EPRI

REALISTIC ESTIMATES OF THE CONSEQUENCES OF NUCLEAR ACCIDENTS

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P R E A M B L E

The safety of nuclear power plants has been defended - and attacked - on the basis of how likely it is that a major release of radioactivity will occur. Nuclear advocates say once every million reactor years at most; people opposed to nuclear power say it can happen at any time and will happen fairly often. This dialogue has revolved around the probability and neither side has bounded the size of the public risk from the worst release that could really happen.

The lethal content of a physical system is not a measure of its risk. For example, a swimming pool contains enough water to fill the lungs and thereby drown about 100,000 people, but no one considers this a true measure of the hazard of swimming pools. Similarly, the air in any small office, injected 50 cc at a time into people's veins, is capable of killing over 500,000 people - but that air represents no real hazard. The same is true of the radioactivity in a nuclear power plant - widely dispersed it could cause a catastrophe, but no such dispersal mechanism exists, accident or not. Every historical reactor accident, every nuclear weapons accident, as well as many experiments demonstrate that the dispersal mechanisms act to limit large releases of radioactivity. This is why an accident causing widespread and serious health effects to the public will not happen.

Simply stated, the ultimate safety of a nuclear power plant does not depend on the engineering features of the plant. These features determine the plant reliability and frequency of failures and accidents. However it is natural processes (chemical reactions, aerosol settling, effects of moisture, etc.) that prevent a public catastrophe from occurring. This simple fact is often lost sight of in discussions on the safety of nuclear power plants.

Now, in the aftermath of TMI, people are perhaps more open to asking the questions: Why weren't the public health effects greater? Was it but for the grace of God? No! but it was due to the grace of Nature. Engineered barriers, after all, are always subject to failure. Not so with natural phenomena. Our experience has shown natural phenomena to be very effective in containing radioactivity. These same natural barriers will also act in future accidents. The inherent safety of nuclear reactors rests on these demonstrable phenomena - not on theoretical arguments or hypothetical scenarios. Whether an accident does or does not occur depends on our skill, although some like to think of it in terms of luck or probability. But the consequence of such an accident is not a question of skill, or luck, or probability - natural processes will limit the dispersal of significant radioactivity to the near vicinity of the accident. As a result, a public catastrophe will not occur.

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PREFACE

The authors wish to acknowledge the many people, too numerous to name, who have reviewed early drafts of this paper and who have made many valuable suggestions toward its improvement. It became clear during the development of the ideas contained herein that several researchers in this country and others have been thinking along similar paths. The accident at Three Mile Island Nuclear Unit II posed the question as to why so little iodine and particulate matter escaped the plant relative to the gaseous releases. The fairly obvious conclusion was that natural processes were acting more efficiently than the modeling predicted. This paper simply attempts to reinforce that conclusion, and to bring a new perspective on the interpretation of some new, but also much old, empirical data. As long as the interpretations of such data were not used to set emergency response and other criteria, there was no motivation to extensively reevaluate the data. But the recent emphasis on evacuation and siting policy and Class 9 accidents makes realistic reevaluation of the consequences of nuclear accidents important.

I. INTRODUCTION

Radiation exposure estimates form the basis for emergency response planning in the event of an accident at a nuclear reactor. A reexamination of the current estimates show that they may be high by a factor of ten or more. If this is so, public concerns about nuclear safety may be exaggerated and our strategy for dealing with such an accident may be incorrectly biased, particularly in the case of evacuation policy. For the reactor accidents and the resulting releases of radioactivity that could actually occur, for instance, mass evacuation does not appear to be the safest strategy. Sheltering (sometimes with the evacuation of the few individuals at close-in locations) appears to be superior, in that it may result in a lower overall risk to the general population.

In a reactor accident, the principal concern is that the engineered safety features will fail resulting in a large release of radioactivity. The radioactive fission products in the core will then be redistributed by various natural processes (chemical reactions, aerosol behavior, condensation, effects of moisture, etc.). The failure of each engineered barrier to function properly, however, still does not mean that a significant amount of radioactivity will escape. Experiments and experience demonstrate quite the opposite. This raises the question of why current estimates are so high and how much radioactivity could really escape.

The risk to the public from a nuclear emergency is based on three quantities:

(A) The <u>probability</u> of some sequence of undesirable events occurring

(B) The <u>consequences</u> that would follow if these undesirable events occur

(C) The <u>action</u> taken to mitigate the accident

Considerable work has been done on developing a probabilistic methodology for evaluating part (A). A good example of this technique is that used in WASH-1400, the <u>Reactor Safety Study</u> (1). We believe the probabilistic models have been developed to the point where their usefulness is not limited by their technique, but by the validity of the data used in evaluating part (B), the consequences.

When accident consequence estimates lead to actions (such as evacuation of an area) which pose significant safety, health, and economic risks, then these estimates must be consistent with what is actually likely to occur (see Figure 1). In addition, the risks posed by a nuclear accident and the mitigating action should be evaulated on the same basis. If the risks of the mitigating action are treated less conservatively than the accident risks, incorrect conclusions will be reached and faulty emergency strategies may result.

