS - Ref. 4), and more particularly of a relevant comparative study (Ref. 24).

TABLE 12

Possible consequences of the most serious accident in a PWR as presented in recent studies

		Dutch Health Council (Ref. 6)	RASIN[4] (Ref. 5)	WASH-1400 (Ref. 3)
Evacuation		1.5 km	5 km	-
Risk per reactor year		$1 \cdot 10^{-6}$	$5 \cdot 10^{-6}$	$8 \cdot 10^{-6}$
Acute death probability[2]			28-129	350-6 200[1]
	70%	0-50		
	10%	50-500	(average	
	10%	500-2 000	for all	
	10%	2 000-10 000	weather	
			conditions)	
	maximum	40 000		
Man-rem		$2.5\text{-}30 \cdot 10^6$	$0.96\text{-}2.7 \cdot 10^6$	
Latent cancer deaths[3]		500-6 000	96-270	probability
				10^{-6} 200
				10^{-7} 15 000
				10^{-9} 42 000
Source of information		Health Council Table 6.2 (release category PWR-2) +)	RASIN Part IV-B Table 7.5-4 (release category PWR-2) ++)	WASH-1400 Table VI 13-6 Figure VI 13-33 (release category with approximately the same consequences as PWR-2 or accident with minimum consequences)

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[1]The figure is dependent on the result of evacuation and applies to unfavourable weather conditions.

[2]The probability is determined by weather conditions.

[3]Calculation carried out by the Health Council: 200 deaths per 10^6 man-rem; RASIN 100 deaths per 10^6 man-rem; WASH-1400 presents a more differentiated breakdown by taking account of the man-rem distribution over the population in question, and this gives rise to Fig. VI 13-33. In the foregoing it is assumed that X latent-cancer fatalities per year yields a total of 30 X cases of latent cancer per year for a period of 30 years (see last paragraph, pages 13-39 and Fig. VI 13-26 (Annex 5)).

[4]For the sake of simplicity the site of Diemen was not taken into consideration.

+) Appendix I

++) " II

Remarks concerning Table 12

1. The consequences of the most serious accidents as calculated in SUSS are not included in the foregoing table. These can be only roughly assessed from the following summary:

   There is a risk of 10^{-10} per year that 0-10 deaths occur in the case of a restricted 2 km population zone and 0-300 deaths in the case of a similar 0.5 km zone.

   Latent effects (cancer, genetic) may occur to such an extent that they can be distinguished from the normal occurrence of these phenomena.

2. The various tables and graphs in the afore-mentioned reports point to consequences other than those mentioned in the table above (genetic effects, thyroid nodules, radiation diseases). These effects are important but they are closely related to the figures already included here in the tables. In order not to complicate matters I have not devoted any attention to them.

3. The failure probabilistics and the release categories applied in WASH-1400 were used in the RASIN study (see Part IV-B, page 498).

2. Evacuation in such extreme cases

The Health Council considers evacuation up to 1.5 km.

RASIN (Ref. 5) considers evacuation up to 5 km for a half-life of nine hours. RASIN makes particular mention of the fact that in the case of Borssele, PWR-2, evacuation would not have much effect (136-129 "acute" victims) because not many people live within a radius of 5 km. It would have been interesting to know the effect of a power station in a more densely populated region (see pages 549-550 and Tables 7, 5 and 6 in Part IV-B).

WASH-1400 takes a weighted average of the following possible measures:

- no evacuation (most people indoors)
- an ineffective evacuation (most people outdoors), speed 0 mph
- effective evacuation, speed 1.2 mph
- effective evacuation, speed 7 mph

The second of these possible measures may have the effect of increasing the number of "acute" victims by a factor of 3 or 4.

WASH-1400 recommends further study concerning evacuation models (see App. VI, pages 13-34, Table VI 13-6).

SUSS (Ref. 8 and 24) does not consider evacuation, because it does not believe it would be effective. It presents the following rough calculation: 2-2.5 hours necessary for the order to evacuate; 5-6 hours to evacuate 75% of population; a week in order to evacuate the entire population (S-483, page 27).

It becomes therefore clear that if accident conditions and possible evacuation measures of this type are to be included in emergency planning, different conditions must be considered for each individual site. In such hypothetical and most exceptional situations, it may perhaps be safer to remain indoors and to breathe through a wet cloth (ref. 5 RASIN Study). In addition, the various hypotheses for reactor core melt in the period of time in which this occurs may influence the radioactive cloud formation to such an extent that, on the basis of theoretical models, evacuation may be taking place when exposure is at a maximum.

3. Conclusions

To sum up the implications of quantitative risk assessment studies such as WASH-1400 or other WASH-1400 inspired studies on siting practices and emergency planning, the following observations and opinions are put forward:

1) The potential nuclear reactor accident situation has in theory a very wide range of possible frequencies of occurrence and of consequences, as shown quantitatively by the recent risk-analyses.

