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TITLE: DESIGN AND ANALYSIS OF A STRUCTURAL SYSTEM FOR ZTH

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DESIGN AND ANALYSIS OF A STRUCTURAL SYSTEM FOR ZTH*

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ABSTRACT

A structural support system comprised largely of laminated epoxy fiberglass bulkheads has been designed for the ZTH air core machine, the initial experiment in the Confinement Physics Research Facility (CPRF) at LANL. Fiberglass was chosen to minimize magnetic field errors due to eddy currents.

Magnetic fields for ZTH are produced, in part, by 18 poloidal field (PF) coils. Sixteen, equally spaced, 4 inch thick, radial G-10 bulkheads, positioned and held by a series of stainless steel ring beams, support the PF coils and the toroidal front end assembly. PF coils transfix and are supported by the bulkheads at locations dictated by magnetic field effects.

The toroidal front end is mounted to the bulkheads by a spline ensuring constant alignment with the coil set while allowing differential expansion.

The entire machine assembly is mounted on a central concrete cylinder with outboard stainless steel columns.

Finite element analyses were performed as an integral part of the design process for the ZTH structure. Because of irregular shapes, multiple materials, different load cases and numerous geometric discontinuities conventional analyses of the structure could not be performed. Static and dynamic coil loads were applied to a model of the prototype support system to examine structural response. A discussion of the model, assumptions, load cases, boundary conditions, and results is given. Influence of the results on the design are presented.

I. INTRODUCTION

ZTH is a large, (up to 4MA) toroidal, reversed field z-pinch, air core machine that will be the initial experiment in the Confinement Physics Research Facility at LANL. Structure for the machine, Fig. 1, utilizes a laminated epoxy fiberglass bulkhead concept to support the large coil magnetic forces present during operation, while allowing accurate alignment of machine components and providing good diagnostic access. An integrated design and analysis approach has been used to produce an effective structure for the experiment.

II. DESIGN

Coil configuration and coil forces were of paramount importance in selecting a concept and designing a structure to support the ZTH experiment. The 18 poloidal field (PF) coils comprised of 10 magnetizing and 8 equilibrium coils are arranged in a horizontal array adjacent to the torus as shown in Fig. 2. Forty-eight toroidal field coils are mounted on the torus or "front end".

Minimum magnetic field errors due to eddy currents were an important design objective for ZTH. Fiberglass reinforced epoxy is a material that obviates these effects; it was therefore chosen for major structural support members.

The machine structural concept is based on supporting the critical components comprised principally ...

