SUPPLEMENTAL HYDROLOGIC ENGINEERING SUMMARY
ON STALLED HURRICANES
ST. LUCIE UNITS 1 & 2
DOCKET NUMBERS: 50-335 & 389

Background

During the ASLB construction permit hearings for Unit 2, the integrity of safety related features with respect to hurricanes was questioned. Specifically, the safety of the plant with respect to the erosional consequences of stalled hurricanes was questioned by the intervener. Both we and the ASLB each concluded that additional information on the subject was necessary to establish that the plant is both acceptably located and that no damage to safety related features would occur in the event of a stalled hurricane. It is noted that hurricanes were considered previosuly, and that a design basis event was selected for the site using criteria suggested in Regulatory Guide 1.59-Design Basis Floods for Nuclear Power Plants. The design basis event is called a Probable Maximum Hurricane (PMH), and is considered the worst hurricane event that might reasonably occur. The selection of the parameters for this postulated event is based upon information generated by the National Oceanic and Atmospheric Administration (NOAA); these parameters were discussed in detail in our previously published SER summary in which we concluded that adequate hurricane protection was being provided.

Examination of PMH parameters (summarized in the SER) postulated for the St. Lucie site indicates such an event would be a hurricane moving with a finite and relatively high forward speed of translation (i.e., it would not be a "stalled hurricane").

In addressing the question of stalled hurricanes, we requested the applicant to: (1) undertake a review of historical hurricane data in the general region of the site to identify historical occurrences of stalled, looping, or slowly moving hurricanes; (2) to postulate storm conditions for the site which could be associated with a severe stalled or looping hurricane; (3) to identify the surge and wave conditions associated with such an event; and (4) to evaluate the possible consequences of a stalled hurricane in terms of erosion and its effects on the plant. In amendments 34, 27 and 51 to the St. Lucie 2 application, the applicant provided information in response to our request. The following paragraphs describe both the applicant's and our evaluations of the consequences of stalled hurricanes at the subject site. Specific reference is made herein to the nuclear island. The term is used to describe the fill placed on Hutchinson Island for the St. Lucie plant. All safety related facilities are on or adjacent to the nuclear island.

Historical Hurricanes -- The applicant's survey of historical hurricane data indicated that approximately 20 storms could be classified as looping. Only two looping severe hurricanes (Betsy, 1965 and Gracie, 1959) possessed ten minute sustained wind speeds in excess of 100 knots.

Only two hurricanes could be classified as having "stalled", and their average translational speeds during the stall period were 4 knots. The maximum wind speeds in these hurricanes that stalled occurred 24-48 hours after the "stall", and following storm acceleration and translation away from the initial stall location. No historical evidence of storm intensification of fully developed and severe hurricanes during stalling or looping was noted. The applicant also provided a discussion of theoretical considerations relating to hurricane dynamics. Two general atmospheric circulation patterns which would cause a hurricane to stall were identified. The applicant concluded hurricanes would not intensify during a stall or loop because of the increase in the amount of upwelling that would occur. The process of upwelling is one which brings cooler bottom waters to the sea surface, changing the sea-air heat flux and thereby causing a severe storm to weaken.

Our consultant, Hugo V. Goodyear reviewed both the applicant's analysis and historical storm data. A copy of his report is attached. He identified about 30 hurricanes that stalled or looped in the general site region out of a sample of 508 tropical storms, of which 304 were classified as hurricanes (maximum winds of 74 mph or higher). In addition, he studied 53 hurricanes or tropical storms which stalled or looped in a recent 36 year period.

While he agreed in general with the applicant's conclusions, he also indicated weak storms have intensified during looping, but most likely near or after the looping period and when increases in translational speeds were noted. He also cautioned against transposing severe historical hurricanes without modification, unless their original track was close to the site for which a transposition was to be made.

We also noted from our review of the applicant's analysis of historical stalled or looping hurricanes, our consultant's report, and relevant NOAA reports (references 1 & 2) that approximately 225 tropical storms or hurricanes have been reported as stalling, looping, or recurving out of a total of about 500 storms recorded in the 93 years between 1871 and 1963. Of the 225 storms, approximately 38 were reported as looping. Because of the ways in which tropical storm and hurricane data were collected prior to regularly instrumented aircraft flights, a greater number of historical looping or stalled storms than reported is considered likely by the staff. Table 1 summarizes some of the pertinent historical data for stalled or looped hurricanes.

Based upon the observed characteristics of stalled hurricanes and the frequency with which they have occurred, we concluded that a stalled hurricane should be considered a design basis event for the St. Lucie site, and postulated a sequence of severe storm conditions for use in evaluating the potential erosion at the site. The postulated event is a PMH which would stall approaching the continental shelf, deintensify and drift shoreward at a minimal rate. Each parameter specified (see Tables 1 and 2) was considered severe, and the resultant storm likelihood as small or smaller than the previously established design basis Probable Maximum Hurricane. In particular, the PMH atmospheric pressure differential reduction of 20 percent, and a translation speed of 1 knot over a critical approach to the site for a substantial duration, were considered conservative.