The Reactor Safety Study attempted to model the important natural phenomena to produce a realistic assessment of the risk of a nuclear accident. It succeeded to the extent that it is much improved over an earlier Brookhaven study (WASH-740) (2) on the same subject. However, in terms of correctly handling all of the details of the many removal processes which limit the release of radioactivity, it is still quite far from what would actually happen in reactor accidents. The objective of WASH-1400 was to methodically examine potential accident sequences and obtain estimates of the plant response and public consequences for such sequences. Emphasis was placed on examining large Loss-of-Coolant Accidents (LOCA). Limits on time and resources led to simplifying assumptions in the study. It was hampered by a lack of ability to define with precision the conditions existing during an accident. The outcome was an efficient but simplified model, that contained conservative assumptions, in many areas of complex or uncertain phenomena. As a result, WASH-1400 has a tendency to greatly overestimate consequences.

In judging whether a model such as WASH-1400 is adequate, experience with previous reactor accidents, especially those involving complete or partial core melt, and those with an absent or breached containment, should be accorded special attention. Also important are the many large- and small-scale experiments. If discrepancies exist, results of the modeling must be used with great care. Some of the important benchmarks against which models should be compared are given in the next section.

II. RADIATION RELEASES FROM DAMAGED REACTORS

There have been a number of serious accidents at reactors involving significant core damage where no significant amounts of radioactive material were released to the environment (3). These accidents occurred at Detroit Edison's Fermi Unit-1, the Experimental Breeder Reactor-I in Idaho (1955), the Sodium Reactor Experiment (SRE) facility in California (1959), the NRX reactor at Chalk River (1952), and the Westinghouse Test Reactor (1960). There have also been at least three major reactor accidents that resulted in radioactive releases [illegible] environment. These occurred at Windscale, the SL-1 reactor, and at Th[illegible]e Island; at each, there was major damage to the reactor core. Both the Windscale and SL-1 accidents occurred in noncommercial reactors. Neither of these two reactors had containment buildings. Nevertheless, the radiological releases were quite limited. In all these accidents the point of interest is the fractional inventory release; i.e., the amount of radioactivity escaping relative to the radioactivity in the core.

In October 1957 a major fire occurred in the Windscale No. 1 reactor on England's western coast (4). Windscale was an aircooled reactor for the production of plutonium, and was not typical of commercial reactors. The burning of the graphite and uranium core and the lack of a containment system allowed the escape of radioactive fission products from the reactor's 400-foot stack to the surrounding countryside. The reactor continued to burn for more than two days. Substantial amounts of radioactive iodine existed in the core, much of which was released from the fuel during the fire. Only a small fraction, however, ever exited the stack. The highest radiation level reported off-site was about 4 mR/hr. This reading was reported at a single location about 1 mile from the reactor. Monitoring of the areas surrounding Windscale, and of locally produced milk, was undertaken. In certain areas, the consumption of milk was temporarily halted as a precautionary measure (5).

On January 3, 1961, the SL-1 reactor at the Idaho National Reactor Testing Station experienced a reactivity insertion accident (6). The sudden removal of a control rod, under abnormal conditions during maintenance, was the cause. This sudden reactivity insertion led to a power excursion and extensive core melting. Three employees were killed due to injuries sustained from mechanical effects of the steam pressure. The SL-1 was a small, natural-circulation, 3 MW_{th} boiling water reactor (BWR). It was a prototype military reactor operated by military personnel. Its metallic fuel elements were constructed of highly enriched uranium-aluminum alloy, surrounded by aluminum alloy cladding. Few engineered safety features existed. In these respects, it differed appreciably from a modern power reactor.

Fuel that melted contained about 19% of the total core fission product inventory. However, in spite of the fact that the sheet metal building which housed the reactor was "drafty" and vented to the atmosphere, less than 0.1% of the nongaseous inventory actually reached the atmosphere during the first two days following the excursion event. For instance, environmental sampling results indicated that only about 20 Ci of I-131 had escaped from an initial core inventory of 28,000 Ci (7). Further sampling indicated total releases of only about 0.5 Ci of Cs-137 (core inventory 3100 Ci) and about 0.1 Ci of Sr-90 (core inventory 3070 Ci) for the accident (8).

In comparing this accident to what might happen in a commercial nuclear plant, the presence of a containment building, and the multicompartment nature of such containment buildings would further decrease the amounts of radioactivity released. Nevertheless, at SL-1, releases of fission products, particularly of the volatiles and particulates, were quite small because of the physical and chemical laws governing their behavior, not because of the existence of engineered safety features or a containment building. Recent calculations (10) were done using updated versions of the CORRAL and CRAC codes to reproduce the radioactive releases from SL-1. The calculations demonstrate that unless the physical/chemical phenomena connected with the initial rapid dispersal are properly accounted for, the analysis will greatly overestimate the environmental releases.

The recent accident at TMI in March 1979 resulted in the release of about 15 Curies of I^{131} to the environment (11). This was less than one part in ten million of the iodine in the core. A much larger quantity of the noble gases Xe and Kr were released (approximately 2.5 million Curies or 2% of the noble gas inventory). Negligible amounts of Ba-140 were released (9). These noble gases were quickly dissipated. Radiation levels outside the reactor site were quite low, mostly below 1 mR/hr.

There was no failure of the reactor containment building during the accident, and as a result there were no direct releases from the containment. The releases that did occur were secondary leaks from auxiliary systems. The amount of material leaking from the containment building was further attenuated in the auxiliary building by the operation of plating and fall-out mechanisms prior to escaping to the atmosphere.

