LOUISIANA POWER AND LIGHT COMPANY
WATERFORD STEAM ELECTRIC STATION
UNIT NO. 3

SUMMARY EVALUATION
STRUCTURAL SIGNIFICANCE OF BASEMAT NONDESTRUCTIVE TESTING RESULTS

REVISION 2*

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New York, NY 10048

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1.0 PURPOSE

The purpose of this report is to review the results of nondestructive testing (NDT) of Nuclear Plant Island Structure (NPIS) basemat cracks and to evaluate their significance with respect to the structural integrity of the NPIS.

2.0 SCOPE

The scope of this report covers the following:

1. Review and interpret data and results of NDT related to basemat as presented in the Muenow and Associates, Inc. Report of October 1984 and Appendix 6 of that report which was issued November 13, 1984.

2. Evaluate the significance of the cracks on the structural integrity of the NPIS basemat.

3. Study the crack patterns as defined by NDT, such as inclination, depth, spacing, and width in order to determine the probable causes of basemat and wall cracks.

3.0 BACKGROUND

An NDT program of the basemat cracks was performed by Muenow and Associates, Inc. to determine the following:

1. Inclination of the cracks - whether the basemat cracks are vertical and/or diagonally inclined.

3.0 BACKGROUND (Cont'd)

2. Estimate depth, length, and width of the basemat cracks.

As an auxiliary study, the depth of some cracks of the Reactor Containment Building (RCB) wall surfaces above the basemat was evaluated.

This NDT examination was performed at the Waterford 3 Site mainly during the months of July and August 1984.

4.0 NDT RESULTS SUMMARY

4.1 CRACKS IN BASEMAT (Tables 1, 2 and 3)

The majority of the cracks are oriented in an east-west direction and located within a distance of thirty (30) feet from the east-west centerline of the RCB. Based on their appearance and nearness to each other they are grouped into 10 families:* 4 on the east side of the RCB and 6 on the west side of the RCB. Seven cracks beneath the RCB were also identified by NDT, four of these cracks (Numbers 1, 4, 5 and 7) appear to coincide with east-west cracks on either side of the RCB and probably are interconnected (Figure 1).

Other cracks are oriented in a northeast/southwest or northwest/southeast direction (diagonal cracks) and they are grouped into a total of 7 families. Of these families, 4 were evaluated by NDT: 3 in the northeast and 1 in the northwest corners of the RCB. These cracks are also referred to as East or West Diagonal cracks in the Muenow and Associates, Inc. Report. Two of the cracks beneath the RCB (Numbers 2 and 6) appear to coincide with the East or West Diagonal cracks and probably are interconnected (Figure 1).

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*The grouping by families is somewhat arbitrary and intended only to present an overview of the mat cracking. No analyses or conclusions are dependent upon the grouping.

4.1 HAIRLINE CRACKS OF BASEMAT (Cont'd)

One crack, number 3, appears to be independent of all others and is relatively short in length.

Ebasco review indicates that within the above families of cracks, the data show most cracks originate from the top surface of the basemat (top cracks), that a few noncontinuous cracks originate from the bottom surface of the basemat (bottom cracks), and a small number lie within the middle portion of the basemat (middle cracks).

Tables 1 and 2 present a summary of the NDT examination of the basemat cracks on each side of the RCB. This includes length, depth, group spacing and inclination of cracks which originate from the top surface of the basemat. In addition, a summary of cracks in the middle or near the bottom of the basemat is included.

Table 3 presents a summary of cracks beneath the RCB. These cracks are oriented mainly in the E-W direction.

4.1.1 Depth

East-West Cracks Outside RCB

The depth of the top cracks varies depending on the locations of the cracks. Generally, individual cracks do not extend into the bottom region of reinforcing steel located approximately ten (10) feet depth from the top surface.

The neutral axis for positive bending (tension at top surface of the basemat) is calculated to be approximately 10'-6 from the top surface. The total basemat thickness is 12'-0.

The bottom cracks are found mostly in the vicinity of the east-west centerline of the RCB and their depths range from 2 to 3 feet, measured from the bottom of the basemat. Within this area a possible local interconnection between top and bottom cracks is indicated for Cracks J and Ke.

4.1.1 Depth (Cont'd)

East-West Cracks Outside RCB (Cont'd)

The middle cracks are randomly distributed. In general, they are not interconnected with top or bottom cracks.

Cracks Beneath the RCB

The interpretation of the crack depths beneath the RCB reflects the difficulties of extending the NDT technique to such long distances. Differing interpretations have identified these cracks as being noncontinuous and variable in depth, and also as being continuous and rather continuously extending to near the bottom of the basemat.

Diagonal Cracks (Northeast/Southwest and Northwest/Southeast)

The depth of these cracks, which in plan view run diagonally to the plant grid, is generally less than six (6) feet. A few bottom and middle cracks are present, however, there are no indications of interconnection between the top and bottom cracks.

4.1.2 Inclination

All cracks in the basemat evaluated by NDT are essentially vertical. In Page 2, of the Muenow and Associates, Inc. report it is stated that "there is no evidence of diagonal (shear) cracks; either occurring singularly or as a connection between two individual cracks within the areas investigated."

4.1.3 Length

The cracks are variable in their length. The east-west cracks outside the RCB extend between the exterior wall of the RCB and the wet cooling tower walls. In the one case where visible and accessible for NDT examination, family VI-cracks U, V, X, the cracks extend to the area of the external walls of the NPIS. The diagonal cracks extend from the

4.1.3 Length (Cont'd)

exterior wall of the RCB but end well before they reach the exterior wall of the NPIS. When the cracks intersect with a construction joint they go through the construction joint. It appears that there are 6 cracks that extend from the east to the west side of the NPIS basemat since many of the individual families located in three areas (east, west and beneath the RCB) coincide and are probably joined.

