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FINAL REPORT
MATERIAL RESPONSE STUDIES (MARS I)

Volume I

SUMMARY

by
S. J. Green
R. D. Perkins
S. G. Babcock

Materials & Structures Labortory
Manufacturing Development
General Motors Corporation

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FOREWORD

This report was prepared by the Applied Mechanics Section of the Materials and Structures Laboratory, Manufacturing Development, General Motors Technical Center, Warren, Michigan, under Air Force Contract F04694-67-C-0033. The work was administered by the Air Force Space and Missile Systems Organization, Air Force Systems Command, with Major N. J. Azzarita as technical administrator. Mr. R. B. Mortensen, Mr. R. A. Needham, Dr. F. A. Field and Dr. W. Barry of the Aerospace Corporation served as principal technical monitors for the Air Force.

Because of the different types of work performed in this study, the report is divided into seven separately bound volumes listed below. The present volume is one of these parts.

Volume I:	Summary
Volume II:	High Strain-Rate Response of Three Heat Shield Materials at Elevated Temperatures
Volume III:	Development of Multiaxial Stress High Strain-Rate Techniques
Volume IV:	Dynamic Mechanical Properties at Ablative Temperatures - Techniques
Volume V:	Dynamic Behavior of Polymers and Composites
Volume VI:	Mechanical Properties of Beryllium at High Strain Rates
Volume VII:	Ablation Test Specimen Environment at High Temperature

The work was performed under the supervision of Dr. C. J. Maiden. Program Manager and Principal Investigator was Mr. S. J. Green. Other project scientists included:

S. G. Babcock, Dr. A. Kumar, R. G. Kumble, J. D. Leasia,

W. F. Dais, R. D. Perkins, F. L. Schierloh.

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This technical report has been reviewed and is approved.

Nicholas J. Azzarita
Major, USAF
Project Officer
SAMSO/SMYSE

ABSTRACT

The purpose of this final report is to present the results of work performed in the Material Response Studies (MARS I). Most of the descriptions of equipment and discussions of experimental techniques that were used to perform the investigations are presented in other reports and referenced here. In addition, special reports of other work (related or of direct interest to this study) performed by the Materials and Structures Laboratory are referenced as is appropriate.

This volume of the final report is a summary of the work performed. This is the first of seven volumes and basically contains the introduction and conclusions from the other six volumes. Each of the six technical volumes has been written as an integral unit with data, conclusions and technique discussions repeated as required for completeness. Each volume has been kept as brief as possible without compromising on completeness and clarity. Furthermore, each volume is written as an engineering report rather than as a scientific journal because it is realized that much of the information is to be used directly as design data.

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INTRODUCTION

The purpose of the Material Response Studies (MARS I) program was to develop new techniques for evaluating the response of current and anticipated reentry vehicle materials to impulsive loads, such as a blast from a nuclear device, and to continue investigations of characterizing the mechanical properties of these materials at high strain rates and elevated temperatures. Three engineering tasks of this study dealt with development of new techniques. The remaining task, which constituted a substantial portion of the overall effort, dealt with generating engineering data directly applicable to the design of present and future space and reentry vehicles.

The four engineering tasks were:

Task 2 - Uniaxial Stress Behavior to 10^4/second

Task 3 - Development of Multiaxial High Strain-Rate Test Techniques

Task 4 - Mechanical Properties of Ablative Materials up to Active Ablation Temperature

Task 5 - Fundamental Study of the High Strain-Rate Behavior of Composites

Each of the tasks is discussed as follows: Task 2 is presented in Sections II and VI; Task 3 in Section III; Task 4 in Sections IV and VII; and Task 5 in Section V. In each section an introduction is presented along with general conclusions reached from the completed work.

The references presented here are for related work previously published by the Materials and Structures Laboratory as well as other publications of interest to the work.