III. RADIATION RELEASE FROM CONTROLLED EXPERIMENTS

In addition to the experiences with reactor accidents already described, other empirical data exist which demonstrate the role of natural phenomena in limiting the dispersal of radioactivity. These data come from experiments investigating the various aspects of fission product dispersion.

A. Small-Scale Experiments

The first point of departure for any evaluation of the radioactivity released during a major reactor accident concerns the melting and vaporization of the fuel itself. Recent experiments (12) on high temperature, high concentration UO_2 aerosols carried out at Rockwell International have shown the tendency for fuel-like aerosols to exhibit a fall-out behavior characteristics of two relaxation times. The first operates on a time scale of seconds, during which time more than 90% of the mass of airborne particles is removed from the air, while the second operates on a time scale of tens of minutes, during which remaining fine particles settle out. Previous experiments were not able to detect this effect because of difficulties in making measurements earlier than a few minutes after the creation of the aerosol and in making an accurate mass balance. The more recent studies further show that at high concentrations (.07 to 1.09 kg/m^3) agglomeration is so rapid (milliseconds) and the resulting particulates so large (100-400 μm) that the giant agglomerates (containing a large fraction of the available aerosol mass) will fall out rapidly and will sweep out additional aerosol mass during their gravitational fall.

Studies at Karlsruhe (13) on core meltdowns require that there be between 1 and 2.5 tonnes of aerosol to be consistent with release fractions. The total aerosol would consist mostly of fuel and structural materials which are nonradioactive. This aerosol would be distributed mainly in the pressure vessel or reactor cavity area depending on the scenario chosen. Such a condition is highly unstable, and aerosols sould be quickly removed from the airborne state by natural processes. Particulate fission product will then be removed with the much greater amounts of inactive aerosol. Note that this will occur even if moisture is not present, although the presence of moisture would greatly accelerate the aerosol depletion.

An earlier experiment at Oak Ridge National Laboratory (14) with UO_2 fuel showed that indeed nearly all of the iodine, tellurium, and cesium and more than half of the strontium, zirconium, ruthenium, barium, and cerium are released from the melted fuel. With the exception of the iodine, tellurium and cesium, however, all these fission products condense and plate out in the high-temperature region around the fuel. Recent experimental work at ORNL (15) shows the formation of CsI in the fuel prior to release from the matrix. A similar chemical reaction of tellurium with cesium in the fuel is expected to form Cs_2Te (16,17). As a result, during an accident the iodine, tellurium, and cesium isotopes are predominantly in the ionic state and retained by any moisture present. This is an important phenomena, due to the importance of these isotopes in predicting early and latent fatalities as the result of an accident. Still other work at ORNL (18) showed that in partially melted multi-pin fuel experiments, only very minor amounts of particulate activity escaped the immediate furnace liner surrounding the experiment. A most striking reduction in release, compared with the more commonly performed single-pin experiments, occurred in the multipin release. This release was lower by a factor of one hundred. The results showed that the unmelted parts of the fuel and surrounding structure offers a suitable plate-out surface for released fission products.

In a reactor accident which includes core melting there will be many cooler regions above the core (in the pressure vessel, piping, or pressure vessel compartment). This condition will be assured by the presence of single- and two-phase water-steam mixtures. Results (19) from the General Electric Aircraft Nuclear Propulsion Dept. (ANPD) show that cesium plates out on such surfaces when the temperature is in the range 1000-1800°F, and iodine in the range 80-600°F. Other work at BNL (20) found that in certain instances, 90% of the iodine released into air in a reduced state, due to a steam environment, can be collected on surfaces whose temperature is below 120°F. Qualitatively identified in still other experiments (21), but not measured, is the absorption of cesium and iodine on the surface of particulates. In high-concentration aerosols, this phenomenon can take place rapidly. This observation has important implications in considering accidents where large amounts of water may not be present in the immediate vicinity of the core. In such cases, materials (such as the 500 kg of Ag-In-Cd in the control rods of PWRs) with low melting points may become aerosols coincident with the release of the iodine and tellurium, and thus serve as a blanket of condensing and sorption surfaces for these elements.

Other work conducted at Hanford (22) on high-temperature release of fission products from molten fuel in helium, steam, and air atmospheres produced the following result: radioactivity released in steam was between two and ten times less than that released in air. This experiment was carried out on metal fuel, but the aerosol behavior is directly applicable to the oxide fuel used in commercial LWRs. A second important result was that after the fission products were released from the fuel, the fraction of the released volatiles--iodine, tellurium and cesium--deposited in the apparatus was significantly higher in a steam atmosphere. Such deposition occurred within a few centimeters of the molten fuel. In the case of iodine, 10% was deposited in dry air, 60% when steam was present, roughly a sixfold increase in attenuation. The effects of steam condensation in removing fission products was next investigated. Approximately 97% of the iodine, 77% of the tellurium and 80% of the cesium were found in the steam condensate. It was concluded that condensation of fission-product-laden steam is nearly as effective as high efficiency filters in removing fission products released from the melted fuel. Other experiments show similar results (23,24).

Leak paths through the concrete walls if failure were to occur would be long irregular cracks which have rough surfaces so that additional aerosol removal phenomena, such as impaction, are operative and reduce even further the mass of the aerosol transmitted (25). Experiments on aerosols show that such removal phenomena are very effective and that a major fraction of the entering aerosol mass is retained in the crack. Moreover, moisture will collect in such cracks, serving to further filter the releases.

