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BRUCE GS A

4 x 740 MW(e), Nuclear GS

Design Calculation Summary Sheet

Equipment and Rotating Machines Unit

Engineering Analysis Department

Nuclear Technology Services

System:	Steam Generator - Primary Divider Plate
Design Calculation for:	**Bruce A Skin Fix**
Method of Analysis:	Finite Element Analysis
Computer Code Used:	ABAQUS/EXPLICIT
Method of Verification:	Review

Conclusion: See the Summary page

Prepared By:	**E.H. Mileta**
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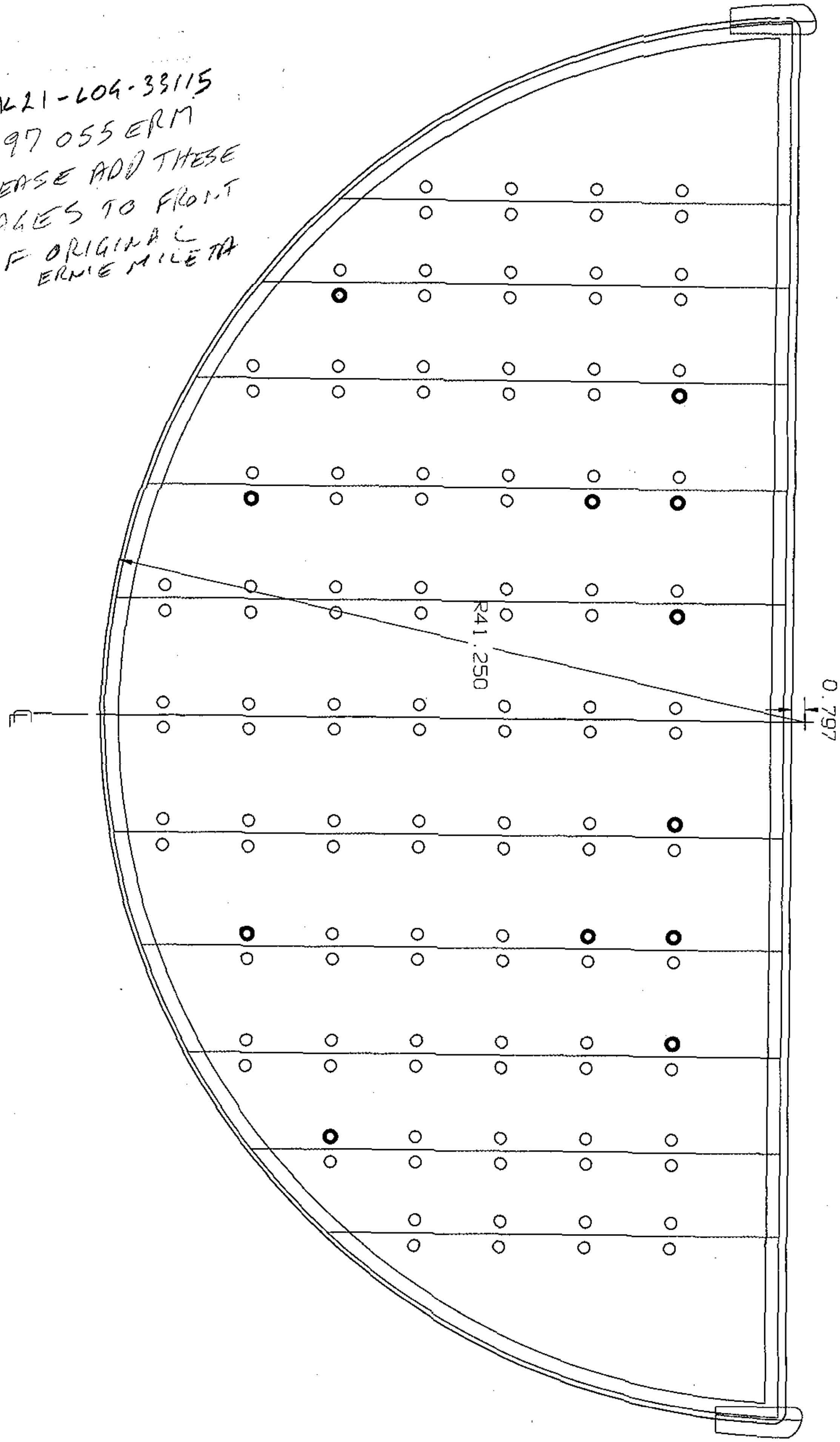
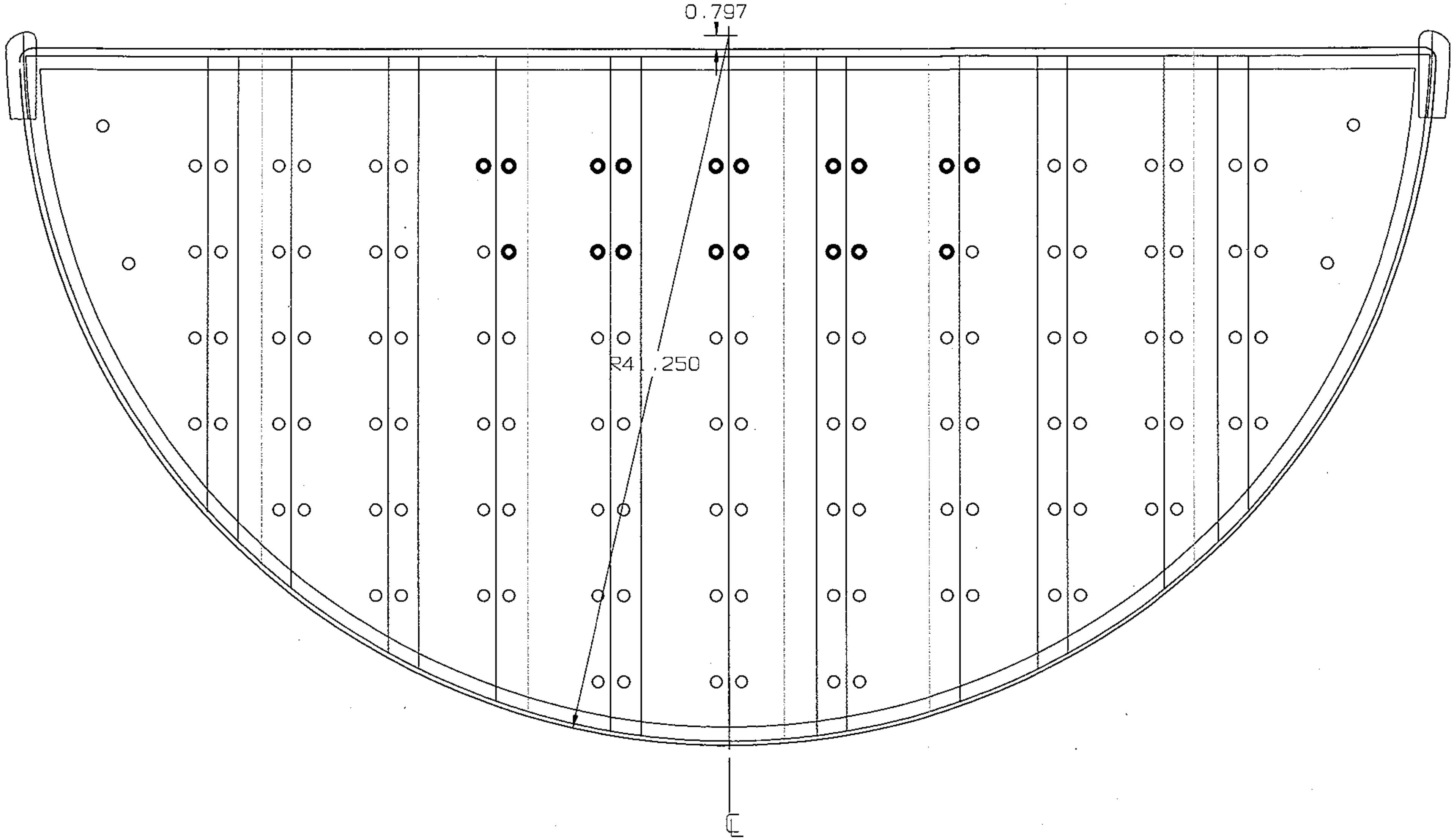


CASE 2B

CASE 1D



SUMMARY

Problem Description

The Bruce NGS A steam generator divider plate is an assembled plate that separates the boiler primary head into 2 compartments : the inlet side and the outlet side. The identified need to reduce the leakage past/through the divider plate assembly has resulted in a proposed "fix" (Reference 6) to address this issue. The proposed fix is to install an Inconel membrane over the plate and to install clamping plates that cover the complete surface. New nuclear grade bolts would be installed in the process. Although this is expected to significantly reduce the leakage for a relatively small cost, the impact on the LOCA safety needs to be evaluated.

The effect of the new configuration was expected to make the divider plate stronger and stiffer but the current analysis makes use of the flexibility of the divider plate assembly to reduce the impact of LOCA transient conditions. In order to analyze these LOCA conditions, a coupled fluid/structure "interactive" analysis was used which included the flexibility of the divider plate assembly in the analysis.

Purpose and Scope

This analysis is intended to show the change in behaviour of the divider plate under a sample LOCA loading given the increased stiffness provided by the clamping plates in the new design. This analysis is based on load case "CASE1B" of reference 1. The analysis was carried out using the same methods and assumptions used in reference 1. The ABAQUS/Explicit version 5.5 (Reference 2) finite element program was used. The finite element model is shown on Figures 3 and 4. Only one half of the structure was modelled as the divider plate assembly structure and the applied loading have a plane of symmetry. The nominal thickness of the plates (1.5" for the panels and 0.75" for the clamp-plates) was used in the model. Contact and sliding (with friction μ=0.2) between all abutting components were modelled.

In addition to the LOCA analysis, several analyses were performed on a truncated portion of the model (figures 12 and 13). The test model consisted of a portion of the primary head and seat bar with half of the two centre panels which were cut at mid-span where symmetry conditions were applied. The purpose of the test model was to determine the changes in behaviour with different bolt materials and bolting configurations. In addition the effect of preload was also reviewed given the increase in surface area over which friction is applied (i.e. the sealing skin). Two bolting configurations (current vs "Big Holes") with two different bolt materials (SA 193 vs SA 540) were analyzed with and without preload applied. In total 8 load cases were analyzed:

- No Preload, current bolting configuration with material A (SA-193)
- No Preload, current bolting configuration with material B (SA-540)
- Preload, current bolting configuration with material A (SA-193)
- Preload, current bolting configuration with material B (SA-540)
- No Preload, modified bolting configuration with material A (SA-193)
- No Preload, modified bolting configuration with material B (SA-540)
- Preload, modified bolting configuration with material A (SA-193)
- Preload, modified bolting configuration with material B (SA-540)

Results

The analysis results described in Section 6 with details in appendices D through N. Table 1 and figures 17 to 21 illustrate differences between specific cases. The following is a summary of the analysis results:

LOCA Loading Case1D Using the New "Fix" Design

Results for this case are provide in Section 6 with details in appendices D and E. The first bolts failed at 80ms of analysis time (5 bolts) with an additional 4 bolts failing at 90ms. The divider plate assembly remains intact and engaged to the seat bars throughout the analysis with small strains in the seat bar and filler piece welds. The pattern of bolt failure indicate that the predominant loading is undercutting of the bolts due to the relative movement of the panels with the first two rows of bolts closest to the tubesheet seat bar most affected.

LOCA Loading Case1B Using the original Design

This can be compared with the earlier analysis of reference 1 where 6 bolts failed at by the end of the analysis with the first three bolts failing at 92 ms, 95 ms and 107 ms respectively. The divider plate assembly remained intact and engaged to the seat bars throughout the analysis with small strains in the seat bar and filler piece welds. The pattern of bolt failure indicated that the predominant loading is undercutting of the bolts due to the relative movement of the panels with the most affected bolts found on both the tubesheet and primary head ends of the lap plates and on the lap plate edge closest to the centre.

Comparison of Case1 results

The peak load determined through the interactive analysis (Case1D) was 40psi higher (271 vs 231) than in the earlier analysis (Case1B). Displaced volume at unloading as approximately ½ of the earlier value (1.51E-2 m^3 vs 3.18E-2 m^3).

Test Cases on Truncated Model

Test Case	Time of First Bolt Failure	Applied Load at First Bolt Failure	Displacement of Central Node at 70 ms (250 psi)	Displaced Volume at 70 ms (250 psi)	Results Provided in Appendix
NoPreload-A	70 ms	250 psi	1.212"	153.6 in^3	G
NoPreload-B	70 ms	250 psi	1.089"	138.6 in^3	H
Preload-A	70 ms	250 psi	1.126"	146.8 in^3	I
Preload-B	72 ms	260 psi	0.983"	125.5 in^3	J
Big Holes NoPreload-A	76 ms	280 psi	1.302"	168.3 in^3	K
Big Holes NoPreload-B	72 ms	260 psi	1.112"	142.4 in^3	L
Big Holes Preload-A	74 ms	270 psi	1.173"	154.1 in^3	M
Big Holes Preload-B	72 ms	260 psi	0.985"	126.6 in^3	N

Conclusions

LOCA Loading Case1D

The new design exhibits higher load carrying capacity than the current design as expected. The increased stiffness leads to more a severe response to LOCA loading initially. Once the first set of bolts fail, the sudden change in the structures flexibility leads to results that more closely follow those of the earlier analysis (Figure E-3 in appendix E).

Test Cases

The test cases were designed to show sensitivity to several basic assumptions. The results of all cases are similar but some possible trends are evidenced:

- Use of "Slotted" or "Big" holes provides for some increase in load carrying capacity.
- Application of High Preload acts to increase the stiffness of the structure and therefore reduce displacement
- Using First bolt failure as criteria, the stronger SA-540 bolt material (Material B) leads to failure at the same time or later than the SA-193 bolt material (Material A) using the current bolting arrangement where undercutting is a factor. When slotted or "Big" holes are used, the stronger SA-540 bolt material fails earlier than the SA-193 bolt material.

