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Prepared for
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ABSTRACT

Using a previously formulated equation which calculates the elastic, plastic and creep strains during loading at a constant elevated temperature, a method and a computer program have been developed that will predict the strain due to creep during anisothermal tests at constant load. Comparisons were made with results from anisothermal tests for AS A149, an Australian steel close to the specification for ASTM A36. Agreement is excellent for several linear heating rates and one nonlinear heating rate.

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SYMBOLS

a, b, c, d, f, g - functions of temperature.
t_1 (TIMEHEAT)* - time during heating ramp, min.
t_2 (TIMECOOL) - time during cooling ramp, min.
A - length of time spent at temperature T during heating ramp, min.
B - temperature step change during ramping, °C.
C - cooling rate, °C/min.
D - total duration of the fire, min.
E - Young's modulus, ksi.
F - time spent at maximum temperature, min.
H - heating rate, °C/min.
J=K - necessary for programming.
K - length of time spent at temperature T during cooling ramp, min.
L - initial temperature, °C.
M - equivalent time at temperature T+B needed to generate ϵ_{CRC}.
N=A - necessary for programming.
T - temperature, °C.
TMAX, TTOP - maximum temperature, °C.
X - equivalent time at temperature T+B needed to generate ϵ_{CRH}.
ϵ_e (EL) - elastic strain, %.
ϵ_p (PL) - plastic strain, %.
ϵ_c (CR) - creep strain, %.
ϵ_{CRH} (CRH)* - creep strain during heating, %.
ϵ_{CRC} (CRC) - creep strain during cooling, %.
α (TE) - thermal expansion strain, %.
ϵ_T (TOTAL) - total strain due to stressing, %.
σ - stress, ksi.
σ_{YRT} - room temperature yield strength, ksi.
σ/σ_{YRT} (S) - ratio of applied stress to room temperature yield strength.

* - Symbols in parentheses are those used in the computer program.

In this report the units used for temperature and stress are °C and ksi, respectively. This was done to be consistent with the report(1) from which the original data were taken. To convert stresses from ksi to MPa the value of stress in ksi should be multiplied by 6.895. In the computer program stress is entered as the ratio of applied stress to room temperature yield strength ($S=\sigma/\sigma_{YRT}$) and is therefore dimensionless.

TABLES

FIGURES

1. Introduction

The increased use of structural steel in high rise buildings and bridges has created a need to further understand the mechanical behavior of such steel in a fire. In a previous report[2] an equation was developed that predicts the elastic, plastic, creep and total strains generated for any given temperature (up to 650°C), stress, and time (up to 8 hours). However, it was assumed that the temperature was constant over the duration of the fire, no allowance being made for heating or cooling times. This makes the prediction overly conservative. In order to simulate more closely the conditions existing in a real fire, these allowances need to be considered. It is the purpose of this study to develop such an analysis.

The original equation to calculate the total strain, ϵ_T, was made up of the elastic recoverable strain, ϵ_e; the plastic time-independent stain, ϵ_p; and the creep time-dependent strain, ϵ_c, as follows

$$\epsilon_T = \epsilon_e + \epsilon_p + \epsilon_c \qquad (1)$$

which was written in the form

$$\epsilon_T = d\sigma + f\sigma^g + at^b\sigma^c \qquad (2)$$

where σ is stress, t is time, and a, b, c, d, f, g are functions of temperature and are listed in Table 1.

The inclusion of heating and cooling periods will only affect the time-dependent creep strain, which can be written as

$$\epsilon_c = at^b\sigma^c \qquad (3)$$

This is the Norton-Bailey equation for creep.

2. Creep Strain Theory during Heating and Cooling Ramps

Following Penny and Marriott[3] and Kraus[4] the creep strain history can be predicted from the strain hardening rule. This approach is illustrated in Figure 1. Assume that a constant stress is applied at a temperature, T, for a given length of time, A. The creep strain follows the T curve to a value of ϵ_{CRH} (where ϵ_{CRH} stands for the creep strain during heating). When the temperature increases to T+B the strain will follow the T+B curve. It is possible to link the two curves at time A by moving horizontally from the T curve to the T+B curve, keeping the strain constant. This gives rise to a time, X, equivalent to that which would have elapsed if the creep strain, ϵ_{CRH}, had been generated at temperature T+B alone. This procedure can be repeated until the maximum temperature is reached, see Figure 2. (For programming purposes, the subsequent time for which the stress is applied at each temperature is given as N, where N=A.)

The final value of X is equivalent to the time that the specimen would have had to spend at the maximum temperature in order to produce the sum of the creep strains generated at each of the lower temperatures. This time, X, will be known here as the "equivalent time".

Exactly the same procedure can be used to find the equivalent time, M, during the cooling ramp. In this case the temperature step change remains as B, but the time at temperature T is given as K and the subsequent times at each temperature step are represented by J, where J=K. (Once again this equality is necessary for programming purposes.) The creep strain generated during the cooling ramp is represented by ϵ_{CRC}.

The same procedure is also used for the nonlinear heating ramp with B as the temperature step change. However, in this case N, the time at each step of temperature, is not a constant, but increases with increasing temperature. The creep strain generated during the nonlinear heating ramp is also given as ϵ_{CRC}.

In order for the temperature ramp to be a smooth line the steps A and B have to be small. Actual values recommended will be given later. Results from previous work(2) indicate that no significant creep strain occurs below 350°C. Therefore, this temperature is used as the initial temperature, T, in all following calculations.

3. Heating and Cooling Scenarios

For the proposes of this study five heating and cooling scenarios, as shown in figures 3a-3e, were considered:

a. The temperature increases linearly to a maximum value TTOP.
b. The temperature increases linearly to TTOP and then decreases linearly.
c. The temperature increases linearly to a maximum value of TMAX and holds steady for a time interval F.
d. The temperature increases linearly to TMAX, holds steady for a time interval F and then decreases linearly.
e. The temperature increases nonlinearly to a value of TTOP.
The reason that two notations are given for maximum temperature (TTOP and TMAX) is for clarity in the computer program. This program allows two choices:

1. Specify the maximum temperature (TTOP); the heating rate (H); and the cooling rate (C), if any. The deformation during the ramps, will be calculated as shown in Figure 4a.
2. Specify the heating rate (H); the cooling rate (C), if any; the initial temperature (L); the total duration of the fire (D); and put a limit on the maximum temperature that can be reached (TMAX), see Figure 4b. The program will then calculate the actual temperature reached (TTOP). If TTOP does reach TMAX the length of time (F) spent at TMAX is calculated. Resulting strains are found for the sum of the times spent during a) the heating ramp, b) at constant temperature, and c) the cooling ramp, if any. See figures 3c and 3d.

The calculation of TTOP is illustrated in Figure 4a, where

$$TTOP = (t_1*H) + L \tag{4}$$

$$TTOP = (t_2*C) + L \tag{5}$$

$$t_1 + t_2 = D \tag{6}$$

These equations lead to the following

$$TTOP = L + \frac{DCH}{C+H} \tag{7}$$

In Figure 4b it can be seen that

$$t_1 = \frac{TMAX-L}{H} \tag{8}$$

$$t_2 = \frac{TMAX-L}{C} \tag{9}$$

$$F = D-(t_1+t_2) \tag{10}$$

where F is the length of time at constant temperature TMAX. Therefore

$$F = D - \left(\frac{TMAX-L}{H}\right) + \left(\frac{TMAX-L}{C}\right) \tag{11}$$

The value to be used for the initial temperature, L, needs to be considered. If the heating rate were truly linear from the lowest temperature, L would be the ambient temperature, say 20°C. However it is likely that a higher temperature is reached very quickly, before the heating rate can be considered to be linear. For instance, in the nonlinear ramp shown in Figure 5 a temperature of 300°C is reached in only 5 minutes, compared to a time of 56 minutes at a heating rate of 5°C/min.

4. Computer Program to Calculate Creep Strain

The creep strain during the heating ramp, the time at constant temperature and the cooling ramp can be calculated using

$$\epsilon_c = at^b\sigma^c \tag{3}$$

$$\text{with} \quad t = X + F + M \tag{12}$$

where F is the actual time at constant temperature TMAX, and X and M are the equivalent times at TMAX during the heating and cooling ramps as discussed previously.

A computer program, written in BASIC and suitable for a personal computer was developed such that elastic, plastic, creep and total strains can be calculated. In addition, thermal expansion strains can be found using an equation developed by Knight et al.[1] in which

$$\alpha = 0.87\left(\frac{T+273}{1000}\right) + 0.50\left(\frac{T+273}{1000}\right)^2 - 0.30 \qquad (13)$$

where α is the thermal expansion due to a rise in temperature above 20°C and T is the temperature in ° C.

In the discussion of Figure 1 it was stated that for the temperature ramp to be approximated by a smooth line the temperature and time steps, B and A, have to be small. Table 2 shows values of ϵ_{CRH} calculated using decreasing values of A and B for a temperature of 600°C, a stress/room temperature yield stress ratio of 0.5 and heating rates of 1, 5 and 10°C/min. It can be seen that values of calculated creep strain increase with decreasing A and B and converge towards a limiting number. A value for B of 1°C was chosen to give a close approximation to this number. Similar results are also obtained during the nonlinear heating ramp and once again B is set equal to 1°C.

5. Previous Results

Equation 2 was previously developed using experimental data from Skinner[5] and Knight, Skinner and Lay[1] for the Australian steel AS A149. This steel has specifications close to ASTM A36. The chemical compositions, yield and tensile strengths at room temperature for these steels are listed in Table 3. All data used were obtained from isothermal tests where specimens were brought to a constant temperature and then loaded in tension.

Skinner[5] also conducted anisothermal creep tests, in which the specimens were first loaded in tension and then the temperature was increased. Loads of $0.33\sigma_{YRT}$ and $0.67\sigma_{YRT}$, where σ_{YRT} is the room temperature-yield stress, were applied. Four linear heating rates in the range 25°C/hr to 600°C/hr were used. One nonlinear rate was tested. This rate is based on a modified form of the time-temperature curve used for the control of the furnace temperature during fire testing of structures[6]. The particular relation chosen was

$$T = 185\log_{10}(8t+1) \qquad (14)$$

where T is in ° C and t is in minutes. It is intended to approximate the temperature of the steel rather than that of the furnace atmosphere. Changes of temperature and heating rate with time are shown in Figures 5 and 6.

6. Results

The computer program developed to predict elastic, plastic, creep and thermal expansion strains during anisothermal tests from data collected during isothermal tests is listed in Appendix 1.

Predictions made using this program are given in Tables 4 to 11 and illustrated in Figures 7 to 11. It should be noted that the results given by Skinner do not include thermal expansion, which is therefore listed separately in the tables. The experimental data obtained by Skinner[1] are plotted as solid lines while the predicted results are shown as dashed lines. Figure 7 shows results for a stress of $0.33\sigma_{YRT}$ during a heating rate of 25°C/hr. It can be seen that the agreement is excellent. Figure 8 includes stresses of $0.33\sigma_{YRT}$ and $0.67\ \sigma_{YRT}$ and a heating rate of 100°C/hr. It should also be noted for this curve that beyond 650°C the predicted data are obtained by extrapolating the equation above the limit provided by the original data base. In this case the prediction is excellent but caution should be used when extrapolating outside the data base. In fact, the present program does not run when such extrapolations are requested.

Figure 9 is for a stress of $0.33\ \sigma_{YRT}$ and heating rate of 250°C/hr. Again the predicted results above 650C use extrapolation, and again there is excellent agreement. Figure 10 shows results for both stress levels and a heating rate of 600°C/hr. For this case predicted results significantly overestimate the total strains generated. A possible explanation is that the steel did not heat up as fast as was believed. A heating rate of 600°C/hr is high and it is possible that the specimen did not have time to come to equilibrium before each reading was taken. Alternatively, the limits of applicability of the strain hardening rule have been exceeded.

Finally, Figure 11 shows the curves for both stress levels under conditions of nonlinear heating described by Equation 14. Agreement between measured and calculated results is good.

7. Conclusions

1. An analysis was made and a computer program was written that predicts creep strains generated during anisothermal tests from data obtained during isothermal tests.
2. Agreement of predicted and measured strains for stresses of $0.33\sigma_{YRT}$ and $0.67\sigma_{YRT}$ is very good for linear heating rates of 25, 100, and 250°C/hr and for the one nonlinear heating rate tested.
3. For the linear heating rate of 600°C/min the predicted values of strain are conservative. Possible explanations are that the steel did not heat up as fast as was believed, or that the assumptions inherent in the present approach were not justified.
4. The present approach shows that it is possible to predict results for anisothermal, constant load tests using data obtained during tests at constant temperatures.

