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Protective action recommendations based upon plant conditions

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Abstract

Analyses conducted by the Nuclear Regulatory Commission (NRC) indicate that timely and effective protective action would be necessary to protect the public in a major nuclear power plant accident. Given the large amount of time required to implement an evacuation around most reactor sites, protective action recommendations (PARs) must be based upon specific plant indicators regarding the status of the core and systems that protect the core. This article describes the assumptions made, and the analyses conducted, by the NRC in developing its procedures for PARs based upon plant conditions. © 2000 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

A major release from a nuclear power plant would take the form of a cloud (also called a plume) that consists of radioactive gases, aerosol particles (smoke), and water vapor (mist). The cloud will travel downwind and the radioactive materials will tend to disperse as it travels farther from the plant. As the concentration of radioactive materials in the plume decreases, the dose rate to the affected population also will decrease. Thus, those who are farther away from the plant generally will be at less risk.

Fig. 1 shows the pathways that can result in public exposure early in a nuclear reactor accident. A person can receive a dose from a plume via three pathways. First, dose can

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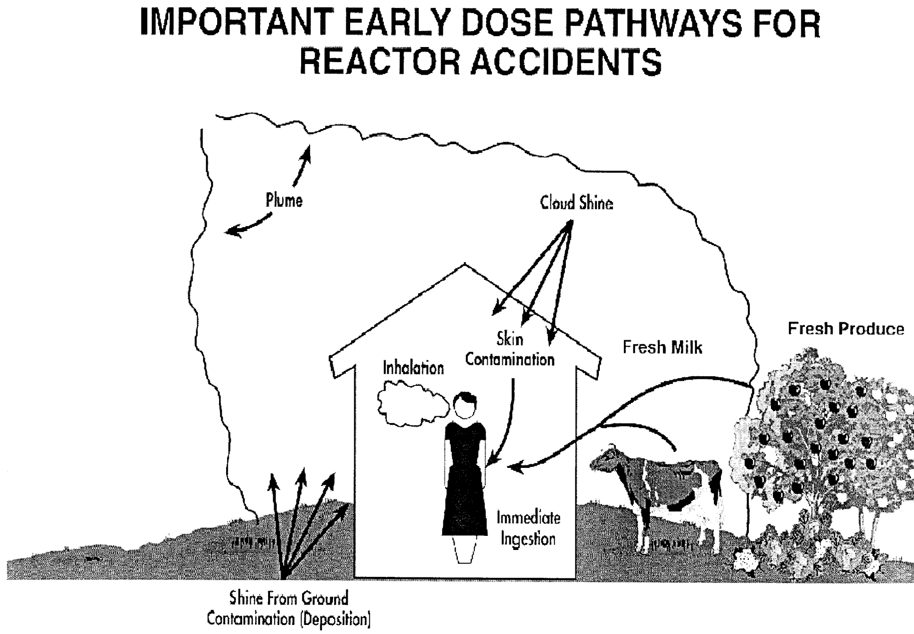

Fig. 1. Radiation dose pathways.

be received externally from the radiation given off by the passing plume or the deposited materials. These types of doses are called cloud shine and ground shine, respectively.

In addition, dose can be received by contacting the radioactive material in the plume, which can result in contamination of skin or clothing. Finally, breathing radioactive material into the lungs causes inhalation dose, while eating contaminated food or drinking contaminated water causes ingestion dose. Inhaled or ingested material, in addition to directly providing a dose, contains certain elements that concentrate in particular organs (e.g., lungs or thyroid) and thus, become a special threat to those organs. The differences between the inhalation and ingestion pathways have led the Nuclear Regulatory Commission (NRC) to establish an Emergency Planning Zone (EPZ) of about 10 miles in radius for plume inhalation protective action planning and another about 50 miles in radius for ingestion protective action planning [1].

An atmospheric release of major fractions of the radioactive material contained in the reactor core could result in two types of health effects that might require emergency response. The first type is acute effects (early or deterministic), which are deaths and injuries that would occur within weeks or months of exposure. The second type is the longer-term (latent) health effects (e.g., cancer) that would not be directly observable in the immediate aftermath of an accident. Acute effects generally would appear at doses above 50–100 rem (0.5–1 Sv) to the whole body (bone marrow), and early deaths would be expected at doses of 200–600 rem (2–6 Sv).

The risk of cancer, generally, is presumed to be proportional to dose, *no matter how small*. The models assume that a collective dose of about 5000 person–rem (e.g., 1 rem to 5000 people) will result in one member of the affected population getting cancer. Because the release is spread over a larger area and, therefore, exposes a larger population as it moves farther from the plant, most of the cancers will result from very small exposures *beyond 50 miles* from the plant.

Indeed, this could be the principal source of risk if the plume were to be very hot and rise as it left the plant. During the Chernobyl accident, the population close to the plant received relatively modest exposures as the plume passed overhead. However, radioactive particles or aerosols settled out (on the ground, trees, people, etc.) as the radioactive cloud moved away from the reactor site, exposing people at greater distances to significant amounts of ground contamination. Consequently, the vast majority of the thyroid cancers that resulted from the Chernobyl accident occurred more than 50 miles from the plant [2].

To reduce radiation doses, protective actions can be taken to decrease the duration of exposure, increase distance from the source, or to provide shielding for those at risk. Any protective actions taken in response to a severe nuclear accident should have the following objectives.

- To *avoid* doses sufficient to cause early severe health effects (injuries or deaths) that would be seen at whole-body doses above 50–100 rem.
- To *reduce* doses above those limits established by the protective action guides (PAGs) proposed by the U.S. Environmental Protection Agency (EPA) [3,4] and U.S. Department of Health and Human Services Food and Drug Administration (FDA) [5].
- To control total long-term effects (e.g., total cancers resulting from collective doses of 5000 or more person-rem).

Obviously, any immediate protective actions should be directed toward meeting the first objective by keeping the whole-body dose from the passing plume (shine and inhalation) and resulting ground contamination below levels that could result in early deaths or injuries.

The EPA and FDA PAGs pertain to the second of the radiation protection objectives (i.e., reduce doses) rather than the first objective (i.e., avoid acute health effects). The PAG limits were established at levels below which no early health effects would be expected, even for such sensitive populations as pregnant women and children (see Table 1). These PAGs are the dose that can be averted by taking the appropriate protective actions. At any time, previously incurred doses are not to be considered.

