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DESIGN BASIS FLOODS FOR NUCLEAR POWER PLANTS

A. INTRODUCTION

General Design Criterion 2, "Design Bases for Protection Against Natural Phenomena," of Appendix A to 10 CFR Part 50, "General Design Criteria for Nuclear Power Plants," requires, in part, that structures, systems, and components important to safety be designed to withstand the effects of natural phenomena such as floods, tsunami, and seiches without loss of capability to perform their safety functions. Criterion 2 also requires that the design bases for these structures, systems, and components reflect: (1) appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding region, with sufficient margin for the limited accuracy and quantity of the historical data and the period of time in which the data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena, and (3) the importance of the safety functions to be performed.

Paragraph 100.10 (c) of 10 CFR Part 100, "Reactor Site Criteria," requires that physical characteristics of the site, including seismology, meteorology, geology, and hydrology, be taken into account in determining the acceptability of a site for a nuclear power reactor.

Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants," was published in the *Federal Register* on November 25, 1971 (36 FR 22601) as a proposed amendment to 10 CFR Part 100. The proposed appendix would specify investigations required for a detailed study of seismically induced floods and water waves. Proposed Appendix A to 10 CFR Part 100 would also require that the determination of design bases for seismically induced floods and water waves be based on the results of the required geologic and seismic investigations and that these design bases be taken into account in the design of the nuclear power plant.

This guide describes an acceptable method of determining for sites along streams or rivers the design basis floods that nuclear power plants must be designed to withstand without loss of safety-related functions. It further discusses the phenomena producing comparable design basis floods for coastal, estuary, and Great Lakes sites. It does not discuss the design requirements for flood protection. The Advisory Committee on Reactor Safeguards has been consulted concerning this guide and has concurred in the regulatory position.

B. DISCUSSION

Nuclear power plants must be designed to prevent the loss of safety-related functions resulting from the most severe flood conditions that can reasonably be predicted to occur at a site as a result of severe hydrometeorological conditions, seismic activity, or both.

The Corps of Engineers for many years has studied conditions and circumstances relating to floods and flood control. As a result of these studies, it has developed a definition for a probable maximum flood (PMF)[1] and attendant analytical techniques for estimating with an acceptable degree of conservatism flood levels on streams or rivers resulting from hydrometeorological conditions. For estimating seismically induced flood levels, an acceptable degree of

[1] Corps of Engineers Probable Maximum Flood definition appears in many publications of that agency such as Engineering Circular EC-1110-2-27, Change 1, "Engineering and Design–Policies and Procedures Pertaining to Determination of Spillway Capacities and Freeboard Allowances for Dams," dated 19 Feb. 1968. The probable maximum flood is also directly analogous to the Corps of Engineers "Spillway Design Flood" as used for dams whose failures would result in a significant loss of life and property.

conservatism for evaluating the effects of the initiating event is provided by the proposed Appendix A to 10 CFR Part 100.

The conditions resulting from the worst site-related flood probable at the nuclear power plant (e.g., PMF, seismically induced flood, seiche, surge, severe local precipitation) with attendant wind-generated wave activity constitute the design basis flood conditions that safety-related structures, systems, and components identified in Regulatory Guide 1.29[2] must be designed to withstand and remain functional.

For sites along streams or rivers, a hypothetical probable maximum flood of the severity defined by the Corps of Engineers generally provides the design basis flood. For sites along lakes or seashores, a flood condition of comparable severity could be produced by the most severe combination of hydrometeorological parameters reasonably possible, such as may be produced by a probable maximum hurricane[3], or by a probable maximum seiche. On estuaries, a probable maximum river flood, a probable maximum surge, a probable maximum seiche, or a reasonable combination of less severe phenomenologically caused flooding events should all be considered in arriving at design basis flood conditions comparable in frequency of occurrence with a probable maximum flood on streams and rivers.

In addition to floods produced by severe hydrometeorological conditions, the most severe seismically induced floods reasonably possible should be considered for each site. Along streams, rivers, and estuaries, seismically induced floods may be produced by dam failures or landslides. Along lakeshores, coastlines, and estuaries, seismically induced or tsunami-type flooding should be considered. Consideration of seismically induced floods should include the same range of seismic events as is postulated for the design of the nuclear plant. For instance, the analysis of floods caused by dam failures, landslides, or tsunami requires consideration of seismic events of the severity of the Safe Shutdown Earthquake occurring at the location that would produce the worst such flood at the nuclear power plant site. In the case of seismically induced floods along rivers, lakes, and estuaries which may be produced by events less severe than a Safe Shutdown Earthquake, consideration should be given to the coincident occurrence of floods due to severe hydrometeorological conditions, but only where the effects on the plant are worse, and the probability of such combined events may be greater, than the effects on the plant of an individual occurrence of the most severe event of either type. For example, a seismically induced flood produced by an earthquake of approximately one-half the Safe Shutdown severity coincident with a runoff-type flood produced by the worst regional storm of record may be considered to have approximately the same severity as an earthquake of Safe Shutdown severity coincident with about a 25-year flood. For the specific case of seismically induced floods due to dam failures, an evaluation should be made of flood waves which may be caused by domino-type dam failures triggered by a seismically induced failure of a critically located dam and of flood waves which may be caused by multiple dam failures in a region where dams may be located close enough together that a single seismic event can cause multiple failures.

Each of the severe flood types discussed above should represent the upper limit of all phenomenologically caused flood potential combinations considered reasonably possible, and analytical techniques are available and should generally be used for their prediction for individual sites. Those techniques applicable to PMF and seismically induced flood estimates on streams and rivers are presented in Appendix A to this guide. Similar appendices for coastal, estuary, and Great Lakes sites, reflecting comparable levels of risk, will be issued as they become available.

Analyses of only the most severe flood conditions may not indicate potential threats to safety-related systems that might result from combinations of flood conditions thought to be less severe. Therefore, reasonable combinations of less-severe flood conditions should also be considered to the extent needed for a consistent level of conservatism. Such combinations should be evaluated in cases where the probability of their existing at the same time and having significant consequences is at least comparable to that associated with the most severe hydrometeorological or seismically induced flood. For example, a failure of relatively high levees adjacent to a plant could occur during floods less severe than the worst site-related flood, but would produce conditions more severe than would result during a greater flood (where a levee failure elsewhere would produce less severe conditions at the plant site).

