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Emergency Planning for Reactor Accidents

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The politics of the nuclear power debate has foreclosed serious consideration of safety measures to protect the public in case of a reactor accident. The proponents of nuclear power do not wish to alarm the public and the opponents have considerea the matter irrelevant.

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Emergency planning for reactor accidents

Because it has been assumed that a major nuclear accident will never occur, few preparations have been made to mitigate the consequences of large releases of radioactivity in the event of such an accident. In light of Three Mile Island and other earlier events, such as the Brown's Ferry incident, it seems prudent to adopt measures which could dramatically reduce the number of people permanently affected by a bad reactor accident.

Indeed, some preliminary actions have been taken as part of the official response to the Three Mile Island accident. The Nuclear Regulatory Commission, with the help of the Federal Emergency Management Agency, is moving to require utilities and state governments to develop a quick-response capability out to 16 kilometers (~10 miles) from reactors.[1] Beyond 10 miles, ad hoc measures are assumed to be sufficient.[2] Although this initiative is an important first step, it does not adequately take into account the very large number of people beyond the 10-mile zone who would be affected by a large release of radioactivity.

The politics of the nuclear debate is, in part, responsible for the slow development of serious emergency planning. Many anti-nuclear activists see contingency plans as irrelevant, except as an organizing tool. Some also fear that implementation of such plans could lead to a false sense of security among the population. In contrast, the managers of nuclear plants cannot be unaware that their endorsement of serious preparations might be taken as an indirect admission that catastrophic accidents are likely. As a result, no major constituency has pressed for emergency plans.

Effective planning for reactor accidents has also been hindered by the concern that these measures represent an inadequate response to catastrophic accidents. For instance, some government officials responsible for implementing local emergency plans have taken the position that if the dangers from catastrophic accidents are such that measures are needed to protect distant populations, the proper response is to shut down all nuclear plants.

However, a rational decision to halt nuclear power cannot be made solely on the basis that a catastrophic accident might occur. The health consequences resulting from a single very bad release when averaged over, say, a 30-year period might not exceed the numbers of illnesses and deaths attributable each year to air pollution from all coal- and oil-burning electricity generating plants in a large industrial nation.[3]

In any case, even if certain individual nations decided that nuclear power was undesirable, emergency planning would still be necessary for some time. For one thing, it seems unlikely that there will be an international consensus to halt nuclear power development. And because radioactivity from a reactor accident can travel hundreds of miles, even non-nuclear countries within that range would benefit from emergency planning. For another, the process of achieving anti-nuclear consensus within an individual country would take a considerable amount of time. And finally, financial realities suggest that existing plants would be allowed to continue to operate, at least for a transitional period.

The traditional position of nuclear regulators in the United States and abroad has been that regulations relating to safety design have reduced the probability of large releases of radioactivity to such a low level that they can be virtually ignored. This approach has led to an imbalance between the enormous resources devoted to *accident prevention* and the almost negligible resources allocated to the development of *consequence mitigation strategies*. The Three Mile Island accident suggests that it is time to reconsider the priorities.

Airborne release of radioactivity. The major concern in a reactor accident, aside from water contamination, is the possibility of an airborne release. Radioactivity in the form of invisible, "aerosol" particles would rise to some height above the reactor and "float" downwind. Figures 1 and 2 show schematic views of the approximate wedge-shaped region in which the radioactivity would be initially contained for a constant wind direction. These views demonstrate the fallacy of thinking that people in all directions around the reactor would necessarily be exposed in a reactor accident.

