FNP-PAL-040

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July 13, 1979

Mr. Ronald L. Ballard, Chief
Environmental Projects Branch 1
Division of Site Safety
and Environmental Analysis
United States Nuclear Regulatory Commission
Washington, DC 20555

P. B. Haga
Director,
Plant Analysis & Licensing

Subject: Docket No. STN 50-437; Response to NRC Re Particle Transport

Dear Mr. Ballard:

In response to your letter of June 14, 1979 to A. R. Collier, I am enclosing an assessment by Offshore Power Systems of the potential impacts that may result from the release of insoluble core debris particles following a postulated core-melt accident at an offshore Floating Nuclear Plant.

As a result of our analysis, Offshore Power Systems concludes that transport of significant amounts of radioactivity as particulate matter following a postulated core-melt accident is very unlikely. If this form of transportable particles should occur, our analysis and the analogous experience (including measurements) at the Windscale reprocessing plant indicate that dose consequences are likely to be less than for the soluble radioactivity transport cases previously considered in the Offshore Power Systems and Nuclear Regulatory Commission Liquid Pathway Reports and FES-III. Our assessment supports the Staff's conclusion in FES-III that consideration of soluble releases to evaluate consequences resulting from material released as small insoluble particles is a conservative approach.

Sincerely,

P. B. Haga

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CC: V. W. Campbell
A. R. Collier

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PARTICLE TRANSPORT OF CORE DEBRIS

I. Introduction

This information is in response to the letter dated June 14, 1979 from Mr. Ronald L. Ballard of the NRC requesting additional information with regard to potential impacts from the release of insoluble particles produced by a core melt accident.

The Atomic and Safety Licensing Board (ASLB) for the OPS Manufacturing License Application directed seven questions to the Applicant and NRC Staff related to the LPGS study and FES-III by their letter dated March 29, 1979. These questions were responded to by the Applicant via oral testimony at the April 4, 1979, hearing session. At the April 4 hearing session, the NRC Staff informed the Board that the NRC responses would be at a later time and in writing due to the unavailability of Staff members at that time.

Subsequently the Staff discussed with OPS at a meeting on June 8, 1979, questions regarding (1) the formation of particulate material following a core melt-through (as a result the interaction of core melt debris with basin water), (2) dispersion of this radioactive particulate material, and (3) the magnitude, areal extent and temporal extent of dose effects resulting from such particulate material. These questions were associated with NRC Staff preparation to address ASLB question four which is:

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"4. What reasons were there for not considering interactions with sediment in off-shore cases (LPGS, p. 4-13)? Since we believe consideration should have been given, what are the effects of such interactions?"

The material discussed at the June 8, 1979 meeting and the additional evaluations performed by OPS as a result of the June 8 discussions are documented below.

A. <u>Liquid Pathways Reports Treatment of Particulate Transport</u>

The general approach taken in both the OPS LPGS report (Reference 1) and the NRC LPGS Report (Reference 2) in estimating radiological impact that might occur via liquid pathways as a result of postulated core melt events was to assume radioactive species remaining in the debris would be soluble once the debris entered basin water. With this approach, holdup of radioactivity within the basin is minimized, transport outside the breakwater is maximized as is the resulting population dose (man-rem). In the OPS report, maximum individual doses were estimated by considering specific scenarios. OPS recognizes that other scenarios could be postulated to produce larger individual doses via liquid pathways; however, the cases postulated in the OPS LPGS report were considered sufficiently conservative and unlikely by both OPS and the Staff at the time of the reports to

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represent reasonable upper-bound estimates of individual dose via liquid pathways.

Dose effects resulting from transport of primary core debris particulate material was not treated in either the OPS LPGS report or the NRC LPGS report for the following reasons: (1) the low likelihood of an event leading to fine fragmentation of core debris, (2) uncertainty regarding the distribution of particle sizes that would be formed in the molten debris-water interaction, and (3) the fact that a closely analogous situation was evaluated in the LPGS reports. The low likelihood of extensive fragmentation and data regarding core debris size distributions is discussed in Section II following. Analogous evaluations are discussed in the next paragraph.

For the analogous situation treated in the LPGS reports, either rapid release of all of the radioactivity including insoluble species from the debris to basin water was assumed (by the NRC) or a large fractional release for all species including insolubles was assumed (by OPS). An open breakwater with little holdup of radioactivity was also assumed. For ocean and estuarine cases, interaction between the water column and bottom sediments was considered in such a way that there was equilibration between radioactivity in the water column and the sediment. Thus contaminated sediment was in fact considered in these reports. The spectrum of sorbed radionuclides was like that which is present in core melt debris and this spectrum was used

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in estimating dose consequences to biota, to man from ingestion of shellfish and to man from direct contact with beach sediments.