SECTION I

HIGH STRAIN-RATE RESPONSE OF THREE HEAT SHIELD MATERIALS AT ELEVATED TEMPERATURES

Design of reentry vehicles requires the knowledge of the high strain-rate behavior of candidate heat shield and structural materials. Strain rates up to 10 - 10^2/second are produced under blast loading and as high as 10^5 - 10^8/second under shock loading conditions. Since little or no high strain-rate data exist for the newest candidate materials, techniques for characterizing these materials at high strain rates must be developed.

The objective of this program, MARS Task 2, was to extend and continue work initiated under previous defense contracts.(1, 2, 3) This extension called for uniaxial-stress tensile and compressive characterization of candidate materials (quartz phenolic, silica phenolic, and carbon phenolic) at strain rates from 10^{-3} to about 10^3/second at temperatures up to about 600°F. In this study, techniques were developed to determine the effect of heating rate/time at temperature. Some understanding has been advanced previously,(2) but only quantitative results were known. Techniques for conducting very high rate tensile tests (>10^2/second) were also developed. Tensile strain measuring techniques were developed to accurately and reliably determine strain at low and intermediate strain rates and at elevated temperatures.

The inhomogeneity and anisotropy of the heat shield composites must be evaluated for design purposes. In this study, sample size was considered, extending previous investigations,(3) in order to assess the effect of the inhomogeneity, or size effect.

Investigations were performed with the load applied parallel and normal to the fiber layup as well as intermediate angles to the layup to evaluate the material anisotropy. The obtained results were compared to analytical calculations. Hopefully these results will provide an understanding of composite materials under generalized loading conditions.

The objective also called for extending to elevated temperatures the investigations on materials preconditioned with an impulsive load,(3) either a uniaxial-strain preshock or a uniaxial-stress preload. Techniques were developed to perform uniaxial-strain preshocks at elevated temperature and for separating the effects of the shock from those from the thermal cycle. Techniques were also developed to load a specimen in uniaxial stress and stop the test at some precise point just prior to fracture, and then reload to fracture without undergoing a thermal cycle.

Although the primary purpose of this task was to study the high strain-rate response of candidate materials, a major fallout is the evaluation of the reliability of fabrication techniques for composite materials. Indeed in some cases it was discovered that fabrication techniques were at a stage where material reliability was so poor that strength scatter far overshadowed time dependent effects such as strain-rate, temperature, and anisotropy. On this basis, vehicle design would have to rely on highly "degraded" material properties to produce a reliable vehicle.

The outline of this report is similar to previous results.(3) Where necessary, results from the initial work were included in this report for clarity. Appendix A describes the test materials used in these studies. Appendix B describes the equipment used to perform the tests. The derivation and explanation of the statistical approach used to extablish confidence intervals on the test results is found in Appendix C. Appendix D contains the results of a limited room temperature compression characterization of two 3-dimensional weave antenna-window materials.

A summary of the results of this study is as follows:

1. Large material scatter observed in this study points out the requirements for improved material fabrication techniques in order to reliably apply the results from these tests to design problems. Nevertheless, this study has shown that temperatures up to 600°F cause considerable degradation in heat shield structural characteristics.

2. Although not simple orthotropic composites, present candidate two-dimensional heat shield composite mechanical behavior can be predicted using existing theoretical relationships.

3. Fiber reinforced phenolic heat shield materials preconditioned by a compressive shock wave loading exhibit subsequent mechanical degradation depending on the direction and temperature of loading. Room temperature uniaxial-strain preshocks up to 20 kilobars produce 15-20% uniaxial-stress compressive strength degradation when preshocked and completely unloaded then subsequently loaded parallel to the fiber layup. When partial unloading occurs or the test temperature is increased to 600°F, 60-70% degradation can result for this loading direction.

Tensile strength degradation when loaded normal to the fiber layup after 4 - 5 kilobar preshock pulses approaches 95% regardless of test temperature.