8. Acknowledgements

We would like to thank the American Iron and Steel Institute (AISI) for financial support and encouragement of the study reported here. In particular, the efforts of Mrs. Kathleen Almand and Mr. David Jeanes of AISI to collect data and to disseminate the initial results of this work are greatly appreciated.

9. References

1. Knight, D., Skinner, D. H., and Lay, M. G., "Prediction of Isothermal Creep," Broken Hill Proprietary Company, Clayton, Victoria, Australia, Melbourne Research Laboratory Report, MRL 18/2, April 1971.
2. Fields, B. A. and Fields, R. J., "Elevated Temperature Deformation of Structural Steel," National Institute of Standards and Technology, Gaithersburg, MD, NISTIR 88-3899, March 1989.
3. Penny, R. K. and Marriott, D. L., Design for Creep, McGraw-Hill Co. Ltd., 1971.
4. Kraus, H., "Mathematical Modeling of Creep Phenomena," in Creep Analysis, Wiley Interscience, 1980, pp.18-40.
5. Skinner, D. H., "Measurement of High Temperature Properties of Steel," Broken Hill Proprietary Company, Clayton, Victoria, Australia, Melbourne Research Laboratory Report, MRL 6/10, May 1972.
6. International Organisation for Standardization, "Fire Resistance Tests of Structures," ISO/R834-1968 (E).
7. ASTM Book of Standards, Vol. 01.04, 1988.

Table 1. Strain Equation Constants

$$a = -6.10 + 0.00573*T \quad (T < 500C)$$
$$a = -13.25 - 0.00851*T \quad (T > 500C)$$
$$b = -1.1 + 0.0035*T$$
$$c = 2.1 + 0.0064*T$$
$$d = 10^2/(29300 - 12.6*T)$$
$$f = 10_\wedge(-0.00041*(T_\wedge 1.647))$$
$$g = T/(147-0.016*T)$$

Table 2. The effect of changing the temperature step increase, B, for TTOP = 600°C and σ/σ_{YRT} = 0.5.

H °C/min	A min	B °C	X min	ϵ_{CRH} %
1	10	10	14.8	2.80
	5	5	17.0	3.21
	2.5	2.5	18.2	3.43
	1	1	18.9	3.57
	0.5	0.5	19.1	3.62
	0.25	0.25	19.3	3.64
5	2	10	3.40	0.64
	1	5	3.85	0.73
	0.5	2.5	4.09	0.77
	0.2	1	4.23	0.80
	0.1	0.5	4.28	0.81
	0.5	0.25	4.31	0.81
10	1	10	1.81	0.34
	0.5	5	2.04	0.39
	0.25	2.5	2.16	0.41
	0.1	1	2.23	0.42
	0.05	0.5	2.26	0.43
	0.025	0.25	2.27	0.43

Table 3. Compositions and tensile properties for ASTM A36 and AS A149 steels.

	A36	A149
C	max. 0.29% by wt.	0.27
Si	0-0.30	0.128
Mn	0-1.35	0.65
P	max 0.04	0.033
S	max 0.05	0.041
Ni	-	0.086
Cr	-	0.16
Cu	-	0.01
σ_Y Ksi	36.0	35.0
MPa	248	245
σ_T Ksi	58.0 to 80.0	70.5
MPa	400 to 550	487

For A36 there are more detailed specifications for different thicknesses and shapes, as listed in Reference 7.

Table 4. Measured and predicted strains during heating at a rate of 25°C/hr for a stress of $0.33\sigma_{YRT}$ (11.8 ksi)

T C	ϵ_e %	ϵ_p %	ϵ_c %	ϵ_T %	$\epsilon_{Skinner}$ %	α %
401	0.05	0	0	0.05	0.066	0.51
454	0.05	0	0	0.05	0.074	0.60
500	0.05	0	0.01	0.06	0.089	0.67
532	0.05	0	0.02	0.07	0.092	0.72
553	0.05	0	0.07	0.12	0.125	0.76
572	0.05	0	0.18	0.23	0.25	0.79
593	0.05	0	0.52	0.57	0.50	0.83
604	0.05	0	0.92	0.97	0.75	0.85
609	0.05	0	1.19	1.2	1.00	0.86
616	0.05	0	1.72	1.8	1.5	0.87
621	0.05	0.01	2.23	2.3	2.0	0.88
625	0.06	0.01	2.75	2.8	2.5	0.88
628	0.06	0.01	3.21	3.3	3.0	0.89
631	0.06	0.01	3.76	3.8	3.5	0.90
633	0.06	0.02	4.17	4.3	4.0	0.90
636	0.06	0.02	4.89	5.0	4.5	0.90
638	-	-	-	-	5.0	0.91

Table 5. Measured and predicted strains during heating at a rate of 100°C/hr for a stress of $0.33\sigma_{YRT}$ (11.8 ksi)

T C	ϵ_e %	ϵ_p %	ϵ_c %	ϵ_T %	$\epsilon_{Skinner}$ %	α %
400	0.05	0	0	0.05	0.028	0.51
453	0.05	0	0	0.05	0.043	0.60
501	0.05	0	0	0.05	0.048	0.67
554	0.05	0	0.02	0.07	0.053	0.76
602	0.05	0	0.23	0.28	0.25	0.84
615	0.05	0	0.42	0.47	0.5	0.87
624	0.06	0.01	0.65	0.72	0.75	0.88
631	0.06	0.01	0.91	0.98	1.0	0.90
641	0.06	0.03	1.46	1.6	1.5	0.91
647	0.06	0.05	1.94	2.1	2.0	0.92
652	0.06	0.08	2.36	2.5	2.5	0.93
655	0.06	0.10	2.73	2.9	3.0	0.94
659	0.06	0.16	3.3	3.5	3.5	0.95
662	0.06	0.23	3.82	4.1	4.0	0.95
664	0.06	0.29	4.21	4.6	4.5	0.95
665	0.06	0.33	4.41	4.8	-	0.96
666	0.06	0.37	4.63	5.1	5.0	0.96

Table 6. Measured and predicted strains during heating at a rate of 100°C/hr for a stress of $0.67\sigma_{YRT}$ (23.7 ksi)

T C	ϵ_e %	ϵ_p %	ϵ_c %	ϵ_T %	$\epsilon_{Skinner}$ %	α %
401	0.10	0.06	0.02	0.18	0.19	0.51
460	0.10	0.05	0.06	0.21	0.25	0.60
518	0.10	0.12	0.22	0.44	0.50	0.72
534	0.10	0.20	0.44	0.74	0.75	0.73
543	0.11	0.27	0.67	1.1	1.0	0.74
555	0.11	0.46	1.20	1.8	1.5	0.76
561	0.11	0.62	1.62	2.4	2.0	0.77
567	0.11	0.86	2.19	3.2	2.5	0.78
571	0.11	1.08	2.69	3.9	3.0	0.79
574	0.11	1.29	3.13	4.5	3.5	0.80
575	0.11	1.37	3.29	4.8	-	0.80
576	0.11	1.46	3.47	5.0	-	0.80
577	-	-	-	-	4.0	0.80
579	-	-	-	-	4.5	0.80
581	-	-	-	-	5.0	0.81

Table 7. Measured and predicted strains during heating at a rate of 250°C/hr for a stress of $0.33\sigma_{YRT}$ (11.8 ksi)

T C	ϵ_e %	ϵ_p %	ϵ_c %	ϵ_T %	$\epsilon_{Skinner}$ %	α %
401	0.05	0	0	0.05	0.069	0.51
453	0.05	0	0	0.05	0.074	0.60
500	0.05	0	0	0.05	0.089	0.67
526	0.05	0	0	0.05	0.091	0.71
553	0.05	0	0.01	0.06	0.12	0.76
584	0.05	0	0.05	0.10	0.16	0.82
605	0.05	0	0.11	0.16	0.25	0.85
627	0.06	0.01	0.29	0.36	0.50	0.89
637	0.06	0.02	0.46	0.54	0.75	0.91
645	0.06	0.04	0.63	0.73	1.0	0.92
654	0.06	0.09	0.95	1.1	1.5	0.93
662	0.06	0.23	1.36	1.6	2.0	0.95
666	0.06	0.37	1.62	2.1	2.5	0.96
670	0.06	0.62	1.95	2.6	3.0	0.96
674	0.06	1.07	2.36	3.5	3.5	0.97
676	0.06	1.14	2.56	4.0	4.0	0.98
679	0.06	2.19	2.93	5.2	4.5	0.98
681	-	-	-	-	5.0	0.99

Table 8. Measured and predicted strains during heating at a rate of 600°C/hr for a stress of $0.33\sigma_{YRT}$ (11.8 ksi)

T C	ϵ_e %	ϵ_p %	ϵ_c %	ϵ_T %	$\epsilon_{Skinner}$ %	α %
400	0.05	0	0	0.05	0.03	0.51
453	0.05	0	0	0.05	0.03	0.60
500	0.05	0	0	0.05	0.04	0.67
560	0.05	0	0.01	0.06	0.05	0.77
593	0.05	0	0.03	0.08	0.08	0.83
614	0.05	0	0.07	0.13	0.15	0.87
632	0.06	0.01	0.13	0.20	0.25	0.90
644	0.06	0.04	0.25	0.35	0.40	0.92
652	0.06	0.08	0.33	0.47	0.50	0.93
664	0.06	0.29	0.55	0.90	0.75	0.95
672	0.06	0.81	0.76	1.64	1.0	0.97
682	0.06	3.45	1.18	4.70	1.5	0.99
683	0.06	4.04	1.24	5.34	-	0.99
688	-	-	-	-	2.0	1.0
692	-	-	-	-	2.5	
696	-	-	-	-	3.0	
700	-	-	-	-	3.5	
704	-	-	-	-	4.0	
707	-	-	-	-	4.5	
709	-	-	-	-	5.0	

Table 9. Measured and predicted strains during heating at a rate of 600°C/hr for a stress of $0.67\sigma_{YRT}$ (23.7 ksi)

T C	ϵ_e %	ϵ_p %	ϵ_c %	ϵ_T %	$\epsilon_{Skinner}$ %	α %
400	0.10	0.05	0.01	0.16	0.13	0.51
453	0.10	0.05	0.03	0.18	0.16	0.60
502	0.10	0.08	0.05	0.23	0.19	0.67
532	0.10	0.18	0.12	0.40	0.25	0.72
556	0.11	0.48	0.31	0.90	0.50	0.76
567	0.11	0.86	0.51	1.48	0.75	0.78
575	0.11	1.37	0.73	2.21	1.0	0.80
587	0.11	3.08	1.24	4.4	1.5	0.82
589	0.11	3.57	1.37	5.0	-	0.82
595	-	-	-	-	2.0	0.83
599	-	-	-	-	2.5	0.84
604	-	-	-	-	3.0	0.85
607	-	-	-	-	3.5	0.86
610	-	-	-	-	4.0	0.86
613	-	-	-	-	4.5	0.87
615	-	-	-	-	5.0	0.87

Table 10. Measured and predicted strains during a non-linear heating rate, where $T = 185\log_{10}(8t+1)$, for a stress of $0.33\sigma_{YRT}$ (11.8 ksi)

T C	ϵ_e %	ϵ_p %	ϵ_c %	ϵ_T %	$\epsilon_{Skinner}$ %	α %
402	0.05	0	0	0.05	0.069	0.52
454	0.05	0	0	0.05	0.074	0.60
500	0.05	0	0	0.05	0.089	0.67
537	0.05	0	0.01	0.06	0.093	0.73
562	0.05	0	0.03	0.08	0.12	0.78
580	0.05	0	0.10	0.15	0.25	0.81
599	0.05	0	0.30	0.35	0.50	0.84
608	0.05	0	0.49	0.54	0.75	0.85
614	0.05	0	0.74	0.79	1.0	0.87
620	0.05	0.01	1.07	1.1	1.5	0.88
626	0.06	0.01	1.55	1.6	2.0	0.89
629	0.06	0.01	1.87	1.9	2.5	0.89
632	0.06	0.01	2.26	2.3	3.0	0.90
634	0.06	0.02	2.56	2.6	3.5	0.90
636	0.06	0.02	2.91	2.9	4.0	0.90
637	0.06	0.02	3.10	3.1	4.5	0.91
638	0.06	0.02	3.31	3.3	5.0	0.91
640	0.06	0.03	3.75	3.8	-	0.91
642	0.06	0.03	4.27	4.3	-	0.91
644	0.06	0.04	4.85	4.9	-	0.92