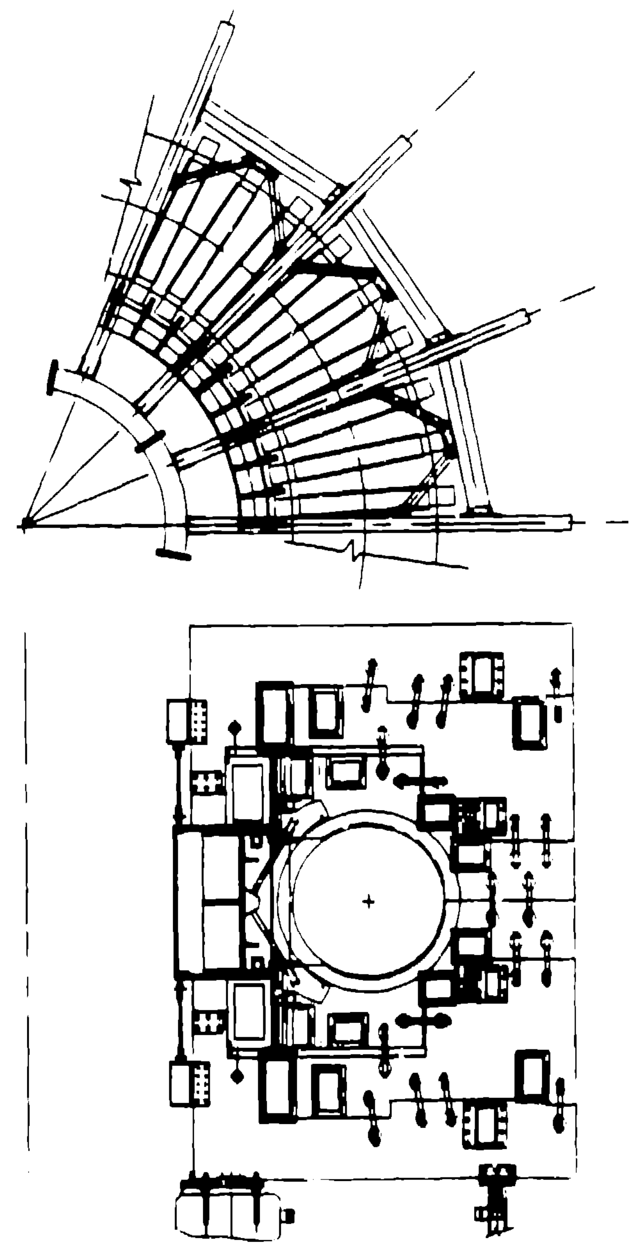

Fig. 1. ZTH Structure

cision construction. Also the structure is to accurately maintain the relative location of the critical components during cyclic operation of the experiment. This necessarily includes thermal expansion effects that are present. The concept must deal with very large internal operating loads while ...

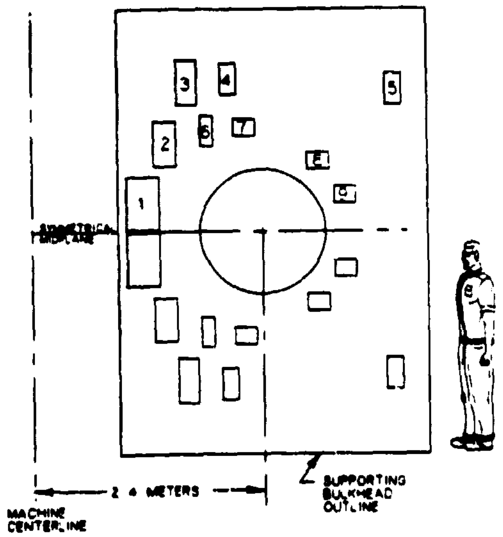

Fig. 2. Coil Configuration

pensive, easily machined, high strength, non-magnetic materials preferably with low t'ermal neutron capture cross sections and short half life isotopes.

An adopted design criteria for the ZTH structure is that the PF coils will support their own individual hoop (circumferential) loading. This is modified by the practical consideration that there will be some friction between a coil and its supporting structure. (A coefficient of 0.1 is an objective for the design.)

The remaining component of the PF coil forces are in the vertical direction; Fig. 3 shows the vertical load histories for the coils. Fortunately these very large forces are symmetric about the machine midplane and can be reacted against their symmetric twin. Sixteen vertical fiberglass reinforced epoxy bulkhead assemblies radiating from the machine vertical centerline have been selected to do this. The very highly loaded coils 1, 2, and 3 are provided continuous support in the vertical direction.

