NASA/TM—2004-213081

The Effect of Solution Cooling Rate on Residual Stresses in an Advanced Nickel-Base Disk Alloy

John Gayda
Glenn Research Center, Cleveland, Ohio

Paul Reynolds and Stephen Mayers
Pratt & Whitney, East Hartford, Connecticut

June 2004

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2004-213081

The Effect of Solution Cooling Rate on Residual Stresses in an Advanced Nickel-Base Disk Alloy

John Gayda
Glenn Research Center, Cleveland, Ohio

Paul Reynolds and Stephen Mayers
Pratt & Whitney, East Hartford, Connecticut

National Aeronautics and
Space Administration

Glenn Research Center

June 2004

Document History

This research was originally published internally as AST031 in September 1999.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

The Effect of Solution Cooling Rate on Residual Stresses in an Advanced Nickle-Base Disk Alloy

John Gayda
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Paul Reynolds and Stephen Mayers
Pratt & Whitney
East Hartford, Connecticut 06108

INTRODUCTION

Gas turbine engines for future subsonic transports will probably have higher pressure ratios which will require nickel-base superalloy disks with 1300 to 1400°F temperature capability. Several advanced disk alloys are being developed to fill this need. For large disks, residual stresses generated during cooling from solution temperatures may require a stabilization heat treatment to relieve these stresses, this is undoubtedly more critical for higher cooling rates achieved with oil quenching. The reduction in residual stress levels lessens distortion during subsequent machining operations and therefore decreases disk cost.

The purpose of this study is to estimate the magnitude of the residual stresses generated upon cooling from solution temperature for an advanced, nickel-base disk alloy at several cooling rates. The disk alloy studied was developed in NASA's HSR and AST Programs. Both analytical and experimental techniques were employed to generate residual stress estimates as a function of cooling rate. In addition, experimental data were also generated to estimate the magnitude of stress relief achieved for various stabilization heat treatments.

MATERIAL & PROCEDURES

The composition of the nickel-base disk alloy studied is presented in Table I and is representative of the next generation disk alloy for advanced turbine engines. In this study, the alloy was used in the as-extruded plus heat treated condition. As with most high strength, nickel-base disk alloys, argon atomization was employed to produce powder which was subsequently compacted and extruded to 3" diameter billet. The billet was then cut to length, machined to the specimen configuration shown in Figure 1, and heat treated according to the conditions outlined in Table II. Note that both supersolvus and subsolvus solution heat treatments were employed to produce coarse grain, about ASTM 6, and fine grain, about ASTM 11, microstructures respectively. Three cooling rates designated, oil quench, air cool, and blanket cool, were employed in the study. Selected specimens were given a solution-only heat treatment while others were solutioned, stabilized, and aged. For supersolvus oil quenching, specimens were first air cooled from 2155°F to 2080°F and then oil quenched to prevent cracking.

Residual stress levels in the heat treated specimens were measured at the top-center and top-edge locations, shown as 0.040" deep holes in Figure 1, using the center-hole-drill technique (Ref. 1). The method consists of applying a strain gage rosette to the area of interest and drilling out a small core of material at the center of the rosette thereby relieving the strain. The strain is recorded and is used to calculate residual stress as a function of depth. In this study stress measurements were made at 0.0050" increments to a depth of 0.0200" followed by additional measurements at depths of 0.0300" and 0.0400".

Residual stresses were also calculated using a finite element method for each of the three cooling rates employed in the solution heat treatments. This analysis provided a complete picture of the stress distribution in the specimens after the solution heat treatment and also served to corroborate the experimental stress measurements. To calculate the residual stresses, a commercial finite element package from Algor was utilized with a "first order approximation" of the thermal and mechanical properties for the disk alloy. The first step in this analysis involved constructing a 2-D axisymmetric model of the specimen. The finite element model and mesh are shown in Figure 2. Note that the center of the specimen is located at the lower left-hand corner of the model. Before the stresses can be calculated, a thermal analysis was run to generate the temperature profile throughout the part on cooling from 2100°F. For this part of the analysis a thermal conductivity of 1.0BTU/HR-IN-°F, a density of 0.3LB/IN^3 and a heat capacity of 0.12BTU/LB-°F was employed with the appropriate heat transfer coefficient for the cooling rate in question. The validity of the heat transfer coefficients and the resulting temperature profiles were checked against actual cooling rate data recorded at the top-center location. Using the temperature profiles as input, a thermoplastic stress analysis of the specimen was then run using the mechanical properties shown in Table III assuming a stress free state at 2100°F. These data provide a simple, piecewise linear approximation of the mechanical properties for this class of alloy. The resulting hoop stress profiles at room temperature were then plotted for each of the three cooling rates studied.

RESULTS AND DISCUSSION

The analytical and experimental cooling curves at the top-center location of the specimens are presented in Figures 3, 5, and 7 for the oil quenched, air cooled, and blanket cooled material, respectively. For the oil quench, a constant heat transfer coefficient of 1.0BTU/HR-IN^2-°F was found to give good agreement between experiment and analysis above 750°F and reasonable agreement below 750°F. Since analysis indicated that most of the residual stress is generated at the upper end of the cooling curve, the aforementioned choice of heat transfer coefficient appears to be justified for a "first order approximation" of the cooling stresses. A similar philosophy was employed to estimate the heat transfer coefficient for the air cooled and blanket cooled solution heat treatment. In these cases, a value of 0.1 and 0.012 BTU/HR-IN^2-°F were used respectively. As temperature differentials within the body at any given time drives stress buildup, it is instructive to look at temperature maps after a short period of time when a majority of the specimen is still hot. In Figures 4, 6, and 8, the temperature distribution is plotted at 0.01HR for the oil quench, 0.05HR for the air cooled, and 0.60HR for the blanket cooled specimens respectively. Note that the center temperature is about 1500°F in each case but the range of temperatures is approximately 800°F for the oil quench, 150°F for the air cooled, and only 15°F for the blanket cooled specimen. As one would expect, these temperature differentials suggest the oil quenched specimen will have dramatically higher cooling stresses than the air cooled specimen, while the blanket cooled specimen will generate very little stress on cooling.

Room temperature, hoop stress plots from the finite element analysis are presented in Figures 9, 10, and 11 for the three cooling rates. Hoop stresses are presented as they are the most important, i.e. largest, stresses in the body and are, perhaps, most intuitive from a human perspective. As expecteded, the oil quenched specimen shows the highest residual stress levels, -140 to -190KSI compression near the surface and about 200KSI tension at the center. At these levels it becomes important to examine the Von Mises stress to check for yielding. This data is presented in Figure 12 and clearly shows that yielding has occurred on the surface and the center as the Von Mises stress exceeds 150KSI at these locations. While the surface stresses are highly compressive at room temperature, during the oil quench a stress inversion occurs. Shortly after the onset of cooling a tensile stress state exists on the surface which is balanced by subsurface compression. This reaches a peak analytically at 0.0017 hours into the quench, Figure 13, then decreases and eventually goes over to a compressive surface stress balanced by a subsurface tensile stress producing the distribution observed at room temperature. A similar scenario produces the room temperature stress distribution for the air cooled specimen, Figure 10. However, the magnitude of the stresses are significantly less as expected, about -30 to -40KSI compression at the surface and 35KSI tension at the center. For the blanket cooled specimen, the absence of any significant thermal gradient during cooling produces a residual stress state which is essentially zero at room temperature, Figure 11.

A comparison between analysis and experiment can be made by comparing the data presented in Table IV with the stress plots previously presented in Figures 9, 10 , and 11. The experimentally determined data presented in Table IV, describe the residual stress state at the two locations shown in Figure 1. At the edge location the hoop stress dominates as the radial stress approaches zero, and at the center location the hoop and radial stress are essentially identical. While stress measurements were taken at various depths there were in general no significant trends over the range of depths investigated and therefore only one stress value is presented in the Table IV for each location and condition. One can think of that value as a near surface number, less than 0.05" deep. With this information in mind, the following comparisons can be made. First, the cooling stresses associated with oil quenching run about –140 to –190KSI along the top surface of the finite element model. Experimentally these numbers range from –125 to –230KSI in this region, combining the subsolvus and supersolvus data. Numbers at or beyond the yield point of the material have a high degree of experimental uncertainty associated with them and probably overestimate the actual stress levels as the center-hole-drill technique assumes elastic response. However, both analysis and experiment indicate the surface stresses for oil quenching are comparable to the yield strength of the disk alloy. In comparison, the air cooled material show surface stresses peaking at –60 KSI experimentally, and about –40KSI analytically. In this case the experimental numbers are clearly within the elastic bounds of the center-hole-drill technique and this discrepancy is more likely to result from the limitations of the finite element analysis. First, the physical and mechanical constants employed were "first order approximations" and, second, a thermoplastic analysis was employed which ignores any creep interactions that become more important with slower cooling rates, i.e. air cool versus oil quench. For the blanket cooled material it is clear that the residual stresses are negligible, experimentally and analytically, and this results from the minimal temperature differential within the body on cooling, Figure 8.

