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FLAME TRENCH ANALYSIS OF NLS VEHICLES

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ABSTRACT

The present study takes the initial steps of establishing a better flame trench design criteria for future National Launch System vehicles. A three-dimensional finite element computer model for predicting the transient thermal and structural behavior of the flame trench walls was developed using both I-DEAS and MSC/NASTRAN software packages. The results of JANNAF Standardized Plume Flowfield calculations of sea-level exhaust plumes of SSME, STME and ASRM were analyzed for different axial distances. The results of sample calculations, using the developed finite element model, are included. The further suggestions are also reported for enhancing the overall analysis of the flame trench model.

SUMMARY

Pads 39A and B are being studied to determine if a new family of vehicles can be launched without damaging the existing structure. The new vehicles are designated as NLS (National Launch System). NLS is a family of vehicles which are built around a common core using different external booster configurations. The engines for the core and boosters have not been determined yet. Options include using old shuttle main engines (SSME), modified Saturn V engines (F-1A), Russian RD-170 engines, and solid fuel boosters. The flame trench capacity will be an important factor in the decision of these available options. Recently, the flame trench has been analyzed using simplifying assumptions for one of the NLS configuration at the Kennedy Space Center. Due to the importance of this problem an accurate, reliable solution is required.

The purpose of this summer research study is to investigate the capacity of the existing flame trench and to establish a better flame trench design criteria for future NLS launch vehicles. The solution of the problem requires the following steps:

1. A three-dimensional finite-element model of the flame trench walls.
2. The exit flow conditions of the rocket engine nozzles.
3. The complete analysis of the sea-level plume characteristics.
4. The plume impingement code to predict the heating and pressure rates on the flame trench.

The above steps are carried out as far as possible in the limited time available. As a first step three-dimensional finite element computer model is developed for predicting the transient thermal and structural behavior of the flame trench using I-DEAS and MSC/NASTRAN software packages. Secondly, the JANNAF Standardized Plume flowfield (SPF) is used to obtain the gas dynamic structure of sea-level exhaust plumes of different rocket exhaust flow fields. The analysis is also needed to gain a better understanding of heating rates and pressure rates on the flame trench walls. Since the steps described above are not completed fully at the present time, the results presented in this report should be looked at in a qualitative manner. However, these results will be used later to improve the required solution. The further suggestions are also reported for improving the overall analysis of the flame trench. It was concluded that the three-dimensional finite-element model of the flame trench can be tested for any given NLS configuration with slight modifications explained in section V.

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LIST OF ABBREVIATIONS AND ACRONYMS

ASRM - Advanced Solid Rocket Motors

FEM - Finite Element Modeling

I-DEAS - Integrated Design Engineering and Analysis System

JANNAF - Joint Army, Navy, NASA, Air Force

LC - Launch Complex

MLP - Mobile Launch Platform

NLS - National Launch System

RAMP - Reacting Multiphase

SFPLIMP - Source Flow Plume Impingement Program

SPF - Standardized Plume Flowfield

SRM - Solid Rocket Motors

SSME - Space Shuttle Main Engine

SSV - Space Shuttle Vehicle

STME - Space Transportation Main Engines

I. INTRODUCTION

The existing flame trench at Launch Pad 39A was built in 1967 for the Apollo space program. An identical launch pad was built in 1969 and named Pad 39B. Both pads were converted to be used with the space shuttle in 1981. The flame trench has not been modified since its construction. Pads 39A and B are being studied to determine if a new family of vehicles can be launched without damaging the existing structure. The new vehicles are designated as NLS (National Launch System). NLS is a family of vehicles which are built around a common core using different external booster configurations. The engines for the core and boosters have not been determined. Options include using old shuttle main engines (SSME), modified Saturn V engines (F-1A), Russian RD-170 engines, and solid fuel boosters. The flame trench capacity will be an important factor in the decision process.

The flame trench is built of reinforced concrete lined with a refractory coating and alumina fire brick. It is 58 feet wide and 42 feet deep. There is a parabolic flame deflector directly under the vehicle to divert the flow to the north and south exists from the flame trench.

The flame trench is limited in temperature and pressure capacity. The effects of an exhaust plume in the trench have not been studied. Excessive amounts of pressures could cause the trench walls to crack and excessive amounts of temperatures could damage the refractory coating.

KSC-STD-Z-0012B, Standard for Flame Deflector Design, is the only design criteria standard currently available to the flame trench. This standard establishes minimum design requirements for the height, width and distance away from the engines that the flame deflector must comply with. Currently, the deflector width has been empirically established as a minimum of 1.6 times the sum of all the vehicle engine nozzle diameters impinging on a common surface. The width and depth of the flame trench must then be sized to accommodate the flame deflector.

The purpose of this study is to investigate the capacity of the existing flame trench for different exhaust configurations and to establish a better flame trench design criteria for future NLS launch vehicles. The study is carried out based on the drawing number 79K10338 and Figure 1 shows the general overview of the PAD39B.

Main thrust of the summer research study can be summarized as:

(1) Survey literature of available computer codes for the problem solution including the nozzle design, plume flow, plume impingement and finite-element programs.

(2) Developing a three-dimensional finite-element model using I-DEAS and MSC/NASTRAN softwares for the flame trench walls.

(3) Using Joint Army, Navy, NASA, Air Force (JANNAF) Standardized Plume Flowfield code (SPF) for predicting the gas dynamic structure of sea-level rocket exhaust plumes.

(4) Better prediction of the pressure and heating rates on the flame trench walls using Source Flow Plume Impingement Program (SFPLIMP).

II. DESCRIPTIONS OF THE COMPUTER CODES REQUIRED FOR THE STUDY

The computer codes required to solve the problem are briefly described below:

2.1 RAMP CODE

The Reacting multiphase (RAMP) code was developed by Lockheed-Huntsville under government funding and used to solve a wide variety of problems associated with real gas, supersonic, compressible flow (Ref. 1). The code is capable of performing rocket nozzle flow calculations and has a direct interface with the JANNAF CODE. The code is fully coupled in that it considers the exchange of momentum and energy between the gas particle plumes. The results of the nozzle solution via RAMP code must be presented in the form of radial distributions of properties at the exit plane as being the initial conditions for the JANNAF code.

2.2 JANNAF CODE

There has been remarkable progress in developing mathematical simulations of the complicated structure and behavior of the plume phenomena in the past decade. A number of review papers and computer programs are available to give the researcher a general overview of the state-of-the-art in rocket exhaust plume analysis (Refs. 2 through 4).

Joint Army, Navy, NASA, Air Force (JANNAF) Standardized Plume Flowfield (SPF) is a computer code which is accepted as government and industry standard for predicting the gas dynamic structure of two-phase low altitude rocket exhaust plumes. Figure 2 illustrates a schematic of the plume flowfield regions. The computational methodology employed in the latest version (SPF-II) of the JANNAF code is described in Ref. 5.

The code mainly contains three principal components: Processor, Shock Capturing and Turbulent Mixing component. Processor component reads the user input data (run parameters, chemical systems, initial conditions and external flow conditions) and data bank (JANNAF thermodynamic and chemical kinetic data for the species). It also creates the input files required for the shock-capturing and turbulent mixing components. Additionally, the Processor uses laminar viscosity and thermal conductivity data embedded in a subroutine.

The Shock-Capturing Component of the code provides an inviscid, frozen chemistry solution of the plume nearfield region. It uses shock-capturing to account for the detailed shock structure, and it fully accounts for gas/particle interactions. The Shock-Capturing Component is utilized for a distance of approximately two inviscid cells which is coded as three times the distance to the Mach disc.

