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EFFECTS OF MATERIAL BEHAVIOR ON THE RESPONSE OF RAPIDLY HEATED STRUCTURES

MCDONNELL DOUGLAS CORPORATION

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An investigation into the theoretical requirements for short time elevated temperature material property data to be used in a structural analysis to predict the response and failure of structures subject to the combined effects of mechanical and thermal loads due to rapid heating was undertaken. An assessment of the ability of the MARC and ANSYS finite-element computer codes to perform the required analysis was made. An evaluation of the suitability of existing mechanical material property data for 6061-T6 aluminum was made

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in light of the theoretical requirements. Uniaxial simulation experiments were performed in which load and temperature were varied as a function of time in order to simulate the loading and unloading behavior that occurs in locally heated structures.

Basic uniaxial material property tests were conducted. These data were used to obtain time independent ("zero" time) temperature dependent elastic-plastic stress/strain curves and time dependent creep curves.

A one-dimensional direct integration code "CREEPARHS" was written to perform the required analysis and to check the results from the finite element codes. Analysis using the newly generated material property data and currently available 10 second isochronous and handbook data was performed. The results were compared with the data obtained in the simulation experiments. The existing stress-strain-temperature data was shown to be inappropriate for the rapid heating analysis because of its inherent built in creep strain. The use of the new "zero" time stress-strain curves in combination with the creep data produced excellent correlation with the simulation experiments. The finite element codes were judged to be capable of performing the required analysis for a more complex structure.

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PREFACE

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Section 1
BACKGROUND AND INTRODUCTION

1.1 BACKGROUND

Many of the initial studies concerning the response of structures subject to high intensity heating assumed material removal and/or burnthrough to be the primary structure damage mechanism. In reality, structural failure due to the reduction of material allowables at elevated temperature and the resultant stress redistribution are more probable and can result from lower intensity heating. In more recent investigations, (References 1 and 2) analytical and experimental studies were conducted to evaluate failure of simple plates and built-up beams due to high intensity heating. The primary objectives of these studies were to investigate failure mechanisms and demonstrate the ability of computer codes to perform rapid heating analysis.

The methodology was applied in the vulnerability assessment of various missiles. These studies showed that catastrophic structural failure could be produced by heating the structure to a temperature much lower than that required to cause melt or burnthrough. Various areas on missiles which are susceptible to such damage include the rocket motor case, elevons, wings and guidance sections.

A plan was formulated to perform ground based tests on the various structural components to determine their vulnerability. In particular, simulation tests were performed on instrumented pressurized and unpressurized rocket motor cases using a graphite heater radiation source.

Analysis to predict the response of the rocket motor cases and to assess the sensitivity of the predicted response to various heat sources was recently performed (Reference 3). An interest in quantifying the data and modeling requirements necessary for accurate analysis/experiment correlation played a key role in formulating the present study. The present investigation addresses the role and appropriate form of material property data to be used for structural response and failure prediction due to short time heating.

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1.2 INTRODUCTION

Prediction of the failure of structures which are subjected to a combination of 1) mechanical loads and 2) thermal loads due to rapid (1-10 seconds), high intensity heating requires knowledge of load and temperature histories and a thorough understanding of the response of the material to these load and temperature histories. For the problem of rapid heating of flight structures such as missiles and aircraft, structural failures typically occur at temperatures between 50-100% of the material melt temperature. These strength or stiffness type failures are caused by a load redistribution and reduced load carrying capability due to the degradation of structural properties of the material at high temperature, an important consideration even in the short heating time.

Once the loads, geometry and materials are known, it is up to the structural analyst to choose the appropriate code or analysis technique to predict the response of the structure. For failure prediction, the analyses, in general, must be capable of handling nonlinear temperature and time dependent material behavior and large displacement effects.

The ability of a code to perform the required analysis can be established by comparing code predictions with the results from experiments. Satisfactory correlation depends upon essentially three factors:
1. Accurate experimental structural response data.
2. Suitable code or analysis capability.
3. "Appropriate" material property data for code input.

Previous studies (Reference 1) have emphasized the predictive ability of the structural response codes using available material property data. The objective of this study is to 1) identify a possible need for further high temperature material property data for short time heating, 2) define an appropriate format for the data for use in the codes, 3) show how this data can be obtained, and 4) evaluate the degree of improvement in the response prediction that can be achieved using these new data.

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1.2.1 Material Properties

It is well known that particular material properties can greatly influence the stress and deformation states in a structure just prior to failure. In indeterminant structures, these failures often occur outside of the intensely heated region. A large uncertainty about the appropriate material property data still exists in the mind of the analyst despite the importance of this data. There are at least three basic reasons for the lack of appropriate data.

1. Most material property data have been obtained for use in sure safe design and analysis. This means that data for structural materials are available only at the operating temperatures of standard structures.

2. Data in the literature are generally presented in a form that is appropriate for linear analyses that are typically employed for sure safe design. For example, only the elastic moduli and yield stress are given as a function of temperature. For failure prediction, it is necessary to account for the full range of stress-strain behavior at temperature.

3. Data in the literature do not account for time dependence in the short time region of interest. Most data of this type are for long service times appropriate for aircraft. This problem is closely related to the lack of high temperature data where short time creep effects become important.

The current emphasis is placed on the importance of mechanical properties. It should be noted that certain physical properties such as specific heat, conductivity and thermal expansion are also important in the prediction of temperature within the structure and thermal deformation. In some cases, these data are also not available at high temperature; however, the type of ("appropriate") physical property data necessary for the analysis is not in question.

An important task in this study will be to establish the "appropriate" mechanical material property data. By "appropriate" we mean that data which when used in a theoretically valid constitutive model in existing codes will allow one to accurately predict the response of the structure. In this context, material property data are assumed to be separable into three types:

1. time independent - temperature and load independent strain (elastic/plastic)

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2. time dependent - temperature and load dependent strain (creep)
3. temperature dependent free expansion strain.

The stress-strain-temperature-time data are generally determined from simple one-dimensional experiments and the appropriate assumptions based on physical insight and mathematical necessities are made to extend these data to multi-axial stress states. This study will focus on one-dimensional behavior both experimentally and analytically as a springboard to understanding multi-dimensional behavior.

1.2.2 Modeling and Computer Codes

Several general purpose and special purpose structural analysis codes exist which have the theoretical capability of performing the various elements of a rapid heating structural response analysis. Two general purpose codes (MARC and ANSYS) were selected as being representative of codes which have the capability of performing the complete time-temperature-load analysis of a complex structure given the proper input data. These codes along with a special purpose one-dimensional code (CREEPARHS-creep-elastic-plastic analysis of rapidly heated specimens) developed at MDAC will be used to predict the response of a one dimensional bar subjected to time varying load and temperature profiles typical of those seen by flight vehicle structures.

1.2.3 Program Plan and Report Organization

This study will establish and demonstrate a systematic procedure which can be used to assess the suitability of mechanical material property data as used by standard structural response codes to predict the response of complex structures subject to rapid heating. The procedure begins with an assessment of the ability of constitutive models in the code to simulate the actual material response, e.g., time dependent elastic-plastic-creep in stress/temperature regimes where creep effects are important. Once the "appropriate" material property data requirements are defined, specimens which will provide the required data are designed and the "appropriate" tests performed. The ability of this data/code combination to accurately predict structural response is then demonstrated by comparing the analytical results with results obtained from simple simulation experiments for typical structural

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load, temperature and time histories. The analysis and experimental correlation on the one-dimensional specimens serve as a basic check on the material models, code operation and experimental results. One can then precede with some confidence to analyze more complex structures. A flow diagram of study tasks is shown in Figure 1. The following sections will present the results of the study. A summary of the work including conclusions and recommendations is given in Section 2. A survey of available analytical methods and models is presented in Section 3 followed by a description of the test equipment and data reduction scheme in Section 4. The material property and simulation experiments are described in Sections 5 and 6 and a discussion of the correlation between analysis and experiment is given in Section 7.

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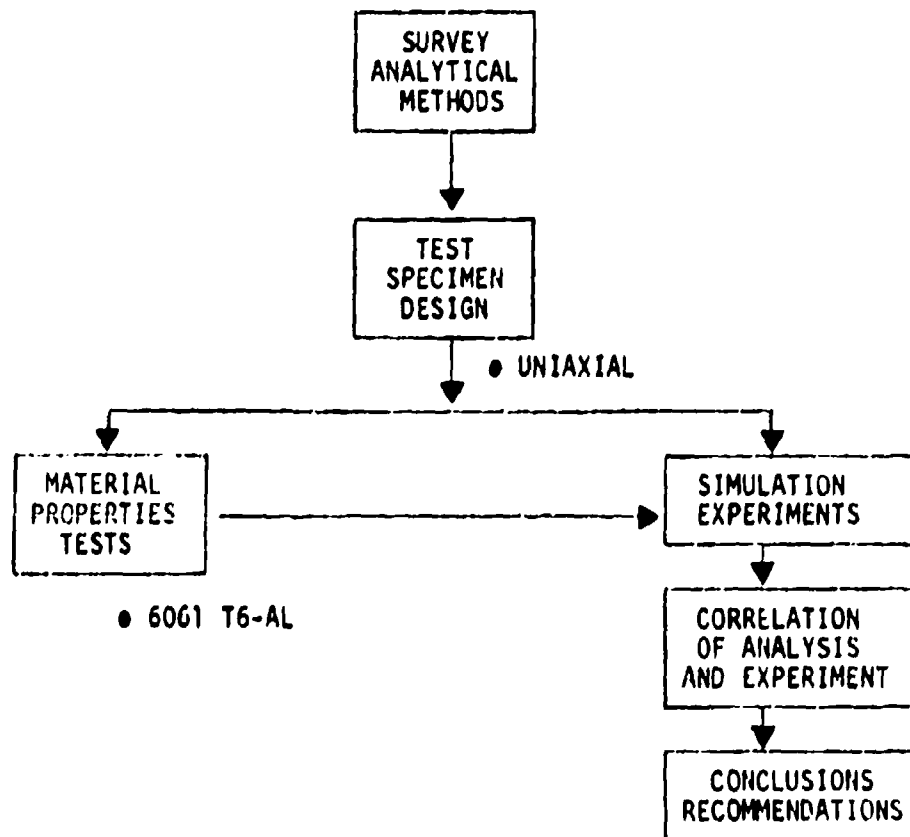
Figure 1. Flow Diagram of Program Tasks.

Section 2
SUMMARY, CONCLUSIONS, RECOMMENDATIONS

2.1 SUMMARY

An investigation of the theoretical requirements for an accurate response
analysis of a structure which is subject to a combination of mechanical
and thermal loads due to rapid heating was undertaken. An assessment of
the ability of current nonlinear structural codes (MARC, ANSYS) to predict the
aforementioned response was made in light of the theoretical requirements. A
critical evaluation of the suitability of existing mechanical material pro-
perty data for input to such codes was made with the intention of minimizing
the complexity of the analysis while remaining on firm theoretical ground.

Basic material property tests which would supply the necessary data for code
input were performed using a simple 6061-T6 aluminum tensile specimen. These
tests allowed the generation of "zero" time or time independent stress/strain/
temperature curves as well as time dependent creep strain curves.

Simulation experiments in which load and temperature were varied as a function
of time over a range which included stresses beyond yield and temperatures
near melt (800°F) were performed on the above mentioned tensile specimens.
Analyses were performed using MARC, ANSYS and a one-dimensional code "CREEPARHS"
with the newly generated material property data. The analytical results were
compared with the results obtained from the simulation experiments.

2.2 CONCLUSIONS

2.2.1 Mechanical Material Property Data/Modeling
Significant time dependent creep strain (on the order of the mechanical strain
or greater) can occur in structures where stresses exceed yield and temperatures
approach melt, even in the 1-10 second engagement time regime. It thus becomes
necessary to account for the time dependent and time independent effects. This

can be effectively accomplished by developing "zero" time or time independent stress/strain/temperature curves or relations augmented by time dependent creep strain relations. The use of these data resulted in a much improved analytical/experimental correlation of the strain/time response in simple uniaxial simulation experiments as compared to the correlation based upon the use of 10 second isochronous or standard handbook data. This is because the isochronous and standard data have built in time-integrated creep strain. The new data is particularly useful in predicting response at very early times (1-3 seconds) and will in fact predict much higher short time allowable stresses for a one dimensional specimen. An investigation into the effects of varying the heat up time or the time required for the specimen to reach test temperature prior to loading showed no significant trend in the 15-60 seconds heat up time regime. This suggests that material property changes due to the above mentioned heat up time has little effect upon the measured properties.

2.2.2 Nonlinear Structural Response Codes

Theoretical considerations and excellent one dimensional experiment/analysis correlation suggest that typical general purpose codes (MARC and ANSYS) and specialized codes (CREEPARHS) are capable of analyzing simple and complex structures subject to rapid heating given the proper material data input. The codes allow separation of time dependent and time independent material property data and thus are well suited to perform combined thermal elastic creep and plasticity analysis as required in the rapid heating problems. The general purpose codes are very expensive to use in their nonlinear mode.

Coding errors which existed in the nonlinear temperature dependent subroutines in MARC and ANSYS have been corrected but it is suspected that these codes are still not error free.

2.3 RECOMMENDATIONS

The following paragraphs consist of a list of specific recommendations (in order of suggested performance) for future work followed by a brief discussion of issues inherent in the recommendations. These recommendations are based

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upon results from present and previous studies concerned with the ability to predict the response of structures subject to rapid heating.

Mechanical Material Properties

● Use "new" data with more sophisticated creep laws to analyze previously investigated problems such as a centrally heated, bi-axial loaded plate.

Two interrelated matters which are of concern in determining the requirements for material property data are constitutive modeling and data acquisition techniques. The modeling of the data should be sufficiently sophisticated to allow for the many combinations of possible load/temperature/time profiles which the structures will see while being simple enough to allow for straight-forward raw data collection as well as ease in analysis. The thermally degraded material properties can have a significant effect on the predicted failure times and failure thresholds of even simple structures. The time dependent or creep effects must be isolated and be properly accounted for in the constitutive modeling and analysis. It is recommended that time independent "zero" time, piece-wise linear stress/strain versus temperature curves, along with a mechanical equation of state for primary and tertiary creep strain, be considered as the basic material models. In addition, various hardening rules (strain hardening, time hardening, etc.) should be evaluated in terms of their predictive capability.

The temperature and loading environments along with the constitutive models will dictate the type of data that is required. It then becomes necessary to perform experiments which will provide the required data. In the present context, it is necessary to bring the specimens to load and/or to temperature in a very short period of time. It is recommended that the stress/strain/ temperature data be obtained by bringing the specimens to, and stabilizing the specimens at temperature as rapidly as possible while loading the specimens to failure in a time period which is small compared to the actual anticipated time to failure of the specimen. Both new and standard data should be used to revisit previously analyzed problems. The sensitivity of the structure to a wide range of material data can then be established.

Nonlinear Code Analysis

- Develop advanced closed form analysis code (CREEPARHS II) to analyze more complicated problems
    - Indeterminant bar
    - Circular Plate
- Exercise/validate general purpose nonlinear codes on above mentioned problems.

- It is essential that each option in the codes be exercised and validated prior to a large scale, complicated analysis. It is recommended that sample problems which are amenable to semi-closed form solutions such as an indeterminant bar and a centrally heated circular plate be used to verify the operation of the code for more advanced problems using the "new" data. A more advanced version of the CREEPARHS code could serve the purpose of checking the multidimensional stress calculational ability of the general purpose codes.

Experiments

- Perform appropriate experiments for code/experiment correlation.
- Simple one dimensional simulation tests (load and temperature vary with time) can serve as the vehicle for combined code/material property validation for more refined creep and hardening laws.

A series of highly instrumented "simple" experiments which demonstrate the various aspects of the overall rapid heating problem should be performed. These should lend themselves to straightforward analysis, and can be limited to elementary structural configurations.

Failure Laws

- Propose and evaluate failure laws for stress and buckling type failures.

Generate Appropriate Data for Alternate Materials

1. References for and discussion of the need for "appropriate" material properties.
2. Suggestions for types of simulation tests.
3. Discussion of the sensitivity of predicted results to material properties/computer code modeling.

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Short Time Heating Analysis Guide

• The need exists for a manual which explains the various aspects of the analysis of a rapidly heated structure. The following material would be included in such a guide:

1. Summary of simplified analysis techniques for typical structural configurations including; bars, plates, shells.

2. Summary of relevant experimental data.

3. Appropriate material property data for nonlinear finite element code analysis.

Section 3
SURVEY OF ANALYTICAL METHODS/MODELS

The initial phase of this study was dedicated to developing an understanding
of the methods and models available for analyzing the nonlinear, time
dependent behavior of metals. The primary consideration was to evaluate the
suitability of existing approaches, or to develop an alternative approach to
material modeling which could be easily incorporated into existing analysis
codes. The material model must have a firm theoretical base but be simple
so as to minimize the amount of material property data that must be gathered.

3.1 THEORETICAL CONSIDERATIONS

In order to understand the behavior of metals, for example 6061-Aluminum, which
are rapidly heated, one must realize that time dependent plastic flow or creep
can occur even in very short periods of time if the temperatures and stresses
in the material are sufficiently high. Any attempt to use constitutive models
which do not account for the time dependent strain explicitly or account for
some time integrated effect of the time dependent strain (Isochronous stress/
strain curves) is likely to introduce major errors if the duration of heating
or loading is short as compared to the time over which the data are taken. In
the case where materials are heated to temperatures approaching melt in
less than 10 seconds, the "appropriate" data must account for the strain as
a function of temperature, stress and time for times less than 10 seconds.

Historically, constitutive models for homogeneous structural materials were
developed in a manner which allowed separation of the material behavior into
linear (elastic) and nonlinear (plastic) time independent behavior and non-
linear time dependent behavior (creep). An excellent summary discussion of
basic concepts of plasticity and creep theory can be found in Reference 4.
Table 1 illustrates the various regimes of material behavior as is used in
most analysis codes. As pointed out in reference 4, there have been a number
of attempts to improve on the classical phenomenological or equation of state

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Table 1

REGIMES OF MATERIAL MODELING FOR STRUCTURAL ANALYSIS - THEORY/ANALYSIS

MATERIAL RESPONSE	DATA (EXPERIMENTAL)	PLASTICITY (TIME INDEPENDENT)	CREEP (TIME DEPENDENT)	PLASTICITY + CREEP
One-dimensional	$\varepsilon_T^{XX}(\sigma_{xx}, \dot{\sigma}, t, \ddot{\sigma}, \dot{\sigma}_{xz})=$ $\varepsilon_E^{XX} + \varepsilon_{PL}^{XX} + \varepsilon_{CR}^{XX}$	1) Cross plot $\varepsilon_T^{XX} + \varepsilon_{PL}^{XX}$ to get "zero" time stress/ strain/temperature curves 2) Cross plot $\varepsilon_E^{XX} + \varepsilon_{PL}^{XX} + \varepsilon_{CR}^{XX}$ to get isochronous stress/strain temperature curves for various times at temperature	1) Develop mechanical equation of state for creep strain rate: $\dot{\varepsilon}_{CR}^{XX} = $ Function $(\varepsilon_{CR}, \sigma_{xx}, T, \dot{\sigma}, \ddot{\sigma}, t)$ where e.g.: $\varepsilon_{CR}^{XX} = h_1(T,\sigma)\{1-\exp(-at)\} + \exp(-QR/T)\sigma_{xx}^n + h_2(T,\sigma)t\,\sigma_{xx}^p\exp(-SR/T)$ (primary + secondary) 2) Determine constants from curve fitting experimental data	Superimpose (in real time) plastic and creep strain state.
Flow Rule (Generalize one-dimensional results to material stress/strain state)	Same + multiaxial data for point-wise analysis correlation	1) Von Mises yield criterion $J_2(\sigma_{ij}) = \frac{1}{3}Y^2(\sigma_{ij})$ 2) Prandtl/Reuss flow rule using generalized stress/strain concept $\varepsilon_{PL}^\circ = $ Function $(\sigma^\circ) + \dot{\varepsilon}_{PL}^{ij} = $ Function $(\sigma^\circ, \varepsilon_{PL})\,S_{ij}$	1) Generalize in manner parallel to plastic strain: Define generalized creep stress/strain functions $\sigma^\circ, \varepsilon_{CR}^\circ$ 2) Assumptions: a) isotropic material b) system having same specific shear strain energy as plastic system will have same creep strain then $\dot{\varepsilon}_{CR}^\circ = $ Function $(\varepsilon_{CR}, \sigma^\circ)$ $\dot{\varepsilon}_{CR}^{ij} = $ Function $(\dot{\varepsilon}_{CR}, \sigma^\circ)\,S_{ij}$	Superimpose creep & plastic strain increments
Hardening Rule (Behavior during loading beyond initial yield and unloading)	Same as above	Definition of yield surface boundary (Y above) and position of center in stress space due to strain hardening 1) Isotropic hardening: $Y(\sigma_{ij}, \omega_{ij}) = F(\sigma_{ij})Y(\sigma_{ij})$ 2) Kinematic hardening: $J_2(\sigma_{ij} - \delta_{ij}) = \frac{1}{3}Y^2(\sigma_{ij})$	Account for time varying stress and temperature: 1) time hardening $\dot{\varepsilon}_{CR} = \dot{\varepsilon}_{CR}F(\sigma^\circ,T,t)$ 2) strain hardening $\dot{\varepsilon}_{CR} = \dot{\varepsilon}_{CR}F(\sigma^\circ, \varepsilon_{CR}, T, t)$	Superimpose
Failure criterion	1) Strain/time experiments for failure strains 2) Fracture strength	Initiation—Von Mises or Max shear Propagation - Fracture mechanics	Same as plasticity	Superimpose

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method of describing creep strain. These theories attempt, for example, to account for certain recovery effects found upon specimen unloading. Most recently, the so called "unified" theories based upon thermodynamic considerations have surfaced. These theories attempt to treat the inelastic time dependent and time independent strain as a single phenomenon.

The point to keep in mind is that the particular constitutive model chosen should explain the observed phenomenon in the simplest possible manner. In a rapidly heated structure, the stress redistribution and subsequent failure arise primarily from the thermally degraded elastic properties, the thermally activated plastic flow and the early time creep. These phenomenon are precisely those which can be modeled by current general purpose nonlinear structural analysis codes. In view of this, the material behavior will be modeled as elastic-plastic-creep. Selected flow and hardening rules will be used to describe the plasticity and a mechanical equation of state will be used to model the creep.

In principle, one can talk about time independent strain (elastic-plastic) and time dependent strain (creep) but in practice one must be able to perform material property tests in a manner which will allow separation of these quantities. Naturally, it takes a finite time to heat a specimen to temperature and apply the load. The standard test to obtain stress/strain data as a function of temperature is to heat the specimen to temperature in a minute or longer and then to load the specimen to failure at a low strain rate of 0.5%/minute. Obviously, a large component of time dependent strain can accumulate during the test. Theoretically, one could obtain "zero" time or time independent elastic/plastic temperature dependent stress/strain curves by either heating a specimen to temperature and applying the load in a very short period of time or by applying the load to a specimen and heating to temperature in a very short period of time. The methods are essentially equivalent in the case where the heating of the specimen does not cause metallurgical changes in the time it takes to heat. The equivalence of the two methods has been a subject of debate. A simple thought experiment ca help to illustrate the problems in having two sets of conflicting "zero" time data as generated by the above mentioned approaches. Consider a flight

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structure operating at some nominal temperature and subject to a quasi-static set of aerodynamic loads. At some point in time, the structure is irradiated by a heat source and portions of the structure are rapidly heated. At that instant, one might argue that the appropriate data might be that generated by applying a load to a specimen and then rapidly heating it. Back at the structure, in the next instant, the local stress field has changed due to thermally degraded material properties. One might then argue that the appropriate data might be that generated in a test where temperature is held constant and load is rapidly changed . From then on, the stress and temperature are in a constant state of change. It is obvious that neither method of obtaining data can be used to exactly model the phenomenon unless the differences between the data are negligible. It is suggested that the primary difference in the data will arise from the accumulated time dependent strain and that either method will produce equivalent "zero" time curves as long as the loading or heating times are short compared to the engagement time.

3.1.1 Determination of "Zero" Time Temperature Dependent Stress-Strain Curves

A procedure has been developed which allows the determination of the "zero" time strain from stress-strain tests performed at various load rates. Consider a uniaxial specimen as shown in Figure 2. Figure 3 shows the load and temperature history for the specimen.
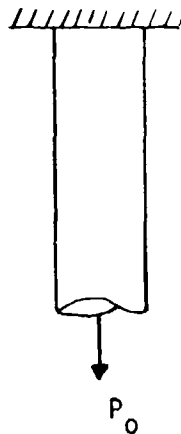

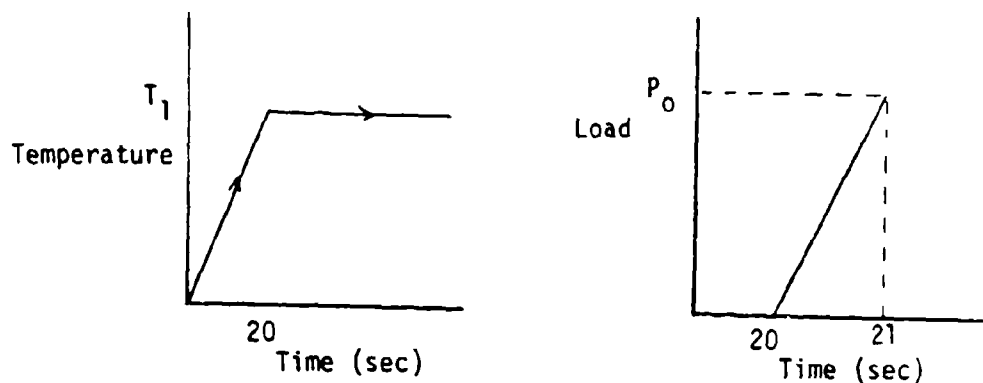Figure 2. Uniaxial Test Specimen

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Figure 3. Material Property Test for Constant Temperature Rapidly Loaded Specimen

The specimen is uniformly heated in 20 seconds or less to test temperature T_1 and then loaded rapidly at a rate $\dot{P}_1 = \frac{dP}{dt}$ to final load P_0. Care must be taken so as to load the specimen rapidly enough to prevent time dependent strain from accumulating but not so rapidly as to produce dynamic effects. The strain is measured for each load P, $0 \leq P \leq P_0$ for fixed load rate $\dot{P}_1$ and temperature T_1. A series of tests are performed in which strain is measured for various load rates and for particular loads (stresses) and temperatures. The strain is then plotted as a function of the time to reach a particular load as shown in Figure 4. These points are fit by a smooth curve and extrapolated back to time zero. This then gives the time independent elastic-plastic strain for a given stress and temperature. A series of tests at various appropriate load rates and temperatures would provide data that can be used to generate "zero" time, temperature-dependent stress-strain curves.
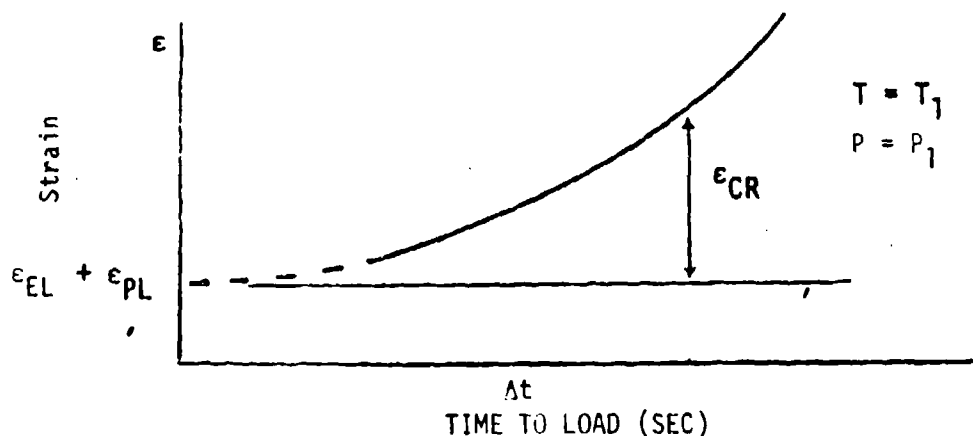

Figure 4. Determination of "Zero" Time Elastic-Plastic Strain

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3.2 NONLINEAR STRUCTURAL ANALYSIS CODES

Many general purpose and special purpose codes exist which have the capability of solving elastic-plastic creep oroblems. The solution algorithms, however, differ in many respects both from a theoretical and operational point of view. An excellent description of the various aspects of the solution techniques can be found in Reference 5. The thermal elastic-plastic algorithms are fairly standard and are flexible enough to allow for various types of material behavior beyond yield and for reversed loading. The solution methods for handling the creep strain are varied and can greatly influence the accuracy of the results and the computation time of the analysis. The original solution methods (and those used most widely today) were based upon the method used for elastic thermal stress analysis. In that approach, a set of "initial" strains depending on temperature and thermal coefficient of expansion are calculated and converted to "initial" loads through the use of elastic and geometric properties. The problem is linear since none of the "initial" quantities depended on the deformation or stress level in the structure. Similarly, "initial" creep strains can be calculated. These strains in general depend on the stress level of the structure and thus can only serve as approximate values. Many alterations to the basic "initial" strain procedure have been made to account for the approximate nature of the solution, including algorithms which select time increments so as to insure that stresses calculated at the end of an increment are compatible with creep strain calculated at the beginning of the increment.

3.2.1 General Purpose Finite Element Codes (MARC, ANSYS)

Two general purpose codes were selected to demonstrate and evaluate the ability of standard nonlinear codes to solve the rapid heating problems. These codes have extensive element libraries and are capable of solving nonlinear problems including plasticity, creep, large deflections and buckling. The codes use essentially the same approach in solving the plasticity and creep problems although MARC allows for user written subroutines to calculate creep and temperature dependent stress-strain behavior. A more detailed description of the codes can be found in References 3 and 5.

3.2.2 Special Purpose Analysis Code (CREEPARHS)

A special purpose one-dimensional direct integration code "CREEPARHS" (creep-elastic-plastic-analysis of rapidly heated specimens) was written for the expressed and important purpose of evaluating the proposed material models in an accurate and cost efficient manner. The code is capable of analyzing the response of an idealized one-dimensional homogenous cylindrical bar subjected to load/temperature histories as shown in Figure 5.
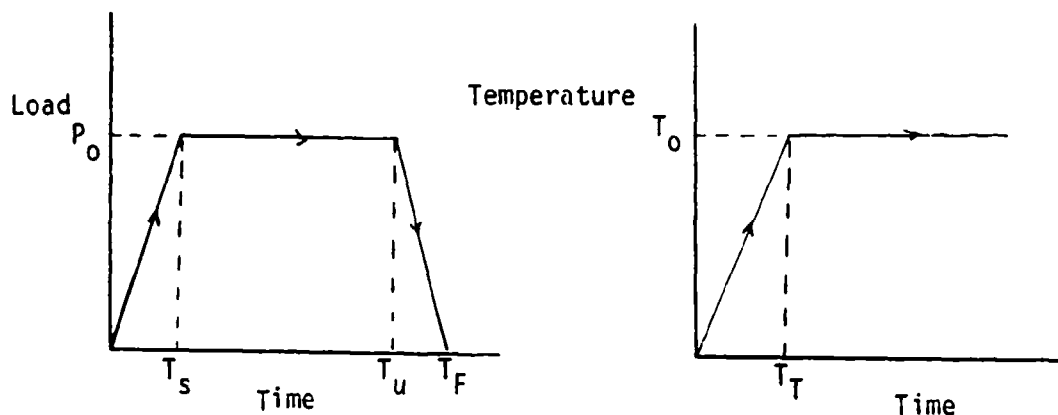

Figure 5. Load/Temperature Input Histories for Simulation Tests

These temperature and load histories were selected as being representative of those seen in more complex rapidly heated structures and to demonstrate the wide range of material behavior that can result from varying the input load and temperature levels and durations.

The code uses time independent multilinear stress-strain-temperature curves and interpolates for temperatures between those inputs. In addition, it calculates creep strain as a function of time using a specific creep strain versus stress, time and temperature relations, and a time hardening creep rule. Finally, thermal strain as a function of temperature is calculated. The output consists of temperature, stress, and mechanical, thermal, creep and total strain at each point in time as well as a listing of the input data and initial conditions. A more detailed description of the code including the governing equations is given in Section 7. A code listing can be found in Appendix 2. It should be noted that the input to this code is identical to that required by most general purpose codes. This allows a direct check on the various procedures used by the codes to solve the nonlinear problems.

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Section 4
EXPERIMENT/TEST SPECIMEN DESIGN AND DATA REDUCTION

Simple uniaxial tensile specimens were used for all of the material property
and simulation tests. The material property tests consisted of stress/strain
tests as a function of temperature and short time creep tests as a function
of stress and temperature. The experiment and specimen designs were based
upon ASTM E150-64, standard recommended practices for "conducting creep and
tension tests of metallic materials under conditions of rapid heating and
short time".

Subsection 4.1 through 4.3 discuss the tests and test specimens. Subsection
4.4 describes the process used to convert the raw data to a form suitable for
input to the analysis codes. This was a major effort and should be automated
in any future work.

4.1 SPECIMEN DESIGN
The tensile specimens were machined from a sheet of 6061-T6 Aluminum. The
final specimen dimensions (Figure 6) were determined experimentally by varying
the specimen length and cross section in order to obtain the most uniform
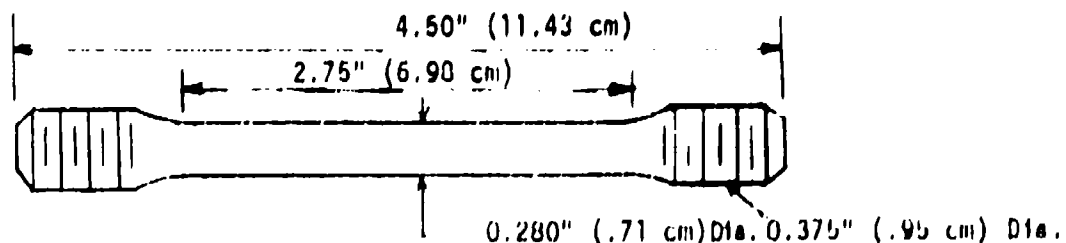temperature field in the gauge length.

4.50" (11.43 cm)

2.75" (6.90 cm)

0.280" (.71 cm) Dia. 0.375" (.95 cm) Dia.