I refer to the airborne radioactivity as a "cloud" even though it could not be seen after it had traveled any appreciable distance from the reactor. (The cloud would only be

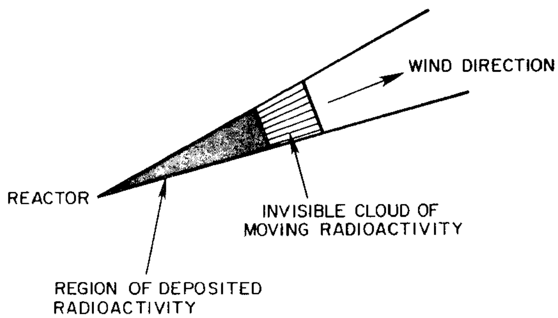

Fig. 1. Schematic view of top of radioactive plume

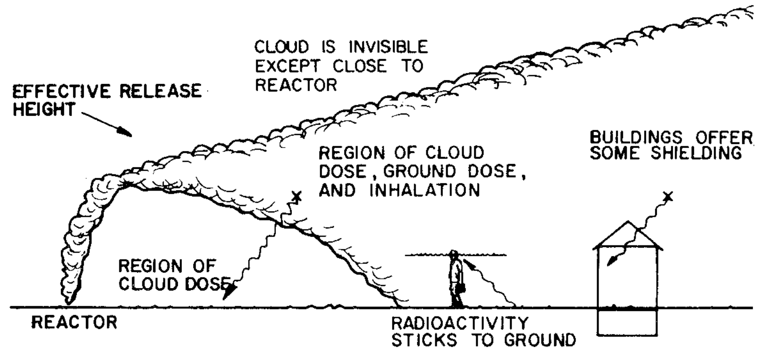

Fig. 2. Schematic view of side of radioactive plume

A major concern in a reactor accident is the possibility of an airborne release of radioactivity, primarily the noble gases, radioiodines and radiocesiums.

Figures 1 and 2 show schematic views of the wedge-shaped region in which the radioactivity would be initially contained for a given wind direction. These views demonstrate the fallacy of thinking that people in all directions around a reactor would necessarily be exposed in a reactor accident.

made visible by entrained water droplets which would evaporate relatively quickly.)

Only the simplest case—that of a constant wind direction—is shown in Figure 1. A shift in wind could change the pattern, producing perhaps a "bent" wedge or a superposition of wedges. The exact pattern would depend upon the timing of the wind shift and the duration of the release of radioactivity.

People caught in the cloud would receive radiation doses from:

- inhaled radioactivity,
- external radiation from the passing cloud ("cloudshine") or
- external radiation from aerosols which stick to the ground and building surfaces ("groundshine").

(These doses are in addition to the dose received from natural background radiation: 0.1 rem per year.)

For those close to the reactor who receive doses of the order of hundreds of rems the resulting "immediate" health effects would be early radiation illness and death.

After the accident, deposited radioactivity would continue to act as a source of radiation superimposed upon natural background radiation. People would receive "delayed" doses of radiation from:

- inhaled radioactivity stored in the body,
- ground contaminated to levels too low to justify evacuation,
- radioactivity in food at levels low enough to be considered acceptable, or
- wind-blown, resuspended radioactivity.

The resulting "delayed" health effects after a major nuclear accident could be cancer, degenerative diseases, or developmental and genetic birth defects. (These effects will occur even among populations which have received low doses. The incidence of effects decreases, however, with decreasing dose.) At high enough ground concentrations, restrictions would have to be put upon land use and attempts might be made to decontaminate.

Over the years, some of the radioactivity on the ground would spread beyond the initial area as a result of wind action. Particles would be eroded, resuspended, and blown about. This spreading, though representing a relatively small amount of the released radioactivity, could be a source of worry for residents of other areas.

Although radioactivity released in a bad reactor accident could remain a problem for many years, it is the initial airborne radioactivity and accumulated groundshine doses during the first few days which are of prime concern for emergency planning. Elaborate prior planning for the long-term dangers is not required, although decision criteria and decontamination techniques should be developed.

There are three major types of radioactive materials that would probably dominate a large release: the noble gases, the radioiodines and the radiocesiums.

The radiation doses from the noble gases are only of concern immediately after a release since they do not stick to the ground and are not absorbed by the body in significant quantities. Radioiodine is readily absorbed by the body after inhalation and delivers most of its internal radiation dose to the thyroid gland where it is selectively stored.

The presence of radioiodine could be of concern for several months after the accident. The resident population would receive radiation doses from radioiodines deposited on buildings and on the ground. If the accident occurred during the grazing season, cows would either have to be shifted to feedlots or their milk diverted from immediate human consumption in order to reduce exposure to radioiodines through the grass-cow-milk food chain.