The Turbulent Mixing Component of SPF provides a viscous, turbulent mixing solution of the plume shear layer with finite-rate chemistry. Gas/particle interactions are fully accounted for, with the local fluid viscosity and thermal conductivity. Code offers different forms of turbulence modeling through this component.

2.3 SFPLIMP CODE

The Source Flow Plume Impingement Program (SFPLIMP) is a program designed to compute the forces, moments and heating rates caused by plume impingement on bodies immersed into plume flow fields. The code is capable of modeling on a wide range of configurations. In addition to the plume and processing data, user must provide a three-dimensional representation of a target geometry. The code is capable of modeling several subshapes including flat plates (right triangles, rectangles and circles) and three-dimensional shapes (circular cones, circular cylinders, spheres and polynomials of revolution).

2.4 I-DEAS FEM PACKAGE

I-DEAS Finite Element Modeling (FEM) allows the user to build a finite element model, including physical and material properties, loads, and boundary conditions. This package has excellent pre-processing and post-processing features. Solving the model generally runs in I-DEAS Model Solution. The model solution can solve problems in linear statics and in steady-state heat transfer. For other types of analysis such as transient heat transfer, I-DEAS Model Solution can write the entire FEA model to outside solver package.

2.5 MSC/NASTRAN CODE

MSC/NASTRAN is a large scale general purpose digital computer program which solves a wide variety of engineering problems by the finite element method. This code can analyze linear, non-linear and transient heat transfer with constant or temperature-dependent convective and radiative boundary conditions. The code can use isotropic and anisotropic temperature dependent thermal conductivity material properties. It also provides a user-selected difference parameter for stability in transient solution algorithm.

MSC/NASTRAN operates in a batch mode. Input to the batch process is usually in the form of a card deck or card image file. The data deck is constructed preparing the cards for executive control deck. The purpose of this deck is to identify the job and the type of solution to be performed. It also declares the general conditions under which the job is to be executed, such as maximum time allowed, type of system diagnostics desired etc. The user next sets the data cards for the case control deck. This deck defines the load case, selects the data from the Bulk Data Deck and makes the output requests for plotting. The Bulk Data Deck is the final step of organizing the card decks. This deck contains the majority of the input data for the file. It includes all the data necessary to describe the thermal model and its loading conditions.

III. METHODOLOGY

Figure 3 shows the computational scheme required for the problem solution. The JANNAF computer code requires the exit conditions of the engine nozzle to start the calculations for sea-level plume definition of the proposed exhaust configuration. The results from the JANNAF code must be run to predict the loading conditions of the finite element model. The I-DEAS and MSC/NASTRAN codes must be then used to determine the capacity of the flame trench for different NLS configurations.

3.1 FINITE ELEMENT MODEL

The flame trench facing to the north side of Pad 39B is modeled by a three-dimensional finite element model starting at the base of the exhaust deflector, running approximately 50 feet toward the north along the centerline of the plume footprint. Figure 4 shows the three-dimensional model used in the study. The model is built of from 280 nodes and 162 solid brick type of elements. The model uses physical and thermal material properties of concrete and brick. The concrete stiffeners shown in drawing 79K10338 were modeled with the restraint set as shown in Figure 5.

3.2. HEATING LOADS AND PRESSURE LOADS

The impingement of the Space Shuttle Main Engines (SSME) and Solid Rocket Motors (SRM) or Advanced Solid Rocket Motors (ASRM) gaseous exhaust plumes on Launch Complex 39 (LC-39) results in pressure loads and convective heating to numerous components. Reference 6 presents the results of a study to determine the thermal and pressure environment imposed on elements of LC-39 by impingement of the Space Shuttle Vehicle (SSV) exhaust plumes at the sea level for a maximum north drift trajectory. The plume properties given in this reference are used to establish pressures and heating loads to objects immersed in the ASRM or SSME exhaust plume. Reference 6 do not take into account for radiation from plume exhaust turned by the Mobile Launcher Platform (MLP) and recirculation. Prediction of this water-cooled launch pad radiation is not readily computed due to the extreme changes of rocket plume flow field properties and recirculated flow field environments during launch.

Both SRM and SSME flame trenches are subjected to heating due to vehicle exhaust gases that have flowed down the trench after having impinged on the flame deflector. A rigorous calculation of the thermal and pressure environments of objects subjected to indirect impingement requires a three-dimensional analysis of the flow field which would be far beyond this study due to time limitation. Therefore, a simplified approach is used for the heating and pressure loads required for the study. The heating rates were calculated for each point on the flame trench as described in Reference 6, assuming that the heating rate at the point where the plume initially strikes the flame deflector varies with the distance down the flame deflector and flame trench, taken to the 0.2 power.

The heat loading conditions, used in the present study, include the face heat influx distribution to fifty-four of the elements as presented in Table 1 as explained in the previous paragraph and face convection applied to the back surface of the model. The heat transfer coefficient for face convection was calculated based on the recommendation of Churchill and Chu (Ref. 7).

The results of the gaseous and particle plume impingement pressure loads from the plumes are also included in Reference 6. It is assumed that the gaseous flow and particles travel parallel to the trench walls. The estimates of pressure loads to the flame trench are presented as a result of indirect impingement. The face pressure level of 2 atmospheres is used as recommended in Reference 6.

IV. RESULTS

Since the I-DEAS software package can not provide transient temperatures and better predictions of the time dependent loads are required, the calculations presented in this section should be looked at qualitatively.

Figure 6 depicts the displacement contour lines for constant applied face pressure loading of 2 atmospheres for the static run only. Contour level 6 indicates the maximum displacement of .002 inches. The maximum displacement contour levels occur close to the midpoint of the two concrete stiffeners at the center of the model. Following program execution the deformed shape of the structure is shown in Figure 7. It is notable that the structure deforms in a manner which agrees with its expected deformation. Figure 8 shows the stress contour levels for the same loading condition.

Figure 9 illustrates the steady-state temperature contours of the resulting model based on the applied face heat flux and face convective heat transfer. Maximum temperatures of 2600 degrees Fahrenheit were observed at alumina brick close to the deflector as expected. Appendix provides the necessary MSC/NASTRAN data cards for transient heat transfer analysis. Table 2 presents the results of the transient analysis with MSC/NASTRAN finite element program during the first three seconds of launch.

Both I-DEAS and MSC/NASTRAN are capable of computing thermal stress analysis due to the thermal loading conditions. In this process, the first run (thermal analysis) will calculate the temperature distribution in the model due to the given thermal loads and boundary conditions. The second run (structural analysis) uses these calculated temperatures as temperature loads to a structural analysis to calculate the displacements and stresses caused by the temperatures. Figure 10 and 11 illustrate the displacement and stress contour lines, respectively.

The sea level plume definitions were calculated with the JANNAF code using an exit plane start line generated with the RAMP code. Tables 3 through 5 include the plume properties (Mach number, temperature and pressure) of ASRM, SSME and STME sea-level plumes for different axial distances at a radial distance of 2 feet.

V. CONCLUSIONS AND RECOMMENDATIONS

A computational scheme has been proposed and partially developed for the flame trench capacity of different NLS exhaust configurations. Three-dimensional finite element model presented in this study can be used effectively to analyze thermal and structural acceptability of the flame trench for proposed loading conditions. Further improvements on the FEA model may include: addition of the reinforced concrete material conditions to the model, addition of the temperature dependence to the properties and the convergence check of the results with a better mesh refinement of the FEA model.

