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IMPACTS OF ACCIDENTAL RADIOACTIVE RELEASES TO THE HYDROSPHERE FROM FLOATING AND LAND-BASED NUCLEAR POWER PLANTS

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Presented at the
ENS/ANS Topical Meeting on
NUCLEAR POWER REACTOR SAFETY
Brussels, Belgium
October 16, 1978

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The floating nuclear power plant concept has been proposed as a means of providing inherent resistance to earthquakes, abundance of cooling water, isolation from heavily populated areas, and as an alternative to land sites whose availability is diminishing. The nuclear industry proposed development of a floating nuclear plant (FNP) in the early 1970's. This plant featured a standardized nuclear steam supply system mounted on a water-tight floating platform instead of the reinforced concrete foundation that supports a land-based plant. This proposed FNP has a rated capacity of 1150 MWe, utilizing a four-loop pressurized water reactor housed in an ice-condenser containment system. An application for a license to manufacture eight standard FNPs was received by the United States Nuclear Regulatory Commission (NRC) in January, 1973, from Offshore Power Systems (OPS). This action initiated both a safety and an environmental review of operation of the proposed design to assure protection of the public health and safety as well as minimizing environmental impacts from manufacture and operation.

As a result of implementing the National Environmental Policy Act (NEPA) of 1969, accident risks are considered by the NRC in the environmental assessments of proposed licensing actions on nuclear power plants. The NRC's environmental impact statements on light water reactors (LWRs) which are sited on land conclude that the risk associated with accidental releases of radioactivity is very low. The validity of this conclusion in the case of FNPs could be affected by three principal factors: (1) significant differences in the probability of an accidental release, (2) significant differences in the magnitude of releases associated with various accidents, and (3) significant differences associated with the pathways by which released materials may impact the environment and man. Based on the NRC's safety review, which assures that the probability of an accident is made acceptably low, no major differences in accident probabilities between an LBP and an FNP have been identified. However, there are design and site-related differences which could affect the second and third principal factors identified above. These have the potential to cause accident risks associated with the FNP concept to be substantially different, qualitatively and quantitatively, than those associated with LBPs. These potentials made it appropriate for the NRC to more fully consider the implications of this unique design/siting concept, as part of the NEPA environmental assessment process. For example, a very unlikely event such as a core-melt accident involving the melting of a major fraction of the core, could result in the dispersal of radioactive materials into surface waters with consequences more severe than if the same event (core melt-down) were to take place at a land site. Therefore, the NRC initiated a program called the Liquid Pathway Generic Study (LPGS) to further consider accident risks associated with the liquid pathway for FNPs and LBPs.

The principal objectives of this study were to compare the relative risks associated with accidental releases to the liquid pathway from FNPs with those from LBPs at selected sites for a spectrum of potential accidents, including a core-melt accident in which the melting of a major fraction of the core is assumed, and to determine if such risks are or can be made low. With these objectives in mind, the framework for conduct of the LPGs was developed as shown by Figure 1. Consequences to man from accidents were calculated in terms of radiation dose resulting from radioactivity that would be received as a result of drinking water ingestion, consumption of aquatic foods, and direct exposure from swimming and beach activities. For the core-melt events, the assessments included the potential for undesirable modifications of ecosystems. This paper will describe the main features of the LPGS, which included extensive analytical work by NRC and OPS, and the important conclusions that were drawn from the study by the NRC. Since this study was generic in nature, site parameters were chosen to be representative of locations suitable for nuclear power plants. Plant design features, however, were representative of land-based or proposed floating power plants with ice-condenser containment.

