CEN-360(V)

Structural and Seismic Evaluation of Palo Verde Charging Pump Block

Prepared for
Arizona Public Service Company

June 1987

Prepared by
C-E Power Systems
Combustion Engineering, Inc.

HDF(SALMS1)1

STRUCTURAL AND SEISMIC EVALUATION OF PALO VERDE

CHARGING PUMP BLOCK

Prepared for

ARIZONA PUBLIC SERVICE COMPANY

JUNE 1987

Prepared by

C-E Power Systems

Combustion Engineering, Inc.

EXECUTIVE SUMMARY

Combustion Engineering has performed an engineering evaluation to justify continued operation of a cracked charging pump block at the Palo Verde Nuclear Power plant. The evaluation consisted of a review of previous C-E failure analyses of similar pump blocks, a detailed fracture mechanics analysis of the Palo Verde block and a seismic evaluation. With the results of the study as a basis, C-E has concluded that a clamp and continued leakage monitoring will allow the use of this pump as an operable pump and will retard further crack propagation. This report is not intended to fully address the Arizona Nuclear Power Project Palo Verde Unit 2 licensing commitment concerning gas binding of charging pumps; a separate testing and analytical program is currently underway to address those concerns.

The results of this analysis indicate that the implementation of a clamping device will preclude further crack growth during normal pump operation. The planned leakage monitoring system will demonstrate that the crack has not reached the pump surface as long as no leakage is observed. During off design conditions, such as gas binding, larger than normal pressure peaks may occur within the pump block for short periods of time. During these conditions the crack may grow, depending on the magnitude and duration of the pressure loadings, but catastrophic failure of the block will not occur. Once the pump returns to normal operation, however, the clamping device will once again close the crack, prevent further growth, and minimize leakage, and the pump will continue to provide the required flow. The leakage monitoring system will be a reliable indicator of any crack growth to the pump block surface. The design loading requirements of the clamp have been established in this study. The planned leakage monitoring system forms the basis for ensuring the effectiveness of the clamp and for permitting continued pump operation.

The seismic evaluation of the charging pump at the Palo Verde Nuclear Power Plant demonstrates that incorporating a block clamping device does not affect the original seismic qualifications of the pump. The modified pump satisfies the Palo Verde seismic loading criteria and the pump and clamping device are acceptable since they will perform their intended functions during and after a seismic event.

TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this report is to:

a. Document the structural and seismic integrity of the Palo Verde charging pump block, with a clamping device utilized to retard crack propagation.

b. Define clamp force requirements to retard crack extension and limit leakage.

c. Justify, for both normal and off design (gas binding) operating conditions, continued declaration of pump operability with the clamp installed and with continued leakage monitoring.

A summary of results and conclusions are presented in Section 2.0 of this report. Detailed analyses and evaluation are presented in Sections 3.0. and 4.0.

1.2 BACKGROUND

The charging pump block (fluid cylinder) of the Palo Verde Unit 1A pump was found to have a crack during an inspection of the pump. This crack in the cylinder bore did not reach the surface of the pump block. C-E was contracted to evaluate the effect of a clamping device on future pump availability and structural integrity under both normal and off-design (gas binding) operating conditions. This analysis was performed to determine the potential for crack growth and to evaluate the structural integrity of a clamped block. The intent of the analysis is to justify declaration of pump operability with a clamped block as an interim measure, since replacement charging pump blocks are not available in the near term. A sketch of the pump block and the reported crack location is presented in Figure 1.

2.0 SUMMARY OF RESULTS AND RECOMMENDATIONS

2.1 SUMMARY OF RESULTS

The principal results of the analysis of the Palo Verde block, as well as prior analyses, are summarized as follows.

1. The present crack is likely to propagate with continued pump use under normal operating conditions if no modifications (i.e., clamping device) are implemented.

2. Continued pump usage could lead to leakage if the pump maintained normal operation pressure and a clamp is not applied.

3. Crack growth is inhibited by the use of a clamp which exerts a compressive force across the face of the crack. The force required to be exerted by the clamp is determined to be 80,000 lbs. The effectiveness of the clamp can be demonstrated by continued leakage monitoring.

4. Leakage monitoring at regular intervals is a meaningful method of determining the existence of crack growth and pump leakage.

5. During an off design operating condition such as gas binding, higher than normal internal pressures may result in crack growth. The clamping device will retard this growth and will close the crack once the pump returns to normal operation. Gross structural failure of the block will not occur, and the pump will continue to deliver the required flow when normal operating conditions resume. The leakage monitoring system will permit confirmation of pump operability and the acceptability of leakage rates during all pump operating conditions. A leakage rate of 0.1 gpm is defined as the acceptance limit for pump operability. This rate is well within the technical specification limit.

6. Seismic stress levels of the modified pump are acceptable. For the pump mounting bolts and base legs as well as the sub-base, tensile and shear stresses are below the corresponding allowables.

