NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-944

Environmental and Physical Effects on the Response of Balsa Wood as an Energy Dissipator

A. C. Knoell

JPL
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

June 15, 1966

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-944

Environmental and Physical Effects on the Response of Balsa Wood as an Energy Dissipator

A. C. Knoell

M. E. Alper

M. E. Alper, *Manager*
Applied Mechanics Section

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

June 15, 1966

Prepared Under Contract No. NAS 7-100
National Aeronautics & Space Administration

CONTENTS

TABLES

FIGURES

FIGURES (Cont'd)

ABSTRACT

30120

This Report describes the environmental and physical effects on the response of balsa wood as an energy dissipator. The description includes the balsa-wood development program, balsa-wood specimens, static testing, and an analysis and discussion of test results. This document also comprises a list of conclusions based on the investigation.

I. INTRODUCTION

The continuing development of spacecraft has generated a definite need to evaluate and develop energy-dissipating materials and devices capable of protecting the gross vehicle, component, or payload devices during lunar or planetary landings. In this application, efficiency and reliability are prime considerations, the latter being readily demonstrated by repeatability of test performance. The efficiency of an energy dissipator must, however, be established in accordance with spacecraft system constraints which include maximum energy dissipation, minimum deceleration, and minimum dissipator weight. These constraints give rise to two types of efficiencies which may be classified as structural and material.

Structural efficiency relates to those parameters whose determination requires the use of the force-displacement diagram obtained during crushing of the energy dissipator. These parameters include specific energy dissipation, crushing stress, crushing stress variation (α), and elastic rebound, which are defined below.

For maximum structural efficiency of an energy dissipating element, the optimum force-displacement history is shown by the solid curve, ABC, in Fig. 1.

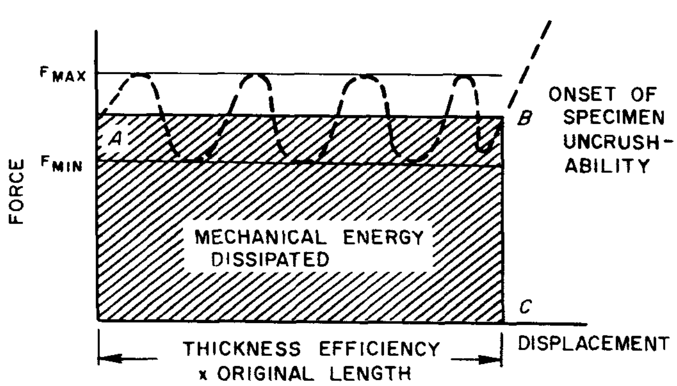

Fig. 1. Optimum force-displacement history

This type of response provides maximum energy dissipation over the entire crushing stroke. The area under the force-displacement curve is the mechanical energy dissipated during crushing. Dividing the mechanical energy dissipated by the gross weight of the structural element establishes the structural efficiency parameter, specific energy dissipation. In addition to being a useful design parameter, specific energy dissipation also serves as a means of comparing the energy dissipating capacity of different dissipators.

Dividing the crushing force by the gross area of the element on which the force is acting determines the crushing stress. This parameter provides a measure of the deceleration level of an impact limiter (payload plus energy dissipator) as given by the general kinetic relation:

$$F = \int_A \sigma \, dA = ma$$

where

σ = crushing stress of the energy dissipator

A = area on which crushing stress acts

m = mass of the impact limiter

a = deceleration of the impact limiter

Crushing stress is also a means of comparing different energy dissipators of the same geometry when one recognizes that, for a given value of specific energy dissipation, lower crushing stress levels result in lower deceleration levels.

Crushing stress variation, α, is the ratio of the maximum to minimum crushing stress (or force if the area of the energy dissipator remains constant during crushing). This parameter provides a gross measure of specimen response during crushing. The parameter, α, and the associated frequency (if the response is periodic as shown by the dash curve of Fig. 1) is useful in the study of impact limiter dynamics during crushing of the energy dissipator.