4. Room temperature uniaxial-stress loadings at strain rates near 1-10/second up to 90% of the "static" (10^{-3}/second) fracture strength produces no degradation on future loadings. Higher loadings produce noticeable degradation depending on how near to the "static" fracture strength the load terminates. Elevated temperature (600°F) produces greater degradation for similar loadings only where the matrix tensile strength plays a role in failure, compression parallel to the fiber layup and tension normal to the fiber layup.

SECTION II

DEVELOPMENT OF MULTIAXIAL STRESS HIGH STRAIN-RATE TECHNIQUES

Determining material response, i.e. strength, stiffness, ductility, and fracture under rapid loading or impulsive loading conditions, has become a necessity as structural applications are subjected to such loadings. Blast loading of structures from conventional blast or nuclear devices, high energy forming techniques and high velocity impact are present applications requiring multiaxial dynamic material properties.

Techniques have been developed to investigate material behavior under high strain-rate uniaxial stress loading,(4-9) and high strain-rate data have been generated on a variety of materials.(10-17) Test techniques are difficult, particularly at the highest strain rates, and must be carefully reviewed before accepting published data. Material response under high strain-rate biaxial or triaxial stress loading is even more difficult to obtain, and only a few attempts at obtaining fundamental data have been made.(18-21)

The most reliable multiaxial stress, high strain-rate data on a wide variety of materials is found in recent flat plate work, where experimenters have impacted one plate into another, thereby creating an uniaxial strain loading.(22-27) Strain rates are 10^5/second and higher in the shock front produced upon impact and decrease as the shock front is attenuated. The conventional stress-strain curve cannot be obtained from these tests, but yield (or fracture) at various strain rates can be studied to some extent by measuring the "elastic" wave magnitude as the shock front is attenuated. These data can be compared to uniaxial stress data by resorting to some assumed yield/fracture criterion. A general yield/fracture criterion, however, cannot be obtained from these tests. The discussion in this volume does not include the flat plate experiments, since only statically determinant loadings are considered.

After searching the available literature on the means of creating a statically-determinant biaxial loading, the method of loading a tubular specimen with axial load and internal or external fluid pressure was selected as the most suitable for nonhomogeneous, nonisotropic materials. On this basis a machine capable of producing these loadings for strain rates to 10^2/second was designed and constructed. Details of the machine design and instrumentation as well as preliminary data on an aluminum alloy are included in this volume.

SECTION III

DYNAMIC MECHANICAL PROPERTIES AT ABLATIVE TEMPERATURES-TECHNIQUES

The development of failure criteria for reentry vehicle heat shields under blast and x-ray loading conditions requires a detailed knowledge of the ablator material response to dynamic loading under conditions of reentry environment. Testing heat shield materials under conditions approaching reentry environments has been limited until recently to screening techniques including material erosion rate studies and rear surface temperature rise studies.(28, 29, 30) Testing materials under conditions of high strain-rate loading and subablation temperatures is currently in progress and several reports on current and future materials have been published.(2, 3, 31)

The objective of this study is to develop a technique or techniques to couple high strain-rate testing with conditions of reentry environment. Early investigators performed mechanical low strain-rate (10^{-2}/second and below) tests on ablator materials such as graphite phenolic by slowly heating the material to a charred state (up to temperatures near 6500°F) in a high temperature furnace in various atmospheres.(32, 33, 34, 35) Other investigators have reported testing similar materials up to temperatures near 5000°F where the material was cooled to room temperature and reheated to the test temperature in a furnace with a testing device located inside.(36, 37) Fracture stress and strain were determined as a function of test temperature. Due to the chemical processes that take place on charring of ablator materials and the fact that time-temperature effects are known to exist, some doubt is raised as to the validity of these test results when applied to the more rapid heating environment typical of reentry. More recent work to study the effect of rapid heating (10^3°F/second) on typical charring ablator materials has eliminated the slow heating environment (and subsequent long times at elevated temperature) and the thermal cycling present in the other studies.(38) This work involved heating materials to ablation temperatures within several seconds using a plasma jet facility and testing the materials in tension at strain rates near 10^{-2}/second. This work suffered from several limitations. The use of a plasma jet limited the upper temperature attained to about 4800°F in addition to placing severe degradation effects on the subsequent bulk material properties that were measured. Very thin specimens were used in order to minimize the thermal gradient (and resulting thermal stresses) developed during heat-up since the plasma jet heats from one surface only. Recent studies on the effect of specimen size on the bulk material properties of laminated heat shield materials(3, 31) indicate that the specimen size used in the plasma jet studies(38) was below the minimum acceptable size.