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List of Appendicies

1.0 INTRODUCTION

The Bruce NGS A steam generator divider plate is an assembled plate used to separate the boiler primary head into 2 compartments : the inlet side and the outlet side. The half-model as shown consists of 6 panels, 6 lap plates, 16 clamps of different sizes and 93 bolts. The panels are joined together with bolts using lap plates. The assembly rests against the primary head and tubesheet seat bars and is held in place by the clamps.

The identified need to reduce the leakage past/through the divider plate assembly has resulted in a proposed "fix" to address this issue. The proposed fix is to install an Inconel membrane over the plate and to install clamping plates that cover the complete surface. New nuclear grade bolts would be installed in the process. Although this is projected to have a signaficant effect on the leage for a relatively small cost, the impact on the LOCA safety needs to be evaluated.

The effect of the new configuration is expected to make the divider plate stronger and stiffer but since the current analysis makes use of the flexibility of the divider plate assembly to reduce the impact of LOCA transient conditions, the increased stiffnes of the plate may cause it to fail sooner.

Under normal operating condition, the pressure drop from the inlet to the outlet is about 30 psi. Under a postulated loss of coolant accident (LOCA) condition, i.e., a pipe rupture in the vicinity of the steam generator inlet or outlet nozzle, the pressure differential is substantially higher. The severity of the differential pressure magnitude coupled with the dynamic effects may cause the divider plate assembly structure to disintegrate. To guard against this type of failure, failure criteria based on plastic strains (see Section 2.1) was proposed to AECB in Reference 5 of Reference 1. Using these criteria, the plastic strain limits for the components of the divider plate were established (see Section 3.0). For the divider plate to remain intact under LOCA loadings, all components including the seat bar to tubesheet and head welds must not exceed their plastic strain limits. In order to analyze these LOCA conditions, a coupled fluid/structure "interactive" analysis is used which includes the flexibility of the divider plate assembly in the analysis.

The "Sealing Skin" is designed to:

- Completely cover the divider plate panels to significantly reduce the PHT leak. A new clamping design is proposed that will replace the current clamping bar arrangement.
- Be fabricated from Inconel (0.030" Thick).

The new "Clamping Plate" design will:

- Be fabricated from 1/2" CS plate (SA 516 Gr.70)
- Be bolted in place using the existing 126 threaded holes used for fastening the old clamping bars to maintain the divider plate sections. An additional 4 threaded holes will be drilled and tapped during installation.
- The bolts (130 pcs) will be torqued to 100 ft-lb and locking tabs will be used.

The finite element model of the current divider plate design (Reference 1) was be used with the following changes:

- The clamping bars will be removed
- The corner panel will be modified to allow for two additional bolts
- The new Sealing Skin will be added
- The new Clamping Plats will be added
- The new bolts and bolting material will be used.

This analysis is intended to show the change in behaviour of the divider plate under a sample LOCA loading given the increased stiffness provided by the clamping plates in the new design. This analysis is based on load case "CASE1B" of reference 1. The analysis was carried out using the same methods and assumptions used in reference 1. The ABAQUS/Explicit version 5.5 (Reference 2) finite element program was used. The finite element model is shown on Figures 3 and 4. Only one half of the structure was modelled as the divider plate assembly structure and the applied loading have a plane of symmetry. The nominal thickness of the plates (1.5" for the panels and 0.75" for the clamp-plates) was used in the model. Contact and sliding (with friction μ=0.2) between all abutting components were modelled.

In addition to the LOCA analysis, several analyses were performed on a truncated portion of the model (figures 12 and 13). The test model consisted of a portion of the primary head and seat bar with half of the two centre panels which were cut at mid-span where symmetry conditions were applied. The purpose of the test model was to determine the changes in behaviour with different bolt materials and bolting configurations. In addition the effect of preload was also reviewed given the increase in surface area over which friction is applied (i.e. the sealing skin). Two bolting configurations with two different bolt materials were analyzed with and without preload applied. In total 8 load cases were analyzed:

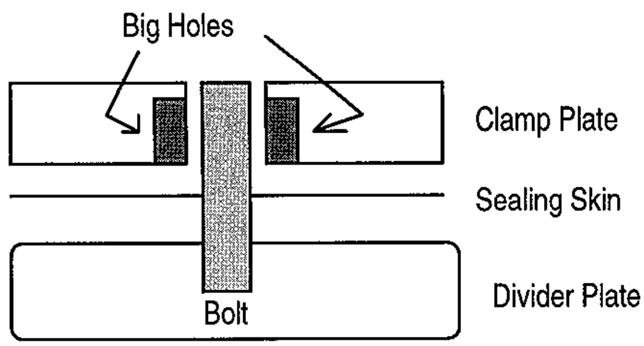
- No Preload, current bolting configuration with material A (SA-193)
- No Preload, current bolting configuration with material B (SA-540)
- Preload, current bolting configuration with material A (SA-193)
- Preload, current bolting configuration with material B (SA-540)
- No Preload, modified bolting configuration with material A (SA-193)
- No Preload, modified bolting configuration with material B (SA-540)
- Preload, modified bolting configuration with material A (SA-193)
- Preload, modified bolting configuration with material B (SA-540)

2.0 ASSUMPTIONS AND SIMPLIFICATIONS

All model assumptions and simplifications used are unchanged from the reference report (ref. 1), with the following exceptions.

1. The sealing skin is "floating", using only compression and friction to hold it in place with no interaction between the skin and the bolts. This simplification will not affect the overall results as the skin does not contribute significantly to inplane strength of the divider plate assembly.

2. For the "Big Holes" Tests, the contact conditions between the clamp plate and the bolt were removed. This simulates holes large enough in diameter that "undercutting" of the bolt does not occur. The head of the bolt was "tied" to the plate through the use of a rigid cap. This arrangement, as shown in the sidebar, allowed for preload to be applied.



3. For the "Preload" Tests, the amount of preload was not uniform across all panel bolts. The amount of preload achieved is considered sufficient to show the sensitivity of the analysis to the use of preload.

4. Two bolt materials were considered for the bolt material tests, SA-193 and SA-540. The SA-193 material was used in the interactive LOCA analysis.

2.1 ACCEPTANCE CRITERIA

Since the divider plate is not an ASME class 1 pressure boundary, the Level D stress limits do not apply. Furthermore, as can be seen later in the analysis, significant yielding and strain hardening have occurred in the bolt and the divider plate, that is strain limits rather than stress limits are more appropriate as the failure criteria. As part of the AECB submission (Reference 5, Section 4.2, of Reference 1), the following criteria for mechanical component allowable strains were proposed :

(a) <u>For Bolts and Welds</u>

Strain-Criteria 1: $\varepsilon_{mem} < 0.7*\varepsilon_f$ Strain-Criteria 2: $\varepsilon_{max} < 0.9*\varepsilon_f$

where

ε_{mem} = membrane strain

ε_{max} = maximum strain

ε_f = failure strain (the ultimate true plastic strain)

(b) For Panels, lap plates, Clamp-Dogs and Seat-Bars

They are identical to (a) above if the strains are not very localized :

Strain-Criteria 1: $\varepsilon_{mem} < 0.7*\varepsilon_f$ Strain-Criteria 2: $\varepsilon_{max} < 0.9*\varepsilon_f$

Local area is an area not greater than 10% of the width of the component where ε_{mem} exceeds 0.6 ε_f . In a local area, the limit is :

$$\varepsilon_{mem} < 0.9*\varepsilon_f$$

3.0 MATERIAL PROPERTIES

The material specifications for the divider plate assembly are :

Component	Material specification	Material-set name	Reference drawing
Panel and Filler piece*	SA-515-Gr.70	SA515	NK21-MN33110-1021 Rev 4
Lap plate and Clamp	A108-1018	A108	NK21-MN33110-1021 Rev 4
Tubesheet	SA-105 Gr.II	SA105	NK21-MN33110-1002 Rev 4
Tubesheet cladding	SB-304 Typ. ER-Ni-Cr3	SB304	NK21-MN33110-1014 Rev 8
T/S seat bar weld	ER-Ni-Cr3	ERNICR3	B&W wps 210248
Tubesheet seat bar	SB-166	SB166	NK21-MN33110-1017 Rev 6
Head seat bar	A-36	A36	NK21-MN33110-1017 Rev 6
Head seat bar weld	E7018-A1	E7018A1	B&W wps 210260
Head	SA-516 Gr 70	SA516	NK21-MN33110-1002 Rev 4
Original Bolts	*A-325*	*A325... A325D9*	*NK21-MN33110-1017 Rev 4*
Proposed Bolts	SA-193 B7	SA193	
Alternative Bolts	SA-540 B22	SA540	
Sealing Skin	SB-443	SB443	

* Filler piece material is not explicitly specified on the drawing. However, it is shown together with the panel on the same drawing with one material title, the panel material of SA-515 Gr. 70 is used.

In the Table above, the column “Material-set name” contains the material ID given to that material in the ABAQUS input.

The material properties (E, Sy, Su and ε_u) were taken from the ASME code (Reference 4). Where two ultimate strains (ε_u) are available, the smaller value was used. As mentioned earlier that, these ε_u's are the room temperature values and were conservatively taken as the strain values at 544°F.

The S_u and ε_u of the ASME code are engineering stress and strain, they are converted to true stress and strain as follows

$$\sigma_{true} = \sigma_{eng}\,(1+\varepsilon_{eng})$$

$$\varepsilon^{plastic}_{true} = \ln(1+\varepsilon_{eng}) - \sigma_{true}/E$$

Since the yield strains are about 0.1% for all materials used in this analysis, the first yield stress (Sy) from ASME code, which is an engineering stress, is used as the true stress. The following Table summarises the material properties together for all components used in this analysis. The values were calculated at the service temperature of 544°F (see Appendix B for details):

Material-set name	ρ slug/in^3	E 10^6 psi	ν	Sy psi	Su $_{true}$ psi	ε_f	allowable ε_{mem}	allowable ε_{max}
SA515	7.22E-04	26.84	0.3	29556	81900	0.1540	0.1078	0.1386
A108	7.22E-04	27.04	0.3	24888	60500	0.1884	0.1319	0.1696
SA105	7.22E-04	26.84	0.3	28000	85400	0.1957	0.1370	0.1761
SB304	7.94E-04	28.87	0.3	28404	104000	0.2588	0.1812	0.2329
ERNICR3	7.94E-04	28.87	0.3	28404	104000	0.2588	0.1812	0.2329
SB166	7.94E-04	28.87	0.3	28404	104000	0.2588	0.1812	0.2329
A36	7.22E-04	27.04	0.3	28000	69600	0.1797	0.1258	0.1617
E7018A1	7.22E-04	26.74	0.3	45623	87500	0.2199	0.1539	0.1979
SA516	7.22E-04	27.04	0.3	29566	81900	0.1540	0.1078	0.1386
A325	*7.22E-04*	*26.84*	*0.3*	*74949*	*136800*	*0.1259*	*0.0881*	*0.1133*
SA193	7.22E-04	26.84	0.3	87092	145000	0.143	0.1001	0.1287
SA540	7.22E-04	26.84	0.3	117140	181500	0.0885	0.06195	0.07965
SB443	7.22E-04	27.97	0.3	47928	143000	0.2573	0.1801	0.23157

4.0 SPECIFIED LOADING CONDITIONS

Loading conditions analyzed in this report are:

1) Interactive LOCA Loading - 200% pump discharge break, 40ms break opening time
2) All Test Cases - 20 ms of zero pressure loading, with preload applied in appropriate test cases, then pressure ramp of 5psi/ms to a maximum of 300 psi.

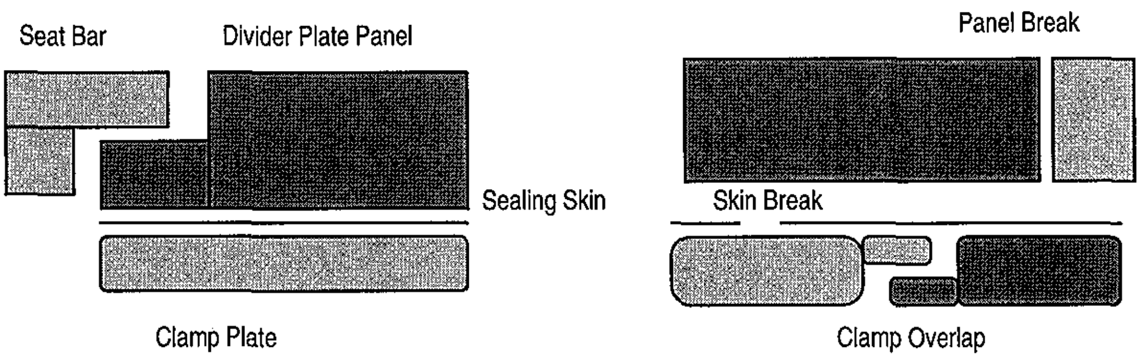
5.0 METHOD OF ANALYSIS

The boundary conditions and method of analysis except for noted model changes are identical to those of the earlier analysis (Reference 1).

The PATRAN finite element modelling program (Reference 3) was used to create the new components that were added to the finite element model of Reference 1.

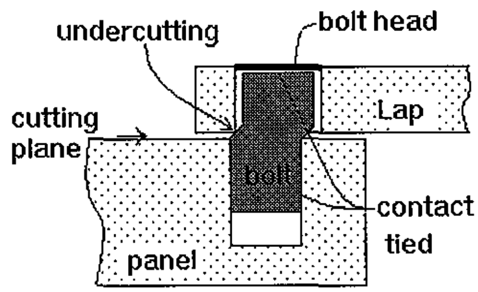
5.1 Model Description

The panels, sheets of sealing skin and clamp plates are arranged as shown above. The breaks between panels, skin sheets and clamp plates are arranges so that there is no direct leak path.