Suggestions for completion of the problem are listed below:

- Use of reacting multiphase nozzle code for Saturn V and Russian RD-170 engines.

- Run of the JANNAF Plume code for Saturn V and Russian RD 170 engine exit nozzle conditions.

- Calculations of the impingement pressure loads, convective heating loads and radiation heating loads on the flame trench walls using SPFPLIMP code.

- Setting temperature and stress limits for the flame trench model.

APPENDIX

```
ID DIRECT TRANSIENT,                          P3DMOD1
$
$   MAXIMUM CPU TIME ALLOWED FOR THE JOB
$
TIME 10 $ UNITS ARE IN MINUTES
$
$   THE THERMAL ANALYZER PORTION OF MSC/NASTRAN IS TO BE USED
$
APP HEAT
$
$   THE TRANSIENT ALGORITHM IS TO BE USED
$
SOL 89
CEND $ END OF EXECUTIVE CONTROL DECK
$
$******
$   END OF EXECUTIVE CONTROL ... START CASE CONTROL
$******
$
TITLE=TRANSIENT PROBLEM      ---     UNITS=BG
$   REQUEST SORTED AND UNSORTED CARD ECHO=S TO SEE COMMENTS
$   IF THIS CARD IS OMITTED ONLY THE SORTED BULK DATA WILL APPEAR
$   COMMENT CARDS WOULD THEN NOT BE PRINTED
ECHO=BOTH
$
$   SPECIFY THE SUPERELEMENTS TO BE RUN. THIS CARD IS REQUIRED
$   AND SPECIFIES ALL FOR THIS MODEL THERE IS BUT A SINGLE
$   SUPERELEMENT WHICH ENCOMPASSES THE ENTIRE MODEL
SEALL=ALL
DLOAD=300
TEMP(ESTI)=400
IC=400
TSTEP=500
$   SELECT THE OUTPUT DESIRED
$   OUTPUT
THERMAL=ALL
SUPER=ALL
FLUX=ALL
SUBTITLE=CASE SET 2, LOAD SET 2
$   END CASE CONTROL DECK
BEGIN BULK
***** BULK DATA RECEIVED FROM THE I-DEAS ******
*****          1085 LINES OF ENTRY        ******
TLOAD2,300,2,,0.,1.+6,0.,0.,+TL1
+TL1,0.,0.
TEMPD,400,70.
TSTEP,500,10,.2,1
PARAM AUTOSPC  YES
PARAMPOST   -2
ENDDATA
```

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2. Dash, S.M., "Recent Developments in the Modeling of High Speed Jets, Plumes and Wakes, "AIAA Paper 85-1616, presented at AIAA 18th Fluid Dynamics Plasma Dynamics and Laser Conference, July 1985.

3. Wolf, D.E., and Dash, S.M., "Interactive Phenomena in a Supersonic Jet Mixing Plumes, Part I: Phenomenology and Numerical Modeling Technique," AIAA Journal, Vol.22, No. 7, July 1984, pp. 905-913.

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6. Environment and Test Specification Levels Ground Support Equipment for Space Shuttle System Launch Complex 39, GP-1059 Volume IV, Engineering and Development Directorate, April 1992.

7. Fundamentals of Heat and Mass Transfer, Incropera, F.P. and Dewitt, D.P., Second Edition, Wiley Publ., 1985.

TABLE 1

The Face Heat Influx Distribution on the Brick Elements using I-DEAS software

HEATING RATE (Ref. 6)
BTU/(FEET**2 SEC)

DISTANCE FROM THE DEFLECTOR BASE (FEET)	DISTANCE FROM THE FLOOR (FEET)					
	3.5	10.5	12.5	24.5	31.5	38.5
2	240.16	282.44	372.68	372.68	282.44	240.56
6	192.81	226.76	299.20	299.20	226.76	192.81
10	174.04	204.69	270.09	270.09	204.69	174.04
15	160.55	188.83	249.16	249.16	188.83	160.55
21	150.12	176.57	232.97	232.97	176.57	150.12
27	142.70	167.83	221.45	221.45	167.83	142.70
33	137.08	161.22	212.73	212.73	161.22	137.08
40.5	131.91	155.14	204.71	204.71	155.14	131.91
47.5	128.86	151.54	199.96	199.96	151.54	128.86

TABLE 2

Results of the Transient Analysis with MSC/NASTRAN Program

TEMPERATURE (DEGREES IN FAHRENHEIT)

DISTANCE FROM THE DEFLECTOR BASE

TIME (SEC)	X=0'	X=12'	X=24'	X=36'	X=50'
0.0	100	100	100	100	100
0.2	227	185	174	168	165
0.4	505	371	337	318	309
0.6	731	523	471	441	426
0.8	893	634	568	530	511
1.0	1037	734	655	610	588
1.2	1160	819	730	679	654
1.4	1272	898	800	743	713
1.6	1376	972	864	802	772
1.8	1474	1043	926	859	826
2.0	1568	1111	985	914	878
2.2	1659	1178	1043	967	929
2.4	1747	1243	1100	1019	979
2.6	1834	1308	1157	1071	1029
2.8	1920	1373	1212	1122	1078
3.0	2003	1436	1268	1173	1126

TABLE 3

Sea Level ASRM, SSME and STME Exhaust Plumes
Axial Mach Number Distributions

Axial Distance (FEET)	MACH NUMBER ASRM	SSME	STME
50	2.363	1.466	2.690
100	2.363	1.145	1.441
150	2.358	0.615	0.812
200	2.096	0.387	0.494
250	1.758	0.278	0.344
300	1.467	0.216	0.262
350	1.224	0.177	0.211
400	1.026	0.150	0.177
450	0.869	0.131	0.153
500	0.743	0.116	0.134
550	0.642	0.105	0.120
600	0.561	0.096	0.109

TABLE 4

Sea Level ASRM, SSME and STME Exhaust Plumes
Axial Temperature Distributions

Axial Distance (FEET)	TEMPERATURE (DEGREES RANKINE) ASRM	SSME	STME
50	3879	4918	4060
100	3879	4564	4849
150	3898	3198	4194
200	4233	2134	2890
250	4607	1597	2080
300	4848	1308	1635
350	4973	1134	1371
400	4988	1021	1202
450	4904	943	1086
500	4740	885	1003
550	4496	842	941
600	4175	808	893

TABLE 5

Sea Level ASRM, SSME and STME Exhaust Plumes
Axial Pitot Pressure Distributions

Axial Distance (FEET)	PITOT PRESSURE (PSIA)		
	ASRM	SSME	STME
50	105.8	51.9	97.6
100	105.8	31.4	43.2
150	105.3	18.6	21.8
200	84.5	16.2	17.2
250	61.6	15.5	15.9
300	45.4	15.2	15.4
350	34.3	15.0	15.2
400	27.3	14.9	15.0
450	23.1	14.9	14.9
500	20.5	14.8	14.9
550	18.9	14.8	14.9
600	17.9	14.8	14.8