Since the primary function of an energy dissipator is to dissipate rather than absorb energy, the amount of elastic recoverable (rebound) energy should be a minimum. The ideal case (no rebound) is illustrated by the vertical line BC in Fig. 1. No definition currently exists for the elastic rebound parameter; however, it could be expressed as a percentage of the total amount of energy absorbed. For the design of an impact limiter, the rebound characteristics of the energy dissipator should be known.

Material efficiency is concerned with the behavior of the energy dissipator during the crushing process and relates to those parameters which may be determined by a physical measurement (although it is generally more expedient to utilize the force-displacement diagram for data reduction). The most significant material efficiency parameter is thickness efficiency, which determines the quantity of dissipator required to dissipate a given amount of energy. Thickness efficiency is defined as the ratio of (1) the difference in energy dissipator height before and after crushing to (2) the height before crushing. It is a measure of the maximum stroke capability of an energy dissipator (assuming no elastic rebound, as in Fig. 1) and is limited by the onset of specimen uncrushability, since the subsequent loading region is of no design interest. In effect, this parameter is a measure of the failure mechanism in the energy dissipating process.

II. BALSA-WOOD DEVELOPMENTAL PROGRAM

Balsa wood, an RF transparent material, is known to be a structurally and materially efficient energy dissipator in an Earth environment. Initial investigations (Ref. 1), which established the response of balsa wood at discrete levels of moisture content and temperature, have demonstrated that balsa wood develops high specific energy dissipation capacities at relatively low crushing stresses. These investigations have led to the design, fabrication, and prototype testing of spherical impact limiters using balsa wood as the energy dissipating material.

The design capability associated with balsa wood impact limiters could be further enhanced, however, by a better understanding of physical and environmental effects on the response of balsa wood as an energy dissipator. To forward this understanding, a developmental program was undertaken to provide engineering data in the form of design relations establishing the effects of temperature, pressure, moisture content, and density on the energy dissipating capability of balsa wood.

In establishing these relations, a range of program parameters was selected to cover potential environmental and physical conditions of the balsa wood impact limiter at lunar or planetary impact. The ranges of parameters considered were:

$-125 < \text{mean temperature } (°\text{F}) < 300$

$10^{-5} < \text{pressure (mm Hg)} < 760$

$0 \leq \text{moisture content } (\%) < 20$

$5 < \text{nominal balsa wood density } (\text{lb/ft}^3) < 15$

Engineering data were obtained within the ranges of these parameters by performing static penetration tests parallel to the grain of balsa wood specimens. Penetration testing, rather than platen testing, was selected to simulate more closely the crushing of a doubly-curved impact limiter since a certain amount of lateral confinement of the loaded element is afforded by the adjacent balsa wood. The program was predicated on providing data points which represent an average of at least three tests.

III. SPECIMENS

A. Balsa-Wood Selection Criteria

Since balsa wood is a natural product, it was recognized that its physical properties could not be closely controlled nor readily varied. However, a method of selection, other than random, was established to obtain balsa wood of good quality and uniform characteristics. The selection criteria were qualitative in nature and were applied to both the timbers and the specimens obtained from each timber. The criteria stipulated that the balsa wood should be clear and free of visual defects, such as decay and splits, and should be composed of straight grain orientation and uniform growth rings. Also, the wood met the specifications for grades A and AA, as established by the U.S. War Production Board (Ref. 2) in 1944.

B. Specimen Development, Characteristics, and Classification

The balsa wood specimens used in the program were 3-in. cubes with a grain orientation parallel to the sides. The growth ring radius (measured at the center of each specimen) varied from 3.5 to 6 in.

In obtaining specimens, a balsa wood timber was first faced on two mutually perpendicular sides to determine the grain orientation of the wood. This provided a baseline from which a rectangular parallelopiped was developed with the sides parallel to the grain of the wood. The specimens were then sectioned normally to the longitudinal axis of the parallelopiped. All specimens obtained from a single timber constituted a batch.