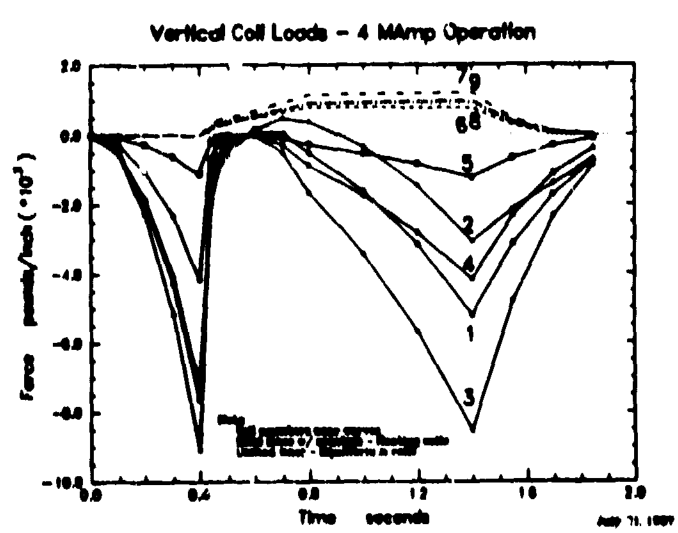

Fig. 3. Vertical PF Coil Forces

Structure to support the machine weight, estimated at 350,000 pounds, is straightforward and simple. It consists of a center cylindrical concrete pier and 16 outboard columns with appropriate cross bracing. Figure 4 shows the machine base.

The 4 inch thick bulkheads are held in position by six ring beams and auxiliary diagonals. Bulkhead assemblies are segmented into six sections to allow for coil placement and assembly/disassembly operations. A plan view, Fig. 5, shows the bulkhead sections, PF coil locations, coil clamps, ring beams, trim coils, and bulkhead fasteners. Also shown between coil 1 and the front end is a stainless steel box assembly that provides continuous support for coils 2 and 3. In addition, the box, with connecting plates to the interior of the machine, provides an assembly fixture for the no. 1 coil pair. Not shown, but part of the bulkhead assembly, are PF coil leads which will be mounted on standoffs from the bulkheads at 90 deg. circumferentially around the machine.

Seams between the bulkhead sections will be closed by multiple pairs of preloaded bolts that connect large diameter through pins located on both sides of the seam. Provision is being made for seam stiffeners to insure against localized buckling.

Pads located at the top and bottom of the central cut-out in the bulkhead assemblies will support the front end. The front end will be mounted to the bulkheads by a spline arrangement allowing differential radial motion without transmission of forces other than gravity loads to the bulkheads. This will be done by mating the front end to each bulkhead assembly with two vertical pins or keys. One key will be on top of the torus, the other, with the same vertical axis, on the bottom. The keys will slide in radial slots of a pad. The bottom pad assembly, shimmed to the correct vertical position, will have a sliding contact surface that will bear the weight of the front end. The top assembly will be positioned with small clearances to prevent any upward motion of the torus. The circumfer-