The results of the present study, considering the problems associated with the other investigations, are described in this report. It is hoped that test results obtained from these techniques will provide detailed data for the establishment of more meaningful material failure criteria. While considering heating techniques that appeared potentially applicable for adaption to existing low-to-medium strain-rate equipment at General Motors, an analytical study of the experimental environment was conducted in order to assist in the data interpretation. Analytical techniques were developed to predict the temperature profile and thermal stress profile of an ablating cylindrical specimen subjected to a heat source either at the surface or internally generated by some in-depth heating source. This analysis is discussed in Section I of this report along with two example cases to show the usefulness of the analysis. Some of the primary physical changes that accompany the heating or cooling of a charring ablator reentry vehicle material are discussed in this section in order to point out the difficulties in any analytical treatment of this subject.

Section II describes in detail the preliminary analysis and subsequent experimental technique feasibility studies made to choose a suitable heating technique. Considerations discussed in Section I were thoroughly infiltrated in the technique study. Heating systems were divided into two major areas: surface heating techniques and body type or in-depth heating techniques. Surface heating techniques discussed include convective heating (electric arc plasma jet) and radiant heating (arc image and radiant infrared). In-depth heating techniques considered and discussed include resistance, induction, dielectric, and electron beam heating sources. Section III discusses temperature measurement at very high temperatures and the proposed solutions for this study.

The primary concern in developing techniques to couple high strain-rate testing with the high temperatures encountered in reentry was to eliminate, or at least minimize, all effects on the strain-rate behavior other than high temperature. Existing techniques for heating ablator materials to very high temperatures, such as plasma jet, arc-image, and radiant infrared heating, are capable of heating materials to 5000°F and higher. These techniques suffer from the major disadvantage that energy is deposited on the surface of the material, or in other words, there is no direct in-depth penetration at the infrared frequencies. Internal heating takes place by conduction only and, therefore, is a time-dependent process. Very large temperature gradients develop in the early stage of heating resulting in thermally-induced stresses. These stresses are superimposed on the mechanical stresses imposed on the material during high strain-rate testing, thus making measurement of the material response highly dubious (actual pretest thermal cracking can occur). Several techniques to overcome this problem are suggested including reducing the test sample size and heating slowly. Both of these techniques are unacceptable since the ablator materials possess definite size-effect limitations and time-at-temperature effects.

In-depth heating, whereby heat is generated within the material volume, reduces thermal gradient magnitudes to acceptable limits. Small thermal gradients are always present in the ablator materials because of the electrical property difference between the fiber and matrix constituents. Initial in-depth heating tests at heating rates near 10^3°F/second using resistance and induction techniques indicated that if any thermal gradients existed between the fibers and matrix, no degradation resulted.

Since existing technology for the surface heating techniques is well documented, primary effort in this study was placed on developing in-depth heating techniques. As for surface techniques, arc-image heating was found to possess ideal advantages for laboratory heating. A unique reflecting-optics system was designed to allow 360° radial coverage of a cylindrical sample. Resistive and inductive techniques were investigated because two of the ablator materials to be tested include carbon phenolic and graphite, which are electrically conductive. In addition, the decomposed carbonaceous char resulting from heating of silica and quartz phenolic is conductive. Both of these techniques, as described in Section II of this report, worked very well. Potential heating rates up to 10^4°F/second to graphite sublimation temperatures ($\sim$ 6500°F) were realized. Adaptation to the existing Medium Strain-Rate equipment at General Motors is simple.