HURRICANE SURGE

The applicant investigated the resultant surge and wave conditions for four postulated hurricanes, one of which was

the event we postulated. We reviewed the applicant's analyses, and independently evaluated the surge and wave conditions for our postulated PMH that stalled. Figure 1 presents estimates of surge levels as a function of time above +8 feet mean low water (MLW) (independent of waves) for (1) our postulated PMH that stalled; (2) the applicant's postulated PMH that stalled; and (3) Flora, the worst historical looping hurricane in the Atlantic identified by the applicant, transposed critically to the site. These surge estimates were made using the same predictive models associated with the PMH discussion in the SER.

WAVE CLIMATE

Waves, particularly when combined with high water levels, can produce extensive erosion of unprotected coastlines. Hurricanes with their high winds blowing over broad open fetches of ocean create severe wave activity. As large waves approach shallow water near the coast, they "feel" the bottom and break because of frictional effects. The peak wave energy can be considered to increase to a maximum for a breaking wave, and then diminish as the wave proceeds shoreward as a broken wave, or during runup.

The applicant first assumed the beach dune fronting the "nuclear island" could be eroded to the existing ground level of +4 to +5 feet MLW during a severe hurricane, once the surge level exceeded +8 feet MLW. This level(+8 feet MLW) is approximately the minimum elevation of the top of the dune in front of the plant. The +4 to +5 feet existing ground level generally supports the dense vegetation characteristic of the area between highway A1A and the beach dune, and the area north and south of the nuclear island. Based upon the projected surge level above the +4 to +5 feet MLW ground level surrounding the nuclear island, the applicant estimated the maximum associated breaking wave height and wave period.

GENERAL EROSION DISCUSSION

Two basic erosion analyses were made as a function of water level and duration. First, an estimate was made of the "littoral drift" that would occur along the faces of the nuclear island. Littoral drift is the term used to define eroded material in motion along a shoreline due to currents created by waves striking the shore at an angle. Secondly, estimates were made of the erosion to be expected along the faces of the nuclear island by direct frontal wave attack. Both estimates were then combined to evaluate potential consequences to safety related facilities. Each erosion component, and the evaluation of potential consequences, is discussed separately below.

LITTORAL DRIFT

The applicant assumed that throughout the period of the postulated stalled hurricane when waves could be attacking the nuclear island, they would be approaching at a critical angle of 45 degrees. Using his analysis of the time distribution of limiting breaking wave heights (as discussed above) for different surge levels to define a range of wave heights to be considered, the applicant estimated littoral drift rates as a function of breaking wave height. This analysis used values 15 percent greater than the worst of five different methods developed from reference 4. The adopted method, including the 15 percent margin, is based upon estimates of the change in longshore wave energy in the breaking wave zone, and an empirical relationship between the energy and the longshore transport rate for sand of different sizes. The magnitude of the applicant's drift rate estimates, including the margin of 15 percent, range from about 500 cubic yards per hour for breaking waves four feet high, to about 7000 cubic yards per hour for breaking wave 10 feet high. Integrating over storm duration and the lengths of the critical north and east sides of nuclear embankment, which would be exposed to the wave attack, the applicant estimated a littoral drift rate for our postulated stalled hurricane of about 35.5 cubic yards per foot on the east side and 10.4 cubic yards per foot along the north side. Estimated drift rates for the applicant's postulated shorter duration stalled hurricane were about 5 percent less.

DIRECT FRONTAL WAVE ATTACK

Erosion rates due to direct frontal wave attack were estimated separately using data generated from wave tank tests. The tests were conducted at the U. S. Army Corps of Engineers, Beach Erosion Board (now the Coastal Engineering Research Center), in a large wave tank that produced waves up to six feet high of variable period impinging on a sand beach with a 1 vertical to 15 horizontal slope, and over a range of water levels to simulate tidal effects. Two sand sizes, 0.22 and .4 millimeter diameters, were tested with greater erosion of the finer sand being recorded. These tests, which indicate decreasing erosion rates with increasing duration of wave attack; were initally used by the applicant in only three increments to estimate erosion during periods of general rising, high, and falling water levels. The postulated stalled hurricane, including consideration of ambient astronomical and anomalous tide conditions, would produce several periods of extreme rising and falling water levels. We requested the applicant to reanalyze the Amd. 37 estimates of erosion from frontal wave attack by incrementally estimating erosion during each successive extreme high water period of rising and falling water level using the higher initial wave tank erosion rates. Subsequently, the applicant provided revised frontal wave attack erosion estimates of about 45.6 cubic yards.

SPECIAL EROSION ANALYSIS FOR KEY LOCATIONS

In addition to estimating littoral drift and erosion from frontal wave attack along the north and east faces of the nuclear island, the applicant gave special consideration to erosion of the northeast corner of the nuclear island, to the ultimate heat sink dam on the northwest side of the nuclear island, to erosion in front of a drainage ditch on the east side of the island, and to current induced erosion through potential breaches in the beach dune and barrier island. Each subject is discussed separately below.

NORTHEAST NUCLEAR ISLAND CORNER

The northeast corner of the nuclear island would be particularly vulnerable to wave attack during a severe hurricane since waves could be expected to first impinge there and begin to establish littoral drift along the north and east faces of the island. The applicant estimated 27,600 cubic yards of material could be eroded at the corner during the staff's postulated stalled hurricane.