Each specimen was weighed and measured at atmospheric pressure and ambient temperature (approximately 75°F), and its nominal density was computed. This provided a means of selecting test specimens of a given nominal density within a tolerance of $\pm$ 0.5 lb/ft^3. It should be noted that the nominal density was based on the weight of the wood and water present in the specimen. To prevent changes in moisture content prior to use, the specimens were enclosed in air-tight plastic containers and stored in a room at approximately 75°F. Specimen moisture content was determined after testing by drying the wood and dividing the difference between the original and dry weight by the original weight.

To facilitate data reduction and evaluation, each specimen was assigned a three-element serial number signifying nominal density, numeral designation, and batch number, respectively. On the basis of this number, specimens were then selected to form test groups which consisted of three or more specimens of the same initial density to be tested under similar environmental and physical conditions. The test group results served to provide data points for developing the design relations outlined in Section II.

The test groups in turn formed part of a test series which consisted of all test groups having the same environmental and/or physical constants (e.g., pressure and temperature). The test series concept provided an effective means of categorizing data for the development of the actual design relations.

C. Specimen Batch Normalization Factor

The fact that batch differences existed in the program (as indeed they would exist in the fabrication of a balsa-wood impact limiter) necessitated the determination of a batch normalization factor which was applied to the structural efficiency parameters of all test specimens of the batch. Specifically, values of normalized mean crushing stress and specific energy dissipation were computed from the test data, and these values were later utilized in the development of design relationships. The normalized parameters are significant as they reflect average performance levels for a given balsa-wood density.

In determining batch normalization or "scaling" factors a minimum of two specimens from each batch (or timber) was tested in the same manner. The tests were conducted at atmospheric pressure and ambient temperature (approximately 75°F) on specimens of natural moisture content (approximately 8%). (The results are presented in Table A-6 in the Appendix.)

Each normalization factor was obtained by computing the ratio of the average batch specific energy to the average specific energy of all batches of the same balsa-wood density. In using this ratio, the actual values of specific energy dissipation and mean crushing stress of all specimens of a particular batch were divided by the normalization factor of that batch to obtain the corresponding normalized values. The normalization factor was applied only to these parameters since the factor was based on specific energy dissipation which can be equated directly to the product of the mean crushing stress and thickness efficiency (which was insensitive to batch differences), divided by the balsa-wood density (which was held relatively constant from batch to batch).

IV. STATIC TESTING

A. Test Apparatus

To establish environmental control during test performance, a multiple-control environmental test chamber was designed and built. This facility, shown in Fig. 2, is capable of maintaining a temperature and pressure environment in which a static penetration test on a specimen can be performed. The chamber consists of a cylindrical plunger of 1-in.^{2} cross-sectional area housed in a 2-in. ID (internal diameter) bellows section having a spring rate of approximately 3 lb/in. of deflection. As a result of this low spring rate, no appreciable degradation of the test record occurred. The bellows section is fastened to the top plate through an "O" ring seal connection. The top plate permits access to the central portion of the main 18-in. ID chamber for specimen insertion and removal. Within the main chamber is a 3-in. cubical copper cavity, fastened to the base plate, that houses the balsa-wood specimen. The walls and bottom of this cavity contain ducts through which the heating/cooling agent passes. In addition, two adjacent walls are spring loaded against the sides of the specimen, resulting in an applied lateral force of approximately 15 lb per side. Thus, specimens can be tested in both the confined and unconfined condition, and the effect of a small amount of lateral confinement can be observed. It should be noted, however, that this confinement is superimposed on that of the wood surrounding the plunger during penetration. To ensure test symmetry, the centers of the plunger and the cavity were aligned.

The chamber was designed to fit within the columns of a Baldwin Mark G static testing machine. This machine has two vertically moving platen heads, and the chamber was inserted between them and fastened to the lower platen. The maximum loading capacity and rate of this facility is 60,000 lb and 20 in./min, respectively.