Table 11. Measured and predicted strains during a nonlinear heating rate, where $T = 185\log_{10}(8t+1)$, for a stress of $0.67\sigma_{YRT}$ (23.7 ksi)

T C	ϵ_e %	ϵ_p %	ϵ_c %	ϵ_T %	$\epsilon_{Skinner}$ %	α %
400	0.10	0.05	0.01	0.17	0.18	0.51
452	0.10	0.05	0.03	0.18	0.23	0.59
466	0.10	0.05	0.04	0.19	0.25	0.62
522	0.10	0.13	0.18	0.41	0.50	0.71
533	0.10	0.19	0.32	0.61	0.75	0.73
541	0.11	0.25	0.50	0.86	1.0	0.74
550	0.11	0.37	0.84	1.3	1.5	0.75
555	0.11	0.46	1.13	1.7	2.0	0.76
559	0.11	0.56	1.43	2.1	2.5	0.77
562	0.11	0.65	1.71	2.5	3.0	0.78
565	0.11	0.77	2.06	2.9	3.5	0.78
567	0.11	0.86	2.30	3.3	4.0	0.78
569	0.11	0.96	2.63	3.7	4.5	0.79
571	0.11	1.08	2.97	4.2	5.0	0.79
573	0.11	1.21	3.36	4.7	-	0.79
574	0.11	1.29	3.57	5.0	-	0.80

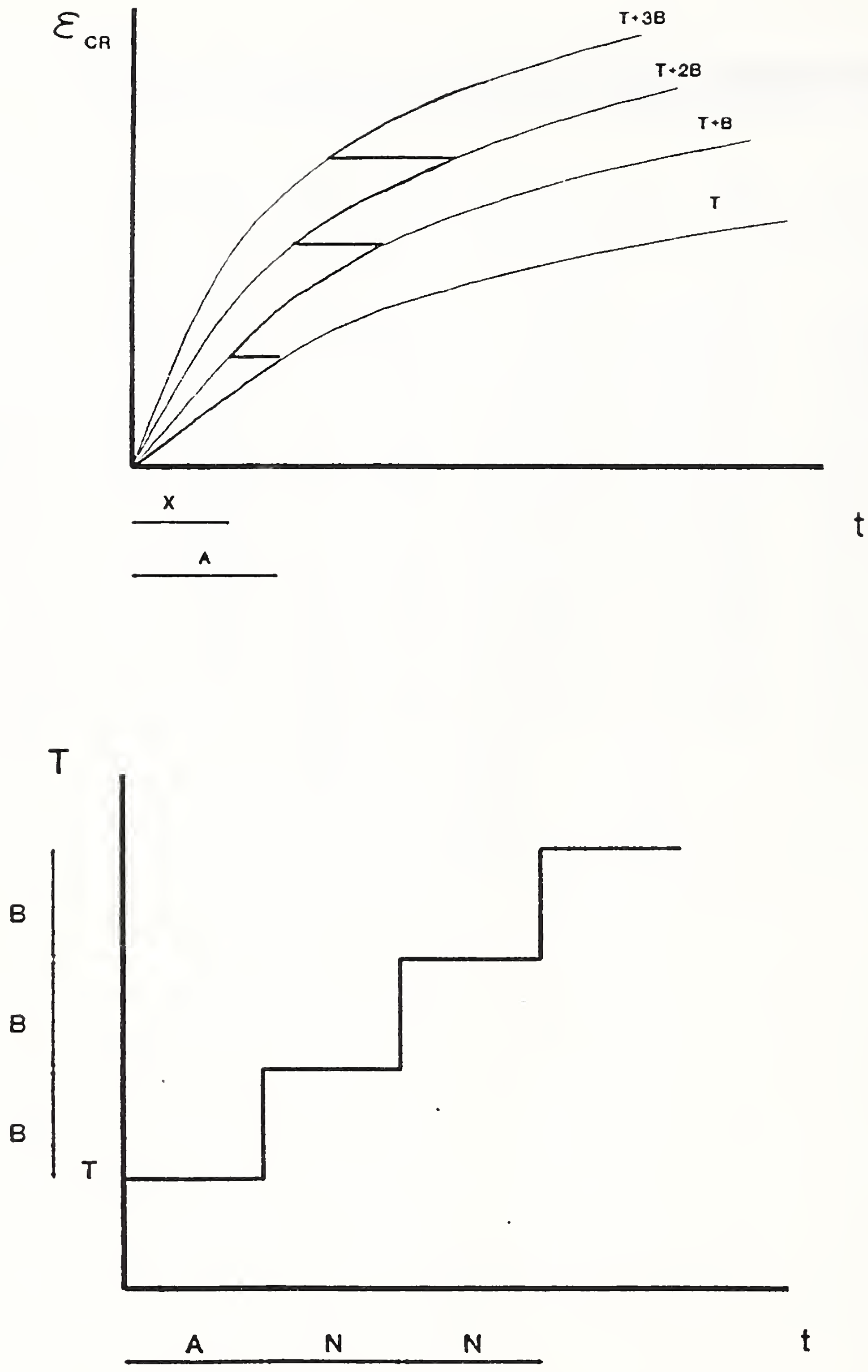


Figure 1. a) Creep strain history prediction from the strain hardening rule, during the increasing temperature conditions shown in b).

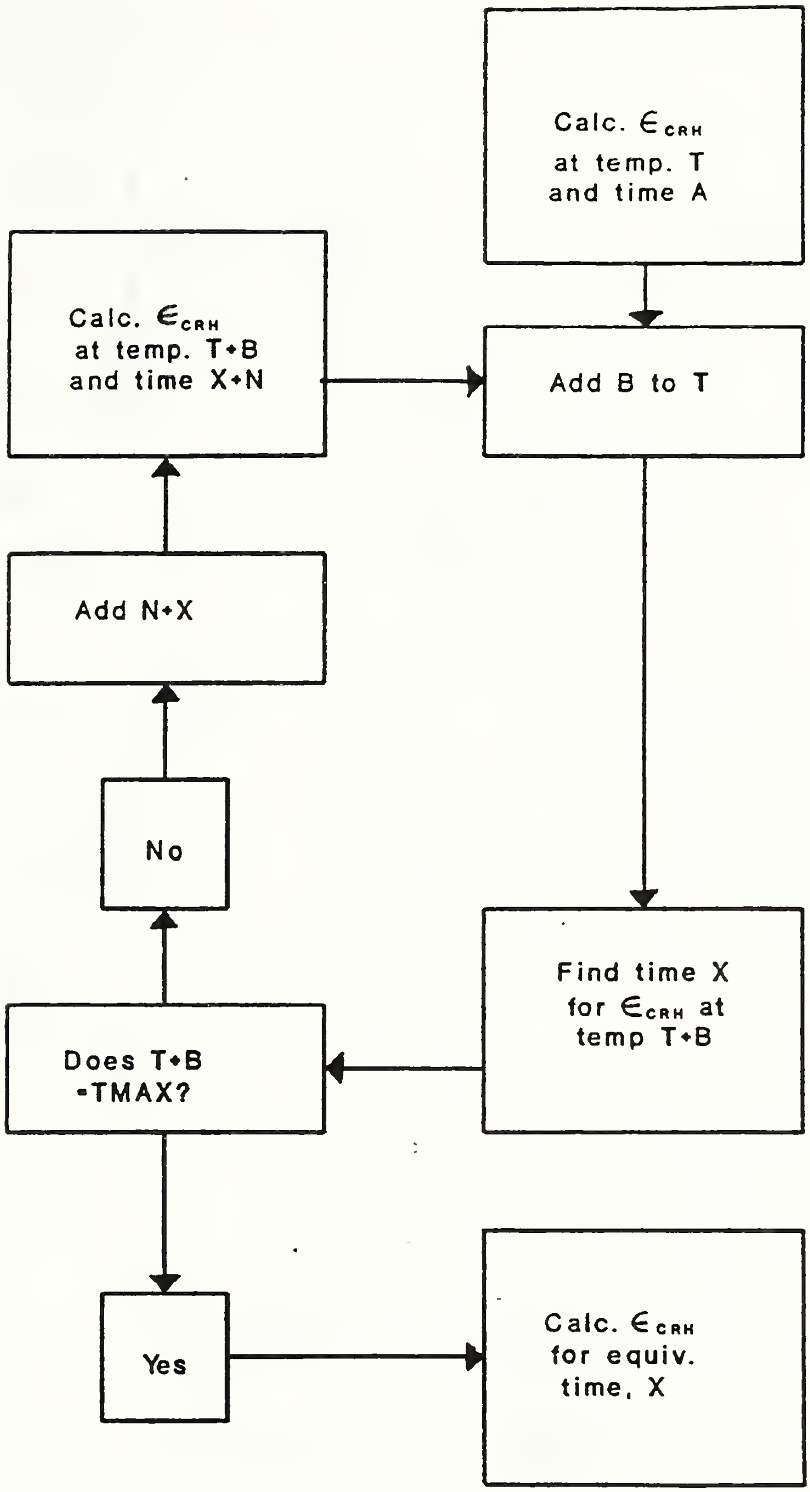


Figure 2. Flow diagram for calculation of strain during temperature ramp.

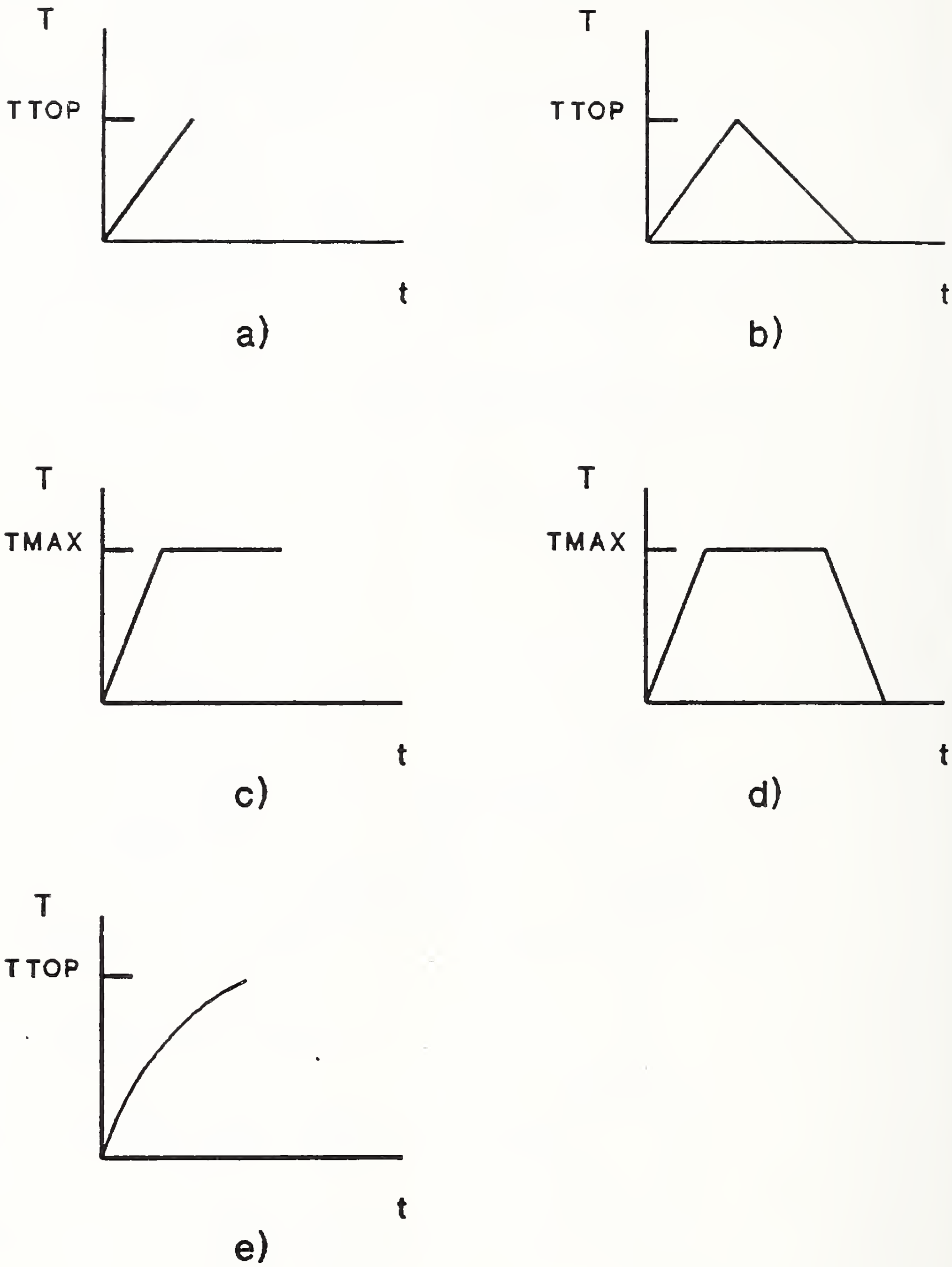


Figure 3. Heating and cooling scenarios.