B. Siting Considerations

NRC has required in FES-III that closed relatively impermeable breakwaters be employed for estuarine or riverine sites. Offshore Power Systems recently proposed in the core ladle design report (Topical Report 36A59) and in PDR Amendment 27 a more definitive wording of the site related criterion. As reworded, the criterion specifies that site structures be such as to reduce the source terms to levels equivalent to similarly sited land-based plants (source reduction of approximately a factor of 1000). Particulate transport outside site structures is then already severely restricted for riverine and estuarine sites. With this in mind, the discussion which follows will be directed at ocean-sited FNP's with breakwaters which provide for relatively free interchange between the plant basin and open ocean.

II. Particulate Formation During Melt Debris - Basin Water Interaction

Interaction between core melt-debris and basin water is discussed extensively in Sections A-2.3.4 and A-2.3.5 of the NRC LPGS report in terms of potential for such an interaction causing a steam explosion. NRC concludes that while an interaction involving a large fraction of

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the debris cannot be precluded, such an event is not expected. The last paragraph of the general section of A-2.3.5 states: "Considering the factors just described, it is the judgment of the staff that energetic steam explosions and extensive fine fragmentations of molten materials would not be expected to occur following hull penetration by the molten material into the salt water basin."

The staff approach to possible but unlikely outcomes of the postulated core meltdown event is discussed in FES-III and particularly in Section 6, Responses K-19 through K-22. In general the staff utilized the more likely scenarios as one component of the comparison of risk via Liquid Pathways of FNP's with Land-Based Plants. The other component was comparison of total risk derived by considering the product of probability and consequence of both the more likely and less likely but possible scenarios. Consideration of dose consequences resulting from release and transport of fine particulate primary core debris certainly falls into the second category so that dose consequences need to be weighted by the low likelihood of extensive fragmentation. It is important to recognize that utilization of a single possible but improbable scenario to reach a conclusion is not appropriate nor consistent with the approach in the NRC and OPS LPGS reports and in FES-III.

A. <u>LPGS Treatment of Particulate Formation and Leaching</u>

Review of the NRC LPGS reports shows that in determining "leach rate" from debris material, a high rate of leaching was used

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based on equivalent 10 to 12 μ diameter particles (which are very fine particles). However, our understanding of the Staff reasoning which lead to these high leach rates is as follows:

1. Experimental data show that particles formed during debris basin water interaction are very porous. As a result, they exhibit a much greater effective surface area than would a hard sphere of an equivalant size. From the standpoint of hydrodynamic transport, the particle diameters are significantly larger than particles sizes which can be effectively transported out of the basin (see section III). For example, the Staff memo from R. Denise to R. Vollmer dated 3/16/77 (Reference 3) recommends an effective particle diameter of 250μ. From the standpoint of leaching, the 250μ porous particles exhibit surface areas equivalent to that of hard spheres in the size range of 10μ to 20μ.

2. Substantial uncertainty existed in the leach rate to be assigned to core debris materials. The Staff took a conservative approach to bound uncertainty in the data. OPS disagreed with the Staff's use of the conservative leach rate (see Enclosure 4 to Appendix A of Reference 2). The high leach rates employed by the staff lead to leaching of essentially all of the radioactivity from the particles in a few days. With this approach, the question of particle transport is moot for particles contain little radioactivity and so represent very little hazard.

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In summary, it is apparent from the discussion in the OPS LPGS report and the NRC LPGS report that the physical state of the debris and the rate of leaching following melt debris-water interaction are not well understood. However, even for the case where extensive interaction was assumed, available data indicates particles are relatively large from the standpoint of hydrodynamic transport ($\sim 250 \mu$). Both the staff and applicant concluded that an energetic steam explosion which might produce more extensive fragmentation and smaller particles was not expected.

B. Specific Cases

Four specific cases are discussed below which cover the range from little or no interaction to extensive interaction and fragmentation of the core melt debris. These cases are:

1. Little or no fragmentation. Debris collects as a pile of large particulate rubble or a reformed slab of hot debris on the bottom of the basin. This case produces few particles. Release of radioactivity to basin water is slow and due to leaching.

2. Formation of a fragmented spongy debris material with large surface area and relatively large particles. Leach rates are like those proposed by OPS in Reference 1. For this case, release of radioactivity from debris is relatively

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slow. There is little if any transport of debris particles from the basin.

3. Same case as 2 with high leach rates as adopted by NRC. There is again little if any transport of debris particles from the basin. However, radioactivity is leached from the debris quite rapidly and can reach the open water body before source isolation.

4. Extensive fragmentation as a result of energetic interaction between molten-debris and basin water to produce fine fragmentation. This case can produce particulate material with potential for transport of particles outside of basin.