Until about the time of the accident at Three Mile Island Unit 2 (TMI-2), many radiation protection professionals assumed that protective action decisions would require a real-time field measurement of dose rate and an incident-specific estimate of release duration to determine a projected dose. Once this dose projection had been calculated, it could be compared to the EPA PAGs and the appropriate protective action recommendation (PAR) selected. The critical limitations of this procedure are — it will provide significant dose reduction only if evacuation can be completed rapidly, sheltering in-place is highly effective, or dose rates from the passing plume are low. As it turns out, none of these conditions can be taken for granted. First, as will be discussed below, dose rates from the passing plume will be high during a major release shortly after severe core damage. Second, there is only a modest dose reduction achieved by sheltering in the wood frame structures typical of the areas around most nuclear power

Table 1
EPA early-phase PAGs

Organ	EPA PAGs[a] for plume exposure (rem/Sv)	Protective action[b]
Effective dose equivalent (whole body)	1–5 (0.01–0.05)	Evacuation
Thyroid	25 (0.25)	Administration of stable iodine

[a]Dose from inhalation and external exposure from passage of the plume and material deposited on the ground.

[b]These actions should be taken if they can avert the PAG dose.

plants [6]. Third, the discussions by Lindell [7] and Urbanik [8] elsewhere in this issue indicate that evacuations generally are quite time-consuming. Consequently, evacuation of the population within 2–3 miles of the plant must start *before or soon after the release* to prevent early health effects in an accident having a major release shortly after severe core damage. This requirement implies that initial protective actions for the population near the plant should not be based upon field measurements because, by definition, field measurements obtained *after* a release cannot produce evacuation *before* that release. Moreover, even if field measurements are taken shortly after release initiation, much time can be consumed in the process of selecting and implementing appropriate protective responses. After assessing dose rates, it is necessary to select a PAR, obtain the concurrence of off-site authorities, and transmit warnings to the population at risk — who must prepare to evacuate and then drive out of the risk area.

Considerable attention also has been given to the use of dose projections determined from incident-specific source term data as the basis for initiating off-site protective actions. However, for some very severe accidents, real-time dose projections would be available too late and would be too inadequate for initiation of effective off-site protective response. This is because several steps are required to predict dose from incident-specific source term data: (1) predicting the quantity and timing of the release from the plant into the atmosphere (source term), (2) predicting the movement of the plume through the atmosphere (transport), and (3) predicting the dose from the plume.

An overall estimate of the uncertainties associated with dose assessment for severe accidents has been made by the NRC technical staff [9]. These estimates, given in Table 2, are estimates of the ratio of what a model may project for an accident sequence and what the actual average dose rate may be. It is apparent that, overall, the best that should be expected in the early time frame is that projected dose estimates may be within a factor of 10 of the true dose value; more likely, they will be even less accurate.

Table 2 also shows that the largest single component of uncertainty is expected to be the uncertainty in the estimate of the source term. Since the TMI-2 accident, the nuclear industry, the NRC, and its contractors have conducted considerable research on this problem. Source term uncertainty is relatively small for non-core damage accidents in which the total release is through a monitored pathway and consists mostly of noble gases. However, the source term could be underestimated by a factor of 100,000 or more

Table 2
Estimated range of uncertainty between early projected dose and actual off-site dose for a severe accident (core melt)[a]

Element	Uncertainty factor[b]		
	At best	Most likely	Near worst
Source term	5	100–1000	100,000
Dispersion			
Diffusion (concentration)	2	5	10
Transport (direction)	22°	45°	180°
Transport (rate)	1	2	10 (low wind speed)
Dosimetry			
Overall dose	10	100–10,000	100,000
Overall direction	22°	45°	180°

[a] These estimates are for an averaged dose at a location (e.g., over 15–30 min), not for a specific or single monitor reading.

[b] Ratio of a likely maximum or minimum value to the expected median value.

in severe core damage accidents involving unanticipated catastrophic containment failure because such a release would most probably be via an unmonitored pathway to the atmosphere. Such unmonitored releases could take place through major failure in the containment building structure or one of its penetrations for piping and instrumentation. As a result, effluent-monitoring systems located in routinely monitored release pathways, such as stacks, will not be able to assess the extent and the characteristics of such a severe release.

This highlights the difficulty of source term estimation because, during an actual accident, detailed plant conditions would not be known. The result is that it will be very difficult to predict the source term with a reasonable degree of accuracy early in the response to a severe accident that results in a major release. Indeed, even if all plant conditions are known, the current computer models could predict the source term only to within a factor of 100 [10].

The problem of source term estimation is compounded by the problem of characterizing the movement of the radioactive material through the atmosphere (i.e., transport). Unfortunately, dose models give a simplistic picture of this very complex process. The inadequacies of existing transport models is clear from the actual deposition patterns from the Chernobyl accident shown in Fig. 2 [11]. This deposition pattern could not have been projected by a model. Moreover, the problem of projecting where the plume will travel is compounded by two additional facts. First, the initial transport of radioactive material from the site after it is released to the atmosphere will be dominated by local conditions (e.g., hills, valleys, lakes, and precipitation). However, there typically is only one local meteorological tower in the vicinity of the plant site. Consequently, this single source of meteorological information cannot give a definitive indication of winds away from the plant. Second, nuclear power plants typically are located in areas (e.g., in river valleys or on the coast) where wind direction and flows