ULTIMATE HEAT SINK

The ultimate heat sink, the facilities necessary to assure a safety related water supply for shutdown and maintenance thereof, includes a barrier wall (or dam) between the intake canal and Big Mud Creek at the northwest corner of the nuclear island. A sheetpile bulkhead and two sheetpile groins on the east side of

the ultimate heat sink channel to Big Mud Creek, and a sheetpile groin on the west side of the channel, will be provided to protect the barrier wall from erosion due to both littoral drift and frontal wave attack.

The applicant considered frontal wave attack from both the ocean and Indian River. Littoral drift produced from waves originating from the ocean was also considered. The applicant estimated a maximum wave height of 8.9 feet (nonbreaking), and a maximum differential static water level of 9.9 feet across the barrier wall. The sheetpile bulkhead along the barrier wall, at an elevation of +16 feet MLW, will minimize the impact of frontal wave attack and serve to tie the groins together. The groins, with top elevations varying from +15 to +11 feet MLW, are expected to trap littoral drift and minimize the effects of erosion on the barrier wall.

DRAINAGE DITCH

The applicant initally assumed that frontal wave erosion would uniformly attack the nuclear island, regardless of the geometrical configuration of the nuclear island fill. At our request, the applicant analyzed separately the effects of erosion from frontal wave attack along the east face of the nuclear island, where a drainage ditch would "collect" and carry away overwash during a severe hurricane. The applicant arbitrarily assumed one third of the embankment material above the eroded embankment profile would be lost in the ditch, and concluded erosion could extend 40 feet closer to safety related facilities by considering such effects.

EROSION THROUGH BREACHES OF THE BARRIER ISLAND.

In examining the topography of Hutchinson Island, and historic records of storm damage on similar barrier islands, we concluded that breaches of the barrier island should be considered. For both the stalled hurricane analysis discussed herein, and for the PMH analysis discussed in the SER, we requested the applicant to consider the consequences of such breaches on safety related facilities during postulated storm conditions. The natural beach dune varies in elevation and width, and could be subjected to both overtopping and wave erosion during a severe storm. Two general failure assumptions were made by the applicant; a general failure along the entire beach early in the storm when stillwater levels (exclusive of waves) would initially reach +8 feet MLW, and isolated failures in the vicinity of selected areas which could result in relatively high current velocity inlets after storm passage when water levels would be higher in Indian River than in the Ocean.

The assumption of a general breach is critical to concluding that storm generated waves can reach the nuclear island with sufficient severity to cause extensive erosion. Based upon consideration of the local topography and potential storm conditions, we conclude the applicant's assumption of general failure is conservative.

The applicant, at our request, assumed isolated breaches of the barrier island at Big Mud Creek (on north side of the nuclear island), at other potential inlet channel locations to the north and south of the island, and at the intake canal and discharge canal dune crossings.

The case of a breach at the discharge canal is discussed in detail in the Unit 2 SER, wherein erosion protection against waves was considered necessary on the "nose" of the discharge canal in the vicinity of safety related facilities. Similarly, we herein require protection of that portion of the discharge canal nose associated with Unit 1. Neither current nor wave caused erosion due to a breach at the intake canal, which could adversely effect safety related facilities, was considered likely by the applicant because of the location of such facilities. We concur. The applicant's analysis of current induced erosion indicated a breach at Big Mud Creek would cause the worst conditions. However, in analyzing the currents along the north face of the nuclear island, the applicant concluded that scour or erosion effects would be minimal. We concur.

EROSION CONSEQUENCES

At our request, the applicant evaluated the estimates of the combined littoral drift-frontal wave attack erosion on safety related facilities. Cross sections, or transects, at various angles across the nuclear island were analyzed for the combined effects of littoral drift and frontal wave attack

assuming no impediments to erosion would exist.

In fact, impediments in the forms of facilities not related to safety (piping, buildings, pavements, etc.) do exist along much of the periphery of a central core of safety related facilities on the nuclear island. Erosion was assumed to occur at levels above +4 feet MLW on the east side of the nuclear island, and +5 on the north side. Both are the levels of the existing ground around the nuclear island. The land area along most of the eastern and northern periphery is covered with rather dense vegetation which could be an erosion retardent during a severe hurricane. No credit was claimed, however, for this retardant.

A base beach, or stable erosion slope, was postulated as 1 vertical to 50 horizontal above the stated ground level (+4 or +5 feet MLW) around the nuclear island. Such a slope is typical of stable beach slopes. A 1 vertical to 15 horizontal active erosion slope based on wave tank tests was assumed to estimate the landward extent of erosion; i.e., using the total estimated erosion (littoral drift and frontal erosion), the 1 on 50 base slope and 1 on 15 eroding slope, the applicant estimated the expected advance of erosion toward safety related facilities. The closest erosion was estimated to approach safety related facilities was on the north side of the nuclear island, about 160 feet from the Unit 1 Reactor Building; although erosion was estimated to extend to within 55 feet of the discharge canal on the northeast side of the nuclear island.