C. Particle Size Distribution Resulting From Energetic Interactions (Case 4 above)

Particle size distribution data resulting from energetic interaction between molten metals or metal oxides and water have been reviewed by both the NRC Staff and OPS. The NRC data summary appears in graphical form in Reference 3 (a copy of which was provided to OPS). The OPS summary, also in a graphical form, is part of the handout for the 9/29/77 ACRS Meeting and is attached as Figure 1. The two sets of curves are similar since they are derived from essentially the same data. For the discussions which follow, a conservative extrapolation of the available data to the smaller size particle range is employed to determine the

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fraction of the particulate material of sufficiently small size for possible transport outside the basin for an ocean sited FNP for the unlikely case of extensive interaction between the debris and basin water.

III. Particle Transport from Basin

This section describes the potential mechanisms to transport particles out of the basin. To escape the breakwater, debris particles would have to be transported from the debris on the bottom of the basin to the edge of the FNP and up to the surface layer of the basin water. Then they would have to be transported out of the basin before settling enough to be trapped within the basin. Although several potential mechanisms exist to transport the particles out of the basin, most can be considered negligible. As is shown below, only ambient currents and possibly wave motion are viable mechanisms for transporting particles out of the basin.

A. Ambient Currents

Assuming the Atlantic Generating Station open breakwater configuration, ambient current flowing through the breakwater openings could transport particles in the surface layer out of the basin should they become entrained in the current. In its study of consequences of core-melt accidents, OPS assumed the ambient ocean current speed to be 5 cm/sec. This is the annual average current speed measured at the AGS site (Reference 4).

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The size particles which could escape the basin was estimated for for a 5 cm/sec current passing through the breakwater openings.

To exit the basin, a particle at the edge of the FNP would have to travel past the sill before it settled to the sill (6m depth). The minimum distance from the FNP to the center of the sill is 107 m. A particle travelling at 5 cm/sec would take 2140 seconds to reach the middle of the sill. Assuming a specific gravity of 4.0 (based on core debris and ladle material) for the particles, only particles less than 40 μ would be transported out of the basin. Particles greater than 40 μ would be trapped inside the basin. Doubling the particle drift speed to 10 cm/sec would increase the size of particles that could escape to 56 μ.

B. Wave Motion

Second order surface wave theory describes a nonperiodic drift in the direction of wave advance. Thus, waves propagating through an open breakwater would create a drift current which could transport particles out of the basin. To estimate the potential magnitude of such a current, the AGS open breakwater configuration was assumed. A wave of 2m in height with a period of 8 sec was assumed outside the breakwater. This height is approximately the maximum significant wave height and the period is the most frequently observed peak spectral period for the New Jersey coast (Reference 4). It is assumed that this wave

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propagates in a direction parallel to the closure breakwater allowing it to pass directly through both breakwater openings. Experimental data (Reference 5) indicates that such a wave travelling outside the breakwater would have its wave height attenuated by a factor of two inside the breakwater. Thus, the resultant wave propagating out of the breakwater would be 1 m in height. The corresponding theoretical wave drift velocity would be a maximum of 1.5 cm/sec at the water surface and exponentially decreases with depth. For this velocity, only particles less than 20μ could escape.

For the AGS site, the larger wave heights are associated with storms and propagate from the offshore direction, i.e. perpendicular to the closure breakwater. The experimental data indicates that such waves would be attenuated by a factor of 5 or more by the breakwater. Such waves would result in a negligible drift current for transport of particles out of the breakwater.

C. Thermal Convection from Hot Debris

The decay heat from the core debris on the bottom of the basin will produce a vertical convection current which could lift debris particles up the water column to the bottom of the FNP. An estimate of the average vertical convection velocity, V. can be calculated from the equation (from Reference 6)

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$$V = 0.76\left(\frac{hQ}{R^2}\right)^{1/3}$$

where

h = height at which the plume is terminated (meters)

Q = heat source (kW)

R = radius of heat source (meters)

If the debris volume is assumed to be cone-shaped with a volume of 140 m^3 and having an angle of repose of 10^o, then R = 9 m. The distance from the debris to the bottom of the FNP, h, is assumed to be 4m. The decay heat is assumed to be 3×10^4 kW which is the magnitude expected within the first day after meltdown. The resultant average vertical convection velocity is 8.7 cm/sec.