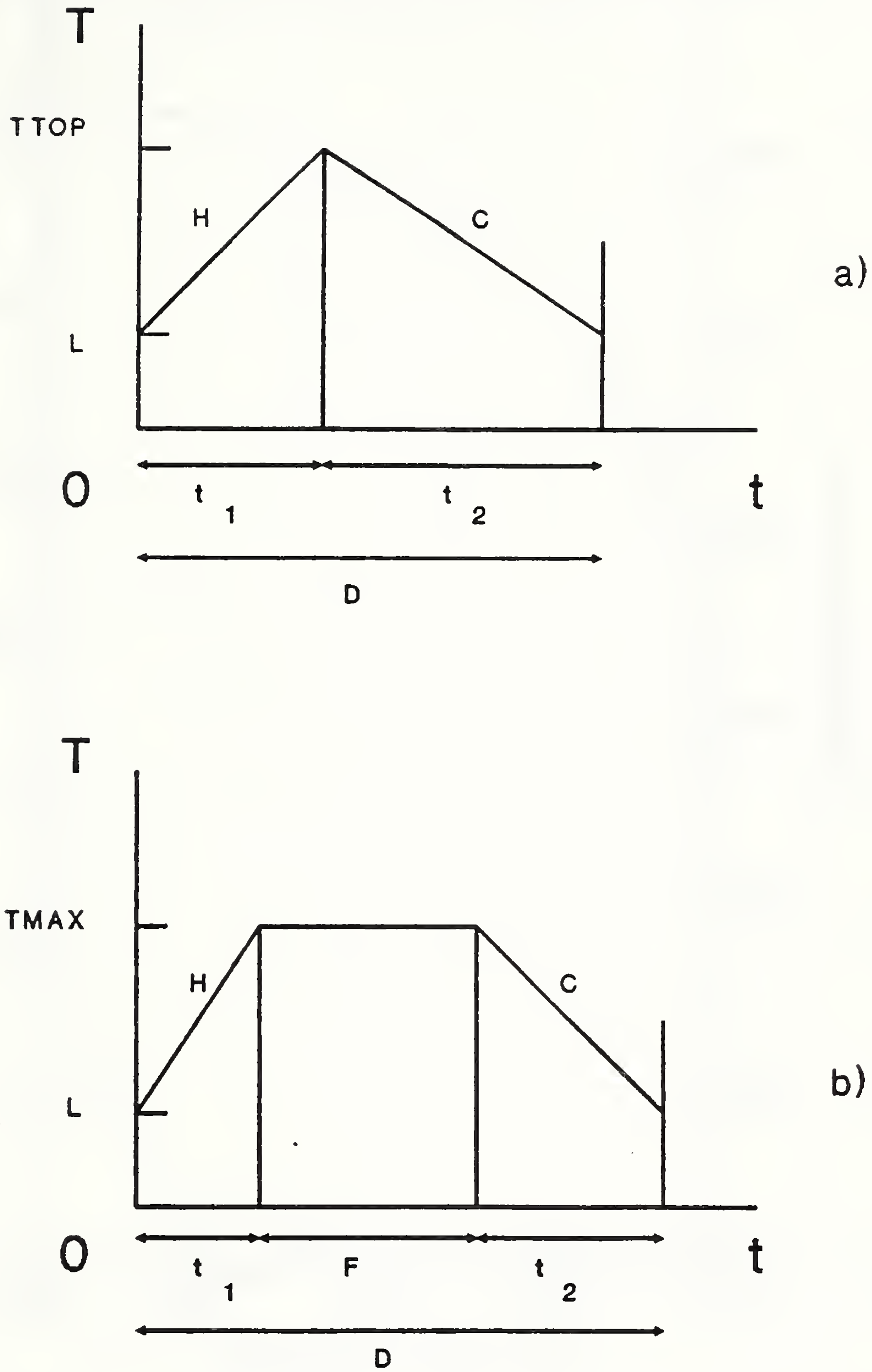


Figure 4. Figure used for calculation of a) maximum temperature (TTOP) and of b) time (F) spent at TTOP.

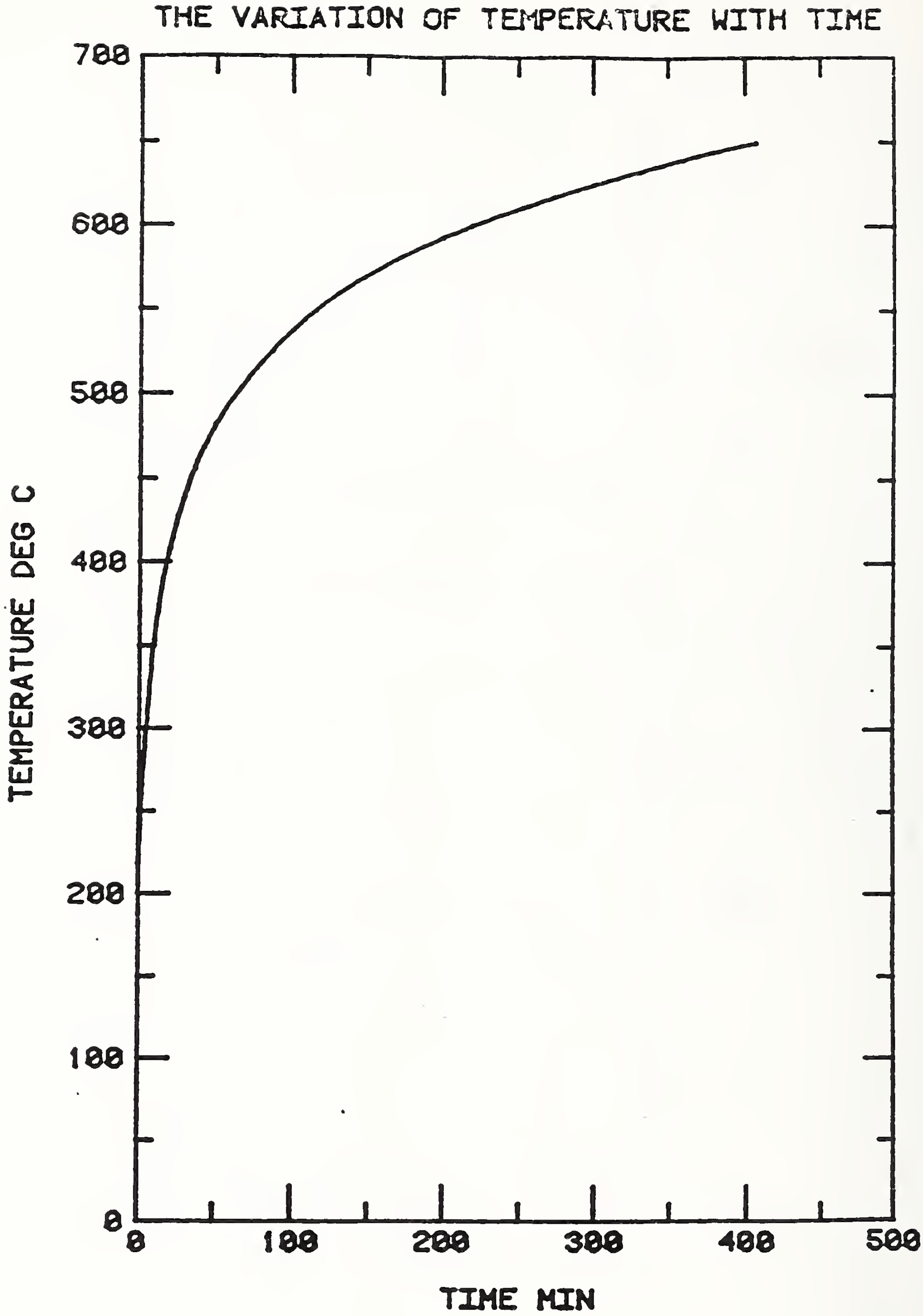


Figure 5. The variation of temperature (T) with time (t) during the non linear heating ramp, where $T=185\log_{10}(8t+1)$.

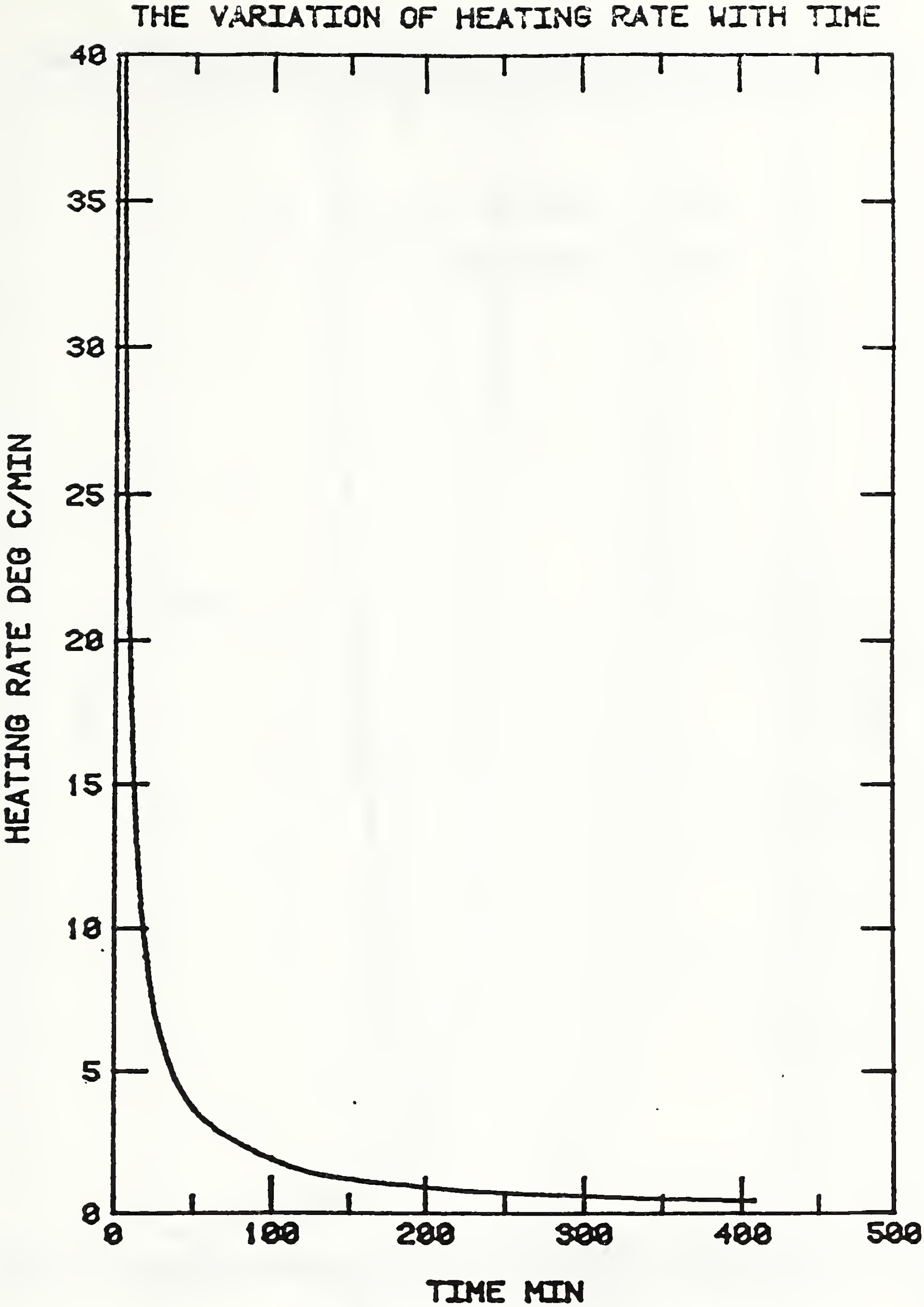


Figure 6. The variation of heating rate (H) with time (t) during the non-linear heating ramp, where $T=185\log_{10}(8t+1)$ and $H=1480/(8t+1)$.