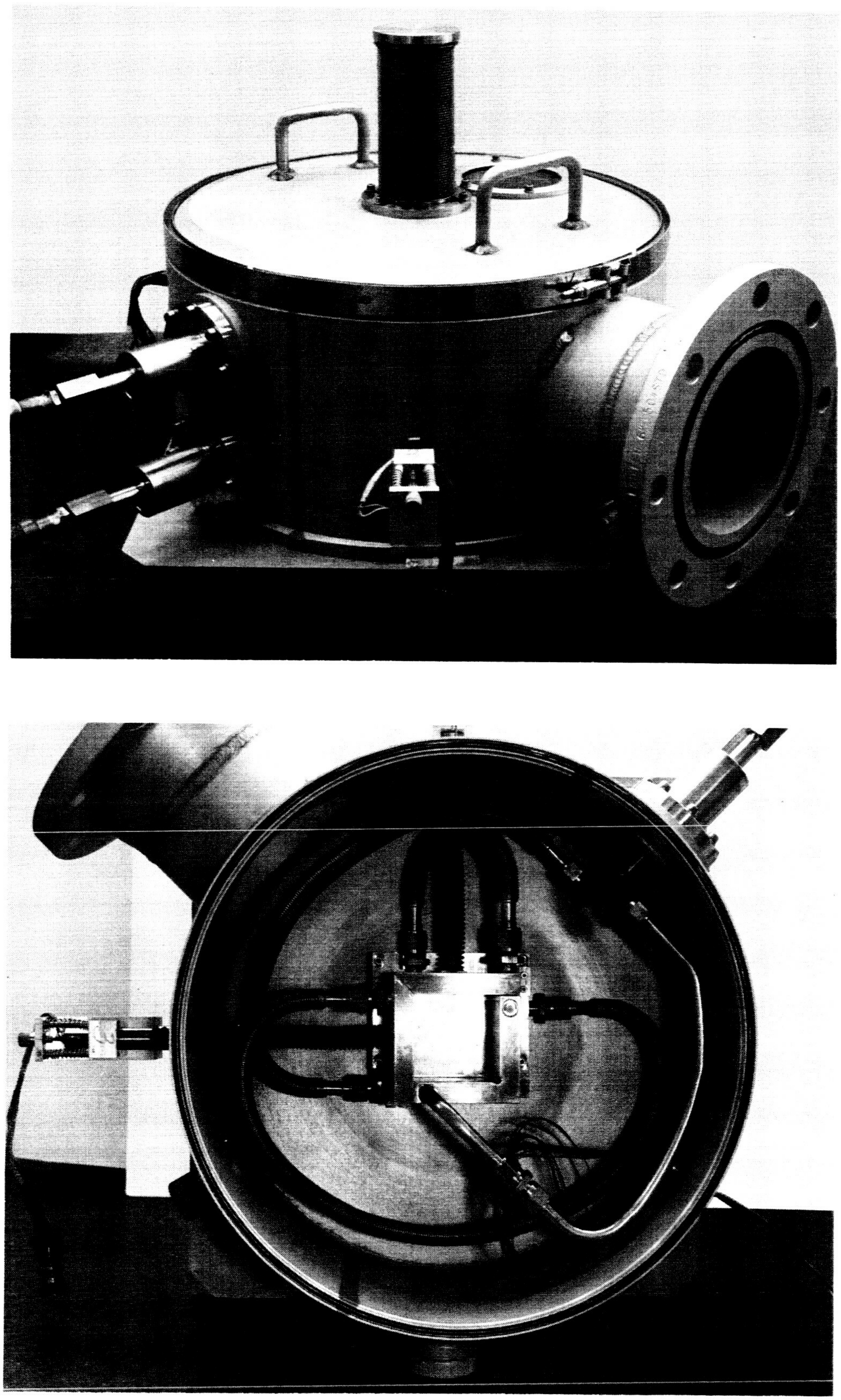

Fig. 2. Environmental static test chamber

For temperature control, a heat exchanger containing two heating elements, each capable of 550°F output, was designed and built. Nitrogen, which was the heating/cooling agent in this system, passed through the exchanger tubing which connected to the duct system in the copper cavity within the chamber. A thermocouple mounted to a wall of the copper cavity was used to monitor the temperature of the copper; it acted as a control source (via a temperature controller with an accuracy of ±5°F) for the automatic heating of the nitrogen as it passed through the unit. When the copper reached the desired temperature, it was automatically maintained by the temperature controller and the specimen was thereby heated or cooled by conduction.

A vacuum environment within the chamber was produced by a Scientific Engineering Laboratory vacuum pump connected to the chamber through a 6-in. ID bellows section. The bellows section was required due to the motion of the platen head to which the chamber was fastened. The vacuum system was capable of lowering the chamber pressure to approximately 10^{-6} torr.

B. Instrumentation

To obtain a permanent record of the specimen force-displacement response diagram, a Moseley Autograph plotter was used. This unit electrically monitored and plotted the force and motion of the platen heads of the testing machine during penetration of the plunger into the balsa-wood specimen.

In conducting tests in a vacuum, a Veco pressure gage was used to determine the pressure inside the chamber. This gage operated electrically and was capable of monitoring pressures to 10^{-9} torr with an accuracy of ±10% of the pressure reading.

Temperatures of both the specimen and copper cavity were monitored by 30-gage Cromel/Constantan thermocouples electrically connected to a temperature recorder having an accuracy of ±2% of the reading.

C. Specimen Preconditioning

Prior to insertion in the environmental test chamber, specimens to be tested in the unmoisturized (0% moisture content) and the supermoisturized (approximately 16% moisture content) condition were subjected to the following preconditioning, respectively:

1. Preconditioning in a vacuum bell jar at ambient temperature for a minimum of 17 hr.