When the particles reach the bottom of the FNP, the thermal currents would tend to move them horizontally out toward the sides of the FNP. The horizontal velocity would be expected to be significantly less than the vertical convection velocity due to the increasing cross-sectional area in the horizontal direction and the high degree of mixing with the ambient basin water. To estimate what size particles can migrate to the edge of the FNP, it is conservatively assumed that the particles move horizontally with a speed equal to the average vertical convection velocity of 8.7 cm/sec. The minimum travel distance to the edge of the FNP for any particle is 30m. For a particle to

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travel to the edge of the FNP and thus have the potential to be lifted up to the surface layer of the basin water, it must arrive at the edge of the FNP before it settles out of the horizontal current under the FNP. Assuming the thickness of this horizontal layer to be 2m which is half the distance from the basin floor to the bottom of the FNP, particles greater than 60μ (assuming a specific gravity = 4.0) will settle before the edge of the FNP is reached. Thus, thermal convection will not make particles greater than 60μ available for possible transport outside the basin.

D. Operation of Second Unit

The systems operating on the second unit (i.e. the unit not under accident condition) would tend to retard ticles from escaping the basin. Since the second unit would be shut down, the condenser circulating water system would not be operating. Only decay heat removal systems which have the intake and discharge structures within the basin would be in operation. Experimental studies (Reference 7) have shown that the recirculation pattern from the decay heat removal systems create a thermocline throughout the basin. This surface thermal layer will limit the rise of the vertical thermal convection flow at the sides of the FNP from the thermal plume since the temperature difference between the flow and the ambient water will be less near the surface thermal layer. Thus, particles rising along the sides of the FNP would be impeded from reaching the

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[redacted]

surface of the basin water. Since they would rise to some lower depth, this would reduce their settling depth and a greater number of particles would settle within the basin.

Thus, the decay heat removal systems of the second unit will retard rather than promote particle transport out of the basin.

E. Tidal Flushing

Conservative estimates of the tidal flushing at the AGS site (period of 12 hours) show that the average tidal velocity is approximately 0.5 cm/sec. This estimate is based on all the tidal flow passing through the two breakwater openings. In fact, the AGS breakwater is porous and the average tidal velocity through the openings may be an order of magnitude less. Therefore, only particles less than a few microns could be transported out of the basin by tidal flushing. Compared to the ambient current case, tidal flushing is not a signifiant factor in particle transport.

F. Flotation of Particles By Attachment of Gas Bubbles

One proposed mechanism for transporting particles to the surface water layer of the basin where they could then possibly be transported outside the basin is attachment of non-condensible gas bubbles to the particles. Such a mechanism is not considered viable for the reasons discussed below.

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Generally the dissolved gas content of sea water in the upper 10 to 15 meters decreases only slowly with depth and corresponds approximately to air saturation conditions for the surface water (for example $\sim$ 6 cc/kg for oxygen at $\sim$ 20 C). In contrast, gas solubility increases with depth as pressure increases. For example, at a depth of 10 meters, the pressure is approximately doubled so that twice as much gas is soluble in the water at 10 meters (30') as is soluble in the water at the basin surface.

While isolated particles of debris in the size range less than 100 μ may be highly radioactive, they do not represent a large enough heat source to cause localized boiling when suspended in a large volume of water. Thus, isolated particles near the surface would not cause boiling and stripping of non-condensible gases. It is concluded that a collection of a significant debris mass on the bottom of the basin would be necessary for boiling to occur.

If water at the basin floor is heated to near its boiling point, the quantity of gas that can be dissolved in the water falls rapidly (as the vapor pressure of the water rises). Should boiling occur, non-condensible dissolved gases will be stripped from the heated water in the region of boiling. The steam bubbles will rapidly condense as they rise through the cooler surrounding basin water. Likewise, non-condensible gases stripped from the water by boiling will be small and tend to rapidly re-dissolve as they rise into the surrounding cooler

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water which, at depth, has significant capability to dissolve additional gas. Thus, while boiling may occur around collected debris at the basin floor, neither the steam bubbles nor stripped non-condensible gases would be expected to rise more than a few meters before they disappear.

Also considered was the possibility of gas generation near the particles due to radiolytic decomposition of the water from radiation emitted by the particles. Gases so formed (H_2 and O_2) at depth can of course be rapidly dissolved by surrounding water. Metallurgical experience in flotation processes indicate that oxide materials tend to be hydrophilic (air bubbles do not attach) unless they are coated w [illegible] oils or organic materials which make them hydrophobic (silicates being an exception). The high temperature of the oxide debris material immediately prior to its contacting sea water would destroy any oils or organic material present in the debris material. It is concluded that the debris material would discourage gas bubble attachment to debris particles.

G. Postulated Steam Explosions

A steam explosion under the FNP from debris-water interaction would create a bubble which would not reach the edge of the FNP (Reference 1). Upon collapse of the bubble, the particles would return to their approximate initial location. Thus, steam

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explosions are not a significant mechanism to transport particles out of the basin.