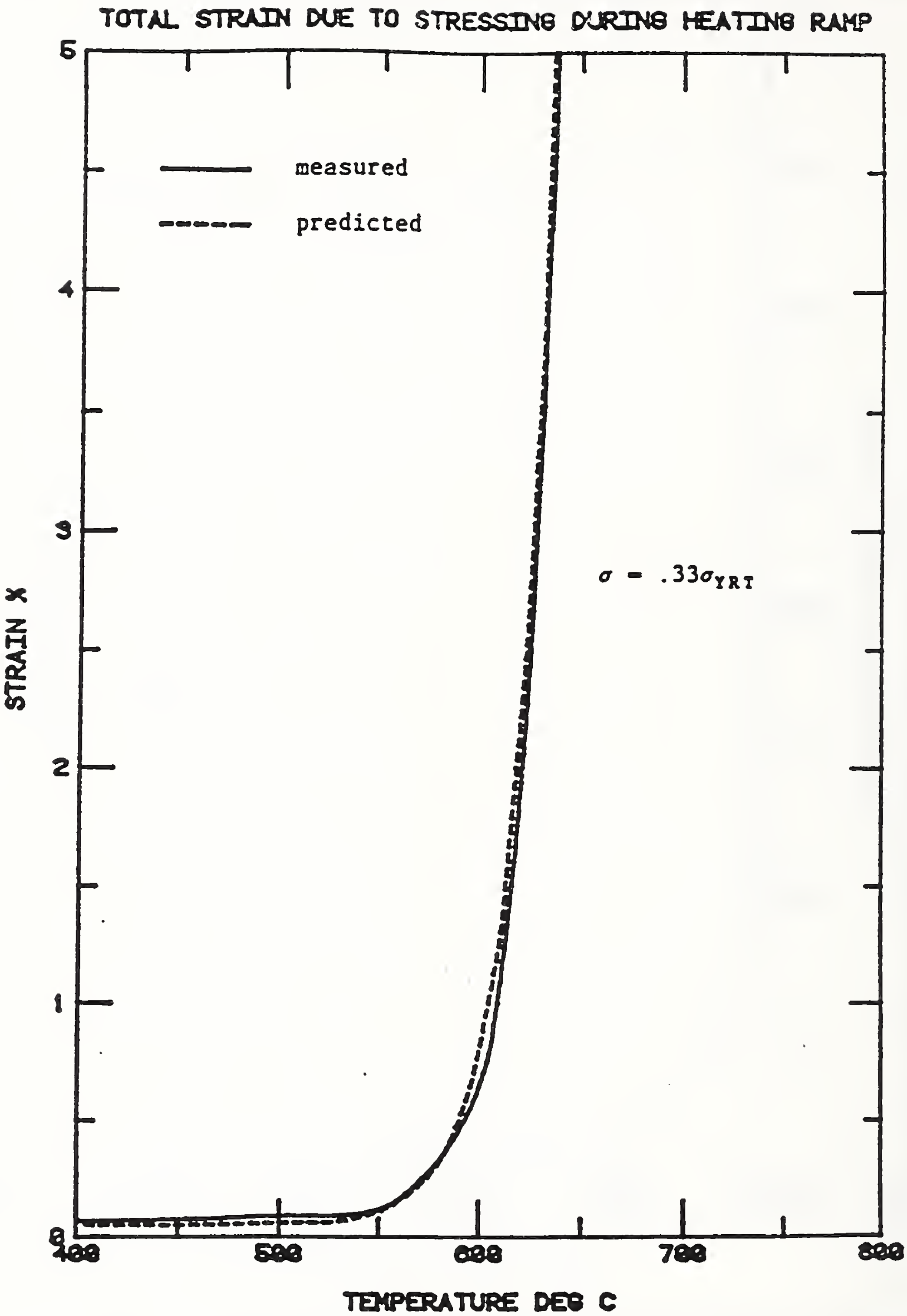


Figure 7. Measured and predicted strains during heating at a rate of 25 degC/hr for a stress of $0.33\sigma_{YRT}$ (11.8 ksi).

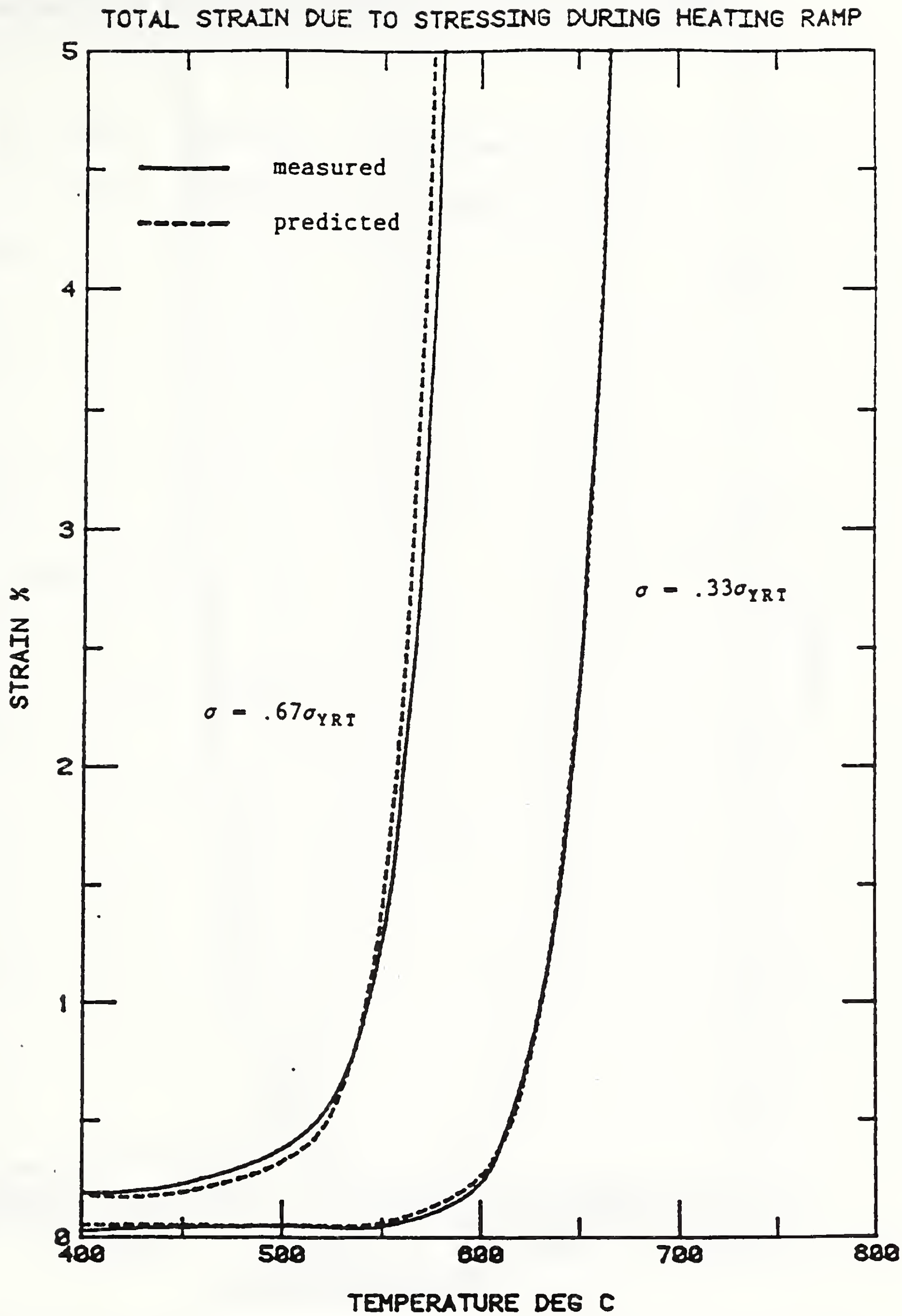


Figure 8. Measured and predicted strains during heating at a rate of 100 degC/hr for stresses of $0.33\sigma_{YRT}$ and $0.67\sigma_{YRT}$ (11.8 and 23.7 ksi).

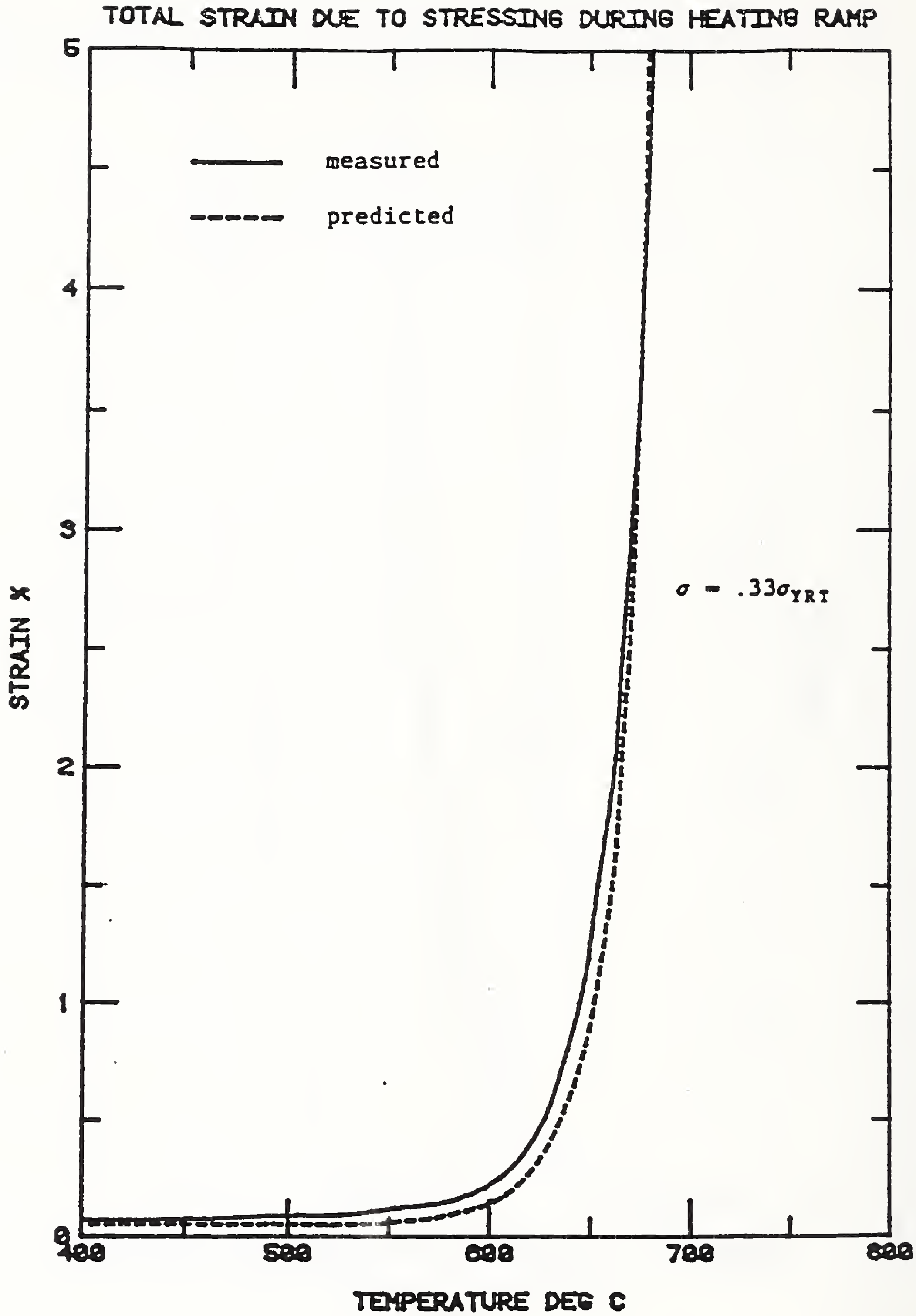
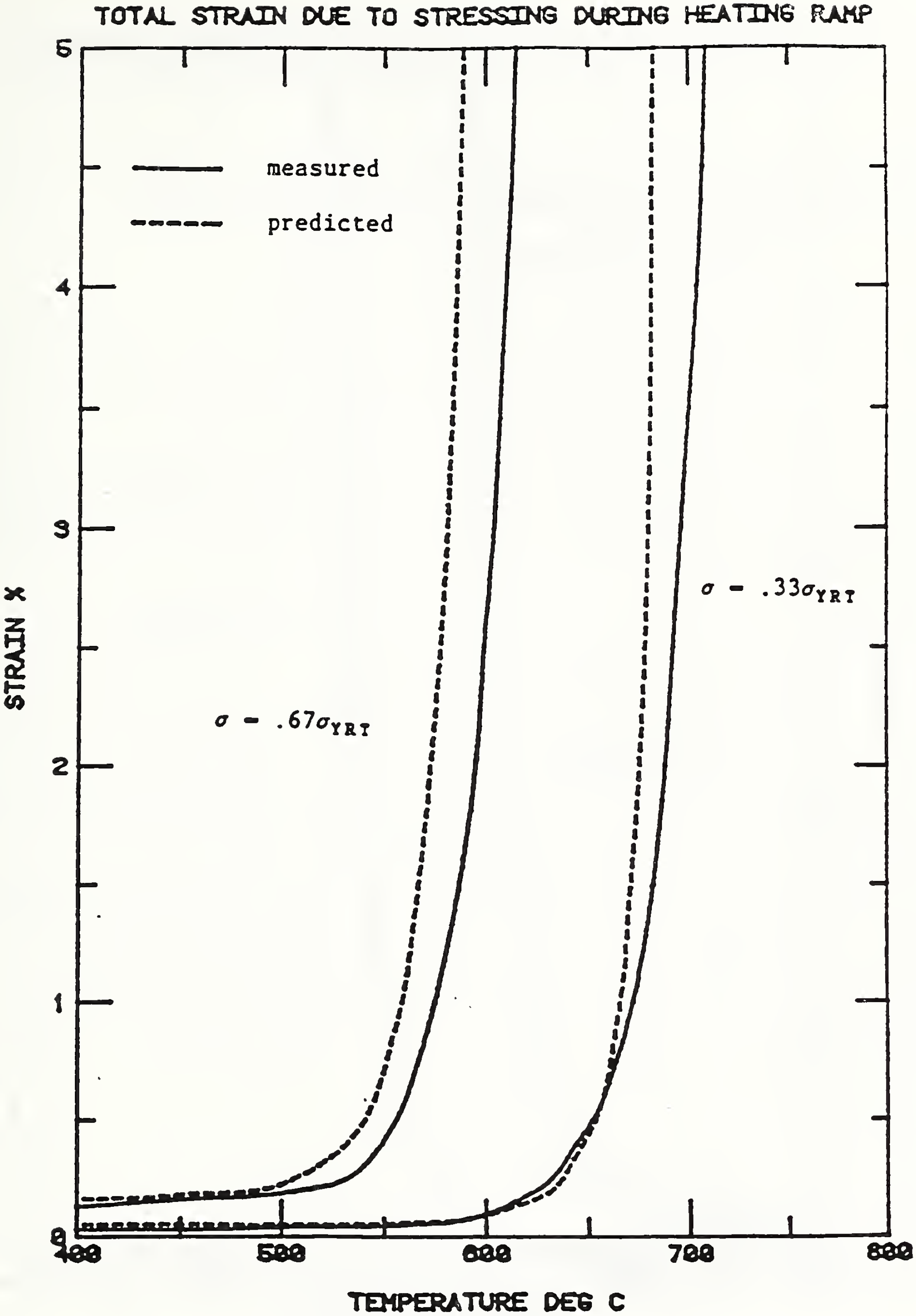