Along with radioactive tellurium, radioiodine would be a major contributor to the short-term groundshine dose in regions close to the reactor, where doses might be great enough to cause early radiation illness and death.

Radioactive cesium-137, with its 30-year half-life, would be expected to dominate the long-term ground contamination problem.

Early fatalities. That early fatalities (death within 60 days) can occur as far as 20 miles from a reactor is not really in doubt, though the probability, based on me-

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tereological factors alone, is very low even for a catastrophic release. The probability of large numbers of early fatalities appears to be much lower than the probability of large numbers of future cancer deaths.

There is a threshold for the occurrence of early fatalities (approximately 150 rem to the whole body), which means it is possible to have a large release without any early fatalities at all. If meteorological conditions are favorable (high winds, high turbulence and low deposition), enormous quantities of radioactivity can pass over an area without doses reaching threshold even if evacuation is very slow. But if meteorological conditions are unfavorable (low winds, low turbulence, and high deposition), threshold doses can extend out beyond 20 miles.[4]

Mortality probabilities in the cloud path following a catastrophic release for two sets of weather conditions are shown in Figure 3 as calculated in the NRC's *Reactor Safety Study*. The maximum distance predicted for early fatalities is about 9 miles. Other weather and accident conditions can extend the range farther, as can be seen in Figure 4. Here, mortality probability has been averaged over all weather conditions and over all wind directions. As a result, the probability of early death drops off very quickly with distance, compared to Figure 3. Nevertheless, the curve does show a non-zero value out to 20 miles, for the "ineffective evacuation" case.

One can easily argue about the exact slope of this curve, and there probably cannot be any wide technical agreement on the matter at this time.[5] The qualitative shape, however, is not controversial. My own independent calculations for the Barsebäck reactor site, carried out for the Swedish Energy Commission, also showed a similar rapid probability decline with distance for early effects.[6] This decreasing probability had nothing to do with reactor technology, but only with meteorology.

Thus, while large numbers of deaths can occur quite far from the site of a reactor accident, the probability of large numbers is low—although it cannot reliably be said exactly how low.

This does not mean that it is sufficient to rely on probabilities for protection against early effects in towns and cities within 20 miles. A reliable evacuation plan adds an additional level of defense.[7] In any case, it is desirable to move people out rapidly to prevent even doses which are too low to cause early fatalities—that is, tens of rems—because these doses do carry significant probability of cancer.

Cancer fatalities and thyroid nodules. Most of the delayed health effects associated with a catastrophic reactor accident would probably appear in the population located beyond 30 miles from the accident site.[8] This is because most of the radioactivity would be carried well beyond 30 miles before being removed from the atmosphere by deposition on the ground. The radioactivity would be much diluted at these distances, but many people over large areas would be exposed. Following a catastrophic accident in Europe, for instance, hundreds of thousands of thyroid nodule cases could occur as well as many tens of thousands of delayed cancer deaths, even under typical weather conditions.[9] The numbers would be somewhat lower in the United States due to lower population density.

Most of the cancer deaths beyond 30 miles would result from fairly *low-level* radiation doses, on the order of tens of rem or less. (Doses in excess of the 150–rem whole body dose threshold for early death due to radiation sickness would only occur, if any occurred at all, within a few tens of miles of the reactor.)

The probability of an exposed *individual* suffering adverse consequences from low-level radiation exposure beyond 30 miles is rather small—less than one percent even in a catastrophic release. Nevertheless, because a thousand or more people far from the reactor might be exposed to low-level doses for each person exposed to high doses close in, the numbers of people who would suffer adverse consequences from low-level radiation effects would ordinarily far exceed those affected by large doses—even in reactor accidents in which massive amounts of radioactivity were released.

Therefore, the much larger numbers of persons potentially affected by low-level radiation beyond 30 miles should be a principal concern in the design of population protection strategies.