Figure 6. Tensile Specimen Design

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4.2 TEST EQUIPMENT

The following items were used in the rapid heating/loading tests:

1. MTS model 810 Servo-hydraulic test machine with a 100,000 pound load frame and a 5,000 pound load cell.

2. MTS model 632.55B-01 elevated temperature extensometer with quartz arms and a one-inch gauge length.

3. Research Inc. THERMAC "A" Power controller with DATA-TRAC Program Control. 100 AMP, 440 volt capacity.

4. Jefferies Transformer, 460 volt primary, 15 volt secondary, 15 KVA capacity.

4.3 TEST TECHNIQUE

Direct resistance heating was used in order to obtain the rapid heating rates required in the tests. A 15 KVA transformer coupled with a Research Inc. Power Controller equipped with a data-trac programmer was used to control heating rates and maximum temperatures. The specimens were instrumented with 4 Chrome-Alumel thermocouples attached by the use of copper clamps made from thin copper sheets. One thermocouple was placed on each side of the one-inch gauge length to monitor the temperature variation. The remaining two thermocouples were used to monitor and control the temperature within the gauge length. The maximum heating rate, maximum temperature, loading rate and maximum load were all preset on the test equipment prior to the start of each test. A diagram of the test equipment is shown in Figure 7. Figures 8 and 9 are photographs showing the entire test system and a closeup of the test specimen/gauge configuration. Many of the tests required heating prior to loading. For these tests, a zero offset technique was used to offset the strain trace by a known amount. This allowed the use of a higher magnification factor for the strain versus time oscillograph trace during the loading phase of the test.

The following is a list of the range of loading and heating parameters which were used in the tests:

- Load rate (7.5 - 80 KSI/Sec)
- Stress (0-45 KSI)
- Heating rate (15 - 40°F/Sec)
- Temp variation across gauge length ($\pm10°F$ at 800°F)

Figure 7. Test Equipment Schematic
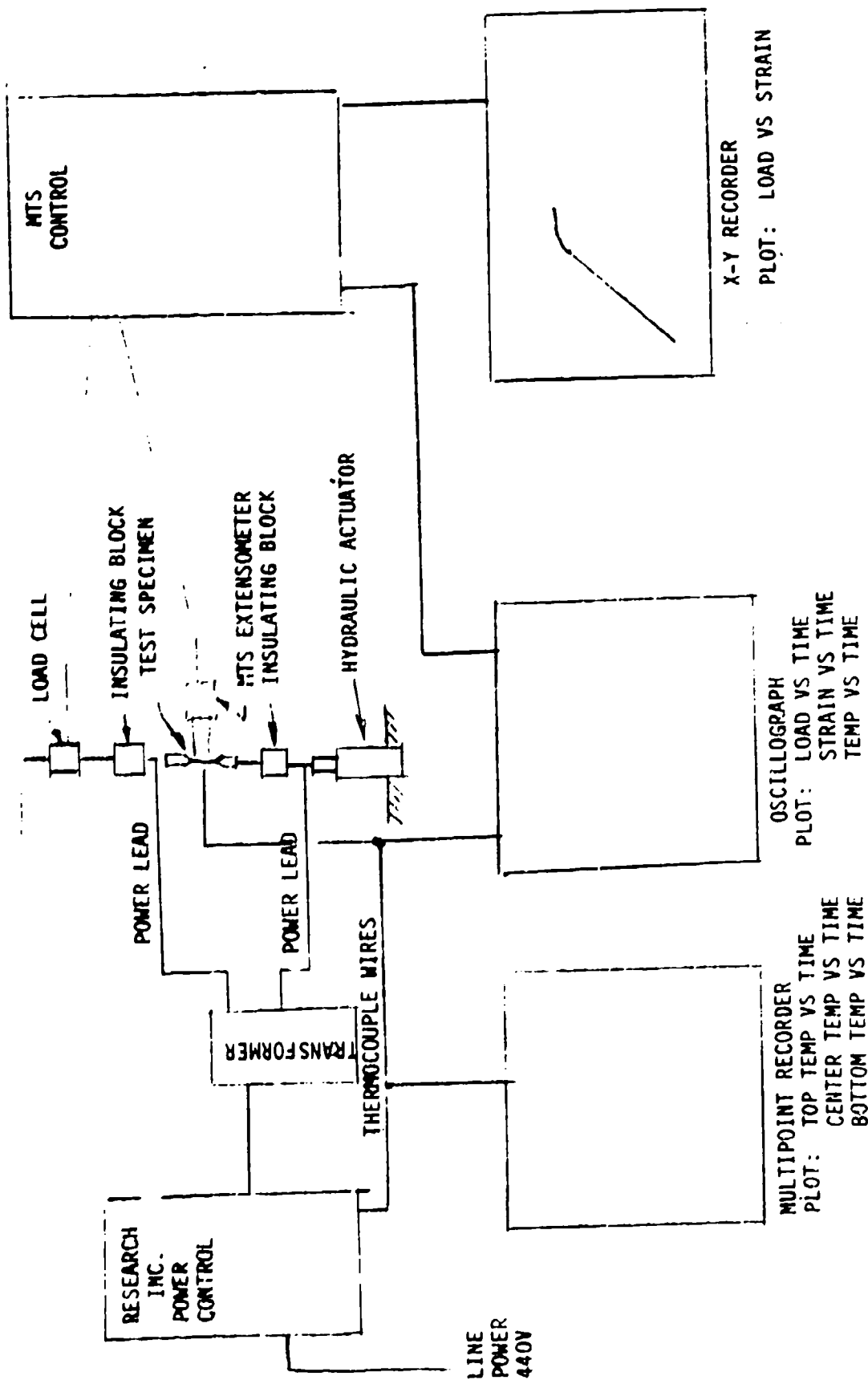
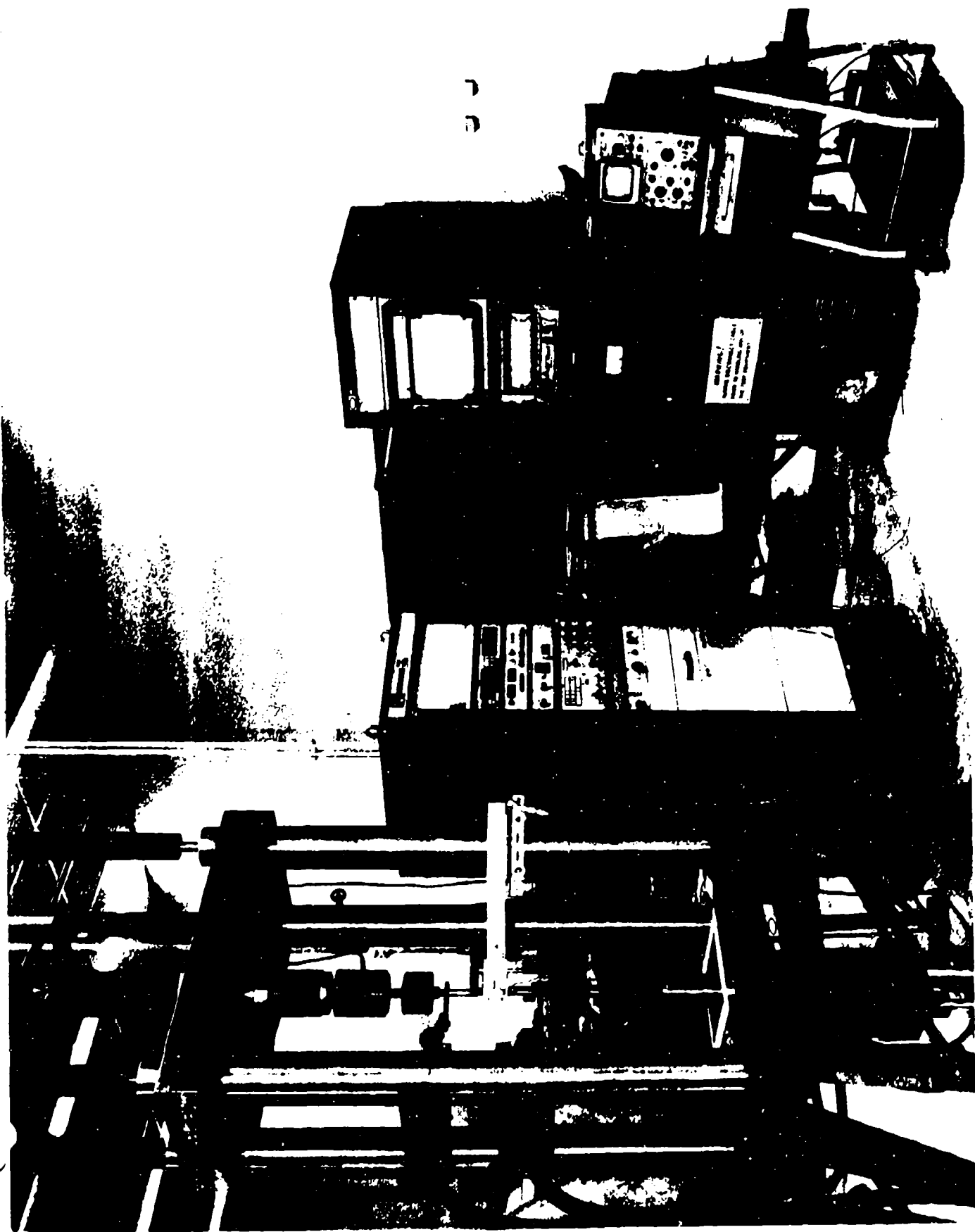Figure 8.   Test System
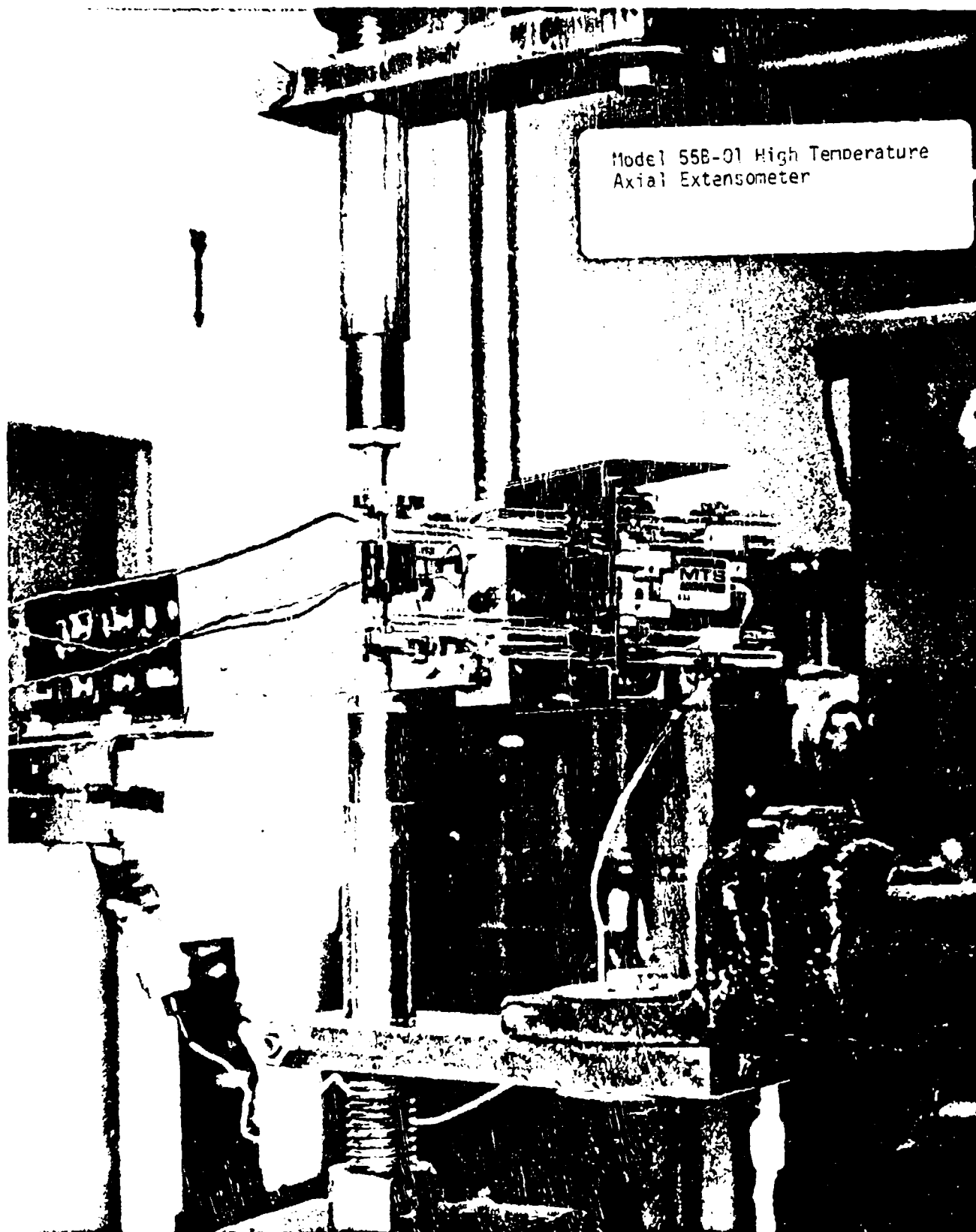
Model 55B-01 High Temperature
Axial Extensometer

Figure 9.   Test Specimen/Gauge Configuration

4.4 DATA OUTPUT AND REDUCTION

The strain versus time as well as the temperature and load histories were mechanically recorded on a standard continuously running oscillograph recorder. In addition, the stress-strain curves were plotted in real test time using an X-Y plotter. An example of the o-graph output is shown in Figure 10.

A major effort in the program was to convert the recorded data into a form which was amenable to analysis. The data reduction task was complicated by the fact that the strain scales and chart recording speeds were varied up to three times during a test and from test to test. The scale changing was necessary because the magnitude of the strain data varied greatly both during the tests and from test to test. The strain versus time was digitized using a trektronix digitizer and then stored on magnetic tape.

A computer program was written which smoothed and provided curve fitting for the raw data and then calculated the parameters necessary for analysis such as the elastic moduli, yield stress, and stress versus plastic strain. In particular, the stress-strain data was fit to a 10th order polynomial and then reduced to a piecewise linear curve with N segments (Figure 11). The N + 1 breakpoints were selected by calculating the N points on the curve with the largest changes in slope. The idea was to best approximate the work hardening effects in the stress strain behavior.

The creep data was fit by various formulas depending upon the intended use.

The general behavior of the creep data is illustrated in Figure 12. One sees the classical primary, secondary and in a few cases tertiary steps. In most cases, the time scale of the secondary stage was very long compared to 1-10 second heating time which is of current interest and thus the data was fit to a fourth order polynomial using a least squares technique in the primary stage and was assumed linear in the secondary stage. The curve fit representations of the creep data are shown in the next section (Figures 20 - 24).
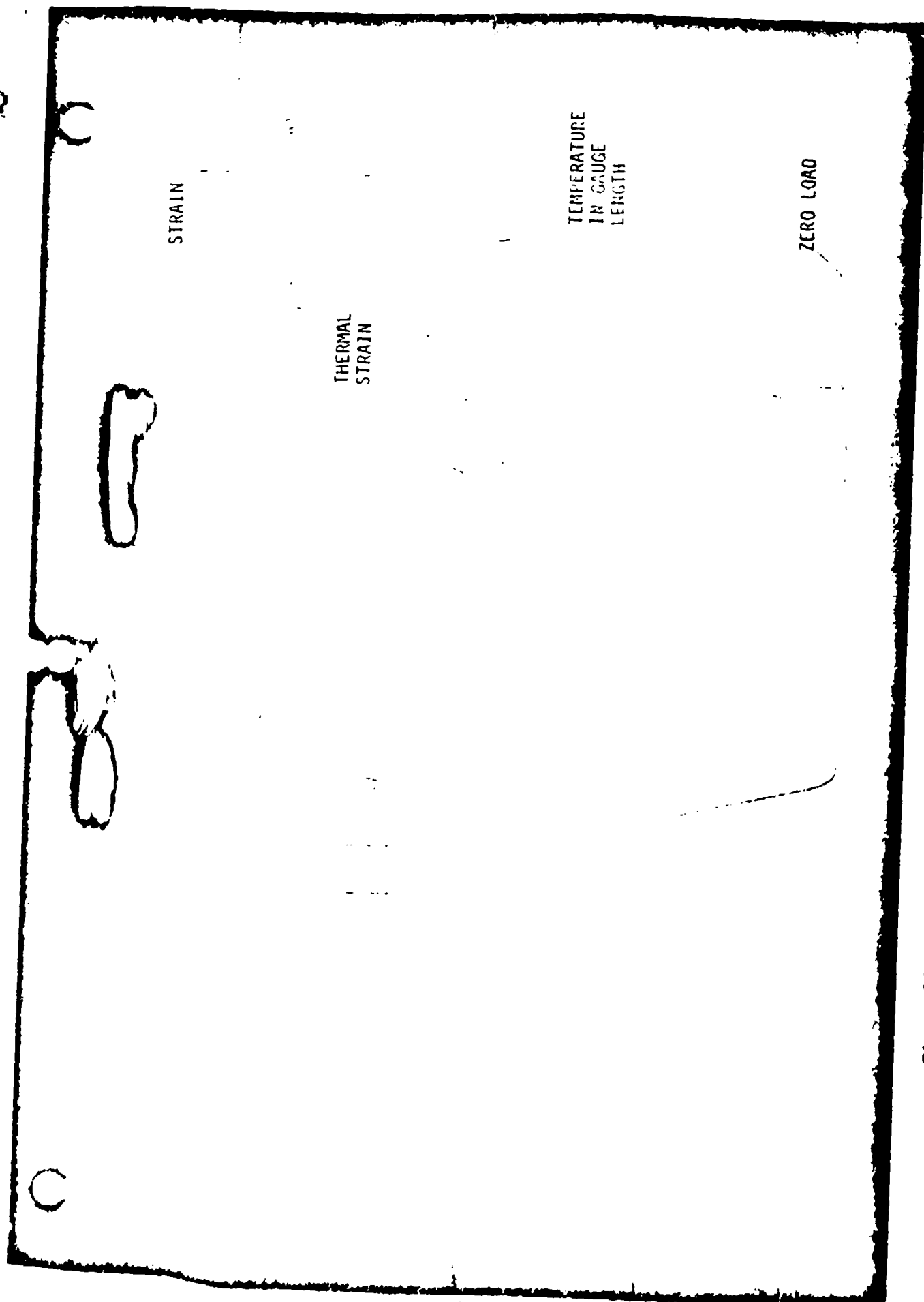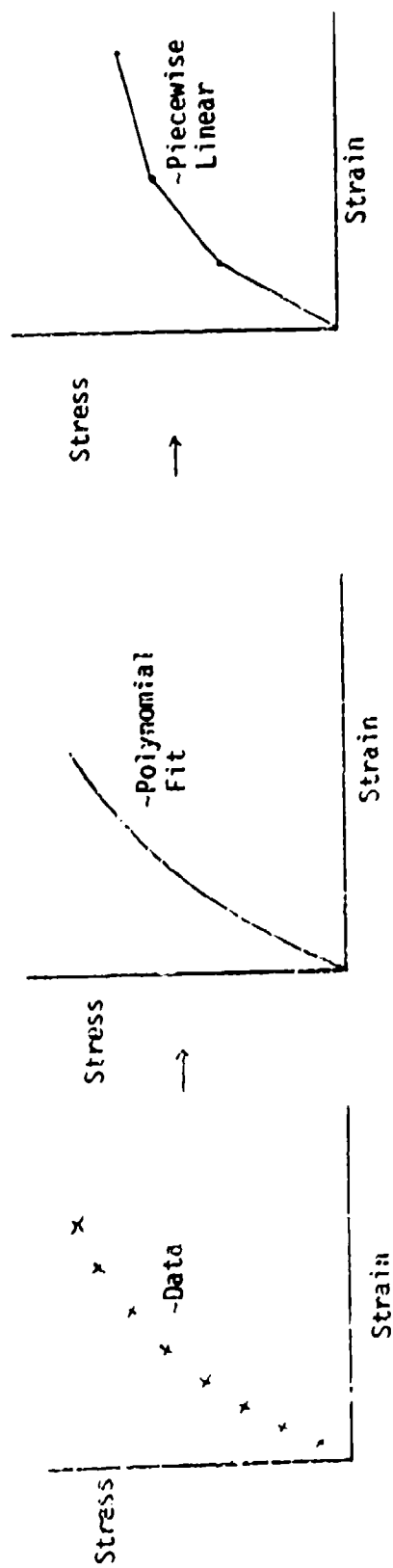
Figure 10. Data Output - Oscillograph Recorder

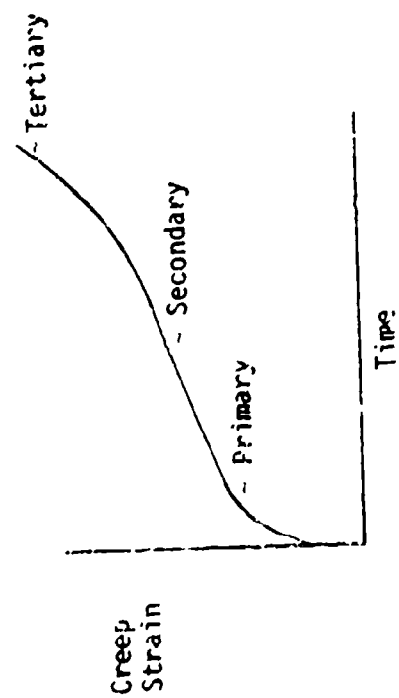Figure 11. Curve Fitting for Stress-Strain Data

Figure 12. General Behavior of Creep Strain Versus Time

Section 5
MATERIAL PROPERTY TESTS

This section includes a description of the tests and a summary of the test results followed by a complete test matrix. The emphasis in this program was not to obtain statistically significant data, but instead to perform tests which would illustrate basic material behavior. Reruns of individual tests were performed only in those cases where the data did not follow anticipated trends. In all cases where the data are used in an analysis, the error in the data is considered small compared to the magnitude of the effect being measured.

The following types of tests were performed to obtain basic material property data. A sketch of the load and temperature history for the test is included in each description.

5.1 TEMPERATURE PREHEAT SENSITIVITY TESTS

These tests were performed to gain an insight into the effect of varying the preheat time on the creep characteristics of the material. In particular, the time to reach 800°F (427°C) was varied from 20-60 seconds. The load was then applied at a rate of 40 KSI/second (275 MPa/second) to a final stress of 4 KSI (27.5 MPa). The strain as a function of time was measured at constant stress. The load and temperature histories are shown in Figure 13.

The results of these tests are shown in Figure 14. The cross hatched region in the lower curves indicates the area where the strain versus time data lies. There was no trend noticed in the behavior of the strain versus time as the heat-up time was varied. This is not to say that no effect exists. The upper curve was a similar single test performed at 40 KSI/second (275 MPa/second) with a 20 second heat up time. It is suggested that a variation of a principal quantity such as stress is far more significant in determining the strain-time behavior than a variation in heat up time. A test matrix is given in Table 2.
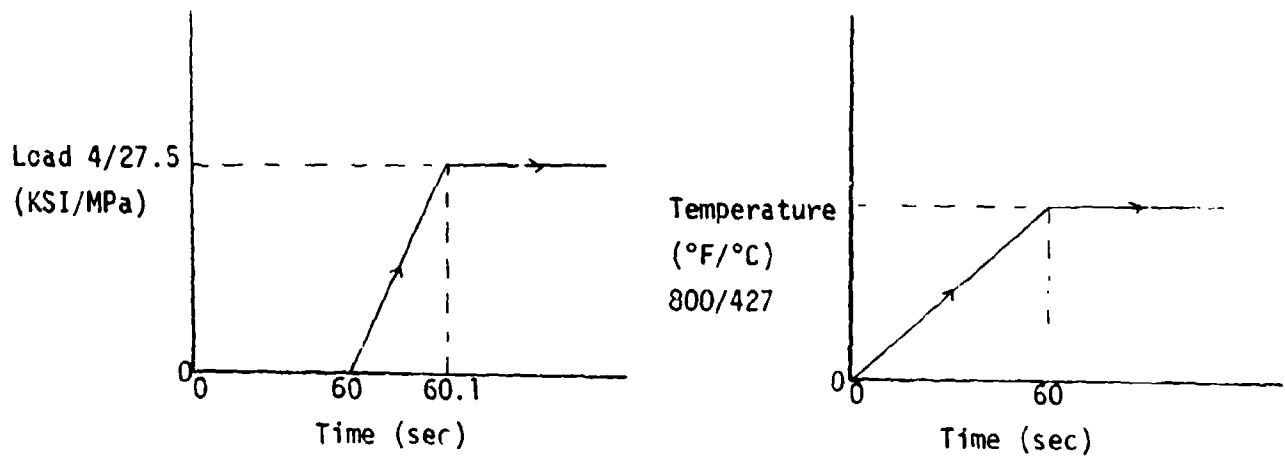
Figure 13. Stress/Temperature History - Preheat Sensitivity Tests.

Table 2
Preheat Sensitivity Test Matrix

Test Type	Test No.	Heatup Rate (°F/Sec)	Final Stress (kSI/MPa)
CREEP	CT1-80	40	4/27.5
CREEP	CT2-80	32	4/27.5
CREEP	CT3-80	16	4/27.5
CREEP	CT4-80	8.9	4/27.5

5.2 STRAIN VERSUS LOAD RATE TESTS

These tests were useu to demonstrate the ability to extrapolate the measured strain to zero time so as to generate the "zero" time or time independent stress-strain-temperature curves.

The specimens were tested at 500°F (260°C) and 800°F (427°C) at stresses well above yield so as to be able to bound the time dependent effects due to temperature and stress. The general procedure was to heat the specimens to
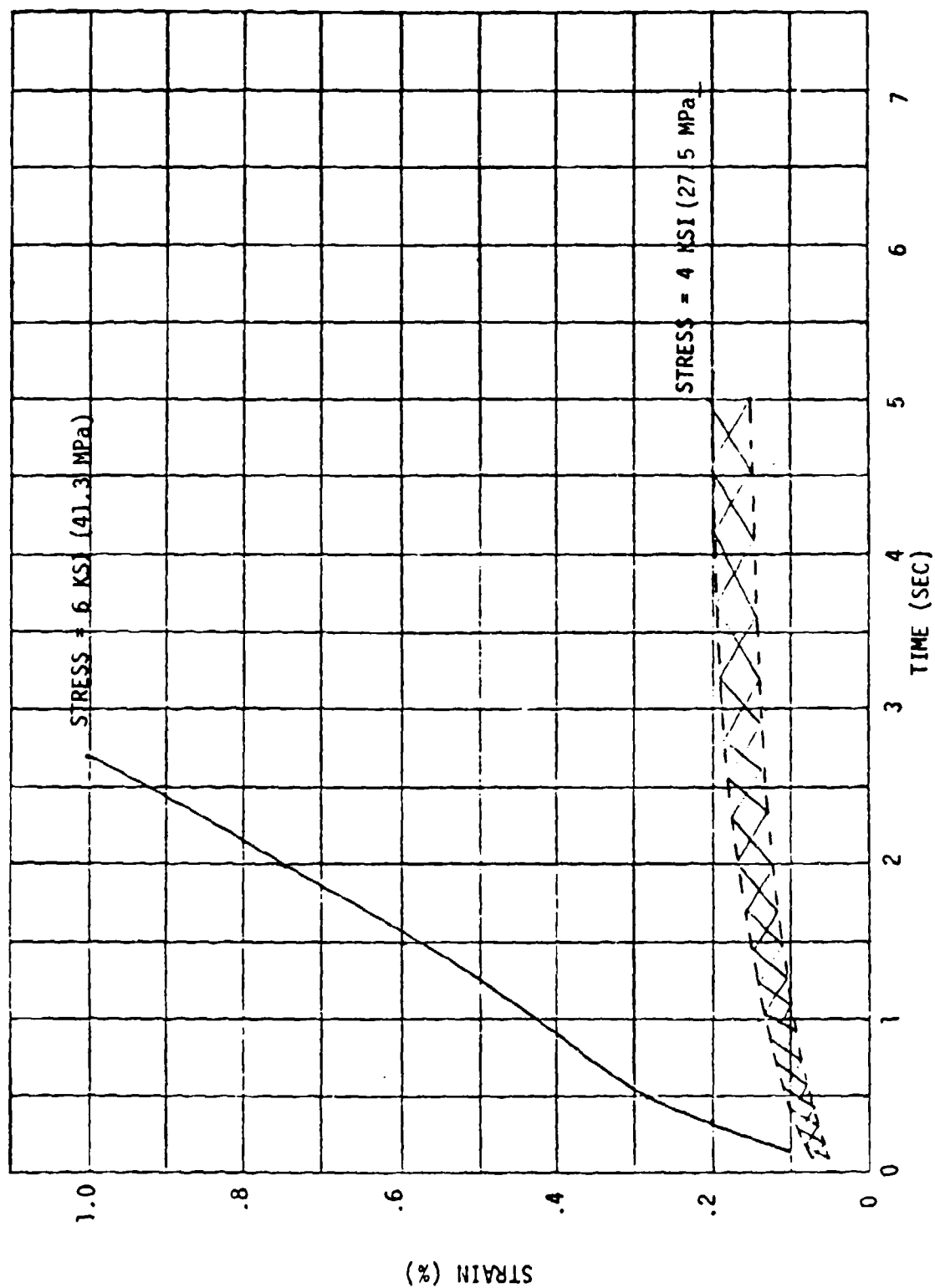
Figure 14. Strain vs Heatup Time – Temp = 800°F (427°C)

temperature T_o in 20 seconds and then apply the load at a constant rate $\dot{P}_1$ until the final load level P_1 was reached. The load rate was then changed to $\dot{P}_2$ and the test repeated. These histories are shown in Figure 15. The specific tests performed are listed in Table 3.
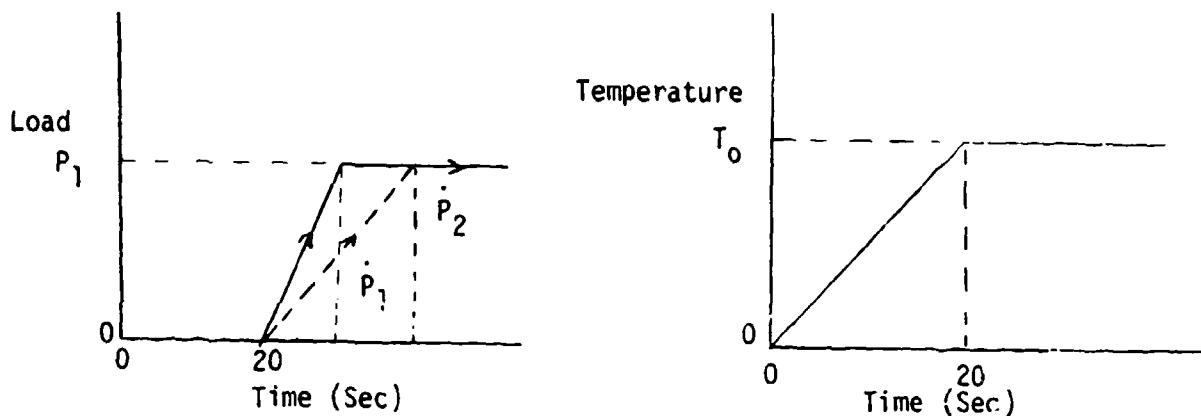

Figure 15.   Stress/Temperature History - Load Rate Sensitivity Tests.

Table 3

Load Rate Sensitivity Test Matrix

Test Type	Test No.	Test Temperature °F/°C	Stress Rate (KSI/MP$_a$/Sec)	Final Stress (KSI/MPa)
Creep	CS1-50	500/260	80/550	28.7/198
	CS2-50	500/260	20/137	28.7/198
	CS3-50	500/260	10/69	28.7/198
	CS1-80	800/427	40/275	4/27.5
	CS2-80	800/427	20/137	4/27.5
	CS3-80	800/427	10/69	4/27.5
	CS4-80	800/427	2.5/14	4/27.5
	CS5-80	800/427	40/275	6/41.3
	CS6-80	800/427	20/137	6/41.3
	CS7-80	800/427	10/69	6/41.3

The strain at 500°F (260°C) is plotted as a function of the time to reach the
final stress (28.7 KSI/198 MPa) in Figure 16. A smooth line is drawn through
the data points and extrapolated to time t = 0. The intercept strain repre-
sents the time independent Elastic + Plastic strain at the given stress and
temperature. It is seen that a reasonable approximation to the time independent
strain (<15% error) can be obtained by loading the specimen to final stress in
one second or less. On the other hand, a 200% error would result if the
specimen were loaded in three seconds. Similar results are shown in
Figure 17 for specimens tested at 800°F (427°C) at two stress levels. It is
seen tnat for a given acceptable level of error, the time tc final load
increases dramatically as the stress increases beyond yield. In this case, a
15% error or less is guaranteed by loading to 6 KSI/41 MPa in 0.15 seconds
or less. Theoretically, one could perform a whole series of tests where the
final load, load rate and temperature were varied. Extrapolation of the
results would lead to a set of "zero" time stress/strain-temperature curves.
In practice one could decide upon an acceptable upper error bound and select
a single load rate which would be used in all of the tests. In this study, a
load rate of 40 KSI/sec (276 MPa/sec) was chosen based upon a maximum 15%
error in the strain at the worst case temperature/stress combination
(800°F/6 KSI)(427°F/41 MPa). This will assure a minimum error in the
majority of the stress/strain/temperature data.

5.3 STRESS-STRAIN-TEMPERATURE TESTS

The tests that were performed in this phase were essentially standard elevated
temperature stress-strain tests with the exception that the load was applied
at a rate (40 KSI/sec) (276 MPa/sec) which was rapid enough to prevent the
accumulation of time dependent strain (see Section 5.2). Figire 18 illustrates
typical load temperature histories. Table 4 contains the complete test
matrix.