2.2 RECOMMENDATIONS

1. A clamping device to inhibit crack growth should be installed to allow declaration of pump operability.

2. The affected pump may be used without restriction once the clamping device is installed, as long as the leakage rate is monitored. A zero leakage rate indicates no significant crack growth is occurring. If crack growth and leakage does occur, a maximum permissible leak rate of 0.1 gpm is allowed for continued declaration of pump operability. There are no adverse safety implications with the use of this pump as long as the recommended leakage rate guidelines are implemented.

3. The pump leakage rate and the total time of operation should be monitored and recorded. Leakage monitoring will be capable of detecting a 0.1 gpm leak rate within one hour.

3.0 DETAILED STRUCTURAL ANALYSIS AND EVALUATION

In order to confirm the effectiveness of the clamping device in retarding further crack growth, a three dimensional finite element structural analysis of the charging pump block has been performed. In this analysis, a conservatively large estimate of the existing crack has been used as the basis for the crack growth evaluation. For a given internal pressure loading, the crack opening deformations have been calculated. It is assumed for the purposes of this evaluation that if the crack opens, crack growth will occur. A detailed fracture mechanics analysis has therefore not been performed.

The analysis is performed using a compressive clamping force at the surface of the block, and the crack closing deformations are calculated. The clamp force necessary to maintain crack closure is determined by comparing the crack opening deformation due to internal pressure with the closing deformation due to the compressive clamping force. As long as the crack remains closed, the crack will not grow. This approach is quite conservative due to two assumptions. The first assumption is that the existing crack is large and extends to the block surface. This assumption maximizes the crack opening deformation prediction.

The second assumption used in this evaluation is to consider any net crack opening deformation to result in significant crack growth. In any case where the crack opening deformations due to internal pressure exceed the crack closing deformation due to the clamping force, therefore, significant crack growth is assumed to occur.

3.1 FINITE ELEMENT MODEL DEVELOPMENT

A detailed three dimensional finite element model of the cracked pump block has been developed using the C-E MARC computer program to permit an accurate determination of the stress field in the block, the crack opening deformation, and the distortion in the various machined bores. The finite element model, as developed with the PATRAN modeling program, is shown in Figure 2. This model has been verified by comparison of results to those obtained in similar models developed for charging pumps at other plants. The model consists of 256 elements and 1735 nodal points. One quarter of the block, as shown in Figure 1, is modeled for convenience.

The reported crack is characterized in Figure 1. The crack is in the center bore, at the 6 O' clock position (viewed from the front, plunger cap side). It apparently originated at the intersection of the valve and plunger bores, as would be typical of block cracks, and travelled toward the front of the block. The crack does not, however, extend to the front surface of the block and has not as yet resulted in leakage during operation.

The assumption of crack geometry and area is very important for the case where bore pressure is assumed to act on the crack surface (i.e., the crack is open to bore pressure), and is also important for determining the clamp force required to keep the crack closed when pressure acts only on either the bore or both the bore and the crack surface. The crack geometry assumed was basically a trapezoid (approximating a rectangle) starting from the intersection of the critical bores (a typical crack origination point), travelling forward through the plunger bore (4 inches) to the front external surface of the block, and down the front surface approximately 2 3/4" (at the 6 o'clock position; in reality, the reported crack does not extend to the front surface). In the valve bore, the assumed crack starts from the intersection of the critical bores, down the valve bore approximately 2 inches, and forward to the front face. The assumed crack surface is indicated on Figure 2. The total assumed crack area is 9.7 square inches.

It is likely that the actual crack is one third to one half of the assumed area, since the reported crack does not extend to the front surface of the block. This large crack size assumption results in a very conservative analysis because the analytical prediction is strongly slanted towards crack extension as a result of the assumed crack size.

3.2 ANALYSIS CASES WITH INTERNAL PRESSURE

These analyses have been performed as unit loading cases for both the internal pressure loadings and the clamping force loadings. The analyses are elastic and the stress and deformation results can therefore be scaled for various pressure loadings and clamping forces. These cases can also be considered by superimposing the pressure loading and clamp force cases for a net result.

In the initial analysis, a unit pressure of 1000 psi was applied to both the center bore and the assumed crack surface to maximize the tendency for crack opening. The crack opening deformations are calculated by averaging the deformation of the elements shown in Figure 2. The stress distribution for this unit loading case is shown in Figure 3. This figure demonstrates that the maximum stresses occur at the crack tip and provide a confirmation that the analytical model is accurately representing the block behavior for the assumed loading case. The average crack opening deformation for this loading case scaled to an internal pressure of 2500 psi (i.e., normal operating pressure) is 6.727×10^{-4} inches.

A second internal pressure loading analysis has also been performed to model the pump configuration where the clamping device closes the crack so that internal pressure does not act on the crack surface. In this case, the pressure loading is applied to the surface of the center bore only, and the resulting stresses and crack opening deformations are determined. The stress distribution for this unit loading case is shown in Figure 4. The average crack opening deformation for this loading case scaled to an internal pressure of 2500 psi is 3.157×10^{-4} inches.

3.3 ANALYSIS CASES WITH CLAMP FORCE

A unit clamp force of 1,500 lbs. was then applied on the outer surface of the block at the same elevation as the assumed crack tip as shown in Figure 5. The force was distributed over a circular area and appears as the bullseye in Figure 5. The effect of crack closure is demonstrated by the deformation of the block due to the clamp force shown in Figure 6. This case considered an open crack with the clamp force directed toward closure of the crack.