4.1.4 Spacing

The east-west crack families have an average spacing of approximately 11'-0. The diagonal (north-east/southwest or northwest/southeast) crack families have an average spacing of approximately 15'-0 at the exterior wall of the RCB.

4.1.5 Width

The NDT evaluation has estimated the crack width to be less than .007 in. and all the cracks are tight. Our recent field surface measurement of crack L, done coincidentally with NDT examinations found the maximum crack width to be .003 in. The crack was observed to be filled with laitance and there was no actual open crack. Our field surface measurements in 1977 found the crack widths beneath the RCB to be between .002 and .005 in. Cracks of this width are commonly referred to as "hairline" cracks. Field measurements were made using a Bausch & Lomb optical comparator.

4.1.6 Evaluation of Confidence in NDT Results

As a result of a consideration of the techniques used in performing the NDT examination of the basemat cracks and the procedures utilized in evaluating the data derived from the NDT with respect to confidence in the accuracy of the reported crack information we conclude:

1. Outside RCB

   The ability to work close to the surface crack indication leads to a high confidence level in the location and orientation of the tested cracks. A somewhat lower, but still high, confidence level is associated with the location of the bottom of the cracks and a slightly lower confidence in the crack width measurements.

a. Location and Orientation of Crack

The location and orientation of the cracks is dependent upon the accuracy of the location of the transducer and the accuracy and precision of the measurement of time. Since both of these can be, and were, closely controlled and not subject to great variation or subjective interpretation there is high confidence that the location and orientation of the cracks are as defined by the NDT.

b. Depth of Cracks

Due to the divergence of the sound waves used in the testing, a precision of 1 ft in the location of the bottom of the cracks is recognized by Muenow(1). This, since the cracks generally extend down from the top of the mat, leads to a conclusion that the actual bottom of the crack can be as much as one foot above the bottom as defined in the Muenow Report, where the latter is defined at the center of the diverging cone. Therefore, the depth of the cracks outside the RCB are no deeper than and could be as much as one foot less than the values reported by Muenow.

c. Width of Crack

The measurement of crack width is not an exact measurement according to the Muenow report, but is an estimate only. Muenow assigns an accuracy of 20% to the value he reports (≲7 mils), which essentially means he is reporting the cracks

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(1) Muenow Report, p. 16

c. Width of Crack (Cont'd)

to be less than 8-1/2 mils. This together with the independent measurement of the surface crack width of 3 mils gives confidence that the cracks are all quite narrow (on the order of 5 mils).

2. Beneath RCB

The technique used beneath the RCB involving greater distances from transducer to crack and requiring several reflections from the top and bottom of the mat results in a lower confidence level for some of the results derived therefrom.

a. Location and Orientation of Cracks

The location and orientation of cracks using a 60° transducer and several reflections from the mat top and bottom is dependent upon the accuracy of the location of the transducer and the measurement of time. Since these were closely controlled, the confidence in the NDT defined location and orientation is high.

b. Depth of Crack

The confidence level in the validity of the data defining the depth of cracks beneath the RCB is substantially below that for the cracks outside the RCB. There appears to be a large measure of subjective analysis and intuition injected into the interpretation of the raw data to determine the crack depth.

2. Beneath RCB (Cont'd)

b. Depth of Crack (Cont'd)

As with the 45° transducer data, the divergence of the sound waves causes a diminishing of the precision of the data. A 2 to 2-1/2 ft precision is quoted by Muenow which may be enhanced by interpretation of frequency content and amplitude. The precision quoted is open to question and the nature of the enhancements is not clearly defined. While such refinements are theoretically possible, they are not demonstrated, and hence must be discounted, resulting in less confidence in the accuracy of the depth of cracks as reported is valid. This lack of confidence renders uncertain whether the cracks are truly as deep as reported.

However, for reasons cited earlier, whatever the uncertainty regarding interpretation of the crack depths, the cracks are never deeper than reported.

In summary, the location and orientation of the cracks, which are the aspects of greatest significance, are known with a high degree of confidence. The width and depth, which are of lesser significance, are known with a lesser confidence.

4.1.7 Crack Model for Evaluation

As a result of this evaluation of the confidence in the reported NDT testing and evaluation, the following model of the basemat cracks can be drawn:

4.1.7 Crack Model for Evaluation (Cont'd)

The basemat cracks are vertical, or nearly so, and generally extend down from the top of the mat at locations where there are top surface indications of a crack. This orients them generally in an east-west direction. They appear to extend in many cases almost completely across the mat. They extend down a variable depth, in some cases to the region of the bottom reinforcing steel. The actual depth of the cracks is questionable along much of the length beneath the RCB, and hence an assumption for conservatism will be made, in the evaluation of their significance, that they extend from the top to the bottom of the mat. It is cautioned that this simplifying conservative assumption is demonstrably not the case for a significant portion of each crack and such assumption is made simply for purposes of ease of evaluation. The crack widths are quite narrow, on the order of 5 mils, and, by visual observation at the top of the mat, filled with a laitance material and not open.

4.2 CRACKS IN RCB WALL

Four hairline cracks on the exterior surface of the RCB wall near the basemat (Elev -35.0 ft) were evaluated using NDT. All of them were found to penetrate less than one (1) ft of the 10 ft wall thickness (Table 4).

5.0 PROBABLE CAUSES OF CRACKS

The causes of the top cracks were evaluated in 1977 and 1983 (Reference 1) and the conclusion was that they were mainly due to flexure of the basemat from initial loading (prior to the completion of superstructure). The NDT evaluation has determined that all of the top cracks are vertical, extremely narrow and do not generally extend below the neutral axis.

Although the predominant cause of cracks has been concluded to be flexure, other factors such as thermal and/or shrinkage strains probably contributed to their development. Also, the early placement of the lower portion of the RCB ring wall apparently influenced the cracking orientation as evidenced by the radial nature of the most northerly and southerly cracks.