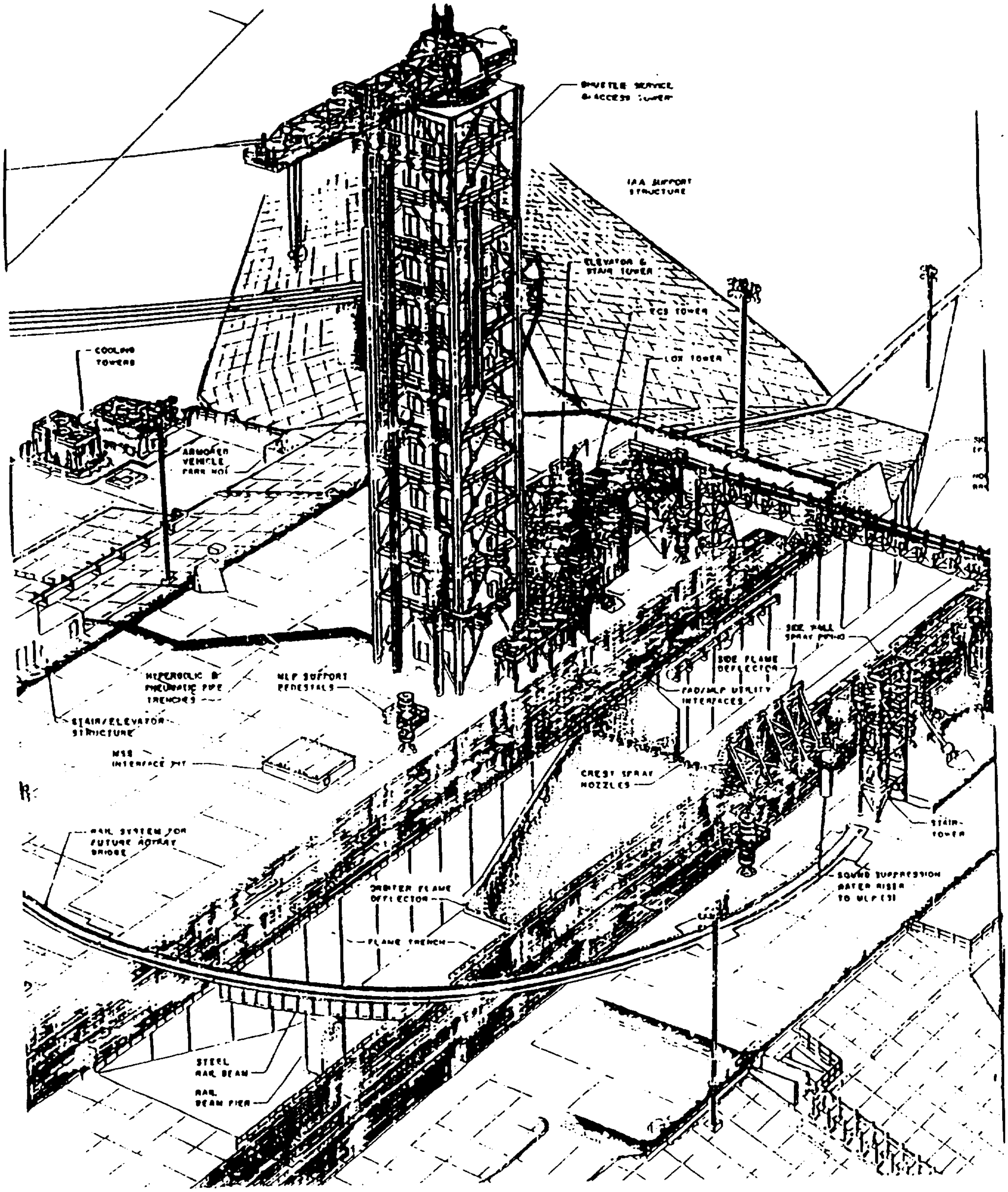

Figure 1 General Overview of PAD 39B

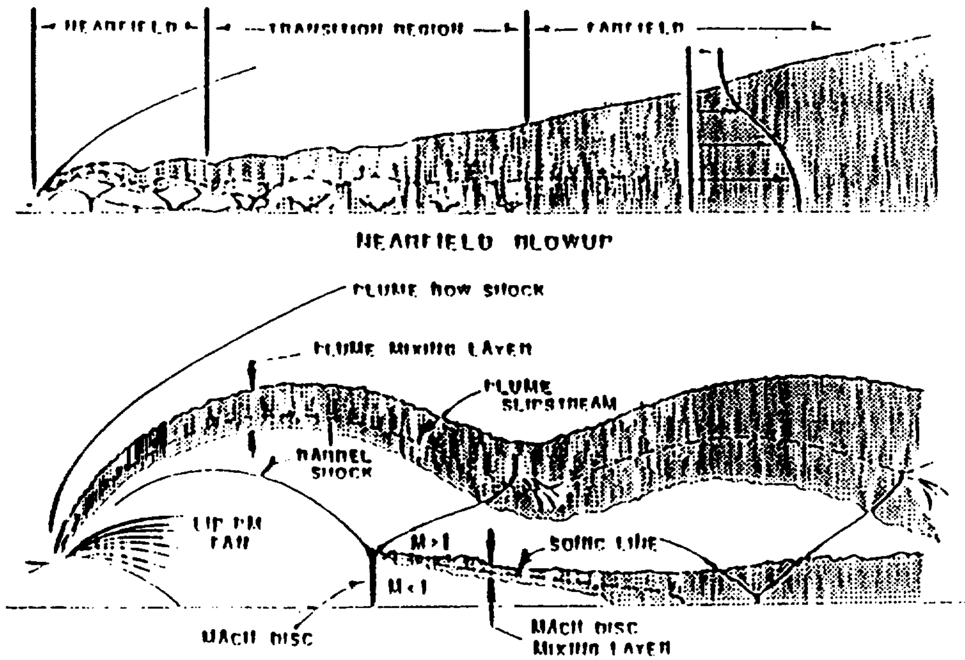

Figure 2 A Schematic Representation of the Plume Flowfield Regions

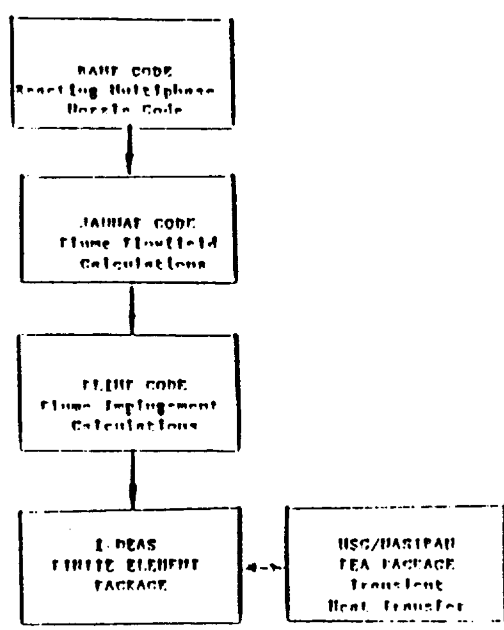