Dielectric (microwave) heating proved satisfactory for the non-conductive silica and quartz phenolic only. Heating in-depth stops as charring begins and surface heating takes place in the form of a plasma on the surface. Rapid heating ($\sim$ 10^3°F/second) is possible with higher power generators. Potential solutions to this problem appear to be in combining microwave heating with resistive or inductive heating.

High energy (2 Mev) electron beam heating proved to be potentially useful especially for very rapid heating ($\sim$ 10^4 - 10^5°F/second) of dielectric materials.

SECTION IV

DYNAMIC BEHAVIOR OF POLYMERS AND COMPOSITES

Predictions of the effect of impulsive loads are based partly on a knowledge of the dynamic properties of the medium. Various computer programs have been developed to which material property parameters are fed as inputs. In order to obtain better agreement between the predictions and the experimental measurements, a constitutive equation of the medium, which incorporates a strain-rate effect, is needed. For this reason, experimentally determined strain-rate effects on reentry vehicle heat shield ablative composites have been reported in Volume II of Material Response Studies$^{(31)}$ (MARS I).

Empirical constitutive relations$^{(39)}$ have been developed to represent the experimentally determined strain-rate sensitive properties of some materials. While the empirical relations are helpful in analytical calculations, they suffer from the disadvantage that extrapolation and interpolation cannot be made with sufficient reliability. An understanding of the basic mechanisms of deformation and fracture provides the only rational basis for the development of the constitutive equation. Such a basic understanding would serve as a guide for the engineer who is primarily interested in analytical expressions for the constitutive equation. The ablative heat shield materials considered are ceramic fabrics such as quartz, silica and carbon in phenolic matrix. The time-temperature sensitive behavior of the ablative composite is attributed primarily to the polymeric matrix at low and moderate temperatures.

Section I of this report constitutes a literature survey supplemented by new data on typical polymers obtained at the GM Materials and Structures Laboratory. A number of polymers were selected as typical of the wide variety of polymers. The primary emphasis is placed on the rationalization of the high strain-rate behavior in terms of the known molecular theories of deformation. The dynamic oscillatory data, which is available for some materials, is frequently used to aid the interpretation of the molecular mechanisms of deformation in polymers.

Section II of this report deals with the nature of the fiber-matrix bond and its effect on the mechanisms of fracturing. The effect of strain rate on the strain required to produce fracture is related intimately to the mode of the fracture. Preliminary work on carbon and quartz phenolic indicates that the effect of increasing the strain-rate on the strain to fracture is different in each of these materials. In the case of quartz phenolic, the fracture is fibrous and the effect of increasing the strain rate is to increase the strain to fracture. In the case of carbon phenolic, however, increasing the strain rate reduces the strain to fracture. A detailed investigation of the mechanisms of fracturing in single ply laminates of carbon and quartz phenolic is presented and applied to real composites. Finally, the fracture strength of composites in compression and in tension at various lay-up angles is explained on the basis of microscopic fracture mechanisms.

A summary of the results of this study is as follows:

1. The strain-rate sensitivity of a number of polymers can be rationalized in terms of the molecular mechanisms of deformation. For PMMA, the stress versus

logarithm of strain-rate curve, at small strains (2 percent), is sigmoidal. This is attributed to the side group rotation corresponding to the β transition in PMMA. At larger strains the effect of the β transition is masked as the movement of the backbone molecular chains becomes more pronounced. The yield stress varies linearly with the logarithm of the strain rate. The strain-rate sensitivity of the yield stress increases with strain but decreases rapidly with increasing temperature.