As in the previous analyses, a unit loading is applied and the stress and deformation results can be scaled for any desired clamp force. For this clamping analysis, the distortion of the piston bores is also determined to evaluate the potential for excessive distortion which could interfere with piston movement.

3.4 LOAD COMBINATIONS

The determination of the clamping force that is required to retard further crack growth and to minimize block leakage is performed by combining and superimposing the unit loading analyses.

Case 1:
Crack opening displacements for the conservative internal loading model where the internal pressure is acting on both the cylinder bore and crack face is determined by scaling the unit load analysis up to 2500 psi pressure. The crack opening displacement for this case is 6.727×10^{-4} inches.

The clamp force required to completely close this crack opening is determined by scaling the unit clamping case up to the same average displacement. This clamping force is 110,000 lbs. Note that this is a conservative, bounding case because the crack opening model considered a large initial crack with full pressure acting on the crack face.

Case 2:
When the clamp is installed, the crack will be closed during normal pump operation and the internal pressure will act only on the cylinder bore surface, and not on the crack surface. For this situation, the crack opening displacements have been determined by pressurizing the bore of an unclamped block to 2500 psi pressure. The crack opening displacement for this case is 3.157×10^{-4} inches, or only 47% of the conservative loading assumption of case 1. The clamp force required to completely close this crack opening is 51,500 lbs, which is also 47% of the case 1 closing force.

Based on these two cases, a design clamping force of 80,000 lbs is recommended for actual pump operation. This force provides some margin for pressure surges and to accommodate some pressure acting on the crack surface. The distortion of the machined surfaces due to this force is very slight, indicating that no detrimental effect on pump performance will result.

3.5 OPERATION WITH GREATER THAN DESIGN PRESSURE

The preceding analysis conservatively demonstrates the adequacy of the cracked charging pump block under normal design operating pressure with the clamping device installed. There is, however, reason to believe that abnormal plant conditions do occur, such as a gas ingestion (or binding) event, which result in internal pump pressure spikes in excess of design pressure. A separate testing and analytical program is currently underway to quantify the magnitude of internal pressure spikes during a gas binding event. However, there is some limited test data to suggest that peak internal pressures may be about 7,000 psi for a relatively short period of time (e.g., minutes) during gas ingestion, prior to the pump cylinder becoming gas bound. Once the pump becomes gas bound, the data shows that pressure peaks are reduced (i.e., due to the compressibility of the gas).

Other analyses of similar charging pump blocks have shown that block failure (i.e., initiated by cracks originating at the intersection of critical bores) is a result of cumulative fatigue failure. Once a crack has initiated, it will propagate if unrestrained. The results of fatigue crack growth studies on similar blocks show that the fatigue crack growth rate for a preexisting unrestrained crack can result in unacceptable leakage in tens of hours under high internal pressures. For conservatism, this evaluation has considered peak internal pressures up to 10,000 psi. A catastrophic failure of the block will not occur even under these conditions.

The planned clamping device may not prevent crack growth under internal pressures significantly greater than normal design operating pressure (i.e., 2,500 psi). Such high pressures, however, are anticipated to occur only for short time periods. Once the pump pressures return to normal, the clamp will once again close the crack and minimize pump leakage. By maintaining leakage below the recommended limit, the pump will continue to perform adequately during normal operation. Leakage may, however, become unacceptable after pump restart following a gas binding event, requiring pump shutdown and isolation. The leakage monitoring limits defined below will provide an effective method for tracking pump leakage and assuring pump operability for all loading conditions.

3.6 LEAKAGE MONITORING

A leak rate calculation has been performed by correlating the crack size versus leakage rate for past charging pump data at other plants and by considering pipe break versus leak data from previous C-E testing and literature searches. These correlations have agreed with field data for previously evaluated charging pump cracks.

The crack size assumed for predicting leakage rates is based on an unclamped block having a through wall crack with pressure acting on both the bore surface and the crack surface. For this case, a leakage rate of 0.1 to 0.2 gpm would be anticipated. Leakage rates above this amount would indicate a crack size that is larger than assumed and would indicate the potential for rapid crack and leakage rate increases. Once again, a conservative approach is utilized. For this leakage rate calculation, the block clamp is ignored and further crack growth is therefore more likely to be predicted analytically than would occur in the field. A leakage rate limit of 0.1 gpm will be utilized for this pump as the cut-off point for pump operability. This leakage limit will assure that the pump will be removed from service well before excessive leakage can occur.

Continued leakage monitoring is key to continued declaration of pump operability for both normal and off-design (e.g., gas binding) operating conditions. The specified clamping force is sufficient to prevent crack growth under normal operating conditions. The crack may, however, grow to the point that leakage exceeds the recommended limit if pump operation were to continue for many hours during a gas binding event (note that such continued operation is improbable). Therefore, for added conservatism, the leakage monitoring system will be designed to be capable of detecting the maximum permissible leak rate within one hour. A catastrophic failure of the block will not occur.