The resulting "zero" time stress-strain curves are plotted as a function of
temperature in Figure 19. It is important to note that a relatively small
increment of stress beyond yield at temperatures above 500°F (260°C) leads
to an increasingly large increment in plastic strain. An important comparison
between these curves and the so called handbcok and isochronous curves is
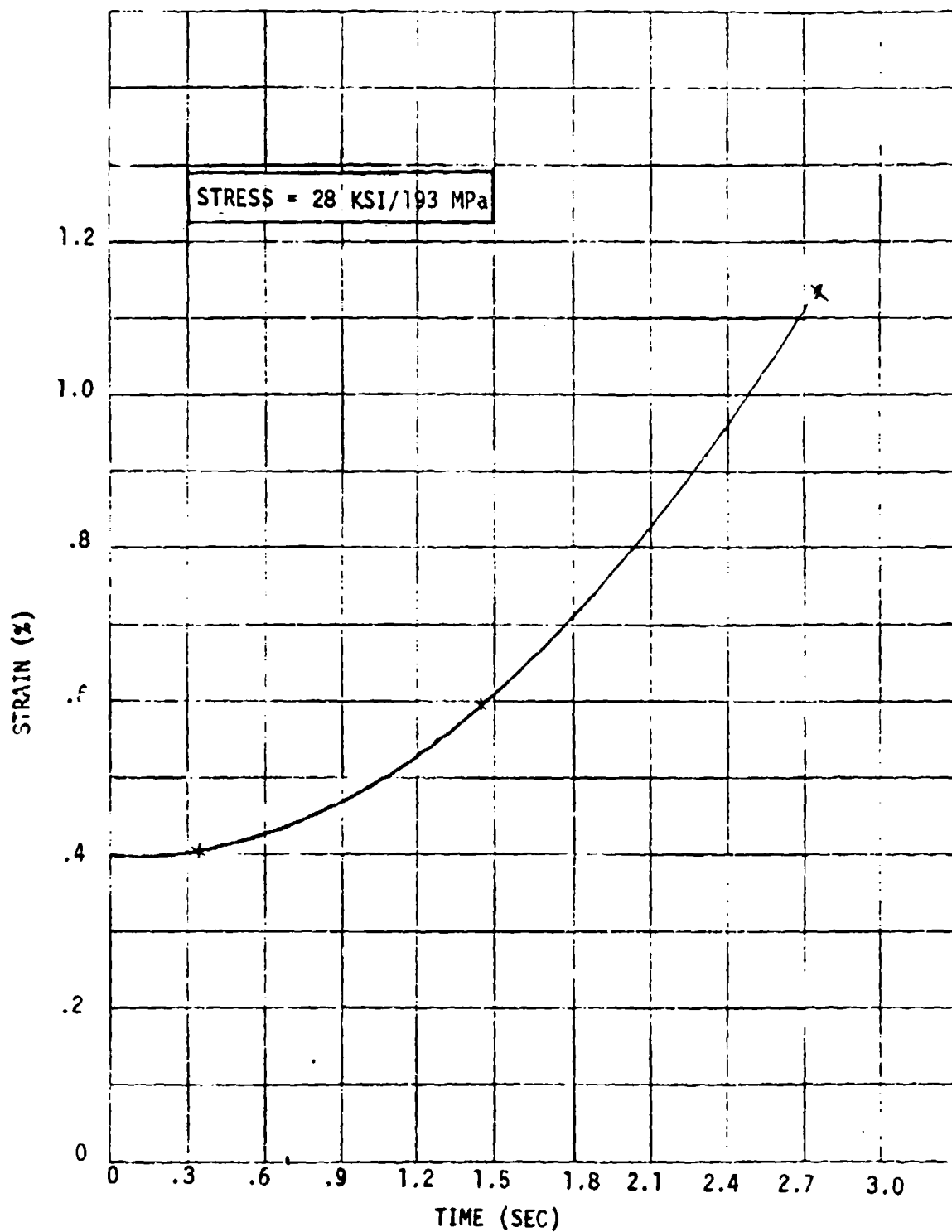presented in the following section.

Figure 16. EXTRAPOLATION OF STRAIN DATA TO "ZERO" TIME - TEMP = 500°F (260°C)
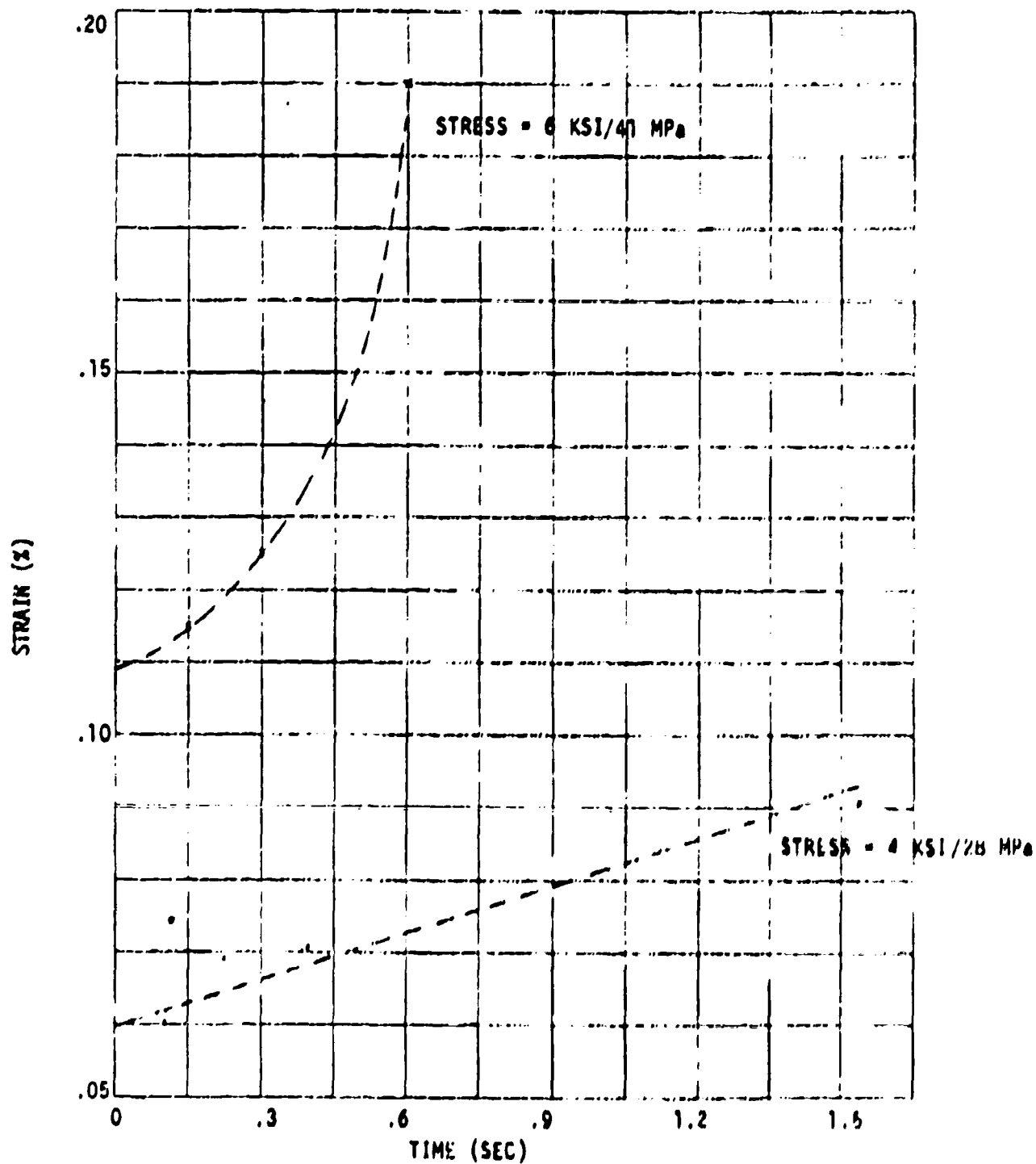
Figure 17. EXTRAPOLATION OF STRAIN DATA TO "ZERO" TIME - TEMP = 800°F. (427°C)
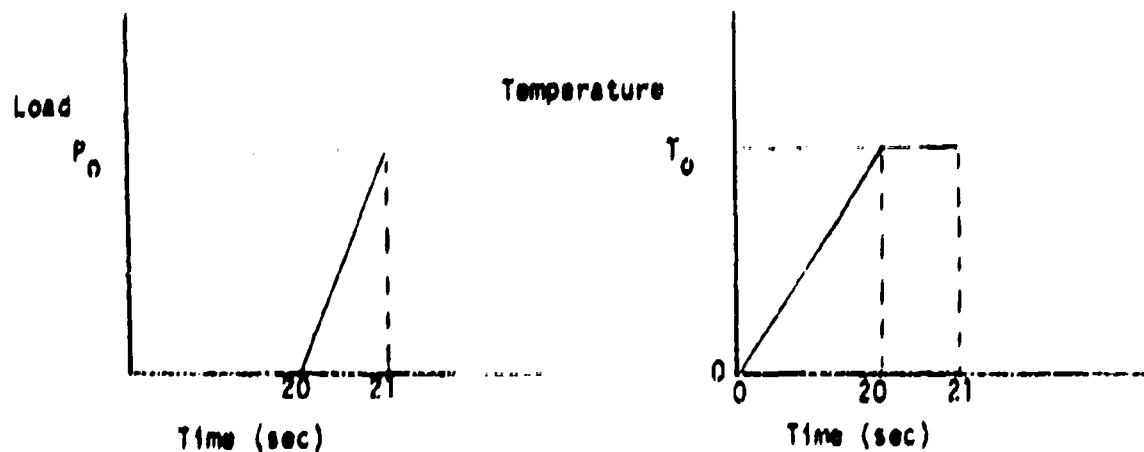
Figure 18. Stress/Temperature History - Stress/Strain Tests.

Table 4

Stress-Strain Temperature Test Matrix

Test Type	Test No.	Test Temperature (°F/°C)	Final Stress (KSI/MPa)	Time To Final Stress (Seconds)
Stress/Strain	SS1-RT	71/21.7	42/289	1.05
	SS4-40	400/204	33/227	0.825
	SS5-60	500/260	28.7/198	0.7175
	SS6-60	600/315	20/138	0.5
	SS7-70	700/371	11/76	0.275
	SS8-75	750/399	8/5.5	0.20
	SS9-80	800/427	6/4.3	0.15

6.4 CREEP TESTS

A series of standard creep tests were performed in which the load and temper-
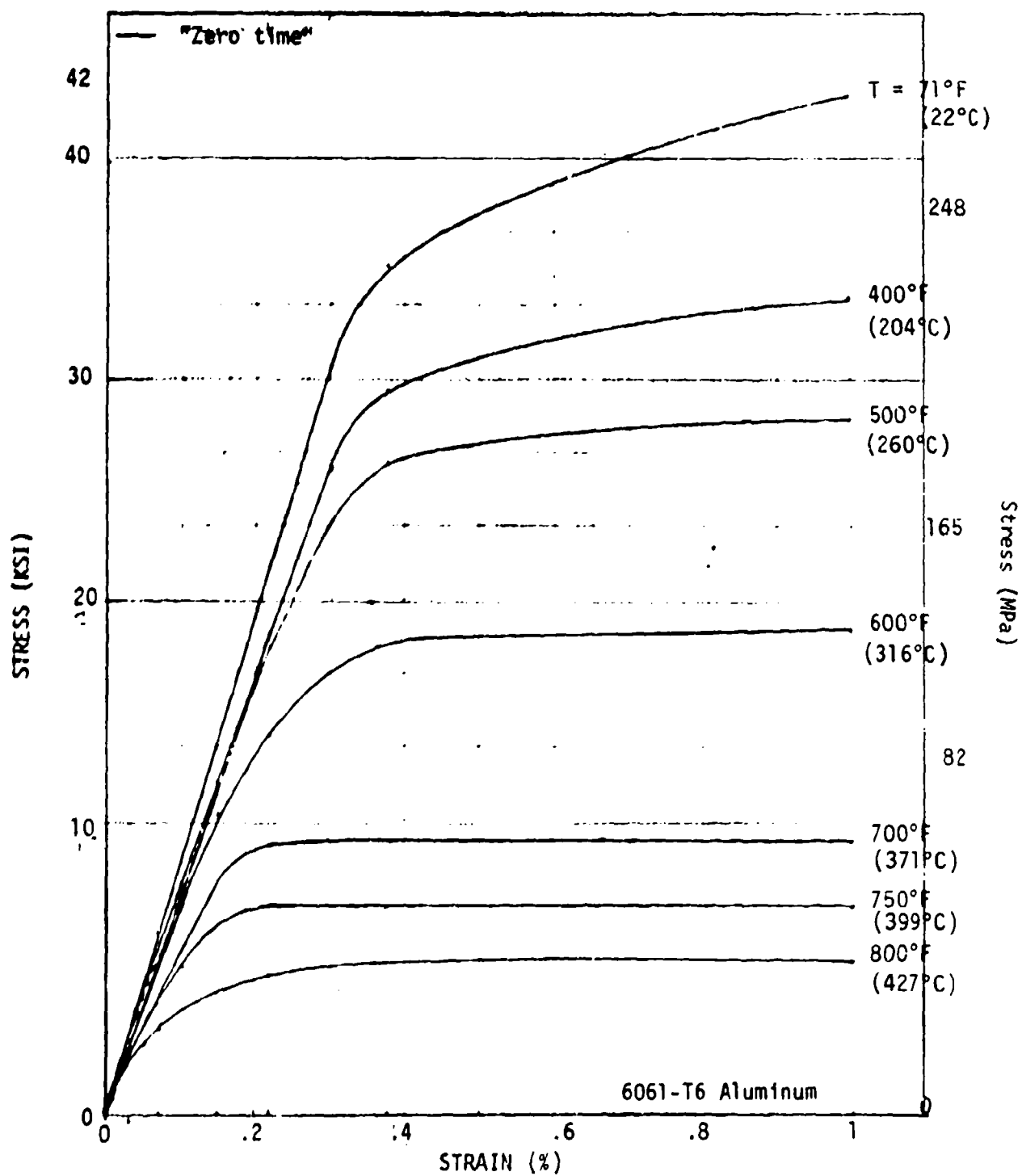ature test levels were selected so as to allow investigation of the creep

Figure 19.   Stress/Strain Curves: "Zero Time"

response of the material over a wide range of loading conditions. In particular, the temperature levels varied from 500-800°F (260-427°C) and the load levels were selected so that at least one test was performed in the following stress-strain regions:

- elastic
- yield
- post-yield

The specimens were heated to temperature in 20 seconds or less and the load was applied at the rate of 40 KSI/second (276 MPa/second). The temperature/load history is the same as that seen in Figure 13. The complete creep test matrix is shown in Table 5.

Table 5

Creep Strain Test Matrix

Test Type	Test No.	Test Temperature	Test Stress (KSI/MPa)
Creep	C1-50	500°F/260°C	13/90
	C2-50		20/138
	C3-50		25/172
	C4-50		27/186
	C1-60	600°F/316°C	8.1/56
	C2-60		11.4/79
	C3-60		17.8/123
	C4-60		19.5/134
	C1-70	700°F/371°C	5.5/38
	C2-70		6.8/47
	C3-70		10.3/71
	C4-70		11.3/78
	C1-75	750°F/399°C	4.5/31
	C2-75		5.8/40
	C3-75		7.8/54
	C4-75		8.4/58
	C1-80	800°F/427°C	1.6/11
	C2-80		2.4/17
	C3-80		3.2/22
	C4-80		4.0/28

The creep strain versus time curves were obtained by subtracting the strain at load and then curve fitting the data as described in Section 4.4. The resulting curves are shown in Figures 20 - 24. Note that creep strain increased dramatically once a certain stress level is reached. This stress level is generally in the center of the knee of the stress-strain curve as can be seen from Figure 19. One then must consider the contribution from creep at stress levels above yield.

The raw data from the creep tests (which includes elastic and plastic strain) can also be used to generate so-called isochronous or constant time stress-strain curves. It is precisely these isochronous curves that have been used in attempts (Reference 3) to solve the rapid heating problems. Unfortunately, the best available isochronous data are 10 second curves. It is evident from the creep data that significant creep can occur during the 1-10 second time period, thus the 10 second data are not appropriate for the analysis.

The isochronous curves are generated by selecting a certain time and then plotting the stress versus strain as a function of temperature. An accurate isochronous curve thus requires data from the large number of creep tests. Examples of isochronous curves which have been generated from the creep data in Figures 20-24 are shown in Figures 25-29. The important thing to notice in these curves is that for a particular value of strain, the corresponding stress decreases dramatically as one moves from the 1 second to the 10 second curve. If the 10 second data were used in the analysis of a simple uniaxial specimen, one would predict failure at a stress level which could be significantly lower than the actual failure stress level. This suggests, for example, that the predicted failure times in more complicated structures might be much shorter than the actual failure times.

5.5 FREE THERMAL EXPANSION TESTS

In each of the previous tests, the thermal expansion strain was measured after the specimen was stabilized at temperature. The coefficient of thermal expansion was calculated by dividing the thermal strain by the temperature. These data were used as input to the analysis codes.
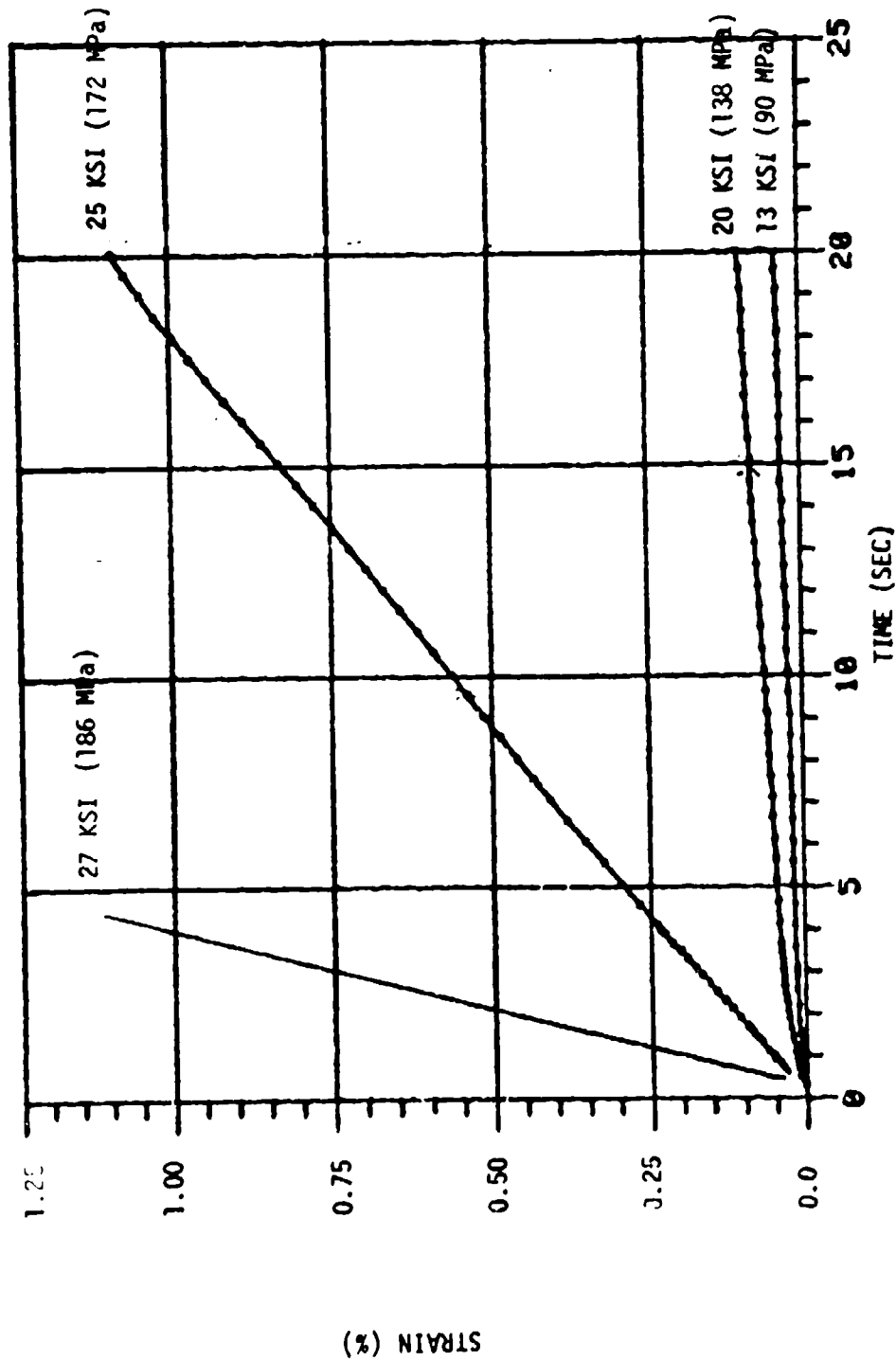
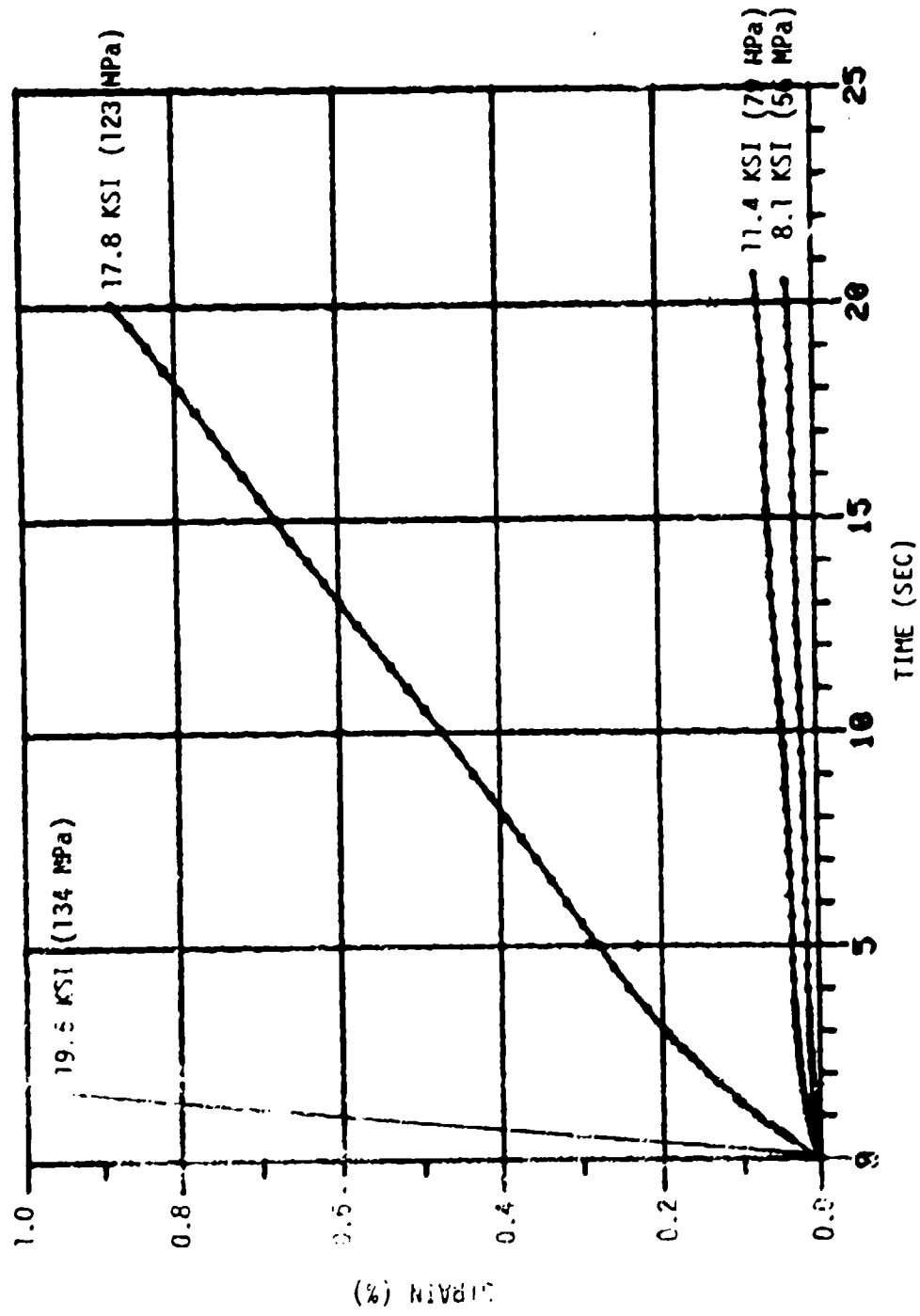Figure 20. CREEP STRAIN vs TIME – TEMP = 500°F (260°C)

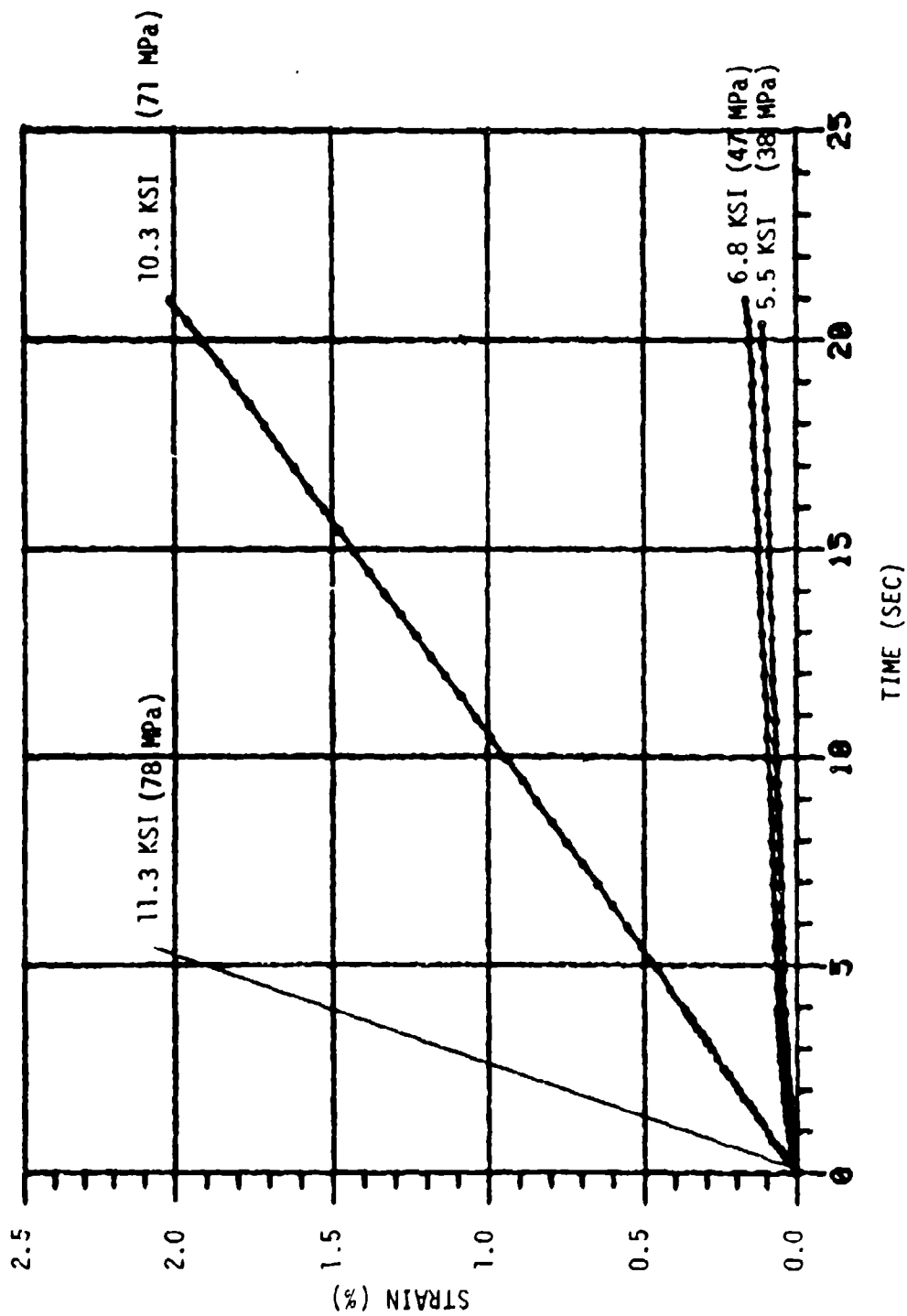Figure 21. CREEP STRAIN VS TIME - TEMP = 600°F (316°C)

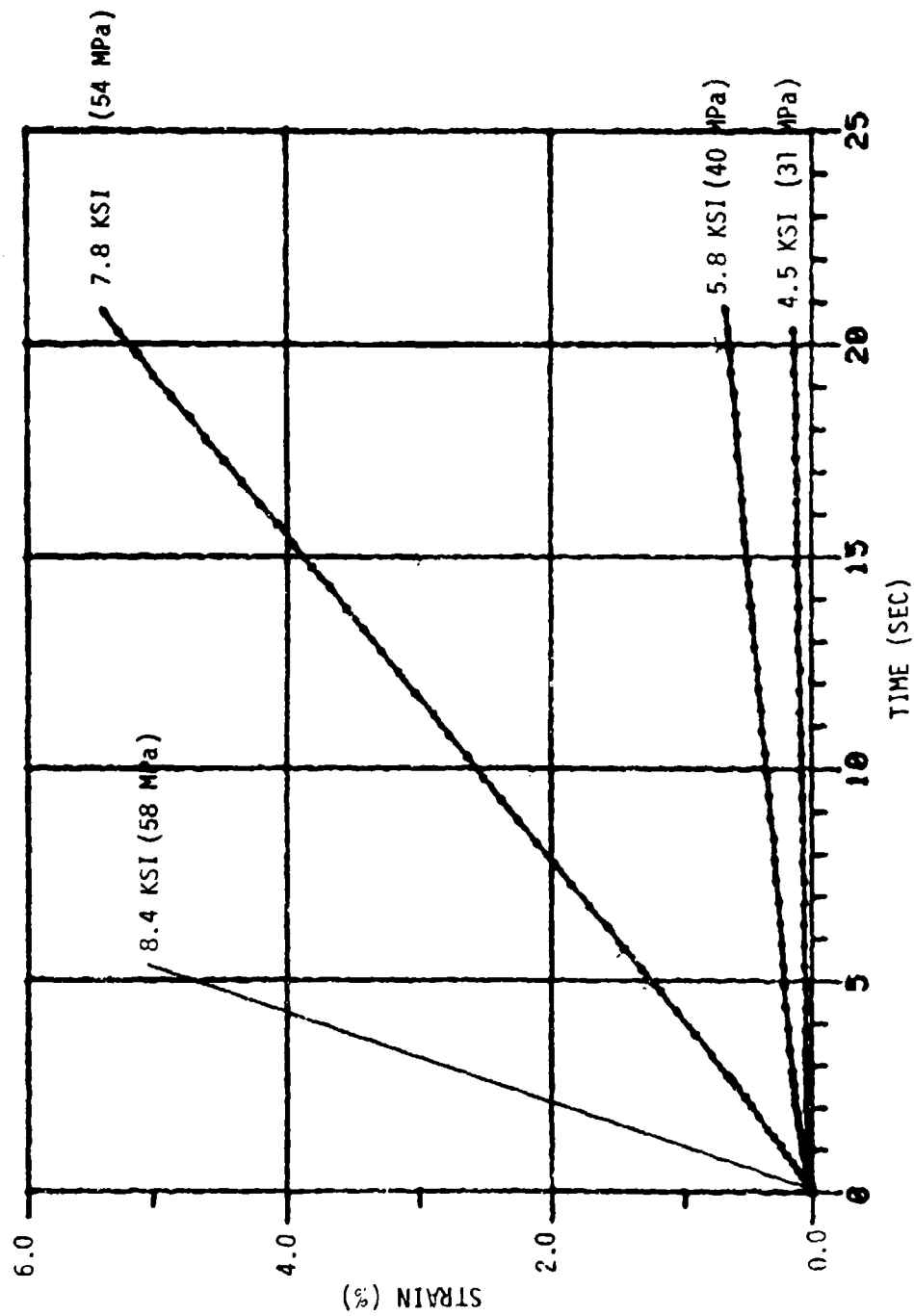Figure 22. CREEP STRAIN VS TIME - TEMP = 700°F (371°C)

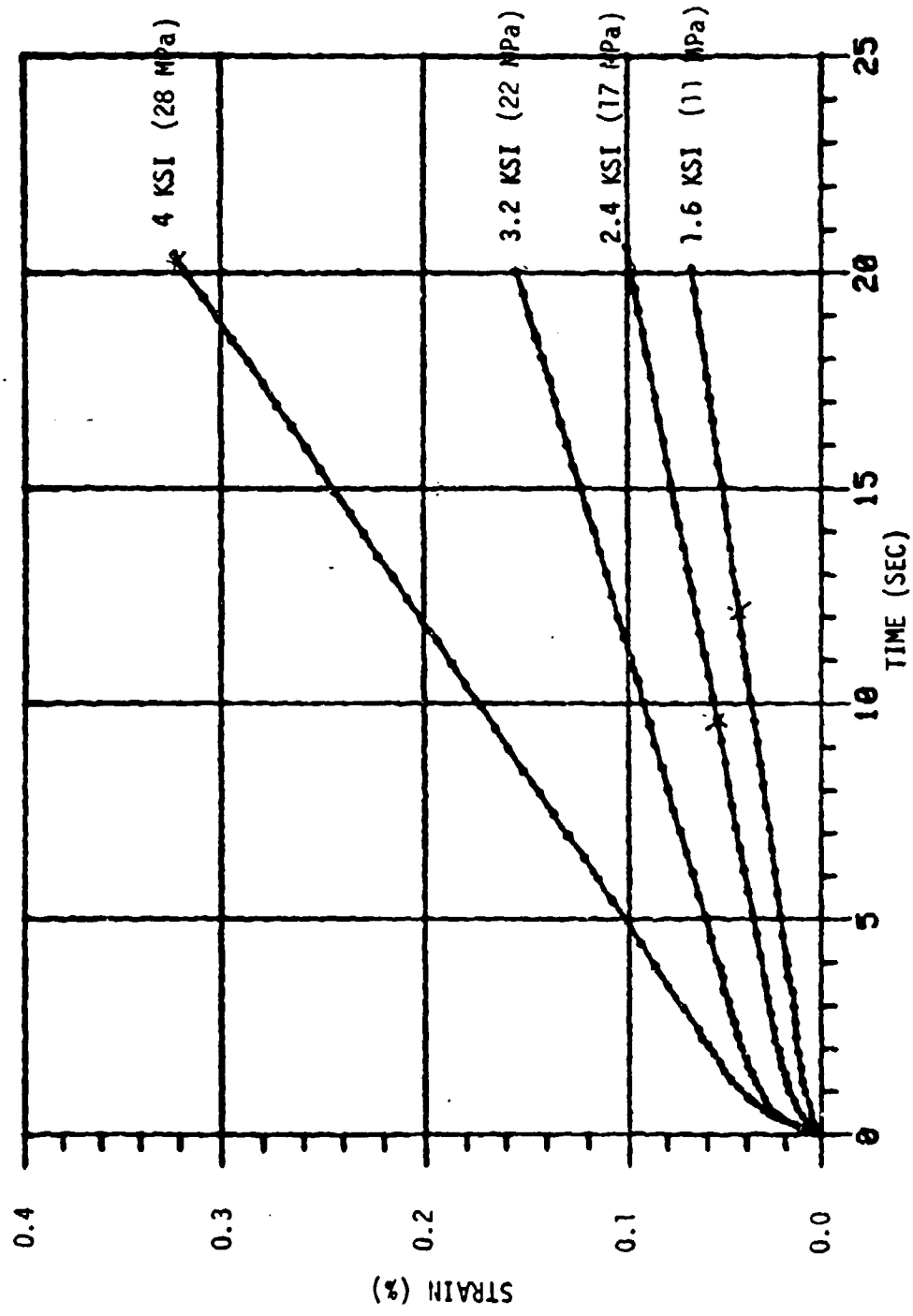Figure 23. CREEP STRAIN VS TIME – TEMP = 750°F (399°C)