CONCLUSIONS

We and our consultants (Mr. Hugo Goodyear and the Coastal Engineering Research Center) have each independently reviewed the applicant's assessment of the likely safety consequences of stalled hurricanes. A copy of reports from each is attached. We have postulated a severe stalled hurricane, and requested the applicant to deterministically analyze the likely erosional consequences of such an event. The assumption is made that the stalled hurricane postulated is of the same general type and severity as other design basis events, and that if the plant can be shown able to withstand it, the plant will also be able to withstand less severe events. During the course of our review of the successive estimates of water level, wave action and erosional consequences, we identified some areas of analysis which we did not consider conservative and, similarly, several areas of conservatism. The areas which we did not consider conservative (hurricane parameters, erosion rates, and erosion consequences) were, at our request, modified by the applicant. The modified analysis, which we conclude is conservative, is summarized above.

We conclude that a stalled or looping hurricane is an appropriate design basis event for the site region. In terms of flood level, however, we conclude that a Probable Maximum Hurricane would produce the highest water level and therefore, the design basis flood level.

The primary characteristic of a stalled or looping hurricane that could produce adverse consequences at the site is a relatively long period of wave induced erosion at high water levels. The reason that this characteristic could be considered adverse at the St. Lucie site is that most safety related facilities are protected from wave attack by erodable fill.

The applicant's analysis of the staff's postulated stalled hurricane indicates considerable erosion of the nuclear island fill around safety related facilities would occur. However, the applicant concluded that sufficient fill would remain (not be eroded) during such an event, and there would be no adverse impact on safety related facilities. Further, less erosion than predicted would more likely occur since no consideration or credit has been taken for the potential erosion retardant offered by facilities not related to safety which are generally located in front of safety related facilities. We conclude that the design of the proposed facility is adequate for a design basis stalled hurricane.

REFERENCES

1. U. S. Dept. of Commerce; Weather Bureau; Technical Paper No. 55-Tropical Cyclones Over the North Atlantic Ocean; by George W. Cry; 1965.

2. U. S. Dept. of Commerce; Natioanl Oceanic and Atmospheric Administration (NOAA); Technical Report NWS - 15, Some Climalological Characteristics of Hurricanes and Tropical Storms, Gulf and East Coasts of the United States; by Francis P. Ho, Richard W. Schwerdt, and Hugo V. Goodyear; May, 1975.

3. U. S. Dept. of Commerce; National Oceanic and Atmospheric Administration (NOAA); Technical Memorandum NWS SR - 56, Memorable Hurricanes of the United States Since 1873; by Arnold L. Sugg, Leonard G. Pardue and Robert L. Cairodus; April, 1971.

4. U. S. Army Corps of Engineers; Coastal Engineering Research Center; Shore Protection Manual; 1973.

TABLE 1
Hurricanes with Translational Speeds below 5 Knots [1]

Hurricane	Date	Central Pressure (Millibars) Before[2]	During[2]	After[2]	Translational Speed during Loop or Stall Knots	Maximum Wind Speeds (Knots) Before[2]	During[2]	After[2]	Minimum Central Pressure (Millibars)
INEZ	9/21-10/11,1966	999	985	990	4.5	52	65	60	927
CAROL	9/16-10/1, 1965	985	987	987	2.5	56	53	60	974
BETSY	8/27-9/10, 1965	1000	994	987	1	55	63	66	941
		943	958	968	3	100	92	85	941
FLORA	9/26-10/13, 1963	996	972	975	3	91	69	79	936
EASY	9/1-9/7, 1950	N.A.	958	N.A.	4	56	94	40	958
1944	10/13-10/21, 1944	N.A.	984	967	3	56	64	90	949
1942	8/25-9/2, 1942	N.A.	N.A.	Disipated	4	56	56	Disipated	N.A.
1941	9/16-9/25, 1941	N.A.	N.A.	985	4	56	56	75	970
NRC HYPO-THETICAL PMH THAT STALLED		896.	906.	924.	1	126	120	114	896

1. 5 Knots is the minimum translational speed for a slow moving PMH in the St. Lucie Site area.
2. Before, During or After the Hurricane Stalled or Looped.
N.A. - Not Available