In summary, this evaluation demonstrates that, with continued leakage monitoring, the clamped cracked charging pump block is structurally adequate for both normal and off-design operating conditions. Furthermore, the pump performance will remain adequate and the pump will continue to deliver the required flow during normal operating conditions, even subsequent to a gas binding event.

Conservatisms inherent in this evaluation include the following:

1. Conservatively large assumed crack area, exacerbating pressure forces acting on the crack and crack opening deformation prediction.
2. Conservative assumption that any net crack opening deformation will result in significant crack growth.
3. Required clamping force includes some margin for pressure surges and to accommodate some pressure acting on the crack surface.
4. Maximum permissible leakage rate takes no credit for the block clamp, which would actually minimize crack growth.
5. Maximum leakage detection time at least an order of magnitude less than that which would be expected to result in unacceptable leakage, even under off-design (gas binding) conditions.

This evaluation justifies continued declaration of pump operability for an indefinite period of time. It is intended, however, to use this pump only as an interim measure.

4.0 DETAILED SEISMIC ANALYSIS

4.1 METHOD OF ANALYSIS AND RESULTS

The original charging pump seismic analysis was reviewed and critical stress locations for the pump assembly were identified. This procedure was then employed for the clamped pump assembly to calculate the required stresses associated with horizontal and vertical seismic loads. The calculated stresses in the pump mounting bolts and base legs, as well as in the sub-base mounting bolts and beam weld, are all below the corresponding allowable values and, therefore, the seismic stress levels of the modified pump are acceptable.

5.0 REFERENCES

1. C-E MARC, Version 1, CYCLE 16; Based on MARC-CDC "Non Linear Finite Element Analysis Program," Rev. H, 1976, Control Data Corp., Minneapolis, MN.