5.1 CRACK PATTERN

From the summary of NDT results, it is clear that the top cracks are greater in number than the bottom cracks. This reflects that the crack pattern generally followed the basemat flexure, which was found to be predominantly convex shape throughout the construction stages. The top cracks are located primarily in an east-west band centered on the RCB centerline. This matches closely the area of maximum convex flexure of the basemat in the early stages of construction as shown on Figure 2.

The causes for the convex flexure of the basemat during construction were the sequence of construction of the basemat blocks for the basemat and the different rates of settlement of the foundation soil beneath each placement block. While the soil beneath the entire basemat is uniform, the loading imposed upon it was placed in segments at different times (each placement block being a loading segment). Thus, the soil beneath each placement block followed the same time-consolidation curve but at a different location on the curve because of the different placing times. As a result, the differential settlement between the last block placed and the first placed was greater than that between those placed earlier and the first. This caused a convex shape to the mat with the earliest blocks placed, at the center of the RCB, being at the top of the convex shape (see Fig. 2). The present convexity is very small being 2-1/2 inches over 380 feet. To prevent any excessive or eccentric differential settlement of the basemat, engineering controls on the placement sequence of the superstructure were utilized. This assured nearly uniform superstructure dead loading on the mat at all times during construction.

5.2 CRACK WIDTH AND DEPTH

The present crack widths are well within the allowable crack width of the ACI Codes. Section 1508.6, ACI 318-63 Code for control of cracking states that "....the average crack width at service load at the concrete surface of extreme tension edge, does not exceed 0.010 in. for exterior members..." Section 10.6.4, ACI 318-83 Code Commentary for control of flexure cracking states that "...for interior and exterior exposure respectively, ... limiting crack widths of 0.016 and 0.013 in."

The NDT examination performed at service load conditions has established the estimated crack width to be less than .007 in. and the actual field measurements of crack "L" less than .003 in. When the basemat cracks were first observed under the RCB in mid-1977, the crack widths were observed to be between .002 and .005 in. The tensile stress in the top reinforcing steel which would correspond to these observed crack widths (approximately .005 in.) is small, on the order of 11 ksi, well within the allowable design limits (Appendix 1). The design yield strength of the reinforcing steel is 60 ksi.

In Reference 1, it was stated that "...The mat, as are all other reinforced concrete structures, is designed to carry loads and in so doing depends only on the compressive and shear strengths of concrete and the tensile strength of reinforcing steel. No credit is taken in the design for the tensile strength of concrete, ... Thus, as loading on the foundation mat causes flexure and resultant tension of the concrete, cracks are expected to form. This cracking enables transfer of the tensile load from the concrete to the embedded reinforcing steel as contemplated in the design of all steel reinforced concrete structures."

The positive and negative bending capacities of the mat are in no way diminished by the presence of the flexural crakcs which are essentially vertical and which are of very modest width. Neither are the bending capacities in any way diminished by the depth of cracks, even if the cracks are assumed to extend completely through the mat thickness.

5.0 PROBABLE CAUSES OF CRACKS (Cont'd)

A single application of bending moment sufficient to crack the mat from the top surface down and to the small observed crack width would not of itself, produce as deep a crack as has been observed. Mechanisms exist, however, which in combination with flexural strains, can produce deep, narrow cracks. One such mechanism is the combination of flexural and thermal strains. The mat, a placement of concrete of substantial volume, will experience considerable temperature increase in the middle due to hydration of cement followed by cooldown over a lengthy period of time. This thermal cycle can result in substantial (on the order of several hundred psi) concrete tensile stresses in the middle and compression stresses at the top and bottom. These stresses in combination with flexural stresses can create a narrow crack extending to substantial depth.

During the early stages of construction the mat experienced time-varying relative displacements; i.e., time-varying flexural curvatures. As shown by Figure 2, flexural curvature of the sense that is associated with tensile strain at the top of the mat was of a larger magnitude at an earlier time than when the cracks were first observed and measured. Corresponding to these earlier larger mat curvatures, there may have been larger crack widths than have been measured at any time since the cracks were first discovered. Presently observed crack depths may reflect these possible earlier crack widths. As construction continued, the mat relative deflections changed, decreasing the curvature and tending to close the cracks.

If, as reasoned above, crack widths at the top of the mat were larger at an earlier time, present crack widths serve only to indicate the maximum possible value of the present rebar tensile stress. If earlier crack width and associated rebar tensile stresses were substantially larger, and particularly if any rebar tensile yield strain was experienced, the present actual tensile stress must be less than implied by the present modest crack width and as estimated in Appendix 1.

There is no reliable basis for determining what actual maximum values of crack widths and associated rebar strain may have occurred during early stages of the mat construction. Different mechanisms have been identified which could account for the presently observed very modest crack widths together with substantial crack depths. A mechanism involving thermal strains can explain the presently observed condition without postulating earlier crack widths wider than at present. The other mechanism involves only flexure and postulates larger crack widths at an earlier time in the construction sequence. The actual sequence of events probably involves both of these mechanisms but the stress/strain conditions during construction are of no consequence to the safety of the structure in its completed state.

The validity of the construction process, including the mat displacement monitoring program, is evidenced by the completed structure not by crack widths and associated rebar stresses during the early construction stages. The earlier conditions are not relevant to the structural integrity of the completed structure, but they serve to explain, qualitatively, the depth of cracking.

5.3 WALL CRACKS

The cracks in RCB walls are found to be superficial by NDT and, therefore, appear to be caused by shrinkage. These cracks are apparently not related to adjacent basemat cracks, which were caused by mat flexure.