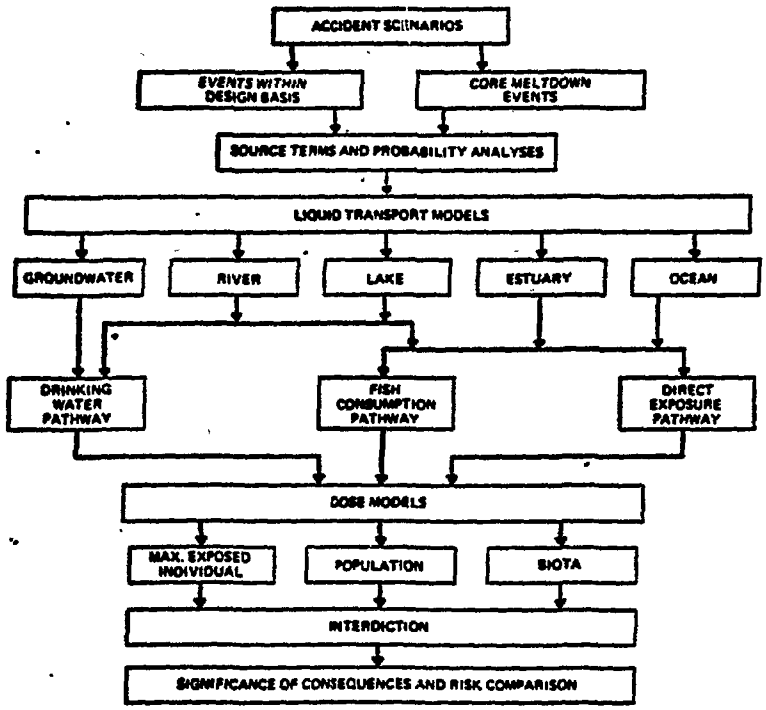

Figure 1. Liquid pathway generic study.

Accident Scenarios

Historically, the radiological consequences resulting from an accidental release of activity to the liquid pathway has not been examined as closely as the consequences from airborne releases. This is because, in terms of overall risk, the airborne pathway has been considered to be the dominant contributor, and because, without multiple errors, a means of liquid release could not be identified.

Most postulated accidents involve the release of contaminated water within the plant either at ambient temperature or at high temperatures. The released activity will be partitioned between the airborne vapor and the liquid left behind. The airborne activity can be held-up and filtered to a considerable extent, but ultimately it is assumed that some portion of this activity escapes into the environment. On the other hand, the liquid that remains behind is contained within a controlled area.

Although both LBPs and FNPs are designed to contain and decontaminate this liquid, for the purposes of this study it was assumed that operator and/or equipment errors occur such that release to the liquid pathway takes place following these postulated events:

(a) radioactive waste system failure
(b) fission product releases as a result of steam generator leaks
(c) refueling accidents
(d) spent fuel handling accidents
(e) limiting events considered in the design basis (loss of coolant, rod ejection, steam line breaks).

For highly improbable accidents involving gross core melting, it was assumed that releases to the liquid pathway would occur via containment penetration (unless, for a land-based site, there was no ground-water present). The prediction of the course of such an event is an exceedingly complex task because of the many and varied processes involved and because in some areas, technology is limiting. Thus, there is a spectrum of possible, though improbable, outcomes with results ranging from minor to severe. The basic sequence leading to a core-melt accident includes an initiating event (e.g., a LOCA), failure to adequately cool the core, core melting, followed by core debris penetration through the bottom of the vessel and then through the containment. Depending on various conditions, different amounts of activity could be released into the atmosphere and the hydrosphere.

The nature of likely waterborne releases was evaluated in terms of information developed specifically for the ice-condenser design and the event sequences of WASH-1400, "Reactor Safety Study - An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants." Two basic release mechanisms were considered -- a prompt release associated with discharge of contaminated gases or sump water and a long-term release associated with leaching of radioactive material from solidified core debris.

Transport Models

Surface waters covered by the LPGS were classified as rivers, Great Lakes, estuaries, and oceans. Rivers were assumed to have uniform, rectangular cross sections, with constant shore-parallel flow and dispersion represented by constant coefficients. Radionuclide discharge was assumed to take place from a vertical line source extending from the surface to the bottom of the river. For estuaries, a one-dimensional tidally averaged (currents) model was used to calculate cross-sectionally averaged concentrations. The estuary was assumed to have a constant cross-section and a constant net downstream velocity.