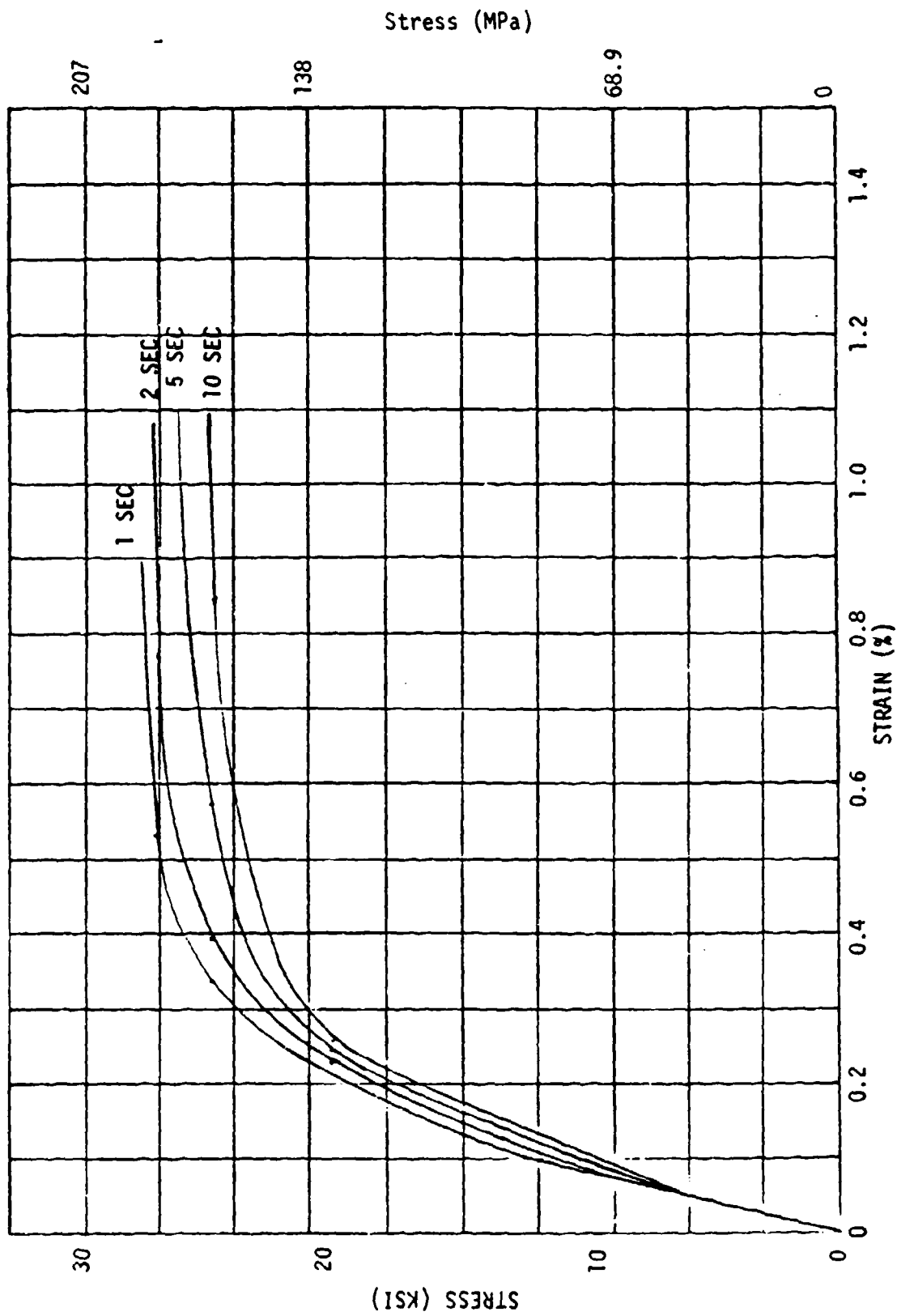Figure 24. CREEP STRAIN vs TIME – TEMP = 800°F (427°C)

Figure 25. ISOCHRONOUS STRESS/STRAIN CURVE – TEMP = 500°F (260°C)

Stress (MPa)

Figure 26. ISOCHRONOUS STRESS-STRAIN CURVE – TEMP = 600°F (316°C)

43

Stress (MPa)

103   62   21   0

STRAIN (%)

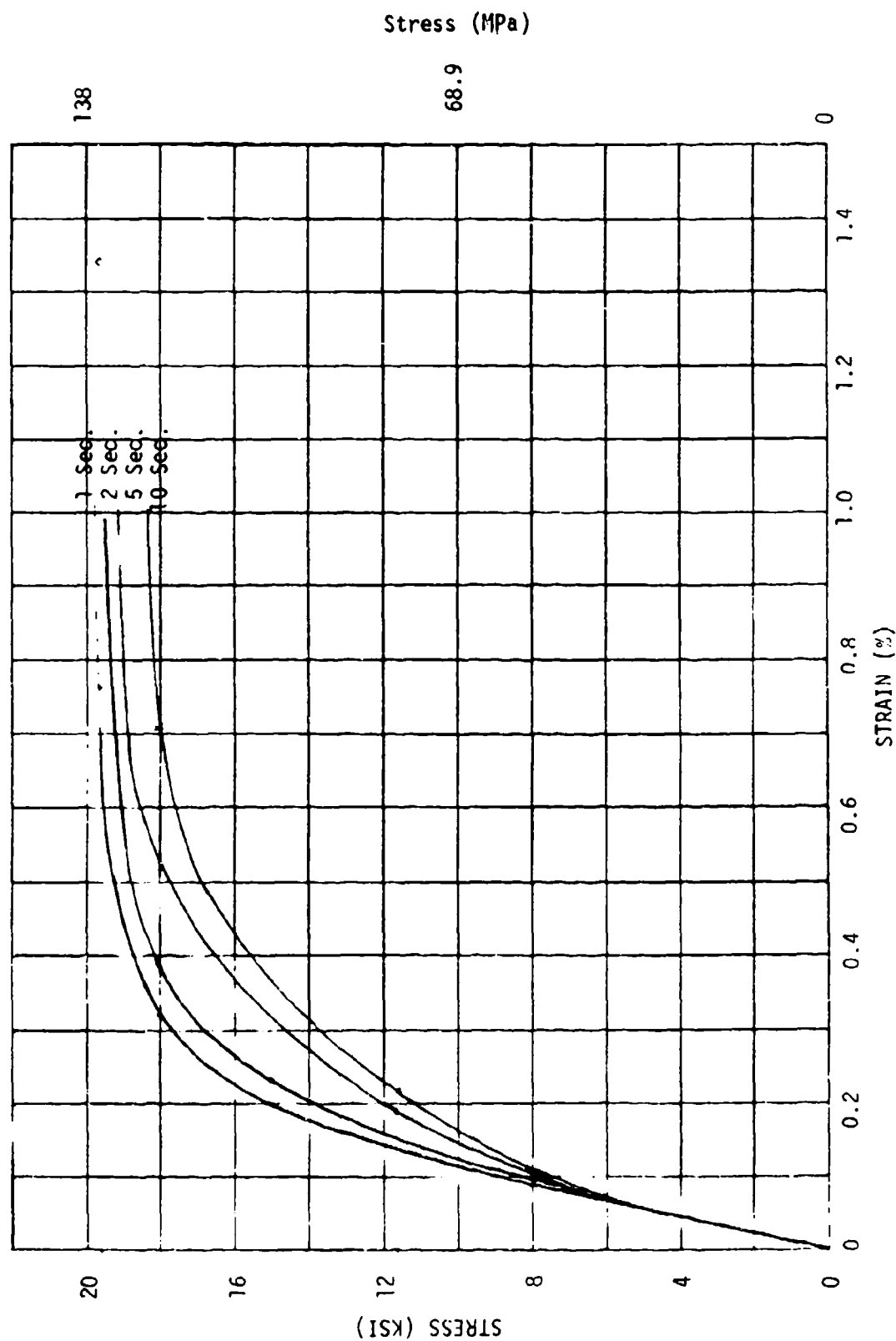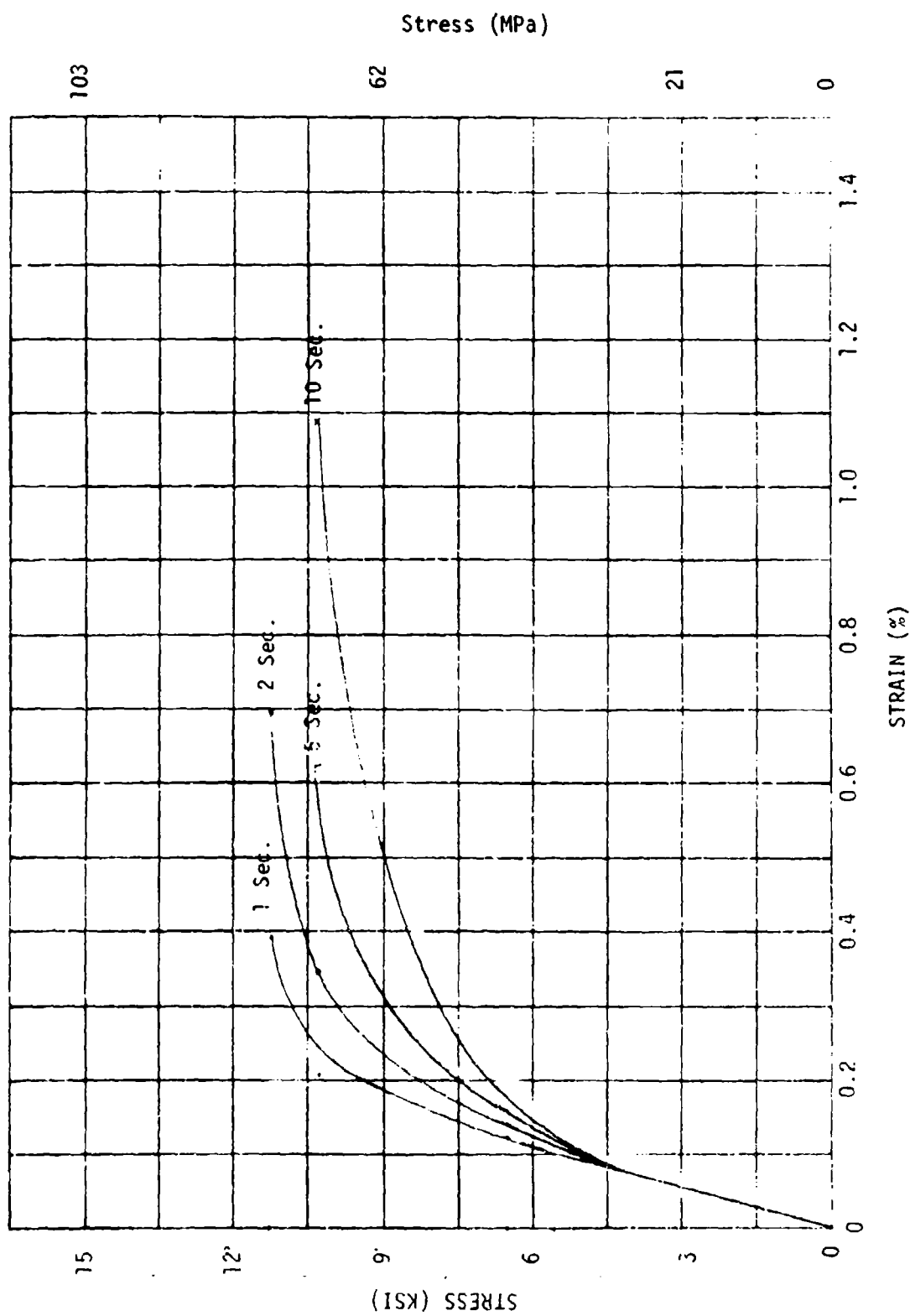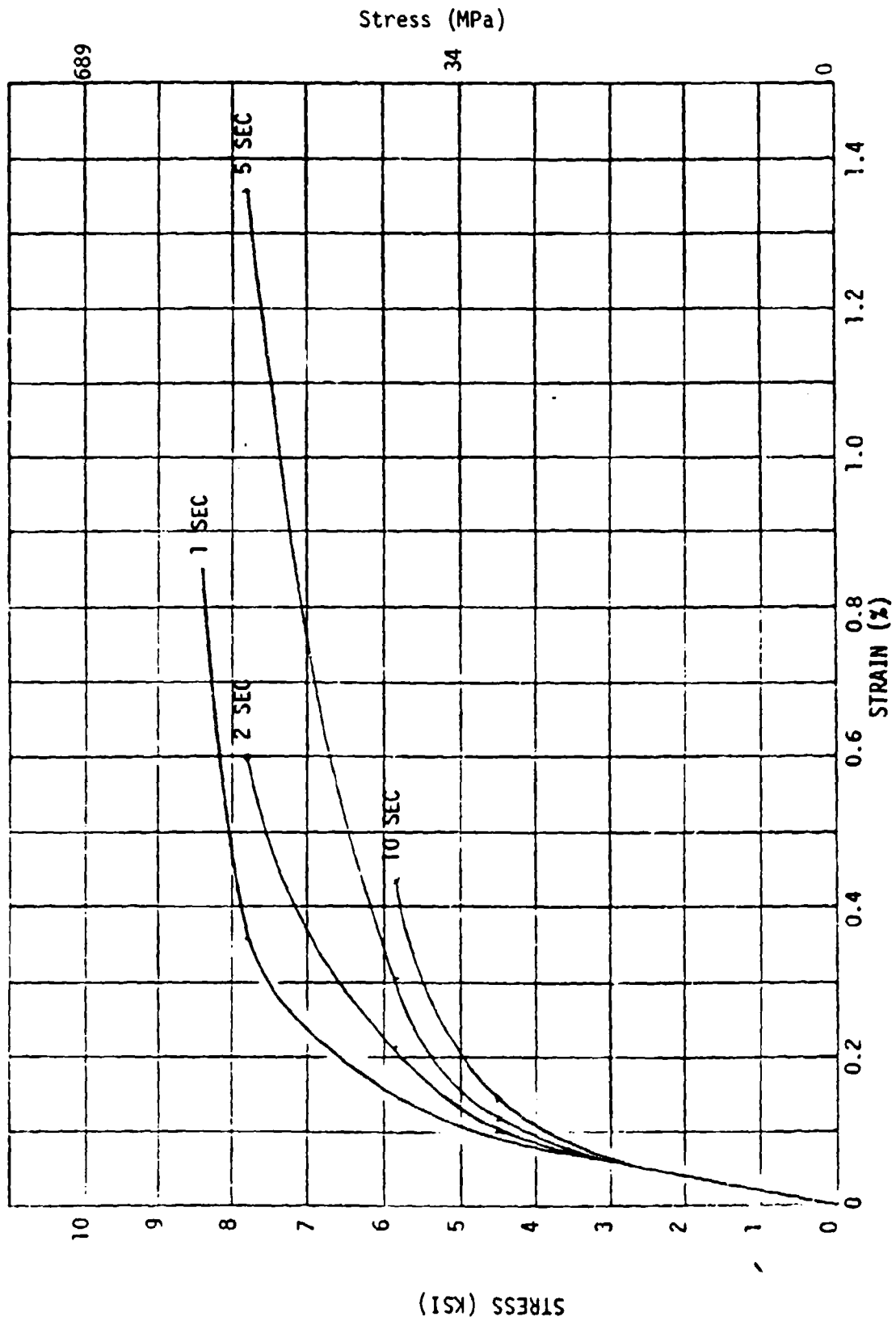Figure 27. ISOCHRONOUS STRESS-STRAIN CURVE - TEMP = 700°F (371°C)

STRESS (KSI)

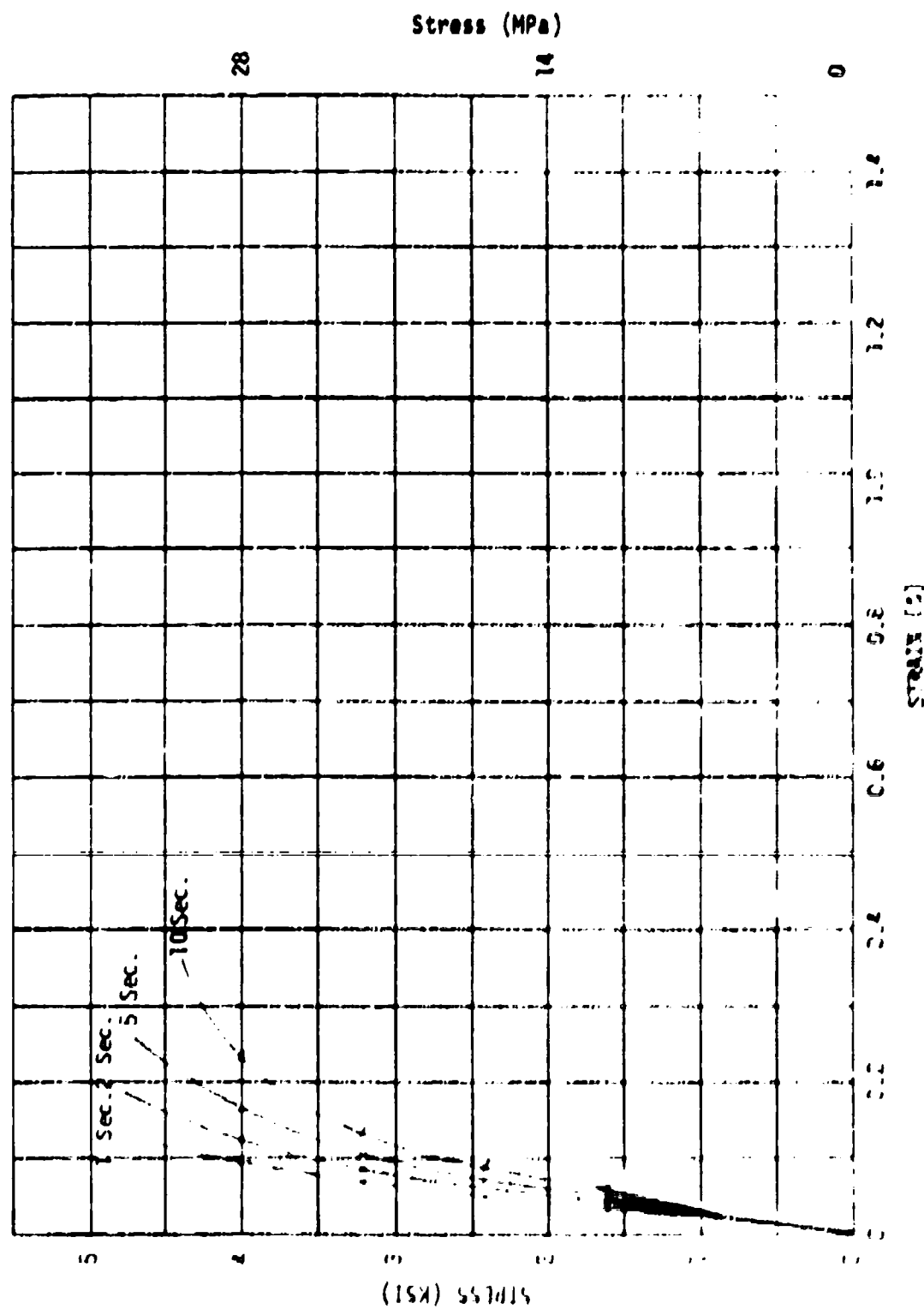Figure 28.   ISOCHRONOUS STRESS/STRAIN CURVE - TEMP = 750°F (399°C)

45

Figure 29. ISOCHRONOUS STRESS-STRAIN CURVE — TEMP = 800°F (427°C)

5.6 STRESS-STRAIN CURVE COMPARISON

The major fault in using either 10 second isochronous or standard* (Reference 6) stress-strain curves is that a substantial amount of time integrated creep strain is automatically built in. This can be easily seen by comparing the stress-strain temperature curves as shown in Figure 30. The first thing to notice is that the 10 second isochronous curves do not differ significantly from the standard curves, especially at temperatures above 500°F (260°C). However, these curves are substantially different than the "zero" time curves. For example, at 600°F (316°C) there is almost a factor of two difference in the maximum stress. One must not forget to add the appropriate creep strain to the "zero" time strain to get a precise comparison between stress-strain behavior, but this correction will become less significant as the time at temperature of the specimen is reduced. In the limit; i.e., as the specimen is instantaneously brought to temperature and load, the creep effect would vanish and the "zero" time data must be used.

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*Standard (handbook) curves are typically generated under low load rate (0.5% strain/minute)/long soak time (30 minutes) conditions.
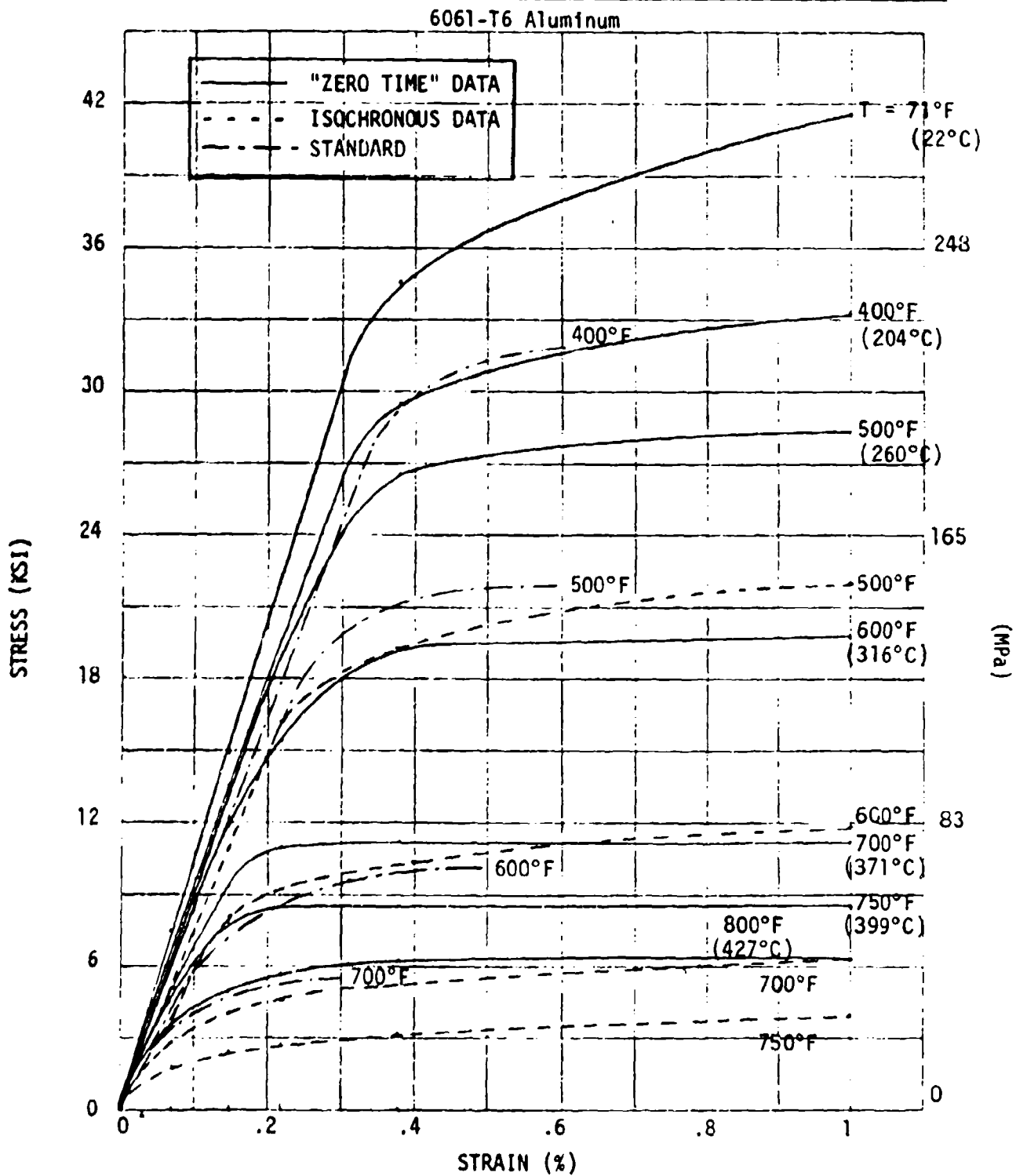
Figure 30.   STRESS/STRAIN CURVES: "ZERO TIME"/10 SEC ISOCHRONOUS/STANDARD

Section 6
SIMULATION EXPERIMENTS

A rapidly heated complex structure would experience a continuous redistribution
of temperature and stress due to heat flow and material property thermal
degradation. In order to have confidence in the ability of an analytical
procedure to predict the response of the structure, one could perform experi-
ments which simulate the important aspects of the structural response and then
compare the results with the analytical prediction. To this end, a series
of uniaxial simulation experiments were performed in which the load and temper-
ature histories were selected so as to cover the spectrum of the postulated load/
temperature histories in the actual rapidly heated structures. The test times
were slightly longer (<25 seconds) than the suggested 1-10 second rapid heating
times. These times were chosen so as to test the suitability of the creep
relation for longer times and so as to be able to reach 800°F (427°C) without
overstressing the experimental heating system. These experiments served three
important functions. The first was to demonstrate the ability to perform the
simulation experiments in a precisely controlled manner. The second was to
provide an experimental base which could be used in comparison with analytical
results. The third was to allow the investigation of material behavior as
influenced by various combinations of time varying stress and temperature.
This investigation ultimately would allow one to make an assessment of the
adequacy of existing and proposed material models.

The most general form of the load/temperature history is shown in Figure 31.
Notice that these forms allow, as special cases, all of the tests performed
in Section 5. Within this framework, 16 different types of tests were
performed in which the following conditions were enforced:
- Constant load and temperature rising with time
- Load and temperature rising with time
- Increasing load followed by decreasing load, temperature constant
- Increasing load followed by decreasing load, temperature rising
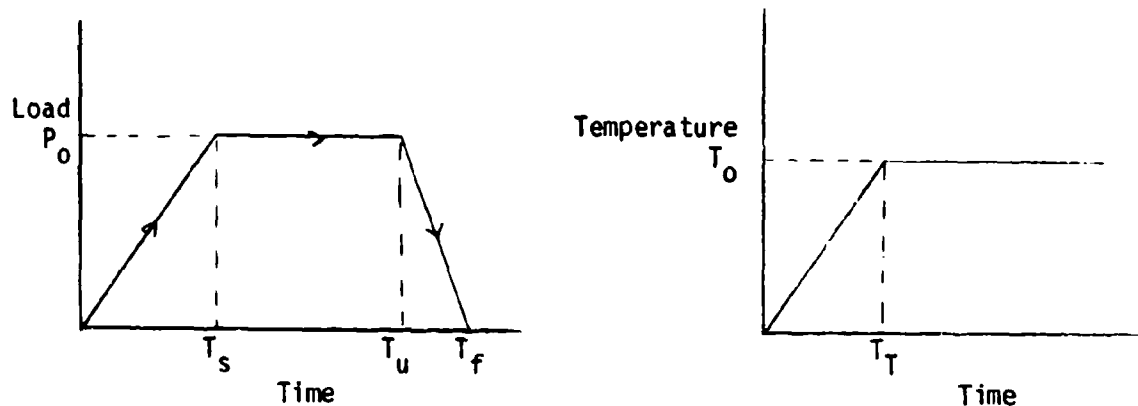with time.

49

Figure 31. Load/Temperature History Simulation Experiments

The following subsections will describe results from one example of each of
the above categories. The balance of results are plotted aginst the results
from the CREEPARHS analysis and are included in Appendix 1. A complete simulation
test matrix is given in Table 6. It will be seen that any combination of
thermal, mechanical and creep strain components can be the primary strain
response modes.

6.1 SIMULATION TEST - CONSTANT/LOAD TEMPERATURE

The strain versus time trace along with the stress-temperature-time histories
are shown in Figure 32. The strain is composed of free thermal expansion,
mechanical and creep components. From the stress-strain curves in Figure 19,
one can see that the mechanical strain is less than 0.1% until the temperature
exceeds 750°F (399°C). We thus see an almost linear rise in strain due to
thermal expansion until 18 seconds when the stress and temperature are constant.
This temperature/stress combination causes significant creep (Tertiary) from this
point on and in fact the specimen ultimately failed. In order to predict
the total behavior, one must account for tertiary creep in the analysis.

CONCLUSION: Thermal strain and tertiary creep are dominant modes.

6.2 SIMULATION TEST - LOAD/TEMPERATURE RISING WITH TIME

The strain versus time trace is shown in Figure 33. The strain is again composed
of thermal, mechanical and creep effects. The response is essentially linearly
elastic until one second when the maximum stress of 20 KSI (138 MPa) is acting.
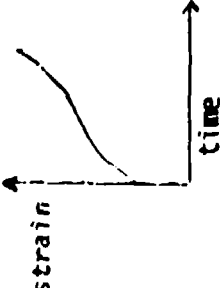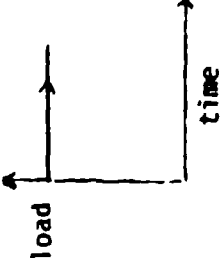
TEST TYPE	TEST #	INITIAL TEMP/ FINAL TEMP (°F/°C)	HEATING RATE (°F/SEC)	INITIAL STRESS/ MAX STRESS (KSI)/MPa	LOAD RATE (KSI/SEC)	STRESS REDUCED AT TIME (t=t_o)	STRESS REDUCED AT TIME (t=t_F)
Const. Stress/ Incr. Temp	67	(71/797) 22/425	39	(6/6) 41/41	-	-	-
	68	(71/800) 22/427	39.6	(3/3) 21/21	-	-	-
	69	(71/595) 22/313	40.3	(20.3/20.3) 140/140	-	-	-
	70	(71/595) 22/313	39.1	(10/10) 69/69	-	-	-

strain ↑ time →   =   load ↑ time →   +   temp ↑ time →

Table 6.1. Simulation Parameters - Constant Load /Increasing Temperature
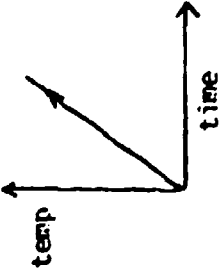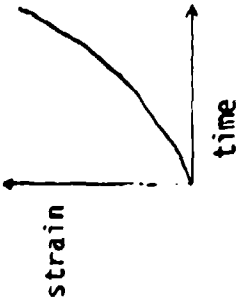
51

TEST TYPE	TEST #	INITIAL TEMP/ FINAL TEMP (°F)/°C	HEATING RATE (°F/SEC)	INITIAL STRESS/ MAX STRESS (KSI)/MPa	LOAD RATE (KSI/SEC)/ MPa/Sec	STRESS REDUCED AT TIME $(t=t_o)$	STRESS REDUCED AT TIME $(t=t_F)$
Incr. Stress/ Incr. Temp	71	(71/795) 22/424	39.6	(0/6) 0/41	5/34	-	-
Incr. Stress/ Incr. Temp	72	(71/798) 22/426	37.9	(0/6) 0/41	0.34/2	-	-
Incr. Stress/ Incr. Temp	73	(71/605) 22/318	38.5	(0/19.5) 0/134	19.5/132	-	-
Incr. Stress/ Incr. Temp	74	(71/603) 22/317	41.6	(0/20.0) 0/138	2.1/14	-	-

Table 6.2. Simulation Parameters - Increasing Load /Increasing Temperature

Table 6.3. Simulation Parameters - Increasing-Decreasing Load/Constant Temperature
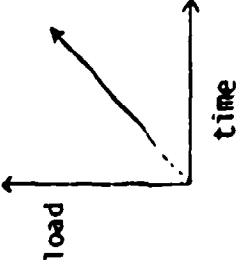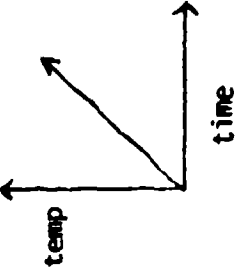
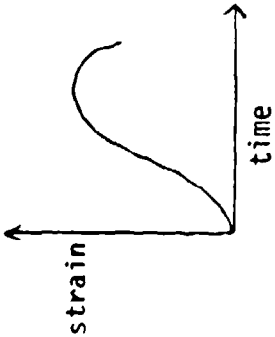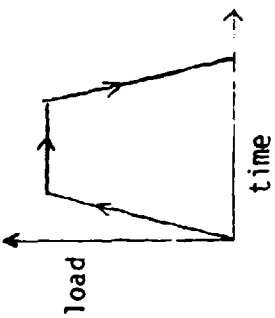| TEST TYPE	TEST #	INITIAL TEMP/ FINAL TEMP (°F)/°C	HEATING RATE (°F/SEC)	INITIAL STRESS/ MAX STRESS (KSI)/MPa	LOAD RATE (KSI/SEC)/ MPa/Sec.	STRESS REDUCED AT TIME (t=t$_o$)	STRESS REDUCED AT TIME (t=t$_F$)
Incr. Stress/ Decr. Stress/ Const. Temp	80	(706/706) 374/374	0	(0/9.8) 0/68	5.2/36	17.9	19.8
	81	(701/701) 372/372	0	(0/10) 0/69	1/7	9.5	18.9
	82	(510/510) 266/266	0	(0/24.3) 0/16	10.1/70	17.4	19.8
	83	(512/512) 267/267	0	(0/24.3) 0/167	2.6/18	9.5	19