The stresses produced on cooling from the solution heat treatment, both subsolvus and supersolvus, were clearly significant on oil quenching and air cooling. To reduce these stresses several stabilization heat treatments were tried at temperatures between 1425°F and 1575°F. The results of these treatments are summarized in Table IV. The 1425°F stabilization appears to reduce stresses for oil quenching to –90KSI while the 1575°F stabilization appears to reduce the stress to –40KSI. For the air cooled cases stabilization at 1500°F appeared to achieve a modest reduction in residual stresses from about –60KSI to –40KSI after stabilization. Obviously, stabilization had negligible effect on blanket cooled specimens as stresses were low before and after stabilization. While no finite element analysis of the stabilization treatments were run, as that would require a viscoplastic code, comparison with relaxation data for this alloy (Ref. 2) supports the post stabilization data from the center-hole-drill experiments in Table IV. The stress relaxation data , shown in Figure 14, indicates that exposure at 1400°F relaxes stresses from 140KSI to about 90KSI after several hours while exposure at 1600°F relaxes stresses to about 30KSI after several hours. These stresses are about the same level as that observed after stabilization at 1425°F and 1575°F respectively for oil quenched material.

SUMMARY & CONCLUSIONS

The effects of solution cooling rate and stabilization treatments on residual stresses in an advanced, nickel-base disk alloy were studied using a relatively small cylindrical specimen. Stresses generated by oil quenching, air cooling , and a slow blanket cool were measured experimentally with a center-hole-drill technique and calculated using a finite element method. The oil quench was found to produce compressive surface stresses over -150KSI while the air cool was found to produce compressive surface stresses peaking at about –60KSI. In both cases these stresses were balanced by tensile stresses on the interior. Reasonable agreement between analysis and experiment enhanced the credibility of the residual stress numbers.

Experimental measurement of residual stress levels after stabilization indicated that temperatures above 1500°F reduced oil quench surface stresses from over –150KSI to more manageable levels around –40KSI after several hours. These results agree with stress relaxation data at equivalent temperatures for this disk alloy.

REFERENCES

1. PWA Center-Hole-Drill Technique Reference.
2. J. Gayda, The Effect of Tungsten and Niobium on the Stress Relaxation Rates of Disk Alloy CH98, NASA AST Report 029, October 1998.

TABLE I. ALLOY COMPOSITION.

			COMPOSITION OF DISK ALLOY IN W/O								
Co	Cr	Mo	W	Nb	Ta	Al	Ti	B	C	Zr	Ni
20	13.1	3.8	1.9	1.1	2.25	3.45	3.6	0.03	0.04	0.05	BAL

TABLE II. HEAT TREAT MATRIX.

ID	HEAT TREATMENT
D1-39	SUPERSOLVUS/OIL QUENCH
C1-42	SUBSOLVUS/OIL QUENCH
G2-40	SUPERSOLVUS/AIR COOL
Q1-43	SUBSOLVUS/AIR COOL
F1-41	SUPERSOLVUS/BLANKET COOL
G1-44	SUBSOLVUS/BLANKET COOL
D2-51	SUPER/OQ+1425F/8HR+AGE
C2-46	SUB/OQ+1575F/2HR+AGE
N1-47	SUPER/OQ+1575F/8HR+AGE
H1-49	SUPER/AC+1500F/5HR+AGE
H2-50	SUB/AC+1500F/5HR+AGE
F2-52	SUB/BC+1425F/8HR+AGE
H3-48	SUB/BC+1575F/8HR+AGE
G3-45	SUPER/BC+1575F/2HR+AGE
NOTE	SUPERSOLVUS=2155F/3HR
	SUBSOLVUS=2080F/1HR
	AGE=1400F/8HR

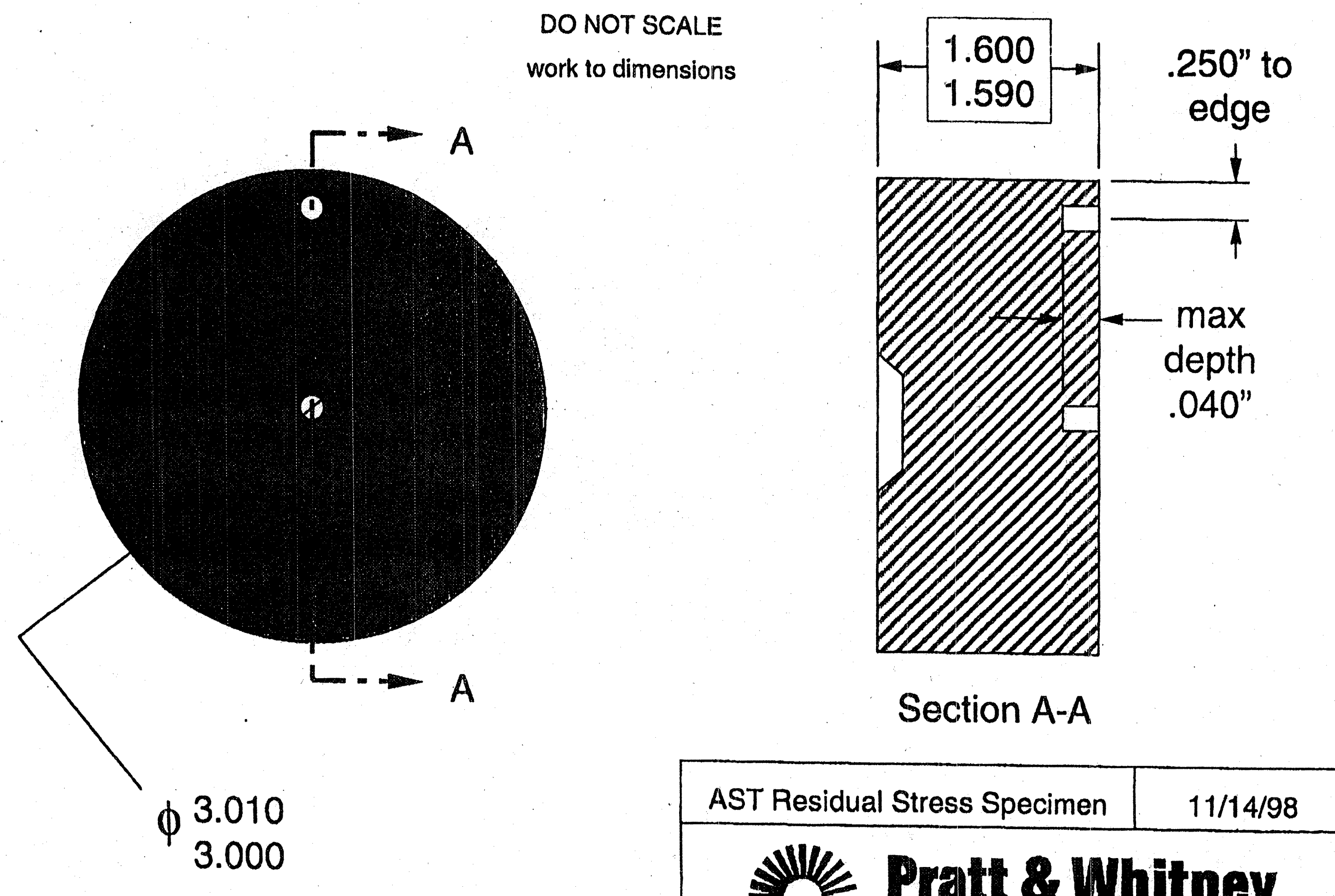


FIGURE 1. SPECIMEN DESIGN.