2. The increase in stress at 2 percent strain ($\sigma_{1000}-\sigma_{.001}$) with increasing strain rate is 1.6 and 2.4 KSI for low (0.92) and high (0.96) density polyethylene respectively. The normalized strain-rate sensitivity equals 1.5 for low density polyethylene and 4 for high density polyethylene. The strain-rate sensitivity increases monotonically with strain rate for both the polyethylenes at room temperature with the increase being more rapid for the high density polyethylene. The strain-rate sensitivity of both polyethylenes decreases with an increase in temperature.

3. The general trends observed for PMMA, namely the decrease in strain-rate sensitivity with increasing temperature and decreasing strain, are also observed for phenol formaldehyde resin. The stress biased thermally activated cooperative segmental reorientation should predict such a behavior.

4. The fracture of quartz phenolic in compression follows the plane of weakness, which is along the layup angle. The limiting criteria here is the interlaminate shear

failure. For carbon phenolic the fracture is along the plane of maximum shear. The failure plane of silica phenolic lies between these two limiting cases.

5. In quartz phenolic the fracture in tension is splintery and considerable bond damage precedes ultimate fracture. Increasing strain rate increases the strain to fracture. In the case of quartz phenolic, the bond strength is much less than the fiber strength and higher strain rates promote the propagation of inclined cracks rather than the catastrophic disc shaped cracks. The zigzag propagation of the cracks delays failure thereby increasing the dynamic ($\dot{\varepsilon} = 10$/second) tensile strength of quartz phenolic. However, in the case of carbon phenolic, the cracks continue at the same level resulting in a straight localized failure. This leads to reduced fracture strain with increasing strain rate resulting in lower dynamic tensile strength.

SECTION V

MECHANICAL PROPERTIES OF BERYLLIUM AT HIGH STRAIN RATES

The metal beryllium is endowed with some exceptional properties such as a high strength-to-weight ratio, high temperature strength, a moderately low thermal expansion coefficient, a high thermal conductivity and a relatively high melting point. This unique combination of properties makes beryllium a very attractive metal for missiles and spacecraft applications. In order to use it as a structural material for these applications, an investigation of its response to impulsive loads at a range of temperatures is imperative. These testing conditions are selected to simulate the loading rate and temperature environment produced by an air blast from a nuclear explosion which could be experienced by a reentry vehicle.

The objective of the present program has been to study the mechanical properties of beryllium at high strain rates of up to 10^3/second and temperatures ranging from room to 700°F. The following types of commercial beryllium were subjected to high strain rates in uniaxial stress, both in tension as well as compression.

		BeO	Grain Size
1.	Ingot Sheet	0.01%	250 μ
2.	S-200 Block	2.00%	35 μ
3.	I-400 Rod	4.00%	8 μ

The two most significant factors influencing the mechanical properties of beryllium are purity and grain size, with the latter being affected by purity and fabrication history.

Thus the effect of grain size and impurity content (BeO) on the yield stress, flow stress, ultimate tensile stress and ductility of beryllium at high strain rates and elevated temperature has been investigated.

Some of the conclusions from this study are:

1. Increase in grain size decreases the strain-rate sensitivity of beryllium.

2. Surface deformation due to machining lowers ductility of beryllium and also produces inconsistent yield strength at strain-rates greater than 10^{-3}/second.

3. Ductility of beryllium is lowered with an excessive increase in grain size or a significant increase in BeO content or increasing strain rates.

SECTION VI

ABLATION TEST SPECIMEN ENVIRONMENT AT HIGH TEMPERATURE

In order to characterize the behavior of selected reentry vehicle ablative materials under conditions of active ablation and high strain-rate deformation, it is necessary to devise techniques to determine material strength, stiffness, and ductility for rates of loading from 10^{-4} to 10^{4}/second and for temperatures up to 4500 - 6500°F. Inherent in such a program is an analytical study of the experimental environment in order to insure and specify its similarity to actual reentry environments. Midwest Applied Science Corporation (MASC) has developed computer programs for describing test specimen thermal history and thermal stress history for a variety of heating and cooling techniques. To describe the ablative materials in an accurate way, these programs make use of all available material property data and in some instances allow for variable properties which might be generated in the future.