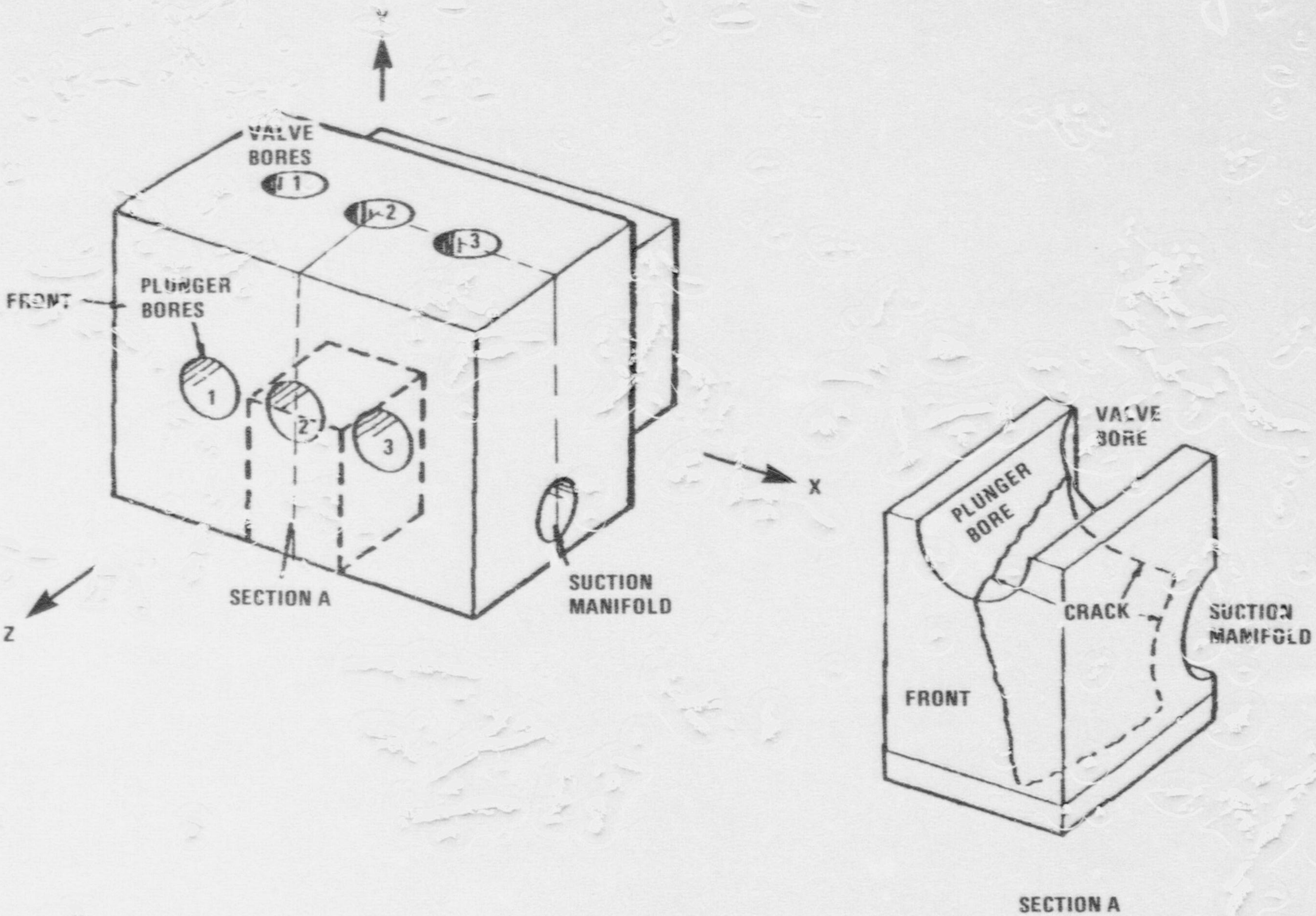

FIGURE 1
CHARGING BLOCK GEOMETRY

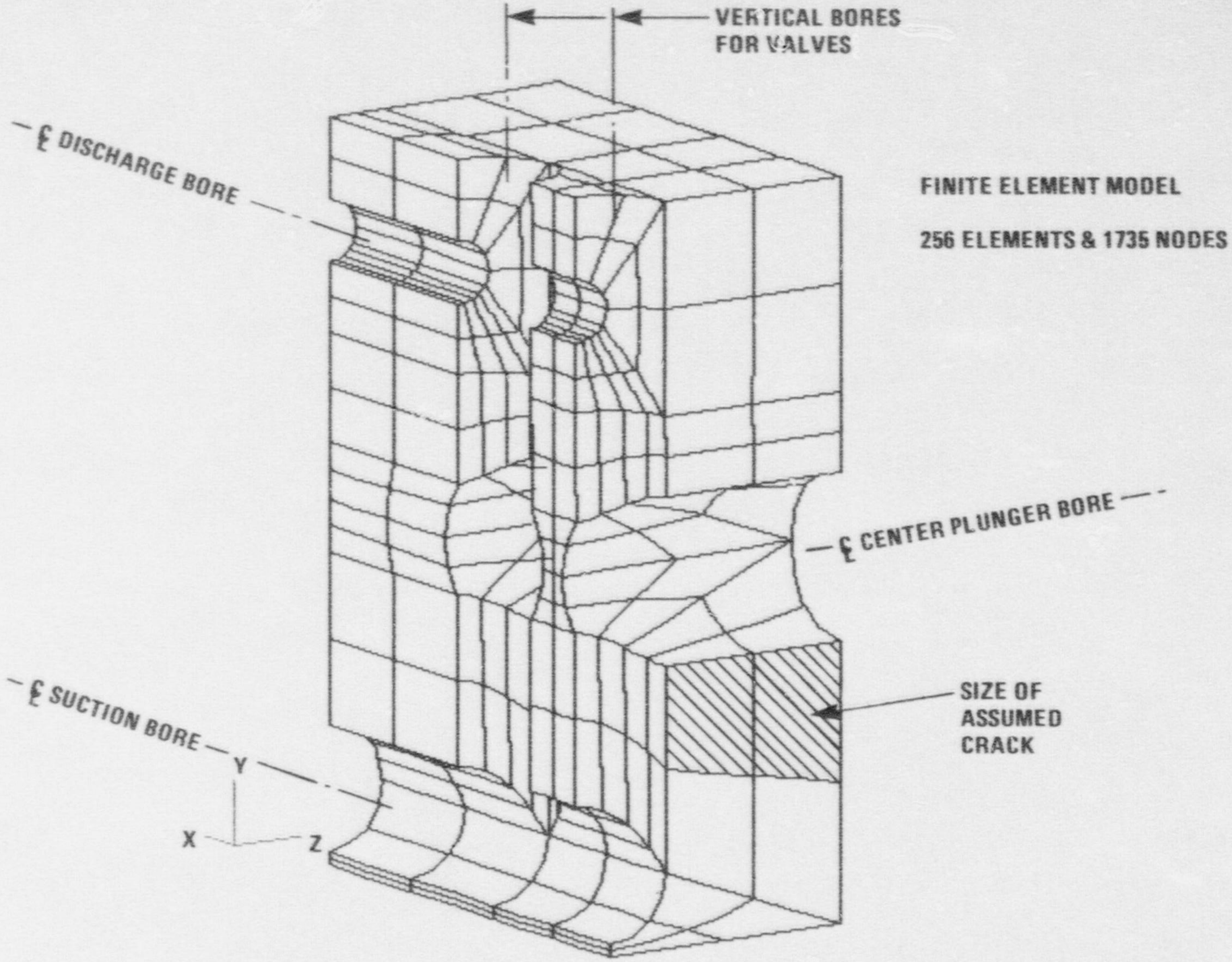

FIGURE 2
FINITE ELEMENT MODEL OF