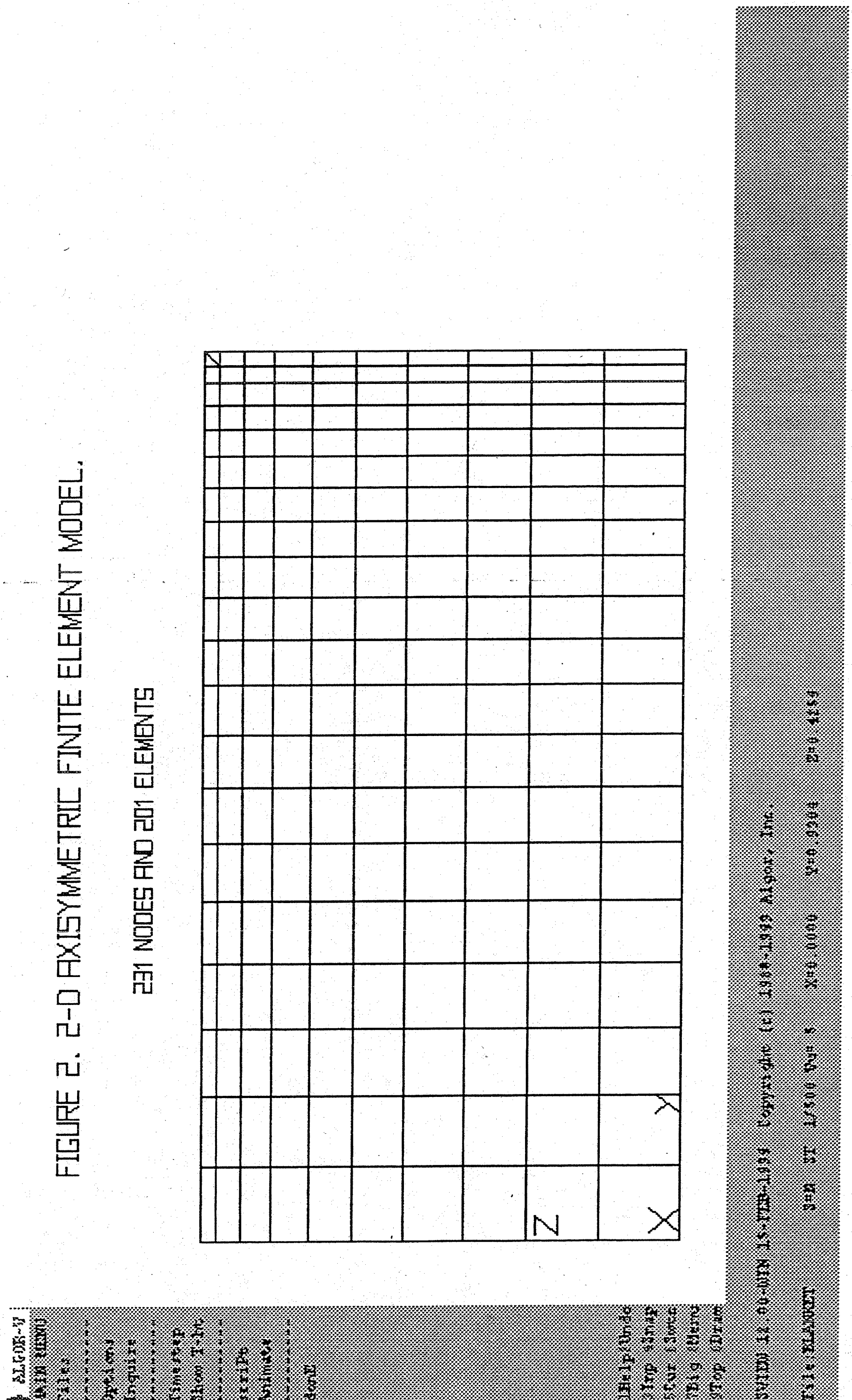
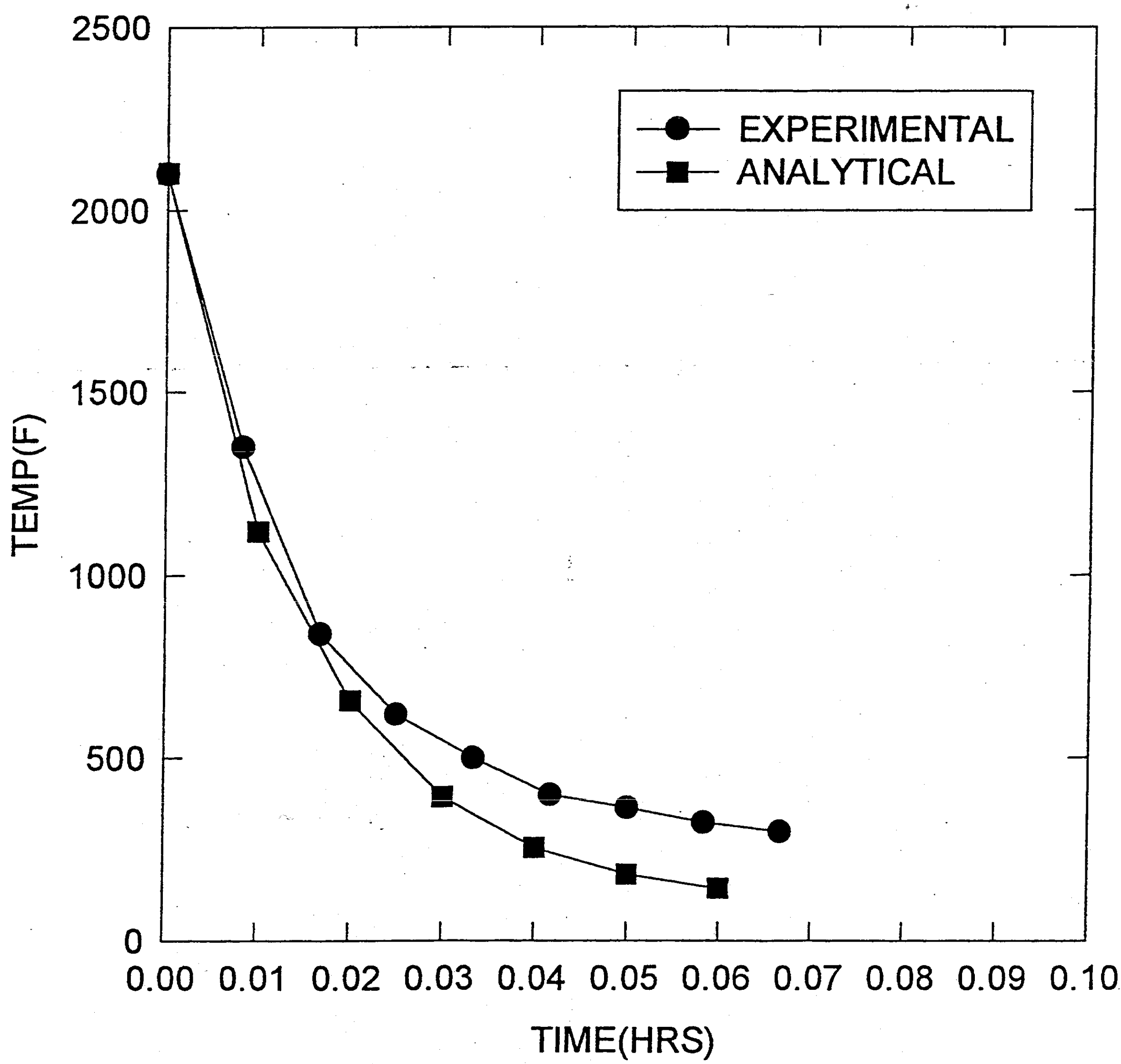


FIGURE 2. 2-D AXISYMMETRIC FINITE ELEMENT MODEL.
231 NODES AND 201 ELEMENTS
Z
X
Y

TABLE III. MATERIAL CONSTANTS.

TEMPERATURE DEPENDENT MATERIAL PROPERTIES			
TEMPERATURE	MODULUS	EXPANSION	YIELD
(F)	(PSI)	COEFFICIENT(F^{-1})	STRENGTH(PSI)
0	3.00E+07	6.00E-06	150000
1200	3.00E+07	6.00E-06	150000
1800	2.00E+07	1.20E-05	10000
2200	2.00E+07	1.20E-05	10000

FIGURE 3. OIL QUENCH COOLING CURVES.