Figure 9. Measured and predicted strains during heating at a rate of 250 degC/hr for a stress of $0.33\sigma_{YRT}$ (11.8 ksi).



gure 10. Measured and predicted strains during heating at a rate of 600 degC/hr for stresses of $0.33\sigma_{YRT}$ and $0.67\sigma_{YRT}$ (11.8 and 23.7 ksi).

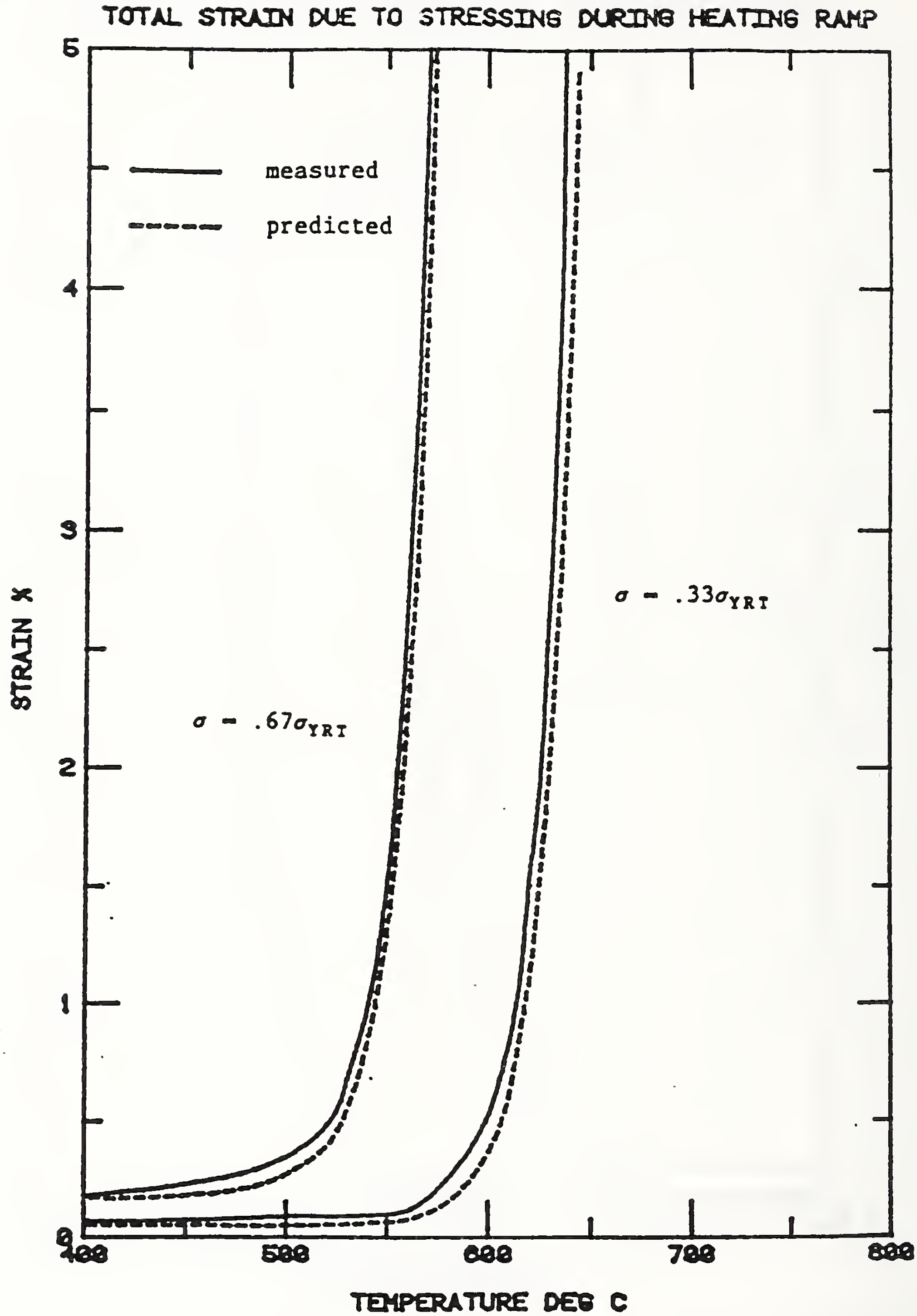


Figure 11. Measured and predicted strains during a non-linear heating rate, $T=185\log_{10}(8t+1)$, for stresses of $0.33\sigma_{YRT}$ and $0.67\sigma_{YRT}$ (11.8 and 23.7 ksi).