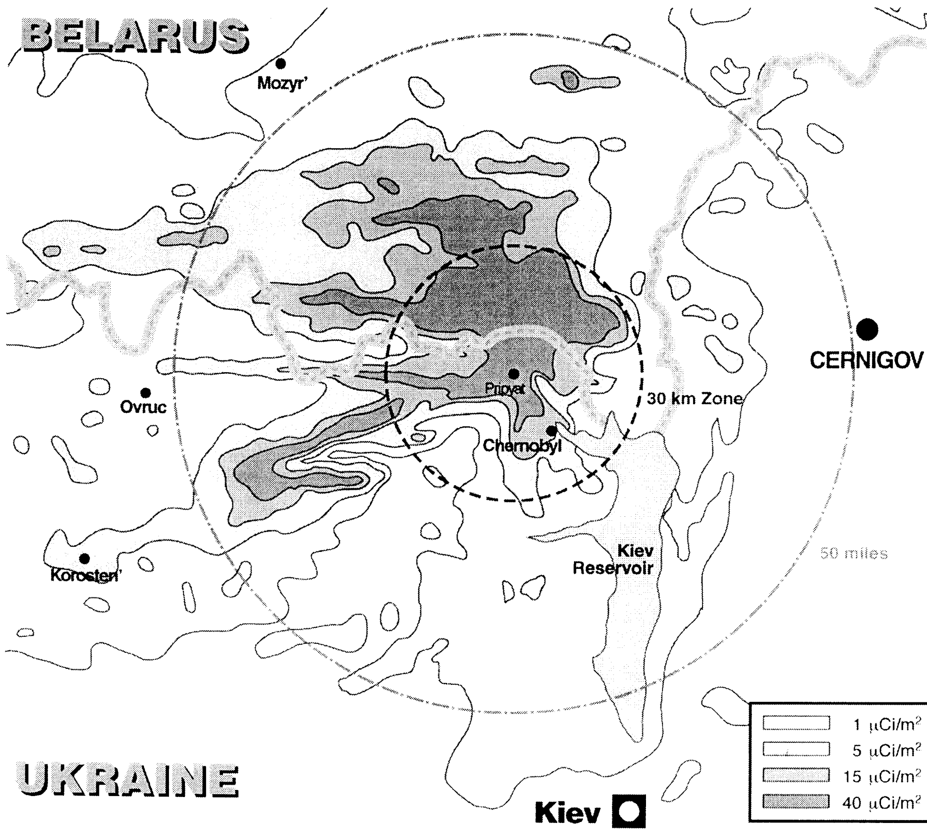

Fig. 2. Radioactive deposition patterns following the Chernobyl accident.

can vary considerably within a short distance of the plant. As an example, sea breeze effects at a coastal site could cause a 180° difference in wind direction.

Finally, problems arise in estimating off-site dose estimates because organizations that will be involved in the response to a nuclear power plant accident use dose models that differ in their assumptions. Thus, these organizations are likely to obtain different projections even if the same input conditions (e.g., source terms and meteorology) are used. For example, the NRC may be concentrating on dose projections based on possible additional plant failures, while the state is making dose projections based on estimates of actual releases. Therefore, a 10- to 100-fold or greater spread in calculated doses must be anticipated among the response organizations such as the licensee, NRC, state and local officials, and U.S. Department of Energy.

In summary, time and accuracy constraints require PARs to be made on the basis of plant conditions that are available very early in the chain of events that might result in a release of radioactive materials. To understand the basis for PARs based on plant conditions, it is necessary to review the basic elements of nuclear power plant design, the location of radioactive inventories, potential accident sequences, and potential release mechanisms. Each of these is addressed in the following sections.

2. Plant conditions as a basis for PARs

The two basic sources of safety problems at an operating nuclear power plant are the very large amount of volatile radioactive materials that, if released, could cause off-site health effects, and the energy in the core that, if not controlled, could release these fission products. Even if the reactor has been shut down, substantial energy is stored in the reactor systems and is being generated by the decay of fission products (decay heat). During the first hour after shutdown, decay heat is on the order of 3% to 5% of full power. If not controlled, it can be a substantial driving force for release of the radioactive materials from the core into the environment.

Table 3, adapted from WASH 1400, shows inventories of the most volatile radioactive materials (noble gases and radioiodine) in various plant systems [12]. Noble gases deserve attention because these are the materials most likely to be released during an accident. Radioiodine also requires attention because it can be a major source of dose to the public early in a severe accident. In addition, small quantities of radioiodine can cause damage to the thyroid gland. Note that the vast majority of radioactive material is contained in the core of the reactor. All other reactor systems contain less than 0.5% of the activity in the core.

Table 3
Typical inventories of noble gases and iodine in reactor systems

Location	Inventory (Ci)	
	Noble gases (Xe, Kr)	Iodine (I)
Reactor core total	400,000,000	750,000,000
Reactor core gap[a]	30,000,000	14,000,000
Spent fuel storage pool	1,000,000	500,000[b]
Primary coolant[c]	10,000	600[c]
Other pressurized water reactor systems		
Waste gas storage tank	100,000	1
Other boiling water reactor systems		
Steam line	10,000[d]	25[d]
Waste gas treatment system	5,000	0.25
Shipping cask	10,000	1

[a] The ‘‘gap’’ is the gaseous fission products in the fuel pin ‘‘gap’’.
[b] One-third of the core is 30 days old; the rest is 1 year old.
[c] Nominal value at normal iodine levels can be much higher or lower (factor of 10) depending on fuel leakage.
[d] Ci/h (circulating).

It is instructive to compare the amount of radioactive material in light water reactor systems to the amount necessary for an atmospheric release to induce doses equal to EPA PAGs; note that dose levels 10 or more times higher than the PAGs are required for early injuries or fatalities. Table 4 shows the number of curies that must be released to the atmosphere to result in doses equal to the PAGs under meteorological conditions that would, for a given release, produce higher-than-average dose levels at a distance of about 1 mile [13]. Under average meteorological conditions, about 10 times more radioactive material would have to be released.

The comparison of Tables 3 and 4 shows that the release of even a very small fraction of the core radioactive material inventory to the atmosphere could result in doses exceeding the PAGs near the site. However, only the core and spent-fuel storage pool contain the requisite amount of inventory. Releases from other systems, such as a rupture of the gas-decay tank, are not expected to result in off-site doses in excess of the early phase PAGs. Furthermore, only the reactor core contains sufficient radioactive material *and energy from decay heat* to result in atmospheric releases that could result in early deaths and injuries off-site.

Although core failure is a necessary condition for off-site health effects, it is not the only condition. Other barriers and engineered safety features also must fail in order to cause a major release. Nuclear power plants are constructed with three fission product barriers designed to prevent the release of radioactive materials to the environment from the reactor core. Individual fuel pellets are stacked upon each other and sealed inside zirconium or stainless steel tubing (called cladding) to form fuel pins, the first barrier to release. The space between the fuel pins is called the gap. The fuel pins (rods) are assembled into fuel elements that all are a part of the reactor core. The reactor core is contained within the reactor vessel which, together with its associated piping, forms the primary cooling system. This is the second barrier to fission product release. Finally, the primary coolant system is contained within the containment building, which is the third fission product barrier.