ONE-QUARTER OF THE CHARGING BLOCK

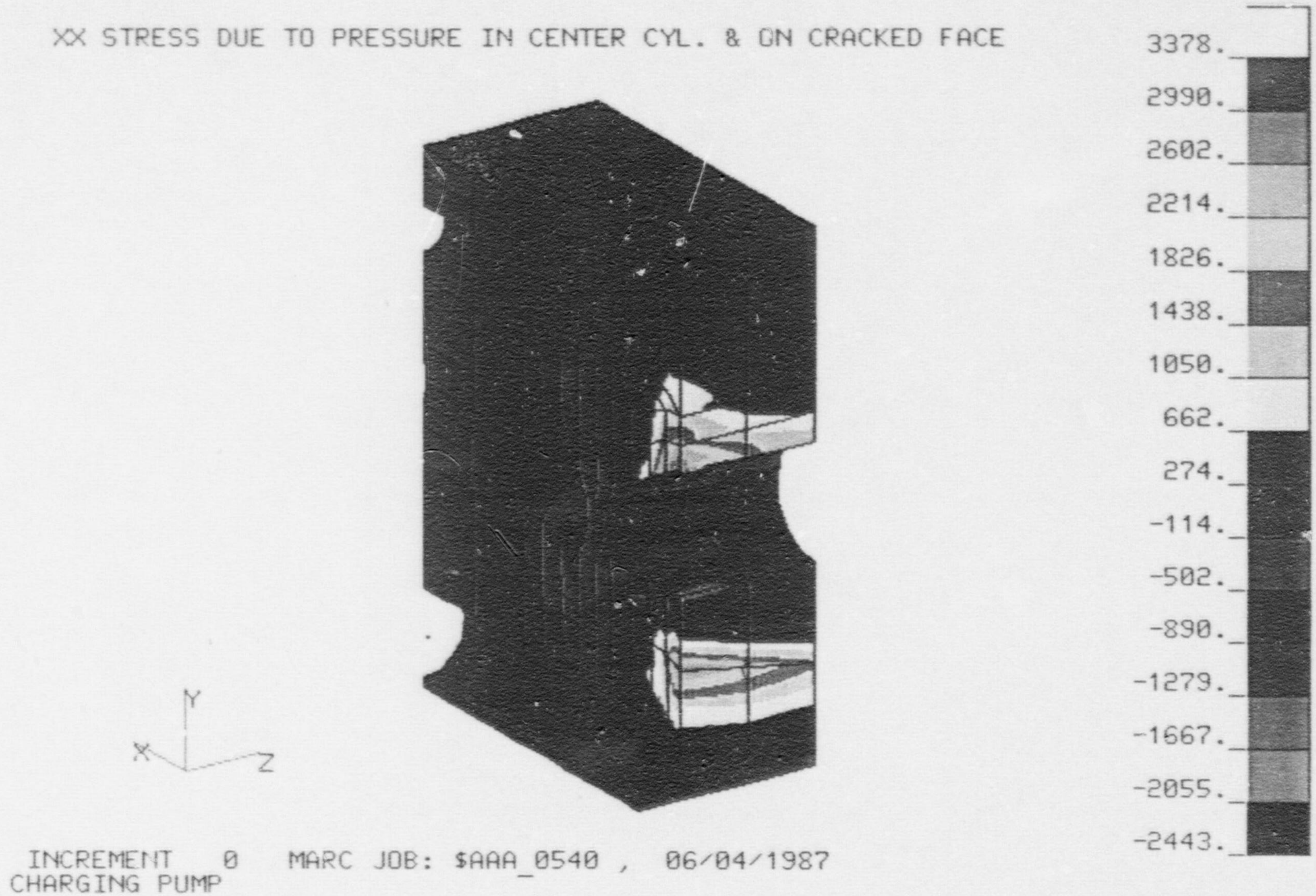

FIGURE 3
STRESS CONTOURS RESULTING FROM PRESSURE
IN THE CENTER CYLINDER AND ON THE CRACKED FACE