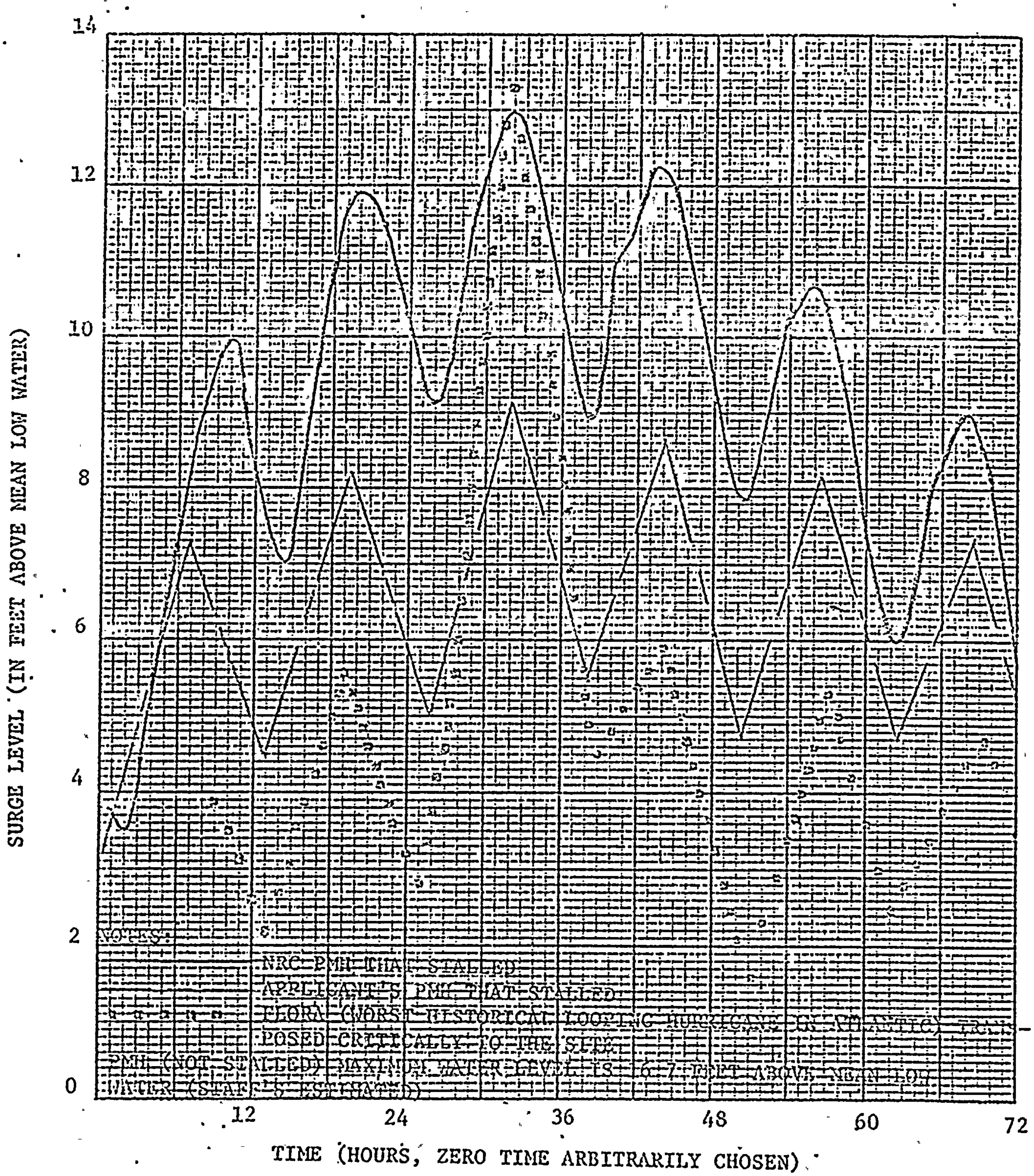
TABLE 2

HYPOTHETICAL STORM PARAMETERS FOR HURRICANES SURGES SHOWN ON FIGURE 1

	Central Pressure (Millibars)		Translational Speed (Knots)		Maximum Wind Speed Knots	
	BEFORE STALL	AFTER STALL	BEFORE STALL	AFTER STALL	BEFORE STALL	AFTER STALL
NRC HYPOTHETICAL PMH THAT STALLED	896	924	5	1	126	114
APPLICANT'S HYPOTHETICAL PMH THAT STALLED	896	991	4	1	126	N.A.
FLORA* WORST LOOPING HURRICANE IN ATLANTIC	996	975	12	3	91	79

*Flora, which looped over Cuba, 10/4-10/8, 1963, is recognized as the worst looping hurricane to have occurred in the Atlantic. The hurricane track was transposed critically to the St. Lucie Site without changing other parameters.

FIGURE 1



HYPOTHETICAL STALLED HURRICANE SURGES AT THE ST. LUCIE SITE

2211 Alder Way
Brandon, Florida
June 3, 1975

L. G. Hulman
Site Analysis Branch
Directorate of Reactor Licensing
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Subject: Review of Hurricane stalls and loops pertinent to the St. Lucie site, Florida. Re: Order No. DR-75-0886

Dear Mr. Hulman:

Enclosed is the final version of the review referred to above. It has undergone some re-editing.

I hope all is satisfactory.

Yours very truly,

Hugo V. Goodyear

Hugo. V. Goodyear

June 2, 1975

CHARACTERISTICS OF STALLED OR LOOPING HURRICANES

A. Purpose and Scope

The purpose of this informal report is to review some pertinent material and available data, and to respond to some questions likely to occur regarding the changes in characteristics that hurricanes in the Gulf of Mexico, the Caribbean, and along the Southeastern Atlantic undergo when they "stall"or "loop", particularly with respect to what is referred to as the St. Lucie Site, Florida.

Of particular concern is the review of data and conclusions provided by the Applicant, Florida Power and Light Company (1), pages Q2.28-1 through Q2.28-72. I have reviewed the above and have provided answers to the questions likely to occur alluded to in the preceding paragraph. Because of the scarcity of data where it is most needed, during loops and stalls, especially before the days of airplane reconnaissance, quantitative answers to most questions are very difficult if not impossible. However, based on some sound theoretical considerations in addition to whatever data is available, and utilizing the results of some extensive work that has been done on hurricane characteristics in general along and near coastal United States, some very sound and reasonable qualitative statements and opinions can be made.