6.0 SIGNIFICANCE OF CRACKS AND EFFECTS ON STRUCTURAL INTEGRITY

The following conclusions are of importance in the determination of the significance of the cracks in the Waterford 3 basemat and their effect upon the structural integrity of the basemat:

1. The cracks are flexural cracks probably influenced in some cases with thermal strains. The consistent vertical orientation of the cracks is the evidence of this.

2. There are no inclined cracks within the basemat. This provides evidence that no excessive diagonal tension, hence no excessive shear, exists or has existed within the basemat.

3. There are no through cracks from top to bottom of the basemat with the possible exception of a very few localized areas. The cracks are primarily extending down from the top surface of the basemat. This is evidence that the cracks are primarily the result of flexure and that the flexure was of an upward convex nature which agrees with the observed deformations of the basemat during construction.

4. Presently there is virtually no water seepage or wetness present at any of the observed cracks and the amount of water seepage in the past has been minimal causing only a wetness of the basemat in the immediate vicinity of the cracks. The cracks are believed to have filled with a laitance derived from the parent concrete material. The general stress condition at the top of the basemat has become compression since the occurrence of the original cracking. This condition will not change during normal operation, hence, the continued minimal water seepage condition during the operation of the plant is assured. Therefore, the amount of water seepage presently meets, and will continue to meet, the original design intent for minimal water leakage.

5. The width of the cracks indicates a low present rebar stress (Appendix 1).

6. The crack pattern is predominantly in an east-west direction (Figure 1), localized in a band running east-west and centered near the RCB centerline. This band is within the region subjected to

the most extreme convex curvature during the early stages of construction (Figure 2). This evidence indicates that the cracks resulted from early settlements of the basemat occurring during placement or shortly thereafter. The cracks lying in a northeasterly or northwesterly direction were influenced by the rigidity of the early placements of the RCB wall.

7. The cracks in the RCB wall are shallow, shrinkage induced and are not related to the cracks in the basemat. The existence of cracks in the basemat and the wall at the same, or nearly the same, location appears to be coincidence.

8. The concrete quality is uniform and there are no significant voids and/or honeycombs within the mat. This indicates that the concrete consolidation was more than adequate during construction. The concrete strength is indicated to be 5,000 to 7,000 psi by NDT, which is higher than the required design strength of 4,000 psi and which is consistent with the strengths measured during the construction inspections.

FLEXURAL CONSIDERATIONS

"It is well known that load-induced tensile stresses result in cracks in concrete members. This point is readily acknowledged and accepted in concrete design. Current design procedures.... use reinforcing steel, not only to carry the tensile forces, but to obtain an adequate crack distribution and a reasonable limit on crack width."(1)

The cracks in the Waterford 3 foundation basemat are to be expected considering the flexural situation. They have no negative effect on the structural integrity or strength of the basemat or on the ability

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(1) Causes, Evaluation, and Repair of Cracks in Concrete Structures - ACI 224 ACI Journal - May-June 1984, Paragraph 1.3.9.

6.0 SIGNIFICANCE OF CRACKS AND EFFECTS ON STRUCTURAL INTEGRITY (Cont'd)

of the basemat to resist adequately any design load combinations, nor can they significantly alter the design response of the structure to seismic vibrations. The cracks, being quite narrow and tight, will not increase the flexure of the basemat and hence will not cause any additional transfer of load to building members than that already accounted for in the design.

Reinforced concrete members subjected to flexural loads are designed to accept cracking of the concrete in the tension zone. The ACI code for design of reinforced concrete structures states that "tensile strength of concrete is to be neglected in flexural calculations,"(2) and that all tensile stresses are to be directed to the steel reinforcing. This is normal concrete cracked section analysis and the concrete must crack since it has a low tensile strain at fracture. Therefore, the steel is the structural component in the cracked tension zone.

When reversal of stresses occur and a previously cracked tension zone becomes subjected to compressive forces, the cracks close and the adjacent sides of the cracks bear against each other. The concrete crack surfaces in the Waterford 3 basemat are well able to bear against each other since they are tight and have been filled with laitance and under flexural loading the basemat will react the same as a normal concrete cracked section. Therefore, the flexural strength has experienced no degradation for bending in either direction and no significant increase in the flexure of the basemat will occur.

SHEAR CONSIDERATIONS

"If a (vertical) plane under consideration is an existing crack or interface, failure usually involves slippage or relative movement along

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(2) Building Code Requirements for Reinforced Concrete, ACI 318-63, Paragraph 1503(e).

the crack or plane."(3) "If an initially cracked specimen is tested, shear can be transmitted only if lateral confinement or transverse steel exists. The irregularities of the surfaces of the two sides of the crack ride up on each other and this tends to open the crack and create forces in the transverse steel ...... In a heavily reinforced shear plane or one subjected to a normal compressive stress, the shear resistance due to friction and dowel action may reach the shear corresponding to failure of an initially uncracked specimen having the same characteristics. In such a case the crack locks and the behavior and strength are similar to those for an initially uncracked section."(4)

The Waterford basemat vertical cracks are both heavily reinforced and under "compressive stress."(5) In addition they are very narrow, do not extend through the basemat, and are filled with laitance. Essentially they are "locked." In actuality, they resemble construction joints and respond similarly.

The Potential for "Shear Slip" on Mat Crack Planes

If vertical shear on the basemat crack planes could produce "shear slip" (ie, a step change in vertical deflection across the crack plane), and if such shear slip were large, it would be appropriate to

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(3) The Shear Strength of Reinforced Members - ACI-ASCE 426R-74, ACI Manual of Concrete Practice, 1983, Part 4, Paragraph 2.2.2.

(4) Ibid - Paragraph 2.2.2b.

(5) Review of Waterford 3 Basemat Analysis Structural Analysis Division, Dept. of Nuclear Energy, Brookhaven National Laboratory, July 18, 1984, p. 21.

investigate its possible significance to the dynamic response of the structure. For the reasons discussed below there is no basis for believing that slip will occur.