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[2] Regulatory Guide 1.29 (Safety Guide 29), "Seismic Design Classification," identifies water-cooled nuclear power plant structures, systems, and components that should be designed to withstand the effects of the Safe Shutdown Earthquake and remain functional. These structures, systems, and components are those necessary to assure (1) the integrity of the reactor coolant pressure boundary, (2) the capability to shut down the reactor and maintain it in a safe shutdown condition, or (3) the capability to prevent or mitigate the consequences of accidents which could result in potential offsite exposures comparable to the guideline exposures of 10 CFR Part 100. These same structures, systems, and components should also be designed to withstand conditions resulting from the design basis flood and remain functional.

It is expected that safety-related structures, systems, and components of other types of nuclear power plants will be identified in future Regulatory guides. In the interim, Regulatory Guide 1.29 should be used as guidance when identifying safety-related structures, systems, and components of other types of nuclear power plants.

[3] See Corps of Engineers Coastal Engineering Research Center "Technical Report No. 4, Shore Protection, Planning and Design," third edition, 1966.

Wind-generated wave activity may produce severe flood-induced static and dynamic conditions either independent of or coincident with severe hydrometeorological or seismic flood-producing mechanisms. For example, along a lake, reservoir, river, or seashore, reasonably severe wave action should be considered coincident with the probable maximum water level conditions.[4] The coincidence of wave activity with probable maximum water level conditions should take into account the fact that sufficient time can elapse between the occurrence of the assumed meteorological mechanism and the maximum water level to allow subsequent meteorological activity to produce substantial wind-generated waves coincident with the high water level produced by the initial event. In addition, the most severe wave activity at the site that can be generated by distant hydrometeorological activity should be considered. For instance, coastal locations may be subjected to severe wave action caused by a distant storm that, although not as severe as a local storm (e.g., a probable maximum hurricane), may produce more severe wave action because of a very long wave-generating fetch. The most severe wave activity at the site that may be generated by conditions at a distance from the site should be considered in such cases. In addition, assurance should be provided that safety systems necessary for cold shutdown and maintenance thereof are designed to withstand the static and dynamic effects resulting from frequent flood levels coincident with the waves that would be produced by the maximum gradient wind for the site (based on a study of historical regional meteorology).

C. REGULATORY POSITION

1. The conditions resulting from the worst site-related flood probable at a nuclear power plant (e.g., PMF, seismically induced flood, hurricane, seiche, surge, heavy local precipitation) with attendant wind-generated wave activity constitute the design basis flood conditions that safety-related structures, systems, and components identified in Regulatory Guide 1.29[2] must be designed to withstand and remain functional.

a. On streams and rivers, the Corps of Engineers definition of a probable maximum flood (PMF) with attendant analytical techniques (summarized in Appendix A of this guide) provides an acceptable level of conservatism for estimating flood levels caused by severe hydrometeorological conditions.

b. Along lakeshores, coastlines, and estuaries, estimates of flood levels resulting from severe surges, seiches, and wave action caused by hydrometeorological activity should be based on criteria comparable in conservatism to those used for probable maximum floods. Criteria and analytical techniques providing this level of conservatism for the analysis of these events will be summarized in subsequent appendices to this guide.

c. Flood conditions that could be caused by earthquakes of the severity used in the design of the nuclear facility should also be considered in establishing the design basis flood. A simplified analytical technique for evaluating the hydrologic effects of seismically induced dam failures discussed herein is presented in Appendix A of this guide. Techniques for evaluating the effects of tsunami will be presented in future appendices.

d. In addition to the analyses of the most severe floods that may be induced by either hydrometeorological or seismic mechanisms, reasonable combinations of less-severe flood conditions should also be considered to the extent needed for a consistent level of conservatism. Such combinations should be evaluated in cases where the probability of their existing at the same time and having significant consequences is at least comparable to that associated with the most severe hydrometeorological or seismically induced flood.

e. To the water levels associated with the worst site-related flood possible (as determined from paragraphs a., b., c., or d. above) should be added the effects of coincident wind-generated wave activity to generally define the upper limit of flood potential. An acceptable analytical basis for wind-generated wave activity coincident with probable maximum water levels is the assumption of a 40-mph overland wind from the most critical wind-wave-producing direction, unless historical windstorm data can be used to substantiate that such an event (i.e., wind direction and/or speed) is more extreme than has occurred regionally. However, if the mechanism producing the maximum water level, such as a hurricane, would itself produce higher waves, then these higher waves should be used as the design basis.

2. As an alternative to designing "hardened" protection[5] for all safety-related structures, systems, and components as specified in regulatory position 1. above, it is permissible to not provide hardened protection for some of these features if:

a. Sufficient warning time is shown to be available to shut the plant down and implement adequate emergency procedures;

b. All safety-related structures, systems, and components identified in Regulatory Guide 1.29[2] are

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[4] Probable Maximum Water Level is defined by the Corps of Engineers as "the maximum still water level (i.e., exclusive of local coincident wave runup) which can be produced by the most severe combination of hydrometeorological and/or seismic parameters reasonably possible for a particular location. Such phenomena are hurricanes, moving squall lines, other cyclonic meteorological events, tsunami, etc., which, when combined with the physical response of a body of water and severe ambient hydrological conditions, would produce a still water level that has virtually no risk of being exceeded." (See Appendix A to this guide)

[5] Hardened portection means structural provisions incorporated in the plant design that will protect safety-related structures, systems, and components from the static and dynamic effects of floods. Examples of the types of flood protection to be provided for nuclear power plants will be the subject of a separate regulatory guide.

designed to withstand the flood conditions resulting from a severe storm such as the worst regional storm of record[6] with attendant wind-generated wave activity that may be produced by the worst winds of record and remain functional;

c. In addition to the analyses required by paragraph 2.b. above, reasonable combinations of less-severe flood conditions are also considered to the extent needed for the consistent level of conservatism; and

d. In addition to paragraph 2.b. above, at least those structures, systems, and components necessary for cold shutdown and maintenance thereof are designed with "hardened" protective features to withstand the entire range of flood conditions up to and including the worst site-related flood probable (e.g., PMF, seismically induced flood, hurricane, surge, seiche, heavy local percipitation) with coincident wind-generated wave action as discussed in regulatory position 1. above and remain functional.

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[6] For sites along streams and rivers this event is characterized by the Corps of Engineers definition of a Standard Project Flood. Such floods have been found to produce flow rates generally 40 to 60 percent of the PMF. For sites along seashores this event may be characterized by the Corps of Engineers definition of a Standard Project Hurricane. For other sites a comparable level of risk should be assumed.

APPENDIX A

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PROBABLE MAXIMUM AND SEISMICALLY INDUCED FLOODS ON STREAMS AND RIVERS

A.1 INTRODUCTION

This appendix has been prepared to provide guidance for flood analyses required in support of applications for licenses for nuclear power plants to be located on streams and rivers. Because of the depth and diversity of presently available techniques, this appendix summarizes acceptable methods for estimating probable maximum precipitation, for developing rainfall-runoff models, for analyzing seismically induced dam failures, and for estimating the resulting water levels.