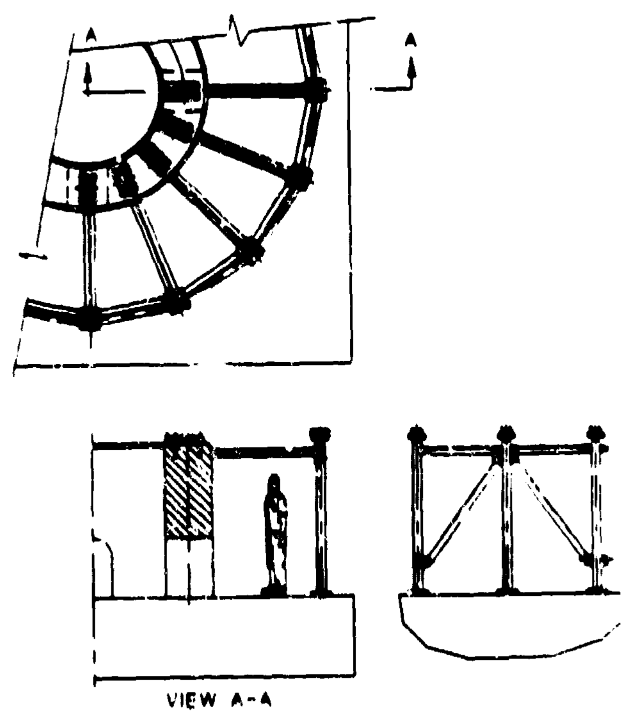

Fig. 4. Machine Base

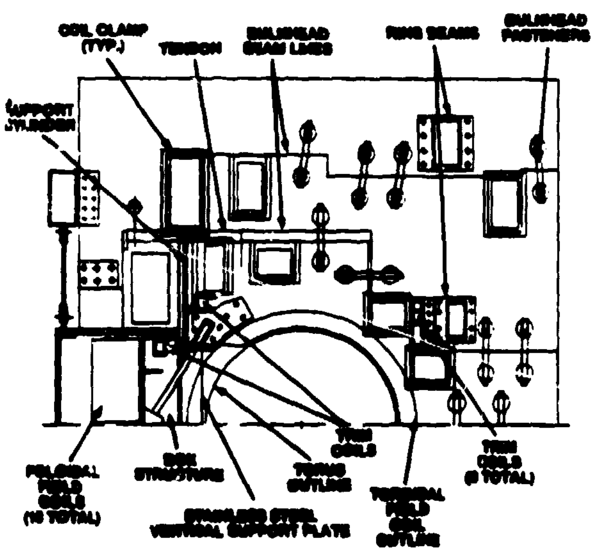

Fig. 5. Bulkhead Detail

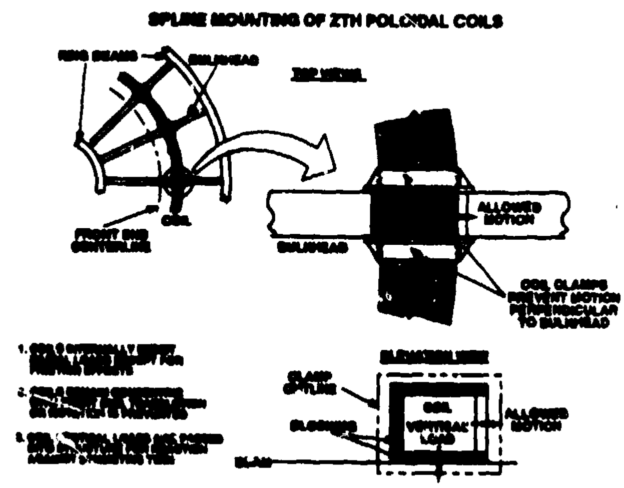

Fig. 6. Coil Mounting

ential location of the support pads on the bulkhead will be adjustable and lockable because the front end assembly will be a considerably more precise structure than the bulkhead system that supports it. This will allow quick mounting of the front end on the structure. The front end shell will internally resist liner vacuum loads and toroidal field coil forces.

ZTH will use 3 or 4 reference optical positions to precisely locate individual field coils as the machine is built. Positions will be verified by magnetic measurements. Coils will be held in position by blocking, in the vertical and radial directions, at the points where they transfix the bulkheads. In the case of the radial direction, coil restraint will be only on the inside of the coil. Coils will be kept in alignment by 32 clamps on each coil as shown on Fig. 6. Clamps will abut both sides of each bulkhead and allow only radial motion, i.e., the coils will be splined to the bulkheads. This will also ensure constant concentricity of the coils with the front end. Modest deviation of the bulkheads from their theoretical true radial positions will not be critical because coil and front end positioning and alignment are insensitive to this.

Machine construction will start with the center pier which is constructed from concrete and fiberglass reinforced rebar. Bearing plates for each of the 16 bulkheads are precisely located atop the pier by means of a jigging ring. The plates, with ring attached, are leveled by nuts on tie bolts which have been emplaced in the concrete. After grouting beneath the plates, the plates are securely bolted down and the jigging ring is removed.

With the outboard columns of the machine base in place the bottom course of bulkhead sections are erected. An adjustable head on the columns allows leveling of the 16 individual bottom bulkhead pieces. With a modicum of care this method will easily allow the bottom course of bulkhead sections to be set level within .030", thus ensuring an accurate base upon which to construct the balance of the machine.

III. ANALYSIS

The CPRF/ZT-H machine is a complex structure with many interdependent parts. The many odd shaped components to be analyzed mandate that a numerical analysis method be used in the design process. Finite element analysis naturally lends itself to this type of problem, and is used extensively in the structural design of the CPRF/ZTH experiment.