IV. Particle Dispersion Outside the Basin

This section describes the dispersion of particles of core debris that escape the basin. Based on the discussion of Section III above, any particles that can escape the basin will be less than 40μ. Based on the particle size distribution discussed in Section II above, particles less than 40μ would account for no more than 10% of the core mass and probably less than 1% of the core mass.

A. Initial Deposition

Table 1 describes some of the physical characteristics of 10μ and 40μ particles. For each size, it is assumed that the particles make up 10% of the core mass or 6×10^6 gm and 10% of the core activity or 10^8 Ci. The Stokes settling velocity is 13m/day for the 10μ particles and 208m/day for the 40μ particles. The Stokes settling velocity is a discrete settling velocity, and if the particles settled as a cloud rather than as discrete particles, they would have a higher effective settling velocity.

Assuming that the particles do get out of the breakwater, they will be transported in the near field by currents until they settle on the bottom, and then will be transported along the coast and off the shelf as sediment bed load. Based on the

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particle settling velocities in Table 1and a water depth of 10m, the current transport will be completed in about a day. The shelf sediment transport will take place much slower. Since the shelf sediment transport is a dispersive process, the maximum bottom concentrations (no. particles/m^2 or Ci/m^2) will occur after initial deposition and then decline due to sediment transport.

Assuming a drift current of 5cm/sec (4.32km/day), the 10μ particles would be deposited on the ocean sediment over a distance of less than 5 km from the breakwater. The 40μ particles would settle within 200 m of the breakwater.

B. Long Term Sediment Transport

Particles of sizes from 10μ to 40μ may be transported from the basin and initially settle to the bottom sediments in the region near the breakwater. The particles may then be resuspended during storm events and transported and dispersed over a greater area to lower particle densities (no. particles/m^2). In general, the coastal transport of particles is a dispersive process with the particles having lower and lower densities on each successive stage of transport. Their maximum benthic density would be after the first stage of settling and before resuspension by a subsequent storm. Thus, biological uptake and doses will be at a maximum after initial settling.

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Since the 10μ particles are similar in size to fine silt found on the continental shelf and the 40μ particles are of the size of fine shelf sands, it is expected that the particles would be transported in a manner similar to these two components of shelf sediment. The fine silt and fine shelr sands are transported by different mechanisms that represent a spectrum of processes which transport them along the coast and off the shelf.

The larger sized particles would participate in the bed load transport of fine sands. Studies of transport of shelf sands have been conducted in the RIST (Radio Isotope Sand Tracer) experiments (Reference 8). Sands which are resuspended during storm events are transported and dispersed by the drift currents. Because of their high settling velocities (approximately 200m/day) they are rapidly redeposited on the bottom. Resuspension typically takes place every two to three weeks and has a duration of about one day (Reference 9). Some of the material can be reworked to depths of 10cm to 20cm by benthic organisms and may not be transported by each storm event.

Portions of the fine shelf sands are transported along the beaches. Coastal sediment transport rates as high as $100,000m^3$/year along the Delmarva Coast have been estimated (Reference 10). This transport rate represents about 10^5 times the maximum number of 40μ particles that might be released and so is representative of the order of minimum dilution of the particles if they initially participated in coastwise transport.

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The exchange of coastal sands with sands in estuaries was investigated by examining the chemical composition of silt and sands in the mouths of estuaries and was summarized in Reference 11. There is little evidence for net transport of sand into the mouths of estuaries. As much of the fine sand must be ejected from an estuary as enters an estuary, usually during storm events. Fine sands that do enter an estuary, are not transported very far up the estuary.

The small particles will be transported with the fine silt. The cross-shelf transport of fine silt have been studied in Reference 12. The main source of fine silt is the residual of river silt loads initially deposited in the estuaries along with residual organic matter. Silt "plumes" are found to extend out of the mouths of most estuaries and are re-entrained on successive tides. The general tendency is, however, for the fine silt material to have a net transport outward from the estuary and across the shelf rather than deposition of costal silt in the estuary.

V. Radiological Effects

A. Dose to Biota

The analysis of dose to crustacea in the OPS LPGS report (Reference 1) showed the area of mortalı. - the largest release case was 13 km in length and about 2 km wide. As

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discussed in Section IV above, particles of 10 μ or larger would be deposited within 5 km of the breakwater assuming a drift current of 5 cm/sec. Even selecting the largest monthly resultant surface current measured at the AGS site during 1973-1974, which is 14 cm/sec., the particles 10μ and larger would be deposited within 13 km of the breakwater. Assuming the entire area of particle deposition was lethal to crustacea, this area of mortality is about the same as that calculated in Reference 1 for the most severe soluble radioactive release.

B. Dose to Man

The dose to man from seafood ingestion assuming totally soluble radionuclides was calculated in Reference 1 using the bioaccumulation factor method to estimate radionuclide concentrations in edible portions of fish and invertebrates. Since this method is not applicable for insoluble radionuclides in particulate form, the dose to man is evaluated by calculating the dose per particle and then considering the potential for ingesting the particles from edible portions of fish and crustacea.