Appendix 1. Program in Basic for calculating the strains generated during anisothermal testing at constant load. Saved as A36FIRE.

```
100 CLS
110 PRINT "********************************************************************
**********"
120 PRINT "********************************************************************
**********"
130 PRINT "********************************************************************
**********"
140 PRINT "********************************************************************
**********"
150 PRINT "****************                                      ***************
**********"
160 PRINT "***************    Determination of Elastic, Plastic    *************
**********"
170 PRINT "**************    and Creep Strains for ASTM A36 Steel    ***********
**********"
180 PRINT "****************         at Elevated Temperatures         *************
**********"
190 PRINT "********************                by                ******************
**********"
200 PRINT "***********************     B.A.Fields, PhD.     *********************
**********"
210 PRINT "*************************                    ************************
**********"
220 PRINT "********************************************************************
**********"
230 PRINT "********************************************************************
**********"
240 PRINT "********************************************************************
**********"
250 PRINT "********************************************************************
**********"
260 PRINT
270 PRINT "This program was written with support from the American Iron and
          Steel Institute, while the author was a Guest Scientist in the Fire
          Research Division, NIST, Gaithersburg, MD 20899, in May 1990."
280 PRINT
290 PRINT
300 INPUT "Do you want further information?  (Y/N)  ", HELP$
310 IF HELP$ = "N" OR HELP$ = "n" THEN 1130
```

```
320 CLS
330 PRINT "This analysis will calculate elastic, plastic, creep and thermal
          expansion strains for given values of heating rate, temperature,
          stress and time in steels similar to ASTM A36."
340 PRINT
350 PRINT
360 PRINT "You have two main choices."
370 PRINT "1. You can specify the heating rate (H), cooling rate (C) and the
              duration of the fire (D) and put a limit on the maximum
              temperature that can be reached (TMAX). This program will then
380 PRINT "   calculate the actual temperature reached (TTOP).  If TTOP = TMAX
              the length of time (F) spent at TMAX is calculated.  Resulting
              strains are predicted for the sum of the times spent during:
390 PRINT "   a) the heating ramp, b) at constant temperature and c) the cooling
              ramp, if any.  When asked enter 1."
400 PRINT
410 PRINT "2. You can specify the maximum temp. reached (TTOP), the heating rate
              (H) and the cooling rate (C), if any, and calculate the
              deformation occuring during the heating or heating and cooling
420 PRINT "   ramps only.  When asked, enter 2."
430 PRINT
440 PRINT
450 PRINT "PRESS ENTER TO CONTINUE"
460 INPUT XX
470 CLS
480 IF AA = 3 GOTO 1250
490 PRINT "You have the choice of using:"
500 PRINT
510 PRINT "1. A linear heating rate (H).  A typical value of H might be between
              1 and 10 deg C/min."
520 PRINT
530 PRINT "2. A non-linear heating rate such as that found in time-temperature
              furnace control curves.  In this case H will be the derivative of
              the equation linking temperature and time and needs to be written
540 PRINT "   as a function of temperature in the relevant subprogram.
550 PRINT
560 PRINT
570 PRINT
580 PRINT "PRESS ENTER TO CONTINUE"
590 INPUT XX
600 CLS
610 PRINT "In predicting deformation resulting from a fire the following
          information is needed:"
620 PRINT "1. The maximum temperature expected to be reached (TMAX) in deg C.
              To use this analysis TMAX must be >349C and <651C."
630 PRINT "2. The applied stress / room temperature yield stress (S)."
640 PRINT "3. The rate of heating (H) in deg C/min.  This can be either a
              constant value or a function of temperature."
650 PRINT "4. The rate of cooling (C) in deg C/min."
660 PRINT
670 PRINT
```

```
680 PRINT "If you are going to calculate TTOP and F as mentioned in choice 1 you
          will also need to know:"
690 PRINT "5. The initial temperature (L) in deg C."
700 PRINT "6. The total duration of the fire (D) in min."
710 PRINT
720 PRINT
730 PRINT "PRESS ENTER TO CONTINUE"
740 INPUT XX
750 CLS
760 PRINT "The following points should be noted:"
770 PRINT
780 PRINT "a. If the duration of the fire (D) is small or the heating or cooling
               rate is low it is possible that TMAX is not reached.  In this case
               the highest temperature reached (TTOP) is calculated and printed"
790 PRINT "    out and the time spent at TMAX is automatically set to 0."
800 PRINT
810 PRINT "b. If TMAX is reached, the time (F) spent at this temperature is calc
ulated and     printed out.  This analysis is only valid for F <481 mins."
820 PRINT
830 PRINT
840 PRINT "PRESS ENTER TO CONTINUE"
850 INPUT XX
860 CLS
870 PRINT
880 PRINT
890 PRINT "The following points should also be noted:"
900 PRINT
910 PRINT "a. The highest value of plastic strain in the data base from which
               this analysis was developed was 3.5%.  Extrapolation beyond this
               value should be viewed with caution."
920 PRINT
930 PRINT "b. The highest value of creep strain in the data base from which this
               analysis was developed was 6.3%.  At higher stresses the creep
               strain can increase very rapidly with increasing temperature."
940 PRINT "    In order to avoid a possible computer overload during the loop
               calculating creep strain, a limiting value of 6% has been placed
               on the creep strain.  Values greater than this are considered out"
               .
950 PRINT"     of range for this analysis."
960 PRINT
970 PRINT "c. In the equation given to calculate the thermal expansion strain
               the starting temperature is 20C.  Since a structure prior to a
               fire is normally at room temperature this is considered to be a"
980 PRINT "    reasonable assumption.  If a different starting temperature is
               required an adjustment can be made to the relevant equation."
990 PRINT
1000 PRINT
1010 PRINT "PRESS ENTER TO CONTINUE"
1020 INPUT XX
```

```
1030 CLS
1040 PRINT
1050 PRINT
1060 PRINT "For the loop calculating the creep strain during the increasing
            temperature ramp you have the option of printing out the values of
            thermal expansion, elastic, plastic and creep strains at specified"
1070 PRINT "temperature intervals, eg. every 10C, or of waiting until the
            calculation is complete for a print out at the final temperature
            alone.  The first option is not available during the decreasing"
1080 PRINT "temperature ramp."
1090 PRINT
1100 PRINT
1110 PRINT "PRESS ENTER TO CONTINUE"
1120 INPUT XX
1130 CLS
1140 PRINT
1150 PRINT
1160 PRINT "Do you want a linear heating rate (H)?  Enter 1"
1170 PRINT
1180 PRINT "Or do you want a non-linear heating rate?  Enter 2"
1190 PRINT
1200 PRINT
1210 INPUT LINEAR
1220 IF LINEAR = 2 THEN GOTO 4250
1230 PRINT
1240 PRINT
1250 PRINT "Do you want to specify a limiting maximum temperature (TMAX) and
            calculate the actual temperature reached (TTOP) and the time (F)
            spent at (TMAX), if applicable?  Enter 1"
1260 PRINT
1270 PRINT "Or do you want to specify the maximum temperature reached (TTOP), le
t           F=0 and analyse only the heating ramp or heating and cooling ramps?
            Enter 2"
1280 PRINT
1290 PRINT "If you need help enter 3"
1300 PRINT
1310 PRINT
1320 INPUT AA
1330 IF AA = 3 THEN 320
1340 CLS
1350 IF AA = 1 THEN 1440
1360 PRINT "Enter maximum temperature (TTOP) in deg C  (349< TTOP <651 deg C)."
1370 INPUT TTOP
1380 IF TTOP < 651 AND TTOP > 349 THEN 1520
1390 PRINT
1400 PRINT "TTOP <350 or >650 and is out of the range used for this analysis"
1410 PRINT
1420 PRINT
1430 GOTO 1360
1440 PRINT "Enter maximum temperature (TMAX) in deg C  (349< TMAX <651 deg C).
            This is a limiting temperature and may not actually be reached."
1450 INPUT TMAX
1460 IF TMAX < 651 AND TMAX > 349 THEN 1520
```

```
1470 PRINT
1480 PRINT "TMAX < 350C or > 650C and is out of the range used for this analysis
"
1490 PRINT
1500 PRINT
1510 GOTO 1440
1520 PRINT "Enter the ratio of stress to room temperature yield stress (S)"
1530 INPUT S
1540 PRINT "Enter heating rate (H) in deg C/min"
1550 INPUT H
1560 IF AA = 2 THEN 1610
1570 PRINT "Enter initial temperature (L) in deg C"
1580 INPUT L
1590 PRINT "Enter total duration of fire (D) in mins."
1600 INPUT D
1610 INPUT "Do you want to include a cooling period?  (Y/N)   ", COOLING$
1620 IF COOLING$ = "N" OR COOLING$ = "n" THEN 1690
1630 PRINT "Enter cooling rate (C) in deg C/min"
1640 INPUT C
1650 IF AA = 2 THEN 1890
1660 TTOP = (H * (D + L / C) + L) * (C / (C + H))
1670 F = D - ((TMAX - L) / H + (TMAX - L) / C)
1680 GOTO 1720
1690 IF AA = 2 THEN 1890
1700 TTOP = (H * D) + L
1710 F = D - (TMAX - L) / H
1720 IF F < 481 THEN 1770
1730 PRINT "F > 480 mins. and is out of the range used for this analysis"
1740 PRINT
1750 PRINT
1760 GOTO 2430
1770 IF TTOP > TMAX THEN LET TTOP = TMAX
1780 IF TTOP < TMAX THEN LET F = 0
1790 PRINT
1800 PRINT "Highest temp. reached (TTOP)"
1810 PRINT TTOP; "deg C"
1820 IF TTOP >.350 THEN 1870
1830 PRINT
1840 PRINT "TTOP <350.  Creep strain in this range is negligable.  Plastic strai
n cannot be determined for temperatures <350C using the above equation."
1850 PRINT
1860 GOTO 2430
1870 PRINT "Time at constant temp (TMAX)                    TMAX "
1880 PRINT F; "min                               ", TMAX; "deg C"
1890 REM B = the temp. step change used in the calculation of strain during ramp
ing
1900 LET B = 1
1910 REM A = length of time at each step of increasing temp.
1920 A = B / H
1930 IF COOLING$ = "N" OR COOLING$ = "n" THEN 1970
1940 REM K = length of time at each step of decreasing temp.
1950 K = B / C
```

```
1960 LET J = K
1970 LET N = A
1980 GOTO 3450
1990 IF COOLING$ = "Y" OR COOLING$ = "y" THEN GOTO 3980
2000 IF AA = 1 THEN 2050
2010 TIMEHEAT = TTOP / H
2020 IF C = 0 THEN LET TIMECOOL = 0
2030 IF C = 0 THEN 2050
2040 TIMECOOL = TTOP / C
2050 PRINT "Highest temp. reached (TTOP) or (TMAX)"
2060 PRINT TTOP; "deg C"
2070 PRINT "Stress/Room temperature yield stress (S)"
2080 PRINT S
2090 PRINT "Time at const. temp. TMAX (F)"
2100 PRINT F; "min"
2110 PRINT "Total equivalent time at maximum temp. (X+F+M)"
2120 PRINT X + F + M; "min"
2130 LET CR = 10 ^ (P + Q * TTOP) * (X + F + M) ^ (R + U * TTOP) * (S * 35.5) ^
(V + W * TTOP)
2140 PRINT
2150 TE = ((.0087 * (TTOP + 273) / 1000) + (.005 * ((TTOP + 273) / 1000) ^ 2) -
.003) * 10 ^ 2
2160 PRINT "Thermal expansion"
2170 PRINT TE; "%"
2180 PRINT
2190 E = 29300 - 12.6 * TTOP
2200 EL = 100 * (S * 35.5) / E
2210 IF LINEAR = 2 THEN 2240
2220 IF COOLING$ = "N" OR COOLING$ = "n" THEN 2240
2230 PRINT "Final elastic strain is 0, because the temperature has returned to
          its starting value and the load has remained constant."
2240 PRINT "Elastic strain when under load"
2250 PRINT EL; "%"
2260 I = .00041 * TTOP ^ 1.647
2270 Y = 10 ^ -I
2280 G = TTOP / (147 - .161 * TTOP)
2290 PL = Y * (S * 35.5) ^ G
2300 PRINT "Plastic strain"
2310 PRINT PL; "%"
2320 IF PL < 3.5 THEN 2360
2330 PRINT
2340 PRINT "Plastic strain > 3.5%.  This is above the limit of the original
          data base and should be viewed with caution."
2350 PRINT
2360 PRINT "Total creep strain"
2370 PRINT CR; "%"
2380 IF CR<6 THEN 2410
2390 PRINT
2400 PRINT "Creep strain > 6%.  This is above the limit of the original data
          base and should be viewed with caution.  Probable cause - the time
          at maximum temperature is too long for the applied stress level."
2410 PRINT
```

```
2420 TOTAL = EL + PL + CR
2430 PRINT "Total strain due to stressing"
2440 PRINT TOTAL; "%"
2450 PRINT
2460 INPUT "Do you want to have a final print out?  (Y/N)  ", ANSWER$
2470 IF ANSWER$ = "Y" OR ANSWER$ = "y" THEN 2490
2480 GOTO 3420
2490 IF LINEAR = 2 THEN 2530
2500 IF AA = 2 THEN 2530
2510 LPRINT "Starting temperature (L) deg. C"