Finite element analysis was particularly useful as a design aid for the bulkhead assembly. A disadvantage of large, complex finite element analysis is the long time necessary to perform the analysis and examine the results. A large analysis can be started and have the design change so radically that it invalidates the analysis. For the the bulkhead assembly, however, the fixed location and nature of the applied loads and other design criteria prescribed the basic shape of the bulkhead parts; the underlying precepts of the design were fixed. Analysis of a pilot design, therefore, yielded many facets of the response which could not be ascertained otherwise and provided extremely useful information for subsequent design refinements. Analysis successfully detected weak design areas that might otherwise have gone undetected.

Finite element analysis helps the design process because it reveals both qualitative and quantitative information about the structural response. The qualitative aspects of bulkhead assembly response affect the shape of the bulkhead sections, design and locations of fasteners, and expected interaction of the bulkhead with other parts of the machine. Quantitative results are used to make design decisions about highly stressed parts or those which would be expensive to design or fabricate.

Prior analyses of similar structures had assumed a static response. A dynamic analysis was decided upon, however, because of the nature of the load curve (Fig. 3) and the possibility of inertial effects in the [illegible]ge structure. Results from the dynamic analysis could then be used to identify particular combinations of coil loadings which affect the response of different regions, and to determine inertial effects. If the response did turn out to be at least quasi-static then simpler static analyses could be done in future analyses.

A. MODELING

Several assumptions were made to perform the bulkhead assembly analysis:

1. Gravity loads were ignored. Therefore the bulkhead assembly could be considered to be symmetric about the midplane.
2. The important aspects of the bulkhead assembly response could be ascertained with a two dimensional analysis in the plane of the bulkhead.
3. The response of the bulkhead would not depend on the bending response of any small/thin part. Small/thin parts were modeled with few, sometimes one, elements through the thickness which kept the number of degrees of freedom to a minimum.
4. Assembly parts would move independently, necessitating a finite element code with a large displacement formulation.
5. All materials would behave as elastic, isotropic materials. All materials are required by the design to remain elastic. The fiberglass is designed to have very low stress levels to which it should respond isotropically.

It was hoped that the above assumptions would simplify the analysis to allow the response of the bulkhead assembly over an entire load cycle, lasting 1.8 seconds, to be determined.

The finite element code PRONTO[1] was chosen for the analysis. PRONTO is a very fast, fully vectorized, explicit finite element code. It has a large displacement, or geometrically nonlinear, formulation which allows independant motion of regions and contact surfaces between regions so that forces can be transmitted across regional boundaries during contact. It has been shown to be extremely accurate on test problems; this was important because a large number of steps would be necessary for the analysis.

The bulkhead assembly can be characterized as a plate structure. PRONTO does not have a plane stress (or plate) element available. However, one of the precepts of the design and the analysis was that all materials must remain elastic. This allows a transformation[2,3] of the elastic modulus and Poisson's ratio to be used to simulate plane stress behavior with plane strain elements. The transformation changes the material parameters of materials which have a low Poisson's ratio, such as G-10 fiberglass, less than the uncertainty in the parameters themselves. So, the transformation was not used for the fiberglass parts in the bulkhead assembly. However, for materials which are well characterized and which have higher Poisson's ratios, such as stainless steel, the transformation is worthwhile. All stainless steel plate material parameters were modified to simulate plane stress. The material properties for G-10 fiberglass and stainless steel are given in Table 1.

TABLE 1

BULKHEAD ANALYSIS MATERIAL CONSTANTS

	G-10 Fiberglass	Stainless Steel
Elastic modulus	3,500 ksi	29,000 ksi
Poisson's ratio	0.15	0.30

PRONTO does not allow the use of plane strain and axisymmetric elements in the same analysis. Consequently, the radial motion of the coils had to be determined in a separate, axisymmetric, analysis and applied to the coil models in the bulkhead assembly analysis. The axisymmetric analysis of the coil motion was simple: Each coil was modeled axisymmetrically and allowed to slide radially between two rigid surfaces, the radial and vertical loads were applied, and the radial motion was determined. The ring beams also could have been modeled axisymmetrically. The ring beams constrain the bulkhead assembly to radial motion in the plane of the analysis. They also inhibit radial motion because they must stretch or contract for the bulkhead assembly to move radially. These were modeled as radial springs in the shape of the ring beam cross section.