Some of the radionuclides in the particles are soluble in sea water and will be rapidly leached leaving only the less soluble nuclides. The nuclides remaining in the particles can be determined by the leach rate factor, F (Reference 1, Appendix J). Based on consideration of total activity released, solubility and the radiological characteristics of specific

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nuclides, the nuclides listed in Table 2 were determined to be potentially important. The resultant doses from ingesting particles of 10 μ and 40 μ are also given in Table 2.

For an ingestion dose to man, particles containing radioactivity must be retained in the edible portions of seafood. In the case of both marine fish and invertebrates, there would be little transfer of insoluble materials from the gut to edible tissue. Radioactive particulates cannot pass directly through membranes and be absorbed in tissue in fish (Reference 13). Direct ingestion of sea water is a more effective mechanism for accumulation of radionuclides in marine fish and invertebrates than ingested food (Reference 14 and 15).

Since there is little transfer of insoluble radionuclides to edible portions of fish, the fish ingestion pathway to man is not considered to be a significant dose pathway for particulate matter. In addition, the fish ingestion doses calculated in Reference 1 assuming soluble releases of radioactivity would be expected to be greater than doses resulting from ingested particulate matter.

Some marine biota such as oysters, quahogs, mussels and soft shell clams which are eaten whole would be a potential dose pathway to man since any insoluble particles of radioactivity contained in the organism would be ingested. These organisms feed on suspended or deposit material and have the capability to

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reject particles on the basis of size, density or indigestibility (References 16 and 17). If the particles are ingested by the organism, removal of the organism from the contaminated environment would result in the depuration of the organism in one to two days (Reference 18). This removal process would afford adequate interdiction to minimize the dose to man.

As discussed in Section IV above, the maximum concentration of activity will occur after initial deposition and result in an area of mortality to biota. Assuming source interdiction to reduce the number of particles by a factor of 100 and a dilution factor of 10^5 as discussed in Section IV above, the maximum particle density would be expected to be no more than 10 particles/m^2. Assuming a person ate a bivalve containing all the radioactive particles in a square meter with no depuration, the GIT dose would be 14.4 mrem. This is three orders of magnitude less than individual doses calculated in Reference 1 for soluble releases.

C. Effects of Particles on Population Dose

Analysis of the effects of sedimentation on population doses for estuarine sites showed that for periods less than 100 days, the effect of sedimentation was to reduce the population dose (Reference 2). For times greater than 1000 days, the population doses with and without consideration of sedimentation were approximately equal. Thus, the population dose, when integrated

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over relatively long times, is almost entirely dependent on the activity released. By analogy, the effect of assuming a particulate form of radioactivity rather than soluble radioactivity is to reduce the population doses for shorter times.

D. Windscale Experience

The experience at Windscale, England is analogous to the postulated scenario discussed here. The fuel reprocessing plant at Windscale, England has discharged plutonium nuclides in its effluent to the Irish Sea for many years. Approximately 10^4 Ci of Pu 239 were discharged between 1967 and 1974. It is estimated that 96% of the plutonium discharged to the water is deposited to the sediments in the immediate vicinity of the outfall. (Reference 19)

Measurements of the plutonium concentration in the sediment indicate that the concentrations are about the same order of magnitude within 9km of the outfall.

From these measurements, it was concluded therefore that the fraction of plutonium which leaves the water does so because it joins the particulate phase, which in turn is being dispersed with the general sediment load. In this respect, other fission products such as Ru106 and Ce144 are found to behave in a similar fashion to plutonium. Following their discharge to sea, these nuclides, like plutonium, are lost rapidly from the water

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phase, but their concentration in sediment relative to the prevailing water concentrations shows very little enhancement in the vicinity of the outfall compared with the concentration at distance.

The concentrations of plutonium in the important food materials in the Irish Sea have been evaluated and the safety of past discharges in a public health context has been clearly demonstrated. No evidence of build-up of plutonium in any material has been found and concentrations in sea water, sediment and biological materials have been related by a constant factor to the rate of discharge of the nuclide.

In the postulated core-melt accident, even with the highly conservative estimate of the number of particles that escape the basin, interdiction using dredging could reduce the remaining activity in the sediments to levels of the order of 10^4 Ci. Based on the experience at Windscale, no significant public health effects would occur due to assumed particle transport of radioactivity out of the basin.

VI. Interdiction

Interdiction to mitigate the consequences of debris particle deposition outside the basin would be feasible. Monitoring would readily identify the areas of high concentrations of radioactivity.