Background Regarding Shear Strength and Shear Slip on Crack Planes

The matter of shear strength along a crack plane, or a potential crack plane, has been relevant to reinforced concrete design. This is of interest primarily at the junctions of precast concrete members (where large shear forces must be transferred across such planes), in short reinforced concrete (R/C) brackets (where large shear forces sometimes accompanied by tensile forces must be transmitted across such planes), and in R/C membranes subjected to concurrent large shear and tensile forces acting on transverse crack planes. In contrast, for beams and slabs designed to resist internal transverse shear force and bending moments rather than membrane forces, the question of shear strength across potential transverse crack planes normally does not arise. Also, the evaluation of shear resistance across these planes is not normally a part of the design process. This is true even though transverse (flexural) cracks can develop in beams and slabs, particularly when there are bending moment reversals. It may be noted that provisions for shear reinforcement focus on inclined crack planes. The requirements for such reinforcement may be satisfied by transverse bars (which do not cross any potential transverse crack) and such a reinforcing pattern is acceptable for very substantial magnitudes of transverse shear stress. The validity of this practice for conventional beams and slabs reflects (a) the absence of large tension forces on actual or potential crack planes, which could imply large crack widths; and (b) the great shear strength and slip resistance along a crack plane if the crack is closed (or of small initial width), and if "clamping" (compression) force of adequate magnitude is available. This compression force may be provided either by the compression component of a bending moment acting on the section, by tension (flexural) steel crossing the section, by both, or by an externally applied compression force.

Much of the present understanding of shear strength and slip on crack planes was developed by research studies stimulated by the design of R/C containment shells for nuclear power plants. Such shells are subjected to very large membrane forces (i.e., large tension and shear forces) acting on transverse crack planes. The tensile forces can cause cracks of substantial width, and both shear strength and shear slip are matters of design interest. This is a very different condition than exists in the Waterford 3 basemat, but some of the results of the research on the membrane problem are relevant to this discussion of the basemat. In particular, we refer to a report of tests conducted at Cornell University (Reference 3), which for crack planes with initial crack widths of 0.01 in., and subjected to cycles of shear stress reversals of about ± 180 psi, demonstrated the following results:

1) clamping forces developed in the bars that were used to restrain crack width growth did not exceed 20 percent of the applied shear force; and

2) total slip, after 25 cycles of shear reversal, did not exceed 0.01 in.

It should be noted that the clamping forces developed here were from reinforcing steel responding to the shear slip displacement, an active clamping force only present when slip occurs.

Basemat Strength and Slip Resistance on Crack Planes

The cracks in the basemat are predominantly east-west oriented, and are everywhere less than 0.01 inch in width. Of major importance is the fact that the crack planes are not subjected to any tensile force. Indeed there is a very substantial compression force (exerted by soil and water pressure on the north and south boundaries of the mat and the walls above), which is conservatively neglected for purposes of computing shear strength on the crack plane. With regard to its influence on slip, the effect of this compression force, conservatively ignored for strength, is particularly relevant and will be accounted for. Any north-south bending moment, whether positive or negative, which may be acting on the crack plane does not diminish the shear strength of the crack plane. Bending moment which causes tension force in the bottom rebars must cause an equal and opposite compression force in the top few feet of the section. Similarly, bending moment which causes tension force in the top rebars must cause an equal and opposite compression force in the bottom few feet of the section. Thus, diminished resistance in the bottom (or top) is offset by an enhanced resistance in the top (or bottom).

In the regions of interest the top rebars are #11 @ 6", i.e., 3.12 in^2/ft, and the minimum bottom rebars are #11 @ 6" + #11 @ 12", i.e., 4.68 in^2/ft. Over a representative crack plane length (50 ft) the maximum total shear forces on any crack plane are found at either end of the East-West running cracks. The maximum total shear forces on these 50 ft representative lengths correspond to the following values:

Loading Condition	Total Shear Force	Unit Shear Force
1.5 x Gravity Load	42 K/ft	27 psi
1.1 x E-W EQ*	96 K/ft	61 psi
1.1 x Vert EQ	5 K/ft	3 psi
1.1 (Vert EQ + E-W EQ)	101 K/ft	64 psi
1.5 Gravity + 1.1 (Vert EQ + E-W EQ)	143 K/ft	91 psi

*N-S EQ (earthquake) gives smaller shear forces.

It should be noted that averaging of forces over a 50 ft crack length is very conservative since this is only about 4 times the mat thickness. The average shear forces would decrease rapidly with increase in the crack length considered. It also should be noted that the corresponding shear forces on any other 50 ft length of any other cracks are less than the values tabulated above.

Shear Capacities

Using shear provisions of Section 11.7.4, ACI-1983, shear strength of the entire section is given by:

$$V = \Phi V_n = \Phi A_{vf} \; f_y \; \mu$$

where V = available shear strength at section
Φ = strength reduction factor = 0.85
V_n = nominal shear strength
A_{vf} = area of shear-friction reinforcement
f_y = specified yield strength of reinforcement = 60 ksi
μ = coefficient of friction = $1.4\,\lambda$
λ = correction factor related to unit weight of concrete = 1.0

therefore,

$$V = 0.85\ (3.12 + 4.68)\ 60 \times 1.4 \times 1.0 = 556.9 \text{ K/ft}$$

which corresponds to an average unit shear strength of:

$$v = \frac{556{,}900}{12 \text{x} 11 \text{x} 12} = 352 \text{ psi}$$

Because the rebars are concentrated near the top and bottom of the section, rather than distributed throughout the depth of the section we conservatively reduce the above shear capacity by 50 percent, i.e., to 278 K/ft. This is 1.9 times the 143 K/ft shear demand.