2. Preconditioning in a moisturized steel capsule which was heated in an oven at 180°F for a minimum of 17 hr.

The first type of preconditioning was achieved by placing a specimen in a vacuum bell jar and reducing the pressure below the vapor pressure of water at ambient temperature, thus causing the water to vaporize from the specimen. This method of achieving zero moisture content (rather than heating the specimens) was considered to be more representative of the zero moisture content condition as it would occur in deep space.

To determine the time required for adequate vacuum preconditioning, three standard balsa specimens with a nominal density of approximately 7, 11, and 15 lb/ft^3 were tested. The test consisted of measuring the loss in weight of the specimen, mounted on a spring-type weight measuring device, during pump-down of the bell jar. In all cases the weight loss vs time plot became generally asymptotic after 17 hr or slightly less, and the pressure was approximately 10^{-4} torr or lower. Thus, a 17-hr preconditioning period for a zero moisture content condition was established.

The second type of preconditioning was used to establish a supermoisturized state in a specimen. Experimentally, it was found that adding 4.5 and 10 grams of water to steel capsules containing specimens of 6 and 10 lb/ft^3 nominal density, respectively, and heating the capsules in an oven at 180°F for 17 hr were sufficient to increase the moisture content of the specimens from approximately 8% (natural) to approximately 16%. The moisture content was determined after specimen exposure in a circulating air oven at 250°F for approximately 17 hr.

The moisture was uniformly distributed throughout the balsa-wood specimens. This was verified by sectioning supermoisturized samples of both nominal densities into three equal volumes and determining the densities of each section.

In comparing the natural moisture content of vacuum-dried and oven-dried similar specimens, it was experimentally found that the natural moisture content of vacuum-dried specimens was greater than that of the oven-dried specimens. The difference is indicated in Fig. 3. The results indicate that perhaps a small amount of volatiles in the balsa wood specimens were given off during the vacuum exposure.