The primary cooling system is filled with cooling water that keeps the temperature of the fuel cladding at an average of about 600°F during normal operation. If the cooling water falls below the top of the fuel, the temperature of the fuel cladding will rise at a

Table 4
Atmospheric release (Ci) necessary under poor meteorological conditions[a] to result in early phase PAG levels at one mile

Radioactive material	Pathway	Curies released[b]	
		25 rem — Thyroid[c]	5 rem — Effective dose equivalent
Iodine (I-131)	Inhalation	1000	
Noble gases (gamma emitters — Xe, Kr)	Cloud shine		1,500,000

[a] Conditions that result in doses higher than those projected under average conditions.
[b] Approximate minimum.
[c] Child's thyroid.

rate of about 1–2°F/s. Table 5 describes the temperature of the core and the condition of the UO_2 fuel pellets as a function of the time since core uncovery. At temperatures above 1800°F, the fuel cladding will begin to react (burn)-increasing the heat-up and fuel failure rate. In addition, at these temperatures the volatile radioactive materials such as iodine and cesium could be released from the fuel at approximately 1%/min [14]. This temperature can be reached in 15 min once the core is uncovered. Once the cladding fails, radioactive material in the fuel can escape into the primary system, the containment building, or the atmosphere depending upon the accident sequence. Therefore, an accident is considered severe whenever the fuel cladding temperature is expected to reach 1800°F.

There are many reactor systems designed to protect the fission product barriers. The effectiveness of these systems can be assessed in terms of how well they perform a few critical safety functions. The critical safety functions will, if maintained, prevent damage to the core. Each of these functions is performed by a number of redundant engineered safety features. Basically, these functions are to (1) shut down the reactor (stop the fissions), (2) maintain coolant level (keep the core covered), and (3) maintain coolant temperature (remove heat from the cooling water). The performance of these critical safety functions in a severe accident is assured because they are performed *whether or not the situation is an emergency*. Specifically, Control Room staff are trained to follow specific emergency operating procedures in monitoring the status of these critical safety functions and, consequently, the projected status of the fission product barriers. Therefore, routinely monitored instrumentation should provide Control Room personnel with ample warning well before a major atmospheric release occurs [15].

Once the reactor has been shut down, the prevention of core damage is a fundamentally simple task because of the diverse and redundant systems available to maintain the remaining two functions — coolant level and coolant temperature. About 1 h after shutdown, a flow of only a few hundred gallons of water per minute is needed to keep the core cool. Moreover, there are many redundant ways to get sufficient flow to replace

Table 5
Average fuel pin temperature and fuel condition as a function of time since core uncovery

Time since core uncovery	Temperature (°F)	Fuel condition
45–90 min	5400	Melting of fuel pellets
		Possible melt through of reactor vessel
	4800	Release of all volatile fission products
30–60 min	4200	Possible formation of uncoolable core
	3600	Formation of ‘‘liquefied fuel’’
		Fuel dissolves into melted components
20–40 min	3000	Very rapid release of iodine, cesium and noble gases
	2400	Very rapid steam-zircalloy reaction
		Release of hydrogen and failure of fuel cladding
10–20 min	1800	Possible cladding burst
		Release of fission products in fuel gap
	600	Normal operating temperature

coolant lost through a leak or keep the core cool by boiling water. Some of these systems are designed to maintain the critical safety functions even under such severe accident conditions as a total break in the largest piping in the primary reactor coolant system.

The availability of redundant methods of core cooling means that core damage would require the failure of several engineered safety features (e.g., including the emergency core cooling system) that have been designed to maintain the critical safety functions. Thus, to produce a major release, a systems failure must be followed by:

- failure of one or more engineered safety features,
- failure to meet one or more of the critical safety functions,
- failure of fission product barriers, and
- movement of radioactive material through plant systems.

The redundant design, which requires that *all* of these conditions must occur before an atmospheric release occurs, will reduce the likelihood of a release, or at least decrease its severity. The significance of these conditions for protective action decision-making is that considerable instrumentation exists in the Control Room to indicate the status of the critical safety functions, fission product barriers, and (grossly) the movement of radioactive material. The availability of key plant safety parameters such as core temperature, coolant level in the reactor vessel, and highly elevated levels of radioactivity in the containment building will allow Control Room personnel to surmise the extent of core damage. Therefore, the status of key plant safety systems and parameters in conjunction with radiation monitoring will provide the best, clearest, and probably the only indicators of core damage and movement of radioactive material through plant systems. These indications of actual or likely core damage should be clearly evident in the Control Room *before* a release to the atmosphere.

In addition to core damage, a release sufficient to result in early casualties would require a direct pathway to the environment and a driving force (e.g., steam). The radioactive material released from the core must move rapidly through the primary coolant system (the second barrier) and containment (the third barrier) without being significantly filtered or reduced by other safety features such as containment sprays. Even if the containment sprays fail, natural removal processes such as condensation and scrubbing will remove most of the particulate fission products from the atmosphere of an intact containment building over time. Thus, if the containment building holds for several hours or safety systems such as sprays are working, early injuries or fatalities would be highly unlikely even if there were a total failure of the containment building following core damage.

Severe-accident analyses have identified low-probability accident sequences that could result in significant off-site releases. Fig. 3 uses an event tree to display the potential consequences for public health due to severe accidents [13]. Moving from left to right, ‘‘yes’’ or ‘‘no’’ answers to conditions at the top of the figure generate a series of branches that identify the likely off-site consequences. For example, if only the