Bolt modelling

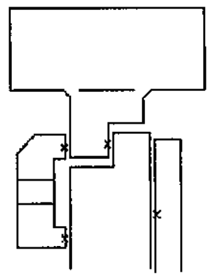
For ease of identification, the bolts are referred by number (see Figures 2 and 3). Bolts 1 to 30 are the 1¾" long clamp bolts; and bolts 31 to 95 are the 1½" long lap bolts (longer than original 1¼"). Contact "tied" was used to connect the bolt head with the bolt body. Contact "tied" means the nodes are tied to the surface in translational DOF's, being unable to separate from or slide along the surface. Contact "tied" was also used to tie the thread-in portion of the bolt to the panel. The relative movement of these contacting surfaces can induce significant shear forces in the bolt at the cutting plane; i.e. an "undercutting" or shear deformation of the bolts can occur. Since high stress is expected in the vicinity of the cutting plane, very fine mesh (0.0688" in size) were used in this area. To determine the degree of undercutting occurring during the analysis,



The two additional bolts modelled on the corner panel were modelled slightly differently. The bolts are modelled with a tied surface rather than penetrating the surface of the panel. These bolts do not experience significant undercutting and this modelling simplification introduces negligible error.

Since the time step of the analysis is governed by the smallest element size, mass density of some bolt elements was increased as required.

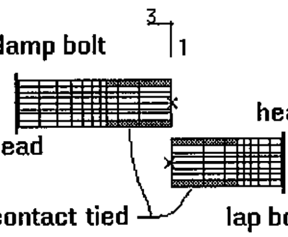
Contact Surfaces



A clearance of 0.0001" was given to all contacting surfaces. This was done so that initial overclosure of the contacting surfaces would not occur. The 0.0001" was taken out from surfaces marked with a "x" on the Figure at right. On this Figure, the components were spaced out laterally for visibility; in the vertical direction the actual clearance is shown.

For panel to panel contact, the 0.0001" was taken out from the left side of each panel.

For "tied" surfaces on the bolt, since ABAQUS can adjust (with parameter ADJUST=0.001") the initial overclosure automatically, no other modelling precaution need be made except that on the bottom of each bolt, 0.0001" was taken out in the z-direction so that its nodes do not protrude the bolt hole contacting surfaces.



Contacts between all components were accounted, i.e.

- Contact between the panels was modelled
- Contact between the clamp-plate and the sealing skin was modelled.
- Contact between the sealing skin and the panels was modelled
- Contact between the clamp and panel was modelled.
- Contact between the clamp and seat bars was modelled.
- Contact between the clamp and the bolt was modelled.
- Contact between the panel and seat bars was modelled.
- Contact between the bolt and lap-plate and the was modelled
- Contact between the filler piece and the seat bars
- Contact between the filler piece and the panel
- Contact between the filler piece and head inner surface (filler piece envelope)
- Contact between the centre panel and the rigid centre surface.

5.2 Boundary Conditions

- At the XZ symmetry plane, symmetry boundary conditions were applied to the tubesheet, head, seat-bars, clamps and the lap plate but not the panel.
- The tubesheet and the head were fixed completely. The rigid surface reference nodes for the filler piece envelope and the symmetry plane were also completely fixed.

5.3 Loading

The initial condition for the LOCA cases is a steady state pressure differential across the divider plate of 30.2 psi in the forward direction (see Reference 1). The load was applied in an identical manner to the earlier analysis in Reference 1.

The test cases were analyzed with identical load ramps to facilitate comparison. Each case had a 20ms Zero pressure applied during which preload was applied for the cases that required preload. For the remainder of the analysis a straight ramp of 5psi/ms was applied up to a maximum of 300 psi.

6.0 RESULTS OF ANALYSIS

The results of the analysis cases are presented below with details in appendicies D through N. For each case key analysis data was recorded:

- Overall displaced volume over time
- Model displacement and velocity over time
- Bolt Plastic Stress and Strain history
- VonMises Stress and Equivalent Plastic Strain plots of major components near time of peak loading
- Overall Displacement plots near time of peak loading

6.1 Interactive LOCA Analysis - Case1D

The detailed results for this case are provide in appendices D and E. The first bolts failed at 80ms of analysis time (5 bolts) with an additional 4 bolts failing at 90ms. The divider plate assembly remains intact and engaged to the seat bars throughout the analysis with small strains in the seat bar and filler piece welds. The pattern of bolt failure indicate that the predominant loading is undercutting of the bolts due to the relative movement of the panels with the first two rows of bolts closest to the tubesheet seat bar most affected.

This can be compared with the earlier analysis of reference 1 where 6 bolts failed at by the end of the analysis with the first three bolts failing at 92 ms, 95 ms and 107 ms respectively. The divider plate assembly remained intact and engaged to the seat bars throughout the analysis with small strains in the seat bar and filler piece welds. The pattern of bolt failure indicated that the predominant loading is undercutting of the bolts due to the relative movement of the panels with the most affected bolts found on both the tubesheet and primary head ends of the lap plates and on the lap plate edge closest to the centre.

The peak load determined through the interactive analysis was 40psi higher (271 vs 231) than in the earlier analysis. Displaced volume at end of unloading as approximately ½ of the earlier value (1.51E-2 m^3 vs 3.18E-2 m^3), see figure E-2 in appendix E.

6.2 Test Cases

Test Case	Time of First Bolt Failure	Applied Load at First Bolt Failure	Displacement of Central Node at 70 ms (250 psi)	Displaced Volume at 70 ms (250 psi)	Results Provided in Appendix
NoPreload-A	70 ms	250 psi	1.212"	153.6 in^3	G
NoPreload-B	70 ms	250 psi	1.089"	138.6 in^3	H
Preload-A	70 ms	250 psi	1.126"	146.8 in^3	I
Preload-B	72 ms	260 psi	0.983"	125.5 in^3	J
Big Holes NoPreload-A	76 ms	280 psi	1.302"	168.3 in^3	K
Big Holes NoPreload-B	72 ms	260 psi	1.112"	142.4 in^3	L
Big Holes Preload-A	74 ms	270 psi	1.173"	154.1 in^3	M
Big Holes Preload-B	72 ms	260 psi	0.985"	126.6 in^3	N

7.0 RETRIEVAL OF COMPUTER FILES

The PATRAN and ABAQUS data and input files were saved together with the analysis output files on tape in VAX save-set format (5). A listing of the tape save-sets was given in Appendix G.

The following is a brief description of the various directories contained in the save-set :

Directory	Description
[baskin.ba.fix]	Interactive LOCA Analysis
[baskin.test.cut]	Test Cases

8.0 REFERENCES

1. San Ho, "Bruce NGS A - Primary Divider Plate Under LOCA Loads - TUF/ABAQUS Interactive Simulation", Design Calculation, NK21-LOG-33115-97010-ERM, Rev 0, June 27, 1997

2. ABAQUS User's Manual, Version 5.5-1 Hibbitt, Karlsson & Sorenson Inc.

3. MSC-PATRAN User's Manual, version 2.5.

4. ASME Boiler and Pressure Vessel Code, Section II, Part D - Properties, 1992 and 1995 Editions without Addenda, and Code Case N-71-16, 1992 Edition.

5. Ontario Hydro Nuclear, Nuclear Technology Services, Engineering Analysis Department, Vax Tape No. P0020, P0037 and P0044.

6. Ontario Hydro Emails and Attachments, Bruce A Divider Plate Sealing Skin ACAD DXF files. Copies in Appendix A.

ABAQUS Time of Bolt Failure (ms)

Lg. Model Bolt Number	Sm. Model Bolt Number	No Preload Mat. A	No Preload Mat. B	Preload Mat. A	Preload Mat. B	Big Holes No Preload Mat. A	Big Holes No Preload Mat. B	Big Holes Preload Mat. A	Big Holes Preload Mat. B
34	5	-	74	-	74	80	76	-	75
35	6	72	72	72	**72**	78*	74	76	74
36	7	**70**	**70**	**70**	**72**	**76***	**72***	**74**	**72**
41	9	76	76	-	76	80	78	-	-
42	10	72	72	74	74	78	76	-	75
43	11	72	72	72	74	78	74	77	75
48	13	76	76	-	76	-	78	-	-
49	14	72	72	74	74	78	76	-	75
50	15	72	72	72	**72**	78	74	77	74
55	17	74	74	74	74	-	78	-	-
56	18	72	72	72	**72**	78	74	77	74

*Note: These bolts contain elements that exceeded strain limits since failure properties were not globally defined for the entire bolt.

Lg. Model Bolt Number	Case 1D - Time of first bolt Failure (ms)
31	80
32	80
38	80
39	90
45	80
46	90
52	80
53	90
58	90