The upper half of the bulkhead assembly was modeled with the machine midplane as a symmetry boundary (the mesh is shown in Fig. 7). The stainless steel plates and the stainless steel box subassembly at the midplane are restrained to prevent vertical motion of the bulkhead assembly. The fiberglass bulkhead section terminates at the midplane. It interacts with a rigid surface to mimic the interaction between it and its mirrored twin on the other side of the midplane. Radial motion is limited by the ring beams. The coils could conceivably limit radial motion if the bulkhead or the coils were to move far enough for the vertical contact surfaces between the coils and the bulkhead to interact.

The only load case considered in the bulkhead assembly analysis is loading generated by the coils. Vertical coil loads were applied directly to the surface of the coil as a pressure load, which traveled through the coil and was transferred to the bulkhead through the contact surface. The radial forces are generated by the coils also, by moving the vertically loaded coil over the contact surface between the coil

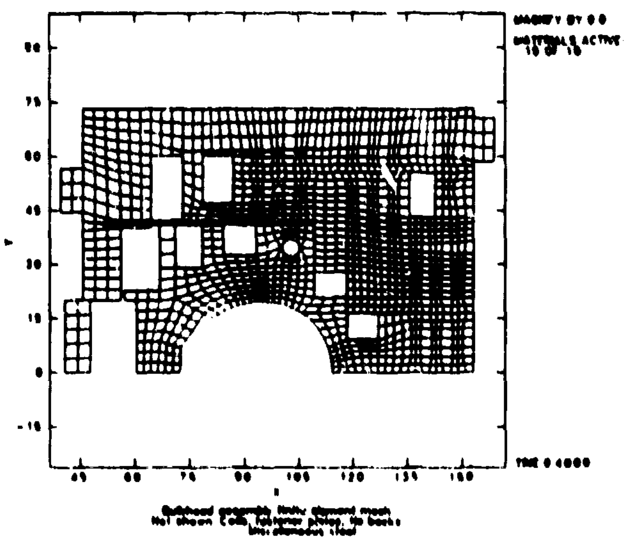

Fig. 7. Bulkhead Assembly Finite Element Mesh

and the bulkhead with the appropriate coefficient of friction.

The response of the entire assembly was saved for 181 time steps through the analysis time of 1.8 seconds. From this data base, the response of any portion of the system could be examined.

B. RESULTS

The motion of the structure was to flex down, and away from the center of the front end during the first 0.4 seconds of loading. At this time only the ohmic heating coils are operating. Although this is the load case with the highest stress, deflections are quite small (Fig. 8). After 0.4 seconds, a rapid decrease in the load results in a rebound effect that is accentuated by the equilibrium coils and coil 2 exerting loads directed away from the midplane. As the ohmic heating coils begin loading the structure toward the midplane again, the structure flexes, but less than at 0.4 seconds because the equilibrium coil loads are in opposition to the ohmic heating coil loads. This load state peaks at 1.4 seconds and then dies out quadratically. Peak von Mises stresses occur at 0.4 seconds (Fig. 9) and at 1.4 seconds (Fig. 10).

The bulkhead operates at a large factor of safety in most materials. A high factor of safety is necessary because of the degrading effects of cyclic loading. Figure 11 shows the expected factor of safety against material failure in shear in the fiberglass. Factors of safety against material failure in shear were determined by using half the Tresca stress as the shear component of the stress and comparing that to a nominal shear strength of 7,000 psi. This implies a uniaxial strength of 14,000 psi for G-10 fiberglass. The actual strength in the plane of the weave is much higher, making the safety factors conservative.