B. Large-Scale Containment Tests

Six experiments (26) were performed at BNWL in the 2,286 and 26,500 ft^3 Containment Systems Experiment (CSE) containment vessels in the early 1970s. The time dependence of iodine, cesium, ruthenium and uranium concentrations were studied. The experiments were carried out in containment vessels of two sizes, of which the larger was approximately a 1/5 linear-scale model of a PWR reactor containment building. No engineered safety features were provided. All fission product retention occurred solely by natural, passive processes. The natural attenuation processes, in increasing order of importance, were retention in the release apparatus, in-containment removal by surfaces, and removal in leak paths (27).

This study also found that iodine attaches itself to solid particles and is absorbed by liquid droplets. The cesium particles which were introduced with the iodine reacted to form cesium iodide. In spite of the fact that 100% release was attempted, 28% of the iodine and 67% of the cesium were retained in the release apparatus and injection line. As soon as the particles were introduced into the steam in the containment building, they acted as condensation nuclei to form fog droplets. Elemental iodine was absorbed into these fog droplets very rapidly until the equilibrium relationship was reached between gas and liquid. The initial time for 50% removal of the iodine in the gas space was found to be between 9 and 24 minutes; later this "half-life" increased to 20 or so hours. After two hours, iodine decontamination factors ranged from 30 to 1000. After one day, they ranged from 100 to 2500. Cesium behaved in much the same way, although decontamination was less at 2 hours and much higher at one day. Most of the cesium (72-90%) was observed to settle on the floor by gravity. About 50% of the iodine and 10% of the cesium was retained by the paint on the inside surface of the vessel. (The average LWR has 10 to 20 tons of paint on surfaces within containment.)

C. Experimental Reactors Tested to Destruction

At various occasions in the past, experimental reactors have been deliberately tested to destruction to verify that large reactivity excursions were self-limiting and would automatically terminate the nuclear reaction. These tests verified that this was indeed the case. The tests were designed to violently disassemble the core and melt or vaporize part of the reactor fuel. Dispersion of radioactivity was monitored and provided information on how widespread such dispersal was likely to be. Three tests of this nature were the BORAX-I test (3) (1954), the SPERT-I test (28) (1962), and the SNAPTRAN tests (29) (1963). All these tests were conducted in the Idaho desert. The cores involved were relatively clean, with low fission product concentrations. If higher concentrations had been used, other natural processes such as high density aerosol behavior, might have further limited radioactive dispersal.

The BORAX-I experimental apparatus had been used for a highly successful series of tests on reactor transients. It began to show signs of hard use. In view of indications that its effective usefulness was near an end, it was decided to run a destructive experiment to find out what would happen. One of the effects to be investigated was to see what fraction of the fission product inventory in the core would be released to the environs upon destruction and vaporization of the fuel. The reactor was fitted with special control rods designed for explosive ejection and loaded with excess reactivity.

The reactor was contained in a tank, which was sunk partly into the ground. There was no building over the reactor. Motion pictures taken during the test showed that the low-pressure water tank holding the experiment burst and most of its contents were ejected into the air. Recognizable fuel fragments were thrown as far as 200 ft. but essentially all the fuel could be accounted for within 350 ft. of the reactor. A wind of 8 mph at ground level (20 mph at 250 ft. altitude) was blowing. Even under these conditions, the phenomenological mechanisms limiting dispersal were operative.

The SPERT-I destructive experiment also was conducted in an open tank facility. It was covered by a light structure not intended for containment purposes. A large insertion of reactivity was performed on November 6, 1962, under fully documented meteorological conditions. Approximately 35% of the aluminum alloy core was melted, with all the fuel plates in the core experiencing melting to some degree. The maximum temperature of the fuel exceeded 1200°C. Approximately 20 kg of "spongy" metallic debris ranging in particle size down to below 100 um was recovered from the reactor tank. An estimated 2.4×10^5 curies were released to the atmosphere, representing less than 1% of the fission-product inventory in the core. Iodine was detected only in the reactor water. The building was reentered four hours after the test. A radioactive cloud, ranging between 700 and 2000 feet wide, was monitored for a distance of 15 miles, and deposition rates recorded. The measurement of the dissemination of fission products in the SPERT-I test indicated that the release to the atmosphere was roughly 1% of core inventory. This was more than an order of magnitude less than that expected from pretest hazard evaluations (16%).

The SNAPTRAN-3 destructive test was conducted in May 1963 in an open tank without any covering structure. Again, a large amount of reactivity was inserted, destroying the core and ejecting half the water out of the tank. About 500,000 Curies of radioiodine was generated in the burst. All the iodine was found in the remaining water. In an earlier test with a dry tank, a large iodine release occurred.

The significance of the source-term evaluation experiments described in this section is that even though the laboratory and larger scale experiments were designed to give maximum release, they all resulted in smaller source terms than that predicted by the models used currently for licensing reactors.