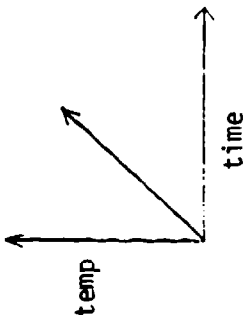| TEST TYPE	TEST #	INITIAL TEMP/ FINAL TEMP (°F)/°C	HEATING RATE (°F/SEC)	INITIAL STRESS/ MAX STRESS (KSI)/MPa	LOAD RATE (KSI/SEC)/ MPa/SEC	STRESS REDUCED AT TIME $(t=t_0)$	STRESS ZERO AT TIME $(t=t_F)$
Incr. Stress/ Decr. Stress/ Incr. Temp	77	(71/795) 22/424	38.9	(0/5) 0/34	2.1/14.5	17.4	19.8
	79	(71/798) 22/426	39.8	(0/5) 0/34	0.53/3.7	9.5	19.0
	84	(71/500) 22/260	38.5	(0/24.2) 0/167	12.4/85.4	10.45	12.35
	85	(71/501) 22/261	38.7	(0/24.3) 0/167	4.1/28.2	5.9	11.8

strain

=

load + temp

time   time   time

Table 6.4. Simulation Parameters - Increasing-Decreasing Load /Increasing Temperature
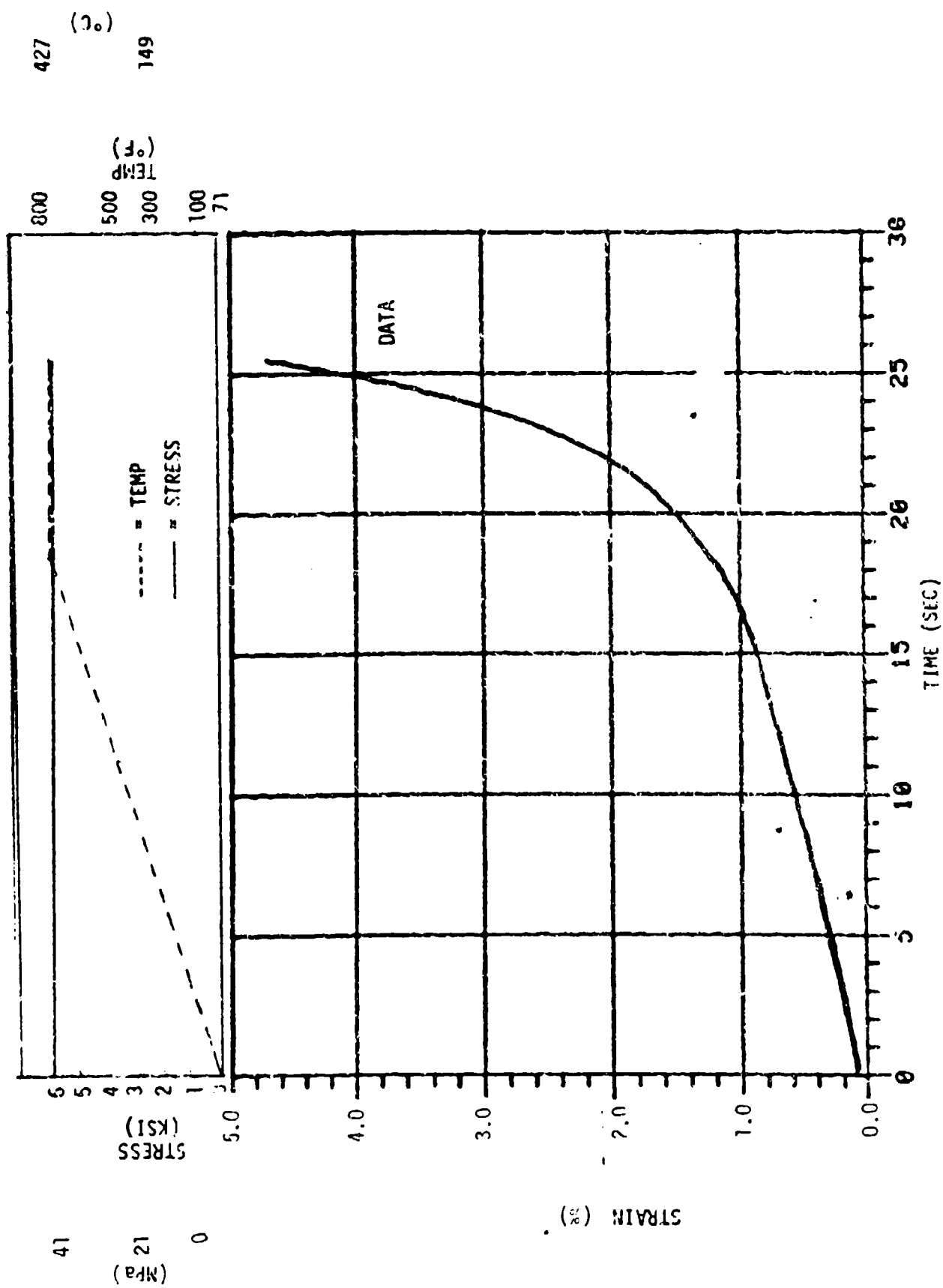
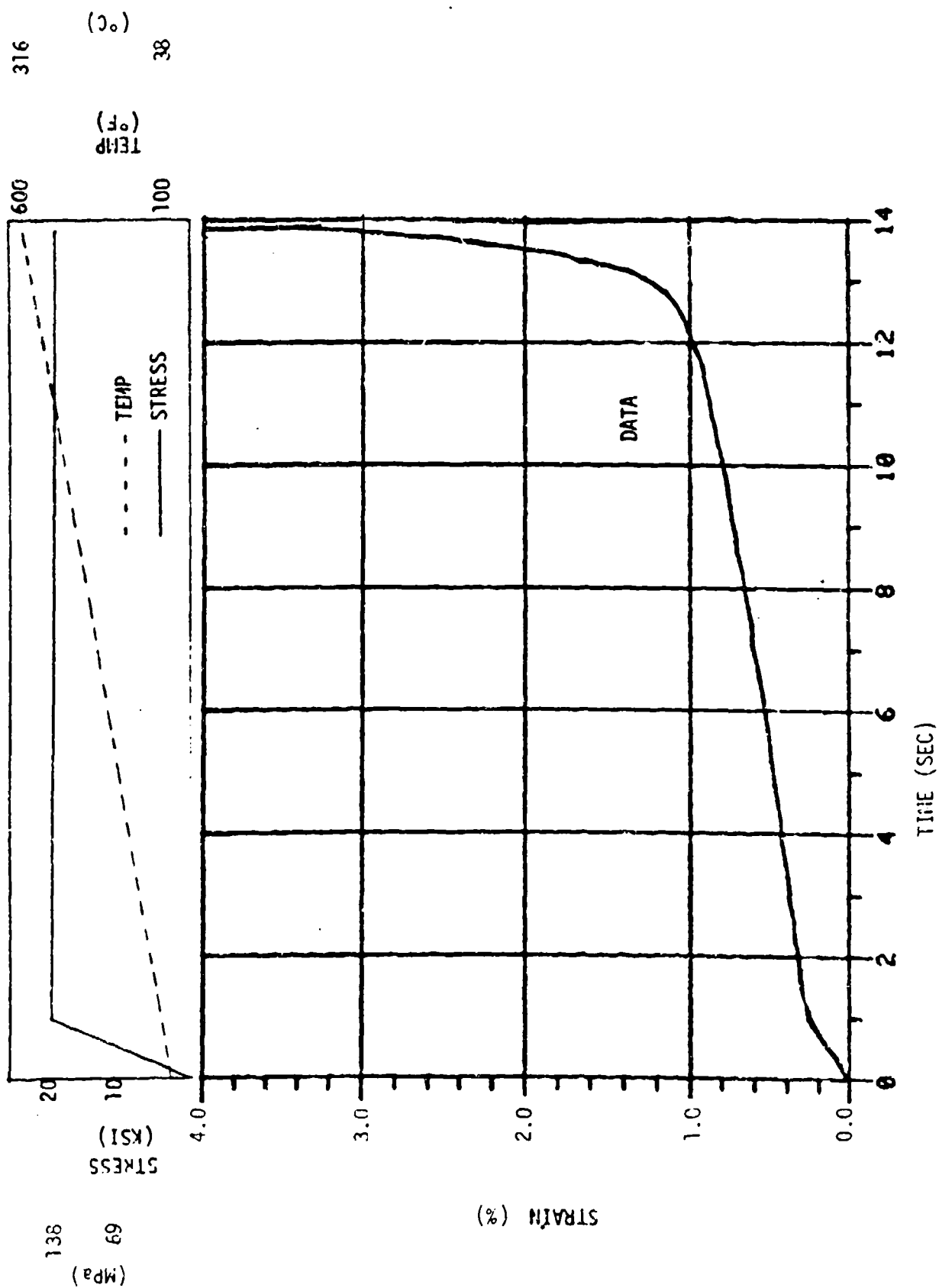Figure 32. Simulation Test 67 Constant Load/Increasing Temp

Figure 33. Simulation Test 73 Load Increasing – Temp Increasing

From Figure 19 one can see that the response is elastic for 20 KSI (138 MPa) stress until the temperature exceeds 500°F (260°C). This is seen in Figure 33 as the thermal and elastic strain increase almost linearly until 12 seconds have elapsed. As the temperature exceeds 500°F (260°C), the maximum allowable stress at temperature is exceeded and the specimen rapidly fails due to plastic and creep strain.

CONCLUSION: Thermal strain and plastic strain are dominant modes.

6.3 SIMULATION TEST - LOAD-INCREASING, DECREASING/TEMPERATURE CONSTANT

This is the first example of a case where unloading occurs. The thermal strain has [due to constant temperature at 500°F (260°C)] been subtracted out of the strain-time history and the results are shown in Figure 34. From Figure 19, one can see that the stress is always in the elastic range. The nonlinear behavior seen in Figure 34 in the seven to ten second time interval must be due to creep. One also notices that unloading causes a linear reduction in strain. Finally, a permanent component of strain remains after the load has dropped to zero.

CONCLUSION: Elastic and creep strain are dominant modes.

6.4 SIMULATION TEST - LOAN-INCREASING, CONSTANT, DECREASING/TEMPERATURE
     INCREASING

This is the final and most complicated example. Note in Figure 35 that the maximum stress and temperatures are the same as in the previous example but the strain versus time history is very different. The strain is composed of elastic, thermal and creep components in this case   The creep component plays a small role due to the fact the temperature does not rise sufficiently until the end of the test. One can see a linear increase in elastic strain until two seconds have elapsed. The strain increases due to thermal effects until approximately 11 seconds when the load is reduced to zero. The strain reduces linearly and only the thermal and a small creep component remain.

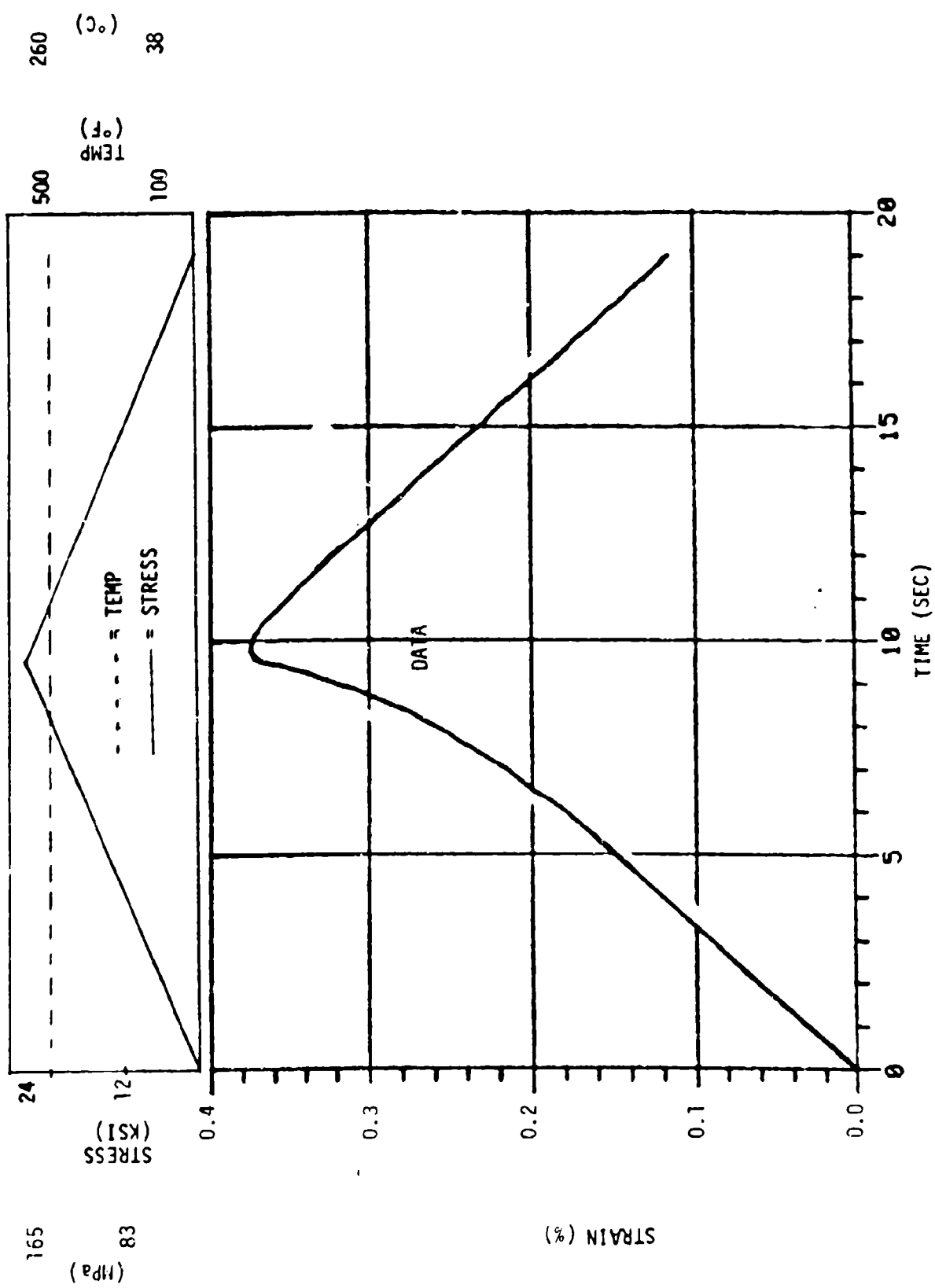CONCLUSION: Elastic and thermal strain are dominant modes.

Figure 34. Simulation Test 63 Load (Increasing/Decreasing) -
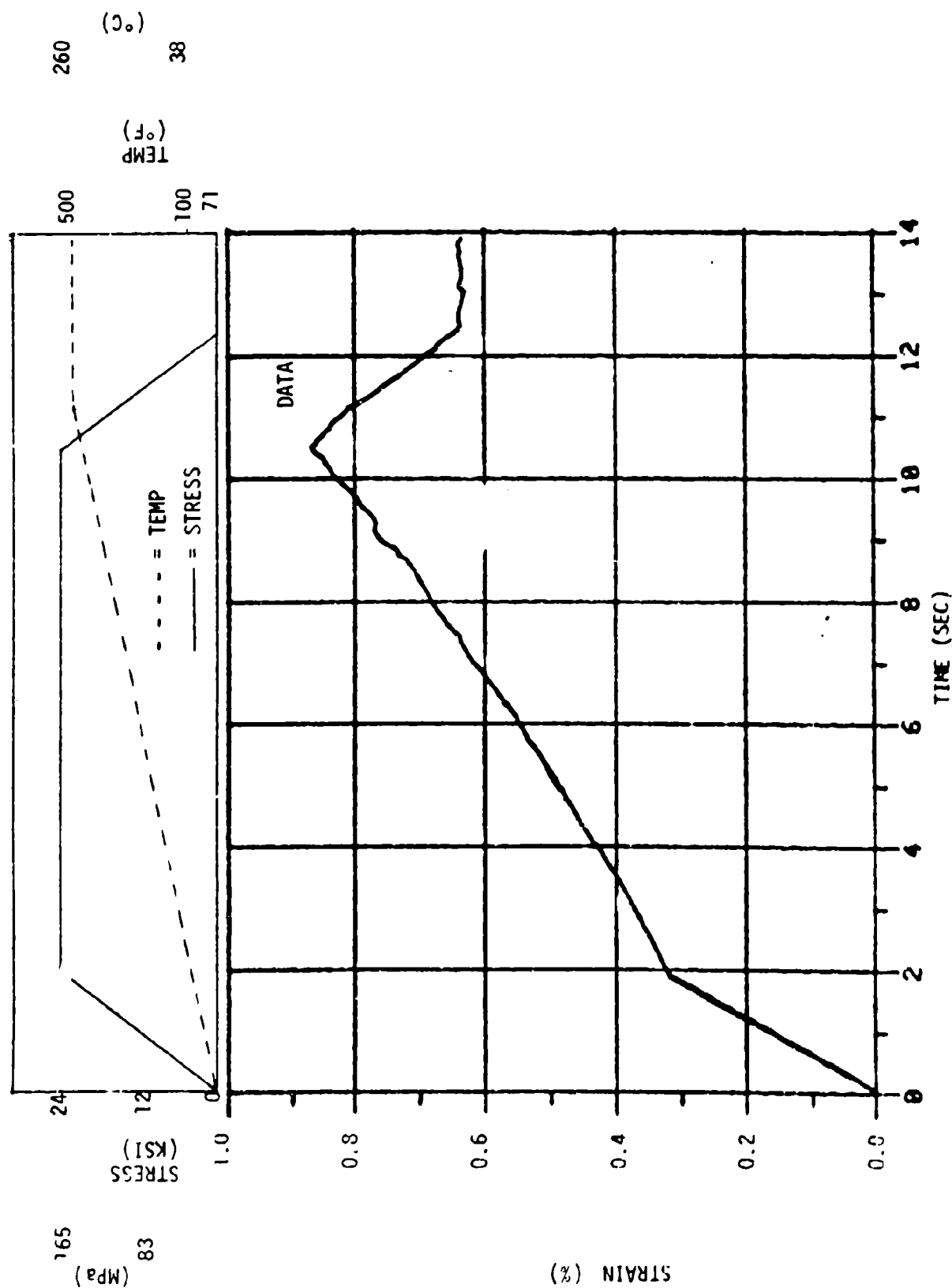Temp Constant

Figure 35. Simulation Test 34 Load (Increasing/Constant/Decreasing) - Temp Increasing

Section 7
ANALYSIS AND EXPERIMENT - CORRELATION

This section will describe the results that were obtained from the correlation
analysis and compare those results with the results from the simulation exper-
iments. In particular, four examples of the CREEPARHS versus test data
comparison (one for each general category of test) will be discussed. The
difference in results obtained by using "zero" time data and 10 second
isochronous data will be demonstrated. A comparison of the results obtained
for MARC, ANSYS and CREEPARHS will be made for two of the above mentioned
problems.

7.1 STRUCTURAL CODE "USABILITY"

It is appropriate to state at the outset that the general purpose nonlinear
codes such as MARC and ANSYS are not practical for use in investigating the
response of a structure to many combinations of thermal and mechanical applied
load states. The codes are expensive to use (as will be seen) for even the
simplest of problems. In many cases, the dominant physics of the problem are
obscurred due to the "black box" approach used in the codes, and it is
precisely an understanding of these physics that offers one the opportunity to
gain an understanding of the effects of the material behavior on the response
of a structure.

An additional and ever more serious problem is that general purpose codes may
not be error free. It is our experience that the H.2 version of MARC has
"bugs" in the routines which allow the calculation of plastic strain. These
"bugs" have been corrected in the H.4 revision. Further, we found that the
revision 3 update 37 version of ANSYS has problems in calculating the
temperature dependent stiffness for the first element in any model. A method
of circumventing the problem allows the use of this version in the current
study. For these reasons, it was decided to develop a simple one-dimensional
code CREEPARHS which could perform the required simulation analysis. The
majority of the analysis was performed using this code.

7.2 MATERIAL PROPERTY MODEL FOR TENSILE SPECIMEN

The tensile specimen used in the simulation experiments can be characterized by a one-dimensional stress state. The quantity of interest which was measured in the experiments was the extensional strain as a function of time. The total strain can be decomposed into elastic, plastic, thermal and creep components as shown in equation 1.

$$\epsilon = \epsilon_E \, (\sigma,t) + \epsilon_p(T,t) + \epsilon_{TH}(T) + \epsilon_{cr}(\sigma,T,t) \tag{1}$$

where

ϵ_E = elastic strain

ϵ_p = plastic (time independent strain)

ϵ_{TH} = thermal strain

ϵ_{cr} = creep strain

and σ, T, t are applied stress, temperature, and time.

The elastic component can be rewritten as

$$\epsilon_E = \frac{\sigma}{E(T)} \tag{2}$$

where $E(T)$ is the elastic temperature dependent Young's modulus. The elastic modulus is tabulated as a function of temperature and a linear interpolation scheme is used to calculate a value at any intermediate temperature.

The plastic component can be represented by a series of multilinear, stress-plastic strain curves. Each curve corresponds to a different temperature. Linear interpolation is used to calculate the strain for intermediate values of temperature.

The thermal component can be written as

$$\epsilon_{TH} = \alpha(t) \, T$$

where

α = thermal expansion coefficient = integrated thermal strain between room temperature and temperature T divided by the temperature T. A table of temperature-dependent thermal expansion coefficients is then compiled and an interpolation scheme used for intermediate values.

The creep strain can be written in a functional form which has the following properties:

    1. Approximates short time creep behavior in primary and tertiary stages.

    2. Allows simple calculation of coefficients using analytic as opposed to hand reduction techniques.

    3. Matches the form of the creep equations which are either built in or can be added to general purpose codes.

The most general form of the relationship is given in Equation 3.

$$\varepsilon_{cr} = \underbrace{A_0\ [1-\exp(-A_1 t)]\ \exp(-A_2/T)\sigma^{A_3}}_{\text{(primary)}} + \underbrace{B_0(t^{B_1})\exp(-B_2/T)\sigma^{B_3}}_{\text{("generalized" secondary)}} \qquad (3)$$

where

    A_0, A_1, A_2, A_3, B_0, B_1, B_2, and B_3 are constants.

It was found that little was gained by fitting the data to both primary and "generalized" secondary portions of Equation 3. Thus, the "generalized" secondary relationship was adopted. The data from the curves in Figures 20-24 was fit to Equation 3 using a multiple linear regression procedure as outlined below and described in References 7 and 8.

$$\text{Given } \varepsilon_{cr} = B_0 t^{B_1} \exp\ (-B_2/T)\sigma^{B_3} \qquad (4)$$

then

$$\ln \varepsilon_{cr} = \ln\ (B_0) + B_1 \ln(t) - B_2/T + B_3 \ln\ (\sigma) \qquad (5)$$

Define for each data point (i) in each creep strain curve

$$\overline{\varepsilon}^i_{cr} = \ln \varepsilon_{cr}^i$$

$$\overline{B}_0 = \ln\ (B_0),\ F_i^{\ 1} = \ln(t_i)\ F_i^{\ 2} = -\ 1/T_i,\ F_i^{\ 3} = \ln(\sigma_i) \qquad (6)$$

then the following system of algebraic equations can be solved for the unknowns,

    $\overline{B}_0$, B_1, B_2, B_3

$$\sum_{i=1}^{n} \bar{\epsilon}_{cr}^{\;i} = \bar{B}_0 N + B_1 \sum_{i=1}^{n} F_i^1 + B_2 \sum_{i=1}^{n} F_i^2 + {}^{n} F_i^3$$

$$\sum_{i=1}^{n} \bar{\epsilon}_{cr}^{\;i} F_i^1 = \bar{B}_0 \sum_{i=1}^{n} F_i^1 + B_1 \sum_{i=1}^{n} F_i^1 F_i^1 + B_2 \sum_{i-1}^{n} F_i^1 F_i^2 + B_3 \sum_{i-1}^{n} F_i^1 F_i^3$$

$$\sum_{i=1}^{n} \bar{\epsilon}_{cr}^{\;i} F_i^2 = \bar{B}_0 \sum_{i=1}^{n} F_i^2 = B_1 \sum_{i=1}^{n} F_i^1 F_i^2 + B_2 \sum_{i=1}^{n} F_i^2 F_i^2 + B_3 \sum_{i=1}^{n} F_i^2 F_i^3$$

$$\sum_{i=1}^{n} \bar{\epsilon}_{cr}^{\;i} F_i^3 = \bar{B}_0 \sum_{i=1}^{n} F_i^3 + B_1 \sum_{i=1}^{n} F_i^1 F_i^3 + B_2 \sum_{i=1}^{n} F_i^2 F_i^3 + B_3 \sum_{i=1}^{n} F_i^3 F_i^3$$

(no sum on i)

In principal, a whole series of equations such as Equation 4 could be developed, each corresponding to a particular temperature and stress. In order to calculate creep strain for intermediate values of stress and temperature, one can interpolate between curves. This procedure would most likely give better results in the simulation analysis. A single master equation can only give least square type averaged values of creep strain. Unfortunately, many codes, including ANSYS, do not allow for multiple creep equation entry and thus the single equation approach was taken.

In order to calculate the total strain at any point in time, one must add all of the increments in strain up to that point in time. If $d\epsilon_{total}$ is the incremental change in strain between time t and time t + Δt, then the total strain at time t_0 is given by Equation 7.

$$\epsilon_{total}\Big|_{t=t_0} = \int_0^t d\epsilon_{total} + \epsilon_{total} \text{ (initial)} \tag{7}$$

Theoretically, one could evaluate Equation 7 exactly, given analytical forms of the stress and temperature histories. In practice it is much more convenient to simply evaluate the total strain by numerically stepping through time in an incremental fashion. This is the procedure used in MARC, ANSYS and CREEPARHS. In particular, one calculates the stress and temperature at

a specific point in time. This allows direct calculation of the elastic and
thermal strain. If the particular combination of temperature and stress
imply a loading state with respect to the previous state, then one can move
up the plastic stress-strain curve and calculate the plastic strain.

If the new temperature and stress state imply unloading, then the incremental
change in plastic strain is zero and one unloads elastically. The calculation
of the creep strain requires the adoption of a particular hardening rule.
That is, one must prescribe how the creep strain rate depends on the creep
strain, temperature, etc. A "time-hardening" rule was selected both for the
sake of convenience and because this rule is thought effective when the
material is subject to temperatures near melt (Reference 5). In accordance
with the time hardening hypothesis, the creep strain rate at any time and
stress/temperature level is assumed not to depend upon the current value of
creep strain. If the stress/temperature is changed from σ_1/T_1 to σ_2/T_2 at
time t_2, the creep rate is determined at point (B) (Figure 36). Then the
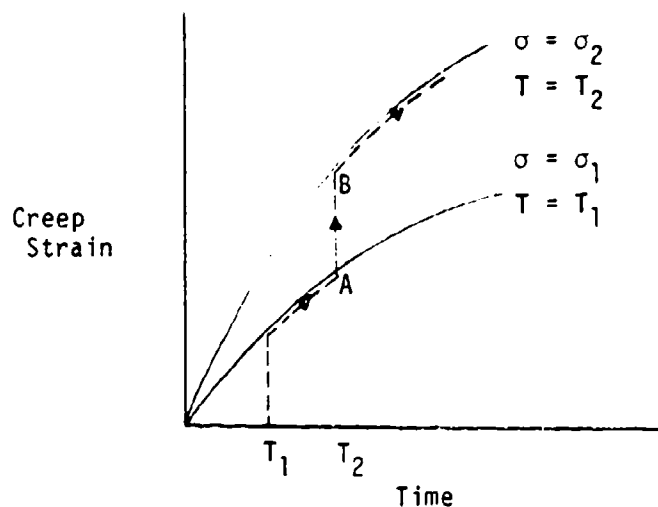creep rate is found from Equation 8.

Figure 36. Creep Strain - Time Hardening Rule

Function $(\varepsilon_{cr}, T, \sigma, t) = 0$ (8)

Using Equation 3 it can be shown (Reference 9) that the creep strain rate is given by Equation 9.

$$\dot{\varepsilon}_{cr} = [A_0 A_1 \exp(-A_1 t) \exp(-A_2/T) \sigma^{A_3} + B_0 B_1 t^{B_1-1} \exp(-B_2/T)\sigma^{B_3}] \quad (9)$$

The creep strain at any point in time t_1 is given by Equation 10.

$$\varepsilon_{cr}^1 = \Sigma\Delta \dot{\varepsilon}_{cr}(t_n) * (t_n - t_{n-1}) \quad (10)$$

Note that delayed creep recovery effects are not included in the model because it is thought that the time scale of the delayed effects is long compared to the time considered in the current problems.

7.3 CODE-MATERIAL DATA INPUT
The specific material property data which was input into MARC, ANSYS and CREEPARHS consisted of the following:

1. Thermal stress versus temperature
2. Piecewise linear stress-strain curves (Figures 37 and 38)
3. Master creep strain curve (Equation 11)

$$\Delta\varepsilon_{cr} = B_0 B_1 t^{(B_1 - 1)} \exp(-B_2/T)\sigma^{B_3} \Delta t \quad (11)$$

where

$$B_0 = 1.975 \times 10^{-6}$$

$$B_1 = 0.7056$$

$$B_2 = 1.273 \times 10^4 \ (^oRankine)$$

$$B_3 = 2.836$$

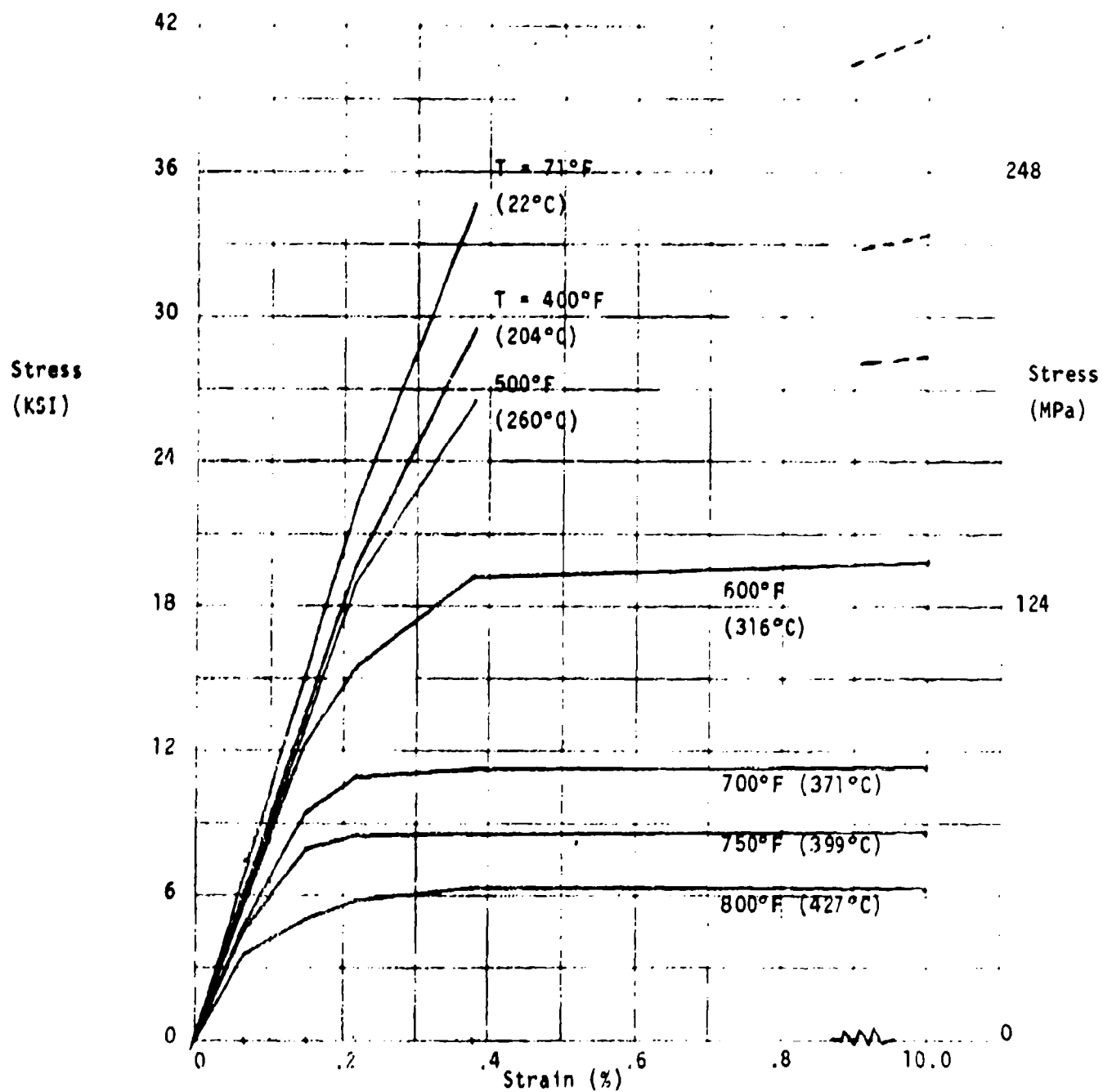An excellent summary of existing creep material property data can be found in Reference 10.