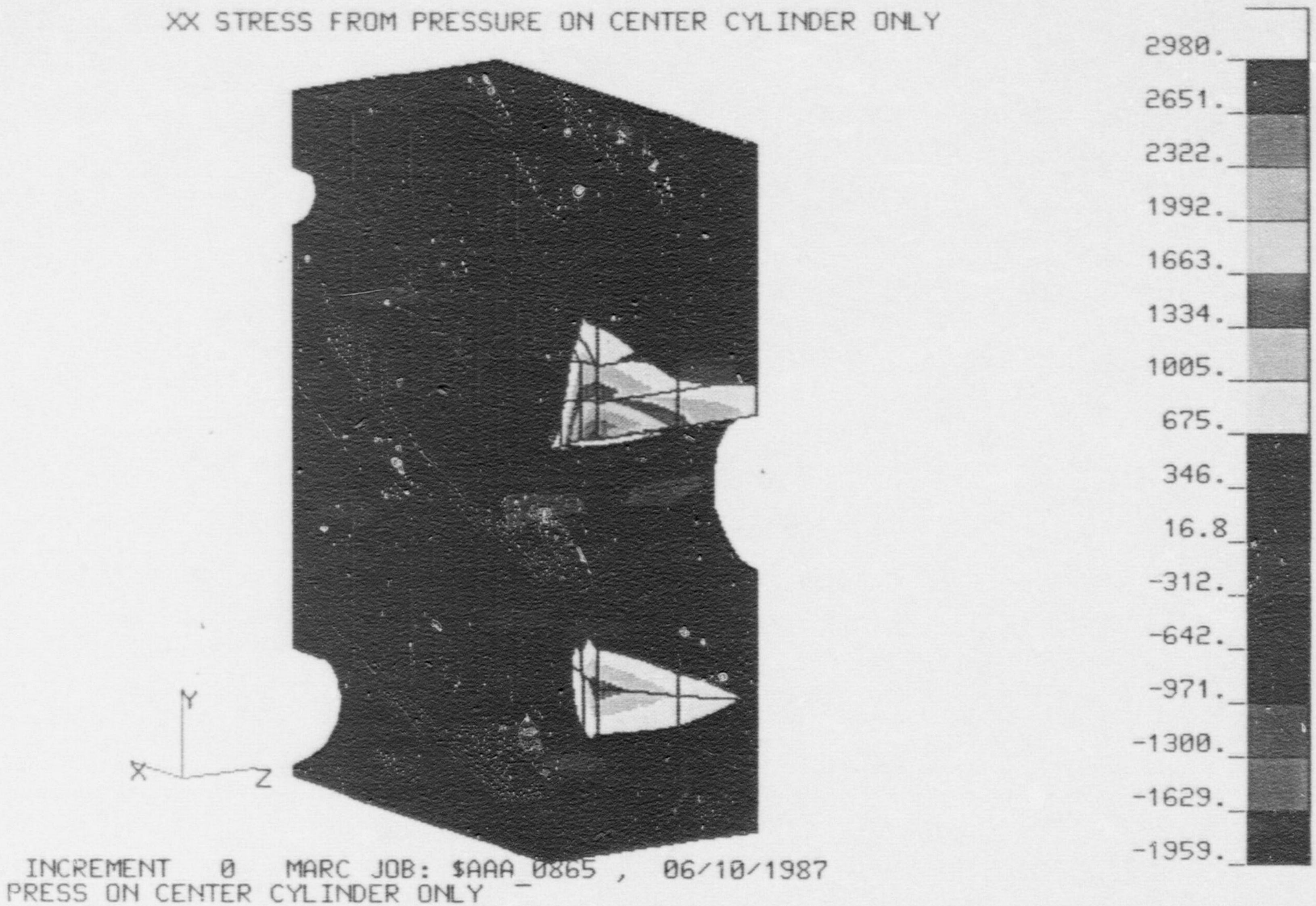

FIGURE 4
STRESS CONTOURS RESULTING FROM PRESSURE
IN THE CENTER CYLINDER

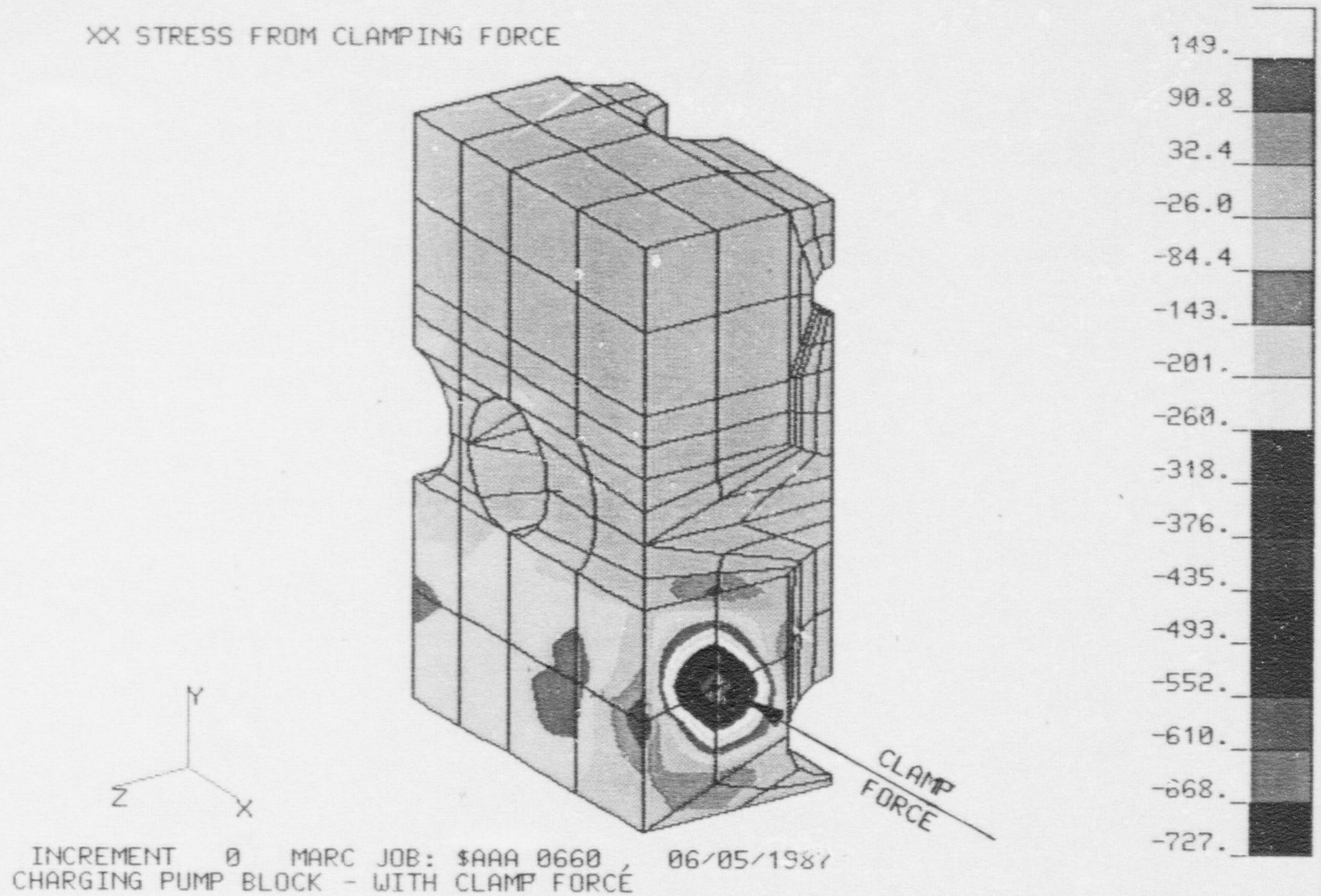