IV. POTENTIAL OFF-SITE HAZARDS EVOLVING FROM REACTOR ACCIDENTS

A. A Question of Source Term

Although analytic studies such as WASH-1400 have their limitations, an important insight derived from them is that only reactor accidents involving significant core melting will result in any significant risk to the public (30). However, for simplicity, these models usually assume that any melting of the reactor core will within minutes lead in all cases to a catastrophic failure of the reactor pressure vessel and containment building. This assumption and others listed in Table 1 are not realistic. But even with these assumptions, the studies indicate that in less than 2% of the instances will the failure of the containment building be an above ground failure. The other containment failures considered are due to the core itself penetrating the building by melting through the concrete base mat. In either event, these analyses predict that the amount of radioactivity escaping the containment building would be quite large. The near-term dose to the population in these examples is due largely to the radioactive iodine and tellurium released. The second largest contributor is the aerosols. Less significant, making up only a few percent of the total, is the dose due to the noble gases.

Such models may be useful in illuminating the sequences leading to core meltdown and in doing relative risk studies. The data currently used and the lack of detailed consideration of postmelting physical phenomena, however, give rise to predictions of amounts of radioactivity released to the atmosphere that are invariably high.

An example is the iodine reduction factor estimated in one Reactor Safety Study accident sequence. Table 2 shows such a case (31), which only partly accounts for condensation or solution effects, washout due to dripping water and condensing steam. A total attenuation factor of 1.5 results. When different sets of assumptions (Table 3) for the same accident sequence are used (including some dissolution in the quench tanks but no effect of water and steam in the containment building, or significant aerosol fall-out), the attenuation factor increases to between 6 and 10^5. This indicates the sensitivity of the calculated results to small changes in assumptions. Inclusion of all relevant phenomena may give even higher attenuation factors.*

When discussing the consequences of reactor accidents some of the important physical properties of radioisotopes to keep in mind are:

*For comparison in the SL-1 and Windscale accidents, the attenuation factors were approximately 10^3, for TMI about 6×10^5.

- Stable, dispersible aerosols are difficult to create. Highly concentrated aerosols coalesce rapidly. Low density aerosols increase their effective density extremely rapidly in the presence of water vapor, serving as condensation nuclei. The effective size of the particle becomes that of the water droplet (32).

- Aerosols agglomerate and tend to be trapped when passing through cracks and penetrations whether in pipes, compartment walls, or containment buildings (33).

- Agglomerated aerosols formed at high concentration are physically dense, and settle out close to their source. The original mass of particulates, although it may be large, is not significant, because only a small proportion survives this settling process and remains airborne (34).

- Iodine in its many forms is chemically and physically reactive. Since nearly all of the surface area inside containment is covered with paint, plastic or organic films, iodine retention is high. In addition, iodine will be adsorbed on the surface of aerosol particles, that themselves are rapidly agglomerating and falling out (35). In either instance, much of the iodine is quickly immobilized.

- The reactor containment building and the equipment in it present a large amount of surface area for fission product plate-out and adsorption. The compartmentalization of the building and the complexity of piping and hardware means that any escaping material passes multiple surfaces prior to escape. This is at best only partially accounted for in the modelling (36).

- The moisture conditions in the reactor containment building will cause most of the soluble fission products that become airborne to go into solution (37). A core melt accident will always be accompanied by large amounts of steam and water because coolant loss from the primary system is the sine qua non of core melting. "Rain" or "fog" will exisc in the building even if the containment spray system is never used. This is due to the heat capacity of the building and equipment causing condensation and dripping from all the surfaces. Such a condition would wash out large fractions of the various fission products prior to atmospheric release (26). As mentioned earlier, moisture further tends to agglomerate aerosols and enhance their density.

- The earth itself acts as a filter and effectively suquesters any escaping fission products in the event of a "melt-through" accident or an "atmospheric release" accident (which, in spite of its name, would likely result from a below-grade failure of the containment building in many cases). If the overpressurization in an accident blew out the penetrations or seals in the reactor containment building, the path for escaping radioactive materials usually would be through other buildings. This would provide further opportunity for plate-out and fallout of radioactivity.

- The presence of large amounts of water and vapor plus the heat capacity of the containment building and debris would be sufficient to immobilize a large fraction of the radioactivity in the event of a postulated massive reactor building failure (38). The important role of moisture was demonstrated by the SNAPTRAN tests (29).

As a result of these phenomena, the potential off-site hazard from a nuclear accident is greatly diminished. The above phenomena all act in the same direction to reduce the magnitude of the predicted fission product release and change the character of the release in that iodine and particulates are greatly reduced relative to the noble gases. Both changes reduce the consequences to the public in terms of acute and latent fatalities and greatly diminish the area around the reactor over which a serious threat may exist. None of these phenomena is dependent on somebody making the right decision, equipment functioning correctly, or power being available. They are always acting.

The fact that the commonly used models do not treat in sufficient detail the phenomena that reduce the fission products available for release explains, at least in part, why the models predict consequences from accidents so much greater than any that historically occurred.

B. A Question of Time

If realistic consequence scenarios are considered, it becomes apparent that evacuation of very large areas is neither needed nor effective. The principal threat to the majority of the population is the passage of a dispersing radioactive cloud. This cloud would contain mostly the noble gases xenon and krypton. Against this threat, sheltering may be the best option in the short term (hours and days), and time then exists to determine what long-term actions (months and years) are required. There is no acute need for evacuation.

Concerning the evolution of an accident, some of the current analyses assume that once any local region of the reactor core, no matter how small, reaches a sufficiently high temperature, melting of the entire core occurs in short order, and there is an inexorable and quick progression to pressure vessel failure, containment failure and major radioactive releases. In fact, the completion of physical processes for this to occur does not happen instantaneously, nor is the progression inexorable (39).