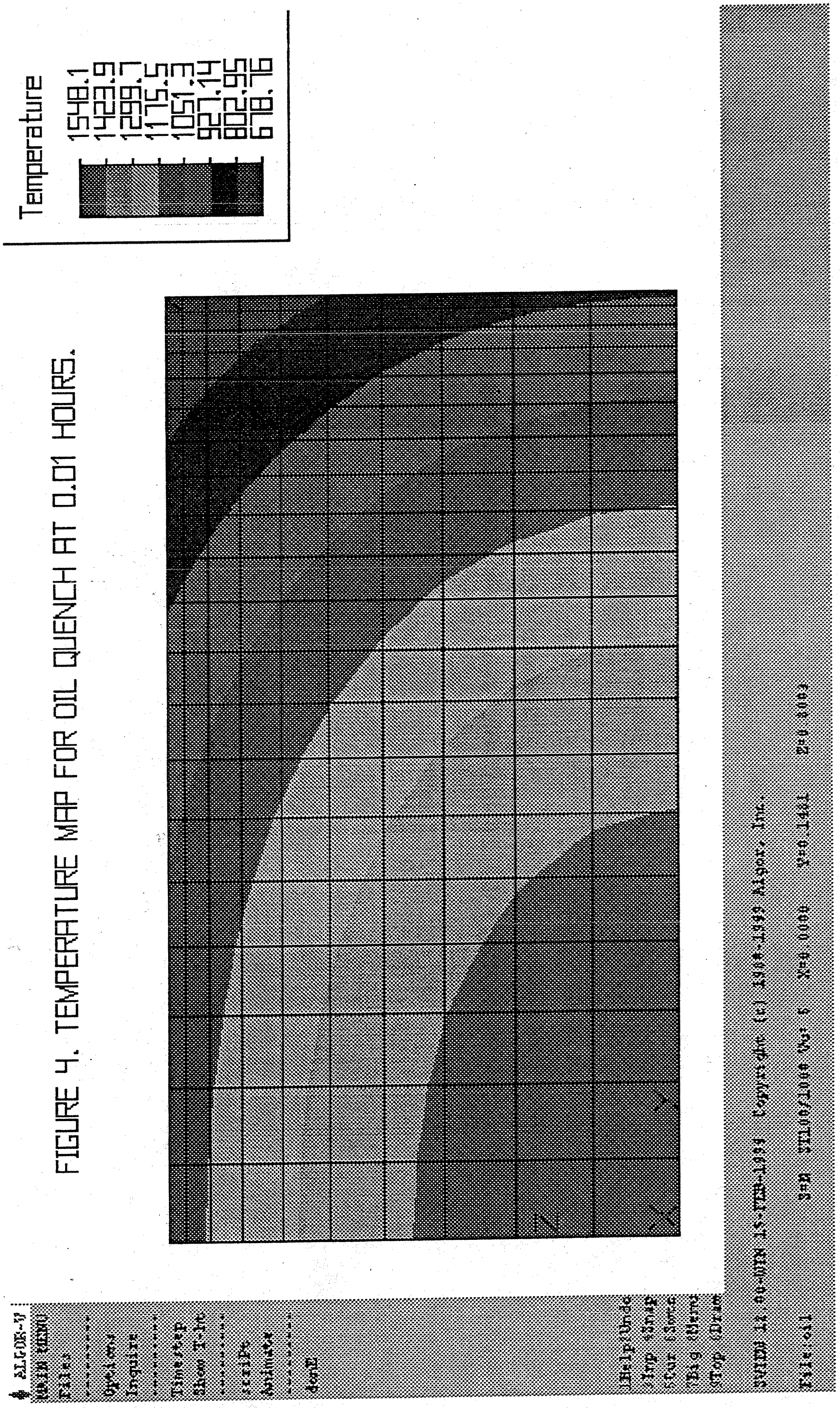
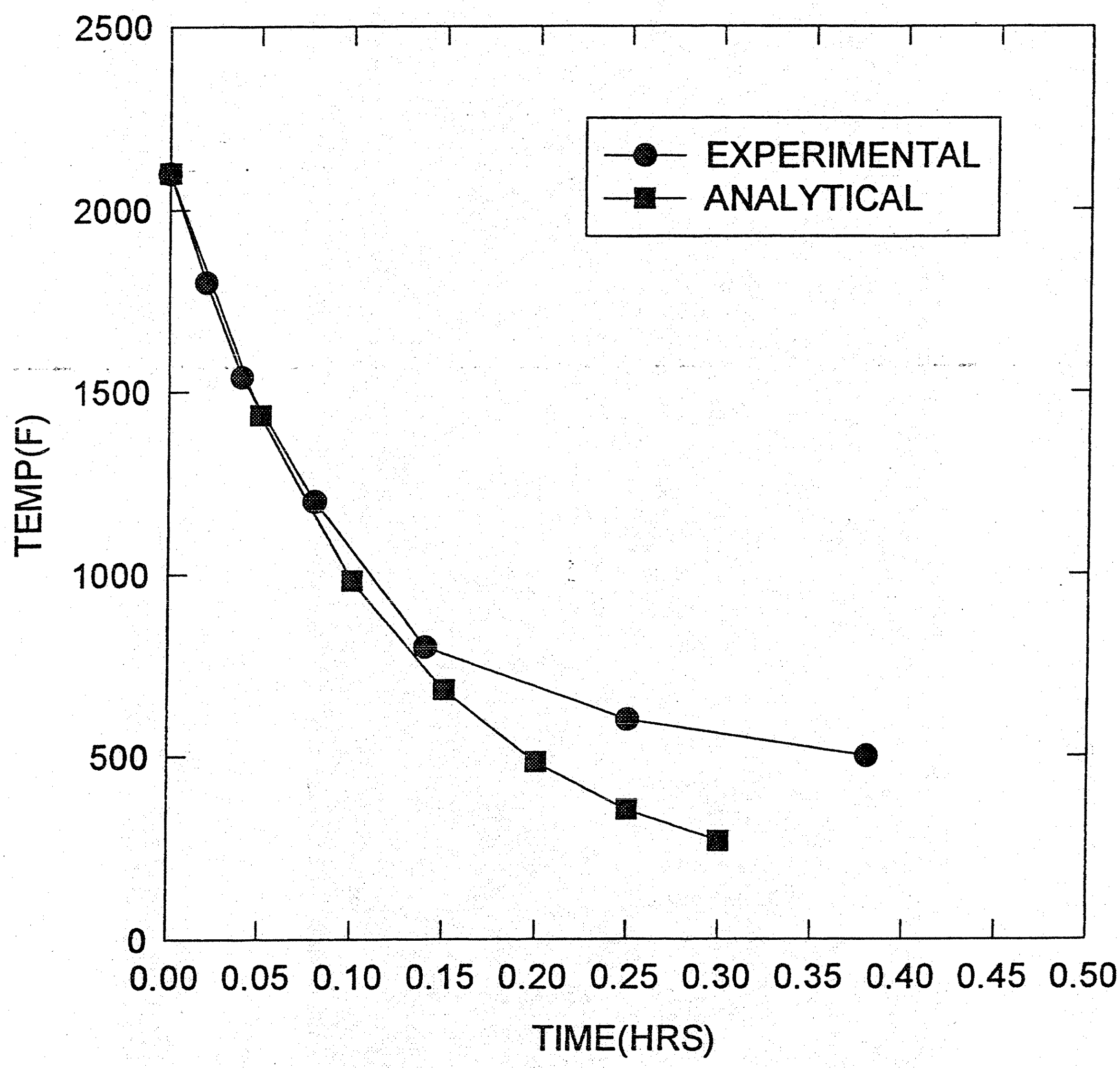


FIGURE 4. TEMPERATURE MAP FOR OIL QUENCH AT 0.01 HOURS.
Temperature
1548.1
1423.9
1299.7
1175.5
1051.3
927.14
802.95
678.76

FIGURE 5. AIR COOL COOLING CURVES.