B. Data and References

In addition to the data included in the report furnished by the Applicant, I obtained additional data from the National Hurricane Center at Coral Gables, Florida. Another source of much information and data was the Water Management Information Division of the Office of

Hydrology, U. S. Weather Service (3, 5, and 6)-- some of this material is unpublished. A Bibliography is appended.

C. Definition of Some Pertinent Terms.

(1) - Intensity of a Hurricane: Ideally, this should be defined so as to take into account all the energy in a hurricane, both vertically and horizontally to as far out as the cyclonic circulation exists. From a more practical standpoint, and especially for the engineer, the intensity of a hurricane should suggest an idea of its potential for producing damages caused by winds, high tidal surges and waves as it strikes or comes near some coastal site. Aside from the central pressure deficit (peripheral pressure minus the lowest pressure at the center), which can add significantly to the tidal surge due to its inducing an upward "hump" in and near the "eye", the greatest proportion of the energy in a hurricane is in its kinetic energy, the strength of the windfield. In addition, a high percentage of the kinetic energy in a hurricane is within a ring centered close to the eye of the storm and extending outward a distance of several times the Radius of Maximum Winds (R).

It is considered that the one characteristic of a hurricane which is most indicative of its intensity is the maximum wind as a 5 to 10 minute average, and for standardization, estimated at a height of 30 feet above sea-level. Lacking an estimate of this, the minimum sea-level pressure at the center may be used, which gives a good estimate of the maximum winds, especially when used in combination with R, if available.

I find nothing in the literature wherein a writer has attempted to put values to the adjectives "weak, or barely a hurricane", "moderate", "severe", "extremely severe", or whatever. Subjectivity

seems to get in the way, an investigator's opinion sometimes being colored by the resulting damages rather than by the energetics of the storm itself.

In summary, the intensity of a hurricane, at least for engineering purposes, should be judged by the maximum winds and the central pressure deficit, the former being the most important. Both the stronger miximum winds and the greater central pressure deficits have positive correlations with the tidal surge produced at a particular site.

(2) - <u>Intensification or deintisification</u>: In view of item (1) above, the definitions of the two terms are fairly obvious, and are considered useful generalizations, but sometimes lead to oversimplifications.

For example, if the definitions are to apply to the life history of a <u>particular</u> storm consideration should be given to the Radius of Maximum Winds (R), if available. Background material used in the development of the Standard Project Hurricane indicates that once a hurricane reaches maturity, which may be loosely defined as peak intensity, it tends to expand. R gets larger, but the maximum winds decrease somewhat. This is more noticeable after recurvature. The two changes tend to negate each other, and the energy available for damage production does not change much. As a generality, however, the definitions of the above terms are considered reasonable and have the useful advantage of simplicity.

(3) - <u>Radius of Maximum Wind (R)</u>: The radial distance from the hurricane center to the location of highest winds which usually occurs just outward from the hurricane eye-wall cloud. It is usually located to the right of the direction of forward motion of the storm.

(4) - <u>Stall</u>: For the purposes of this report a stalled hurricane

will be considered one that has lost or is losing its systematic forward motion, and for a considerable period of time, 12 to 24 hours or more, moves at an average forward speed of less than 5 knots. This may include one or several short periods when the storm comes to a virtual standstill or meanders around within a small area. The choice of the "12 to 24 hours or more" and the "less than 5 knots" criteria were prompted by two considerations: first is the consideration that the characteristics of a Probable Maximum Hurricane (see reference 5) already includes the probability of a translational speed of 5 knots with no time limitations, and second is the availability of data. With very minor exceptions, the only indication an investigator has of the translational speed of a hurricane, is the 12- or 24 - hourly positions shown in the published tracks, such as in reference 2 in the Bibliography. The minor exceptions are some very intense or notable hurricanes which were subjected to special investigations because they entered, or just barely by-passed, the U. S. coast, causing extensive damage. In addition, stalls of less than 12 hours duration, preceded and followed by translational speeds of 5 knots or greater, are almost impossible to single out, with the minor exceptions alluded to above. The Applicant has included, in table 2.28-7 of reference 1, some of the above minor exceptions for comparison purposes. These exceptions are mentioned further on in this report. Their stalling durations were for some 3 to 6 hours. The duration of stalls found in the investigation, aside from the exceptions mentioned above, varied from 60 to 96 hours in the Applicent's report, and 12 to 96 hours in my investigation. The lower limit of 12 hours comes from Hurricane Fern (1971), which was of barely hurricane intensity most of the time.

(5) - Loops: Simply, a portion of the storm's track wherein it

describes roughly a circular, oval, or tear-drop shaped path and recrosses a position it previously occupied. Double and more intricate loops occasionally occur. A lot of the evidence and data for loops as well as stalls came from Technical Paper No. 55, "Tropical Cyclones of the North Atlantic Ocean" (2), from numerous articles in the Monthly Weather Review (4), and from some detailed studies made in the Office of Hydrology. A short discussion on looping may be found in pages 18 to 23 of Reference 2, above, and it very generally bears out some of the finding in this study.