Mitigation measures. Evacuation before the radioactive cloud arrives is the most obvious defense against a release of radioactivity. The fact that large numbers of people have been evacuated without panic following accidents involving toxic chemicals, flammable materials and poisonous gases suggests that evacuation is a practical way to protect at least some of the population at risk at most reactor sites. However, no one knows whether or not special fears about radiation might make this experience with evacuation invalid in the nuclear case. Panic over the possibility of a dreaded "nuclear meltdown" could trigger disorderly evacuation attempts even far from the reactor, preventing orderly movement of traffic. Therefore, emergency planning strategies for reactor accidents should be designed keeping in mind the psychology of evacuation under highly stressful

The development of public confidence prior to the accident in the adequacy of the protective strategies available should help to prevent panic.

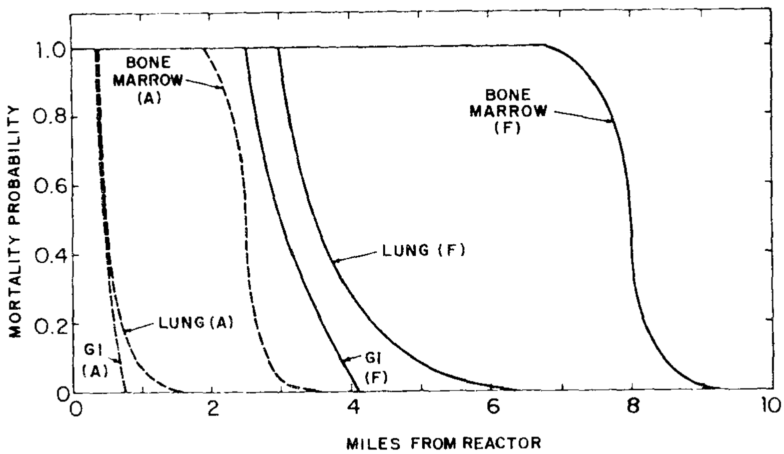

Fig. 3. Probability estimates of early death for persons residing in the cloud path as a function of distance from the reactor following catastrophic release of radioactivity.

Separate morality probabilities are shown for doses delivered to the lung, gastrointestinal tract and bone marrow. The maximum predicted distance for early fatalities for this example is a distance of about 9 miles for the reactor.

Calculations are given for two sets of weather conditions: A = daytime wind with a speed of 0.5 miles per hour; B = night wind with a speed of 2.0 miles per hour.

Source: NRC, *Reactor Safety Study*, WASH-1400 (1975), p. VI-13-8.

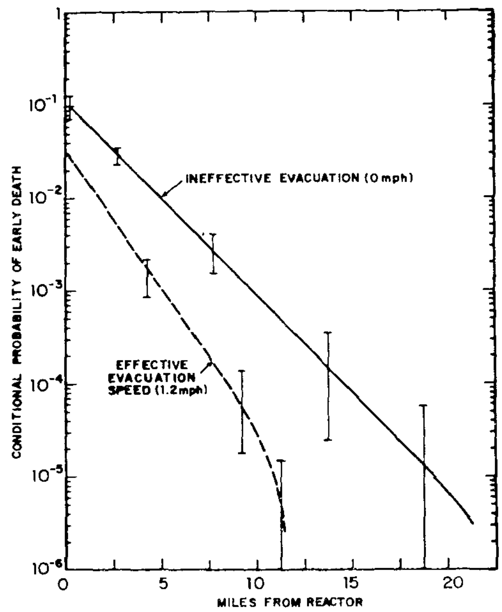

Fig. 4. Conditional probability estimate of early death as a function of distance from pressurized water reactor following catastrophic release of radioactivity.

The curves show in Figure 4 that early deaths can occur as far as 20 miles from the reactor. Probability drops off very rapidly with distance when averaged over all wind directions and weather conditions. Calculations for two effective evacuation speeds are shown. (The "ineffective evacuation" curve assumes no movement for 4 hours, after which it is assumed the occupants leave the contaminated region.)

Source: NRC, *Reactor Safety Study*

conditions. The development of public confidence *prior to the accident* in the adequacy of the protective strategies available should help to prevent panic.