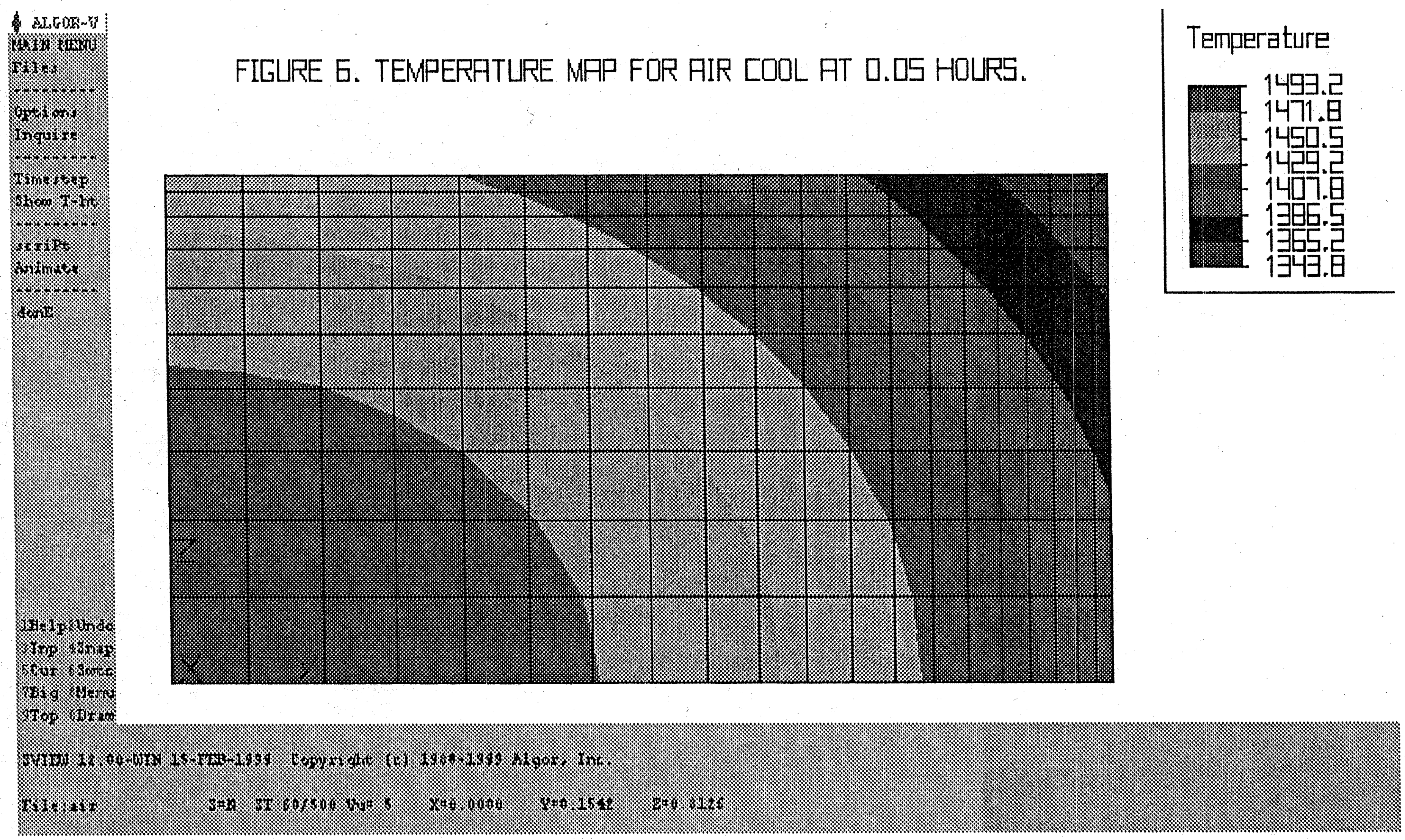
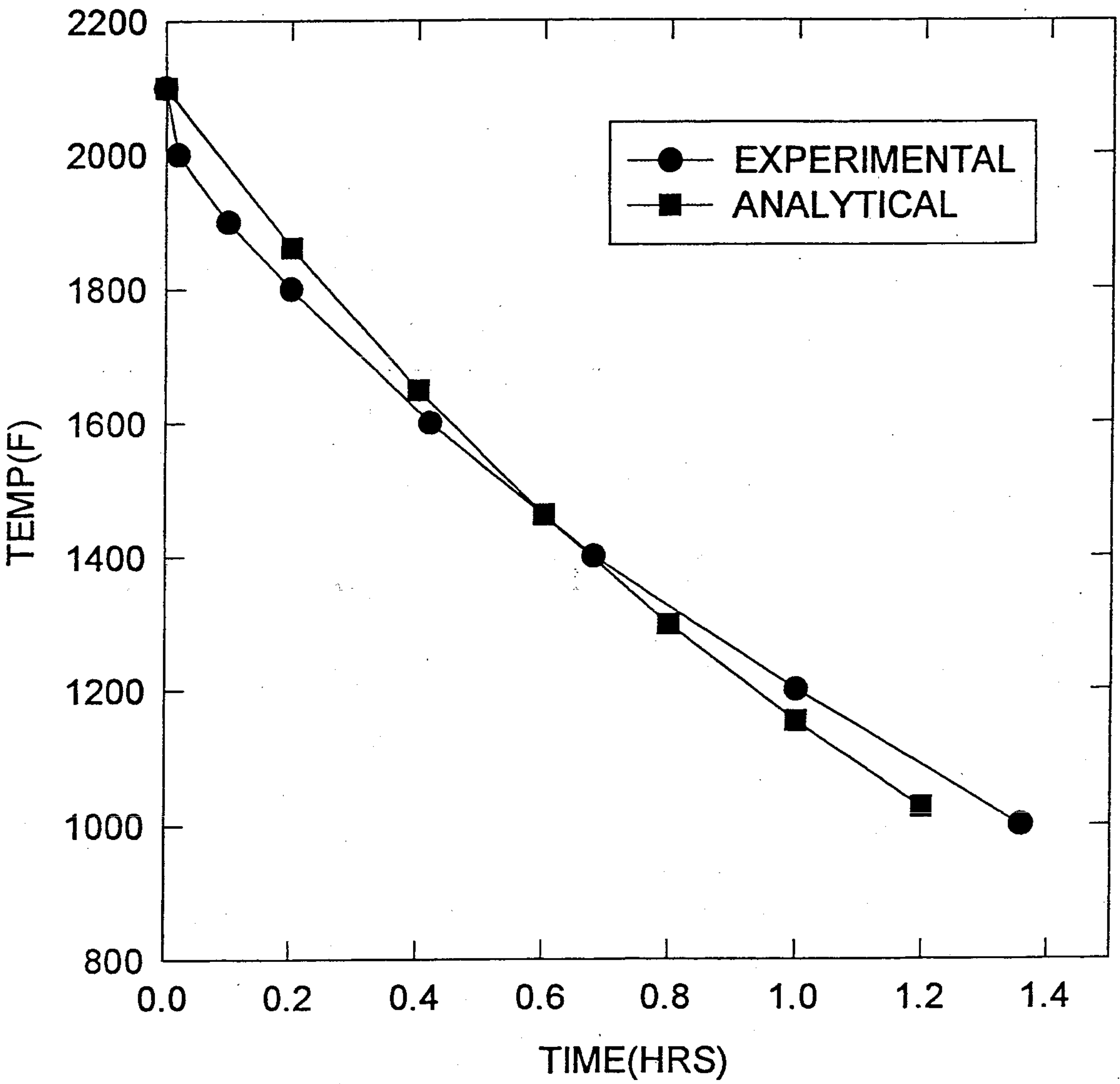


FIGURE 6. TEMPERATURE MAP FOR AIR COOL AT 0.05 HOURS.

FIGURE 7. BLANKET COOL COOLING CURVES.



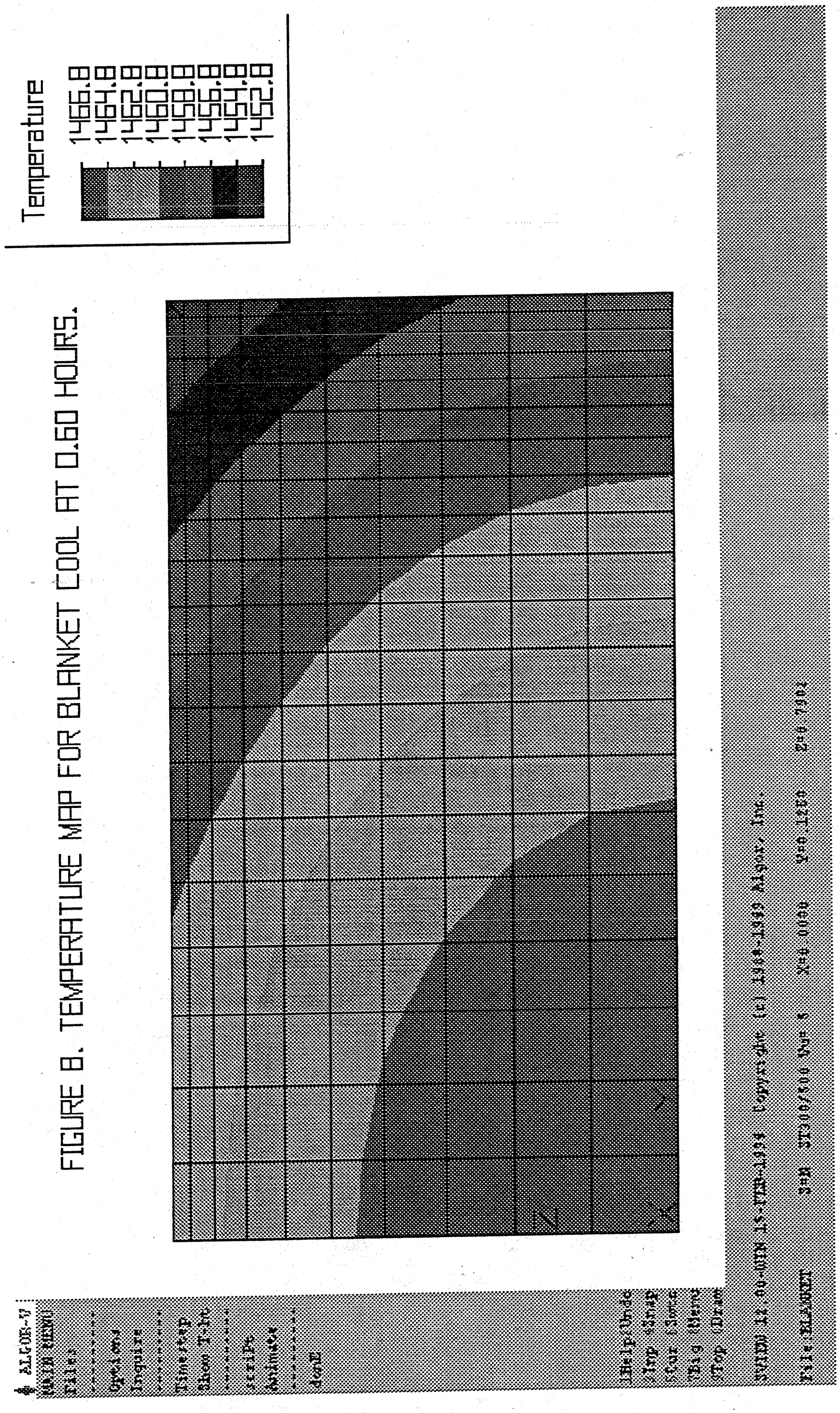


FIGURE 8. TEMPERATURE MAP FOR BLANKET COOL AT 0.60 HOURS.
Temperature
1466.8
1464.8
1462.8
1460.8
1458.8
1456.8
1454.8
1452.8