For the Great Lakes, three models were used to simulate the transport processes. A two-dimensional model was used in the nearshore zone for distances up to 15 miles from the source, which is approximately the distance a particle of water can move between wind generated current reversals. A phenomenological model based on instantaneous dye-release data was used for the offshore zone. This patch spreading model was assumed valid until the limits of the patch extended over the whole area. A mixed-tank model was then used after the patch had spread over the whole lake area. The released material was then assumed to be uniformly distributed throughout the entire lake and to be removed only by decay and freshwater flowing through the lake. Concentrations also can be estimated using this model for a series of lakes.

The models for oceanic dispersion were similar to the models for nearshore and offshore Great Lakes, For instantaneous releases, a phenomenological model of the spreading of a radially symmetric Gaussian patch based largely upon offshore dye experiments was used. Continuous releases were modeled by accounting for lateral dispersion and longitudinal advection by the prevailing current.

Two models were used to evaluate the movement of radionuclides through groundwater. The first (Point Concentration) simulates movement from a point source through an aquifer of constant thickness to calculate concentrations at some point (a well) downgradient from the release. The second (Surface Water Interface) computes the amount and time variations of radionuclides being released from the groundwater to the surface water. The effects of radionuclide sorption and the aquifer media were accounted for in both models by the assumption that the concentrations in the solid and liquid phases would be in chemical equilibrium (distribution coefficient concept).

Exposure Pathways

In order to satisfy the principal objectives of the study, numerical estimates were made of the radiation dose to man (consequences). Typically, predictive radiological impact assessments of postulated releases to the environment considered: (1) doses to individuals exposed in various pathways operating in the near field of the release -- the so-called maximum exposed individual, and (2) the population or collective dose -- a quantity which represents the sum over all contributing pathways, of the individual doses. Although these two quantities are not mathematically independent, i.e., the population is composed of individuals, they do represent distinctly different characterization of the impact of the release.

The maximum exposed individual is generally associated with pathways in the near field of the releases. In this region the predicted nuclide concentrations in the dispersing medium, and thus the pathway media, are strong functions of the spatial separation of the release and the pathway location. This dependence can be so pronounced that the assessment is largely independent of the general characterization of the environs. For example, the waterborne concentrations in the near field of a discharge into a lake are so dominated by the initial dispersion that for all practical purposes the concentration time history is similar to what might be expected on a river. Thus, the maximum exposed individual dose is insensitive to the general characterization of the environs.

The population dose is the result of an integration over the exposed population. This quantity reflects the physical and biotransport of the released radioactivity throughout the environs and man's usage of the environs. The population dose quantity possesses a high sensitivity to the various siting environments considered in this study and has been employed as the primary numerical index to judge the comparability or lack of it between FNPs and LBPs. It is important to appreciate that the population dose is only a representation of the total exposure of a group of people. Its significance in terms of possible health consequences to the group is dependent upon the extent to which such health effects are linearly proportional to the dose received by individuals. The population dose was used in this study to make a direct comparison of one exposure situation with another.

In making predictions of the consequences associated with releases of radioactivity, consideration is given to a number of potential pathways by which radioactivity might be expected to move to man. In practice, it is generally found that a few pathways are so dominant that the multitude of alternative pathways that can be conceived are insignificant contributors to the total consequences for a given release. In this study, the dominant population exposure pathways were found to be the following:

(a) ingestion of drinking water (dominant for fresh-water sites);
(b) ingestion of aquatic foodstuffs (dominant for salt water sites);
(c) external exposure to contaminated shoreline sediments (beaches); and
(d) external exposure while immersed in the water during swimming.