They appear in a rather large range of sizes, from less than 10 miles in diameter to as large as the huge loop executed by Doria (1967), which covered an area of about 10 degrees of latitude in length and took about 8 days to complete. Looping occurs either clockwise or counterclockwise with almost equal frequency, and there is no reason to believe that looping and/or stalling are not caused by the same dynamic factors.

D. Discussions of Some Specific Questions

1. Does the Applicant respond adequately to the questions posed as No. 2.28 and is the choice of historical data adequate? Yes, on both counts. The following comments are offered:

(a). The choice of data is adequate, covering a period of over 60 years, a sample of 30 hurricanes that either stalled or looped within the areas specified by the question. During this 60 year period a total of about 508 tropical storms were recorded, of which 304 were of hurricane intensity (maximum winds of 74 mph or higher). I looked at storms encompassing a more recent period of 36 years, obtaining a sample of 53 stalling or looping hurricanes or tropical storms. The difference in sample number is mostly accounted for by

the fact that I included storms that were of less than hurricane intensity during all or a significant part of the time from about 24 hours before to 24 hours after the loop or stall. These weaker storms are useful in testing the hypothesis that a tropical storm, less than hurricane intensity, necessarily, or even usually, intensifies during a period of "stall". Excluded from the survey are what are considered to be the initial stages of a storm.

Ideally, all tropical storms should be surveyed, since only a finite number have been recorded during the last few centuries. However, reliable data of any value are rarely available in the older storms, and we are forced to rely heavily on the data from more recent years, and assume this data is representative of previous years.

(b). The conclusions that the Applicant arrives at, based on the available data, is essentially correct. The reviewer, using added data, deems the conclusions reasonable. Here are specific comments on the eight (8) conclusions discussed on page Q2.28-1 of the revised version of the report dated May 9, 1975, reference 1.

(1.) - Good conclusion. Should have defined, at least qualitatively, what the term 'moderate' means.

(2.) - Correct.

(3.) - Essentially correct - some of the weaker storms, or those of barely hurricane intensity, do intensify somewhat during looping, but apparently almost always near or after the end of the looping period and are picking up translational speed.

(4.) - The remark is good, although the sample is on the small side. A larger Sample, if available, would probably give the same relative numbers.

(5.) - This is essentially true of the weaker or moderate storms. The records are not as clear on the more intense ones, but indications are very strong that the more severe storms weaken during and after stalling and/or looping.

(6.) - Agreed.

(7.) - I would modify this conclusion to read, "It is therefore incorrect to state that a well-developed hurricane will......etc."

(8.) - The remark is certainly true for intense storms.

A few more remarks appear in order:

a. The Applicant does not appear to discuss the question of how R varies relative to the variation of the other parameters in a looping or stalling hurricane. Admittedly, values of R, especially during stalls and loops, are very scarce: note that only about half the storms listed in Table 2.28-7 of reference 1 have estimates of R. Successive values of R taken during the loops and stalls are needed. However, I furnish some opinions pertaining to the variations of R further on in this report, particularly in question 6.

b. The discussion of meteorological and oceanographic factors which cause or contribute to stalling and looping is very good.

c. One particular point was perhaps not stressed enough. With no exceptions that I have been able to find, the extremely severe storms, from the maximum wind standpoint, have moved 'right along'. Carla (1961) was a slight exception. Even then, it had an average forward speed of over 6 mph during the close to 36 hours that it underwent a short stall followed by a small loop some 6 to 8 hours later. Beulah (1967) slowed down to near 3 knots for a few hours, but only after landfall, some 140 miles NNW of Brownsville. By then it had weakened considerably.

2. Can hurricanes such as Camille (1969), Beulah (1967), Carla, (1961), and hurricanes of August 21-31, 1949, September 6-20, 1928, two in 1933, July 25 to August 5, and August 31 to September 7,

and the notable hurricanes of September 4-[illegible], 1947, be transposed as is so as to affect the St. Lucie site?

As far as the first three storms above are concerned, I would strongly recommend against it. Transposition of any kind of storm without modifying or adjusting the characteristics, should only be attempted within very small areas and distances wherein all climatological and perhaps oceanographic factors are homogeneous, or almost so within negligable small limits. In this case the distances involved in transposition are not only relatively great, but it is virtually impossible to assess the effects to a hurricane of the differences in the factors mentioned above.

For the remaining storms the answer is yes. For these the distance of transposition is almost trivial, and in my opinion no adjustments in storm characteristics are necessary. A word of caution is in order, keep the transposed track generally parallel to the original track of the storm in question.

3. If the storms mentioned in item 2. above were transposed, and the parameters adjusted as suggested by the criteria of the SPH, would any parameters exceed those of the PMH? -

No. This type of difficulty was kept in mind during the development of the PMH, and it is felt it cannot happen if the adjustments are correctly made.

4. Are the criteria for a PMH as presented in Memorandum HUR 7-97 (5) still considered conservative? Is it still providing adequate answers to the questions it addresses itself to?

Yes, on both counts.

5. In the opinion of the reviewer, does Memorandum HUR 7-97 provide hypothetical storms that provide characteristics for a PMH that will give the greatest possible surge level at any particular

open coast site?