The probable maximum flood may be thought of as one generated by precipitation, and a seismically induced flood as one caused by dam failure. For many sites, however, these two types do not constitute the worst potential flood danger to the safety of the nuclear power plant. Analyses of other flood types (e.g., tsunami, seiches, surges) will be discussed in subsequent appendices.

The probable maximum flood (PMF) on streams and rivers is compared with the upper limit of flood potential that may be caused by other phenomena to develop a basis for the design of safety-related structures and systems required to initiate and maintain safe shutdown of a nuclear power plant. This appendix outlines the nature and scope of detailed hydrologic engineering activities involved in determining estimates for the PMF and for seismically induced floods resulting from dam failures, and describes the situations for which less extensive analyses are acceptable.

Estimation of a probable maximum flood (PMF) requires the determination of the hydrologic response (losses, base flow, routing, and runoff model) of watersheds to intense rainfall, verification based on historical storm and runoff data (flood hydrograph analysis), the most severe precipitation reasonably possible (probable maximum precipitation–PMP), minimum losses, maximum base flow, channel and reservoir routing, the adequacy of existing and proposed river control structures to safely pass a PMF, water level determinations, and the superposition of potential wind-generated wave activity. Seismically induced floods such as may be produced by dam failures or landslides, may be analytically evaluated using many PMF estimating components (e.g., routing techniques, water level determinations) after conservative assumptions of flood wave initiation (such as dam failures) have been made. Each potential flood component requires an in-depth analysis, and the basic data and results should be evaluated to assure that the PMF estimate is conservative. In addition, the flood potential from seismically induced causes must be compared with the PMF to provide appropriate flood design bases, but the seismically induced flood potential may be evaluated by simplified methods when conservatively determined results provide acceptable design bases.

Three exceptions to use of the above-described analyses are considered acceptable as follows:

a. No flood analysis is required for nuclear power plant sites where it is obvious that a PMF or seismically induced flooding has no bearing. Examples of such sites are coastal locations (where it is obvious that surges, wave action, or tsunami would produce controlling water levels and flood conditions) and hilltop or "dry" sites.

b. Where PMF or seismically induced flood estimates of a quality comparable to that indicated herein exist for locations near the site of the nuclear power plant, they may be extrapolated directly to the site, if such extrapolations do not introduce potential

errors of more than about a foot in PMF water level estimates.

c. It is recognized that an in-depth PMF estimate may not be warranted because of the inherent capability of the design of some nuclear power plants to function safely with little or no special provisions or because the time and costs of making such an estimate are not commensurate with the cost of providing protection. In such cases, other means of estimating design basis floods are acceptable if it can be demonstrated that the technique utilized or the estimate itself is conservative. Similarly, conservative estimates of seismically induced flood potential may provide adequate demonstration of nuclear power plant safety.

A.2. PROBABLE MAXIMUM FLOOD (PMF)

Probable maximum flood studies should be compatible with the specific definitions and criteria summarized as follows:

a. The Corps of Engineers defines the PMF as "the hypothetical flood characteristics (peak discharge, volume, and hydrograph shape) that are considered to be the most severe reasonably possible at a particular location, based on relatively comprehensive hydrometeorological analysis of critical runoff-producing precipitation (and snowmelt, if pertinent) and hydrologic factors favorable for maximum flood runoff." Detailed PMF determinations are usually prepared by estimating the areal distribution of "probable maximum" precipitation (PMP) over the subject drainage basin in critical periods of time, and computing the residual runoff hydrograph likely to result with critical coincident conditions of ground wetness and related factors. PMF estimates are usually based on the observed and deduced characteristics of historical flood-producing storms and associated hydrologic factors modified on the basis of hydrometeorological analyses to represent the most severe runoff conditions considered to be "reasonably possible" in the particular drainage basin under study. In addition to determining the PMF for adjacent large rivers and streams, a local PMF should be estimated for each local drainage course that can influence safety-related facilities, including the roofs of safety-related buildings, to assure that local intense precipitation cannot constitute a threat to the safety of the nuclear power plant.

b. Probable maximum precipitation is defined by the Corps of Engineers and the National Oceanic and Atmospheric Administration (NOAA) as "the theoretically greatest depth of precipitation for a given duration that is meteorologically possible over the applicable drainage area that would produce flood flows of which there is virtually no risk of being exceeded. These estimates usually involve detailed analyses of historical flood-producing storms in the general region of the drainage basin under study, and certain modifications and extrapolations of historical data and reflect more severe rainfall-runoff relations than actually recorded, insofar as these are deemed reasonably possible of occurrence on the basis of hydrometeorological reasoning." The PMP should represent the depth, time, and space distribution of precipitation that approaches the upper limit of what the atmosphere and regional topography can produce. The critical PMP meteorological conditions are based on an analysis of air-mass properties (e.g., effective precipitable water, depth of inflow layer, temperatures, winds), synoptic situations prevailing during recorded storms in the region, topographical features, season of occurrence, and location of the respective areas involved. The values thus derived are designated as the PMP, since they are determined within the limitations of current meteorological theory and available data and are based on the most effective combination of critical factors controlling.

A.3 HYDROLOGIC CHARACTERISTICS

Hydrologic characteristics of the watershed and stream channels relative to the plant site should be determined from the following:

a. A topographic map of the drainage basin showing watershed boundaries for the entire basin and principal tributaries and other subbasins that are pertinent. The map should include the location of principal stream gaging stations and other hydrologically related record collection stations (e.g., streamflow, precipitation) and the locations of existing and proposed reservoirs.

b. The drainage areas in each of the pertinent watersheds or subbasins above gaging stations, reservoirs, any river control structures, and any unusual terrain features that could affect flood runoff. All major reservoirs and channel improvements that will have a major influence on streamflow during flood periods should be considered. In addition, the age of existing structures and information concerning proposed projects affecting runoff characteristics or streamflow is needed to adjust streamflow records to "pre-project(s)" and "with project(s)" conditions as follows:

(1) The term "pre-project(s) conditions" refers to all characteristics of watershed features and developments that affect runoff characteristics. Existing conditions are assumed to exist *in the future* if projects are to be operated in a similar manner during the life of the proposed nuclear power plant and watershed runoff characteristics are not expected to change due to development.