The timing of radioactive release scenarios is important in the consequence modeling. Even a few minutes between core melting and containment failure would be extremely important. For example, consider a postulated metal water explosion leading to early penetration of the RCB. Although such an explosion is no longer considered energetic enough to rupture the pressure vessel, let alone containment (40), the time between the release of the volatile fission products from the fuel and the drop of the molten core into the plenum of the pressure vessel allows sufficient time for chemical reactions, condensation phenomena and the effects of moisture to occur. A subsequent explosion would produce a high density aerosol, initially in contact with water, that would rapidly coalesce and fall-out, not unlike the destructive experiments described in Section IIIC. A similar case could be made for postulated early containment failure due to a hydrogen explosion.

If an accident progresses at a modest rate, the time gained thereby helps in three ways: the residual decay heat decreases, the energetics of core damage diminishes and the radioactive inventory decays. More importantly, hours elapse before the point is reached where the last engineered barrier between the public and the radioactive fission products, the containment building, might be in danger of being breached. Recent work in Germany indicate that a failure of the containment building due to overpressurization would require several days to materialize (41). In the meantime, all depletion phenomena have been functioning to further reduce the source term available for release.

V. VALUE OF SHELTERING VERSUS EVACUATION

If a reactor accident were to occur, those charged with the health and safety of the public would have to decide how to protect the public. Various factors should influence their decision, including the risks of evacuation, deaths due to traffic accidents and heart attacks, and psychic trauma brought on by the str.sses of evacuation, relative to radiation risks. To model the effects of a given emergency response, detailed sheltering and evacuation models exist which consider the dynamics of radioactive plume dispersal and that of population movement. Even with the models and source terms used in the Reactor Safety Study (42), the technical basis for widescale evacuation is marginal. When more realistic source terms for radioactive release are considered, even less justification for such an evacuation exist. For core melt accidents, the off-site doses would probably exceed those specified in EPA's draft Protective Action Guides (43) only within a very limited area outside of a reactor site boundry. Only within this area would it appear that evacuation might be prudent to consider, although not necessarily more effective than sheltering in mitigating the whole body dose to the population. The time before such a threat would evolve is relatively long. However, it should be recognized that if a threat were to materialize very early in an accident, sheltering would be the only real option. Also it should be recognized that while evacuation plans may be prudent to develop the decision to implement such a plan should be based on actual conditions that exit at the time.

Also important is information, or lack there of, concerning the magnitude of the actual danger. While calculations that employ "conservative" assumptions are generally believed to increase safety margins, in instances where an evacuation decision is required such a treatment may significantly increase the risk by inadvertently introducing hazards not considered in the calculations. The concept that evacuation of very large areas is desirable or necessary for public safety is probably wrong on both counts.

Inadequate recognition is being given to the safety margin provided by sheltering and controlled air supply - these mean nothing more complicated than staying indoors, closing the doors and windows, and shutting off ventilation fans. The relative merits of evacuation versus sheltering depend greatly on the particulars of a given accident. Parameters to be considered are severity, site location, meteorological conditions, etc. However, only in a few instances, and only for a few individuals, will evacuation be better than sheltering. Precise answers to the questions of whether to evacuate particular individuals, when to evacuate them, how far, and in which direction to evacuate them, are site- and accident-specific. But in no case can an analysis be considered complete if sheltering calculations have not been included, and the nuclear and non-nuclear risks considered on an equally conservative basis.

As has been outlined above, the primary source of exposure to the general population in the near term probably will come from noble gas fission products. This is likely to be true even if the containment building suffered a major breach. Due to the dilution and dispersal characteristics of gaseous fission products, the radiation dose that any off-site location receives will be small and transient in time.

At Windscale, as at SL-1 and TMI, the radiation from the radioactive plume represented the largest exposure. Although some radioiodine was dispersed over a large area around Windscale, the dose from it was quite small. The hazard, if any, would have been due to its subsequent concentration in humans. This does not occur directly, and it was guarded against by the temporary dumping of milk produced in affected areas. Aerosol dispersal was not a problem at SL-1 or TMI. The EPA draft Protection Action Guide currently establishes levels of 500 mRem whole body dose and 1500 mR to the thyroid as "action" threshold doses. If projections indicate that these levels will be exceeded, then protective action should be considered. Clearly, in each of the historical incidents, much time was available (several weeks in the most serious, the Windscale event) before these dose limits would have been reached. The combination of dilution dynamics of the noble gases, plus the fact that physical phenomena associated with aerosols and iodine prevent their gross release, assures that time will be available to take whatever further precautionary measures are required.

Equally important is the matter of taking advantage of simple protective measures. Closing the windows greatly reduces the potential inhalation dose (44). The concentration of noble gases is not as strongly reduced by such measures, although factors of two or three are likely. Precise estimates depend on the ventilation rate. If the ventilation rate were high, however, due to the presence of windy meteorological conditions, such conditions would also considerably shorten the time of passage of any radioactive cloud that existed and rapidly disperse it.