The Purpose and Scope, on page 2 of Memorandum HUR 7-97 (5), states that it is to provide hurricanes specifications that are meteorologically and geographically consistent for use in planning and evaluating design criteria for hurricane protection works; and establishes characteristics which, when considered in combination, yield the most severe hurricane possible.

The only parameter that is 'fixed' for any location along the coast is the CPI, or lowest central pressure. The other parameters are allowed a wide range of values, at any location along the coast, consistent with the meteorological data used in developing these criteria. Since surface winds are highly depended on pressure gradients a nomogram is provided in the Memorandum which is used to obtain the maximum wind, using the CPI value as the criterion.

Since the maximum wind is the one most important factor in assessing the surge - producing potential of a hurricane, and this has been maximized as much as seems reasonable, the answer to the above question is yes.

6. If we assume that a real PMH is approaching the St. Lucie site, could we conjecture that it could slow down to a T that is slower than the PMH criteria allows? If yes, what happens to its other characteristics and give some opinion as to how long it would take for these changes to take place.

No to the first question as it stands.

With a further qualification the answer could be yes. This is that the storm would no longer be of PMH intensity. The maximum winds would decrease, the CPI would increase. Other characteristics would probably also change.

Since the implication is that it is approaching a stall, or even a

loop, this opinion is supported not only by theory, but by the few hurricanes that were already fairly well-developed before stalling or looping. A total of 22 cases of loops or stalls are listed in Table 2.28-7 (1) for which maximum wind estimates were available for before, during, and after the stall or looping. Only 5 cases are listed where the maximum winds were of hurricane proportions, before looping, the estimates ranging from 81 to 116 mph. All 5 storms weakened during the loop or stall, 2 of them to less than hurricane intensity. Only one of the above 5, Flora (1963), recovered a significant portion the intensity it lost during the loop of some 80 hours duration, but only after it left the loop and was accelerating northeastward rapidly.

The rest of the data consisted of cases that were less intense before looping, and about half did intensify during looping. A storm that fell in this category was Easy (1950). It appeared to have intensified to over 100 mph (109 mph) during looping. Some continued to intensify after completing the stall or loop, but by that time they were moving away from the area comparatively rapidly.

The sparse data indicates this decrease in intensity, of a PMH, that is, will amount to some 15 to 20% of the miximum wind within 24 hours. With only one exception, Flora (1963), the storms that were once severe continue to weaken for some additional 48 to 96 hours, although at a slightly lower rate. Since this stalling we are conjecturing is occurring near the coast it is fair to assume that weakening would occur at a faster rate than indicated by the data. Reasons for this weakening, as a severe storm approaches a land area, are well known.

The question as to what happens to R, the radius of maximum winds, during this period of deintensification, is difficult to answer

because pertinent data during periods of looping or stalling are practically non-existent.

Data from more ordinary storms support the idea that R increases during weakening. Most of the reliable data available on this subject comes from that acquired for the development of the SPH. There is no doubt that there is a negative correlation, although small, between storm intensity and R, as also a positive correlation between latitude and R. The two effects can be probably separated by statistical methods, but since we are here dealing with problems of extremes (what happens when a PMH weakens?) it may not be worthwhile. The problem concerns what happens to a particular storm.

It is the opinion of the reviewer that if the PMH approaches with the smallest allowable R, about 5 n. mi., R will increase to about 10 to 15 n. mi. during the period of weakening. If R is at or near the highest possible allowable for a PMH it will probably increase by only a very insignificant amount.

Simultaneously, the size of the cyclonic circulation of the hurricane windfield should enlarge somewhat, but only by a modest amount, probably insignificant from an engineering standpoint insofar as its affect on a particular small site is concerned.

7. Qualitatively, what happens to a PMH if it slows down to practically a standstill? Does it fill rapidly, loop, stall for a considerable time, or whatever?

It should fill, or weaken, very rapidly. Whether it subsequently loops or not depends on the combination of meteorological factors present at the time. A fairly wide range of changes are possible, though not necessarily with equal probabilities. If it loops the real question is for how long and what the size of the loop is.

How long will the weakened storm remain within a short enough distance that waves of significant size continue to affect the site for a matter of several days? This is highly improbable very close to the coast. Judged by available data, the storm will very soon weaken and dissipate, probably in from 12 to 48 hours.

8. In my opinion, does the report by the Applicant conservatively characterize the historical storms that have a bearing on the problem of anomilies caused by stalls and loops?

Yes.

E. Additional Remarks:

1. There appears to be only a relatively low probability of a tropical storm looping at or very near to the site in question. The probability of a well-developed hurricane doing the same is even less.

2. A stalling tropical storm, or hurricane at the site, has a smaller probability than a loop. Recognizable loops in storm tracks seem to occur about 3 times as often as stalls, as we have defined a stall.

3. A "stalling" storm, or one that moves very slowly, can move in along a relatively straight track, thus prolonged on-shore winds can be experienced at the site, perhaps for a duration of up to 4 days. However, the fact that the storm should weaken considerably as it approaches and makes landfall should be kept in mind. This is particularly true the closer to land a looping or stalling storm occurs.

4. In a "looping" storm near the site, there is a good probability that part of the time the surface winds will be offshore at the site, weakening its potential for prolonged surge wave action.

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