(2) The term "with project(s)" refers to the future effects of projects being analyzed, assuming they will exist in the future and operate as specified. If existing projects were not operational during historical floods and may be expected to be effective during the lifetime of the nuclear power plant, their effects on historical floods should be determined as part of the analyses outlined in Sections A.5, A.6, and A.8.

c. Surface and subsurface characteristics that affect runoff and streamflow to a major degree, (e.g.,

large swamp areas, noncontributing drainage areas, groundwater flow, and other watershed features of an unusual nature to the extent needed to explain unusual characteristics of streamflow).

d. Topographic features of the watershed and historical flood profiles or high water marks, particularly in the vicinity of the nuclear power plant.

e. Stream channel distances between river control structures, major tributaries, and the plant site.

f. Data on major storms and resulting floods of record in the drainage basin. Primary attention should be given to those events having a major bearing on hydrologic computations. It is usually necessary to analyze a few major floods of record in order to develop such things as unit hydrograph relations, infiltration indices, base flow relationships, information on flood routing relationships, and flood profiles. Except in unusual cases, climatological data available from the Department of Commerce, The U.S. Army Corps of Engineers, National Oceanic and Atmospheric Administration and other public sources are adequate to meet the data requirements for storm precipitation histories. The data should include:

(1) Hydrographs of major historical floods for pertinent locations in the basin, where available, from the U.S. Geological Survey or other sources.

(2) Storm precipitation records, depth-area-duration data, and any available isohyetal maps for the most severe local historical storms or floods that will be used to estimate basin hydrological characteristics.

A.4 FLOOD HYDROGRAPH ANALYSES

Flood hydrograph analyses and related computations should be used to derive and verify the fundamental hydrologic factors of precipitation losses (see Section A.5) and the runoff model (see Section A.6). The analyses of observed flood hydrographs[1] of streamflow and related storm precipitation (Ref. 1) use basic data and information referred to in Section A.3 above. The sizes and topographic freatures of the subbasin drainage areas upstream of the location of interest should be used to estimate runoff response for each individual hydrologically similar subbasin utilized in the total basin runoff model. Subbasin runoff response characteristics are estimated from historical storm precipitation and streamflow records where such are available, and by synthetic means where no streamflow records are available. The analysis of flood hydrographs (Ref. 2) should include the following:

a. Estimates of the intensity, depth, and areal distribution of precipitation causing the runoff for each historical storm (and rate of snowmelt, where this is significant). Time distributions of storm precipitation are generally based on recording rainfall gages. Total precipitation measurements are usually distributed, in time, using precipitation recorders. Areal distributions of precipitation, for each time increment, are generally based on a weighting procedure in which the incremental precipitation over a particular drainage area is computed as the sum of the corresponding incremental precipitation for each precipitation gage where each value is separately weighted by the percentage of the drainage area considered to be represented by the rain gage.

b. The determination of base flow as the time distribution of the difference between gross runoff and net runoff.

c. Computation of distributed (in time) differences between precipitation and net direct runoff, the difference being considered herein as initial and infiltration losses.

d. The determination of the combined effect of drainage area, channel characteristics, and reservoirs on the runoff regimen, herein referred to as the "runoff model." (Channel and reservoir effects are discussed separately in Section A.8.)

A.5 PRECIPITATION LOSSES AND BASE FLOW

Determination of the absorption capability of the basin should consider antecedent and initial conditions and infiltration during each storm considered. Antecedent precipitation conditions affect precipitation losses and base flow. These assumptions should be verified by studies in the region or by detailed storm-runoff studies. The fundamental hydrologic factors should be derived by analyzing observed hydrographs of streamflow and related storms. A thorough study is essential to determine basin characteristics and meteorological influences affecting runoff from a specific basin. Additional discussion and procedures for analyses are contained in various publications such as Reference 2. The following discussion briefly describes the considerations to be taken into account in determining the minimum losses applicable to the PMF:

a. Experience indicates the capacity of a given soil and its cover to absorb rainfall applied continuously at an excessive rate may rapidly decrease until a fairly definite minimum rate of infiltration is reached, usually within a period of a few hours. Infiltration relationships are defined as direct precipitation losses such that the accumulated difference between incremental precipitation and incremental infiltration equals the volume of net direct runoff. The infiltration loss relationships may include initial conditions directly, or may require separate determinations of initial losses. The order of decrease in infiltration capacity and the minimum rate attained are primarily dependent upon the vegetative or other cover, the size of soil pores within the zone of aeration, and the conditions affecting the rate of removal of capillary water from the zone of aeration. The infiltration theory, with certain approximations, offers a practical means of estimating

[1] Streamflow hydrographs (of major floods) are available in publications by the U.S. Geological Survey, National Weather Service, State agencies, and other public sources.

the volume of surface runoff from intense rainfall. However, in applying the method to natural drainage basins, the following factors must be considered:

(1) Since the infiltration capacity of a given soil at the beginning of a storm is related to antecedent field moisture and the physical condition of the soil, the infiltration capacity for the same soil may vary appreciably from storm to storm.

(2) The infiltration capacity of a soil is normally highest at the beginning of rainfall, and since rainfall frequently begins at relatively moderate rates, a substantial period of time may elapse before the rainfall intensity exceeds the prevailing infiltration capacity. It is generally accepted that a fairly definite quantity of water loss is required to satisfy initial soil moisture deficiencies before runoff will occur, the amount of initial loss depending upon antecedent conditions.

(3) Rainfall does not normally cover the entire drainage basin during all periods of precipitation with intensities exceeding infiltration capacities. Futhermore, soils and infiltration capacities vary throughout a drainage basin. Therefore, a rational application of any loss-rate technique must consider varying rainfall intensities in various portions of the basin in order to determine the area covered by effective runoff-producing rainfall.

b. Initial loss is defined as the maximum amount of precipitation that can occur without producing runoff. Initial loss values may range from a minimum value of a few tenths of an inch during relatively wet seasons to several inches during dry summer and fall months. The initial loss conditions conducive to major floods usually range from about 0.2 to 0.5 inch and are relatively small in comparison with the flood runoff volume. Consequently, in estimating loss rates from data for major floods, allowances for initial losses may be estimated approximately without introducing important errors in the results.

c. Base flow is defined herein as that portion of a flood hydrograph which represents antecedent runoff condition and that portion of the storm precipitation which infiltrates the ground surface and moves either laterally toward stream channels, or which percolates into the ground, becomes groundwater, and is discharged into stream channels (sometimes referred to as bank flow). The storm precipitation, reduced by surface losses, is then resolved into the two runoff components: direct runoff and base flow. Many techniques exist for estimating the base flow component. It is generally assumed that base flow conditions which could exist during a PMF are conservatively high, the rationale being that a storm producing relatively high runoff could meteorologically occur over most watersheds about a week earlier than that capable of producing a PMF. One assumption sometimes made for relatively large basins is that a flood about half as severe as a PMF can occur three to five days earlier. Another method for evaluating base flow relates historical floods to their corresponding base flow. The base flow analyses of historical floods, therefore, may be readily utilized in PMF determinations.