Figure 3 Computational Scheme

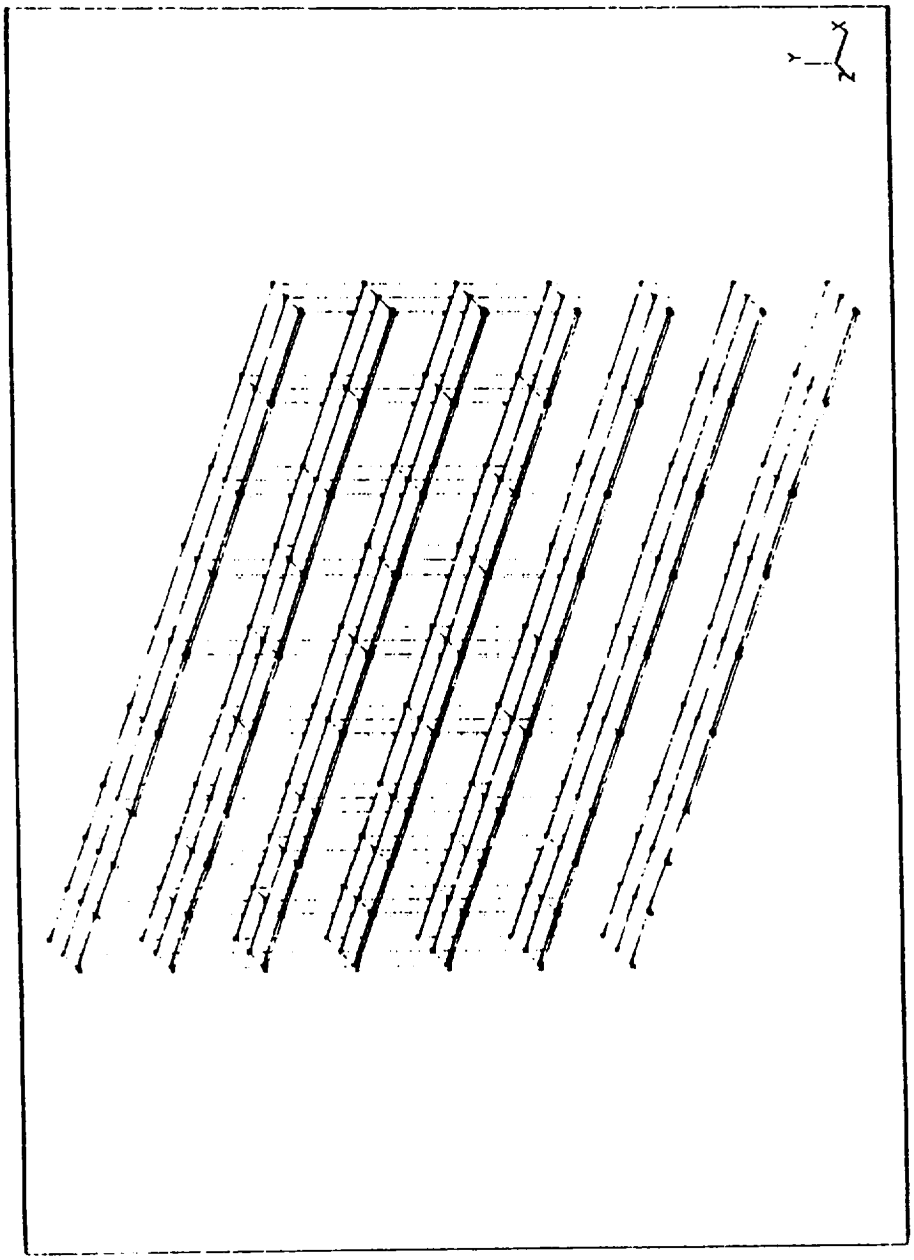

Figure 4 Three-Dimensional Model of the Flame Trench

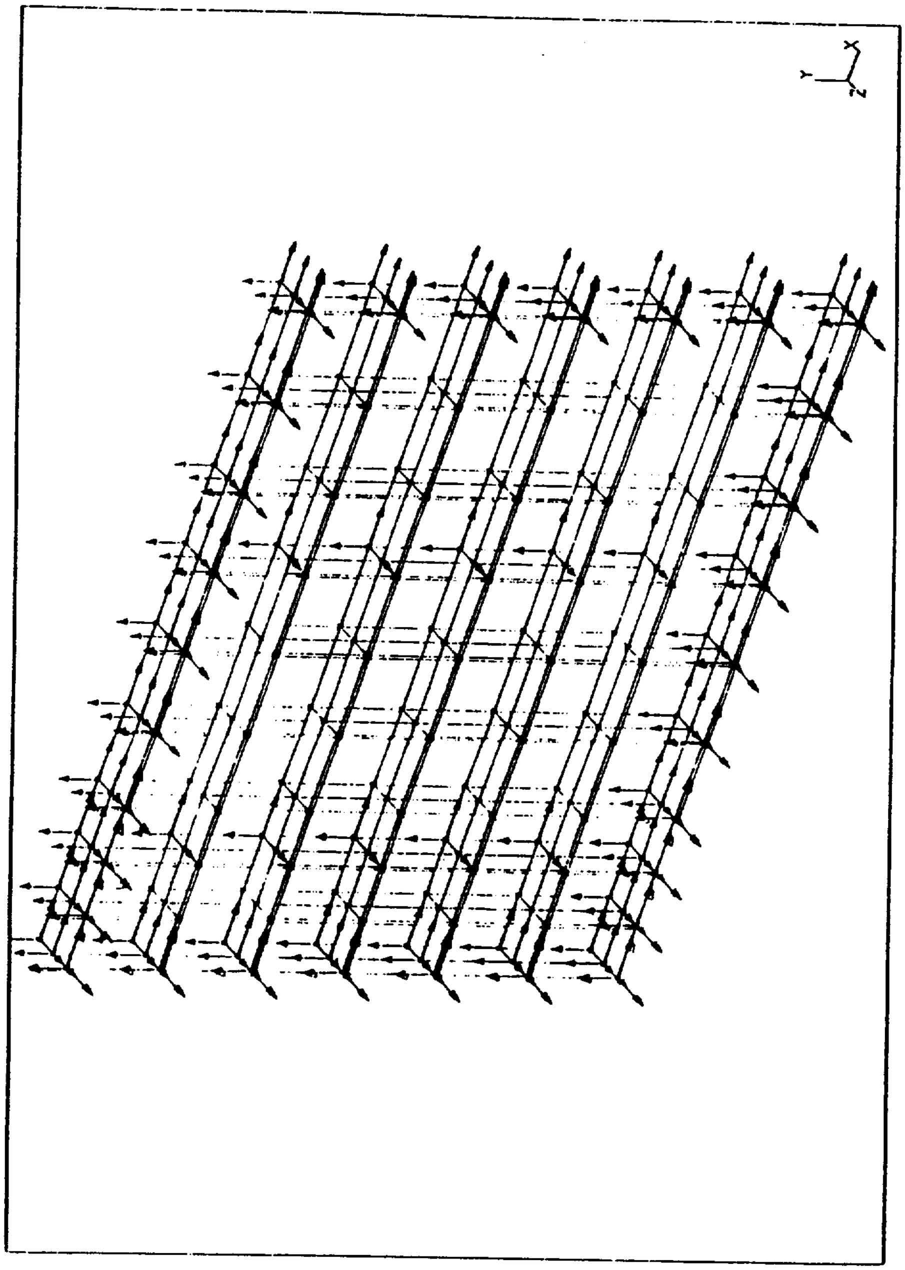