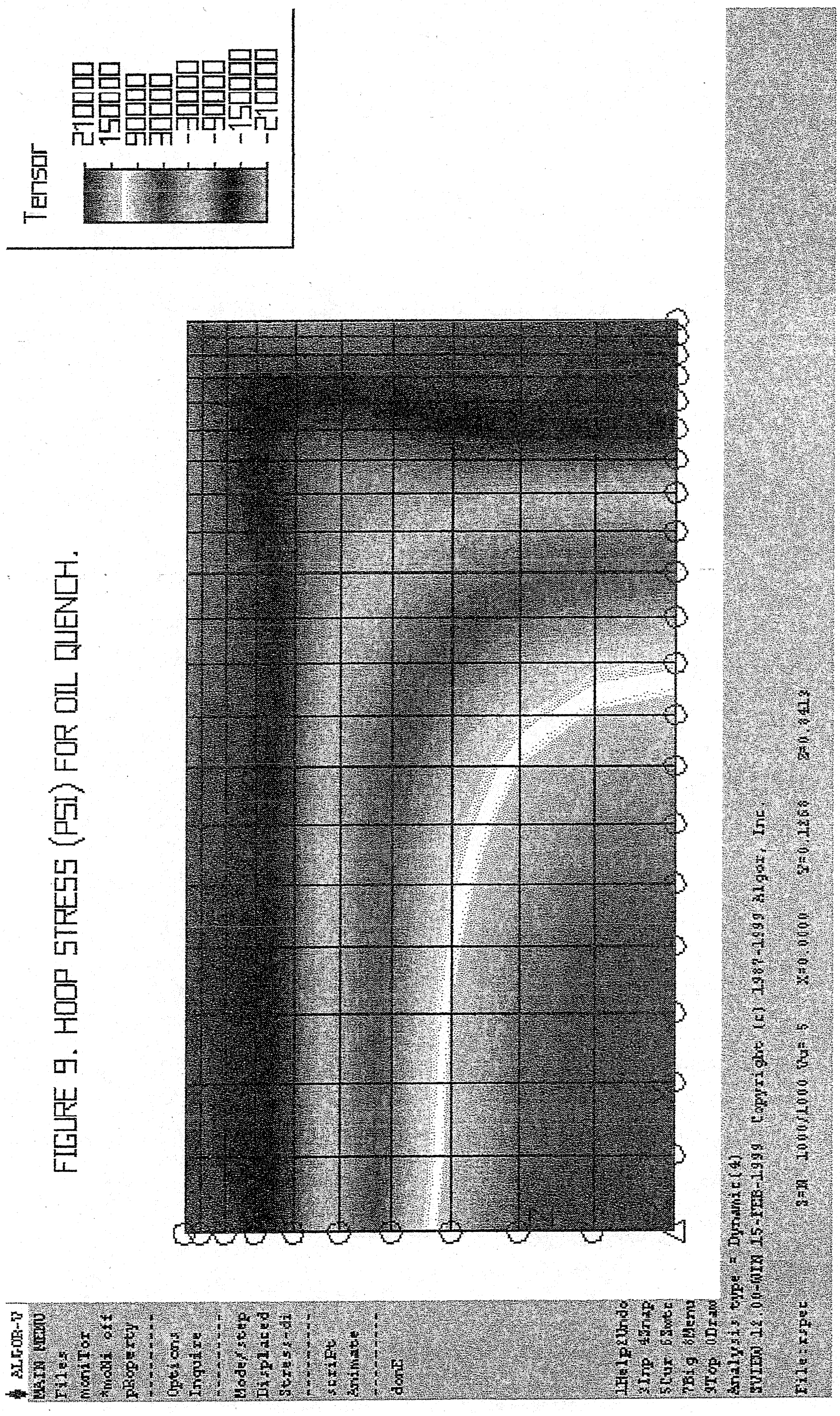


FIGURE 9. HOOP STRESS (PSI) FOR OIL QUENCH.