FIGURE 5
STRESS CONTOURS RESULTING FROM THE CLAMPING FORCE

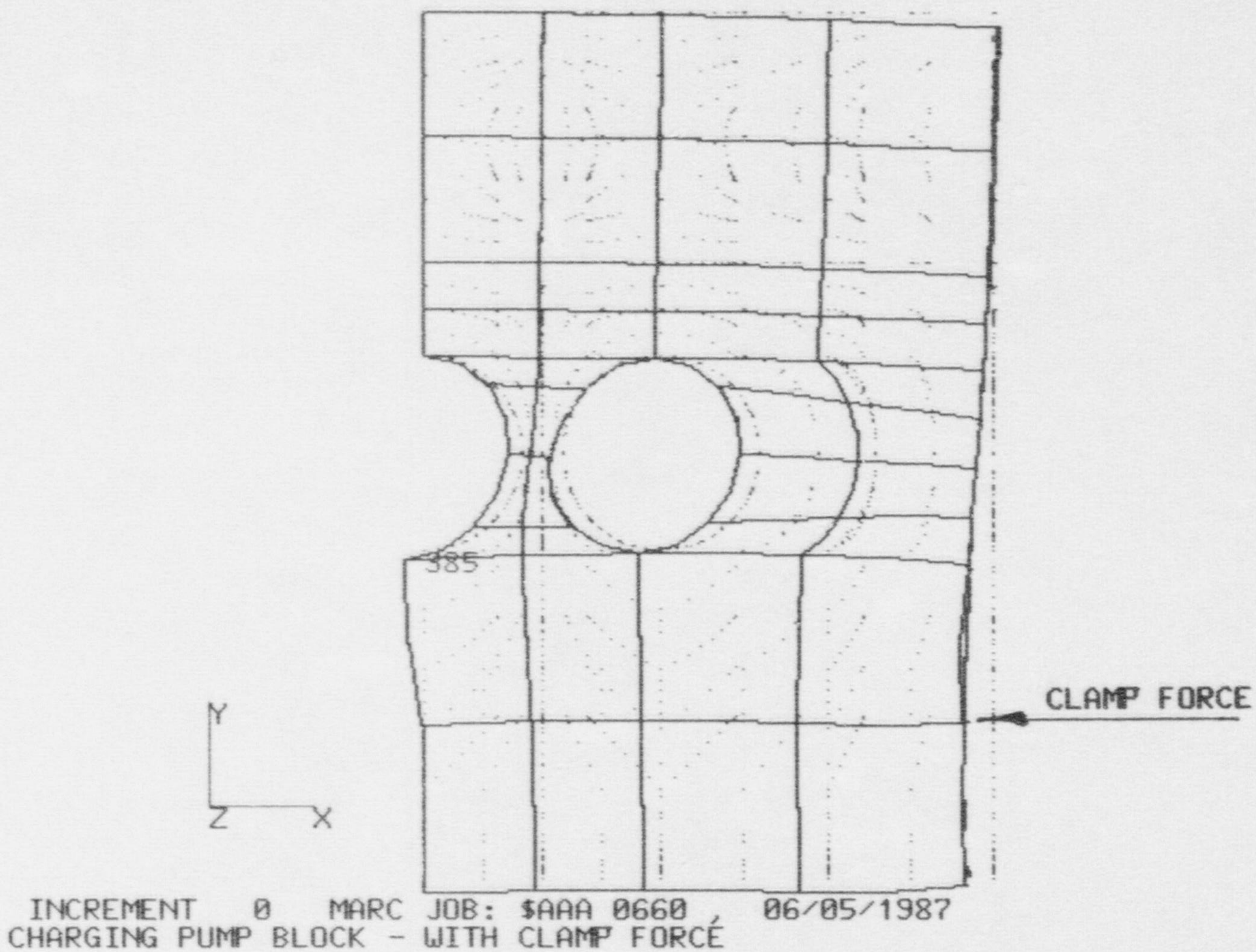

FIGURE 6
DISPLACEMENTS RESULTING FROM THE CLAMPING FORCE