A.6 RUNOFF MODEL

The hydrologic response characteristics of the watershed to precipitation (such as unit hydrographs) should be determined and verified from historical floods or by conservative synthetic procedures. The model should include consideration of nonlinear runoff response due to high rainfall intensities or unexplainable factors. In conjunction with data and analyses discussed above, a runoff model should be developed, where data are available, by analytically "reconstituting" historical floods to substantiate its use for estimating a PMF. The rainfall-runoff-time-areal distribution of historical floods should be used to verify that the "reconstituted" hydrographs correspond reasonably well with flood hydrographs actually recorded at selected gaging stations (Ref. 2). In most cases, reconstitution studies should be made with respect to two or more floods and possibly at two or more key locations, particularly where possible errors in the determinations could have a serious impact on decisions required in the use of the runoff model for the PMF. In some cases, the lack of sufficient time and areal precipitation definition, or unexplained causes, have not allowed development of reliable predictive runoff models, and a conservative PMF model should be assured by other means such as conservatively developed synthetic unit hydrographs. Basin runoff models for a PMF determination should provide a conservative estimate of the runoff that could be expected during the life of the nuclear power plant. The basic analyses used in deriving the runoff model are not rigorous, but may be conservatively undertaken by considering the rate of runoff from a unit rainfall (and snowmelt, if pertinent) of some unit duration and specific time-areal distribution (called a unit hydrograph). The applicability of a unit hydrograph, or other technique, for use in computing the runoff from an estimated probable maximum rainfall over a basin may be partially verified by reproducing observed major flood hydrographs. An estimated unit hydrograph is first applied to estimated historical rainfall-excess values to obtain a hypothetical runoff hydrograph for comparison with the observed runoff hydrograph (exclusive of base flow-net runoff), and the loss rate, the unit hydrograph, or both, are subsequently adjusted to provide accurate verification. A study of the runoff response of a large number of basins for several historical floods in which a variety of valley storage characteristics, basin configurations, topographical features, and meteorological conditions are represented provides the basis for estimating the relative effects of predominating influences for use in PMF analyses. In detailed hydrological studies, each of the following procedures may be used to advantage:

a. Analysis of rainfall-runoff records for major storms;

b. Computation of synthetic runoff response models by (1) direct analogy with basins of similar characteristics and/or (2) indirect analogy with a large number of other basins through the application of empirical relationships. In basins for which historical streamflow and/or storm data are unavailable, synthetic

techniques are the only known means for estimating hydrologic response characteristics. However, care must be taken to assure that a synthetic model conservatively reflects the runoff response expected from precipitation as severe as the estimated PMP.

Detailed flood hydrograph analysis techniques and studies for specific basins are available from many agencies. Published studies such as those by the Corps of Engineers, Bureau of Reclamation, and Soil Conservation Service may be utilized directly where it can be demonstrated that they are of a level of quality comparable with that indicated herein. In particular, the Corps of Engineers have developed analysis techniques (Refs. 2, 3) and have accomplished a large number of studies in connection with their water resources development activities.

Computerized runoff models (Ref. 3) offer an extremely efficient tool for estimating PMF runoff rates and for evaluating the sensitivity of PMF estimates to possible variations in parameters. Such techniques have been used successfully in making detailed flood estimates.

Snowmelt may be a substantial runoff component for both historical floods and the PMF. In cases where it is necessary to provide for snowmelt in the runoff model, additional hydrometeorological parameters must be incorporated. The primary parameters are the depth of assumed existing snowpack, the areal distribution of assumed existing snowpack (and in basins with distinct changes in elevation, the areal distribution of snowpack with respect to elevation), the snowpack temperature and density distributions, the moisture content of the snowpack, the type of soil or rock surface and cover of the snowpack, the type of soil or rock surface and cover in different portions of the basin, and the time and elevation distribution of air temperatures and heat input during the storm and subsequent runoff period. Techniques that have been developed to reconstitute historical snowmelt floods may be used in both historical flood hydrograph analysis and PMF (Ref. 4) determinations.

A.7 PROBABLE MAXIMUM PRECIPITATION ESTIMATES

Probable maximum precipitation (PMP) estimates are the time and areal precipitation distributions compatible with the definition of Section A.2 and are based on detailed comprehensive meteorological analyses of severe storms of record. The analysis uses precipitation data and synoptic situations of major storms of record in a region surrounding the basin under study in order to determine characteristic combinations of meteorological conditions that result in various rainfall patterns and depth-area-duration relations. On the basis of an analysis of airmass properties and synoptic situations prevailing during the record storms, estimates are made of the amount of increase in rainfall quantities that would have resulted if conditions during the actual storm had been as critical as those considered probable of occurrence in the region. Consideration is given to the modifications in meteorological conditions that would have been required for each of the record storms to have occurred over the drainage basin under study, considering topographical features and locations of the respective areas involved.

The physical limitations in meteorological mechanisms for the maximum depth, time, and space distribution of precipitation over a basin are (1) humidity (precipitable water) in the air flow over the watershed, (2) the rate at which wind may carry the humid air into the basin, and (3) the fraction of the inflowing atmospheric water vapor that can be precipitated. Each of these limitations is handled differently to estimate the probable maximum precipitation over a basin, and is modified further for regions where topography causes marked orographic control (designated as the orographic model) as opposed to the general model (with little topographic effect) on precipitation. Further details on the models and acceptable procedures are contained in References 5 and 6.

a. The PMP in regions of limited topographic influence (mostly convergence precipitation) may be estimated by maximizing observed intense storm patterns in the site region for various durations, intensities, and depth-area relations and transposing them to basins of interest. The increase in rainfall quantities that might have resulted from maximizing meteorological conditions during the record storm and the adjustments necessary to transpose the respective storms to the basin under study should be taken into account. The maximum storm should represent the most critical rainfall depth-area-duration relation for the particular drainage area during various seasons of the year (Refs. 7, 8, 9, 10). In practice, the parameters considered are (1) the representative storm dewpoint adjusted to inflow moisture producing the maximum dewpoint (precipitable water), (2) seasonal variations in parameters, (3) the temperature contrast, (4) the geographical relocation, and (5) the depth-area distribution. Examples of these analyses are explained and utilized in a number of published reports (Refs. 7, 8, 9, 10).