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As discussed in section IV above, the 10 μ particles would be initially deposited relatively near the breakwater depending on the ambient current. Based on coastal hydrological current data, the largest area of deposition for 10 μ particles would be expected to be about 25 km^2. For 40 μ particles, the area would be an order of magnitude less. Even an area as large as 25 square kilometers could be dredged to eliminate this contamination. Since radioactivity in the sediment would be expected to be confined to the top 10 cm of the seabed during the first year, the total volume of sediment to be dredged over this contaminated area would be 4 million cubic yards.

Dredging millions of cubic yards in ocean depths of 40 to 50 feet has been accomplished. For example, the beach erosion control project in Duval County, Florida involved dredging 3.3 million cubic yards of sand in 40 to 50 foot depths off the Atlantic coast and depositing the sand along 10 miles of shoreline (Reference 20). The project cost was $10,578,000. Thus the cost of dredging a contaminated area of 25 square kilometers would be expected to be about 13 million dollars. This cost can be compared to the 22 million dollars estimated for source interdiction for a land based plant (Reference 21).

VII. Summary

A conservative evaluation of the mechanisms available to transport contaminated particles out of basin shows that it is unlikely that particles greater than 40 μ could escape the basin. An upper bound of 60 μ for escape is estimated. Both NRC and OPS concluded in the

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LPGS studies that an energetic interaction between molten core debris and basin water to produce fine particulate material is unlikely. Available data show that should such an interaction occur, about 1% of the debris might form small particles, with 10% as an upper bound. For evaluations conducted here, it is assumed that 10% of the debris is fragmented to particles small enough to be transported by currents. Particles in range of 40 μ to 60 μ which do escape the basin would settle out of the water column within 200 meters of the breakwater.

Smaller particles, such as 10 μ, can be expected to be transported out of the basin and would be initially deposited on the sediment within about 5 to 10 km from the breakwater depending on the ocean currents. Source interdiction using dredging can almost completely eliminate potential dose consequences to man from particulate matter.

The area of initial deposition of the 10 μ particles that escape the basin could produce an area of mortality to marine biota as large as 25 km^2 which is the same as the area calculated for the most severe soluble release case in Reference 1. However, after dredging of this contaminated area, any contaminated particles remaining would be diluted by sediment transport to levels which would not result in significant doses to biota or man.

The of initial deposition of larger particles of 40 μ would produce a much smaller area of mortality. In addition, since these larger particles are slower to disperse, more effective dredging would be

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possible. In addition, the sorting mechanism which occurs within organisms that are part of the food chain to man tend to eliminate these larger particles as a significant source of dose to man.

The basis for comparison of FNP and land-based plants in the NRC LPGS report was population dose. Since the population dose depends on the amount of radioactivity released to the environment, population dose to man is not affected by release of part of the activity as particulate matter unless there are interdiction measures. With interdiction to clean up particulate matter, the population dose would be reduced. Effective source interdiction is expected to be easier to accomplish if radioactivity is released as particulate matter as compared with release in soluble form.

A review of the analogous experience at the Windscale reprocessing plant supports the conclusion that no significant dose to man would occur from the particle releases assumed here and with feasible interdiction.

OPS concludes that transport of significant amounts of radioactivity as particulate matter following a postulated core-melt accident is very unlikely. Further, if this form of transportable particles should occur, dose consequences are likely to be less than for the soluble radioactivity transport cases previously considered in the OPS and NRC LPGS reports and FES-III.

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- OPS agrees with the Staff conclusion (see Section 5.3.4 of FES-III) that consideration of soluble releases to evaluate consequences is a conservative approach.