Figure 01 : Tables - Analysis time of First bolt failure for all cases

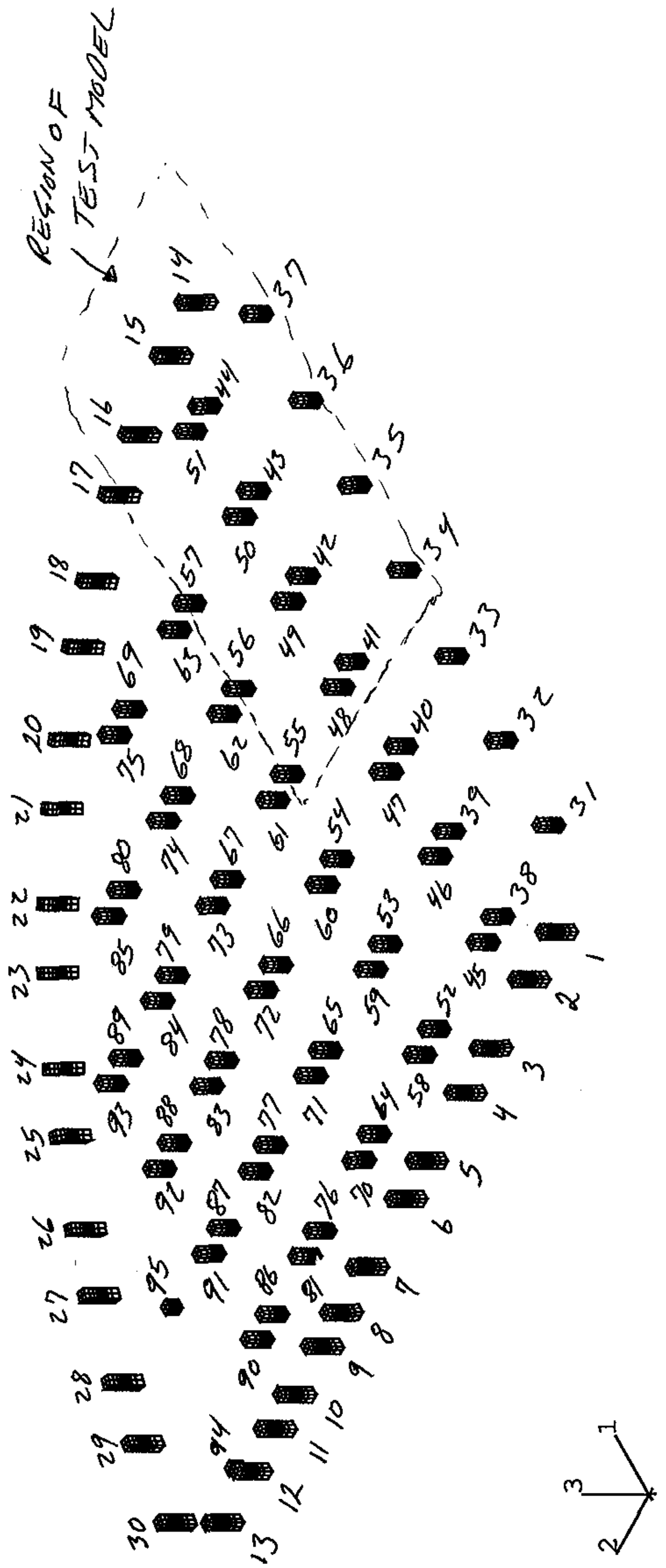


Figure 02 : Plot - Bolt Numbering in overall Fix Model

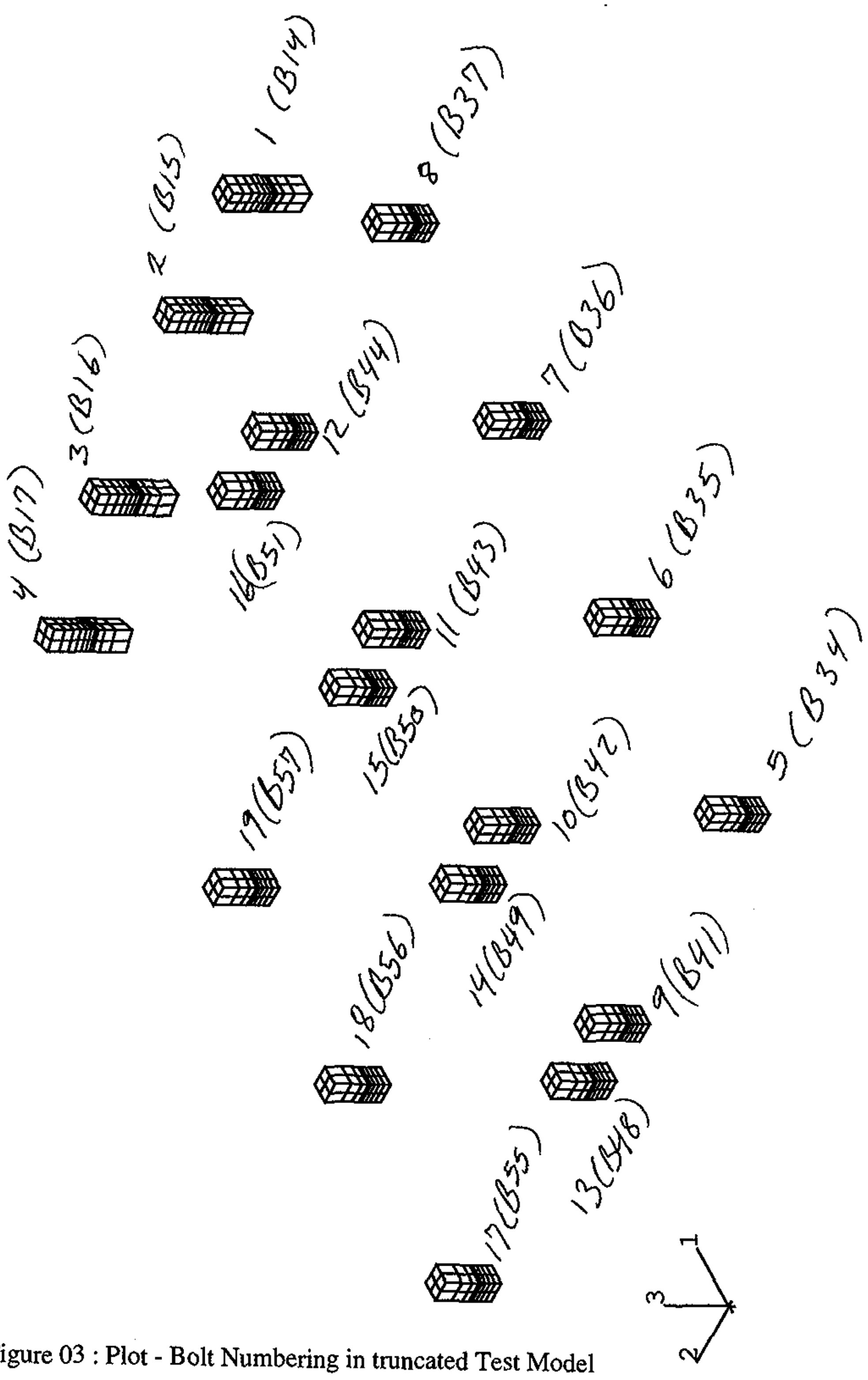


Figure 03 : Plot - Bolt Numbering in truncated Test Model

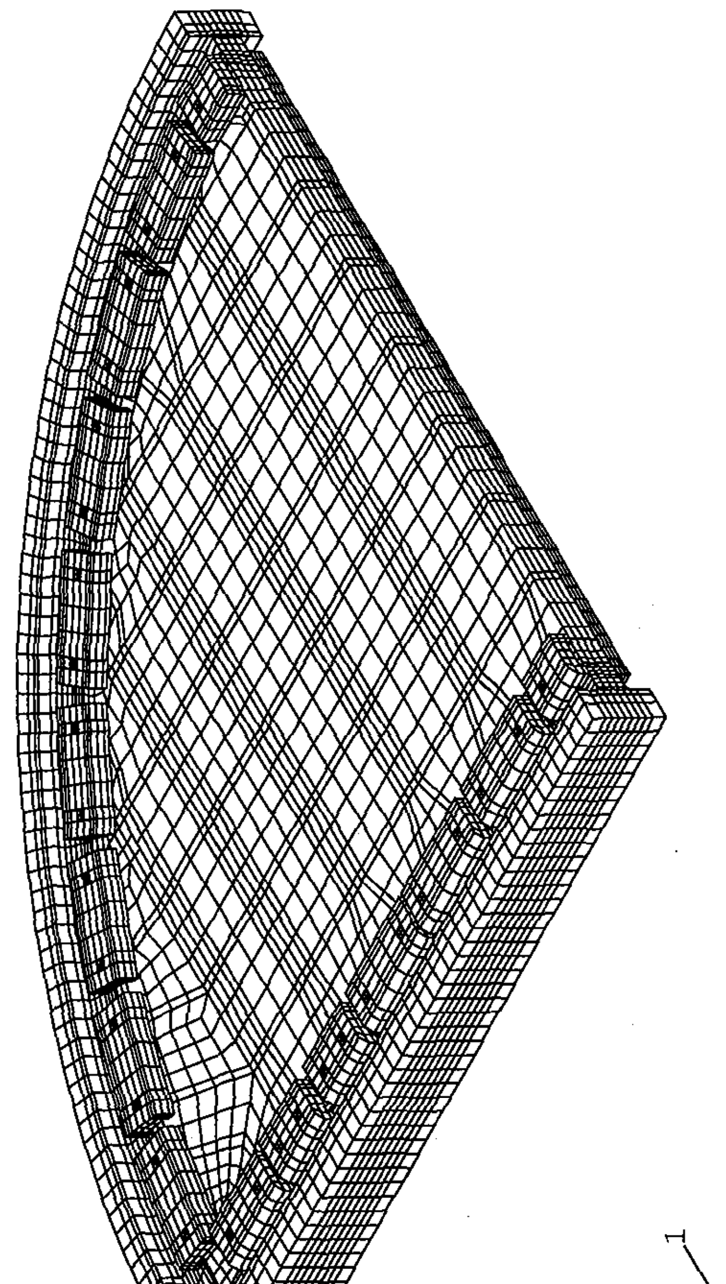


Figure 04 : Plot - Overall FEM Assembly - Fix Model - Top View

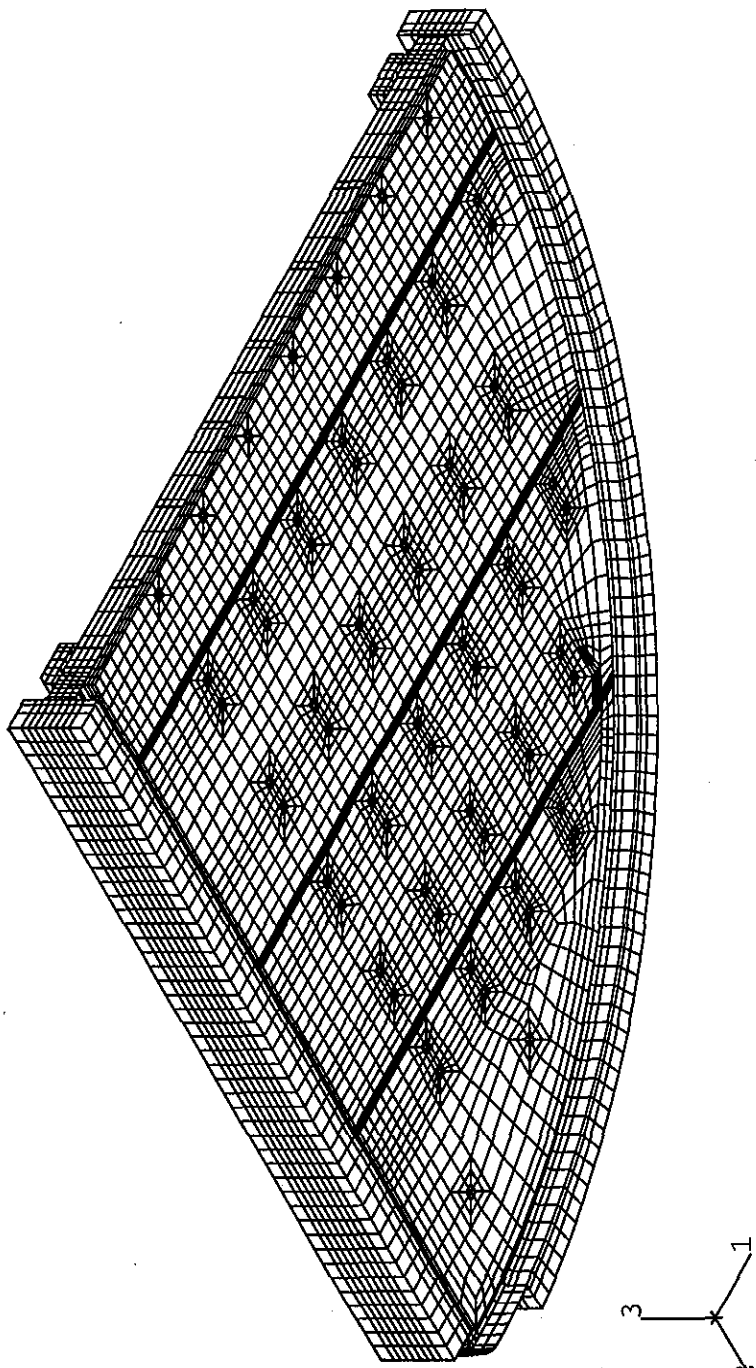


Figure 05 : Plot - Overall FEM Assembly - Fix Model -Bottom View

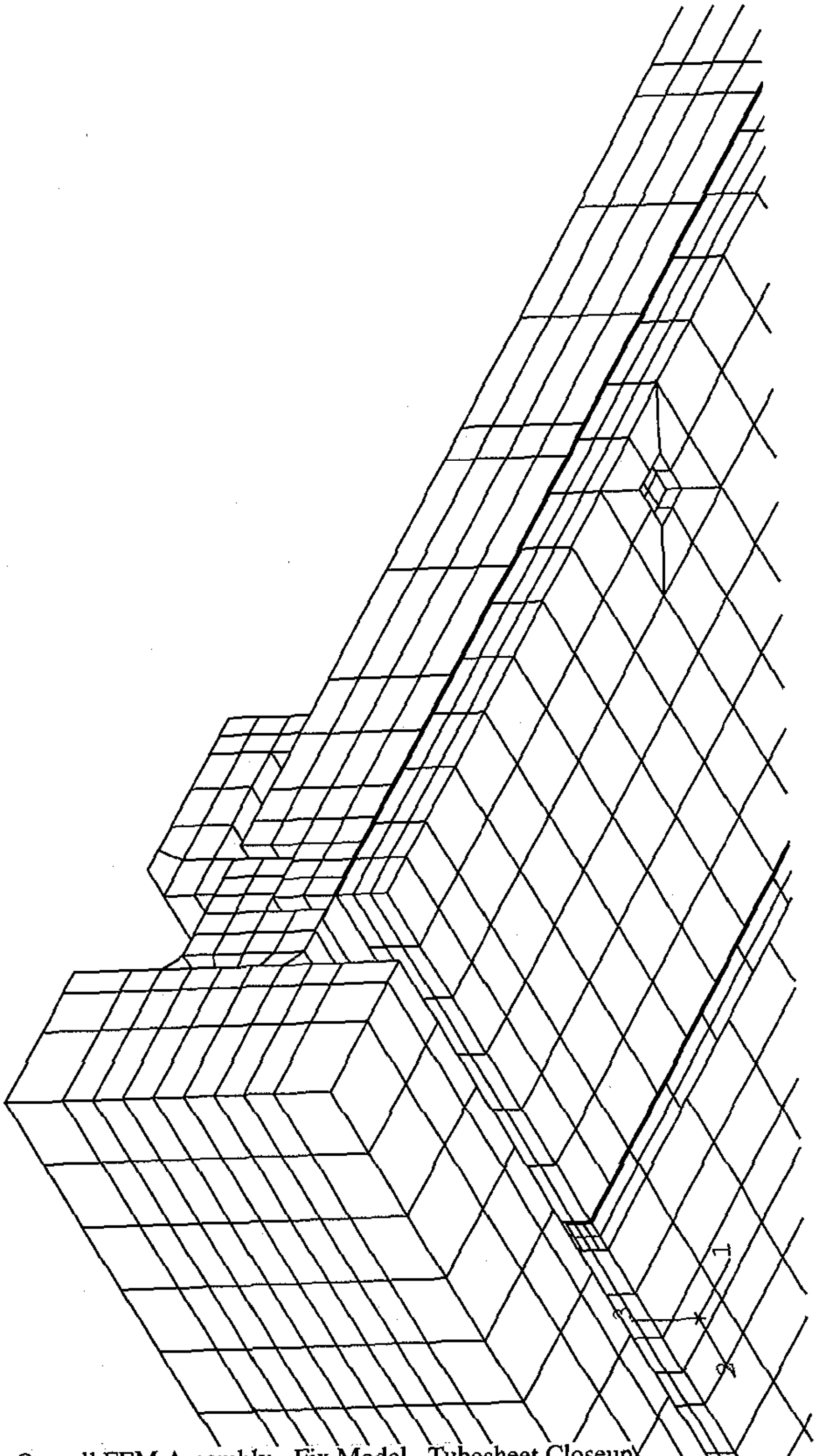