This procedure, supported with an appropriate analysis, is usually satisfactory where a sufficient number of historical intense storms have been maximized and transported to the basin and where at least one of them contains a convergent wind "mechanism" very near the maximum that nature can be expected to produce in the region (which is generally the case in the United States east of the Rocky Mountains). A general principle for PMP estimates is: *The number and severity of maximization steps must balance the adequacy of the storm sample; additional maximization*

steps are required in regions of more limited storm samples.

b. PMP determinations in *regions of orographic influences* generally are for the high mountain regions that lie in the path of the prevailing moist wind. Additional maximization steps from paragraph A.7.a. above are required in the use of the orographic model (Refs. 5, 6). The orographic model is developed for the orographic component of precipitation where severe precipitation is expected to be caused largely by the lifting imparted to the air by mountains. This orographic influence gives a basis for a wind model with maximized inflow. Assuming laminar flow of air over any particular mountain cross section, one can calculate the "life" of the air, the levels at which raindrops and snowflakes are formed, and their drift with the air before they strike the ground. Such models are verified by reproducing the precipitation in observed storms and are then used for estimating PMP by introducing maximum values of moisture and wind as inflow at the foot of the mountains. Maximum moisture is evaluated just as in nonorographic regions. In mountainous regions, where storms cannot readily be transposed (paragraph A.7.a. above) because of their intimate relation to the immediate underlying topography, historical storms are resolved into their convective and orographic components and maximized as follows: (1) maximum moisture is assumed, (2) maximum winds are assumed, and finally (3) maximum values of the orographic component and convective component (convective as in nonorographic areas) of precipitation are considered to occur simultaneously. Some of the published reports that illustrate the combination of orographic and convective components, including seasonal variation, are References 11, 12, and 13.

In some large watersheds, major floods are often the result of melting snowpack or of snowmelt combined with rain. Accordingly, the probable maximum precipitation (rainfall) and maximum associated runoff-producing snowpacks are both estimated on a seasonal and elevation basis. The probable maximum seasonal snowpack water equivalent should be determined by study of accumulations on local watersheds from historical records of the region.

Several methods of estimating the upper limit of ultimate snowpack and melting are summarized in References 4 and 5. The methods have been applied in the Columbia River basin, the Yukon basin in Alaska, the upper Missouri River basin, and the upper Mississippi in Minnesota and are described in a number of reports of the Corps of Engineers. In many intermediate-latitude basins, the greatest flood will likely result from a combination of critical snowpack (water equivalent) and PMP. The seasonal variation in both optimum snow depth (i.e., the greatest water equivalent in the snowpack) and the associated PMP combination should be meteorologically compatible. Temperature and winds associated with PMP are two important snowmelt factors amenable to generalization for snowmelt computations (Ref. 14). The meteorological (e.g., wind, temperature, dewpoints) sequences prior to, during, and after the postulated PMP-producing storm should be compatible with the sequential occurrence of the PMP. The user should place the PMP over the basin and adjust the sequence of other parameters to give the most critical runoff for the season considered.

The meteorological parameters for snowmelt computations associated with PMP are discussed in more detail in References 11, 12, and 14.

Other items that need to be considered in determining basin melt are optimum depth, areal extent, and type of snowpack, and other snowmelt factors (see Section A.8), all of which must be compatible with the most critical arrangement of the PMP and associated meteorological parameters.

Critical probable maximum storm estimates for very large drainage areas are determined as above, but may differ somewhat in flood-producing storm rainfall from those encountered in preparing similar estimates for small basins. As a general rule, the critical PMP in a small basin results primarily from extremely intense small-area storms; whereas in large basins the PMP usually results from a series of less intense, large-area storms. In very large river basins (about 100,000 square miles or larger) such as the Ohio and Mississippi River basins, it may be necessary to develop hypothetical PMP storm sequences (one storm period followed by another) and storm tracks with an appropriate time interval between storms. The type of meteorological analyses required and typical examples thereof are contained in References 9, 15, and 16.

The position of probable maximum rainfall centers, identified by "isohyetal patterns" (lines of constant rainfall depth), may have a very great effect on the regimen of runoff from a given volume of rainfall excess, particularly in large drainage basins in which a wide range of basin hydrologic runoff characteristics exist. Several trials may be necessary to determine the critical position of the hypothetical PMP storm pattern (Refs. 8, 17) or the selected record storm pattern (Refs. 9, 16) to determine the critical isohyetal pattern that produces the maximum rate of runoff at the designated site. This may be accomplished by superimposing an outline of the drainage basin (above the site) on the total-storm PMP isohyetal contour map in such a manner as to place the largest rainfall quantities in a position that would result in the maximum flood runoff (see Section A.8 on probable maximum flood runoff). The isohyetal pattern should be reasonably consistent with the assumptions regarding the meteorological causes of the storm. A considerable range in assumptions regarding rainfall patterns (Ref. 11) and intensity variations can be made in developing PMP storm criteria for relatively small basins, without being inconsistent with meteorological

causes. Drainage basins less than a few thousand square miles in area (particularly if only one unit hydrograph is available) may be expressed as average depth over the drainage area. However, in determining the PMP pattern for large drainage basins (with varying basin hydrologic characteristics, including reservoir effects), runoff estimates are required for different storm pattern locations and orientations to obtain the final PMF. Where historical rainfall patterns are not used for PMP, two other methods are generally employed as follows:

a. Average depth over the entire basin is based on the maximized areal distribution of the PMP.

b. A hypothetical isohyetal pattern is assumed. Studies of areal rainfall distribution from intense storms indicate elliptical patterns may be assumed as representative of such events. Examples are the typical patterns presented in References 8, 14, 17, and 18.

To compute a flood hydrograph from the probable maximum storm, it is necessary to specify the time sequence of precipitation in a feasible and critical meteorological time sequence. Two meteorological factors must be considered in devising the time sequences: (1) the time sequence in observed storms and (2) the manner of deriving the PMP estimates. The first imposes little limitations: the hyetographs (rainfall time sequences) for observed storms are quite varied. There is some tendency for the two or three time increments with the highest rainfall in a storm to bunch together, as some time is required for the influence of a severe precipitation-producing weather situation to pass a given region. The second consideration uses meteorological parameters developed from PMP estimates.

An example of 6-hour increments for obtaining a critical 24-hour PMP sequence would be that the most severe 6-hour increments should be adjacent to each other in time (Ref. 17). In this arrangement the second highest increment should be adjacent to the highest, the third highest should be immediately before or after this 12-hour sequence, and the fourth highest should be before or after the 18-hour sequence. This procedure may also be used in the distribution of the lesser second (24-48 hours) and third (48-72 hours) 24-hour periods. These arrangements are permissible because separate bursts of precipitation could have occurred within each 24-hour period (Reference 7). The three 24-hour precipitation periods are interchangeable. Other arrangements that fulfill the sequential requirements would be equally reasonable. The hyetograph, or precipitation time sequence, selected should be the most severe reasonably possible that would produce critical runoff at the project location based on the general appraisal of the hydrometeorologic conditions in the project basin. Examples of PMP time sequences fulfilling the sequential requirements are illustrated in References 11, 12, and 17. For small areas, maximized local records should be considered to assure that the PMP time sequence selected is severe.