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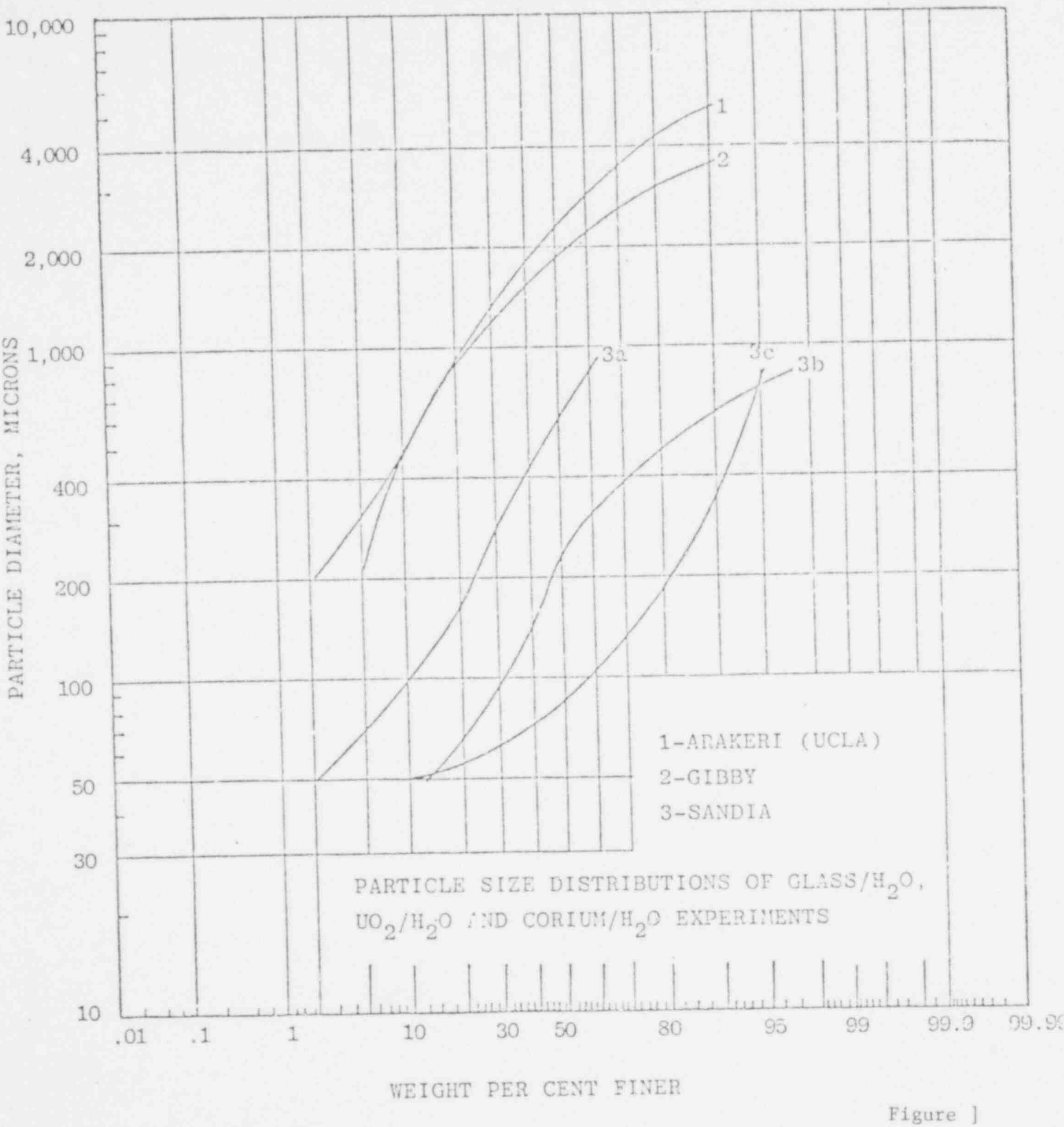

PARTICLE SIZE DISTRIBUTIONS OF GLASS/H_2O, UO_2/H_2O AND CORIUM/H_2O EXPERIMENTS

Figure]

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Table 1 Particle Characteristics for 10% of Total Core

Total mass (10% of Core)	6×10^{6} gm
Total activity (10% of Core)	1×10^{8} Ci
Specific gravity	4.0 gm/cm^3

Particle Size, μ	10	40
Particle Weight, mg	2×10^{-6}	1.3×10^{-4}
Number of Particles	3×10^{15}	5×10^{13}
Settling Velocity (cm/sec)	0.015	0.24
Settling Velocity (m/day)	13	208

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TABLE 2 GIT* DOSE FROM RADIONUCLIDES IN CORE DEBRIS PARTICULATES (MREM PER PARTICLE)

RADIONUCLIDE	ACTIVITY PER PARTICLE (μCi) 10 μm	ACTIVITY PER PARTICLE (μCi) 40 μm	DOSE TO GIT PER PARTICLE (MREM) 10 μm	DOSE TO GIT PER PARTICLE (MREM) 40 μm
Y-91	4.0 (-3)	2.4 (-1)	3.1 (-1)	1.9 (1)
Nb-95	5.7 (-3)	3.4 (-1)	1.2 (-1)	7.1 (0)
Ru-103	4.7 (-3)	2.8 (-1)	1.0 (-1)	6.0 (0)
Ru-106	1.7 (-3)	1.0 (-1)	3.0 (-1)	1.8 (1)
Co-144	3.7 (-3)	2.2 (-1)	6.1 (-1)	3.6 (1)
Pu-238	8.3 (-6)	5.0 (-4)	5.2 (-4)*	3.1 (-2)*
TOTAL			1.44(0)	86.7 (0)

* Gastro-intestinal tract

** Calculated according to methodology of the Report of ICRP Committee II on Permissible Dose for Internal Radiation. International Commission on Radiological Protection, Publication 2, Pergamon Press.

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