Practice drills for all emergency personnel and a system capable of rapid notification of the population appear to be critical for making evacuation successful. A 15-minute warning capability for persons within 10 miles of reactors—probably through the use of sirens—is being promoted by federal authorities.[10] Because an accident might occur in the middle of the night, it would be prudent to use sirens capable of waking the population in the evacuation zone. Such sirens should have their own emergency power, since a reactor accident might lead to disruption of normal electricity service.

Although it would be possible, given enough warning time, to evacuate people beyond the present 10-mile planning limit, evacuation is probably only a viable strategy out to 30 miles from a reactor. It would be almost impossible to move the millions of people beyond that area who might risk low-level exposure. Furthermore, attempts to evacuate people beyond 30 miles might lead to a backup of traffic on roads planned for the escape of persons residing or working near the accident site.

Three other strategies offer some important possibilities for protecting people 30 miles beyond the reactor as well as those closer for whom evacuation is not attempted or is not successful:

- the taking of thyroid-blocking medicine,
- sheltering in buildings, and
- breathing through makeshift cloth filters or distributed respirators.

Complete logistical details for these strategies need to be carefully worked out. None should be rejected prematurely merely because satisfactory implementation may appear, at first sight, to have some difficulties. A combination of all three strategies would be most effective and most likely to prevent panic among those not included in evacuation plans. Successful use of these mitigating measures has three prerequisites, however:

- monitoring and forecasting of the position of the radioactive cloud,
- communication of detailed instructions to the public,
- and, in the case of thyroid-blocking medicine and respirators, a satisfactory distribution system.

These strategies do not represent absolute protection against reactor accident consequences. It is unlikely

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that the necessary instructions or equipment would reach the entire targeted population and, in any case, these methods only reduce, rather than eliminate, radiation doses. Nevertheless, with careful planning they could significantly reduce the risk of illness and cancer. Each would add a separate level of defense to the reactor safety arsenal.

Thyroid-blocking medicine. Potassium iodide pills taken before inhalation or ingestion of radioactive iodine would reduce thyroid doses by 10 to 100 times, due to the blocking of radioactive iodide uptake by the already saturated thyroid.[11] Since thyroid damage could affect more people in an accident (in the absence of thyroid-blocking) than any other radiation effect, this strategy is extremely important. Thyroid-blocking would provide a net benefit at least out to 100 miles in a worst case release of radioiodine.[12]

Potassium iodide is cheap and quite safe at the recommended doses (it is the form of iodine added to iodized salt), and could significantly reduce the number of people affected by an accident. It certainly would not cost more than 10 cent per year per person to keep a fresh supply available.

For example, present quotations from one manufacturer suggest a price, in quantity, of 40 cents per 14–tablet bottle. One bottle would supply even a family of seven with a two–day dosage. (There would be time after the accident to distribute tablets for the necessary 8-day period beyond that.) The assumption of a three–year shelf life and an average residence occupancy figure of three persons implies a yearly cost of 5 cents per person.

Potassium iodide would also have to be stockpiled in the workplace, presumably in containers holding more than 14 tablets and therefore at less cost per person than in individual residences. As a result, the cost of supplying each individual would be higher than 5 cents per year, but certainly not more than 10 cents per year. Should the shelf life prove to be longer than three years, the cost would drop proportionally. And even if the medicine were never used, the expense could be justified as the premium on an accident "insurance policy."[13]

This medicine, in my opinion, should be made available to any population which is likely to be exposed to radioiodine in quantities sufficient to produce a 10 rem or larger thyroid dose.