Figure 06 : Plot - Overall FEM Assembly - Fix Model - Tubesheet Closeup

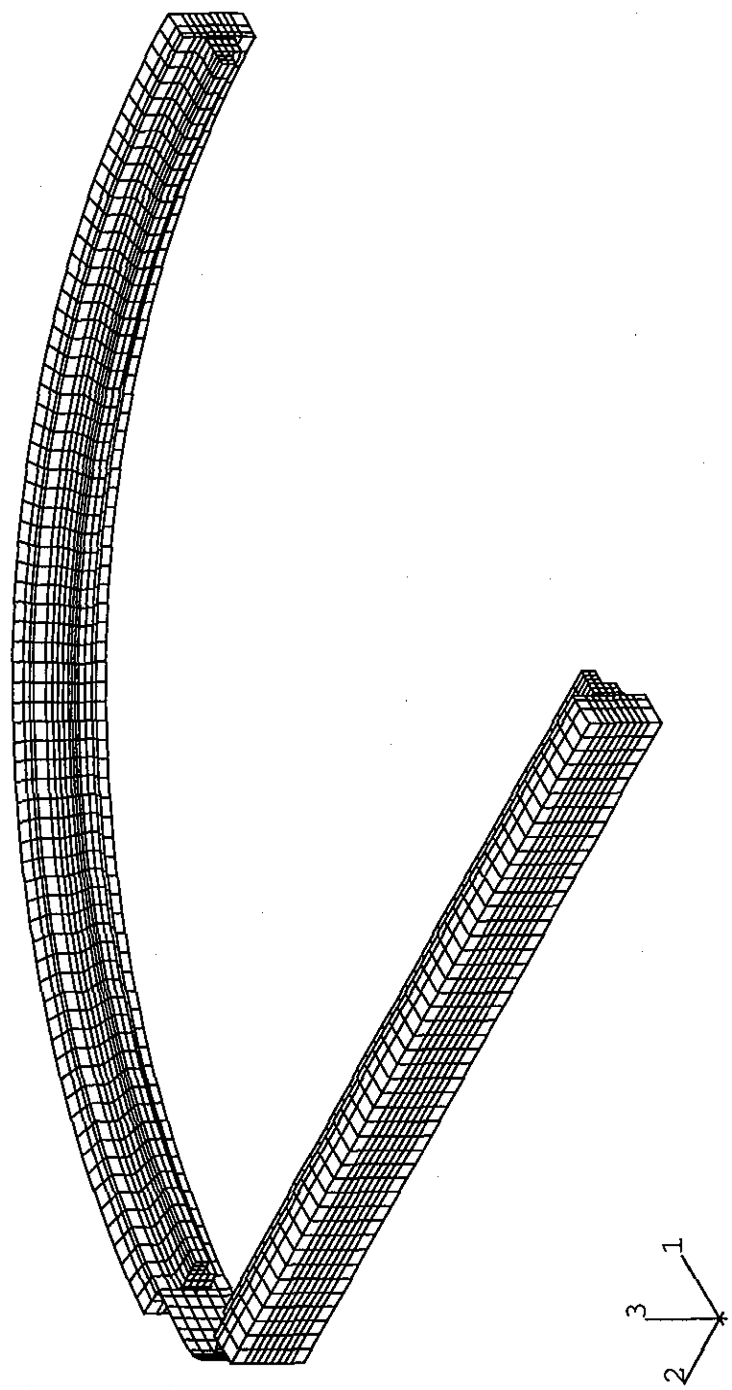


Figure 07 : Plot - Seat bars, Welds and Portions of the Tubesheet and Primary Head - Fix Model

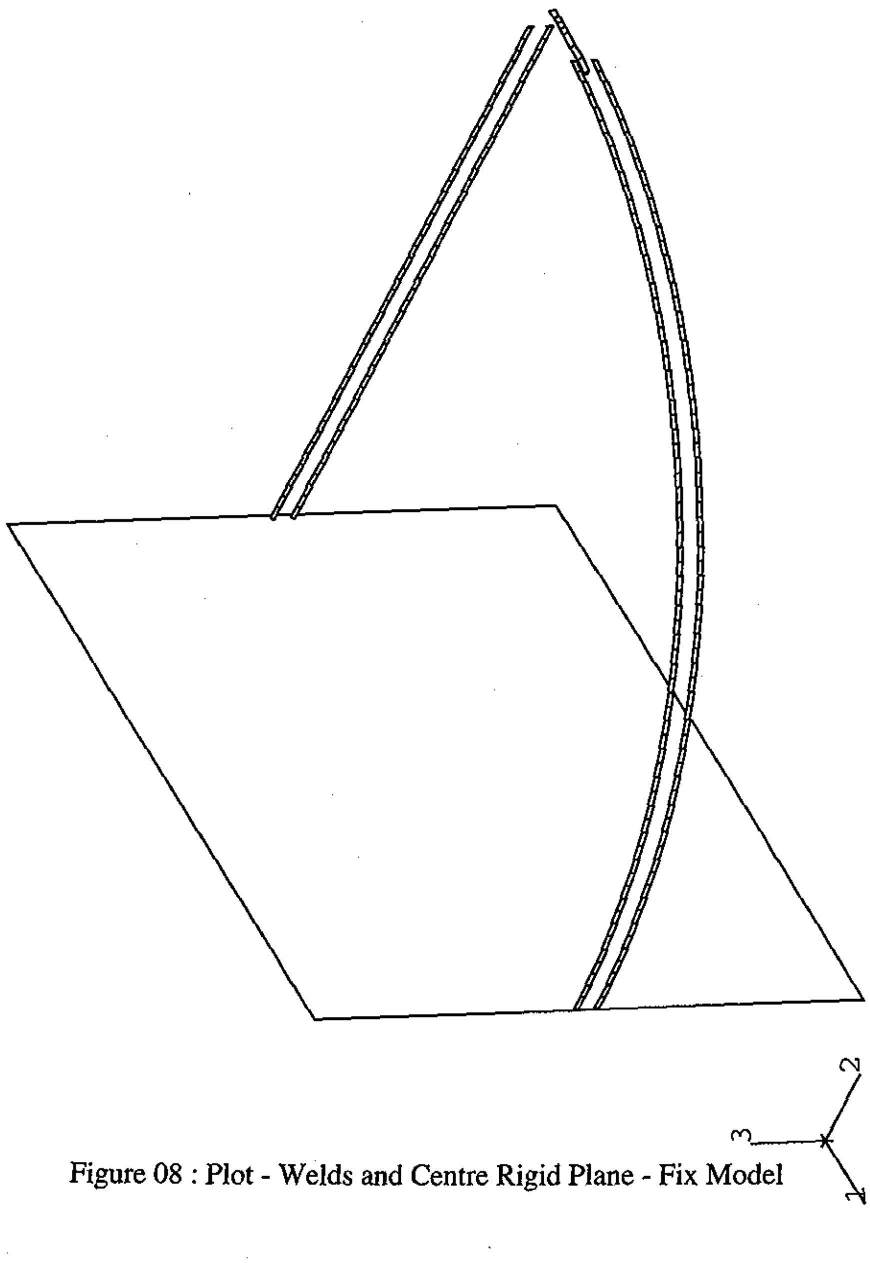


Figure 08 : Plot - Welds and Centre Rigid Plane - Fix Model

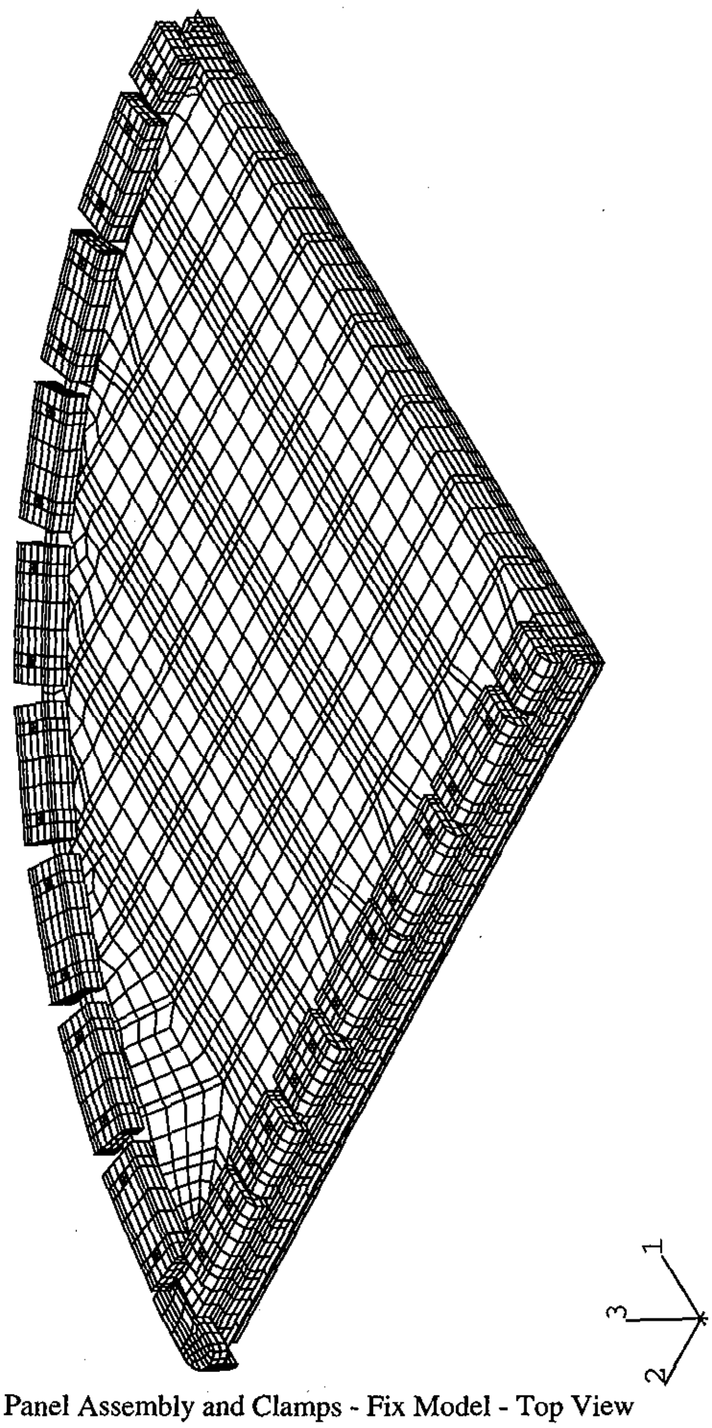


Figure 09 : Plot - Panel Assembly and Clamps - Fix Model - Top View

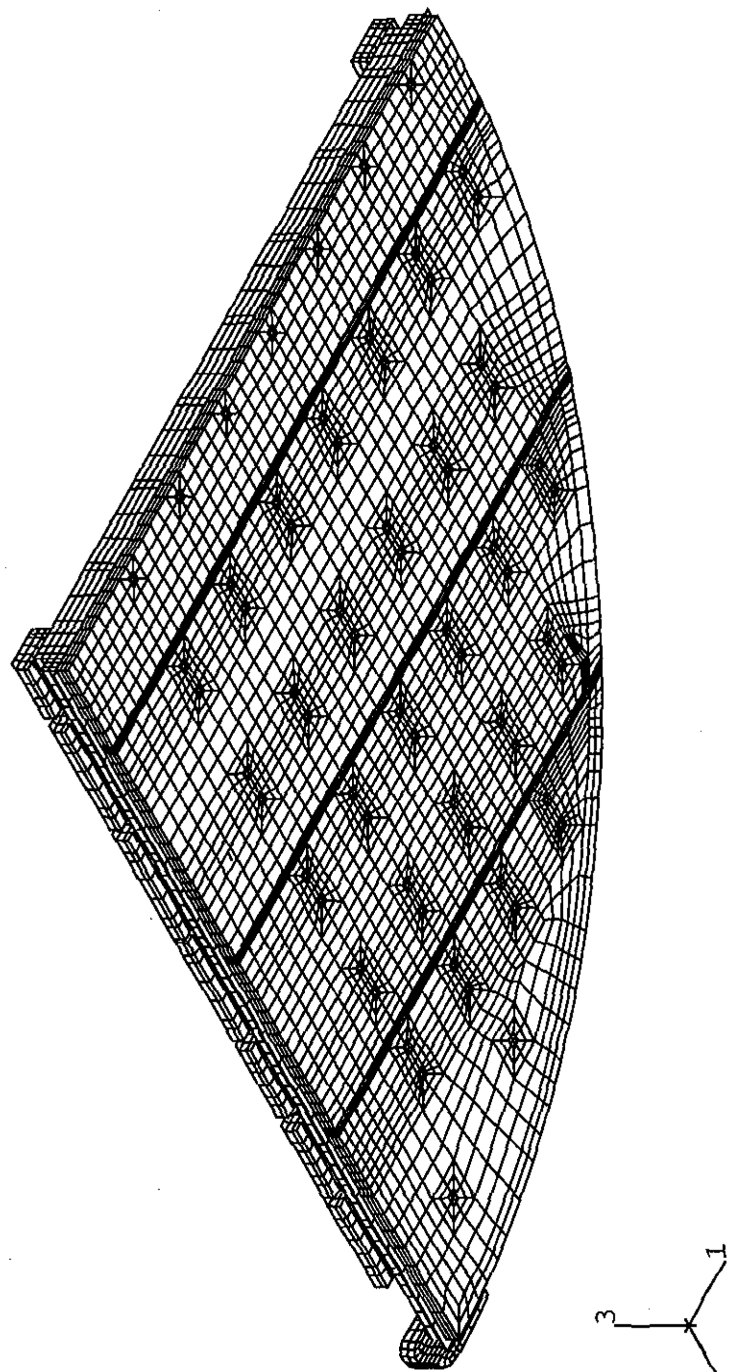
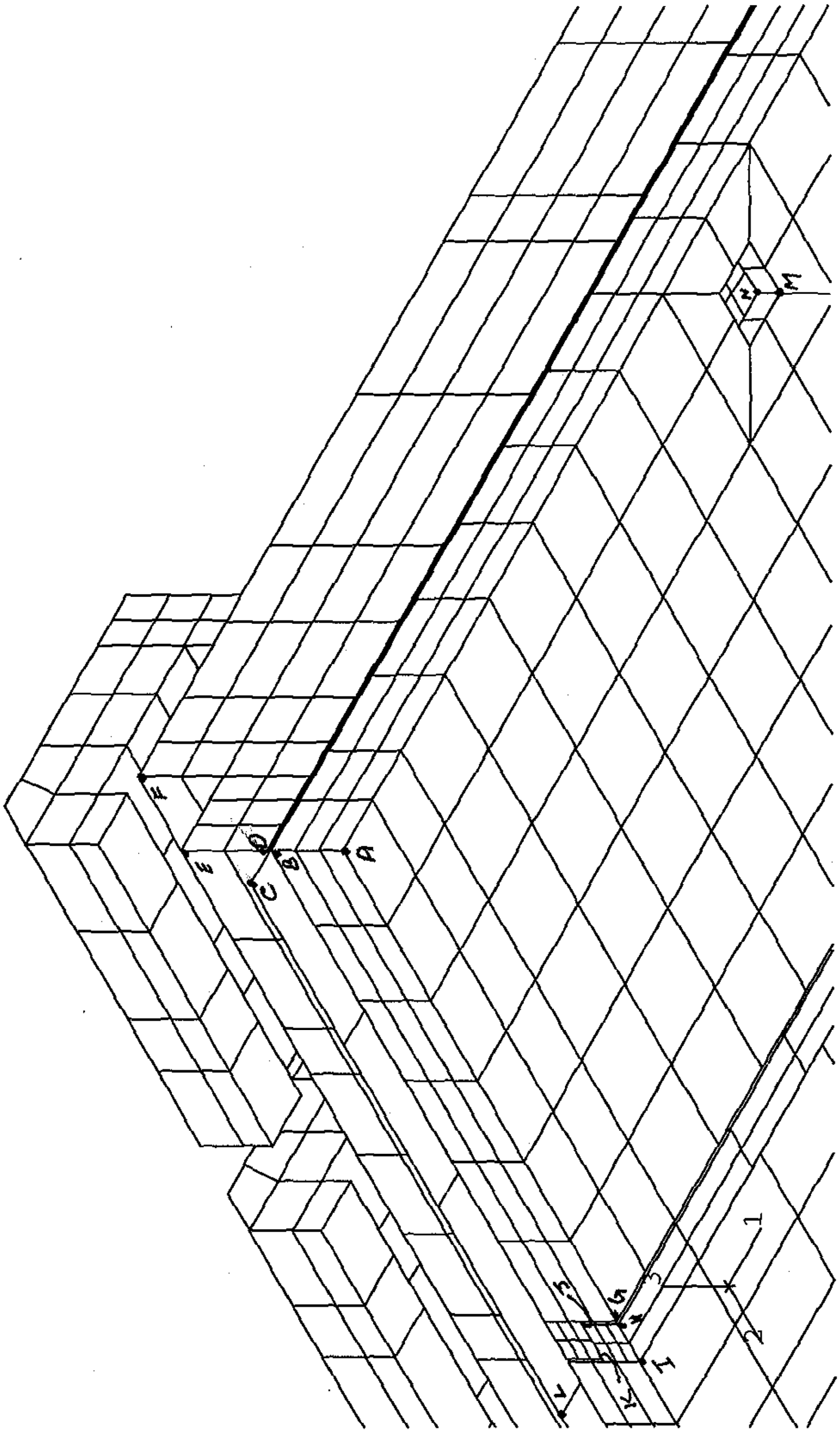