It is the purpose of this report to formulate, develop, and describe these programs. All necessary assumptions are listed and justified. Equations and conditions governing respective phenomena are indicated. Numerical techniques and program operation are discussed. The main body of the report (in three sections) contains essential developments, discussion and conclusions of the integrated thermal history program, and thermal stress history programs. Detailed derivations and operating instructions for these programs are discussed in the lettered Appendixes A, B, C, D and E.

Section I deals with the thermodynamic environment and develops and describes the integrated thermal history program. This program has been devised to give temperature and temperature derivative profiles for cylindrical ablative composites during heating and cooling in a laboratory environment. Actual reentry conditions are not intended to be simulated in total. The program allows for any combination of surface or body heating and provides a punched and printed thermal history output.

Section II deals with the thermal stress environment, and develops and describes the thermal stress history programs. These programs are separate for pre-ablation, and ablation-all char in order to provide for discontinuous heating and cooling situations. These programs take the punched output from the thermal history program directly and print quasi-static principal stress profiles for each separate case. Material properties are considered orthotropic, temperature dependent and visco-elastic. Visco-elastic properties of these composites are accounted for by using the simple quasi-elastic approximation.

Section III contains a discussion of the results of these programs, for example, cases of convective heating. A simple failure analysis is discussed, which, when used with the results of the thermal stress programs, would be useful in predicting thermal cracks in the char prior to high strain-rate testing. Possible extensions of these programs to extremely high thermal energy deposition and to other geometries is discussed briefly.

Appendix A contains the complex finite-difference relationships and equations employed in the integrated thermal history program. Appendix B gives detailed operating instructions and symbols for the temperature program's use. In Appendix C viscoelastic stress analysis and the material property characterization appropriate for the quasi-elastic approximation are described. Appendix D presents the expression which describes the ablation gas pressure in char in the ablation thermal stress program. Appendix E gives detailed operating instructions and symbols for the thermal stress program's use.

The thermal history and thermal stress history programs developed in this study to analyze laboratory test specimen environment are quite general in nature, although they presently are restricted to cylindrical geometry where end effects can be neglected. The quasi-static assumption of the thermal stress programs further restricts their use to moderate heating rates. Temperature-change periods for severe heating rates would have to be compared with the stress wave periods indicated in Section II.

To extend the programs to extremely high rates of energy deposition, the thermal stress problem would have to be reformulated to include wave phenomena. It appears that this can be accomplished although the numerical solution for wave propagation in materials of varying properties will be difficult and involve long computation times. In this respect it is anticipated that the thermal stress program would be directly coupled to the temperature program.

To extend these programs to other geometries than cylindrical, a reformulation will be necessary. The difficulty of such a task depends directly on the symmetry of the problem.

In conclusion, it appears that the programs as developed will provide a realistic analysis of test specimen environment based on all existing material data. Furthermore, it appears that the programs are capable of extension to other cases of interest with the required effort depending largely on the heating rate and geometry of the specific problem.

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13 ABSTRACT

The purpose of this final report is to present the results of work performed in the Material Response Studies (MARS I). Most of the descriptions of equipment and discussions of experimental techniques that were used to perform the investigations are presented in other reports and referenced here. In addition, special reports of other work (related or of direct interest to this study) performed by the Materials and Structures Laboratory are referenced as is appropriate.

This volume of the final report is a summary of the work performed. This is the first of seven volumes and basically contains the introduction and conclusions from the other six volumes. Each of the six technical volumes has been written as an integral unit with data, conclusions and technique discussions repeated as required for completeness. Each volume has been kept as brief as possible without compromising on completeness and clarity. Furthermore, each volume is written as an engineering report rather than as a scientific journal because it is realized that much of the information is to be used directly as design data.

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