2) Past and current practice mostly rules out certain "catastrophic"-type accident conditions for the purposes discussed here.

3) There is however a tendency developing in various countries to include the severest most unlikely accident conditions in siting practice and emergency planning.

   This attitude seems inconsistent with both the purposes and inherent possibilities and limitations of risk-estimate studies.

4) The translation of the potentially most hazardous situations into practical considerations (e.g. in emergency planning) implies that, logically speaking, the same should then - with far more reason - be applied where the risks are higher by a factor of approximately 1000 or more, i.e. in certain conventional activities.

5) Logic would also require that specialized medical assistance (radiation diagnosis and therapy) should be available to cope with such nuclear catastrophic-accident situations and the fact is that sufficient human and material resources are not available except perhaps if a joint civil-military ad hoc international emergency organization were set up. It could also be that if the idea were developed to set up such an intervention task-force in stand-by position, that it would have to wait 100 000 years before being called upon.....

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IX. CONCLUSIVE REMARKS

It is interesting to note two highly qualified overall appraisals on quantitative risk assessment one coming from someone who has been active in the nuclear area, another in the conventional area.

Farmer said (ref. 25)

"The accuracy of the quantification is less important often then the disciplin of the assessment exercise".

Gibson said (ref. 10)

"Although quantitative analysis is an art rather than a science and one that is still developing, I submit that the approach described here is a responsible, moral, but realistic and practical way of reconciling society's conflicting demands for an increasing supply of new products and materials and a reduction of risks to employers, the public and the environment".

MAIN REFERENCE MATERIAL

1) WASH-1400 Reactor Safety Study; an assessment of accident Risks in US Commercial nuclear power plants (draft 1976)

2) WASH-1400 Revision; Executive summary - Oct. 1975

3) WASH-1400 Revision; Main report - Oct. 1975

4) Swedish Urban Siting Study

5) Risico-analyse van de splijtstofcyclus in Nederland (RASIN), June 1975

6) Rapport Gezondheidsraad; Kerncentrales en volksgezondheid - September 1975 (Rapport Commissie Kernenergie 3500 MW)

7) A comparison of public Health Risks: nuclear versus oil-fired power plants; by C. STARR, M.A. GREENFIELD and D.F. HAUSKNECHT Nuclear News/October 1972

8) Social Values in Risk acceptance, by H.J. OTWAY, P. PAHNER, J. LINNEROOTH, rew. 1975; IIASA-RM-75-54

9) Die Bedeutung technischer Risiken, K.H. LINDACKERS; Reaktortagung 1974; Atomwirtschaft Juni 1974

10) Risk Criteria in Hazards Analysis; by S.B. GIBSON; Chemical Engineering Progress February 1976

11) Individual Risk vs. Public Risk Criteria; by H.H. BOWEN; Chemical Engineering Progress, February 1976

12) Accident probability criteria, by R.FARMER, Journal Inst. Nucl. Eng. - Vol. 16 No. 2, April 1975

13) Perspectives in Nuclear Safety; a special report on a joint meeting of the Society for Radiological protection and the institutions of Nuclear Engineers held 29 Jan. 1975; by J.R. LAKEY; Journal Inst. Nucl. Eng. Vol. 16 No. 2.

14) WASH-1250; the Safety of nuclear power reactors and related facilities (1973)

15) Testimony D. OKRENT before J.C.C.A.E. 1976

16) Letter Prof. R. WILSON in November 1975 issue of Bulletin of Atomic Scientists

17) The risk of transporting Plutonium Oxide and liquid plutonium-nitrate by truck, BNLW-1846 (1975)

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18) Probability and Consequences of transportation accidents involving radioactive material shipment in the nuclear fuel cycle; L.B. SHAPPERT, W.A. BROBST, and al. Nuclear Safety Vol. 14, No. 6 Nov. Dec. 1973

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20) Occupational and population radiation exposure from LWR operation; A. MARTIN, November 1975

21) Reports prepared by the "Commission o'évaluation en matière d'énergie nucléaire" for the Belgian Government, March 1976 (technical reports chapter V W. VINCK and chapter VI, MAISIN)

22) Occupational Radiation exposure at Nuclear power plants; Nuclear Safety Vo. 16, No. 5, Sept.-Oct. 1975

23) Safety evaluation studies Doel 1 and 2 (1972) - not published

24) Comparison of the draft of the US. Reactor Safety study and the Swedish Urban Study; J. BENTO, T. MANKAMO, S. VUORS - S - 483

25) Systems Reliability in high risk situations; Seminar held by S.R.S Risley Oct. 1974; reported SRS quarterly digest Jan. 1975

26) Systems Reliability in high risk situations; by D.M. HUNNS; N.C.S.R. Report 2 1974.