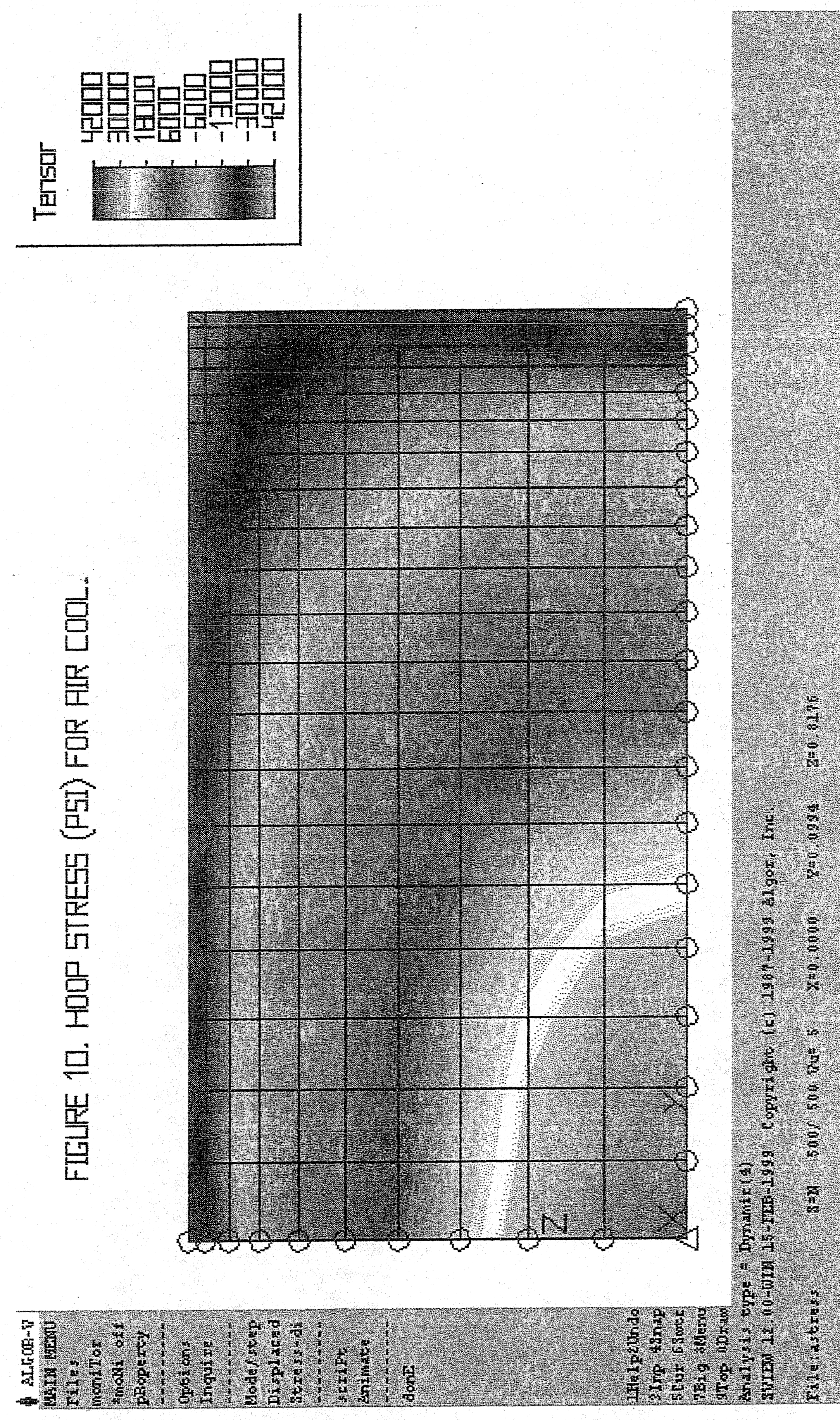


FIGURE 10. HOOP STRESS (PSI) FOR AIR COOL.
Tensor
42000
30000
18000
6000
-6000
-18000
-30000
-42000

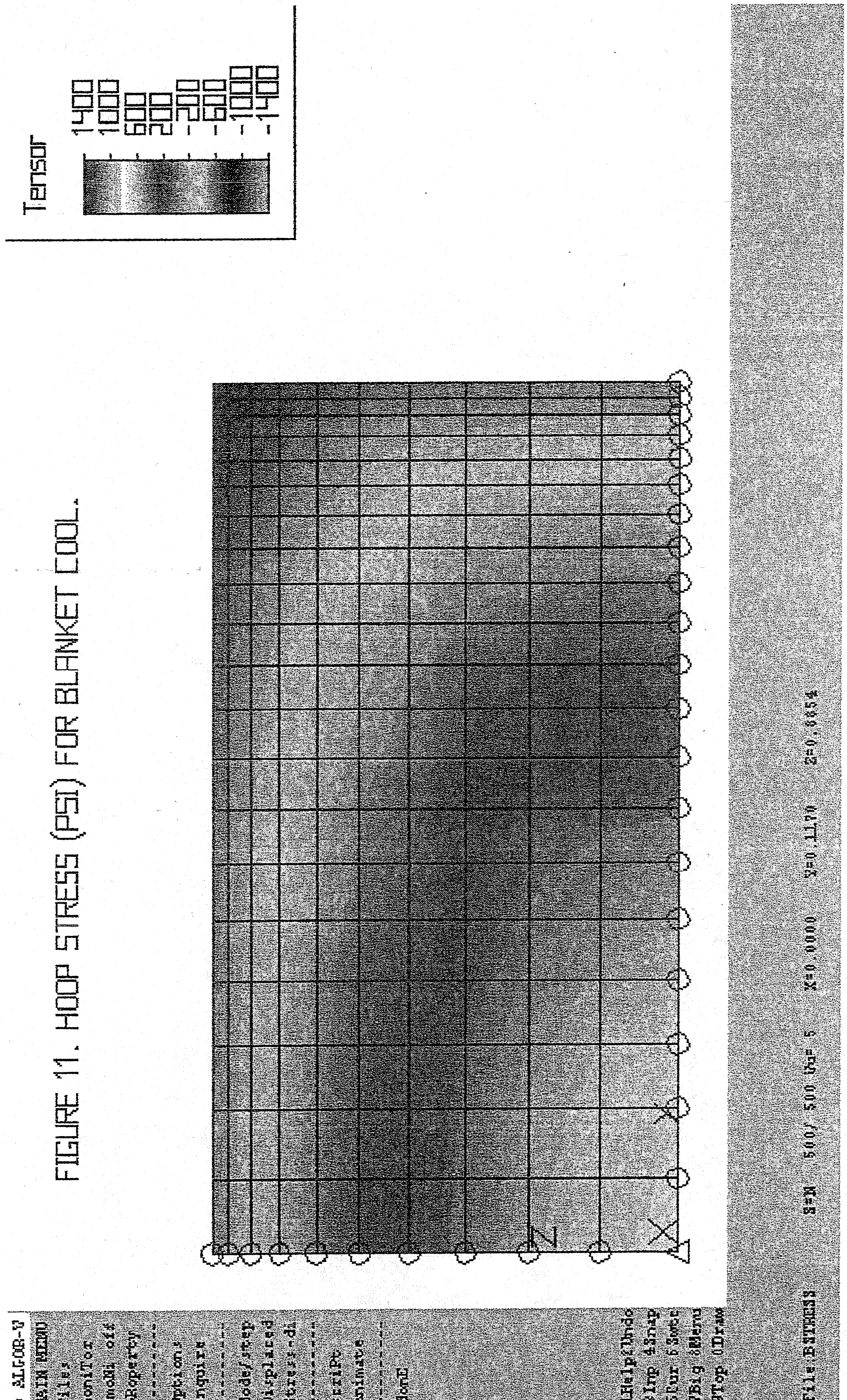


FIGURE 11. HOOP STRESS (PSI) FOR BLANKET COOL.

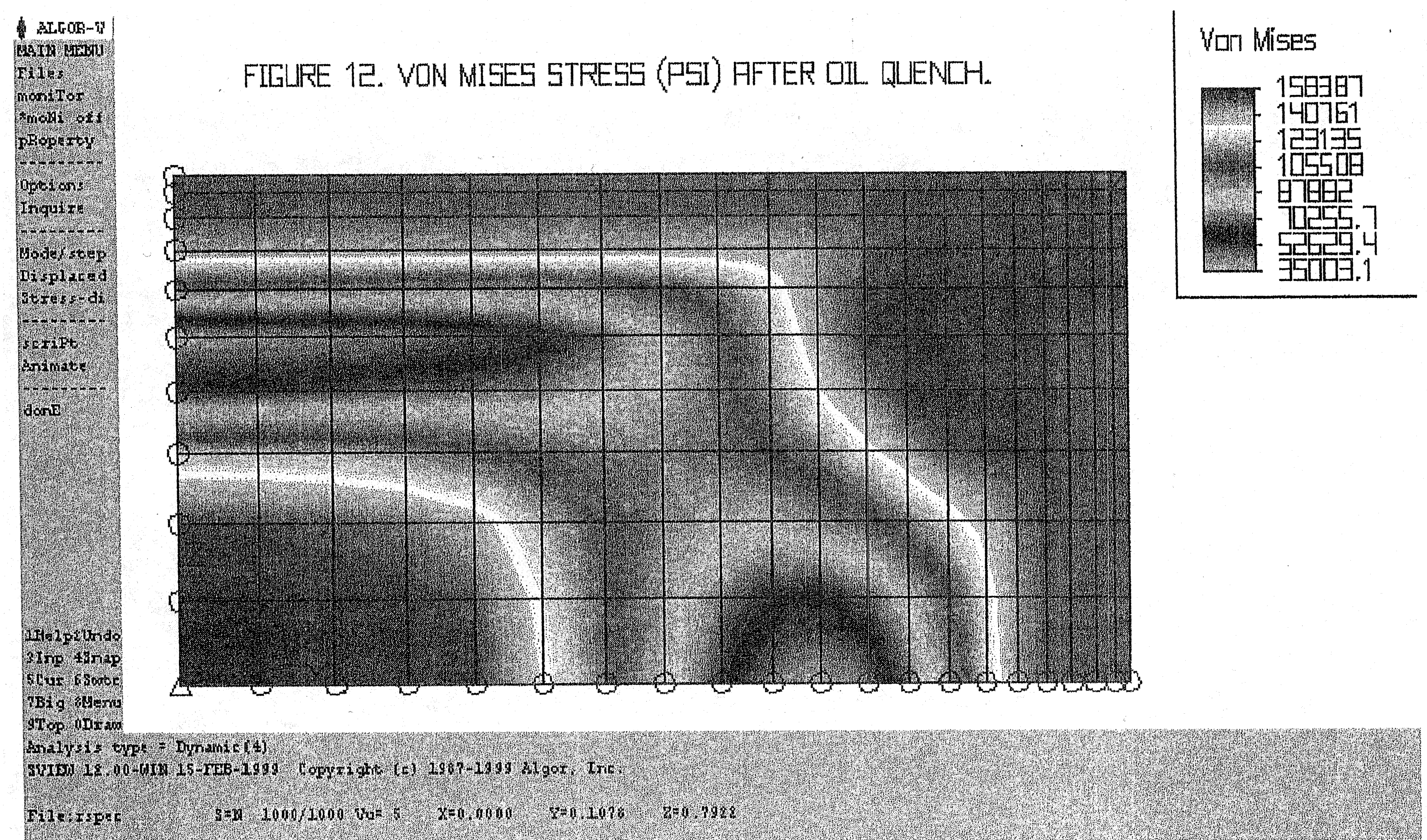


FIGURE 12. VON MISES STRESS (PSI) AFTER OIL QUENCH.