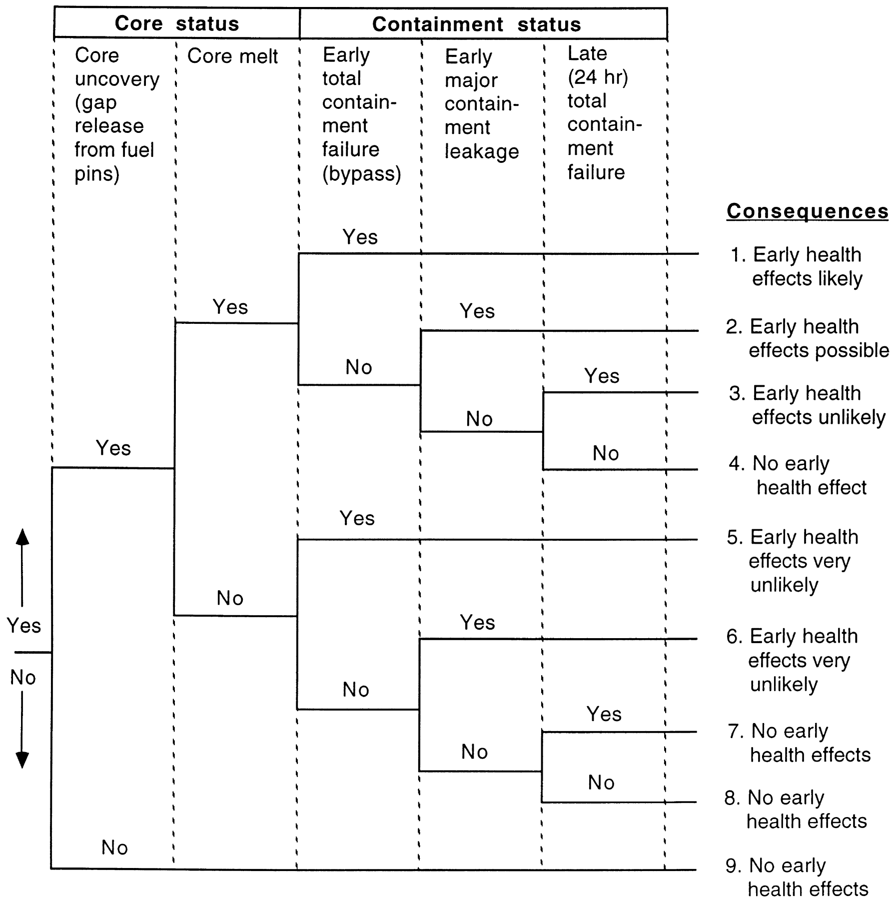

Fig. 3. Potential off-site consequences as a function of plant conditions.

radioactive material contained in the fuel pins (gaps) is released with late containment failure, then Branch 7 indicates that no early health effects are expected. If core uncovery is followed by core melt and early containment failure (i.e., all answers are ‘‘yes’’), Branch 1 indicates early health effects are likely. Fig. 4 indicates that there are two fundamental questions affecting the public health and safety during an emergency response at a light water reactor. The first question concerns the status of the reactor core, while the second question concerns the status of the reactor containment. The answers to these two questions scope the level of threat to the public and the need for off-site emergency response. The Control Room staff will be able to assess the status of the reactor core quite easily because, as we have seen, there will be considerable indications of actual core damage. However, the same is not necessarily true of reactor containment status. As Table 6 indicates, containment buildings can fail in many ways

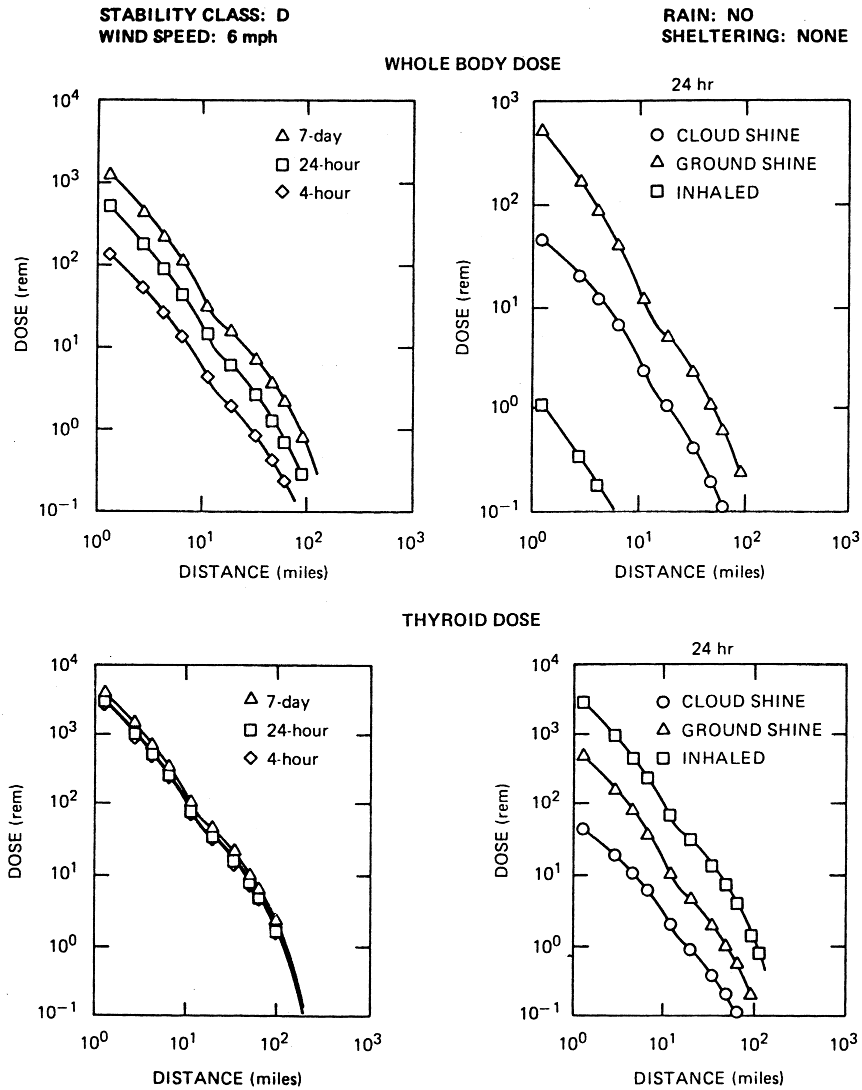

Fig. 4. Whole-body and thyroid doses as a function of distance and timefor various exposure pathways.

during a core damage accident [16]. In particular, containment failures due to mechanisms such as pre-existing leak, hydrogen combustion, bypass, or core melt-through are unpredictable. Thus, the Control Room staff may not be able to predict containment performance with adequate certainty in a severe accident.