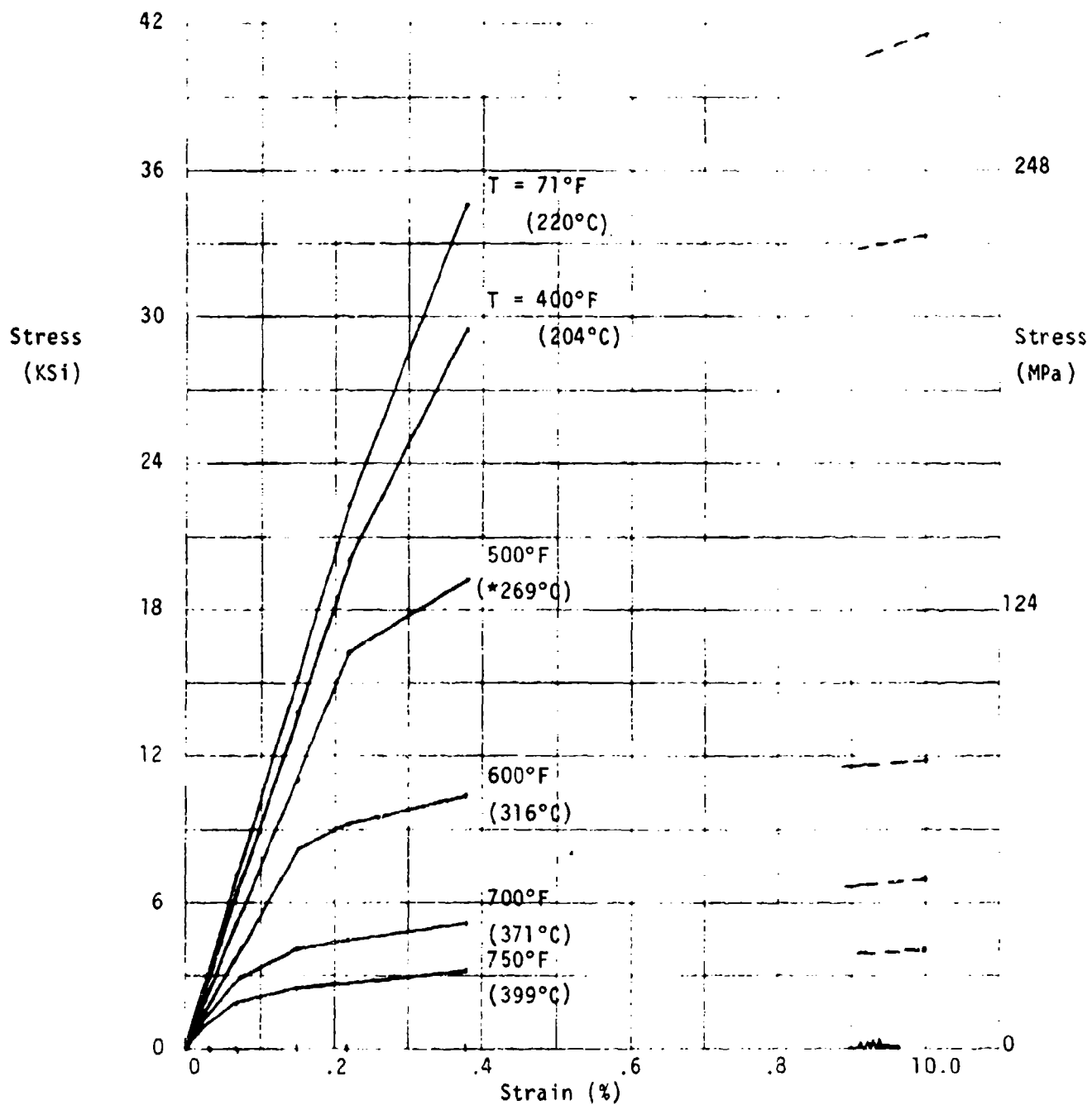Figure 37.   Stress/Strain Input - "Zero" time data

Figure 38. Stress/Strain Input - 10 Second Isochronous Data

7.4 ANALYSIS VERSUS SIMULATION TESTS - CREEPARHS CODE

The strain versus time history as predicted by the CREEPARHS code based upon the use of "zero" time + creep data is plotted against the results from the simulation experiments in Figures 39, 41, 43 and 45. The temperature and loading versus time are shown at the top of the figure.

A 0.25 second time step was used for the creep analysis in Figures 39, 41, 43 and 45. In addition, the predicted curves are broken down into thermal, mechanical and creep components so as to illustrate their relative contributions. Similarly, the strain versus time histories based upon 10 second isochronous data is shown in Figures 40, 42, 44 and 46.

The simplest load temperature history leads to monotonically increasing strain with time as is seen in Figure 39. The analysis predicts a response which is in excellent agreement with the experiment until 21 seconds when tertiary creep leads to ultimate specimen failure. A more refined creep model is obviously needed for this analysis. Examination of Figure 40 where 10 second isochronous data is used shows fair correlation through 15 seconds. This is a result of the fact that thermal strain is dominant until 20 seconds when creep failure occurs.

As the load-temperature history becomes more complicated, the demands on the material models become more stringent. The results from such an experiment are shown in Figure 41. Again, the correlation is encouraging. In this case, the creep is insignificant and a failure due to essentially time independent strain occurs. Figure 42 shows the predicted response when the isochronous data are used. The analysis breaks down at 11 seconds because of the inability of the stress-strain curves to model the plastic strain at the given stress and temperature.

A more realistic simulation of an actual rapid heating problem would include stress unloading due to material property thermal degradation. If one assumes that the material unloads elastically, then any residual strain would be due to permanent plasticity and creep. The results presented in Figure 43 illustrate the importance of accounting for creep strain in a problem where
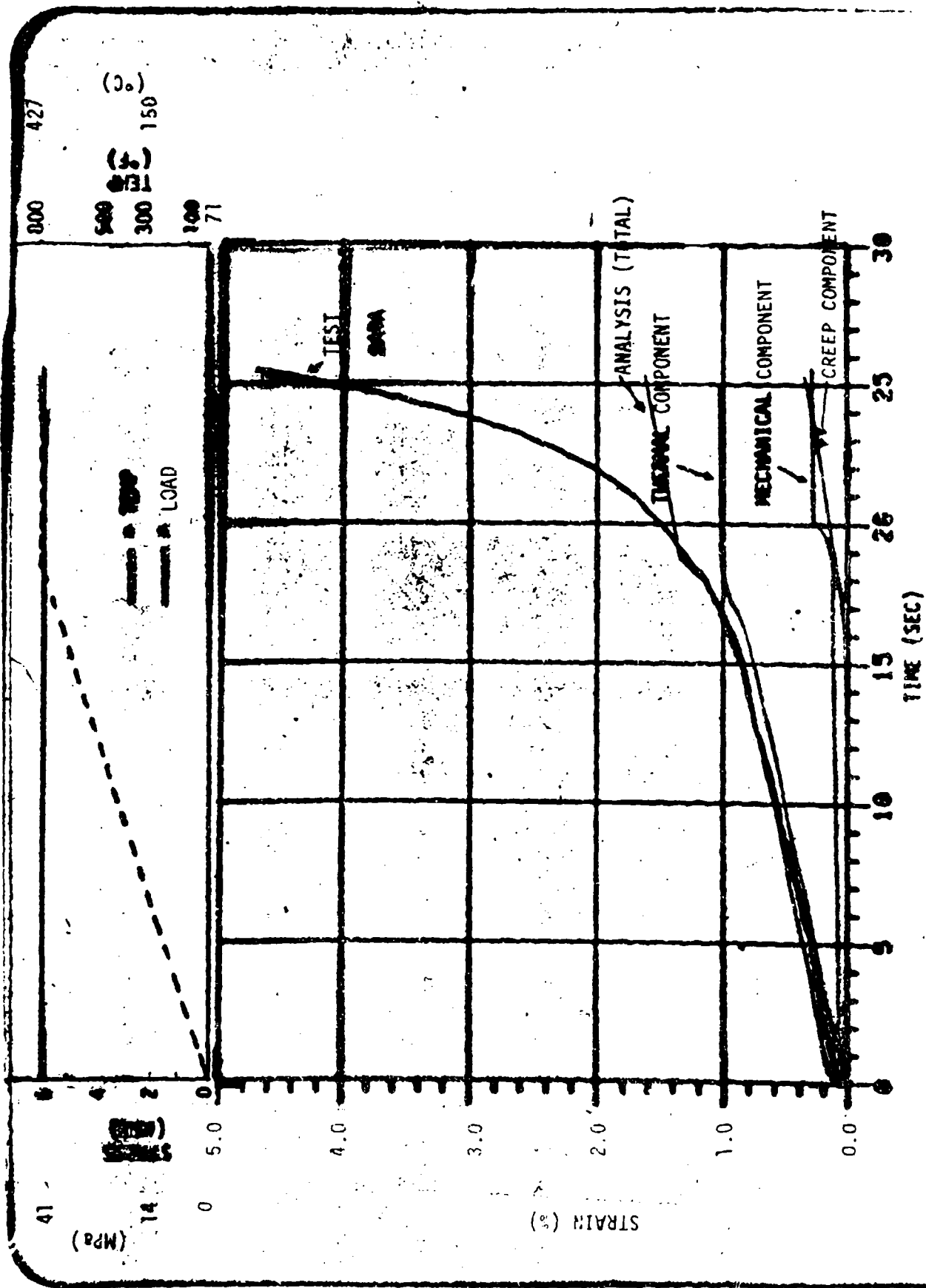
68

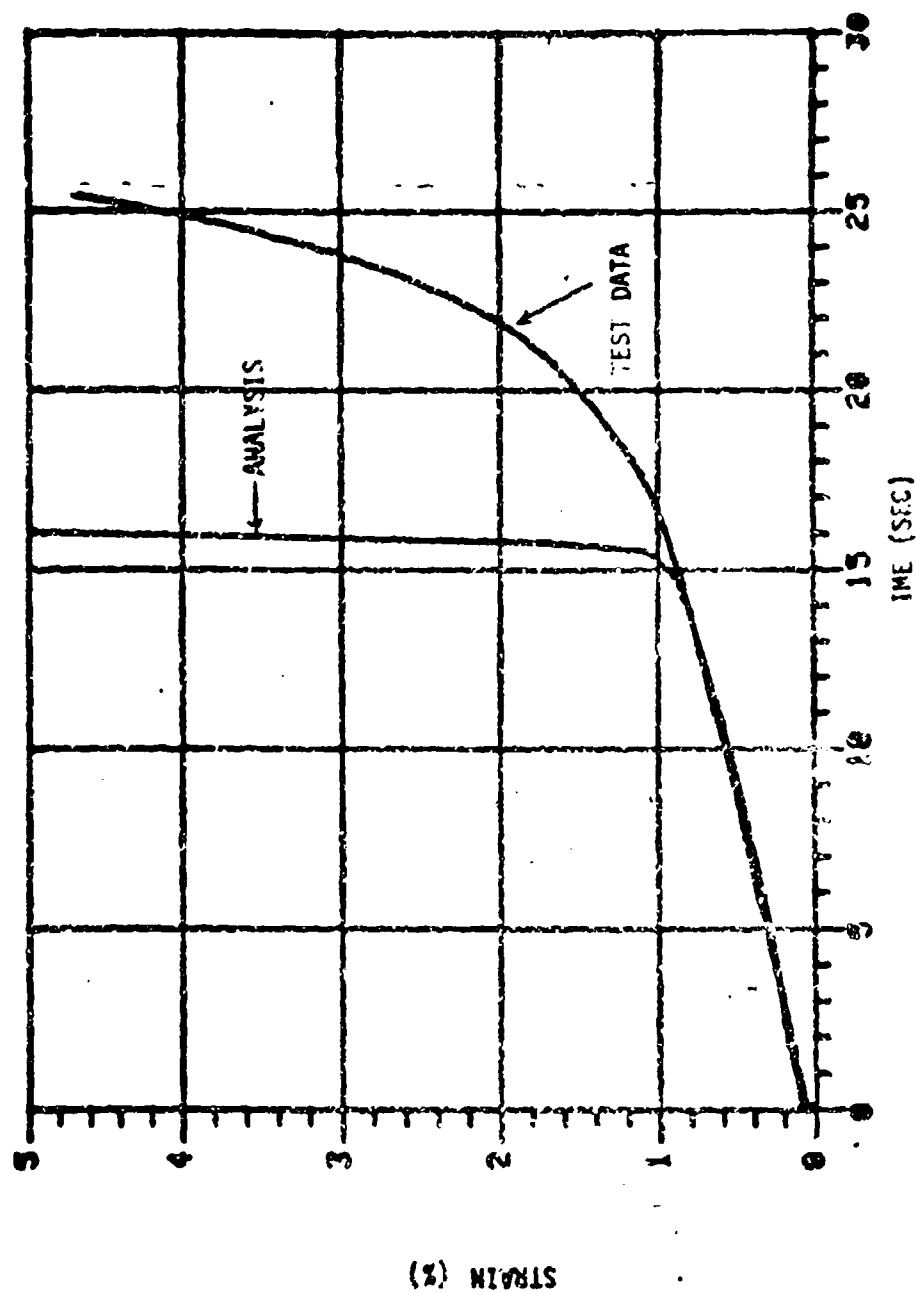Figure 39. CORRELATION - EXPERIMENT VS "CREEPARMS CODE" - TEST 67
"ZERO" TIME DATA

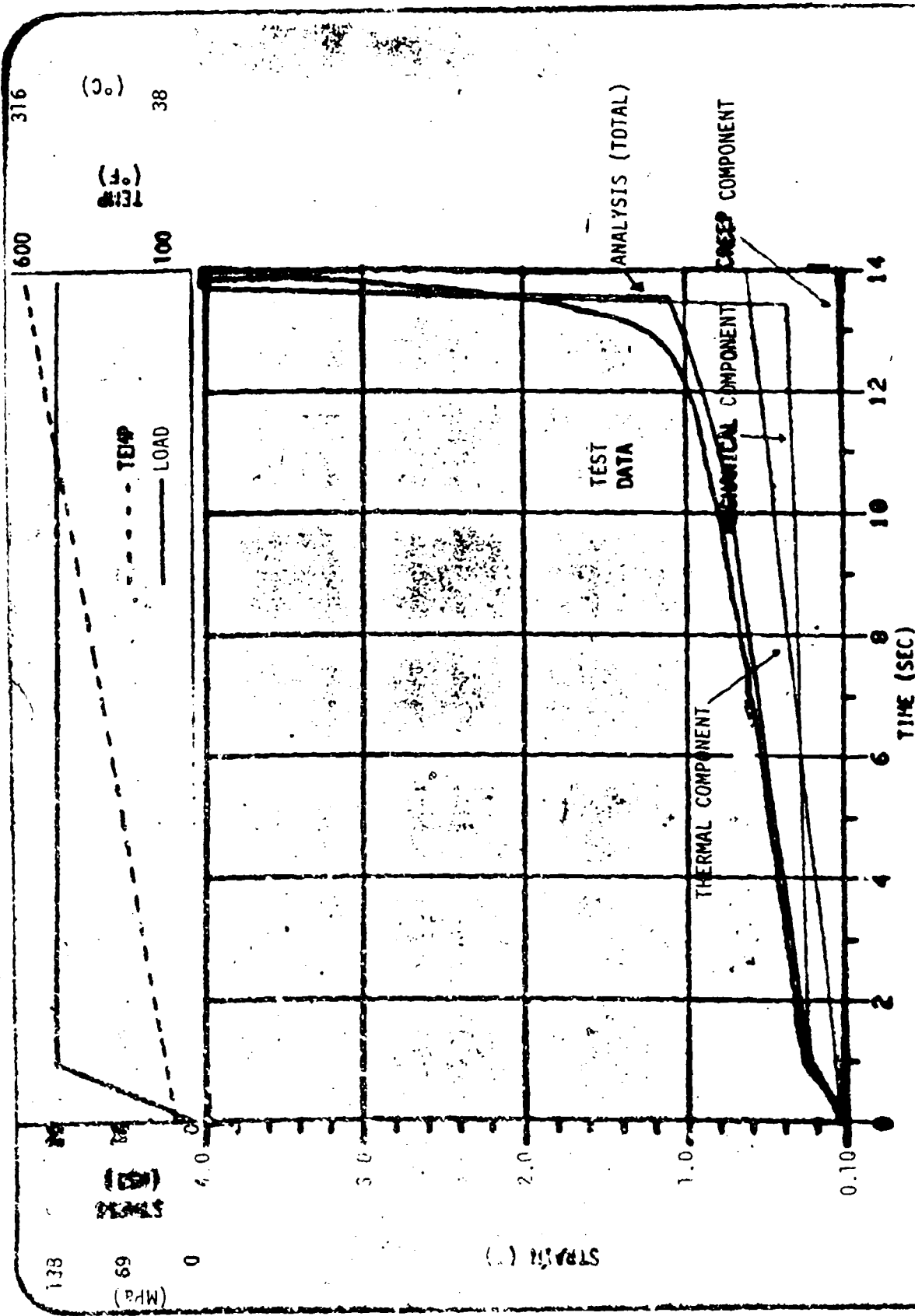Figure 40. CORRELATION - EXPERIMENT VS "CREEPARHS" CODE - TEST 67

ISOCHRONOUS DATA

Figure 41. CORRELATION - EXPERIMENT VS "CREEPARMS" CODE - TEST 73
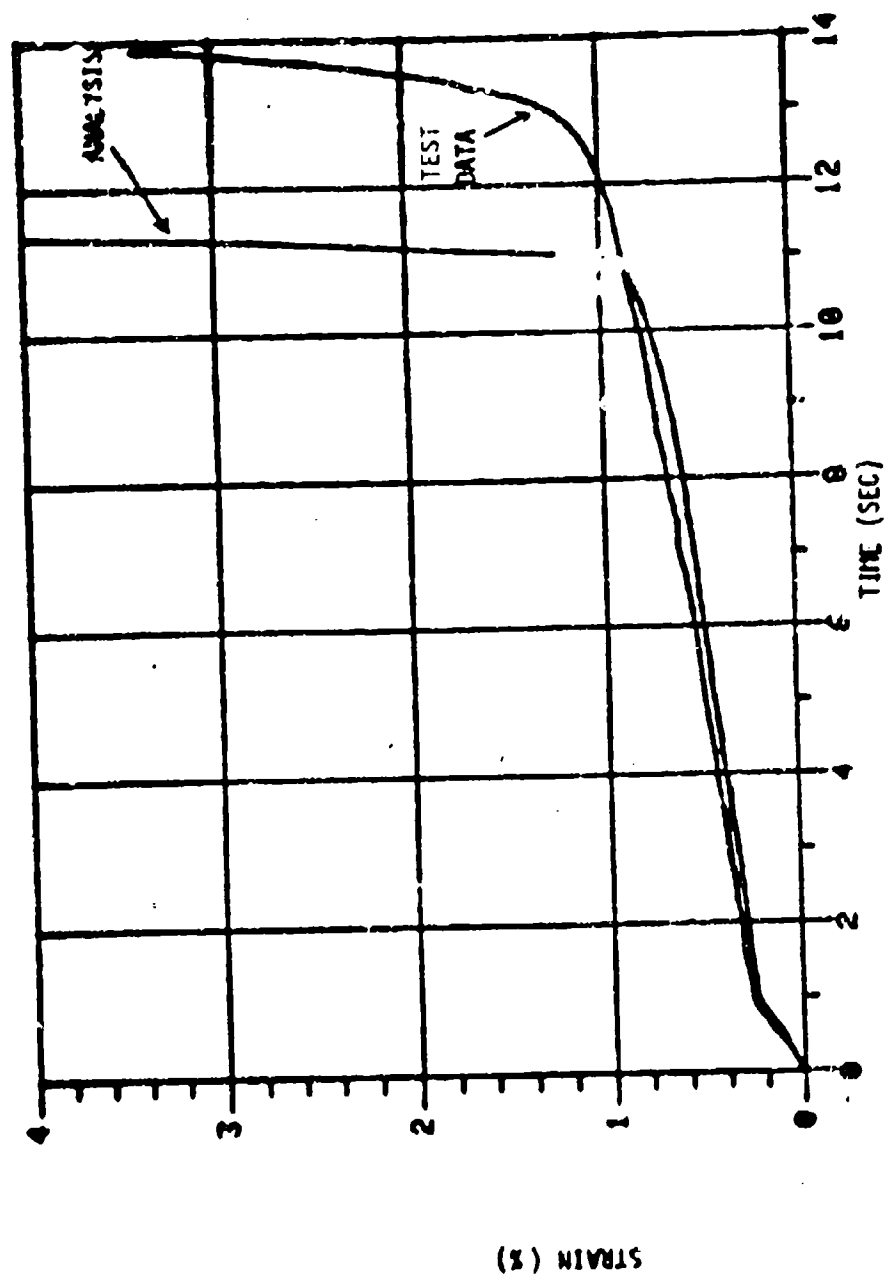"ZERO" TIME DATA

71

Figure 42. CORRELATION - EXPERIMENT VS "CREEPARHS" CODE - TEST 73
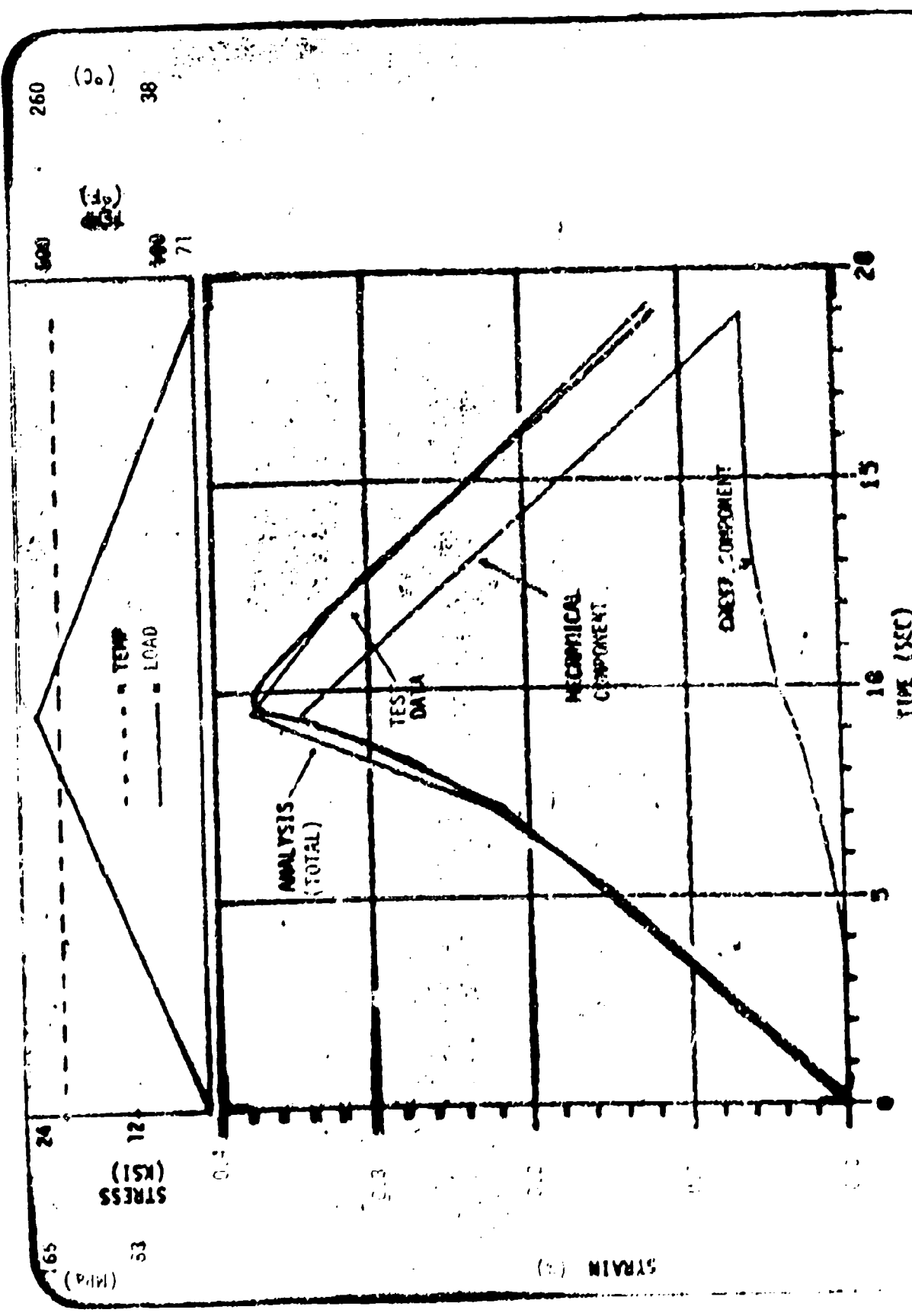
ISOCHRONOUS DATA

Figure 43. CORRELATION - EXPERIMENT VS "CREEPLAWS" CODE - TEST 63

unloading occurs. The results from analysis using the isochronous data are shown in Figure 44. In this case, it is clear that the isochronous data are inappropriate. The use of such data leads to a prediction of failure at a very early time when in fact no failure occurs.

The most complicated load-temperature history leads to the results shown in Figure 45. Obviously, in this example, the qualitative as well as quantitative behavior of the tensile specimen is being accurately modeled by the CREEPARHS code. A comparison with the results shown in Figure 46 shows good correlation through 10 seconds. At this time, the isochronous based analysis again predicts failure.

7.5 ANALYSIS - MARC, ANSYS, CREEPARHS COMPARISON

This section will include a discussion of the models that were used in the MARC and ANSYS analysis followed by a comparison of the results predicted by MARC, ANSYS and CREEPARHS for two of the problems discussed in Section 7.4.

7.5.1 MARC and ANSYS Analysis

The MARC analysis was performed on an IBM 370/168 computer and the ANSYS analysis was performed on a CDC Cyber 74 (6600) computer. The very simple structural model is shown in Figure 47. A plane stress, 4-node isoparametric element (No. 3) was used in MARC and a similar 2-D isoparametric solid element (No. 42) was used in ANSYS. The elements were assumed simply supported at node 1 and roller supported at node 2. The element was loaded by a uniform traction σ and the Poisson ratio was set equal to zero.
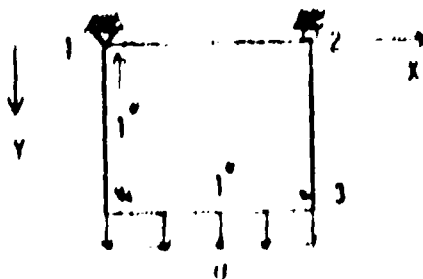

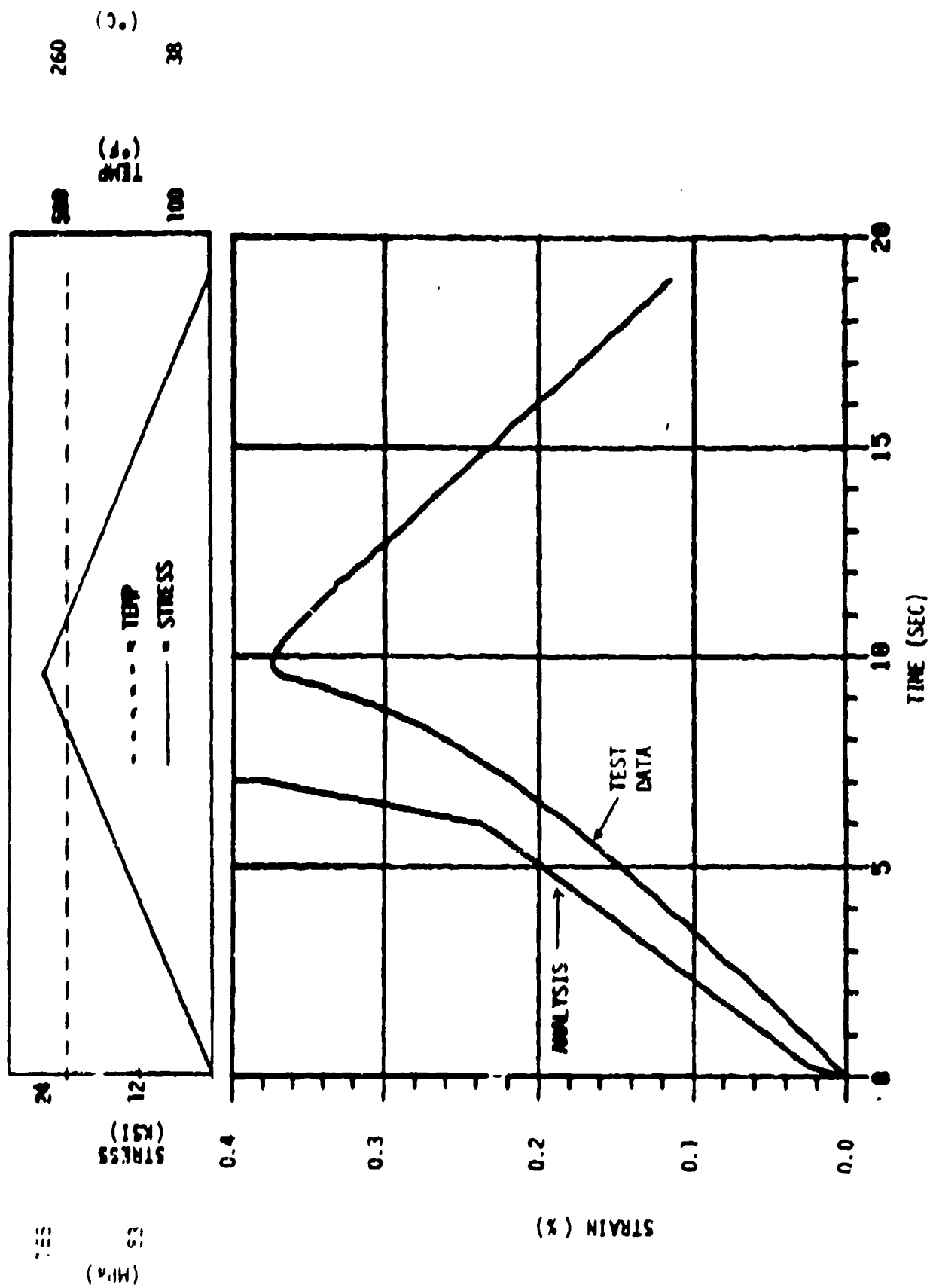Figure 47. ANSYS/MARC Structural Model

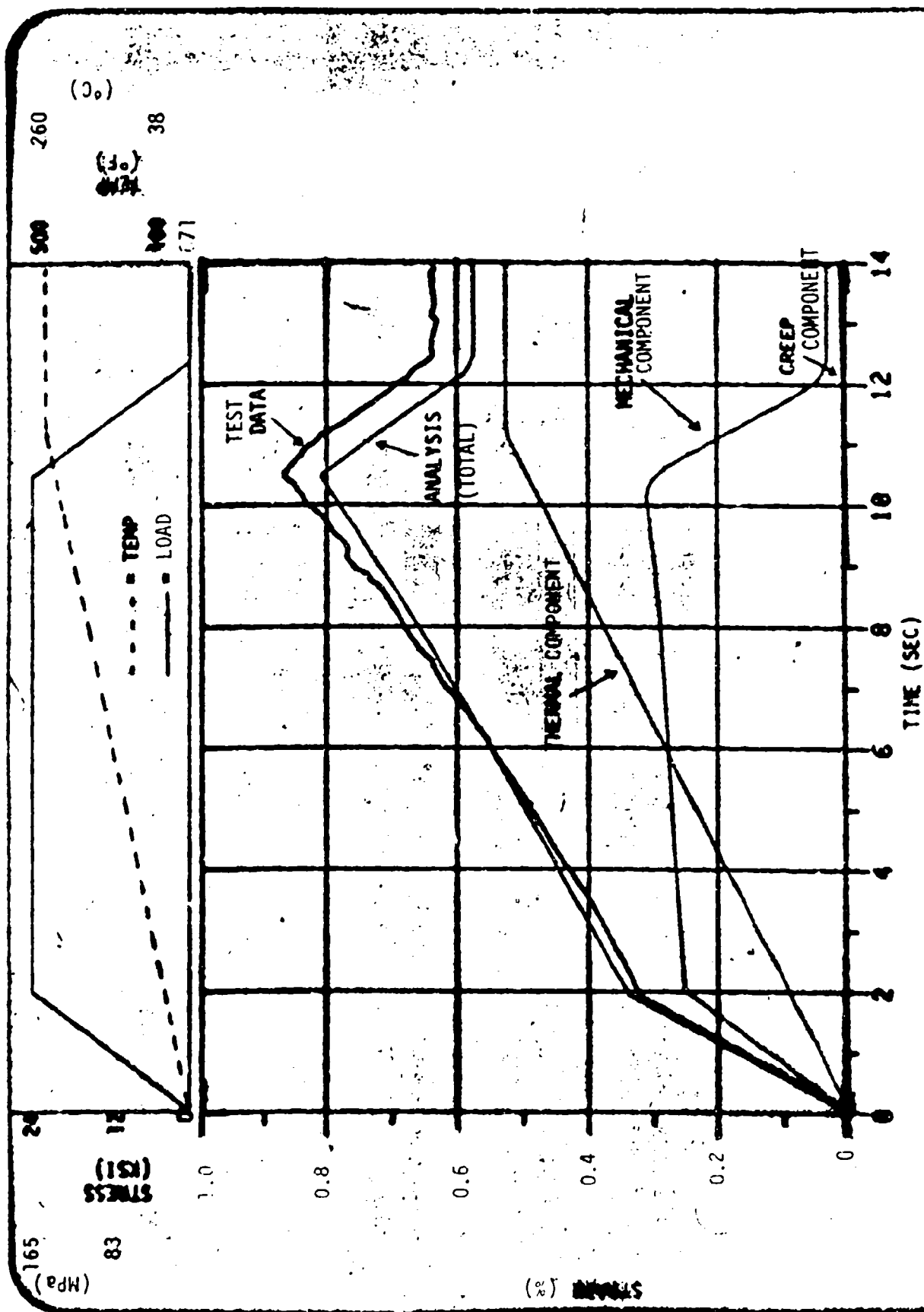Figure 44. CORRELATION - EXPERIMENT VS "CREEPARMS" CODE - TEST 83
ISOCHRONOUS DATA

Figure 45. CORRELATION - EXPERIMENT VS "CREEPARHS" CODE - TEST 84
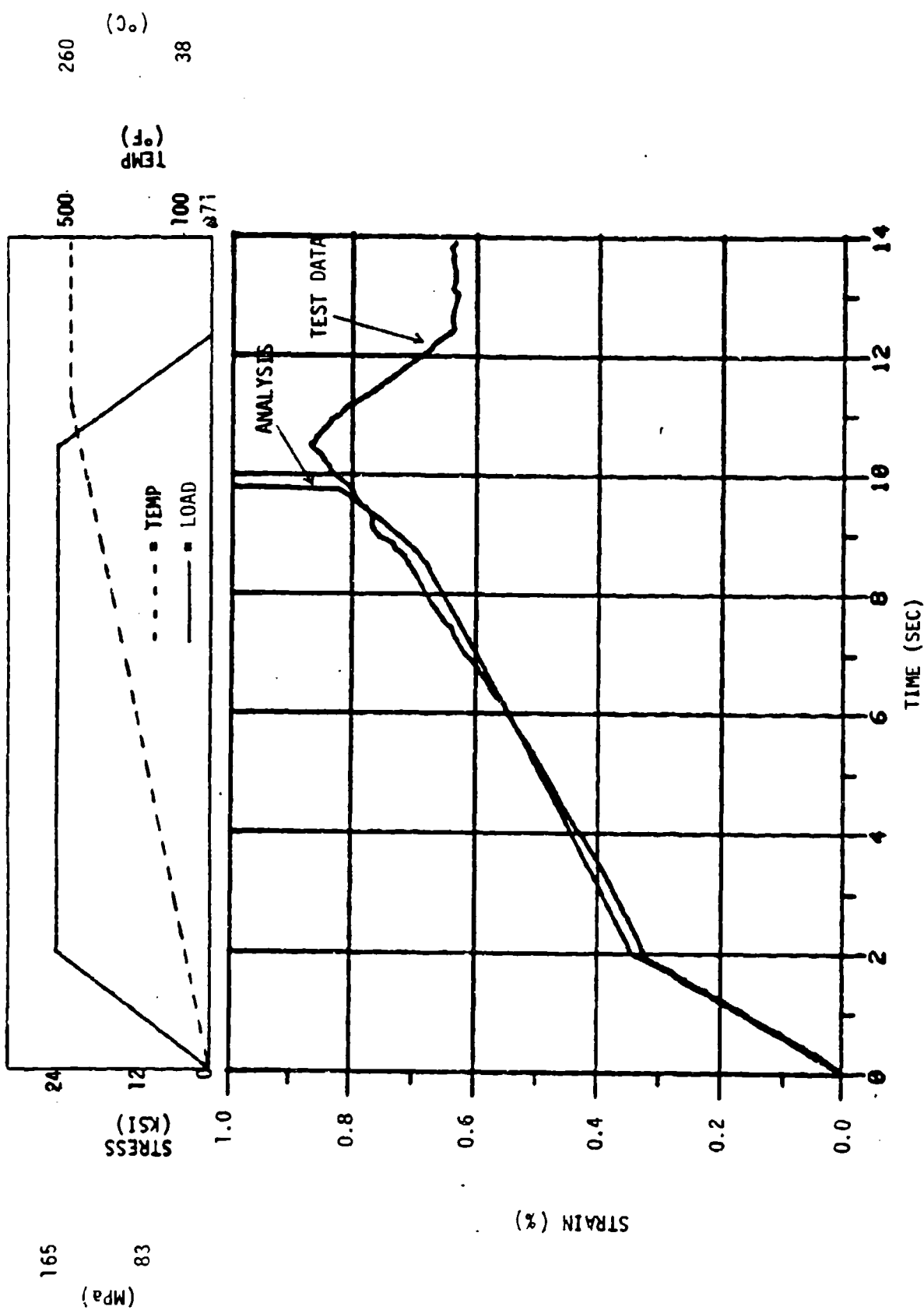"ZERO TIME" DATA

Figure 46. CORRELATION - EXPERIMENT VS "CREEPARHS" CODE TEST 84
ISOCHRONOUS DATA

Material properties modeled as time-independent stress-strain curves, a master creep function and thermal coefficient of expansion versus temperature as previously described were input directly into ANSYS. The MARC input required the development of a user written subroutine for both the creep and the temperature dependent stress-strain data. Care was taken to make sure that the data input was equivalent in both codes.