At the time of the Three Mile Island accident, potassium iodide was not available for mass distribution in the proper doses. The U.S. Food and Drug Administration therefore ordered large-scale production on an emergency basis and within a few days had flown enough into the area in liquid form for more than a half-a-million people. But this would have been too late if the containment building at Three Mile Island had failed early in the course of the accident. In addition, packaging problems would have made mass distribution difficult: the two-and-a-half-inch droppers didn't fit the two-inch-tall bottles, and the dropper outlet produced too small a dosage.[14] According to the Secretary of Health for the State of Pennsylvania, "The most important public-health lesson that we learned is that you just have to be prepared."[15]

The drug is now being produced in tablet form, and one manufacturer has indicated that about half of the states have expressed an interest in it. Although distribution of the drug in a radiation emergency is widely supported by radiation specialists, there is considerable disagreement about the wisdom of distributing it to the general population before an accident rather than stockpiling it.[16] Pre-distribution of medicine (fastened perhaps to all utility meters) may be necessary to insure timely availability and to prevent distribution centers from being overrun by a panicked public. However, the necessity of pre-distribution is controversial.[17]

What is peculiar about the present official status of the drug is that the Nuclear Regulatory Commission appears to be resisting any use at all of potassium iodide as an emergency measure for the general population—a posture for which it has been criticized by the Federal Emergency Management Agency.[18]

Sheltering instructions. Sheltering in buildings is another strategy which could be employed to reduce radiation doses after a release of radioactivity.[19] Some filtering occurs as air penetrates into structures.[20] Also, masonry buildings offer some shielding from external doses from the cloud and from deposited radioactivity. *With proper instructions,* people could position themselves in optimal locations, similar to those recommended for protection against fallout from nuclear weapons.

In addition, there would be a delay before outside radioactive air would seep into buildings. If residents could be informed by radio or television approximately when the cloud would reach them and when it would leave, the delay period could be used to reduce the inhalation dose. By closing windows and doors during cloud passage, when the *indoor* concentration was low, and opening them afterwards, when the *outdoor* concentration was low, some reduction in inhalation doses would be possible. This procedure might reduce inhalation doses by a factor of two or three in summer under low wind conditions, when natural in-

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filtration rates in residences can be made quite small by shutting windows and doors, and sealing other openings. It would be less effective in winter when infiltration rates are often unavoidably high, even with doors and windows closed.

Other measures. Another helpful procedure, during cloud passage and a few hours afterwards, would be to breathe through several layers of cloth. Some of the larger radioactive aerosols would stick to the cloth instead of entering the body. However, because the physical size of the aerosols governs the efficiency of filtration—a factor which cannot be predicted with confidence in a reactor accident—it is difficult to make any quantitative estimates of the effectiveness of this technique. Possibly more efficient filters could be designed and fabricated for distribution with potassium iodide.

After the cloud passed, it would be desirable to relocate certain residents to uncontaminated ground. Since there may be an optimal time to begin traveling out of the contaminated regions, public authorities should be prepared to survey and monitor the ground deposition pattern, as well as keep track of traffic flow rates, in order to notify residents properly when to leave their homes or workplaces.

It is difficult to make a quantitative prediction about the net benefits from these measures, primarily because it is impossible to predict how many people would be able to make use of them. My subjective judgment is that, should a meltdown and aboveground breach of containment occur, say, in continental Europe, 100,000 cases of thyroid nodules and tens of thousands of cancer cases could be prevented. In the United States, the number of cases prevented would probably be less because of the lower population density. (The availability of protective measures should also help to prevent panic before and after any release.)

Industrialized societies have finally come to accept the fact that coal- and oil-burning electricity generating stations have side effects which are deleterious to public health and that reasonable, cost-effective measures must be taken to reduce pollutant emissions. I predict that some day the necessity for reactor accident contingency plans for significant distances from reactors will also come to be accepted—before, one hopes, not after, a large release of radioactivity occurs.□

1. U.S. Nuclear Regulatory Commission, "NRC Action Plan Developed as a Result of the TMI-2 Accident," NUREG-0660 (Washington, D.C.: The Commission, May 1960). See also Federal Emergency Management Agency, "Report to the President: State Radiological Emergency Planning and Preparedness in Support of Commercial Nuclear Power Plants" (Washington, D.C.: FEMA, June 1980).

2. U.S. Nuclear Regulatory Commission and U.S. Environmental Protection Agency, "Planning Basis for the Development of State and Local Government Radiological Emergency Response Plans in Support of Light Water Nuclear Power Plants," NUREG 0-396, EPA 520/1-78-016 (Washington, D.C.: NRC and EPA, 1978). Interdiction of contaminated food and water supplies out to 50 miles is contemplated in this report.