The response of most parts of the bulkhead assembly was found to be benign. The displacements of all parts and the assembly as a whole were within design limits. Fastener plates joining the bulkhead sections were shown to be lightly stressed. The highest stress by far was seen in the columnar steel plate between coil 1 and the front end (Fig. 12). Von Mises stress in the plate peaks at about 35 ksi at 0.4 seconds. The plate carries practically all the load generated by coils 2 and 3 and a significant fraction of the load generated by coil 4. Given the cyclic

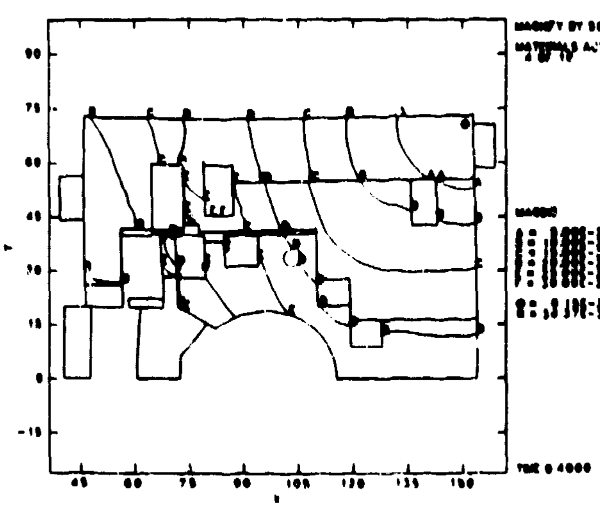

Fig. 8. Deflection Magnitudes at 0.4 seconds.

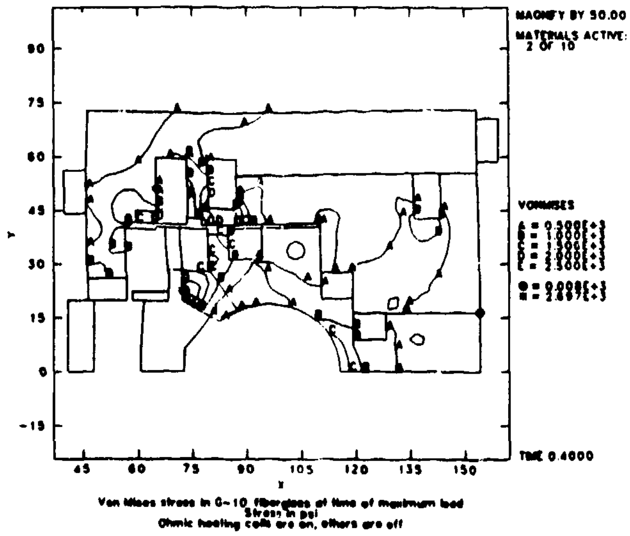

Fig. 9. Von Mises Stress at 0.4 seconds.

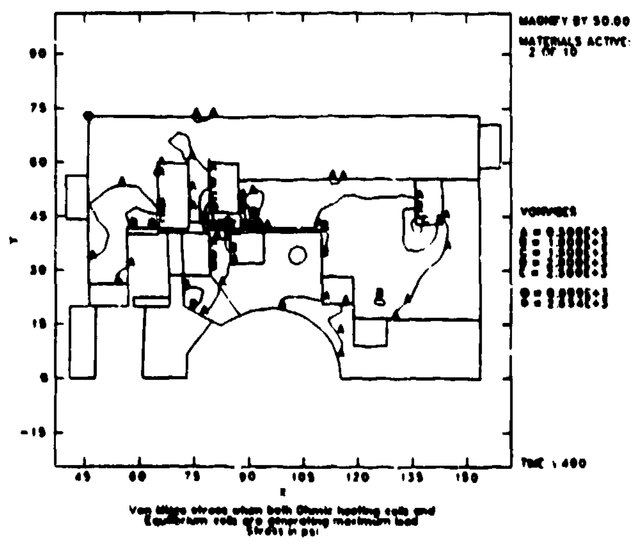

Fig. 10. Von Mises Stress at 1.4 seconds.

nature of the loads, the stress is too high for a working design. The G-10 fiberglass in the region surrounding the tendon shows the highest fiberglass stress; however, as previously mentioned, there is a huge factor of safety at the stress levels seen in this material. Response of the horizontal tendon across the top of coils 2, 6, and 7 shows high bending stresses to be present. This region is considered to be critical because close proximity of the coils allows only limited room for connecting structure.