Figure 5 Restraint Set Number 1 for Static Run

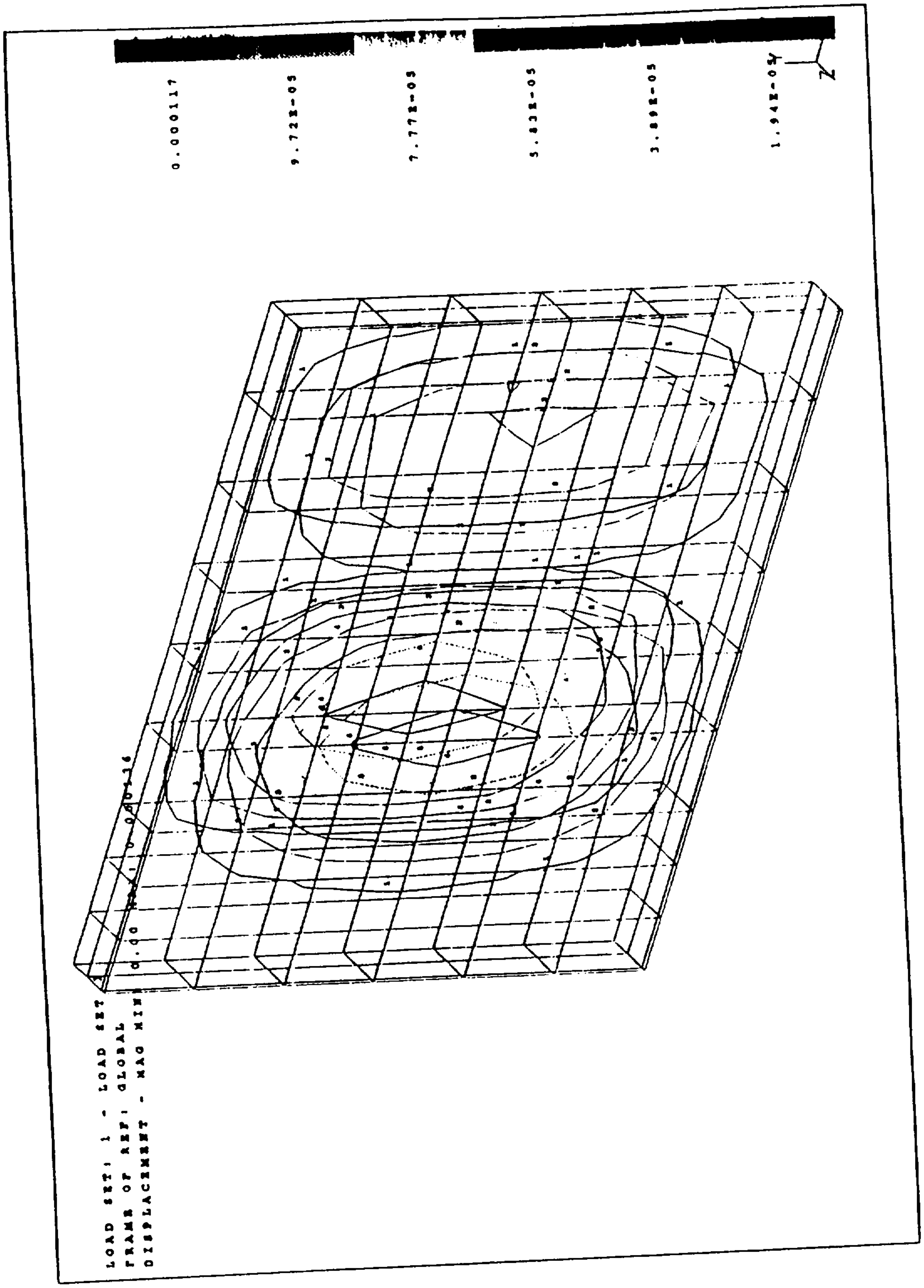

Figure 6 Displacement Contour Lines of Constant Pressure Loading

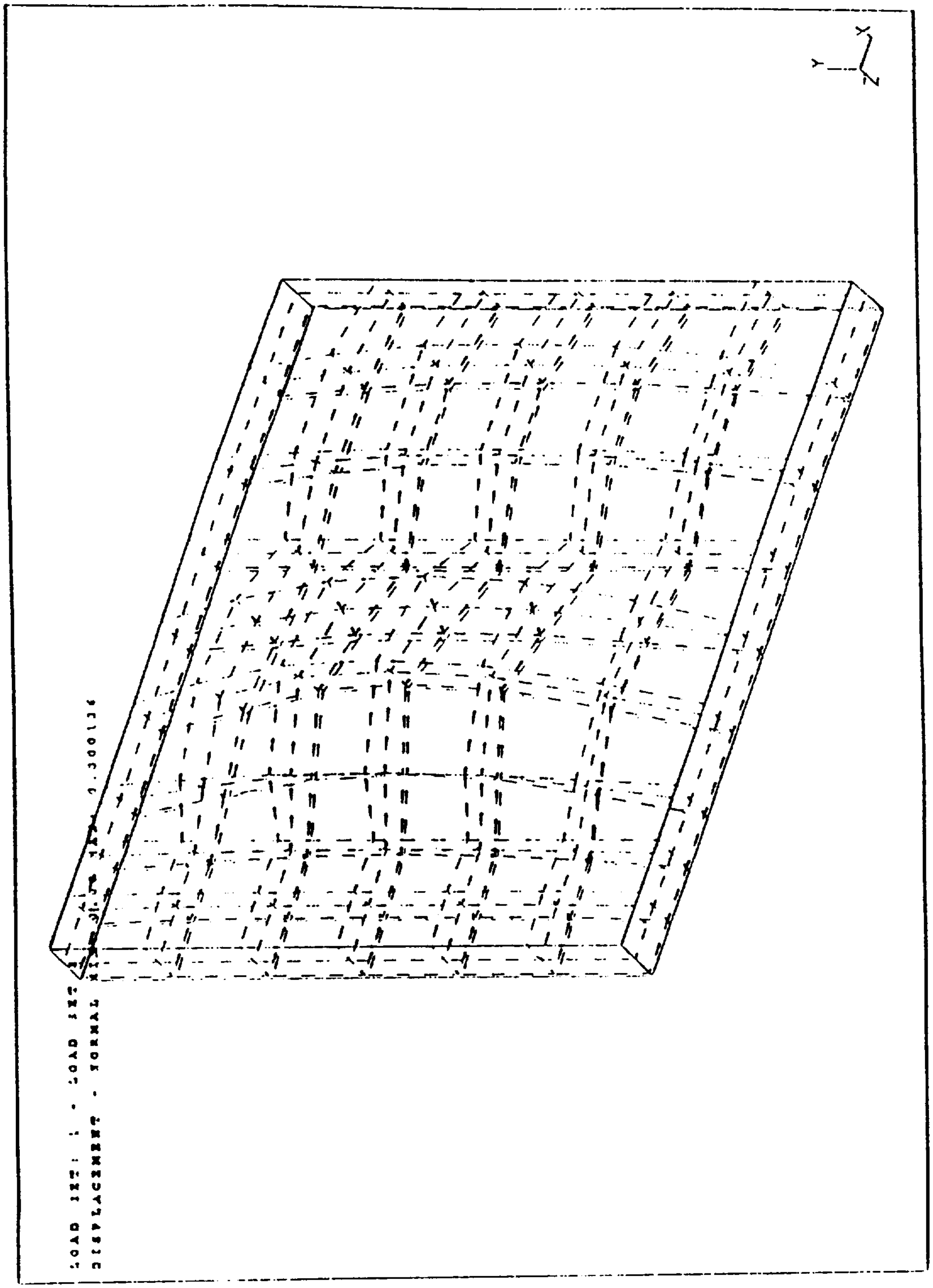

Figure 7 Deformed Shape of the Model with Constant Pressure Loading