As Fig. 3 indicates, uncertainty about containment performance has little significance for risk to the public in the absence of core damage. However, given core damage, there

Table 6
Containment building failure mechanisms

When	Challenge	Predictable?
Start of accident	Existing leak	No
	Isolation failure	No
	Bypass	No
Before vessel melt-through	Overpressurization	No
	Hydrogen combustion	No
	Late bypass	No
	Late SGTR	No
	Venting	Yes
At or soon after vessel melt-through	Steam spike/explosion	No
	Hydrogen combustion	No
	Direct containment heating	No
	Core melt-contact with containment	No
	Venting	Yes
Greater than 2 h after vessel melt-through	Overpressurization	No
	Hydrogen combustion	No
	Basemat melt-through	No

must have been *major* human error or equipment failure. Under these conditions, there may be little assurance that a major release is not possible because the plant systems are well beyond their design. For some containment designs, it is estimated that as many as 1 in 10 core melt accidents would result in a release sufficient to cause acute health effects off-site if protective actions are not taken early in the accident sequence [10].

3. Severe core damage accidents: potential health effects and PARs

Only a *very* severe reactor accident involving core damage (20% or more cladding failure) and early containment failure could result in early death or injury. Such an accident is considered very unlikely but would require prompt and effective protective actions to prevent early health effects off-site. There are many accident sequences that could produce acute health effects, but a *representative* accident involving severe core damage followed by an early containment failure would involve a release of about 60% of the noble gases and 5–10% of the iodine and cesium in the reactor core [10]. The whole-body and thyroid dose as a function of distance and time for various pathways for this accident can be seen in Fig. 4. The doses for this accident were calculated for meteorological conditions on an average day, so actual doses could be somewhat higher or lower depending on the actual weather at the time [17].

The top right figure portion of the figure shows the contributions to the whole-body dose during the first 24 h after the release. The inhalation pathway would contribute the least to projected whole-body dose and the cloud shine dose would be sub-lethal.

However, the additional 24-h ground shine contribution would lead to projected doses in excess of the early injury threshold (100 rem, 1 Sv) out to about 7 miles and the early fatality threshold (200 rem, 2 Sv) out to about 3 miles.

In this example, the early doses (cloud shine and inhalation) are not sufficient to cause early injuries, but they do exceed EPA PAGs for evacuation out to about 10 miles. Other accidents have been postulated that could cause early injuries close to the plant resulting from cloud shine and inhalation. This shows the importance of early protective actions. For an accident of this type involving a puff release with a duration of 1–2 h, the population close to the plant must take actions before or shortly after the start of the release to avoid a major portion of the dose from the plume shine and inhalation. Actions taken after the puff's passage are effective only in reducing dose from ground contamination.

The dose increase between 4 h and 7 days (shown in the top left figure) results from ground contamination deposited by the passing plume. In this example, the direct dose from the plume is not sufficient to result in early deaths or injuries; but if people remain on contaminated ground, their dose will build until it could result in injuries at about 6 h and death at about 12 h. Obviously, after a major release, areas of substantial ground contamination must be identified, and the population must be evacuated.

From the bottom figures, it can be seen that projected thyroid doses are controlled by inhalation doses, with the cloud and ground shine contribution increasing the dose only marginally within 24 h. Thyroid ablation would occur at doses above about 1000 rem (10 Sv), but this would not be expected beyond about 3 miles (about 5 km) from the plant in this accident scenario. It is clear that this accident would result in doses in excess of the EPA PAGs for whole-body (5 rem,.05 Sv) and thyroid (25 rem,.25 Sv) doses; at these levels, evacuation would be appropriate even beyond the plume inhalation EPZ. In general, whole-body dose (not thyroid dose) would be the most important dose for most accidents in terms of early fatalities and injuries.

Although the ingestion pathways can be of concern at distances greater than 50 miles (80 km) from the release point, ingestion dose is not considered a major contributor to early health effects and consequently, does not require immediate protective action. Nonetheless, some early protection actions, such as removing cows from pasture and putting them on stored foods, are designed to minimize subsequent contamination of milk or other foods. The specific actions and criteria for vegetables are addressed by the FDA PAGs [5].

Fig. 5 shows the results of an analysis of various measures taken to protect the public in response to the most severe type of reactor release resulting from core melt and early containment failure [10]. This type of accident results in a very large release similar to the accident discussed above. The scale on the ordinate shows the probability of a person receiving an acute dose to the whole body in excess of the 200 rem (2 Sv) threshold for early deaths at various distances. This shows that, for areas within 3 miles (5 km), the risk of deaths can be reduced almost to zero by starting evacuation, at walking speed, 1 h before the release (Case 4) and substantially reduced by sheltering in a large building (Case 3). Even walking out in the plume (Case 5) is better than basement shelter in a normal home (Case 2). This analysis assumes only that the *evacuation is conducted at walking speed* and all people in areas with significant levels

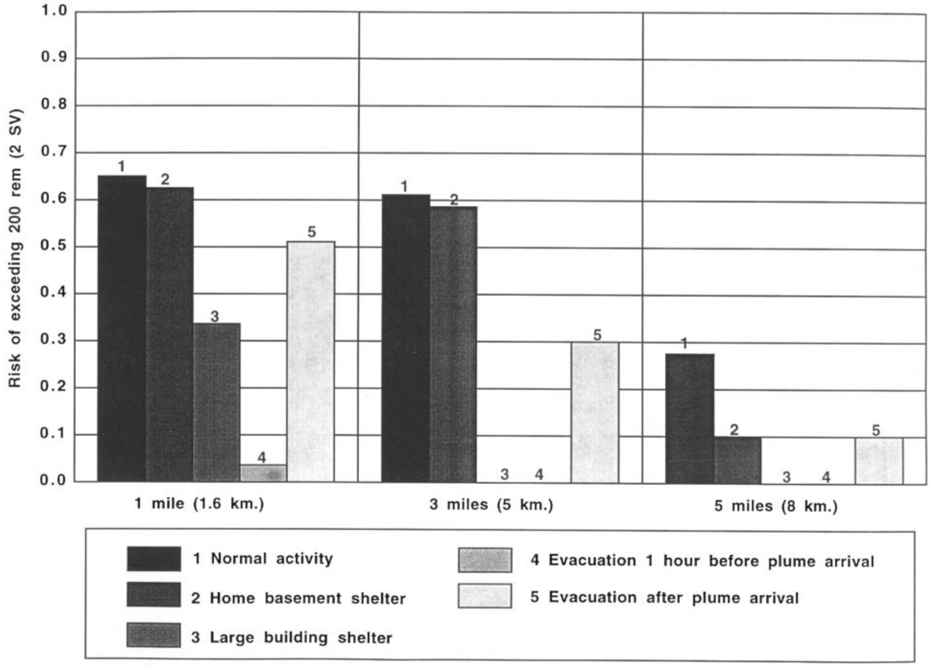

Fig. 5. Risk of exceeding 200 rem (2 Sv) in a severe core damage accident with early containment failure as a function of alternative protective actions.

of contamination are evacuated within 6 h. These data support the following conclusions:

- Evacuation must begin before or shortly after a release to reduce risk substantially,
- Sheltering in-place close to the plant for long periods may not be an effective protective action, and
- Movement of even distances as short as 5 miles (8 km) results in substantial reduction in risk.