C. DISCUSSION

Analysis has demonstrated that the bulkhead assembly considered is a generally viable design. It has shown that the coils can be supported without large deflections. The stainless steel plate near coil 1 is highly stressed. The entire region of support structure near the stainless steel plate is under tremendous loads. A redesign is indicated to lower the overall stress state given the cyclic nature of loading.

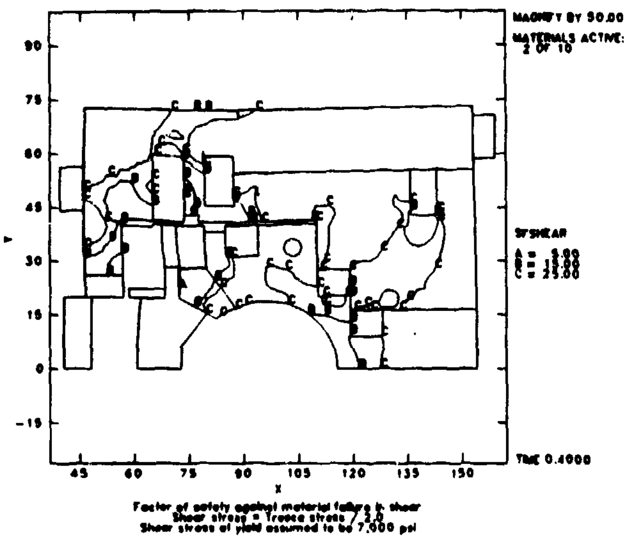

Fig. 11. Shear Safety Factor at 0.4 seconds.

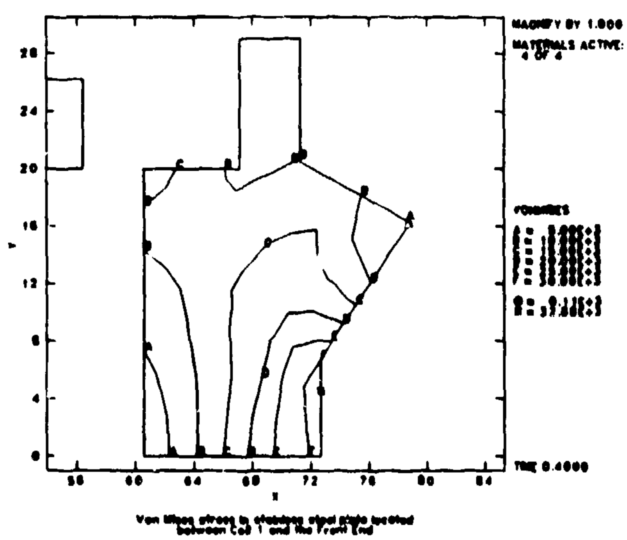

Fig. 12 Von Mises Stress in Columnar Plate at 0.4 seconds.

Although not included in this analysis, buckling could exist in the structure. This important aspect will be investigated for the bulkheads and the highly loaded region between coil 1 and the front end.

IV. CONCLUSIONS

Redesign of the highly loaded structure between coil 1 and the front end has been undertaken as a result of the analysis. Analytical data regarding coil 4 loads will be used to redesign the coil support.

The horizontal tendon above coils 2, 6, and 7 will be redesigned to reduce bending and/or use a more compliant material. Redesign of the bulkhead fastener system is underway; reduced cost is foreseen as a result.

Finite element analysis of the complex ZTH structure has provided vital insights into its design and indispensable information for design correction in critical areas. A more efficient structure is forseen because analysis integrated with design has allowed strengthening in weak areas and reduction of unneeded strength in others.

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