For a discussion of the logic which went into the arbitrary choice of a 10-mile cutoff distance for immediate population protection, see T. Lombardo and T. Perry, *Spectrum,* 17 (July 1980), 30.

3. Jan Beyea and Frank von Hippel, "Some Long-Term Consequences of Hypothetical Major Releases of Radioactivity to the Atmosphere from Three Mile Island," report to the President's Council on Environmental Quality (1979).

4. Regions of high deposition might occur in terrain with a high affinity for aerosols or as a result of rain, sudden reduction in wind speed, or a sudden increase in turbulence.

5. The NRC's *Reactor Safety Study* (WASH-1400) assumed rather optimistic post-exposure health treatment and definition of "ineffective" evacuation (four hours spent on contaminated ground), but there is not much doubt that the probability of early death does decrease relatively rapidly with distance.

6. Jan Beyea, "A Study of the Consequences of Hypothetical Reactor Accidents at Barsebäck" (Stockholm: Swedish Energy Commission, 1978), Figs. I-6.

7. Beyea, "Program BADAC-1, Short-Term Doses Following a Hypothetical Core Meltdown (with Breach of Containment)" (1978). A good emergency plan should be weather-dependent. It would not be difficult to devise emergency strategies for a range of weather variables. Dose calculations useful for developing such strategies have been done for the New Jersey Department of Environmental Protection.

8. Jan Beyea and Frank von Hippel, "Some Long-Term Consequences."

9. Beyea, "A Study" (Sweden), Table I-3b; H. W. Lewis and others, "Report to American Physical Society by Study Group on Light Water Reactor Safety," *Reviews of Modern Physics,* 47, Sup. 1 (Summer 1975), S108.

10. FEMA.

11. Potassium iodide was approved for this purpose by the U.S. Food and Drug Administration in December 1978. See Department of Health, Education and Welfare, Food and Drug Administration, *Federal Register,* "Potassium Iodide as Thyroid-Blocking Agent in a Radiation Emergency" (Dec. 15, 1978), pp. 58798-58800; and *Federal Register* (Feb. 22, 1980), p. 11912.

12. Jan Beyea and Frank von Hippel, "Some Long-Term Consequences."

13. It is the current position of the Nuclear Regulatory Commission that wide distribution of potassium iodide before an accident is not cost-effective. See D. C. Aldrich and R. G. Blond, "Examination of the Use of Potassium Iodide (KI) as an Emergency Protective Measure for Nuclear Reactor Accidents," NUREG/CR-1433 (Washington, D.C.: NRC, March 1980).

14. NRC Special Inquiry Group, M. Rogovin, G. T. Frampton, Jr., et al., "Three Mile Island, a Report to the Commissioners and the Public," Vol. 2 (Washington, D.C.: The Commission, 1980), 1029.

15. New York Times, Oct. 7, 1979, p. 49.

16. Luther Carter "Nationwide Protection of Iodine-131 Urged," 206, *Science,* 201-206; Aldrich and Blond, NUREG/CR-1433.

17. Carter, "Nationwide Protection."

18. NUREG-0660; and NUREG/CR-1433.

19. For numerical calculations, see D. C. Aldrich and D. M. Ericson, Jr., "Public Protection Strategies in the Event of a Nuclear Reactor Accident: Multicompartment Ventilation Model for Shelter," SAND 77-1555 (Albuquerque, N. M.: Sandia Laboratories, 1978); U.S. Department of Environmental Protection, "Protective Action Evaluation as Protective Actions against Nuclear Accidents Involving Gaseous Releases," EPA 520/1-78-001, A and B (Washington, D.C.: EPA, 1978), Parts I and II.

20. A. F. Cohen and B. L. Cohen, "Infiltration of Particulate Matter into Buildings," SAND 74-2079, NUREG/CR-1151, (Albuquerque, N.M.: Sandia, November 1979).