2520 LPRINT L; "deg. C"
2530 LPRINT "Maximum temp. reached (TTOP)  deg. C"
2540 LPRINT TTOP; "deg C"
2550 LPRINT "Stress/Room temperature yield stress (S)"
2560 LPRINT S
2570 IF LINEAR = 2 THEN 2820
2580 LPRINT "Heating rate (H) deg C/min"
2590 LPRINT H; "deg C/min"
2600 IF AA = 1 THEN 2630
2610 LPRINT "Duration of heating ramp (TIMEHEAT) MIN"
2620 LPRINT TIMEHEAT; "min"
2630 IF COOLING$ = "N" OR COOLING$ = "n" AND AA = 1 THEN 2710
2640 IF COOLING$ = "N" OR COOLING$ = "n" AND AA = 2 THEN 2780
2650 LPRINT "Cooling rate (C) deg C/min"
2660 LPRINT C; "deg C/min"
2670 IF AA = 1 THEN 2710
2680 LPRINT "Duration of cooling ramp (TIMECOOL) min"
2690 LPRINT TIMECOOL; "min"
2700 GOTO 2770
2710 LPRINT "Total duration of the fire (D) min"
2720 LPRINT D; "min"
2730 IF F < 481 THEN 2760
2740 LPRINT "F >480 and is out of range for this analysis.  Cause - total durati
on of the    fire (D) is too long."
2750 GOTO 3400
2760 IF COOLING$ = "N" OR COOLING$ = "n" THEN 2780
2770 GOTO 2790
2780 LPRINT "No cooling period included."
2790 LPRINT "Time at constant maximum temp. (F) min"
2800 LPRINT F; "min"
2810 GOTO 2850
2820 LPRINT "Duration of fire (TIME)"
2830 LPRINT TIME; "min"
2840 LPRINT "Heating rate is non linear"
2850 LPRINT
2860 IF TTOP > 349 THEN 2890
2870 LPRINT "TTOP <350.  Creep strain in this range is negligable.  Plastic stra
in cannot be determined for temperatures <350C using the above equation."
2880 GOTO 3400
2890 IF CRH < 6 THEN 2920
2900 LPRINT "Creep strain during heating >6% and is out of range of this
            analysis.  Probable cause - stress may be too high."
```

```
2910 GOTO 3400
2920 LPRINT "Thermal expansion strain"
2930 LPRINT TE; "%"
2940 LPRINT
2950 IF LINEAR = 2 THEN 2990
2960 IF COOLING$ = "N" OR COOLING$ = "n" THEN 2990
2970 LPRINT "Final elastic strain is 0, because the temperature has returned to
            its starting value and the load has remained constant."
2980 LPRINT
2990 LPRINT "Elastic strain when under load"
3000 LPRINT EL; "%"
3010 LPRINT "Plastic strain"
3020 LPRINT PL; "%"
3030 IF PL < 3.5 THEN 3050
3040 LPRINT "Plastic strain >3.5%.  This is above the limit of the original
            data base and should be viewed with caution."
3050 LPRINT "Creep strain"
3060 LPRINT CR; "%"
3070 IF CR < 6 THEN 3110
3080 LPRINT
3090 LPRINT "Creep strain > 6%.  This is above the limit of the original data
            base and should be viewed with caution.  Probable cause - the time
            at maximum temperature is too long for the applied stress level."
3100 LPRINT
3110 LPRINT "Total strain due to stressing"
3120 LPRINT TOTAL; "%"
3130 LPRINT
3140 LPRINT
3150 LPRINT "Final permanent strain (plastic + creep strains)"
3160 LPRINT PL + CR; "%"
3170 LPRINT
3180 LPRINT
3190 LPRINT "Additional information"
3200 LPRINT
3210 LPRINT "Equivalent time at temp. TTOP for period of heating (X) min"
3220 LPRINT X; "min"
3230 LPRINT "Equivalent time at temp. TTOP for period of cooling (M) min"
3240 LPRINT M; "min"
3250 LPRINT "Total equivalent time at temp. TTOP (X+F+M) min"
3260 LPRINT X + F + M; "min"
3270 LPRINT
3280 LPRINT
3290 IF AA = 2 GOTO 3410
3300 IF LINEAR = 2 THEN 3410
3310 CREEPF = 10 ^ (P + Q * TTOP) * F ^ (R + U * TTOP) * (S * 35.5) ^ (V + W * T
TOP)
3320 LPRINT "If the temperature TMAX were reached instantaneously and the fire
            lasted for a period of F min the creep strain would be"
3330 LPRINT CREEPF; "%"
3340 LPRINT
3350 CREEPD = 10 ^ (P + Q * TTOP) * D ^ (R + U * TTOP) * (S * 35.5) ^ (V + W * T
TOP)
```

```
3360 LPRINT "If the temperature TMAX were reached instantaneously and the fire
            lasted for a period of D min the creep strain would be"
3370 LPRINT CREEPD; "%"
3380 LPRINT
3390 LPRINT "These values give lower and upper bounds for the creep strain as
            would have been calculated from the original equation given in the
            previous report (NISTIR 88-3899)"
3400 PRINT
3410 LPRINT CHR$(12);
3420 INPUT "Do you want to do another calculation?  (Y/N)   ", ANSWER$
3430 IF ANSWER$ = "Y" OR ANSWER$ = "y" THEN 1130
3440 END
3450 REM This subprogram calculates the creep strain during the temperature
        increase ramp.
3460 PRINT
3470 INPUT "Do you want to have a print out at fixed intervals of increasing
           temperature up to TTOP?  (Y/N)   ", INTERVAL$
3480 IF INTERVAL$ = "N" OR INTERVAL$ = "n" THEN 3610
3490 PRINT
3500 PRINT "Enter temperature interval desired"
3510 INPUT TI
3520 IF AA = 2 THEN 3550
3530 LPRINT "Starting temperature (L) deg C"
3540 LPRINT L; "deg C"
3550 LPRINT "Maximum temperature (TTOP) deg C"
3560 LPRINT TTOP; "deg C"
3570 LPRINT "Stress/room temperature yield stress (S)"
3580 LPRINT S
3590 LPRINT "Heating rate (H) deg C/min"
3600 LPRINT H; "deg C/min"
3610 LET P = -6.1
3620 LET Q = -.00573
3630 LET R = -1.1
3640 LET U = .0035
3650 LET V = 2.1
3660 LET W = .0064
3670 LET T = 350
3680 IF AA = 2 THEN LET F = 0
3690 LET M = 0
3700 PRINT
3710 PRINT "Calculating, please wait."
3720 REM CRH = the creep strain during heating
3730 CRH = 10 ^ (P + Q * T) * A ^ (R + U * T) * (S * 35.5) ^ (V + W * T)
3740 X = (CRH / ((10 ^ (P + Q * (T + B))) * ((S * 35.5) ^ (V + W * (T + B))))) ^
 (1 / (R + U * (T + B)))
3750 REM X = the equivalent time at temperature T+B needed to generate a creep
        strain during heating of CRH
3760 A = X + N
3770 T = T + B
3780 IF CRH < 6 THEN 3840
3790 PRINT
3800 PRINT
```

```
3810 PRINT "Creep strain during heating >6% and is out of range for this
          analysis.  Probable cause  - stress may be too high."
3820 PRINT
3830 GOTO 2450
3840 IF INTERVAL$ = "N" OR INTERVAL$ = "n" THEN 3880
3850 LET CC = INT((T-350)/TI)
3860 LET DD = (T-350)/TI
3870 IF CC = DD THEN  GOSUB 5200
3880 IF T = TTOP THEN 3950
3890 IF T > TTOP THEN 3950
3900 IF T + B > 500 THEN 3920
3910 GOTO 3730
3920 LET P = -13.25
3930 LET Q = .00851
3940 GOTO 3730
3950 LET CRH = 10 ^ (P + Q * TTOP) * X ^ (R + U * TTOP) * (S * 35.5) ^ (V + W *
TTOP)
3960 PRINT
3970 GOTO 1990
3980 REM This subprogram calculates the creep strain during the temperature
        decrease ramp.
3990 LET P = -6.1
4000 LET Q = -.00573
4010 LET R = -1.1
4020 LET U = .0035
4030 LET V = 2.1
4040 LET W = .0064
4050 LET T = 350
4060 IF AA = 2 THEN LET F = 0
4070 PRINT
4080 PRINT "Calculating, please wait"
4090 REM CRC = the creep strain during cooling
4100 CRC = 10 ^ (P + Q * T) * K ^ (R + U * T) * (S * 35.5) ^ (V + W * T)
4110 REM M = the equivalent time at temperature T+B needed to generate a creep
        strain during cooling of CRC
4120 M = (CRC / ((10 ^ (P + Q * (T + B))) * ((S * 35.5) ^ (V + W * (T + B))))) ^
 (1 / (R + U * (T + B)))
4130 K = M + J
4140 T = T + B
4150 IF T = TTOP THEN 4220
4160 IF T > TTOP THEN 4220
4170 IF T + L > 500 THEN 4190
4180 GOTO 4100
4190 LET P = -13.25
4200 LET Q = .00851
4210 GOTO 4100
4220 CRC = 10 ^ (P + Q * TTOP) * M ^ (R + U * TTOP) * (S * 35.5) ^ (V + W * TTOP
)
4230 PRINT
4240 GOTO 2000
```

```
4250 REM This subprogram calculates the creep strain during a non-linear heating
       ramp.
4260 CLS
4270 PRINT "Do you want to specify the maximum temperature reached (TTOP)?
          Enter 1"
4280 PRINT
4290 PRINT "Or do you want to calculate TTOP?  Enter 2"
4300 PRINT
4310 INPUT BB
4320 IF BB = 1 THEN 4460
4330 PRINT
4340 PRINT
4350 PRINT "Enter duration of fire (TIME) in min."
4360 INPUT TIME
4370 TTOP = 185 * LOG(8 * TIME + 1) / LOG(10)
4380 PRINT
4390 PRINT "Maximum temperature reached (TTOP)"
4400 PRINT TTOP; "deg C"
4410 IF TTOP < 651 AND TTOP > 349 THEN 4550
4420 PRINT
4430 PRINT "TTOP is <350 deg C or >650 deg C and is out of the range used for
          this analysis."
4440 PRINT
4450 GOTO 4330
4460 PRINT
4470 PRINT
4480 PRINT "Enter maximum temperature in deg C"
4490 INPUT TTOP
4500 IF TTOP < 651 AND TTOP > 349 THEN 4540
4510 PRINT
4520 PRINT "TTOP is <350 deg C or >650 deg C and is out of the range used for th
is          analysis."
4530 GOTO 4330
4540 TIME = (10^(TTOP/185)-1)/8
4550 PRINT "Enter the ratio of stress to room temperature yield stress (S)."
4560 INPUT S
4570 PRINT
4580 INPUT "Do you want to have a print out at fixed intervals of increasing
          temperature up to TTOP?  (Y/N)   ", INTERVAL$
4590 IF INTERVAL$ = "N" OR INTERVAL$ = "n" THEN 4690
4600 PRINT
4610 PRINT "Enter temperature interval desired"
4620 INPUT TI
4630 LPRINT "Maximum temperature (TTOP) deg C"
4640 LPRINT TTOP; "deg C"
4650 LPRINT "Stress/room temperature yield stress (S)"
4660 LPRINT S
4670 LPRINT "Heating rate is non-linear"
4680 REM B = the temperature step change used in the calculation of strain
       during ramping."
4690 LET B = 1
4700 LET P = -6.1
4710 LET Q = -.00573
```

```
4720 LET R = -1.1
4730 LET U = .0035
4740 LET V = 2.1
4750 LET W = .0064
4760 LET T = 350
4770 PRINT
4780 REM H = the heating rate
4790 REM Enter equation for H as a function of T in following lines.
4800 H = 1480 / (10 ^ (T / 185))
4810 REM A = the length of time spent at 350 deg C.
4820 A = B / H
4830 PRINT "Calculating, please wait"
4840 H = 1480 / (10 ^ (T / 185))
4850 REM N = the length of time spent at each step of increasing temperature. In
            this case N is a function of temperature.
4860 N = B / H
4870 REM CRH = the creep strain during non-linear heating.
4880 CRH = 10 ^ (P + Q * T) * A ^ (R + U * T) * (S * 35.5) ^ (V + W * T)
4890 REM X = the equivalent time at temperature T+B needed to generate a creep
        strain during heating of CRH.
4900 X = (CRH / ((10 ^ (P + Q * (T + B))) * ((S * 35.5) ^ (V + W * (T + B))))) ^
 (1 / (R + U * (T + B)))
4910 A = X + N
4920 T = T + B
4930 IF CRH < 6 THEN 4980
4940 PRINT
4950 PRINT "Creep strain during heating >6% and is out of range for this
           analysis.  Probable cause - stress may be too high."
4960 PRINT
4970 GOTO 2450
4980 IF INTERVAL$ = "N" OR INTERVAL$ = "n" THEN 5020
4990 LET CC = INT((T-350)/TI)
5000 LET DD = (T-350)/TI
5010 IF CC = DD THEN GOSUB 5200
5020 IF T = TTOP THEN 5100
5030 IF T > TTOP THEN 5100
5040 IF T > 500 THEN 5060
5050 GOTO 4840
5060 LET P = -13.25
5070 LET Q = .00851
5080 GOTO 4840
5090 REM CR = the total creep strain generated during the heating ramp.
5100 CR = 10 ^ (P + Q * TTOP) * X ^ (R + U * TTOP) * (S * 35.5) ^ (V + W * TTOP)

5110 PRINT
5120 PRINT "Maximum temperature reached (TTOP)"
5130 PRINT TTOP; "degC"
5140 PRINT "Stress/Room temperature yield stress (S)"
5150 PRINT S
5160 PRINT "Equivalent time (X) at temperature TTOP for period of heating"
5170 PRINT X; "min"
5180 PRINT
```

```
5190 GOTO 2150
5200 REM This subprogram calculates thermal expansion, elastic and plastic
       strains.
5210 REM TE = Thermal expansion strain
5220 TE = (.0087*(T+273)/10)+(.005*((T+273)/100)^2)-.3
5230 REM EL = Elastic strain, E = Young's Modulus
5240 E = 29300-12.6*T
5250 EL = 100*(S*35.5)/E
5260 REM PL = Plastic strain
5270 I = .00041*T^1.647
5280 Y = 10^-I
5290 G = T/(147-.161*T)
5300 PL = Y*(S*35.5)^G
5310 REM This subprogram prints out strains during increasing temperatures
5320 LPRINT
5330 LPRINT
5340 LPRINT "Temperature (T) deg C"
5350 LPRINT T; "deg C"
5360 LPRINT
5370 LPRINT "Thermal expansion strain from 20C to TTOP"
5380 LPRINT TE; "%"
5390 LPRINT "Elastic strain when under load "
5400 LPRINT EL "%"
5410 LPRINT "Plastic strain"
5420 LPRINT PL "%"
5430 IF PL < 3.5 THEN 5450
5440 PRINT "Plastic strain > 3.5%.  This is above the limit of the original
          data base and should be viewed with caution."
5450 LPRINT "Creep strain"
5460 LPRINT CRH "%"
5470 LPRINT "Total strain"
5480 TOTAL = EL + PL + CRH
5490 LPRINT TOTAL "%"
5500 IF T + TI > TTOP THEN 5520
5510 RETURN
5520 LPRINT CHR$(12);
5530 RETURN
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BSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR TERATURE SURVEY, MENTION IT HERE.)

ing a previously formulated equation which calculates the elastic, plastic and creep rains during loading at a constant elevated temperature, a method and a computer program ve been developed that will predict the strain due to creep during anisothermal tests at nstant load. Comparisons were made with results from anisothermal tests for the stralian Steel AS A149, a steel close to the specification for ASTM A36. Agreement with perimental results is excellent for several linear heating rate and one non-linear ating rate.

EY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

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