A key element in the analysis was formulating a strategy for determining the time/load/temperature steps required for accurate results. A 0.25 second time step was selected for the CREEPARHS analysis and this was the minimum time step used in the MARC and ANSYS analysis. The MARC and ANSYS analyses were performed by marching through a series of mechanical and/or thermal load steps, each followed by a creep step where the temperature and stress corresponding to the previous step is held constant. A rough determination of the number and timing of the steps was made based upon a review of the behavior as seen in the experimental data. The steps were fine tuned after reviewing the analysis results.

The AUTOCREEP option was used in MARC. This is a routine which varies the creep time increment based upon tolerances for calculated ratios of incremental creep strain to total strain and incremental change in stress to total stress. A similar procedure which is built into ANSYS was also used.

A comparison of the results as predicted by the three codes is shown in Figures 48 and 49. These two examples were chosen because all of the various load and temperature effects that are demonstrated in the other tests are inherent in these problems. It is seen, that the results are almost identical. The small variations are due to different methods of inputing discrete load and creep steps and slight differences in the input plasticity data. Any of the three codes could be used to analyze these types of problems with equal success. The actual code selection, however, should be decided based upon problem complexity and cost considerations.

Table 7 shows a comparison of the number of load steps, the total running time and the cost per run for each of the three codes. The difference in the
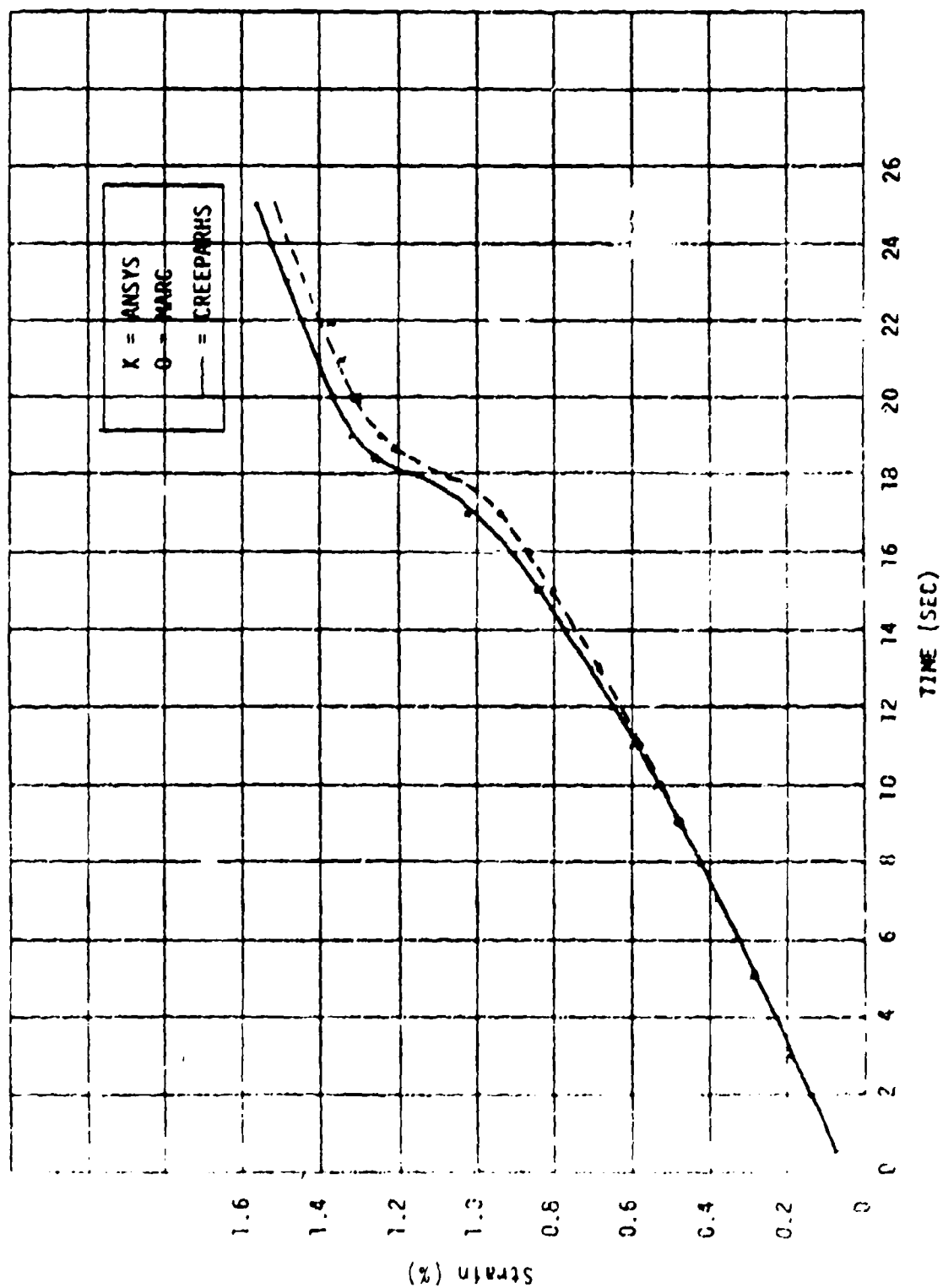
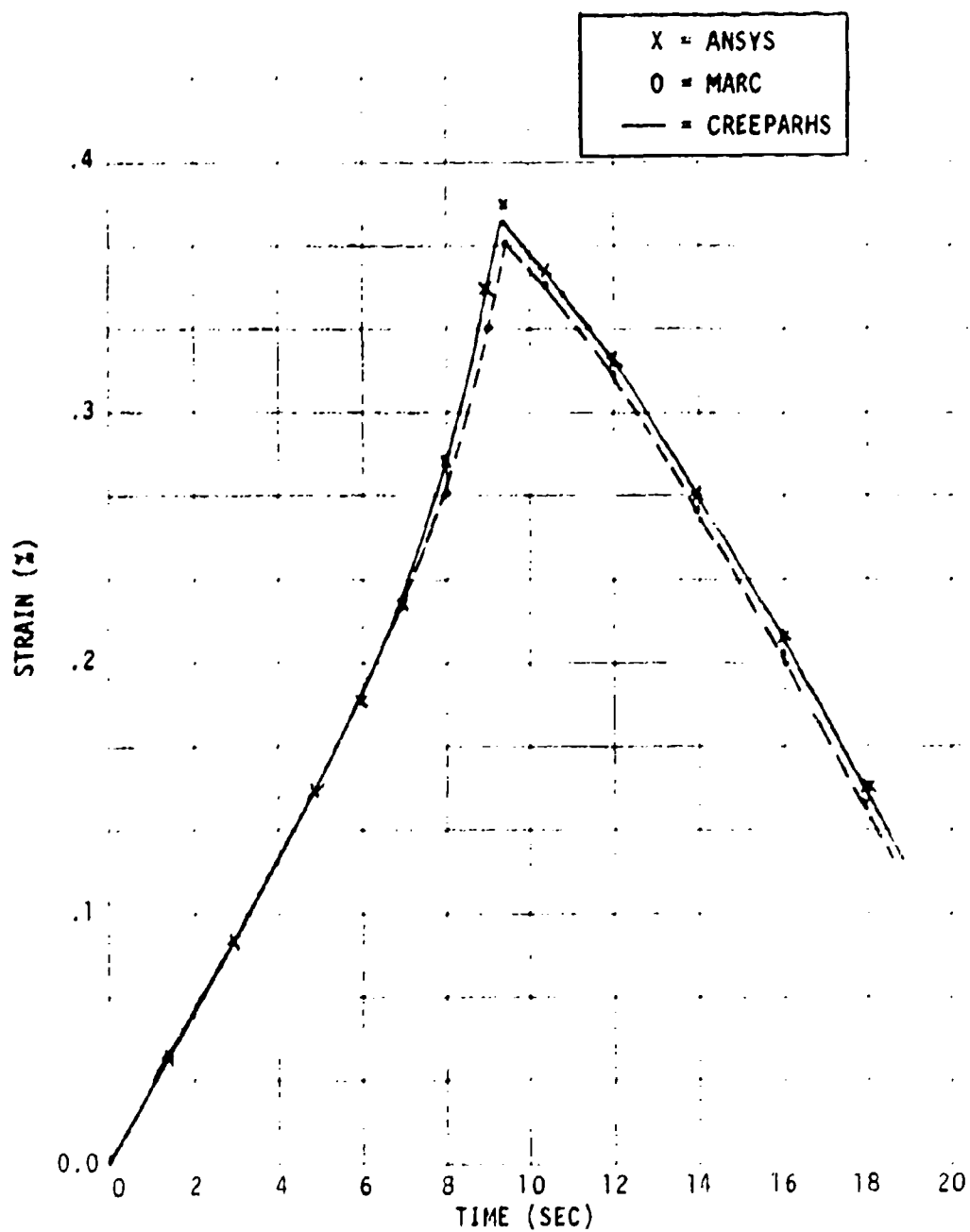Figure 48. Analysis Comparison MARC/ANSYS/CREEPARHS - TEST 67

Figure 49. Analysis Comparison - MARC/ANSYS/CREEPARHS - TEST 83

costs in ANSYS and MARC is mainly due to higher prescribed creep tolerances in ANSYS and the need in MARC to repeatedly access the user written subroutines.

Table 7

Code Execution Comparison

Code	CREEPARHS (CYBER)	MARC (IBM)	ANSYS (CYBER)
TEST 67			
No. of Load Steps	100	9	10
No. Creep Iterations	Same	48	63
Computation Time	T/S MRU = 10	MRU = 8.8, SRU = 54.3	MRU = 9.7, CP = 27.4
Cost	$0.80	$44.30	$20.18
TEST 83	Same		
No. of Load Steps	↓	18	19
No. Creep Iterations		87	48
Computation Time		VRU - 12.2, SRU = 94.9	MRU = 8.35 CP = 21.5
Cost		$69.6	$17.30

The cost of performing this simple analysis suggests that one would want to use a simple code when possible. An efficient solution strategy should be developed before a combined thermal-elastic-plastic-creep analysis of a complex structure is undertaken.

APPENDIX 1

SIMULATION EXPERIMENTS

The following figures (50 - 61) show the results from the many simulation test/CREEPARHS analysis that were performed. Included at the top of each figure is a sketch of the stress and temperature histories.
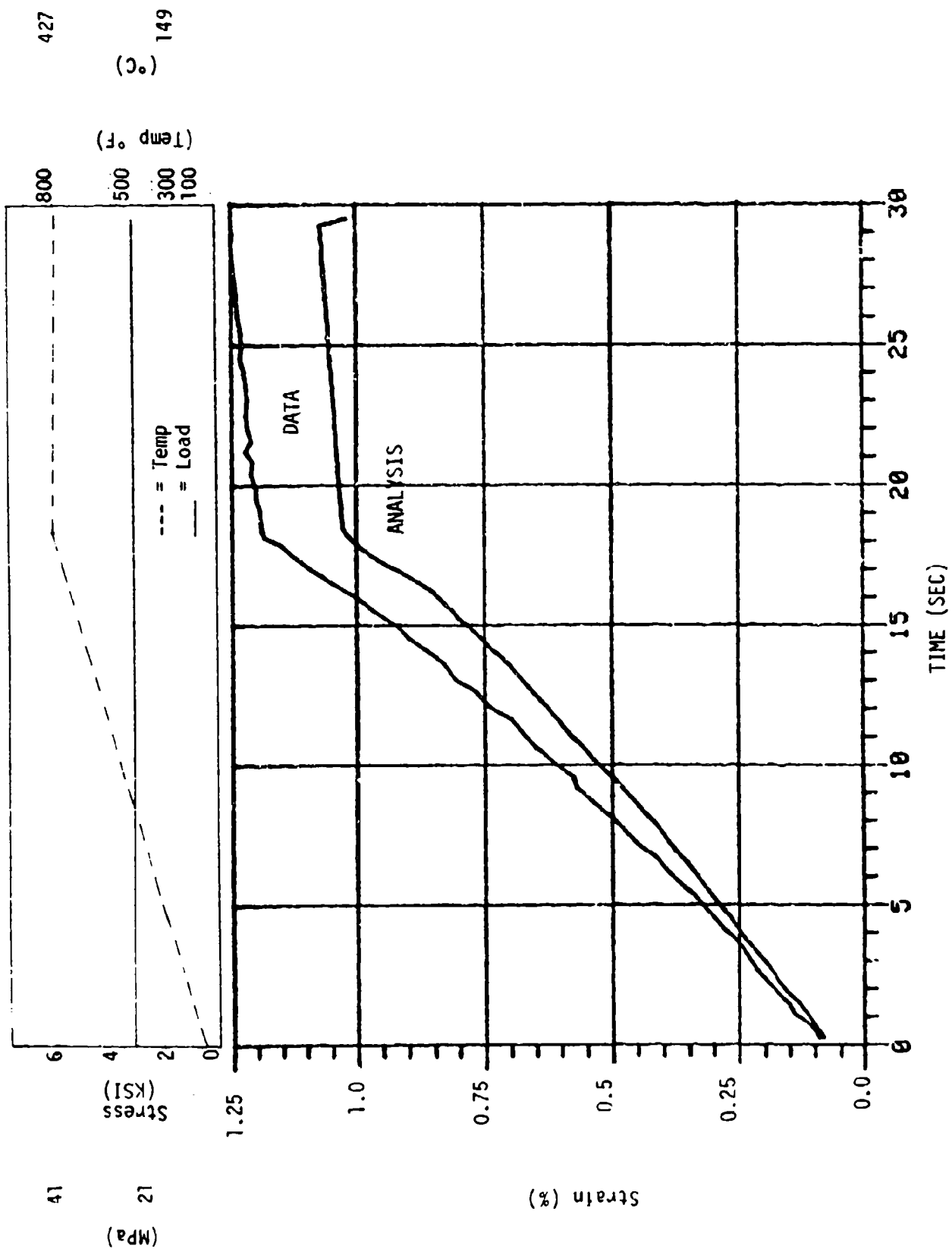
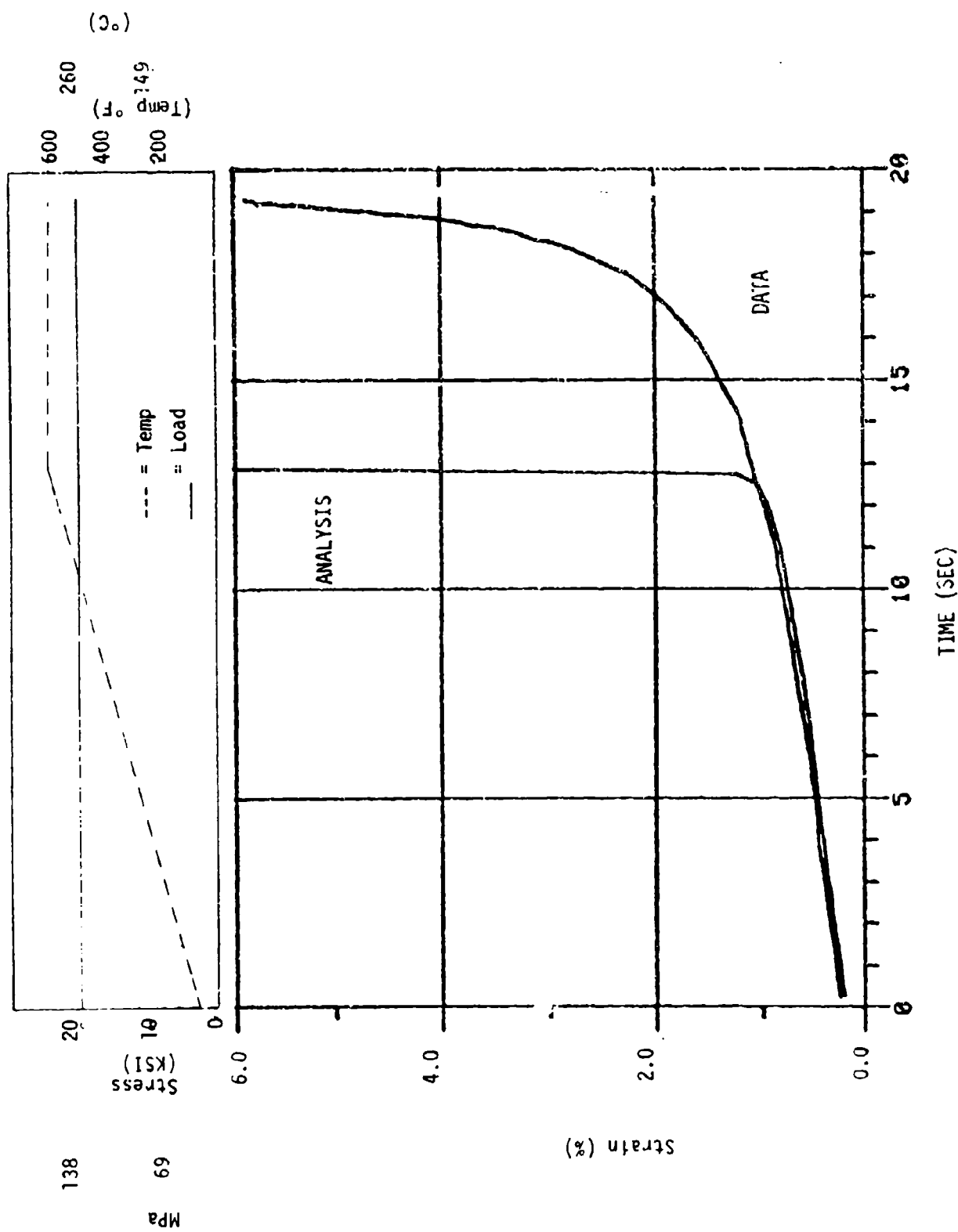Figure 50. Experiment vs. "Creeparhs" code - Test 68 "Zero" Time Data

Figure 51. Experiment vs. "Creeparhs" code - Test 69 "Zero" Time Data
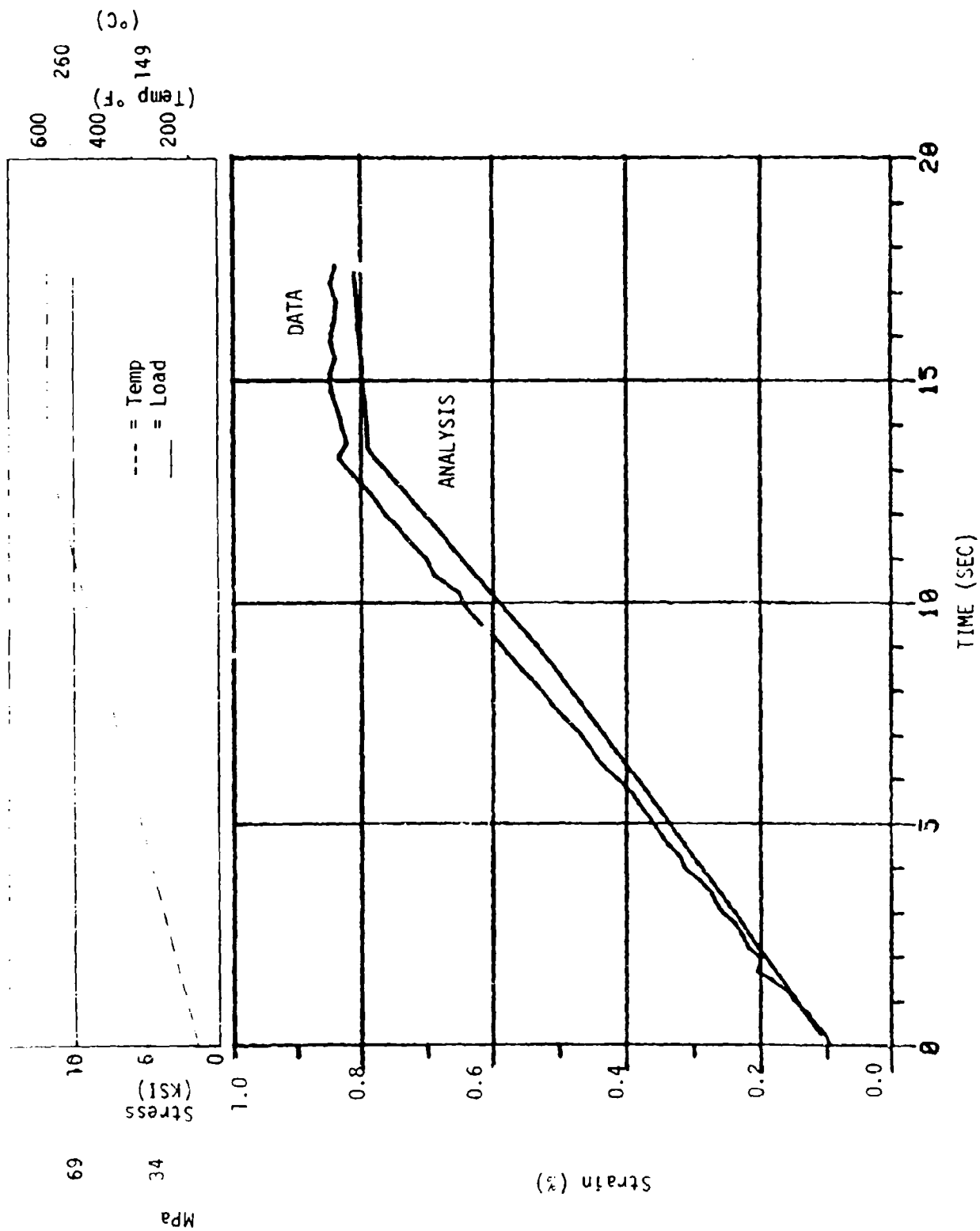
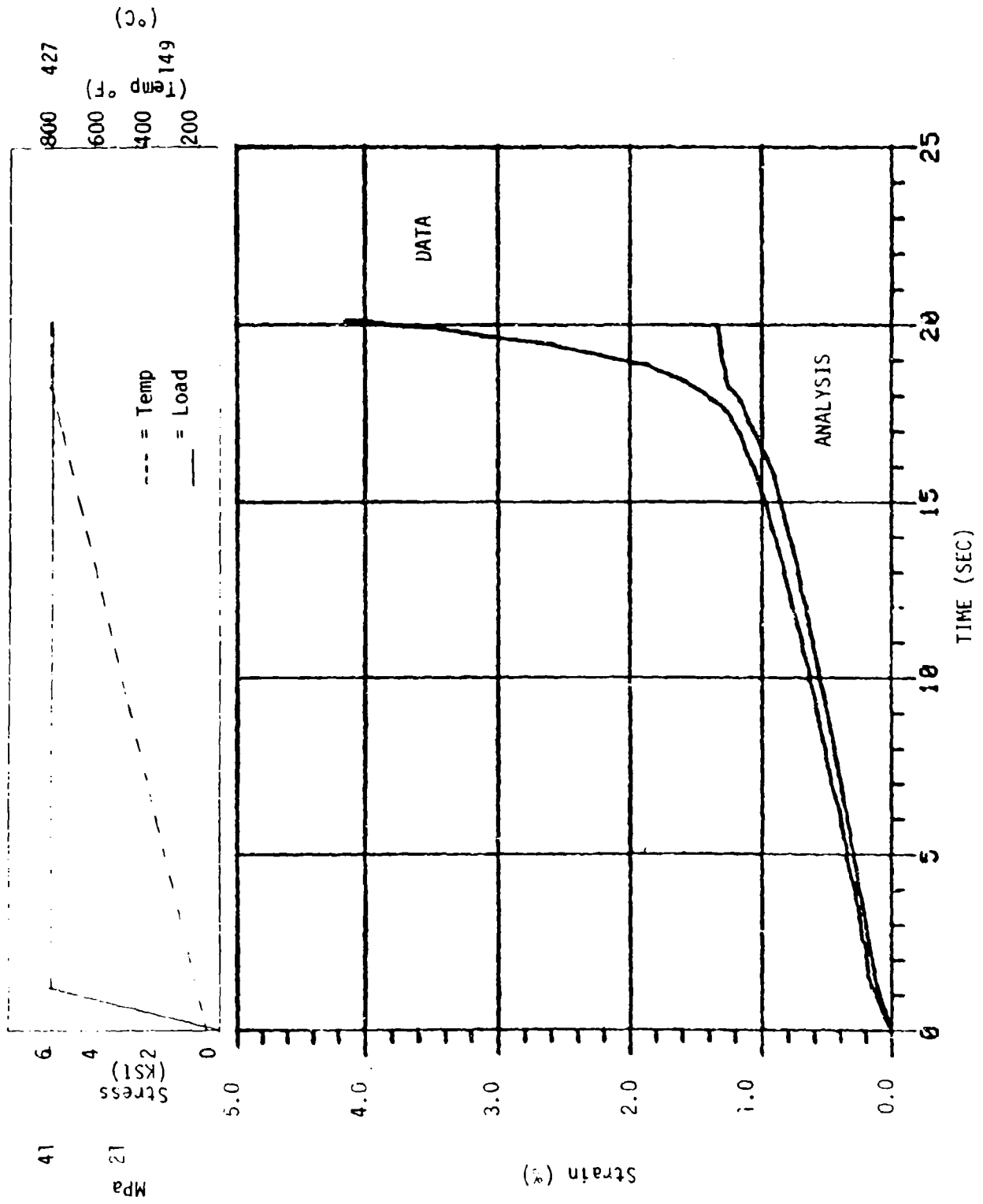Figure 52. Experiment vs. "Creeparhs" code - Test 70 "Zero" Time Data

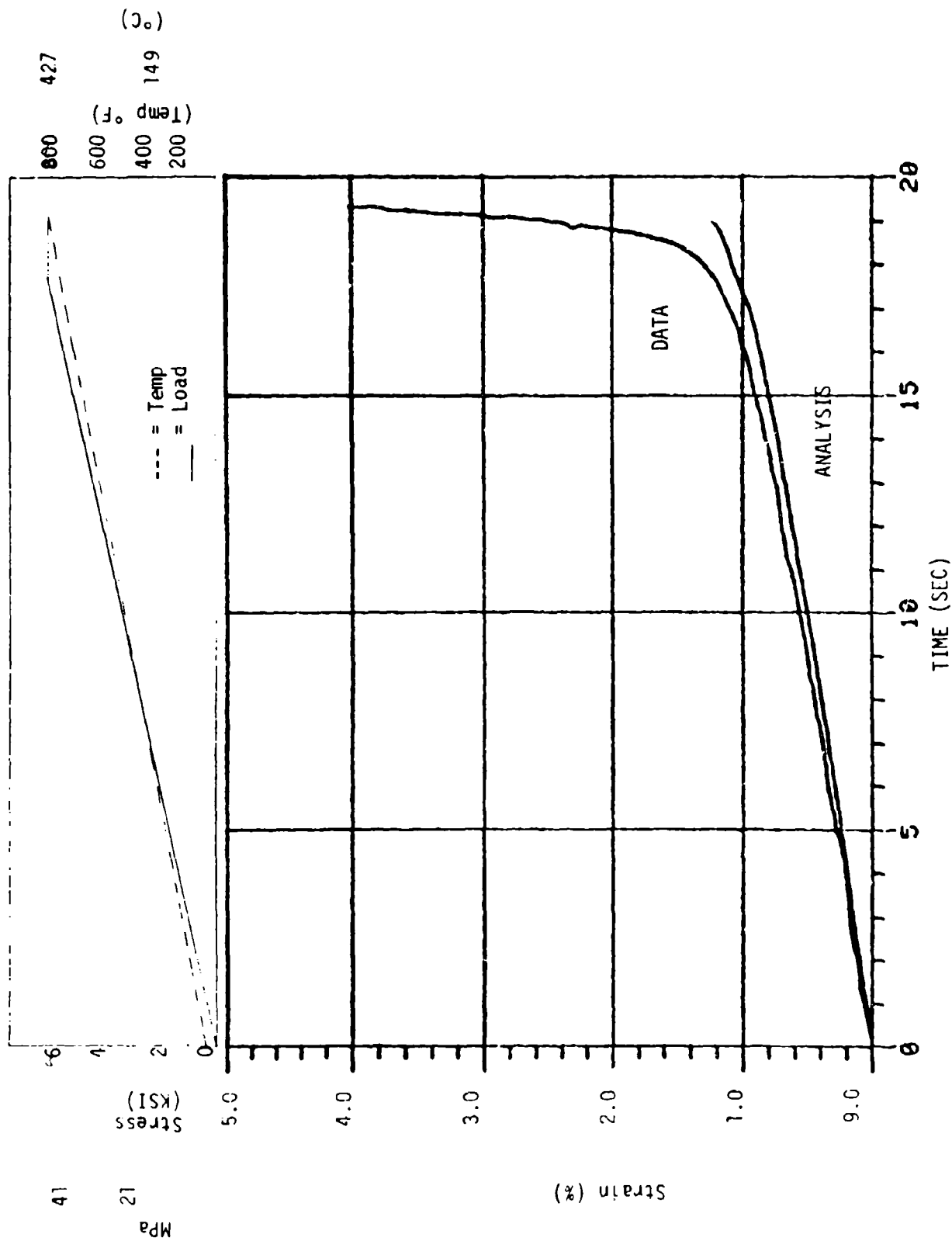Figure 53. Experiment vs. "Creeparhs" code – Test 71 "Zero" Time Data

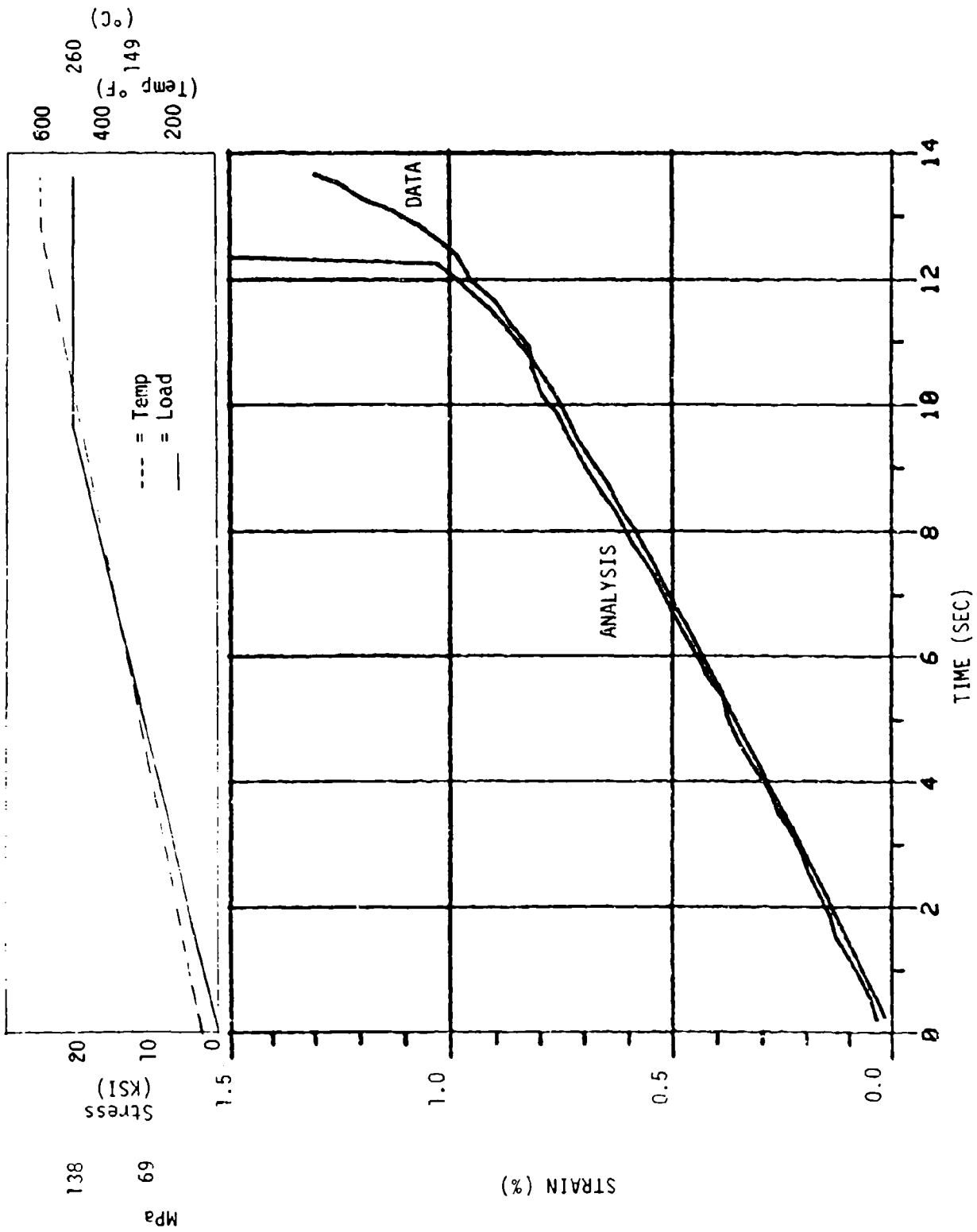Figure 54. Experiment vs. "Creeparhs" code - Test 72 "Zero" Time Data