Figure 10 : Plot - Panel Assembly and Clamps - Fix Model - Bottom View

Figure 11 : Plot - Panel Assembly and Clamps - Fix Model - Tubesheet Side Closeup



*SEE FIGURE 16 FOR COORDINATES

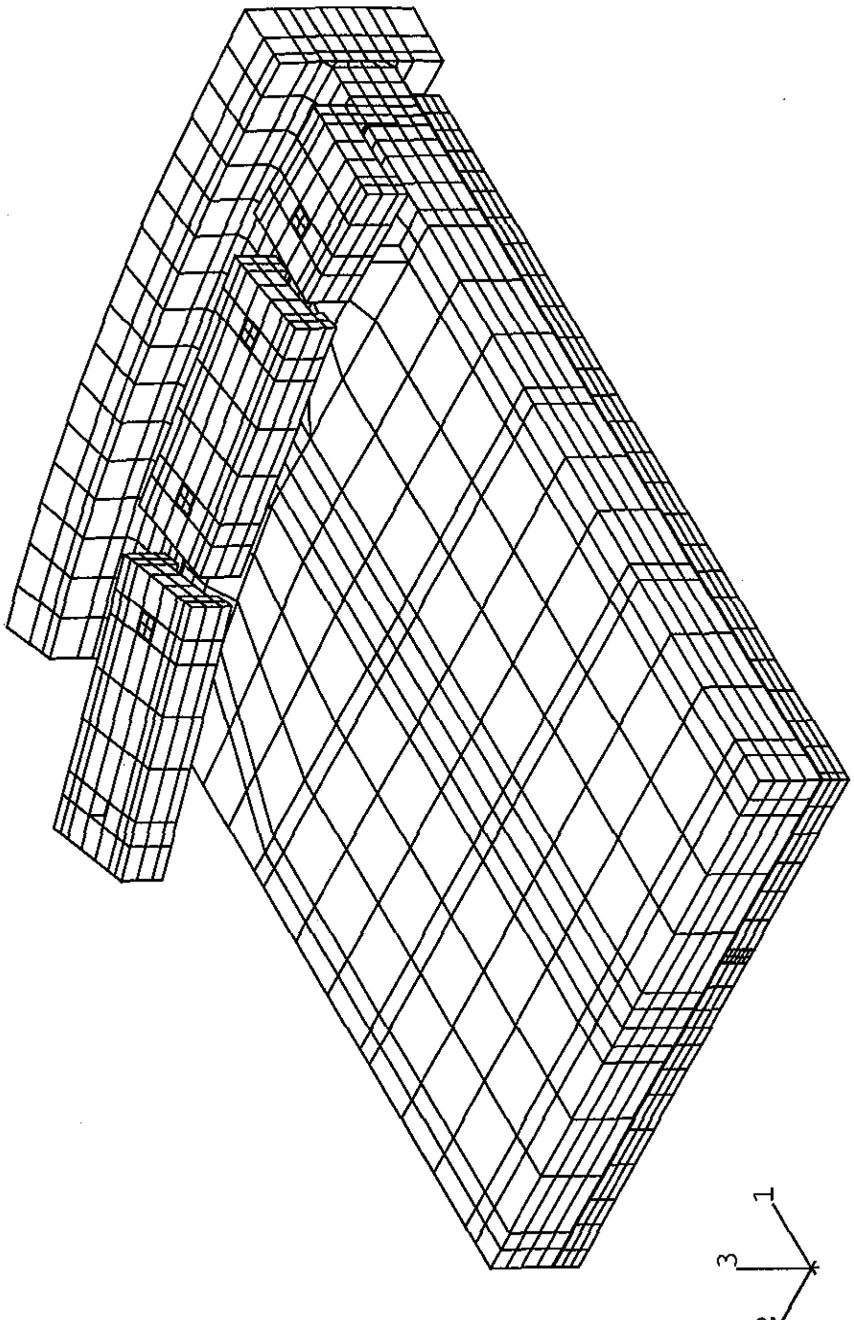


Figure 12 : Plot - Overall FEM Assembly - Test Model - Top View

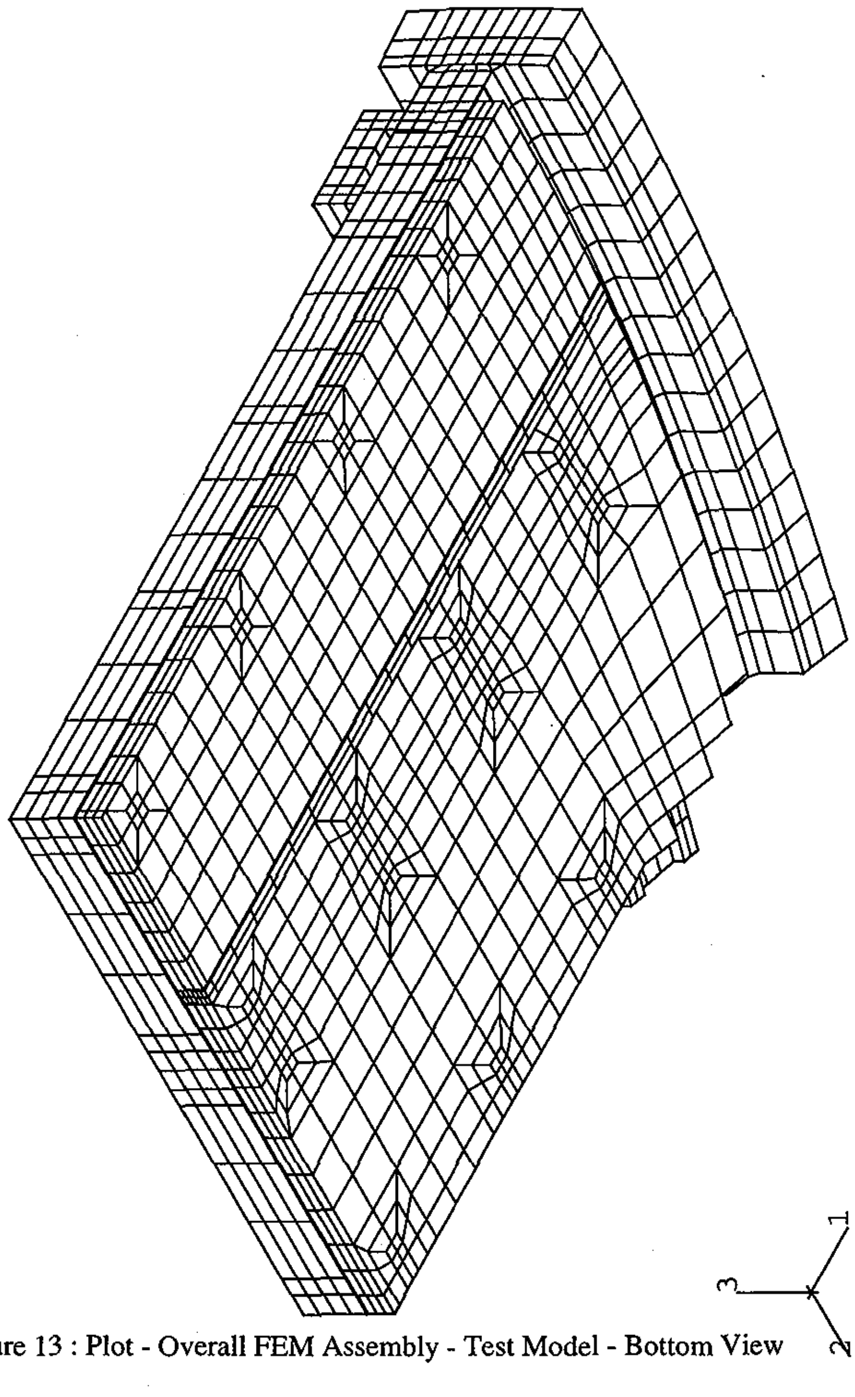
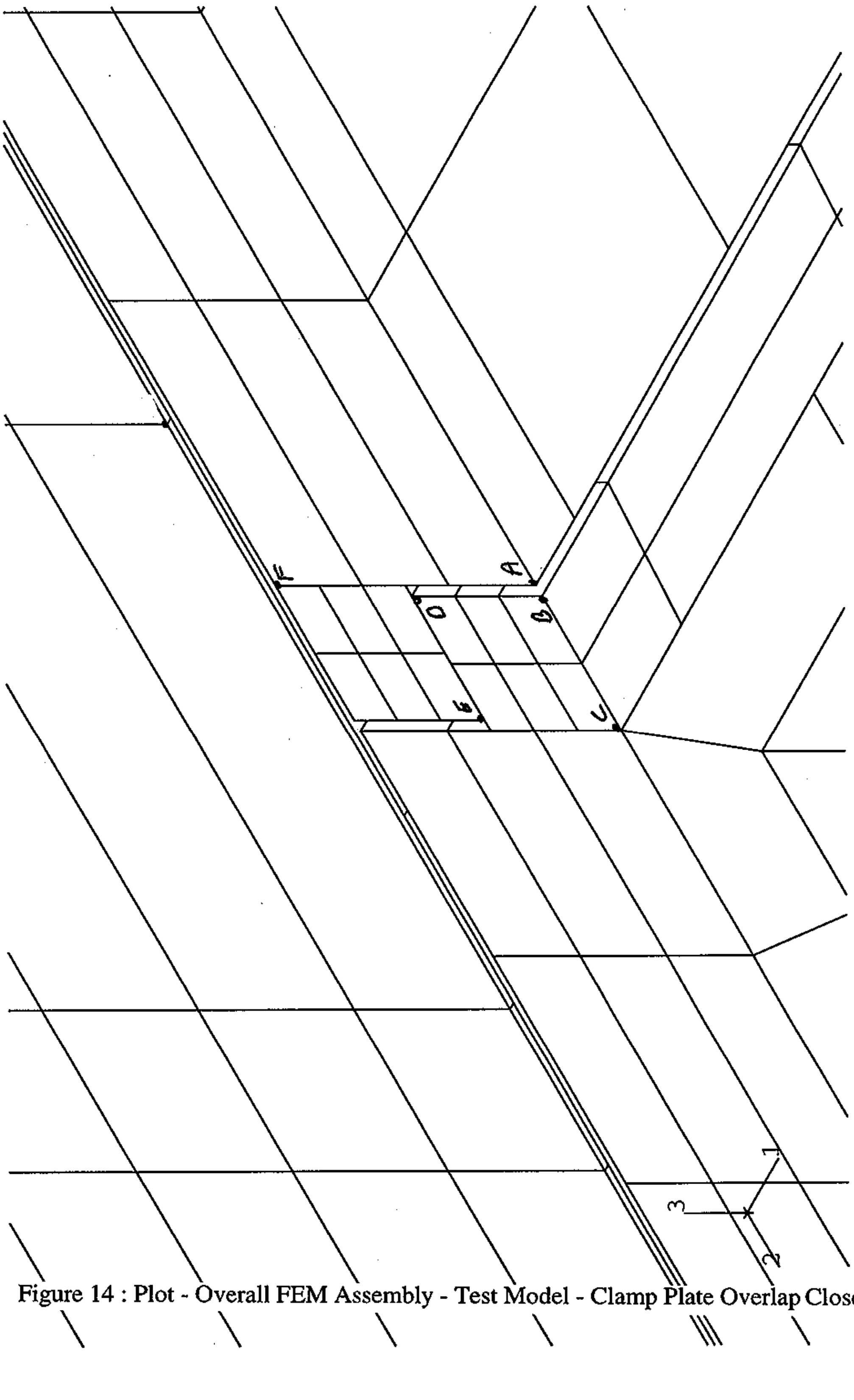
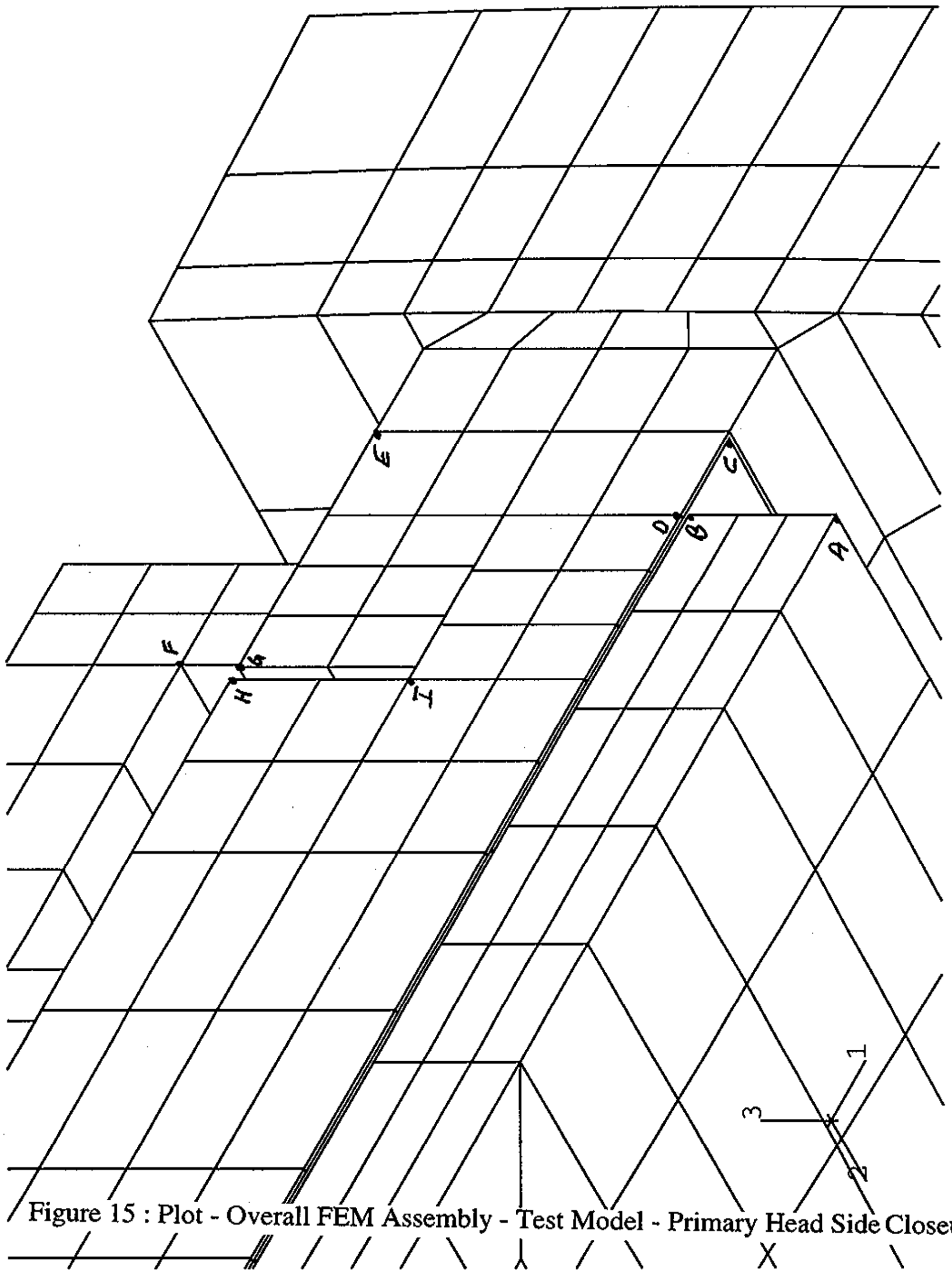