It is clear that the shear strength along the crack plane, even ignoring the inescapable active compression force, is much in excess of the demand.

Slip Resistance

As reported in Reference 3, for an initial crack width of 0.01 inches, and cycles of shear stress reversal to 180 psi a slip of about 0.004 in. was developed at the end of the first cycle increasing to 0.01 in. after 25 cycles. Moreover the maximum clamping force developed during this cycling was only 20 percent of the applied shear force. In the mat we are interested in an applied shear stress of 91 psi, for which a 20 percent clamping force would be 18 psi.

The compression acting on the cracked section, due to horizontal soil and water pressure on the mat and walls, is 50 psi. Based on the finite element model, this compression exists in all areas of the basemat during earthquake loading conditions with the small exception of a very narrow band immediately adjacent to the north and south walls. It is not credible that this compression stress, reduced as may be reasonable for the effect of an earthquake, would not still be substantially in excess of 18 psi. This means that more than the required clamping pressure of 18 psi is available from the outset; i.e., no rebar tension is required to provide the required clamping force. Since, the clamping force is a passive force, the friction resulting from it is available without shear slip and is a static friction.

The conclusion then is drawn that the shear resistance across the crack is a state of static friction wherein the available static friction must be overcome prior to the occurance of any shear slip. Since the available friction is at least equal to and undoubtedly far in excess of the applied shear stress we conclude that the shear resistance would develop without any significant slip. Therefore, there is no change in the rigidity of the mat and no effect upon the dynamic response of the basemat to the earthquake.

7.0 CONCLUSION

Considering each of the above items individually and in concert, we conclude that the cracks in the Waterford 3 basemat, as defined by the nondestructive testing, have no adverse influence on the structural integrity of the basemat. It is fully capable of functioning as required by the design in accordance with the pertinent codes.

REFERENCES

1. Affidavit of Joseph L Ehasz, Ebasco Services Incorporated, submitted before the Atomic Safety and Licensing Appeal Board, USNRC, September 1983.

2. "NPIS Wall Hairline Crack Evaluation," by Ebasco Services Incorporated, April 1984.

3. J P Laible, R N White, and P Gergely, "Experimental Investigation of Seismic Shear Transfer Across Cracks in Concrete Nuclear Containment Vessels," ACI SP 53-9, Reinforced Concrete Structures in Seismic Zones, 1977.

TABLE 1 - SUMMARY OF CRACKS WEST SIDE OF RCB

		Top Crack						Presence of Subsurface Cracks (See Notes)			
								Bottom Crack		Middle Crack	
Family	Crack I.D.	Test Lines	Length (exposed)	Depth (ft.)			Family Spacing	Below Bottom Re-bar	Through Bottom Re-bar		Inclinat
				Min	Max	Average					
I	A	7	7'- 6	1	2	2		*	*	*	vertical
	B	7	9'- 0	2	3	3		*	*	*	vertical
	C	12	16'- 6	1	3	2		*	*	*	vertical
							±10'	*	*	*	vertical
II	D	5	6'- 0	2	5	4		*	***	*	vertical
	E	1	2'- 0	3	3	3		*	*	**	vertical
	F	6	9'- 0	4	10	5		**	**	*	vertical
	G	4	6'- 0	1	5	4		*	*	*	vertical
							±16'				
III	1	4	5'- 0	7	10	8		**	**	*	vertical
	H	6	9'- 0	5	10	8		**	**	*	vertical
	J	20	28'- 0	3	12	9		***	****	**	vertical
	K	10	13'- 0	3	11	8		**	***	*	vertical
							±10'				
IV	L	10	28'- 0	6	10	8		**	**	*	vertical
							±8'				

Notes: *None
**Presence of crack is not probable since only at one or two test line location(s).
***Presence of crack is probable since indication at several test locations but not interconnected with top crack.
****Similar to *** except probably interconnected with top crack.

(Sheet 1 of 2)

TABLE 1 - SUMMARY OF CRACKS WEST SIDE OF RCB (Cont'd)

		Top Crack						Presence of Subsurface Cracks (See Notes)			
								Bottom Crack		Middle Crack	
Family	Crack I.D.	Test Lines	Length (exposed)	Depth (ft.) Min	Max	Average	Family Spacing	Below Bottom Re-bar	Through Bottom Re-bar		Inclinatic
V	M	4	6'- 0	4	5	4		*	*	*	vertical
	N	3	5'- 0	2	6	3		*	*	*	vertical
	2	3	5'- 0	1	3	2		*	*	*	vertical
	3	9	12'- 0	1	5	2		*	*	*	vertical
	P	9	14'- 0	8	10	9		*	**	*	vertical
	R	1	2'- 0	2	2	2		*	*	*	vertical
	Q	3	8'- 0	3	5	4		*	*	*	vertical
	S	3	4'- 0	4	4	4		*	*	*	vertical
	T	14	20'- 0	3	10	6		*	***	*	vertical
	Y	3	6'- 0	1	1	1		*	*	*	vertical
							± 6'				
VI	U	9	14'- 0	2	10	5		*	**	*	vertical
	V	5	13'- 0	2	5	3		*	*	*	vertical
	X	22	25'- 0(+)	1	5	3		*	*	*	vertical
VII	West Diagonal	19	27'- 0	1	4	3		**	***	*	vertical