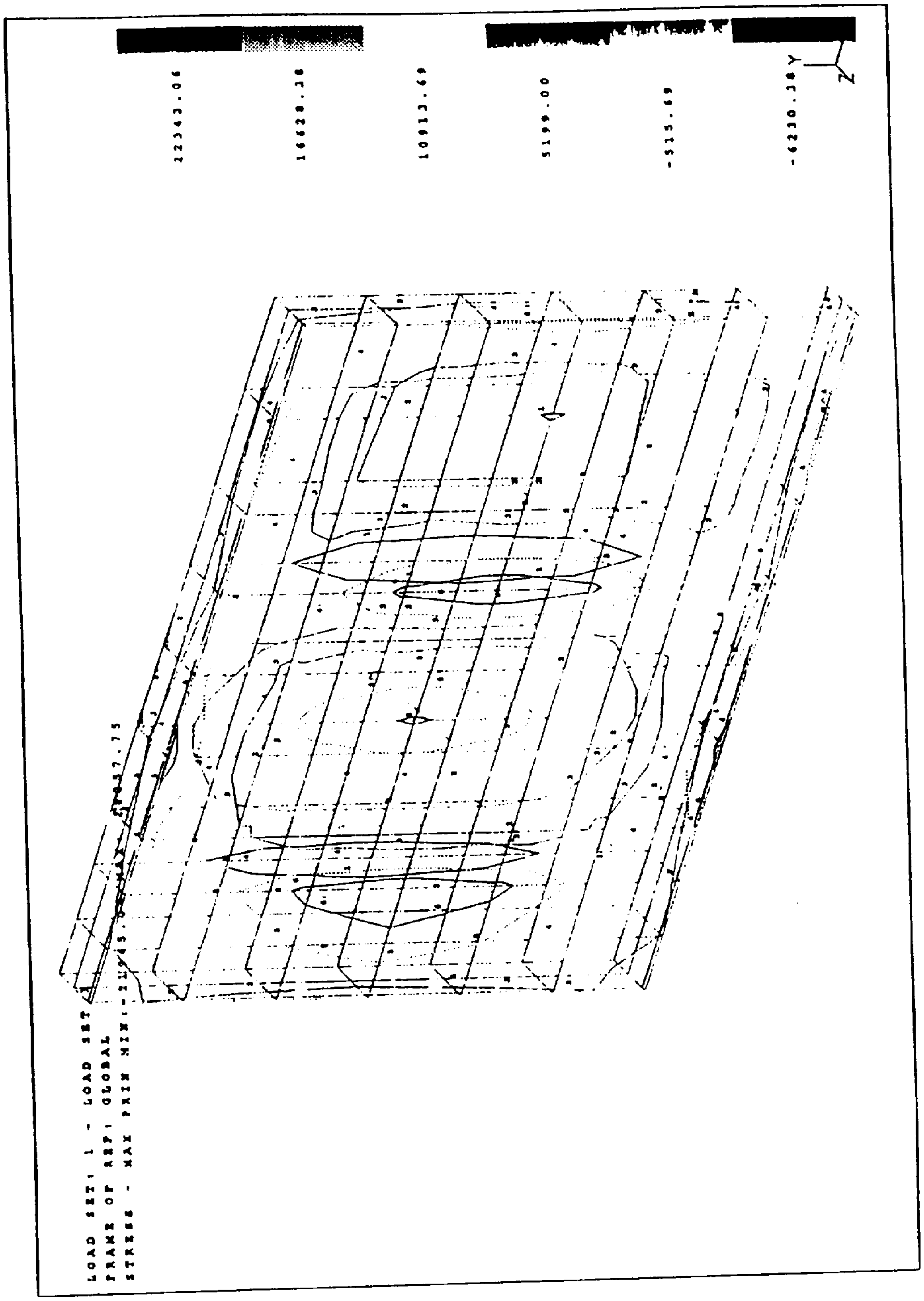

Figure 8 Stress Contour Levels of Constant Pressure Loading

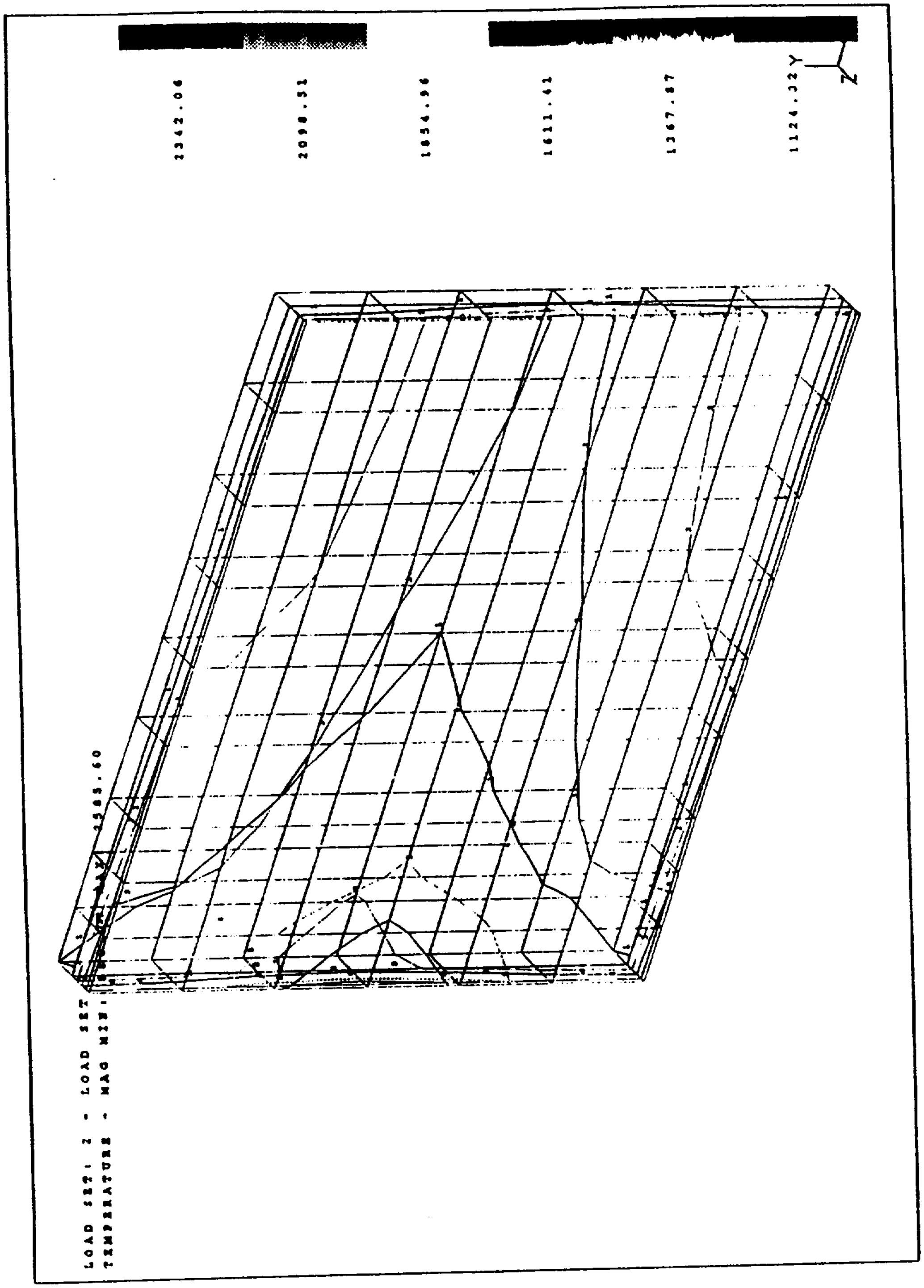

Figure 9 Steady-State Temperature Contours of the FEA Model