Figure 13 : Plot - Overall FEM Assembly - Test Model - Bottom View



* SEE FIGURE 16 FOR COORDINATES

Figure 14 : Plot - Overall FEM Assembly - Test Model - Clamp Plate Overlap Closeup



* SEE FIGURE 16 FOR COORDINATES

Figure 15 : Plot - Overall FEM Assembly - Test Model - Primary Head Side Closeup

N O D E   D E F I N I T I O N S

FIGURE 11

	NODE NUMBER	COORDINATES			NORMAL			SINGLE POINT CONSTRAINTS TYPE	PLUS	DOF
A	60028	1.1250	0.00000E+00	-1.4080	0.00000E+00	0.00000E+00	0.00000E+00	YSYMM		
B	60001	1.1250	0.00000E+00	-0.78300	0.00000E+00	0.00000E+00	0.00000E+00	YSYMM		
C	85305	0.79700	0.00000E+00	-0.76700	0.00000E+00	0.00000E+00	-1.0000	YSYMM		
D	15537	1.1250	1.00000E-04	-0.75000	0.00000E+00	0.00000E+00	0.00000E+00			
E	15561	1.1250	1.00000E-04	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00			
F	15597	1.8750	1.00000E-04	0.75000	0.00000E+00	0.00000E+00	0.00000E+00			
G	60086	1.1250	4.6932	-1.4080	0.00000E+00	0.00000E+00	0.00000E+00			
H	82887	1.1250	4.7232	-1.4080	0.00000E+00	0.00000E+00	0.00000E+00			
I	82889	1.1250	5.0983	-1.4080	0.00000E+00	0.00000E+00	0.00000E+00			
J	82869	1.1250	4.7232	-1.0958	0.00000E+00	0.00000E+00	0.00000E+00			
K	82349	1.1250	5.0682	-1.0953	0.00000E+00	0.00000E+00	0.00000E+00			
L	85369	0.79700	5.3232	-0.76700	0.00000E+00	0.00000E+00	-1.0000			
M	60389	7.6974	1.0099	-1.4080	0.00000E+00	0.00000E+00	0.00000E+00			
N	52641	7.6623	0.97483	-1.2500	0.00000E+00	0.00000E+00	0.00000E+00			

FIGURE 15

A	62534	40.875	0.00000E+00	-1.4080	0.00000E+00	0.00000E+00	0.00000E+00	YSYMM		
B	62507	40.875	0.00000E+00	-0.78300	0.00000E+00	0.00000E+00	0.00000E+00	YSYMM		
C	85365	41.250	0.00000E+00	-0.76700	0.00000E+00	0.00000E+00	-1.0000	YSYMM		
D	18861	40.604	1.00001E-04	-0.75000	0.00000E+00	0.00000E+00	0.00000E+00			
E	40700	41.285	0.00000E+00	0.75000	0.00000E+00	0.00000E+00	0.00000E+00	YSYMM		
F	3199	40.137	0.00000E+00	1.0000	0.00000E+00	0.00000E+00	0.00000E+00	YSYMM		
G	18716	40.063	1.00002E-04	0.75000	0.00000E+00	0.00000E+00	0.00000E+00			
H	39544	40.125	0.00000E+00	0.75000	0.00000E+00	0.00000E+00	0.00000E+00	YSYMM		
I	18708	40.063	1.00002E-04	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00			

FIGURE 14

A	61263	21.500	4.6932	-1.4080	0.00000E+00	0.00000E+00	0.00000E+00	XSYMM		
B	83322	21.500	4.7232	-1.4080	0.00000E+00	0.00000E+00	0.00000E+00	XSYMM		
C	83324	21.500	5.0983	-1.4080	0.00000E+00	0.00000E+00	0.00000E+00	XSYMM		
D	82953	21.500	4.7232	-1.0958	0.00000E+00	0.00000E+00	0.00000E+00	XSYMM		
E	82784	21.500	5.0682	-1.0953	0.00000E+00	0.00000E+00	0.00000E+00	XSYMM		
F	61188	21.500	4.6932	-0.78300	0.00000E+00	0.00000E+00	0.00000E+00	XSYMM		
G	85365	41.250	0.00000E+00	-0.76700	0.00000E+00	0.00000E+00	-1.0000	YSYMM		