Notes: *None

**Presence of crack is not probable since only at one or two test line location(s).

***Presence of crack is probable since indication at several test locations but not interconnected with top crack.

****Similar to *** except probably interconnected with top crack.

TABLE 2 - SUMMARY OF CRACKS EAST SIDE OF RCB

		Top Crack						Presence of Subsurface Cracks (See Notes)			
								Bottom Crack		Middle Crack	
Family	Crack I.D.	Test Lines	Length (exposed)	Depth (ft.) Min	Max	Average	Family Spacing	Below Bottom Re-bar	Through Bottom Re-bar		Inclinatio
Ie	Ae	4	6'- 0	1	1	1		*	*	*	vertical
	Be-Ce	5	6'- 0	1	4	3		*	*	*	vertical
	De	2	4'- 9	1	1	1		*	*	*	vertical
	le	2	3'- 0	3	3	3		*	*	*	vertical
							±10'				
IIe	Ee	4	4'- 6	1	1	1		*	*	*	vertical
	Fe	8	12'- 0	2	10	6		*	***	*	vertical
							+13'				
IIIe	He	5	6'- 0	2	3	2		**	*	**	vertical
	Je	5	7'- 0	2	4	3		***	*	**	vertical
	Le	8	13'- 0	3	12	7		***	**	*	vertical
							±11'				
IVe	Ke	15	26'- 0	4	12	8		**	****	*	vertical
							±16'				
Ve	De1	3	4'- 0	1	1	1		*	*	*	vertical
	De3	15	23'- 0	1	6	3		*	*	*	vertical
	De4	5	10'- 0	1	1	1		*	*	**	vertical
							±15'				

Notes: *None
**Presence of crack is not probable since only at one or two test line location(s).
***Presence of crack is probable since indication at several test locations but not interconnected with top crack.
****Similar to *** except probably interconnected with top crack.

TABLE 2 - SUMMARY OF CRACKS EAST SIDE OF RCB (Cont'd)

		Top Crack						Presence of Subsurface Cracks (See Notes)			
								Bottom Crack		Middle Crack	
Family	Crack I.D.	Test Lines	Length (exposed)	Depth (ft.) Min	Max	Average	Family Spacing	Below Bottom Re-bar	Through Bottom Re-bar		Inclinatio
VIe	De5	17	24'-0	1	10	3		***	*	***	vertical
	De6	5	7'-3	2	6	4		**	*	*	vertical
							± 15'				
VIIe	De7	9	12'- 0	1	6	3		*	**	***	vertical
	De8	8	10'- 0	1	3	2		*	***	***	vertical
	De9	11	15'- 0	1	5	2		**	*	***	vertical

Notes: *None
**Presence of crack is not probable since only at one or two test line location(s).
***Presence of crack is probable since indication at several test locations but not interconnected with top crack.
****Similar to *** except probably interconnected with top crack.

TABLE 3 - SUMMARY OF CRACKS BENEATH RCB

Crack I.D.	Correlation with 1977 Mapping	Depth	Inclination	Spacing @ C.L. RCB
6	None (Note 1)	Variable	Vertical	
				18'
2	None (Note 1)	"	"	
				12'
1	Yes	"	"	
				9'
7	Partial	"	"	
				6'
3	Yes	"	"	
				9'
5	Partial	"	"	
				13'
4	Yes	"	"	
			Average Spacing =	11'

Note 1 - This crack was not identified during 1977 mapping of cracks beneath RCB.

TABLE 4 - SUMMARY OF CRACKS IN RCB WALLS

Crack I.D.	Test Lines	Maximum Dept of Penetration (ft.)	Inclination	Remarks
RCB 1	3	1	Perpendicular to wall surface	Wall thickness = 10'-
RCB 2	3	1	Perpendicular to wall surface	Wall thickness = 10'-
RCB 3	3	1	Perpendicular to wall surface	Wall thickness = 10'-
RCB 4	3	1	Perpendicular to wall surface	Wall thickness = 10'-

APPENDIX 1

REINFORCING STEEL STRESS AS DEFINED BY CRACK WIDTH

Gergely & Lutz Equation ("Causes, Evaluation and Repair of Cracks in Concrete," ACI 224, ACI Journal May-June 1984, p. 218).