The shielding ability of structures also offers subtantial protection. Even a simple wood frame house reduces the dose rate from a passing cloud by a factor of two (45). A masonry structure may give dose rate reductions up to a factor of 10 on the first floor, 50 or more for a person staying in the basement. These shielding factors are for gamma sources with mean energies close to 1 MeV. For sources containing primarily noble gases released a day or two after the accident, the actual shielding offered by such structures is considerably greater because of the much lower average energy of the radiation. These values are also for isolated structures. A town where a third of the area is covered with buildings may provide another factor of three protection (46). In fact, the greater the concentration of people, the more protection is afforded by the surrounding buildings, and also--the more difficult is evacuation. Evacuation, on the other hand, may actually expose people to increased radiation doses, depending upon meteorological conditions, if the evacuation direction coincides with direction of the radioactive cloud. In addition, there is the loss of shielding provided by buildings.

A recent study of the relative safety of sheltering versus evacuation in the case of a tornado is instructive (47). The majority of the fatalities, as well as the highest risk of fatality, was incurred by the group evacuating in the face of the danger. Often they attempted to evacuate across the path of the tornado with tragic results. Those who stayed behind in the relative security of their own homes fared considerably better.

The effective rate at which evacuations have been carried out in the past is quite slow. Evacuations carried out because of natural disasters and transportation accidents have a mean rate of less than 5 miles/hr and a median rate of close to 1 mile/hr (48). For a city or major population center, the time required to evacuate would be very long, probably several days. Even with an effective evacuation procedure, it has been observed that 5% of the population will stay behind regardless of the perceived risk. This last fact was again demonstrated in connection with the attempted evacuation of the area around Mount St. Helens.

Also to be considered is the ease of implementation of sheltering compared to evacuation. When formulating emergency preparedness plans, the simpler of two otherwise equal alternative strategies is always the better one to adopt, as it has the higher probability of being correctly implemented in a stressful situation. In this regard, also, sheltering would be by far preferable to evacuation.

VI. SUMMARY

In estimating the real risk to the public from an accident at a nuclear power plant, several quantities are important: the probability and consequence of the accident itself and the risk resulting from any mitigating action taken. The uncertainties of the risk associated with the accident seem to be dominated by the uncertainties of the consequence estimates. The current procedure of using "conservative" assumptions (usually at each stage) in the calculations produces an estimate of the risk that is likley to be much too high, by an order of magnitude, or more.

In and of themselves, conservative estimate, as typically made in the licensing process may in fact contribute additional risk by overestimating source terms and thus overestimating benefits of activities such as evacuation. This process, in turn, leads inadvertently to putting major segments of society at greater risk than is necessary by encouraging decisions which have higher risk.

The principal areas of concern focus on the treatment of a number of physical processes. These processes are always operative and can be counted on to limit the consequences of a reactor accident. Sufficient credit is not taken for their ability to reduce the release of radioactivity and confine it relatively close to its source. Estimates of risk will improve in direct proportion to improvements in quantification of these phenomena. Empirical evidence from many sources shows that these processes are indeed operative and very efficient in reducing the release of radioactivity. As a result, the policy decisions based on the source term in the event of a major reactor accident must be reassessed.

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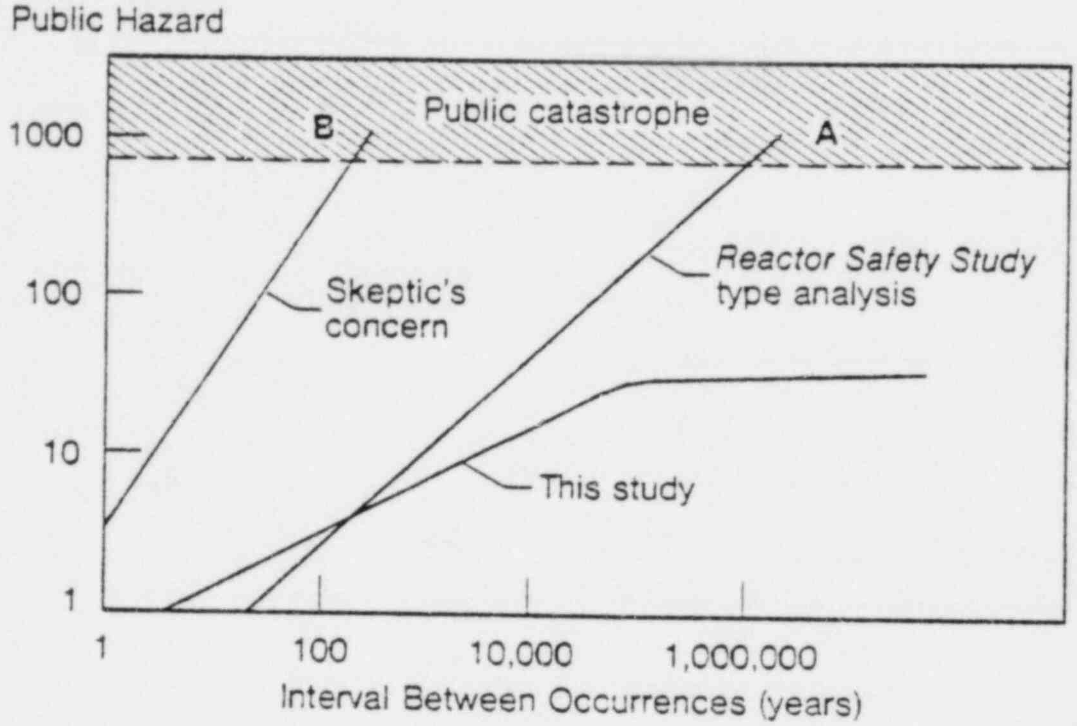
VARIOUS ASSESSMENTS OF PUBLIC HAZARD



- Most detailed probability analysis such as the Reactor Safety Study (WASH-1400) indicate that a public catastrophe might occur no more than once in a million reactor years (A)

- Many people fear that this is not correct and that such a catastrophe might occur more often (B)

- This study suggests that natural processes limit both the spread of radioactivity and associated public hazard.