Figure 55.   Experiment vs. "Creeparhs" code - Test 74 "Zero" Time Data

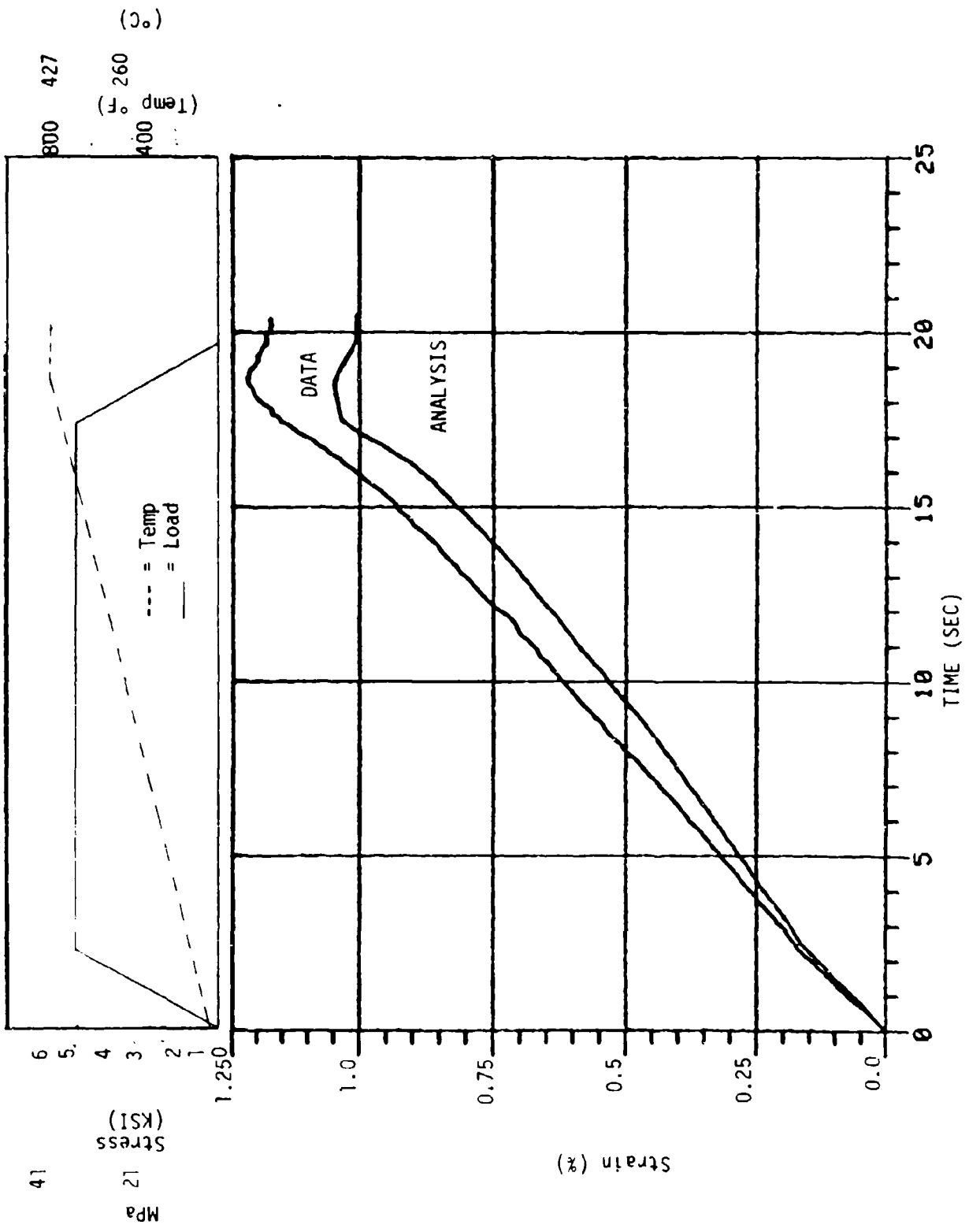Figure 56.   Experiment vs "CREEPARHS" code - Test 77 "Zero" Time Data
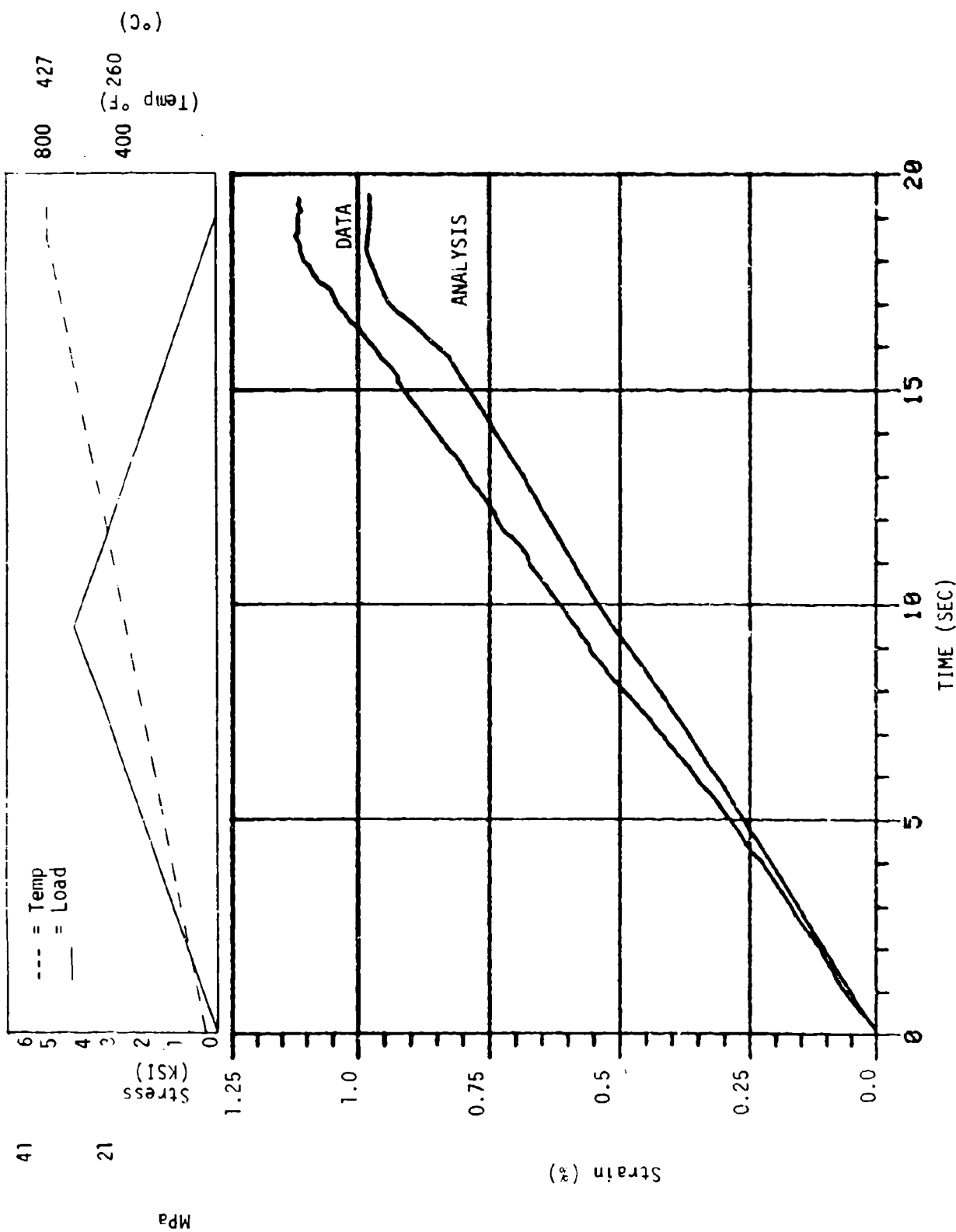
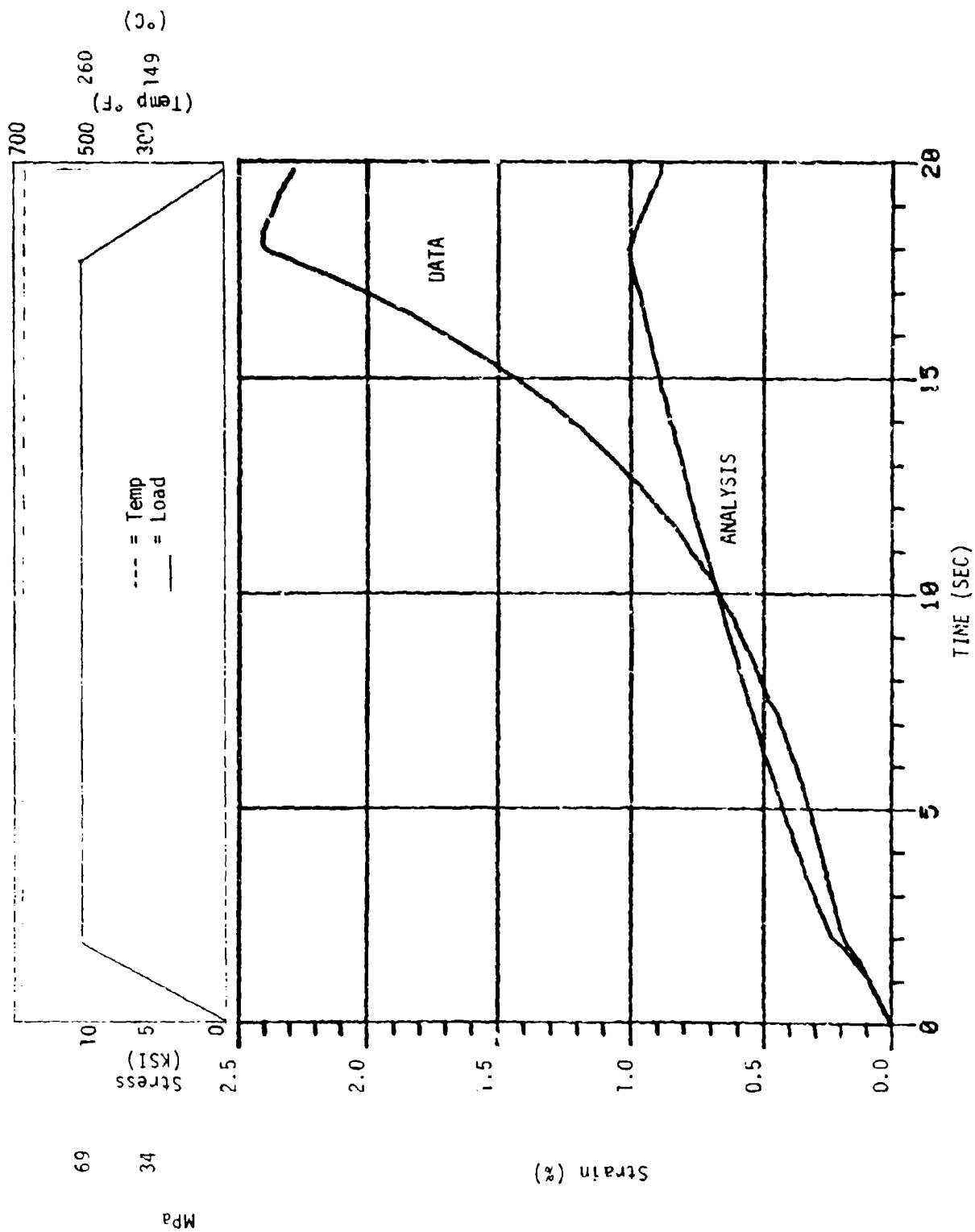Figure 57. Experiment vs "CREEPARHS" Code - Test 79 "Zero" Time Data

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Figure 58. Experiment vs. "CREEPARHS" code – Test 80 "Zero" Time Data
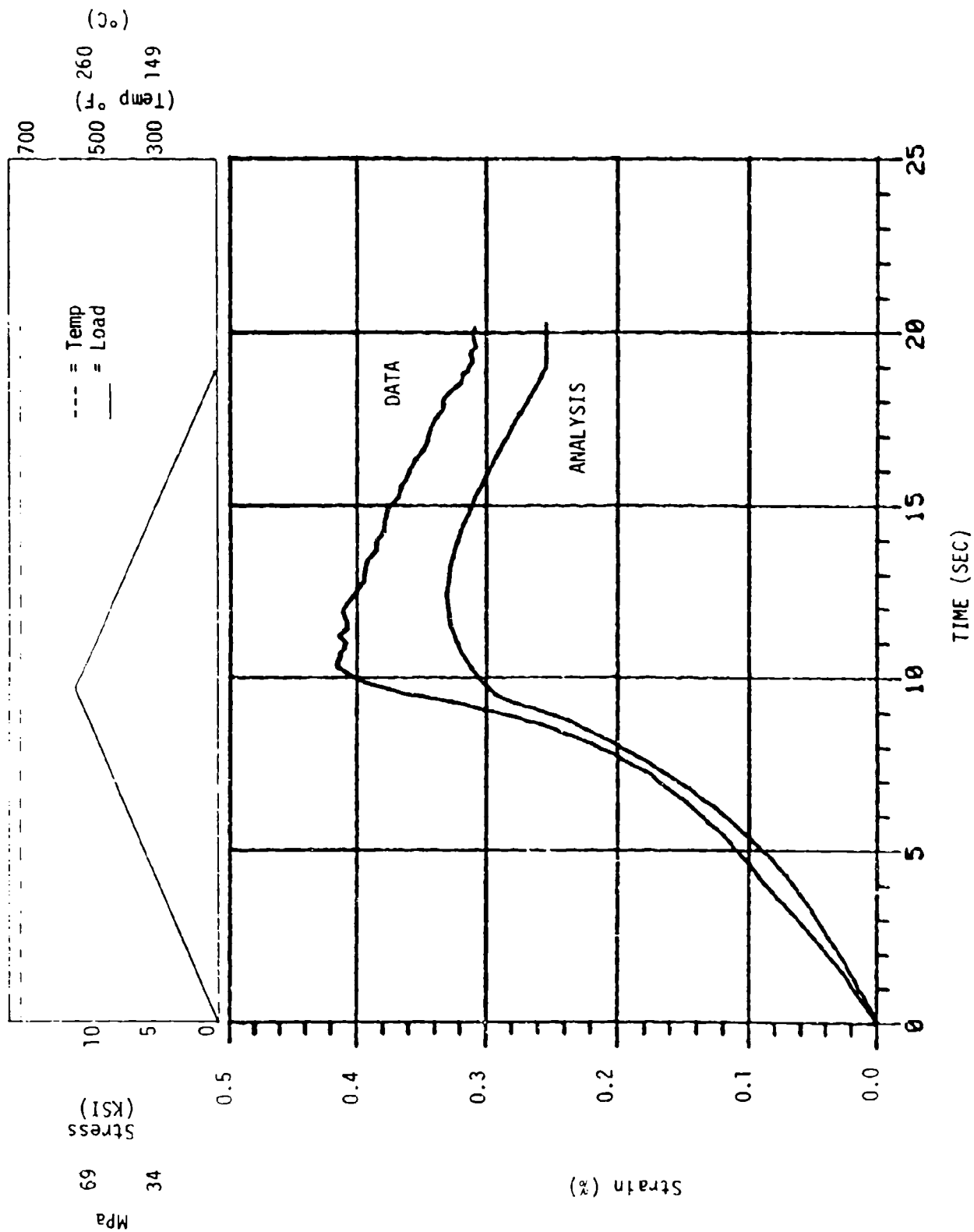
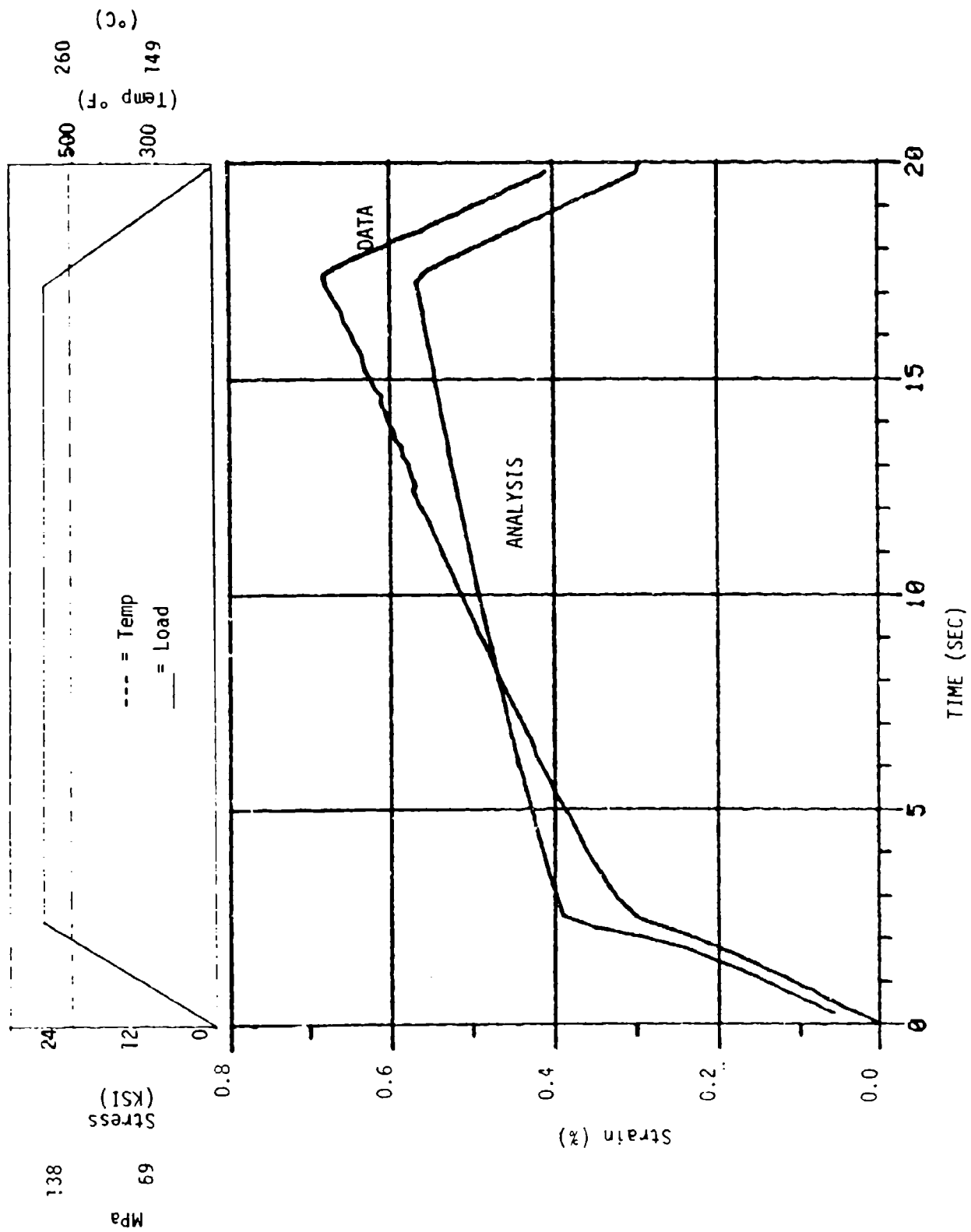Figure 59. Experiment vs. "CREEPARHS" code - Test 8) "Zero" Time Data

Figure 60. Experiment vs "CREEPARHS" code – Test 82 "Zero" Test Data
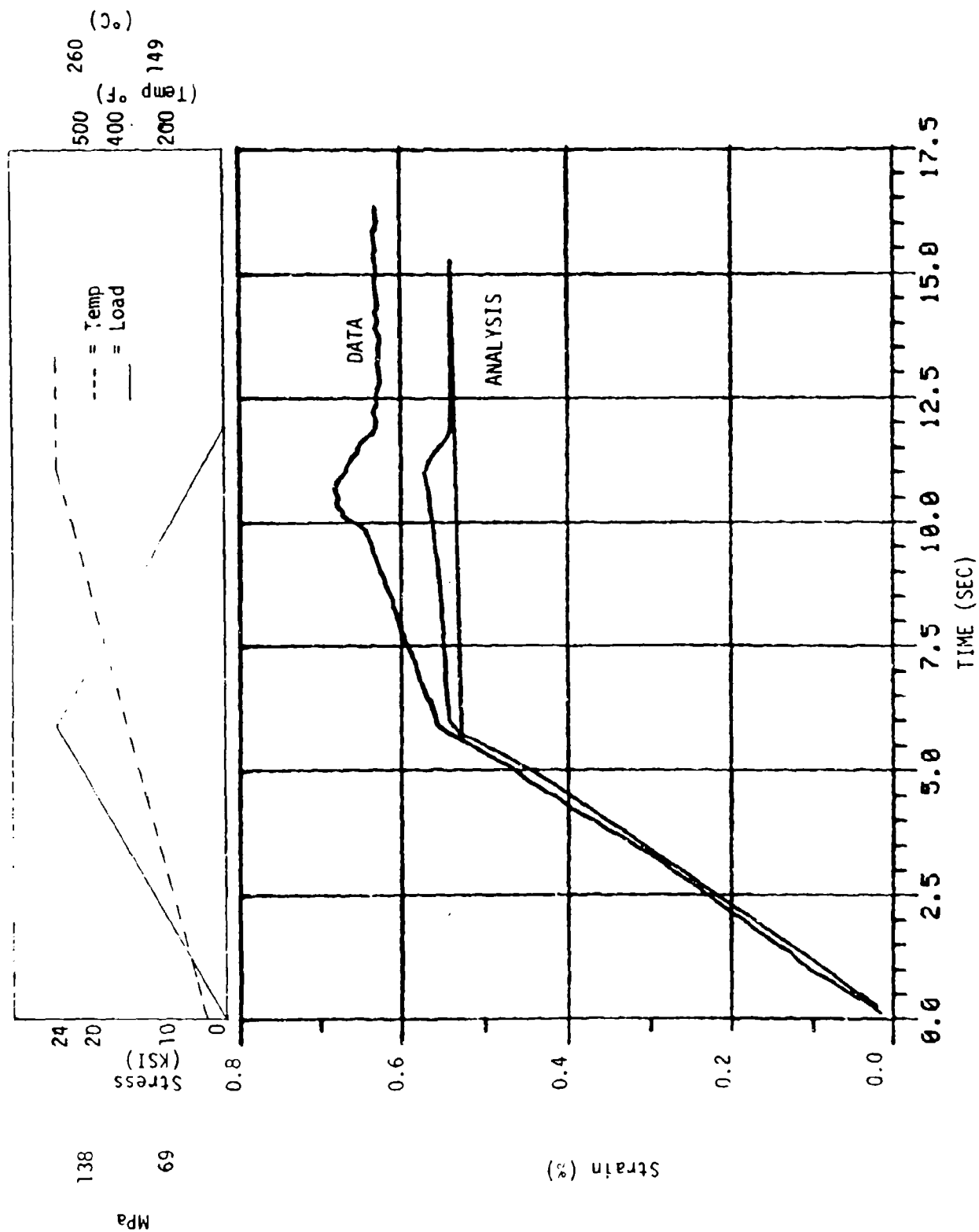
Figure 61. Experiment vs "CREEPARHS" Code – Test 85 "Zero" Time Data

APPENDIX 2

CREEPARHS CODE

The following consists of a definition of the input used in the CREEPARHS code followed by a listing of the code. The code was run interactively on a CYBER CDC computer. [Input temperatures are in (°F).]
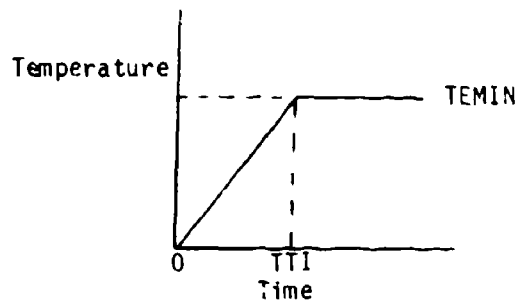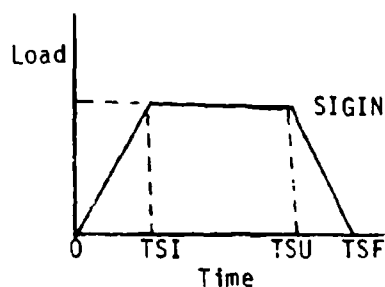
TTF   =   Run Time

TINC   =   Time Step

TINT   =   Initial Temperature (°F)

THIN   =   Initial Thermal Strain

NS   =   Number of temperature dependent sets of material properties.

TEMP(I) =   Ith temperature for material property input.

ALPH(I) =   Ith Coefficient of thermal expansion

Elmod(I) = Ith Elastic modulus

NPBT   =   Number of breakpoints for stress-strain curves

EPBK(I,J) = Jth strain breakpoint for Ith temperature.

STBKP(I,J) = Jth stress breakpoint for Ith temperature

EYBK(I) =   Elastic modulus for Ith temp = Elmod (I)

FOR(I)   Ith creep coefficient $e_c = A_1 \sigma^{A_2} t^{A_4} e^{-A_3/T}$

$$I = 1 \Rightarrow A_1 \qquad I = 3 \Rightarrow A_3$$
$$I = 2 \Rightarrow A_2 \qquad I = 4 \Rightarrow A_4$$

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      PROGRAM CREEP(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT
      DIMENSION ELMOD(10),TEMP(10),ALPH(10),STBKP(10),
     1 E  (10),EPBK (10,10),FOR(4),AL(10),DE(10,10),EL(10)
      COMMON SIGIN,TEMIN,SIGI,TSI,TSU,TSF,TTI,TTF
      TIM=0.0
      SGIN=0.0
      TMIN=0.0
      IEC=0
      ICT=0
      EPSTN=0.0
      THSTN=0.0
      CRSTN=0.0
      READ(5,1) NS,NEPT,TINT,TIM1,THIN
    1 FORMAT(3I3,2F10.2,F15.7)
      READ(5,2) SIGIN,TEMIN,TTF,TINC,TSI,TSU,TSF,TTI
      WRITE(6,3) SIGIN,TSI,TSU,TSF,TEMIN,TTI,TTF,TINC,TINT,TIM1,THIN
    2 FORMAT(2F10.5/2F10.5/3F10.5,F10.5)
    3 FORMAT(3X,*MAX STRESS=*,F10.3,/,3X,*MAX STRESS OCCURS AT
     1 TIME=*,F10.3,/,3X,*STRESS REDUCED AT TIME=*,F10.3,/,3X,*STRESS
     2 ZERO AT TIME=*,F10.3,/,3X,*MAX TEMP=*,F10.3,/,3X,*MAX TEMP
     3 OCCURS AT TIME=*,F10.3,/,3X,*RUN TIME=*,F10.3,/,3X,*TIMESTEP=*
     4 ,F10.3,/,3X,*INITIAL TEMP=*,F10.2,/,3X,*TIME OFFSET=*,F10.3,
     5    /X,*INITIAL THERMAL STRAIN=*,E15.5)
      DO 4 I=1,NS
      READ(5,5) TEMP(I),ALPH(I),ELMOD(I)
      WRITE(6,7) I,TEMP(I),ALPH(I),ELMOD(I)
    4 CONTINUE
      READ(5,17) (EPBK(1,JS),JS=1,NEPT)
      DO 44 IJ=1,NS
      READ(5,16) (STBKP(IJ,IK),IK=1,NEPT)
      EYEK(IJ)=STBKP(IJ,2)/EPBK(1,2)
   44 CONTINUE
      DO 45 IR=1,NS
      DO 45 IT=1,NEPT
      EPBK(IR,IT)=EPBK(1,IT)
      WRITE(6,12) IT,EPBK(IR,IT),STBKP(IR,IT)
   45 CONTINUE
    5 FORMAT(F15.5,2E15.5)
   16 FORMAT(8F8.1)
   17 FORMAT(8F8.5)
    7 FORMAT(3X,*CURVE=*,I3,/,3X,*TEMP=*,F10.3,/,3X,*THERMAL COEFF=*,
     1 E15.3,/,3X,*ELASTIC MOD=*,E15.3)
   12 FORMAT(3X,*BKPT=*,I3,2X,*STRAIN=*,E15.3,2X,*STRESS=*,E15.3)
      DO 8 K=1,4
      READ(5,9) FOR(K)
    8 CONTINUE
    9 FORMAT(F15.5)
      WRITE(6,14) (FOR(M),M=1,4)
   14 FORMAT(3X,*CREEP CONSTANT=*,E15.5,/,3X,*STRESS CONSTANT=*,
     1 F10.5,/,3X,*TEMP CONSTANT=*,E15.5,/,3X,*TIME CONSTANT=*,
     2 F10.5)
   11 CALL STIN(TIM,TINC,SGIN,TMIN,TINT,SIGAV,TIMAV,TEMAV,ICT)
      CALL TSTN(EYEK,TEMP,ALPH,STBKP,EPBK,FOR,DE,AL,EL,SGIN,TMIN,EPSTN,
     1THSTN,CRSTN,TIM,TIM1,THIN,SIGAV,TIMAV,TEMAV,TINC,IEC,NS,NEPT,ICT)
      IEC=IEC+1
      CRSTN=0.0
      TOSTN=EPSTN+THSTN+CRSTN
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```
      WRITE(6,10) TIM,TMIN,SGIN,EPSTN,THSTN,CRSTN,TOSTN
   10 FORMAT( ,3X,*ELAPSED TIME=*,F10.5, ,3X,*TEMP=*,F10.5,
     1 3X,*STRESS=*,F10.2,/,3X,*MECH STRAIN=*,E15.5,/,3X,
     2    *THERMAL STRAIN=*,E15.5,/,3X,*CREEP STRAIN=*,E15.5, .
     3 3X,*TOTAL STRAIN=*,E15.5)
      IF(TIM .GE. TTF) GO TO 15
      GO TO 11
   15 CONTINUE
      STOP
      END
C  SUBROUTINE TO CALCULATE-TIME,STRESS,TEMPERATURE
      SUBROUTINE STIN(TIM,TINC,SGIN,TMIN,TINT,SIGAV,TIMAV,TEMAV,ICT)
      COMMON SIGIN,TEMIN,SIG1,TSI,TSU,TSF,TTI,TTF
      SIG1=SGIN
      TEMA=TMIN
      TIMA=TIM
      SIGA=SGIN
      SGIN=0.0
      TIM=TIM+TINC
      IF(TSI .GT. TIM) SGIN=SIGIN*TIM/TSI
      IF(TIM .GE. TSI  .AND. TSU .GT. TIM) SGIN=SIGIN
      IF(TIM .GE. TSU  .AND. TSF .GT. TIM) GO TO 20
      GO TO 21
   20 SGIN=SIGIN*(1.0-(TIM-TSU)/(TSF-TSU))
      ICT=1
   21 IF(TTI .GT. TIM) TMIN=TINT+TIM*(TEMIN-TINT)/TTI
      IF(TIM .GE. TTI  .AND. TTF .GE. TIM) TMIN=TEMIN
      SIGAV=(SGIN+SIGA)/2.0
      TIMAV=(TIM +TIMA)/2.0
      TEMAV=(TMIN+TEMA)/2.0
      RETURN
      END
C  SUBROUTINE TO CALCULATE STRAIN
      SUBROUTINE TSTN(EYBK,TEMP,ALPH,STBKP,EPBK,FOR,DE,AL,EL,SGIN,
     1 TMIN,EPSTN,THSTN,CRSTN,TIM,TIM1,THIN,SIGAV,TIMAV,
     2 TEMAV,TINC,IEC,NS,NBPT,ICT)
      DIMENSION EYBK(1),TEMP(1),ALPH(1),STBKP(10,10),
     1 EPBK(10,10),DE(10,10),AL(10),SIGSTR(10),FOR(1),EL(1)
      COMMON SIGIN,TEMIN,SIG1
      NS1=NS-1
      IF(IEC .GT. 0) GO TO 2
      DO 1 N=1,NS1
      AL(N)=(ALPH(N+1)-ALPH(N))/(TEMP(N+1)-TEMP(N))
      EL(N)=(EYBK(N+1)-EYBK(N))/(TEMP(N+1)-TEMP(N))
      DO 1 M=1,NBPT
    1 DE(N,M)=(STBKP(N+1,M)-STBKP(N,M))/(TEMP(N+1)-TEMP(N))
    2 DO 3 I=1,NS1
      TL=TEMP(I)
      TU=TEMP(I+1)
      NE=I
      IF(TL .LE. TMIN .AND. TMIN .LE. TU) GO TO 4
    3 CONTINUE
    4 IF(ICT .GT. 0) GO TO 22
```

```
      DO 5 J=1,NEFT
      SIGSTR(J)=STEFF(NE+1)+DE(NE,J)*(TMIN-TEMP(NE+1))
   50 FORMAT(2E15.5)
    5 CONTINUE
      NEFTS=NEFT-1
      DO 6 K=1,NEFTS
      SL=SIGSTR(K)
      SU=SIGSTR(K+1)
      ME=K
      IF(SL .LE. SGIN .AND. SGIN .LE. SU) GO TO 7
    6 CONTINUE
    7 EMN=(EFEK(NE,ME+1)-EFEK(NE,ME))/(SIGSTR(ME+1)-SIGSTR(ME))
      EFSTN=EFEK(NE,ME+1)+EMN*(SGIN-SIGSTR(ME+1))
      GO TO 23
    2 ELMI=EFEK(NE)
      ELM2=EFEK(NE+1)+EL(NE)*(TMIN-TEMP(NE+1))
      EFSTN=EFSTN-0.5*(1.0*ELM1+1.0*ELM2)*(SIG1-SGIN)
   23 WRITE(6,50) ELM1,ELM2
      TMIN=TMIN+(ALFA(NE+1)*ME(NE)*(TMIN-TEMP(NE+1)))+TAI)
      SGIN=ABS(SGIN)
      TKEL=TEMAV*5.0/9.0+255.4
      A3=1.0-FOR(4)
      DELCF=FOR(4)*FOR(1)*(LOGAK*(FOR(2))+...))
    1 EXP(-FOR(3)*TKEL)
      DELCF=DELCF+TINC
      CFSTN=DELCF+CFSTN
      RETURN
      END
```

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