$$\omega = 0.076\ \beta\ f_s\ \sqrt[3]{d_c A_1}\ \times 10^{-3}$$

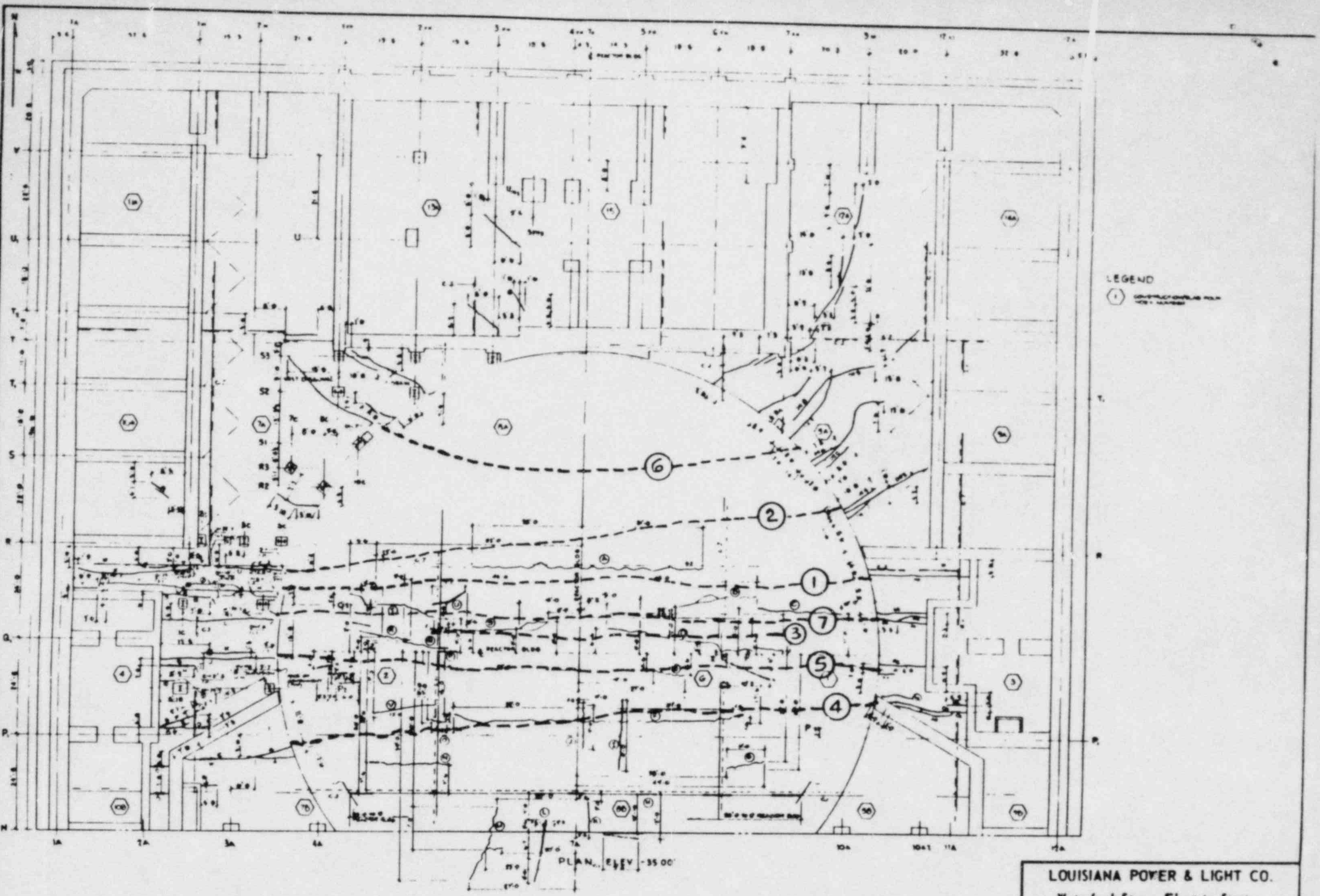
$A_1 = 6 \times 8.5 = 51\ in^2$

$\beta = \frac{10.5}{10.125} = 1.04$

$d_c = 4.25$ in

$\omega = 5$ mils (crack width)

$f_s = 10{,}500$ psi $= 10.5$ ksi



LOUISIANA POWER & LIGHT CO.
Waterford Steam Electric Station

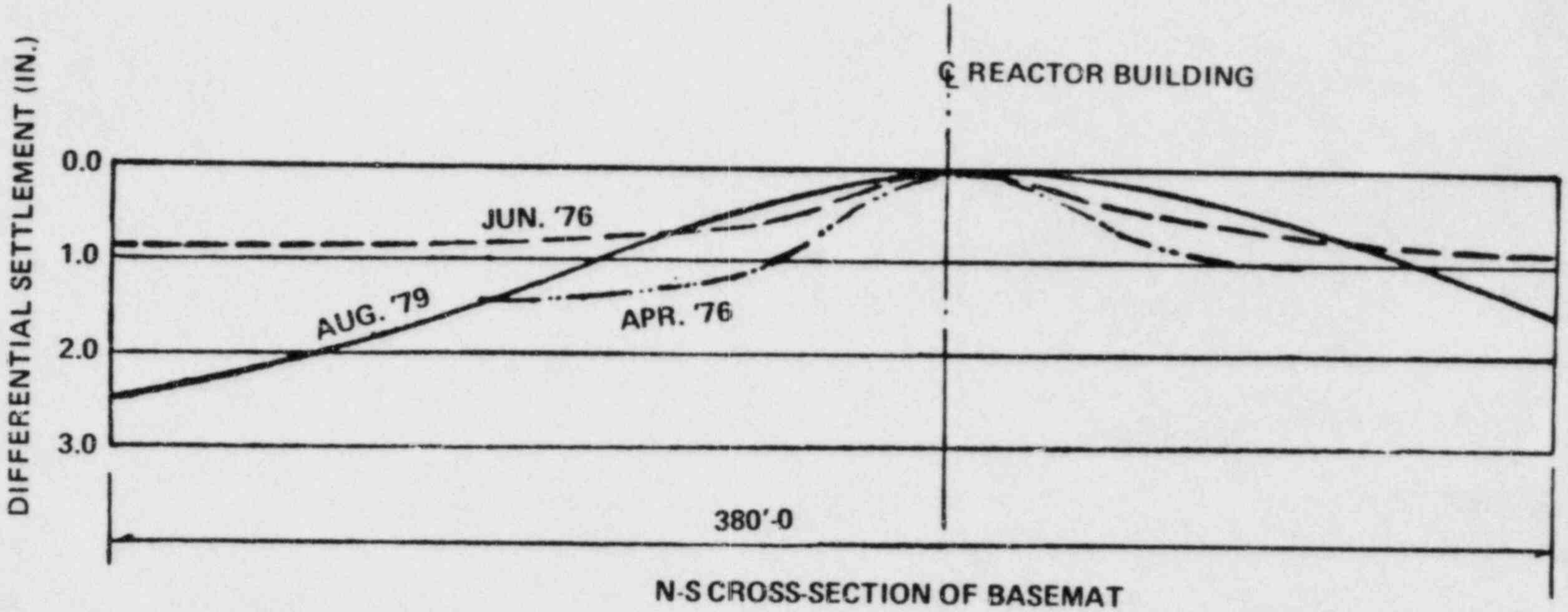
BASE MAT
CRACK MAP

FIGURE 1

LOUISIANA
POWER & LIGHT CO.
Waterford Steam
Electric Station

BASEMAT CURVATURE

Figure
2



NOTES:

VERTICAL EXAGGERATION = 300

DIFFERENTIAL SETTLEMENT IS FROM DAY OF PLACING AND INCLUDES SETTLEMENTS AT VERY EARLY AGES OF EACH CONCRETE PLACEMENT