A number of other pathways that might lead to exposure to a limited population include:

(a) external exposure to items contaminated by adsorption of radionuclides from the water, e.g., fishing gear, marine buoys, dredged materials, etc.;
(b) internal exposure from terrestrial foods contaminated through use of irrigation water or use of trash and spoil fish as fertilizers or animal feed; and
(c) external exposure to irrigated land surfaces.

These pathways, however, were found not to represent a significant contribution to the population dose, largely because of the limited number of individuals participating in the pathway.

Results

In general, for credible accidents, including a major loss-of-coolant accident (LOCA), the resulting consequences at ocean-based FNPs are about one order to magnitude lower in estimated impact to man than those from accidents at representative fresh-water LBP sites. This results primarily from the contamination of the drinking water pathway at certain LBP sites; this pathway does not exist for most potential FNP sites.

The highest doses calculated as a result of all design basis accidents and sites considered, with the assumption that no measures are taken to reduce the doses, are as follows:

- For FNPs at an estuary site, 4×10^{-2} rem thyroid to the maximum individual and 10^{2} man-rem thyroid to the population
- For LBPs at a river site, 1 rem thyroid to the maximum individual and 3×10^{4} man-rem thyroid to the population

It should be noted that since the design basis accident analyses conservatively assumed releases directly to the surface water, the consequences of release at a particular site (e.g., estuary) would be the same for an FNP or LBP if both were located adjacent to one another at that site.

The probability and consequences of very unlikely core-melt accidents for the plants and sites selected were examined in considerable detail to assess risk. The study concludes that the probability of a core-melt accident in an FNP is similar to that of an LBP. The study results also indicate that core-melt events in reactors of the ice-condenser type would ultimately lead to containment failure by over-pressurization, with subsequent melt-through. This would be expected to occur whether the reactors are land-based or floating.

If interdictive measures were not taken (an assumption which does not appear reasonable but does bound the calculated consequences), the expected, or best-estimate consequences of core-melt releases via the liquid pathway are about 0.3×10^{7} to 3×10^{7} man-rem for the FNP and a factor of 6 to 30 lower for the LBP.

The presence of soil beneath the containment of a land-based plant is expected to mitigate the transport of contamination sufficiently to allow effective measures to be taken to isolate radioactive liquid to the plant vicinity. However, intimate contact of a water body with the area beneath the FNP would preclude the isolation of radioactive releases for several days following the accident. Therefore, by consideration of the various scenarios which could lead to core-melt releases, and the expected benefits of interdiction at the source of release, expected values of man-rem for the core melt event are reduced by an order of magnitude of more for the FNP and by several orders of magnitude of the LBP. These results indicate that the consequences of a core-melt accident at an FNP are higher than those expected for an LBP with or without interdiction. Even if the release of radioactive material from the FNP was not rapid, our results show that the likely impact of such an event would be greater for the FNP because of the need to rely primarily on pathway interdiction.

For activity which does reach the open waterbody or aquifer, interdiction in the pathways to man could be effective for both types of plants depending upon the intensity of effort applied. For the FNPs, interdiction of beach areas and consumption of seafood would be effective in dose reduction at the cost of potential social and economic impacts. For LBPs, interdiction of drinking water, fish consumption, and recreational areas would also reduce the dose to man with attendant social and economic impacts. Releases of radioactivity to the liquid pathway from a core-melt accident are not expected to result in acute fatalities, whether interdiction takes place or not, for either type of plant.

With respect to the effects on aquatic ecosystems, only the impact of core-melt releases are of significance. At an LBP, these would be delayed or prevented because of holdup in the soil and passage through the groundwater. For some sites, the impact on aquatic ecosystems might be insignificant because of the retention near the site by radionuclide sorption. However, in cases where activity reaches a water body in which the potential for flushing, dispersal, or dilution is limited, the impacts could be long lasting. In addition, a core-melt event at an LBP could result in restriction of the use of groundwater and surface-water resources. For an FNP, because of the dispersive characteristics of large open ecosystems, impacts would be immediate but are expected to be transient and reversible.