The Corps of Engineers and the Hydrometeorological Branch of NOAA (under a cooperative arrangement since 1939) have made comprehensive meteorological studies of extreme flood-producing storms (Ref. 1) and have developed a number of estimates of "probable maximum precipitation." The PMP estimates are presented in various unpublished memoranda and published reports. The series of published reports is listed on the fly sheet of referenced Hydrometeorological Reports such as Reference 18. The published memoranda reports may be obtained from the Corps of Engineers or Hydrometeorological Branch, NOAA. These reports and memoranda present general techniques; included among the reports are several that contain "generalized" estimates of PMP for different river basins. The generalized studies (Refs. 7, 12) usually assure reliable and consistent estimates for various locations in the region for which they have been developed inasmuch as they are based on coordinated studies of all available data, supplemented by thorough meteorological analyses. In some cases, however, additional detailed analyses are needed for specific river basins (Refs. 7, 8) to take into account unusually large areas, storm series, topography, or orientation of drainage basins not fully reflected in the generalized estimates. In many river basins available studies may be utilized to obtain the PMP without the in-depth analysis herein or in the referenced reports.

A.8 CHANNEL AND RESERVOIR ROUTING

Channel and reservoir routing of floods is generally an integral part of the runoff model for subdivided basins, and care should be taken to assure not only that the characteristics determined represent historical conditions (which may be verified by reconstituting historical floods) but also that they would conservatively represent conditions to be expected during a PMF.

Channel and reservoir routing methods of many types have been developed to model the progressive downstream translation of flood waves. The same theoretical relationships hold for both channel and reservoir routing. However, in the case of flood wave translation through reservoirs, simplified procedures have been developed that are generally not used for channel routing because of the inability of such simplified methods to model frictional effects. The simplified channel routing procedures that have been developed have been found useful in modeling historical floods, but particular care must be exercised in using such models for severe hypothetical floods such as the PMF because the coefficients developed from analysis of historical floods may not conservatively reflect flood wave translation for more severe events.

Most of the older procedures were basically attempts to model unsteady-flow phenomena using simplifying approximations. The evolution of computer

use has allowed development of analysis techniques that permit direct solution of basic unsteady flow equations utilizing numerical analysis techniques adaptable to the digital computer (Ref. 19). In addition, most of the older techniques have been adapted for computer use (Ref. 3).

In all routing techniques, care must be exercised in assuring that parameters selected for model verification are based on several historical floods (whenever possible) and that their application to the PMF will result in conservative estimates of flow rates, water levels, velocities, and impact forces. Theoretical discussions of the many methods available for such analyses are contained in References 2, 19, 20, 21, and 22.

A.9 PMF HYDROGRAPH ESTIMATES

PMF net runoff hydrograph estimates are made by sequentially applying critically located and distributed PMP estimates using the runoff model, conservatively low estimates of precipitation losses, and conservatively high estimates of base flow and antecedent reservoir levels.

In PMF determinations it is generally assumed that short-term reservoir flood control storage would be depleted by possible antecedent floods. An exception would be when it can be demonstrated that the occurrence of a reasonably severe flood (say about one-half of a PMF) less than a week (usually a minimum of 3 to 5 days) prior to a PMF can be evacuated from the reservoir before the arrival of a PMF. However, it is unusual to use an antecedent storage level less than one-half the flood control storage available.

The application of PMP in basins whose hydrologic features var from location to location requires the determination that the estimated PMF hydrograph represents the most critical centering of the PMP storm with respect to the site. Care must be taken in basins with substantial headwater flood control storage to assure that a more highly concentrated PMP over a smaller area downstream of the reservoirs would not produce a greater PMF than a total basin storm that is partially controlled. In such cases more than one PMP runoff analysis may be required. Usually, only a few trials of a total basin PMP are required to determine the most critical centering.

The antecedent snowpack and its contribution to the PMF are included when it is determined that snowmelt contributions to the flood would produce a PMF (see Section A.7). However, these types of hypothetical floods are generally the controlling events only in the far west and northern United States.

Runoff hydrographs should be prepared at key hydrologic locations (e.g., streamgages and dams) as well as at the site of nuclear facilities. For all reservoirs involved, inflow, outflow, and pool elevation hydrographs should be prepared.

Many existing and proposed dams and other river control structures may not be capable of safely passing floods as severe as a PMF. The capability of river control structures to safely pass a PMF and local coincident wind-generated wave activity must be determined as part of the PMF analysis. Where it is possible that such structures may not safely survive floods as severe as a PMF, the worst such condition with respect to downstream nuclear power plants is assumed (but should be substantiated by analysis of upstream PMF potential) to be their failure during a PMF, and the PMF determination should include the resultant effects. This analysis also requires that the consequences of upstream dam failures on downstream dams (domino effects) be considered.

A.10 SEISMICALLY INDUCED FLOODS

Seismically induced floods on streams and rivers may be caused by landslides or dam failures. Where river control structures are widely spaced, their arbitrarily assumed individual total instantaneous failure and resulting downstream flood wave attenuation (routing) may be shown to constitute no threat to nuclear facilities. Where the relative size, location, and proximity of dams to potential seismic generators indicate a threat to nuclear power plants, the capability of such structures (either singly or in combination) to resist severe earthquakes (critically located) should be considered. In river basins where the flood runoff season may constitute a significant portion of the year (such as the Mississippi, Columbia, or Ohio River basins), full flood control reservoirs with a 25-year flood is assumed coincident with the Safe Shutdown Earthquake. Also, consideration should be given to the occurrence of a flood of approximately one-half the severity of a PMF with full flood control reservoirs coincident with the maximum earthquake determined on the basis of historic seismicity to maintain a consistent level of analysis for other combinations of such events. As with failures due to inadequate flood control capacity, domino and essentially simultaneous multiple failures may also require consideration. If the arbitrarily assumed total failure of the most critically located (from a hydrologic standpoint) structures indicates flood risks at the nuclear power plant site more severe than a PMF, a progressively more detailed analysis of the seismic capability of the dam is warranted. Without benefit of detailed geologic and seismic investigations, the flood potential at the nuclear power plant site is next generally evaluated assuming the most probable mechanistic-type failure of the questioned structures. If the results of each step of the above analysis cannot be safely accommodated at the nuclear power plant site in an acceptable manner, the seismic potential at the site of each questioned structure is then evaluated in detail, the structural capability is evaluated in the same depth as for

nuclear power plant sites, and the resulting seismically induced flood is routed to the site of the nuclear power plant. This last detailed analysis is *not* generally required since intermediate investigations usually provide sufficient conservative information to allow determination of an adequate design basis flood.