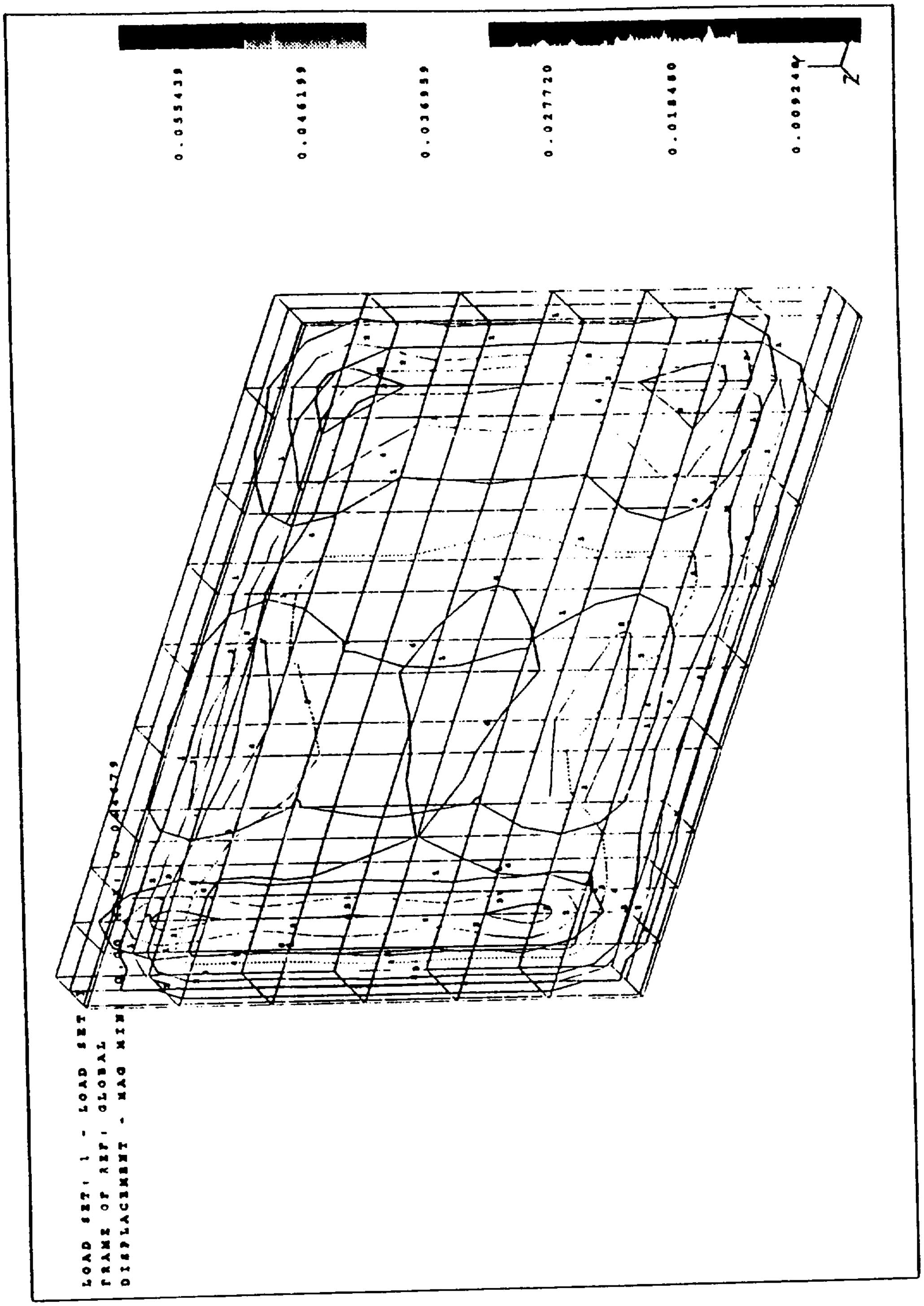

Figure 10 Displacement Contour Lines of Thermal Loads

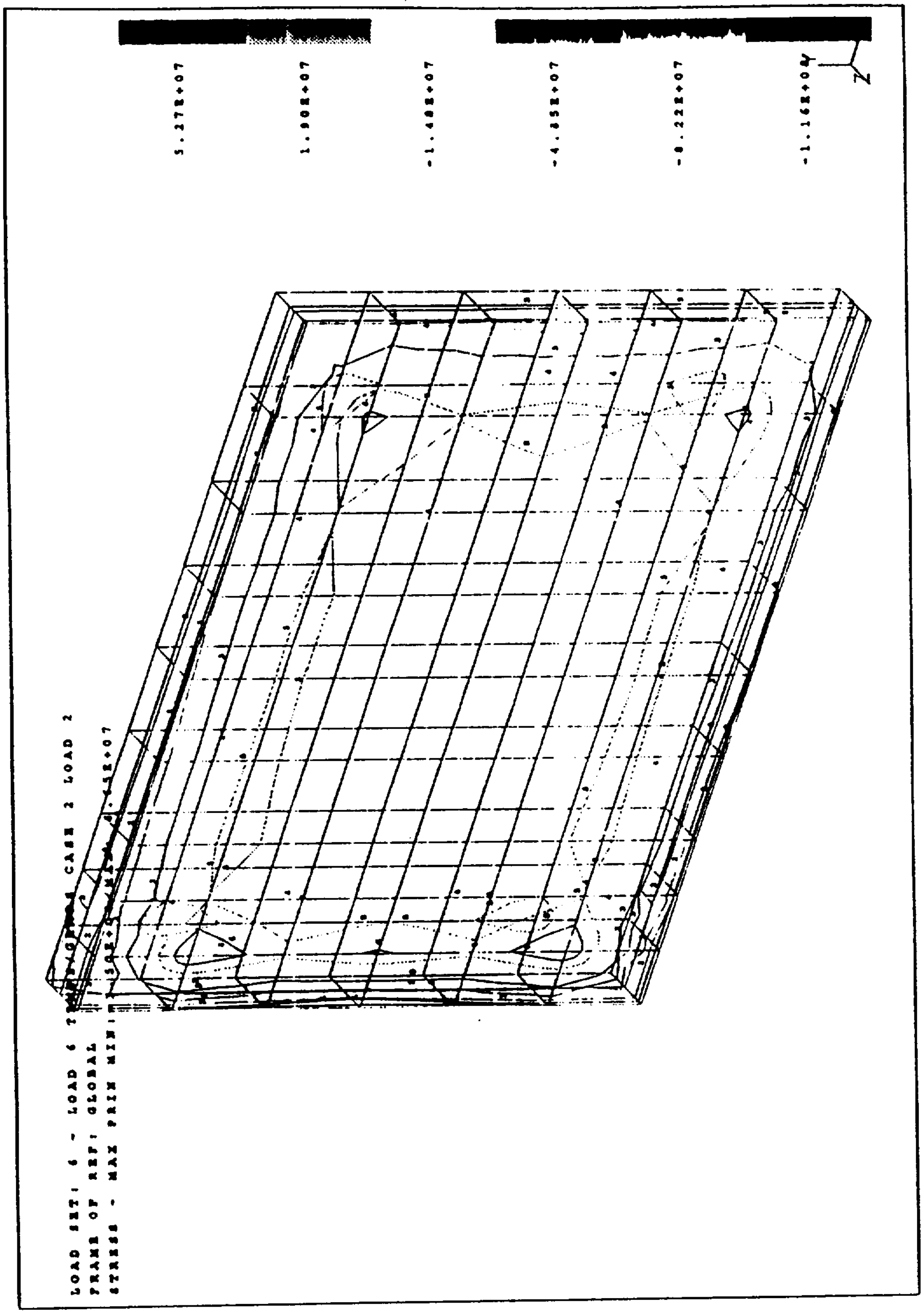

Figure 11 Stress Contour Levels of Thermal Loads