27) A new concept in risk analysis for nuclear facilities; by R. PAPP, P.E. Mc.GRATH, L.D. MAXIM and F.X. COOK, Jr; Nuclear News November 1974

28) The present and the future situation of nuclear energy production and its associated industry - normal operations, accident prevention and mitigation, comparative risk assessment; by W. VINCK and al.; EUR 5001 1973

29) Reflections on accident risks in reactors; by W. VINCK; paper presented at yearly Health Physics Society meeting, Belgium - 1976

30) The Nuclear Power Controversy in the U.S.A., R. WILSON; Physics Department HARVARD 1976

31) Report to the A.P.S. by the study group on light water reactor safety; Reviews of modern physics Vol. 47, supplement 1 1975

32) Planning for Nuclear Emergencies; by D. MOELLER and J.M. SELBY; Nuclear Safety Vol. 17, No. 1 Jan-February 1976

Table 6.2

Possible effects of core melt accidents KO, KM and KE in a 1 000 MWe light-water reactor on the environment of the reference sites (without evacuation).

Accident type (see 6.3.2.5)	KO	KM	KE
Risk per reactor year (see 6.3.2.2 and 6.3.2.5)	$60 \cdot 10^{-6}$	$15 \cdot 10^{-6}$	$1 \cdot 10^{-6}$
Acute deaths (number) probability[1] 70%	0	0	0–50
probability 10%	0	0–10	50–500
probability 10%	0	10–50	500–2000
probability 10%	0	50–1000	2000–10000
Maximum distance at which acute death may occur (km)	0	7	20
Collective whole-body dose (in millions of man-rem)[2]	2.10^{-4}–4.10^{-3}	0.5–5	2.5–30
Latent cancer deaths (number)	0	100–1000	500–6000
Genetic effects (number)	0	50–500	250–3000
Collective thyroid dose (in millions of man-rem)[3]	0.02–0.8	25–250	50–1300
Number of cases of thyroid nodules	6–240	7500–75000	15000–400000
Latent thyroid cancer deaths	0–2	75–750	150–4000
Extent of the area (in km^2) which has become uninhabitable as a result of high radiation intensity.			
probability 70%	0	3–30	50–1000
probability 10%	0	30–200	1000–2000
probability 10%	0	200–500	2000–3000
probability 10%	0	500–700	3000–4000

[1] This probability is determined by weather conditions. These are divided here into relatively unstable and neutral atmospheric conditions, which occur 70% of the time, relatively stable conditions and very stable conditions, which prevail 10% of the time, and an intermediate situation, also with a 10% probability.

[2] This is calculated up to a distance of 800 km and is based on data for the ICRP standard man.

[3] The radiation dose resulting from radioactivity on the ground was taken as a somewhat random criterion for the period between 14 days and one year after the accident. Where this dose exceeds 5 rem, which is the emergency reference level for children (see 4.5.5), and assuming that the radioactivity decreases only as a result of the physical disintegration progress, the expression used here is "uninhabitable in the first instance".

Table 7.5 - 4 - Effects of the most serious accident situation averaged over all weather conditions

Dodewaard power station - release category 2; probability: $2 \cdot 10^{-5}$
Borssele power station - release category 1; probability: $8 \cdot 10^{-6}$
1 000 MWe BWR - release category 2; probability: $2 \cdot 10^{-6}$
1 000 MWe PWR - release category 2; probability $5 \cdot 10^{-6}$

Site and type of reactor		Population dose (10^6 man-rem)	Latent carcinomas	"Acute" victims	Total deaths	Thyroid tumors	Acute illnesses	Total number of illnesses	Genetic effects	Contaminated land surface area (km^2)
Dodewaard		0.3	25	5	50	4 000	11	4 000	25	61
Borssele I		0.7	71	3	126	10 500	17	10 500	71	218
Borssele II	BWR	1.8	180	78	410	30 280	169	30 300	180	598
	PWR	2.7	270	129	568	33 640	227	33 700	270	787
Diemen	BWR	3.5	353	980	1 540	41 570	1 440	42 800	353	665
	PWR	4.6	463	1 410	2 100	44 440	1 880	46 100	463	881
Eemshaven	BWR	0.64	64	25	133	8 870	96	8 920	64	531
	PWR	0.96	96	69	214	9 746	163	9 860	96	666
Flevo	BWR	1.4	138	16	271	23 480	37	23 400	138	693
	PWR	2.2	216	28	377	26 550	83	26 500	216	917
Maasvlakte	BWR	1.6	161	12	332	31 890	67	31 800	161	400
	PWR	2.3	234	31	439	34 880	197	34 900	234	586