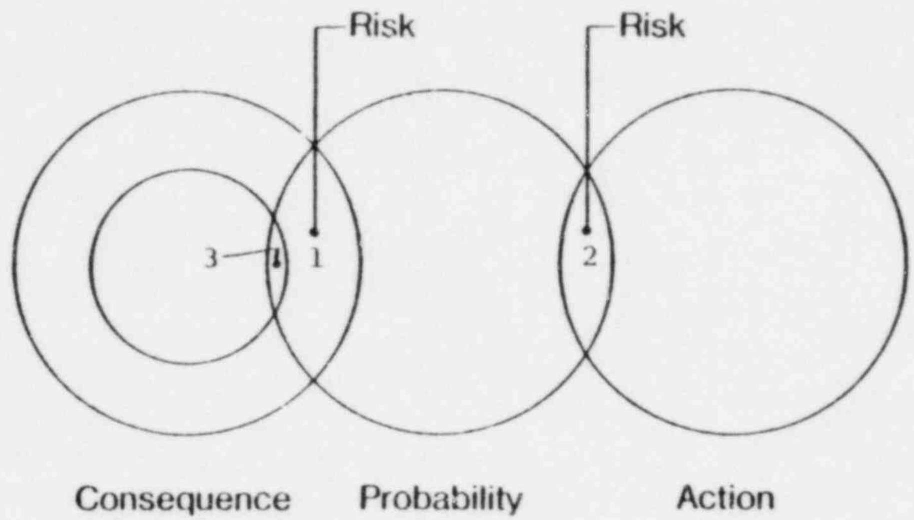


Figure 1 The size of the overlap between the circles is a measure of the risk. If area 1 is much greater than area 2, action to mitigate the consequences of an accident is called for. If, however, the consequences are small, the risk represented by area 3 is smaller than the risk of the mitigating action. In such a case, no action should be taken.

TABLE 1

WASH-1400 Assumptions Concerning
Fission Product Release to the Environment

Primary System Assumptions

- no plateout along transport path for any species in any ECC injection failure sequence
- no significant iodine soluability in residual water

Containment Systems Assumptions

- no deposition along leakage paths to the atmosphere for any species in any accident sequence
- no trapping of any species during water flow through pools
- limited compartmentalization of the RCB
- no retention of any species by auxiliary buildings or structures outside containment

Release from the Fuel

- used 100% release for the volatiles (Xe, I, Cs and Te)
- assumed fuel oxidation very effective in releasing Ru group after steam explosion

Chemical Forms

- assumed iodine would exist in elemental form rather than CsI

Aerosol Behavior

- neglected particulate agglomeration
- only partially modeled steam condensation effects
- neglected particle deposition on walls

Release upon Containment Rupture

- treated as instant percentage loss of airborne contents
- neglected heat capacity of rubble in condensing and trapping fission products

TABLE 2

Iodine Attenuation Factors

Using WASH-1400 Scenario and Models

TMLB'δ Sequence

- electric power never recovered
- sequence treated like a hot leg break large LOCA
- conceptual pathway:

Core Region ⟶ Upper RPV ⟶ RCB Space ⟶ Outside

Event or Process	Value or Assumption	Attenuation Factor	Reason or Comment
Melt release in vessel	90%	—	Full core melt High S/V
PCS plateout	none	1.0	High volatility (I_2 & HI) High temperature Short residence time
RCB plateout	some	1.3	Natural deposition (I_2) Limited time
RCB rupture	gross	1.16	Instant depressurization
Leak path plateout	none	1.0	Huge hole
Total Attenuation Factor		1.5	60% release @ ~ 4 hr

TABLE 3

<u>Iodine Attenuation Factors</u>

Using Basic WASH-1400 Scenario but Modified

TMLB'δ Sequence

- electric power never recovered
- realistic PCS path
- RCB overpressure failure not catastrophic
- path for in-vessel release:

Core Region → Upper RPV → Hot Leg → Surge Line → Pressurizer → Discharge Line → Quench Tank → RCB Space → Leak Paths → <u>Outside</u>

Event or Process	Value or Assumption	Possible Attenuation Factors	Critical Conditions
Melt release in vessel	90%	—	Melt S/V
PCS plateout	Condensation	1 - 10	Temperatures Residence time Chemical/physical forms
Water trapping	Dissolution	2 - 100	Water in quench tank or pressurizer Chemical form Steam - H_2 ratio Water temperature
RCB plateout	λ_N = 1 - 2 hr^{-1} λ_L = 1 hr^{-1}	3 - 7	Surface area Leak rate
Plateout in leak path	Many cracks	1 - 100	Leak path geometry (Length, turns, roughness) Steam condensation Residence time Chemical form

Possible Attenuation Factors Lower value = 6

Upper limit = 7×10^5