A.11 WATER LEVEL DETERMINATIONS

All the preceding discussion has been concerned primarily with determinations of flow rates. The flow rate or discharge must be converted to water level elevation for use in design. This may involve determination of elevation-discharge relations for natural stream valleys or reservoir conditions. The reservoir elevation estimates involve the spillway discharge capacity and peak reservoir level likely to be attained during the PMF as governed by the inflow hydrograph, the reservoir level at the beginning of the PMF, and the reservoir regulation plan with respect to total releases while the reservoir is rising to peak stage. Most river water level determinations involve the assumption of steady, or nonvarying, flow for which standard methods are used to estimate flood levels. Where little floodplain geometry definition exists, a technique called "slope-area" may be employed wherein the assumptions are made that the water surface is parallel to the average bed slope, any available floodplain geometry information is typical of the river reach under study, and no upstream or downstream hydraulic controls affect the river reach fronting the site under study. Where such computations can be shown to indicate conservatively high flood levels, they may be used. However, the usual method of estimating water surface profiles for flood conditions that may be characterized as involving essentially steady flow is a technique called the "standard-step method." This technique utilizes the integrated differential equation of steady fluid motion commonly referred to as the Bernoulli equation (References 22, 23, 24, and 25) where, depending on whether supercritical or subcritical flow is under study, water levels in the direction of flow computation are determined by the trial and error balance of upstream and downstream energy, respectively. Frictional and other types of head losses are usually estimated in detail with the use of characteristic loss equations whose coefficients have been estimated from computational reconstitution of historical floods, and from detailed floodplain geometry information. Application of the "standard-step method" has been developed into very sophisticated computerized models such as the one described in Reference 23. Theoretical discussions of the techniques involved are presented in References 22, 24, and 25.

Unsteady-flow models may also be used to estimate water levels. Since steady flow may be considered a class of unsteady flow, such models may also be used for the steady-flow water level estimation. Computerized unsteady-flow models require generally the same floodplain geometry definition as steady-flow models, and therefore their use may allow more accurate water surface level estimation for cases where steady-flow approximations are made. One such unsteady-flow computer model is discussed in Reference 19.

All reasonably accurate water level estimation models require floodplain definition of areas that can materially affect water levels, flood wave translation, and calibration by mathematical reconstitution of historical floods (or the selection of calibration coefficients based on the conservative transfer of information derived from similar studies of other river reaches). Particular care should be exercised to assure that controlling flood level estimates are always conservatively high.

A.12 COINCIDENT WIND-WAVE ACTIVITY

The superposition of wind-wave activity on PMF or seismically induced water level determinations is required to assure that, in the event either condition did occur, ambient meteorological activity would not cause a loss of safety-related function due to wave action.

The selection of wind speeds and critical wind directions assumed coincident with maximum PMF or seismically induced water levels should provide assurance of virtually no risk to safety-related equipment necessary to plant shutdown. The Corps of Engineers suggests (Refs. 26, 27) that average maximum wind speeds of approximately 40 to 60 mph have occurred in major windstorms in most regions of the United States. For application to the safety analysis of nuclear facilities, the worst regional winds of record should be assumed coincident with the PMF. However, the postulated winds should be meteorologically compatible with the conditions that induced the PMF (or with the flood conditions assumed coincident with seismically induced dam failures) such as the season of the year, the time required for the PMP storm to move out of the area and be replaced by meteorological conditions that could produce the postulated winds, and the restrictions on wind speed and direction produced by topography. As an alternative to a detailed study of historical regional winds, a sustained 40-mph overland wind speed from any critical direction is an acceptable postulation.

Wind-generated setup (or wind tide) and wave action (runup and impact forces) may be estimated using the techniques described in References 26 and 28. The method for estimating wave action is based on statistical analyses of a wave spectrum. For nuclear power plants, protection against the maximum wave, defined in Refernce 28 as the average of the upper one percent of the waves in the anticipated wave spectrum, should be assumed. Where depths of water in front of safety-related structures are sufficient (usually about seven-tenths the wave height), the wave-induced forces will be equal to the hydrostatic forces estimated from

the maximum runup level. Where the waves can be "tripped" and caused to break both before reaching and on safety-related structures, dynamic forces may be estimated from Reference 28. Where waves may induce surging in intake structure sumps, pressures on walls and the underside of exposed floors should be considered, particularly where such sumps are not vented and air compression can greatly increase dynamic forces.

In addition, assurance should be provided that safety systems necessary for cold shutdown and maintenance thereof are designed to withstand the static and dynamic effects resulting from frequent flood levels coincident with the waves that would be produced by the maximum gradient wind for the site (based on a study of historical regional meteorology).

REFERENCES

1. Precipitation station data and unpublished records of Federal, State, municipal, and other agencies may be obtained from the U.S. Weather Bureau (now called National Weather Service). In addition, studies of some large storms are available in the "Storm Rainfall in the United States, Depth-Area-Duration Data," summaries published by Corps of Engineers, U.S. Army.

2. Corps of Engineers publications, such as EM 1110-2-1405 dated 31 August 1959 and entitled, "Engineering and Design–Flood Hydrograph Analyses and Computations," provide excellent criteria for the necessary flood hydrograph analyses. (Copies are for sale by Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.) Isohyetal patterns and related precipitation data are in the files of the Chief of Engineering, Corps of Engineers.

3. Two computerized models are "Flood Hydrograph Package, HEC-1 Generalized Computer Program," available from the Corps of Engineers Hydrologic Engineering Center, Sacramento, California, dated October 1970 and "Hydrocomp Simulation Programming–HSP," Hydrocomp Intl., Stanford, Calif.

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12. "Probable Maximum Precipitation, Northwest States," Hydrometeorological Report No. 43, U.S. Weather Bureau (now NOAA), 1966.

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16. "Meteorology of Hypothetical Flood Sequences in the Mississippi River Basin," Hydrometeorological Report No. 35, U.S. Weather Bureau (now NOAA), 1959.

17. "Engineering and Design–Standard Project Flood Determinations," Corps of Engineers EM 1110-2-1411, March 1965, originally published as Civil Engineer Bulletin No. 52-8, 26 March 1952.

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19. "Unsteady Flow Simulation in Rivers and Reservoirs," by J. M. Garrison, J. P. Granju and J. T. Price, pp 1559-1576, Vol. 95, No. HY5, (September 1969), *Journal of the Hydraulics Division*, ASCE, (paper 6771).

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