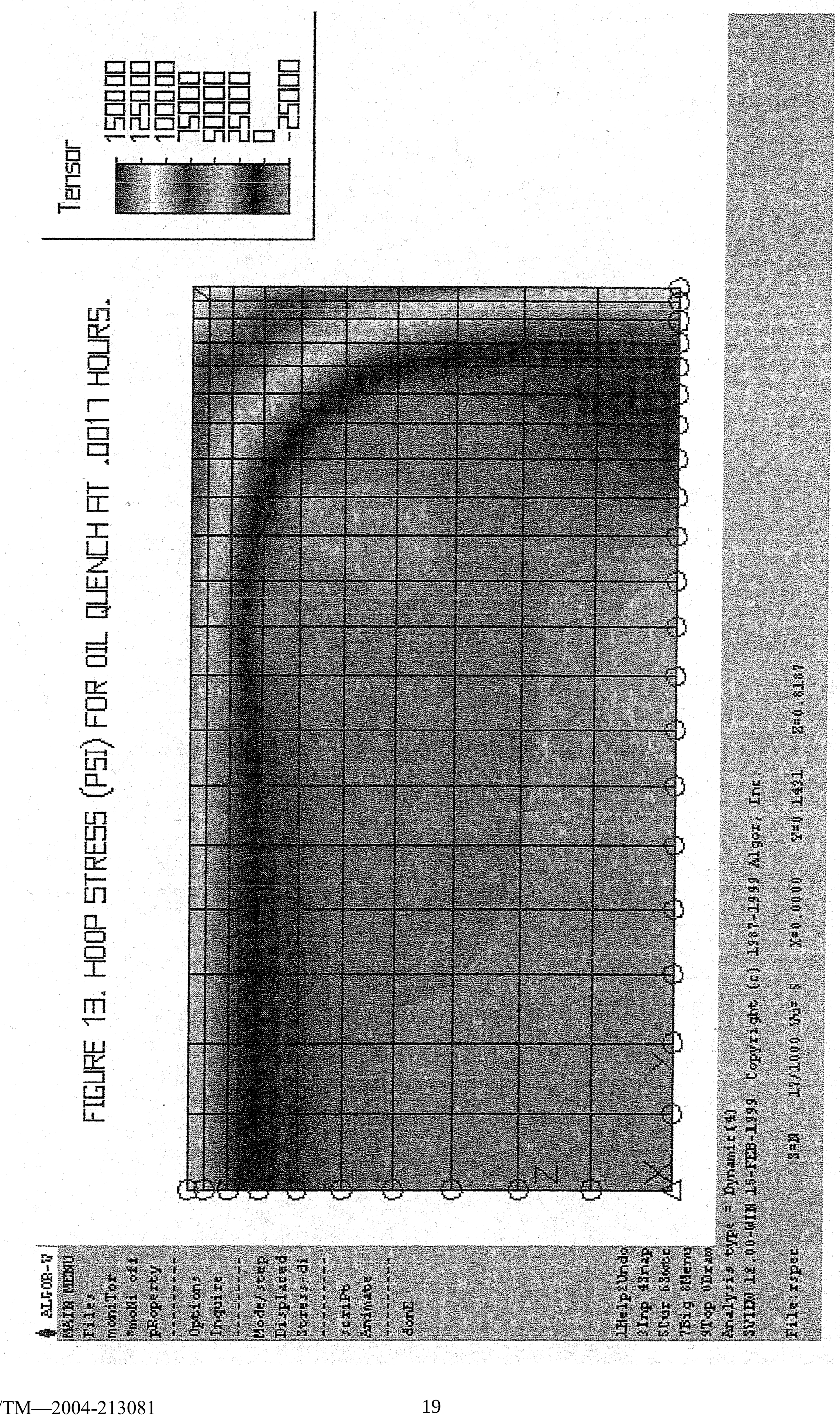


FIGURE 13. HOOP STRESS (PSI) FOR OIL QUENCH AT .0017 HOURS.

TABLE IV. RESIDUAL STRESS DATA.

RESIDUAL STRESSES VIA THE CENTER-HOLE-DRILL TECHNIQUE			
ID	HEAT TREAT	HOOP STRESS(KSI) @ EDGE	STRESS(KSI) @ CENTER
D1-39	SUPER/OQ	-155	-154
C1-42	SUB/OQ	-233	-124
G2-40	SUPER/AC	-60	-49
Q1-43	SUB/AC	-68	-59
F1-41	SUPER/BC	-9	-2
G1-44	SUB/BC	-12	-8
D2-51	SUPER/OQ+1425F/8HR	-105	-85
C2-46	SUB/OQ+1575F/2HR	-36	-39
N1-47	SUPER/OQ+1575F/8HR	-43	-40
H1-49	SUPER/AC+1500F/5HR	-35	-46
H2-50	SUB/AC+1500F/5HR	-33	-25
F2-52	SUB/BC+1425F/8HR	-9	-2
H3-48	SUB/BC+1575F/8HR	-11	-6
G3-45	SUPER/BC+1575F/2HR	-10	-11

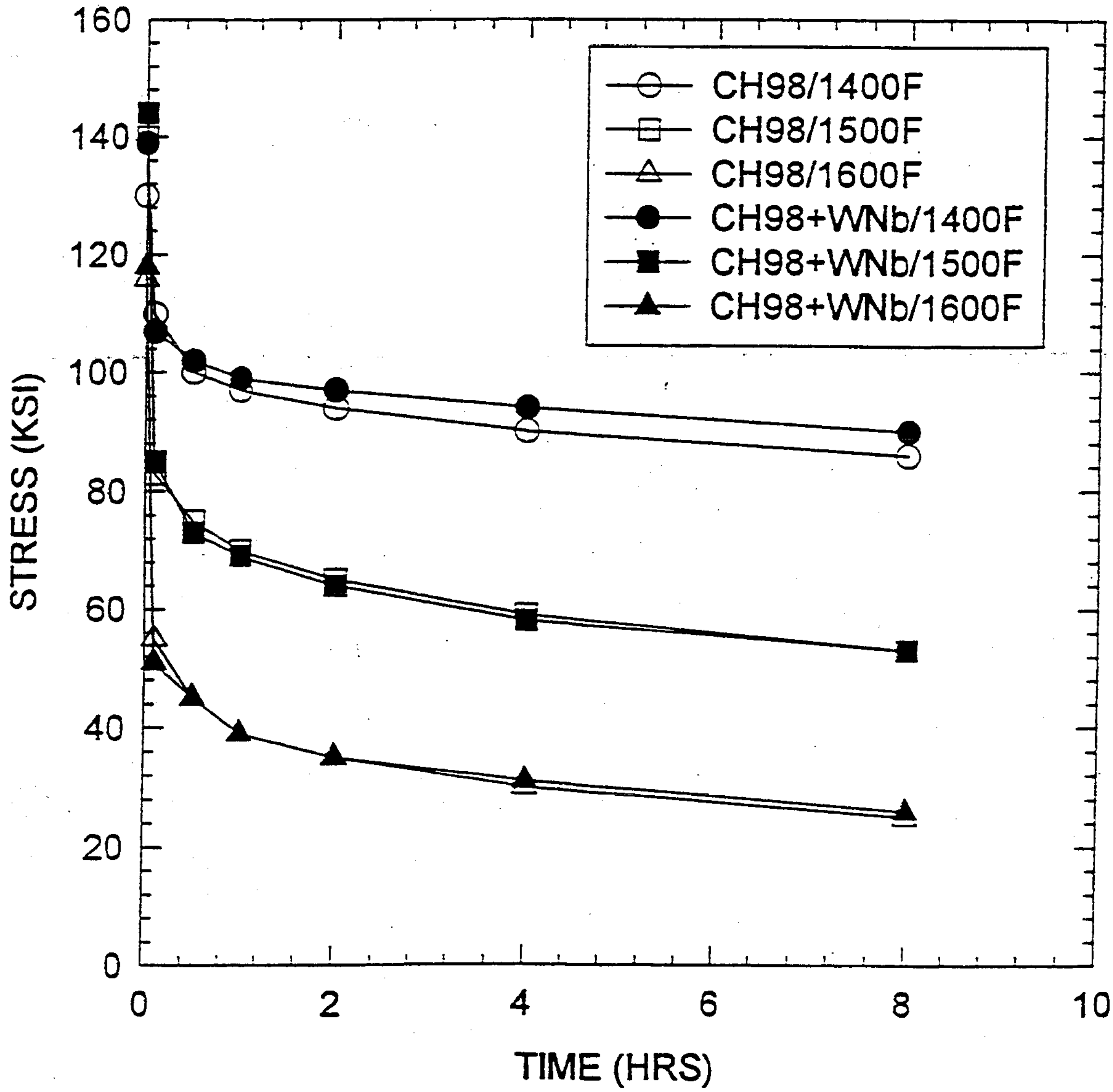


FIGURE 14. STRESS RELAXATION DATA FOR DISK ALLOY.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
June 2004

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
The Effect of Solution Cooling Rate on Residual Stresses in an Advanced Nickel–Base Disk Alloy

5. FUNDING NUMBERS
WBS–22–728–30–09

6. AUTHOR(S)
John Gayda, Paul Reynolds, and Stephen Mayers

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–14559

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2004-213081

11. SUPPLEMENTARY NOTES
This research was originally published internally as AST031 in September 1999. John Gayda, NASA Glenn Research Center; Paul Reynolds and Stephen Mayers, Pratt & Whitney, East Hartford, Connecticut 06108. Responsible person, John Gayda, organization code 5120, 216–433–3273.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 26 Distribution: Nonstandard
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Gas turbine engines for future subsonic transports will probably have higher pressure ratios which will require nickel-base superalloy disks with 1300 to l400 °F temperature capability. Several advanced disk alloys are being developed to fill this need. For large disks, residual stresses generated during cooling from solution temperatures may require a stabilization heat treatment to relieve these stresses, this is undoubtedly more critical for higher cooling rates achieved with oil quenching. The reduction in residual stress levels lessens distortion during subsequent machining operations and therefore decreases disk cost. The purpose of this study is to estimate the magnitude of the residual stresses generated upon cooling from solution temperature for an advanced, nickel-base disk alloy at several cooling rates. The disk alloy studied was developed in NASA's HSR and AST Programs. Both analytical and experimental techniques were employed to generate residual stress estimates as a function of cooling rate. In addition, experimental data were also generated to estimate the magnitude of stress relief achieved for various stabilization heat treatments.

14. SUBJECT TERMS
Superalloy

15. NUMBER OF PAGES
27

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102