Figure 16 : Table - Selected Coordinates Highlighted in Figures 11,14 and 15

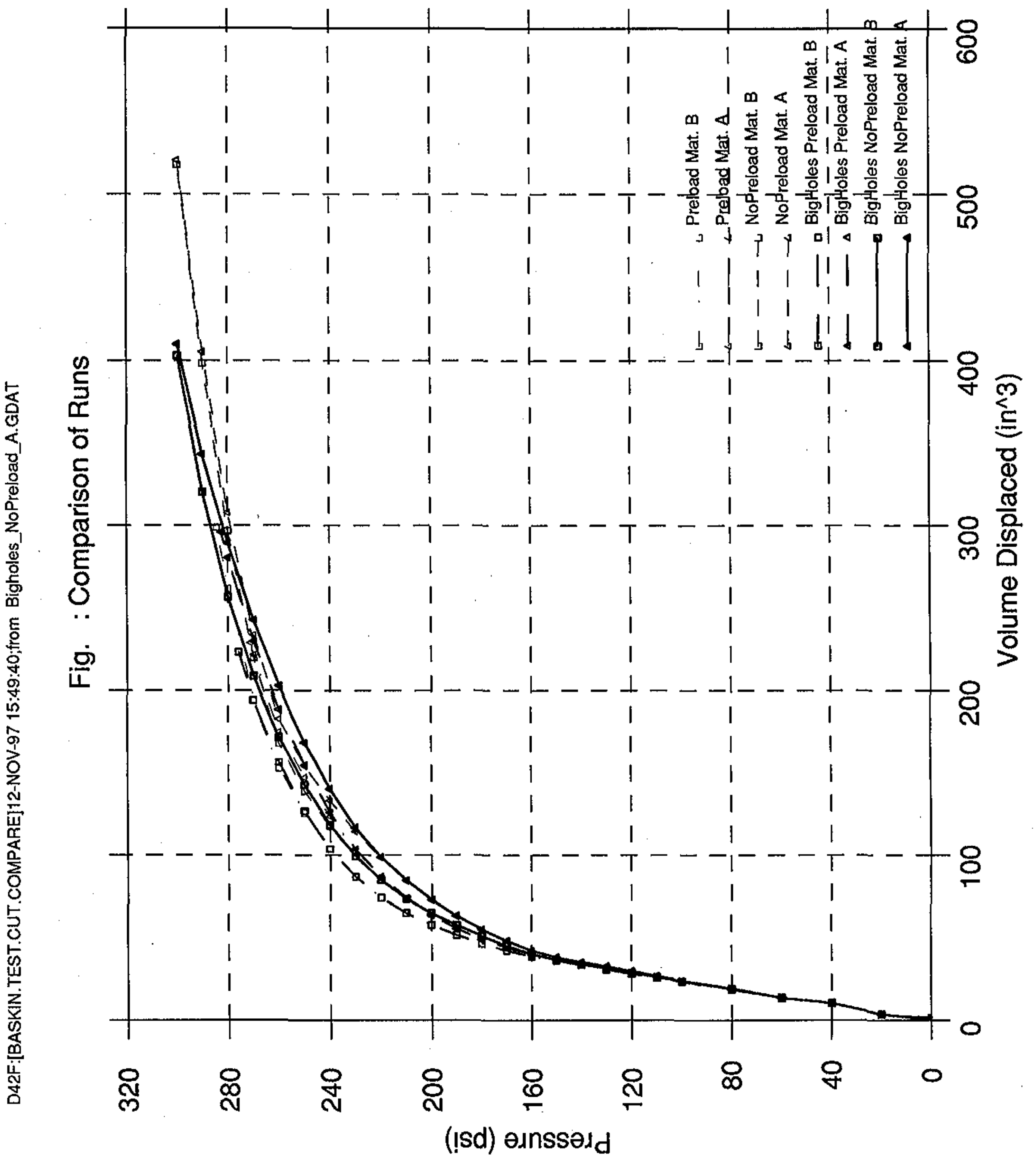


Figure 17 : Graph - Comparison of Test Case Runs - All Cases

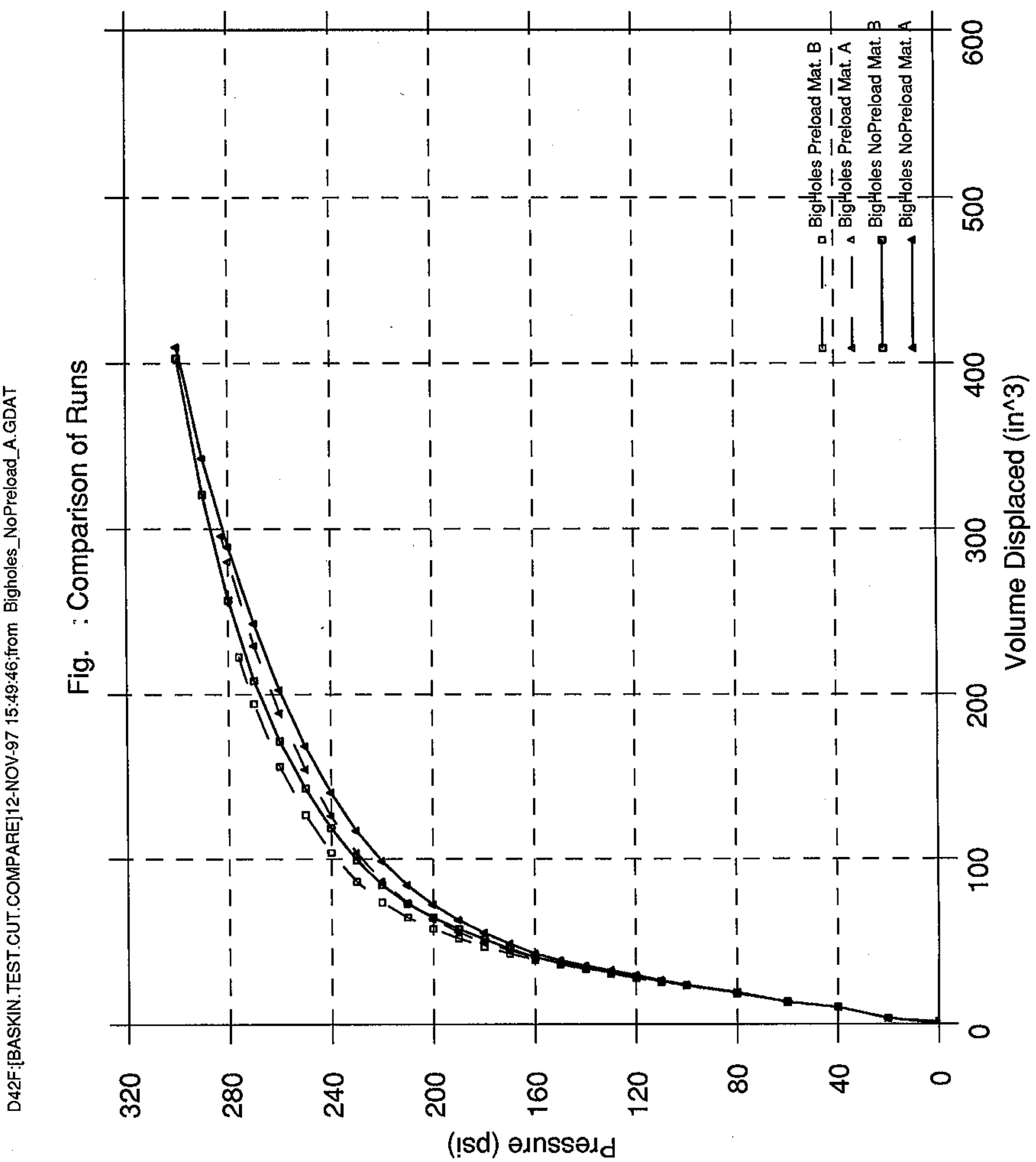


Figure 18 : Graph - Comparison of Test Case Runs - “BigHoles” Cases

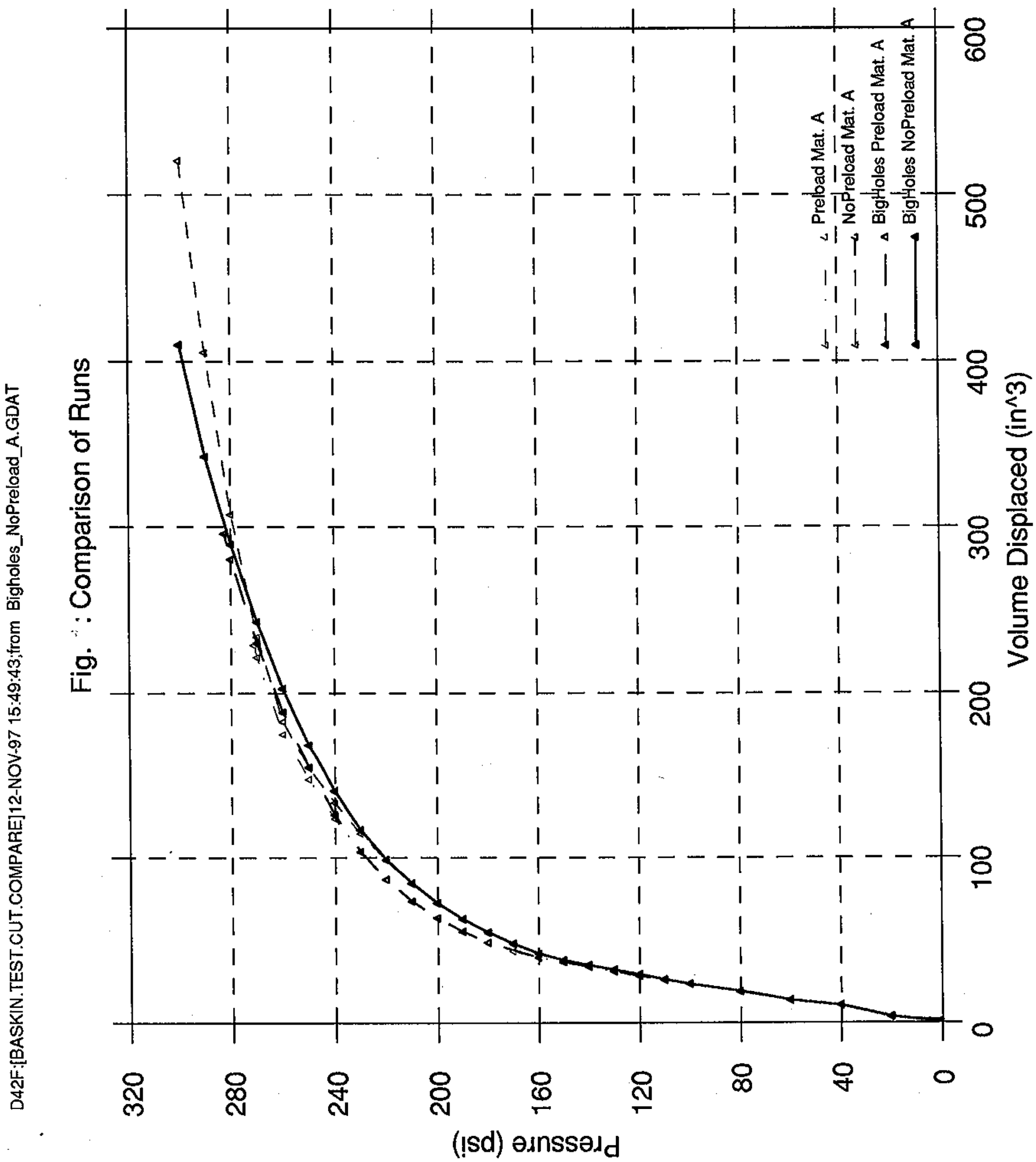


Figure 19 : Graph - Comparison of Test Case Runs - “Material A” Cases

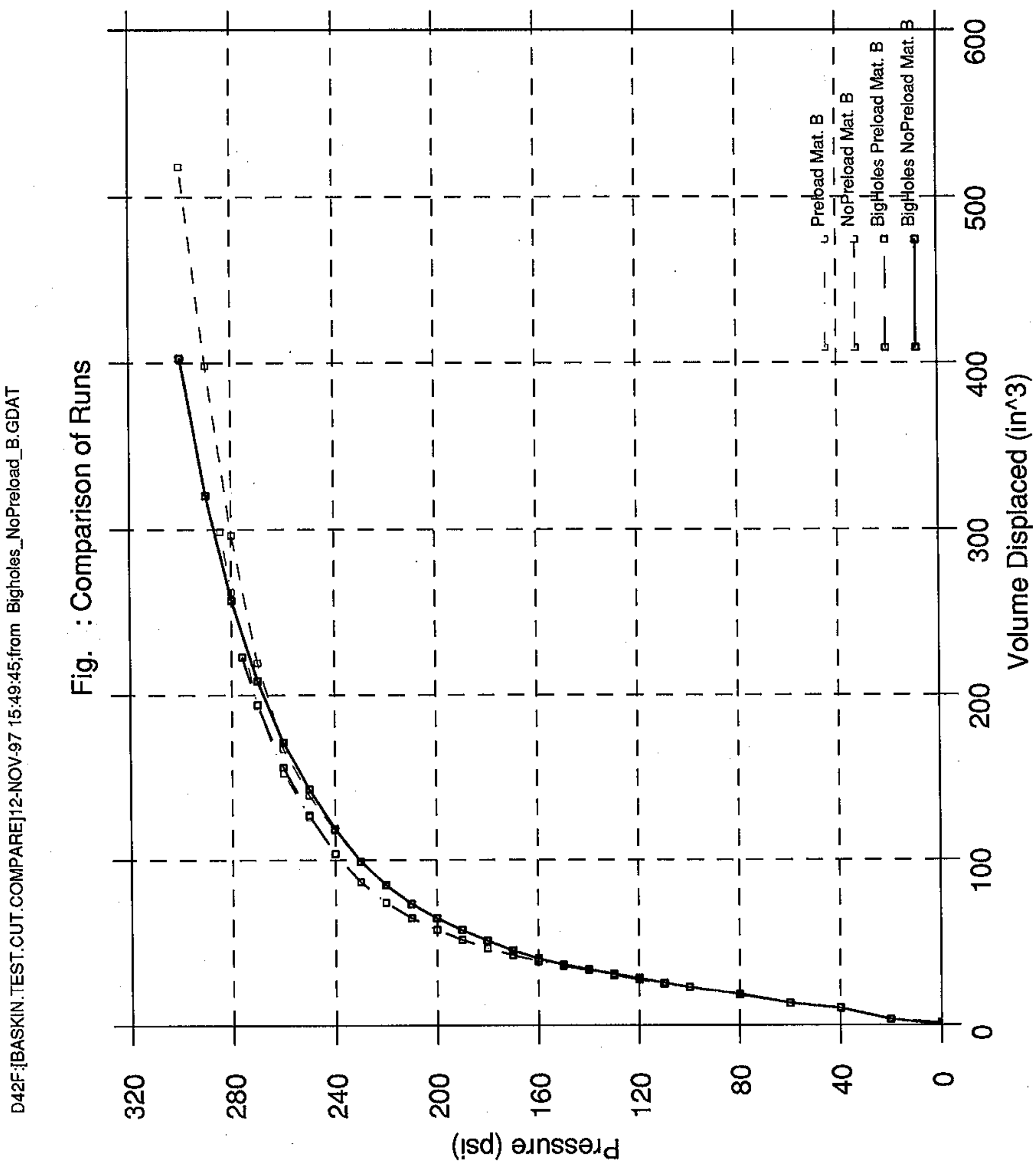


Figure 20 : Graph - Comparison of Test Case Runs - “Material B” Cases

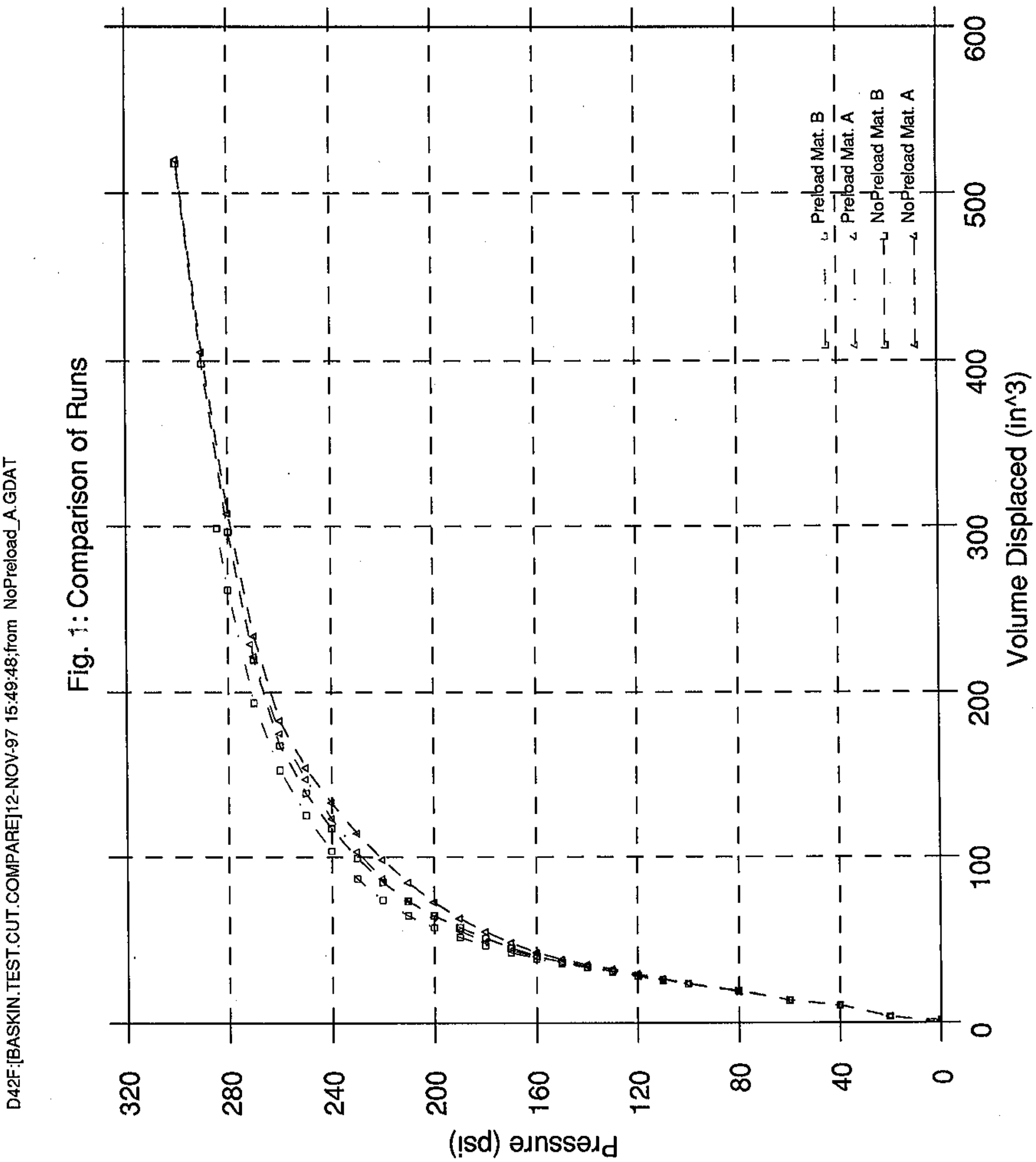


Figure 21 : Graph - Comparison of Test Case Runs - “Standard Holes” Cases