The latter point clearly indicates that protective actions must concentrate first on the area near the plant.

Even though evacuation generally is preferred in areas close to the plant, it may not be feasible in certain circumstances. Sheltering in-place may be the appropriate initial protective action for transit-dependent persons, who should be advised to remain indoors until transportation resources arrive. In addition, sheltering in-place may be the appropriate protective action for controlled releases of radioactive material from the containment if there is assurance that the release is short term and the area near the plant cannot be evacuated before the plume arrives.

Moreover, travel conditions that would present an extreme hazard may prompt off-site officials to initially recommend sheltering in-place until conditions improve rather than evacuating. This is because those who are evacuating could be overtaken by the plume and trapped inside their cars during plume passage if transportation routes are blocked by excessive traffic demand, or adverse weather conditions such as an ice storm. Cars provide no dose reduction, so people in these circumstances might incur greater doses than if they had sheltered in-place. Nonetheless, predetermined evacuation recommendations should be cancelled only if conditions are going to trap people close to the plant for many hours. The emergency response organization always should advise people to evacuate areas near the plant if at all possible — for cause, of course (General Emergency). If early evacuation simply is not possible, emergency personnel should monitor for ground contamination following a release, if any, and advise people to leave any areas found to contain large amounts of contamination (i.e., ‘‘hot spots’’). Most likely, it will not be necessary for people to move very far from such heavily contaminated areas to achieve a significant reduction in their exposure from this pathway.

Although entrapment is a concern that must be addressed, it is unlikely to be a significant problem in an actual emergency. At most U.S. nuclear reactor sites, fewer than 300 people live within the first 2–3 miles around the plant. Moreover, there are few facilities such as hospitals that would be difficult to evacuate (see Ref. [18], for a list of special facilities). At the few reactor sites where the population near the plant is large or difficult to move, emergency planners (and emergency managers) must make appropriate accommodations in the planning process. It must always be remembered, though, that for *all* sites, early evacuation of nearby areas would be most beneficial and for the most severe accidents, early evacuation would be the only protective action available to achieve basic radiation protection objectives for the population near the plant.

It is important to note that these prescriptions depart from past practice, which has advocated implementing protective action only in a downwind direction. Downwind evacuation appears to be a reasonable planning strategy because it would reduce the number of evacuees and, thus, reduce the amount of social and economic disruption. The problem is that it may be difficult — if not impossible — to predict the magnitude and timing of a major release during the early stages of an accident. Consequently, one cannot be certain where ‘‘downwind’’ would be at the time a release occurred. Emergency managers can avoid this uncertainty only by waiting to define ‘‘downwind’’ until an actual major release is underway. However, as we have seen, protective actions that are not initiated until after initiation of a major release provide little, if any, risk reduction potential for the public. *Therefore, the initial, early, precautionary evacuation near the plant should be effected in all directions*.

4. Application to the Three Mile Island accident

To highlight some of these points, certain aspects of the assessments of the TMI-2 accident merit discussion. Fig. 6 presents the hourly wind vector as measured by the site meteorological system during the first day of the accident. It is evident that wind direction at the site varied dramatically throughout the 12-hour period. The accident started at 4:00 a.m., when the wind was blowing nearly due South. By the time that core

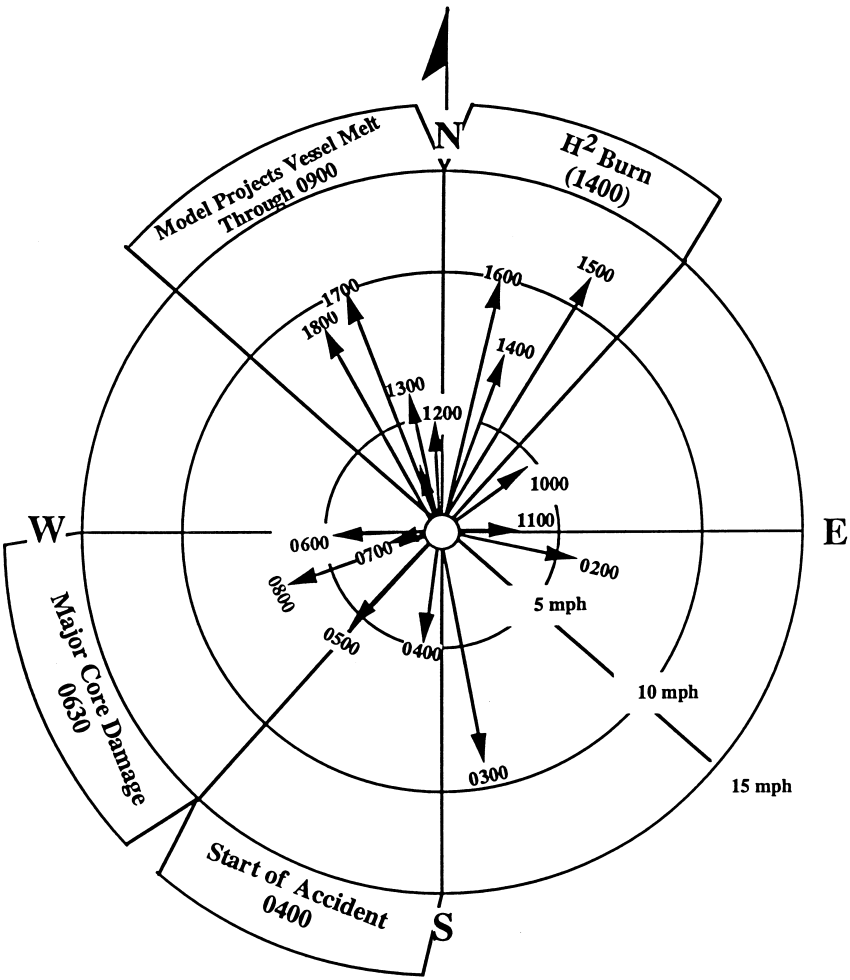

Fig. 6. Variation in wind speed and direction over time during the Three Mile Island accident.

damage occurred at about 6:30 a.m., the wind was blowing in a more westerly direction. Between 7:30 and 8:00 a.m., the State of Pennsylvania issued warnings of imminent evacuation to the west of the site.

By 9:00 a.m., indications of severe core damage were indisputable. Some of the instruments showed core cladding temperatures over 2000°F (well beyond that required for cladding failures), and the containment radiation levels increased to 6000 R/h (more than a 1000 times normal) between 8:20 and 9:00 a.m. However, the decision not to take action was based on the fact that field monitoring had not detected radiation off-site. The NRC Special Inquiry Group concluded that the state offices should have been advised at 9:00 a.m. that ‘‘the core has been badly damaged and has released a substantial amount of radioactivity. The plant is in a condition not previously analyzed for cooling system performance'' [19]. Models have calculated that conditions possibly leading to failure of the vessel existed at about 9:00 a.m. [20]. At this time, the wind had veered around toward the Northwest and, an hour later, toward the Northeast. At 2:00 p.m., there was a significant increase in containment pressure due to a hydrogen burn [21]. If these events had resulted in a major release, downwind evacuation taken early in the event (Southwest of the plant) would not have offered any protection to those under the plume (Northeast of the plant). Accordingly, the NRC Special Inquiry Group noted that omnidirectional evacuation of the entire low-population zone (2.5-mile-radius area surrounding the site) would have been warranted no later than 7:30 a.m.

5. Summary

Guidance for licensees and off-site emergency response organizations on PARs under General Emergency conditions originally was provided in NUREG-0654, Appendix 1 in November 1980 [22]. This guidance requires nuclear power plants to establish four emergency classes for which various levels of off-site response are preplanned. Each emergency class is defined by emergency action levels (EALs) that are based on Control Room instrumentation that would indicate the class of emergency and these EALs are incorporated into each licensee's emergency operating procedures. The most serious emergency class is a General Emergency, which should be declared when plant conditions indicate that severe core damage is imminent or in progress and, thus, events have a very real potential for severe off-site health effects. A General Emergency would warrant immediate transmission of PARs to off-site authorities. While some events have been postulated that could cause very rapid releases, most severe accidents studied by the NRC would be classified as General Emergencies by the EALs well before a major release occurs.

The guid0ance in NUREG-0654 was clarified and illustrated in a flow diagram in NRC Information Notice (IN) 83–28, ''Criteria for Protective Action Recommendations for General Emergencies'' [23]. Licensees, as well as state and local governments, have used the protective action guidance in NUREG-0654 and IN 83–28 as the basis for determining PARs and directives in their emergency plans and implementing procedures. However, the NRC staff position and internal guidance for developing protective actions for severe reactor accidents has evolved from the guidance in NUREG-0654 based primarily on the results of severe accident studies described in Section 4. Experience gained in reviewing emergency plans and in evaluating numerous nuclear power plant emergency exercises has shown that not all emergency response organizations are fully aware of how the NRC's improved understanding of severe accidents affects the application of the guidance on protective action decision-making.

The guidance in NUREG-0654 indicated that the initial protective action for a General Emergency is to shelter the population close to the plant while considering the advisability of evacuation. This initial guidance for the local population to shelter in-place was intended to apply only until a determination was made that substantial core damage sequences were in progress or were projected. NUREG-0654 further indicates that if core damage is in progress and containment failure is judged to be imminent, sheltering in-place should be recommended for people in those areas that could not be evacuated before the plume arrived. Although NUREG-0654 never was intended to imply that the appropriate initial protective action for severe accidents was to only shelter the population that is near the plant, the guidance was not explicit on this point. Having people shelter in-place if they cannot evacuate before the plume arrives was considered to apply only for a short-term release of known duration.

In 1996, the NRC issued simplified guidance on the decision-making process for determining protective actions for the public in the event of actual or projected severe core damage or loss of control of the facility [24]. The NRC staff have concluded that nuclear power plant accidents less serious than core-melt sequences do not warrant immediate, early evacuation. However, in-plant observations (Control Room indicators regarding status of the core and systems that protect the core) diagnostic of severe core damage should be used to declare a General Emergency. The NRC guidance emphasized that the preferred PAR following declaration of a General Emergency is an immediate precautionary evacuation of about 2 miles in radius and about 5 miles downwind, unless other conditions make evacuation dangerous. Persons in the remainder of the plume inhalation EPZ should be directed to go indoors and monitor their Emergency Alert Station while the situation is further assessed. By doing so, they will be able to receive additional instructions, if necessary. These protective actions should be initiated without waiting for real-time dose projections.

Moreover, the licensee and off-site authorities should continue assessment based on all available plant and field monitoring information. *If* a major release occurs, radiological monitoring teams should search for any hot spots (areas with dose rates in excess of 1 R/hr) so these can be identified and evacuated. Other protective actions should be modified as changes in the situation warrant, but should not be relaxed until the source of the threat clearly is under control.

These recommendations are based on the following considerations: (1) the relative ease with which plant staff can use a few key indicators to detect/predict major core damage, (2) the relatively high risk of a major release (e.g., 10%) given core damage, (3) the large uncertainties associated with projecting containment failure, (4) the great difficulties in making accurate and timely dose projections in the face of the latter uncertainty, and (5) the effectiveness of off-site protective actions if initiated before a major release occurred (e.g., precautionary evacuation).

Meteorological conditions should be considered only in assessing whether or not it is feasible to implement an early precautionary evacuation of the immediate area around the plant. Wind direction should not be used to determine where an evacuation should be recommended because of a general inability to determine where ‘‘downwind’’ will be when a significant release occurs, especially if one takes place during an evacuation. Such a predetermined, early, initial evacuation for a General Emergency is considered to be precautionary because a major release may never actually occur, as was the case at TMI-2.

Environmental monitoring data collected after a release should form the basis for *additional* protective actions, not the *initial* protective actions. Segments of the population may need to be relocated following the identification of hot spots to prevent acute health effects or cancer risks due to shine or resuspension from ground deposition.

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