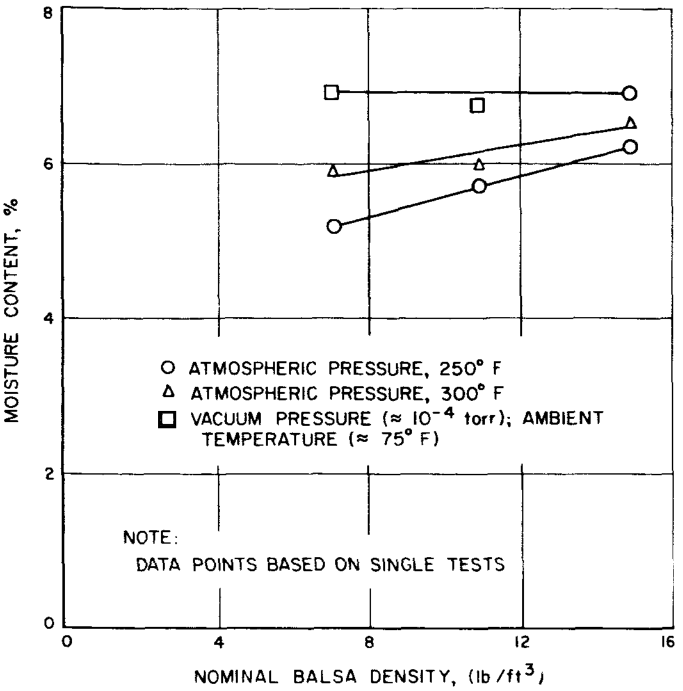

Fig. 3. Moisture content vs density

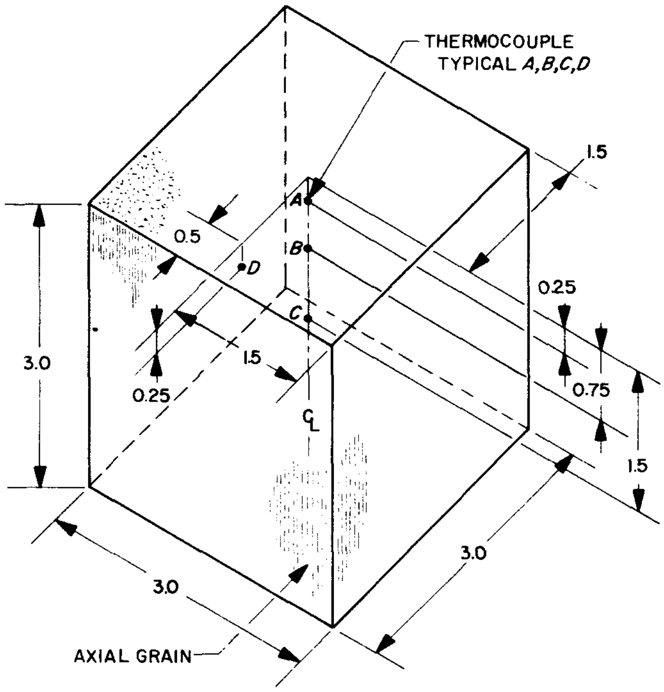

Fig. 4. Thermocouple location in typical balsa-wood temperature-time specimen

D. Test Series Temperature-Time Relation

Except for tests conducted at ambient temperatures, a temperature-time record was obtained for each test group prior to testing. The temperature-time relation was used to establish the mean temperature distribution through the center of the balsa specimens as a function of time. The record was based on the response of a single specimen and considered typical for the test group.

The mean temperature was based on the response of three thermocouples installed along the centerline of the specimen as shown in Fig. 4. In addition, a fourth thermocouple (thermocouple D of Fig. 4) was used as a reference thermocouple and was installed in all test specimens at the same location to provide a measure of repeatability of response among specimens of the same test group. A typical temperature-time record is shown in Fig. 5.

All specimens used to develop a temperature-time relation for a test group were preconditioned as required by the environment of the particular test group. The procedure for conducting the temperature-time tests was the same as that for testing specimens of a given group, except the penetration test was not performed. This procedure is given below.

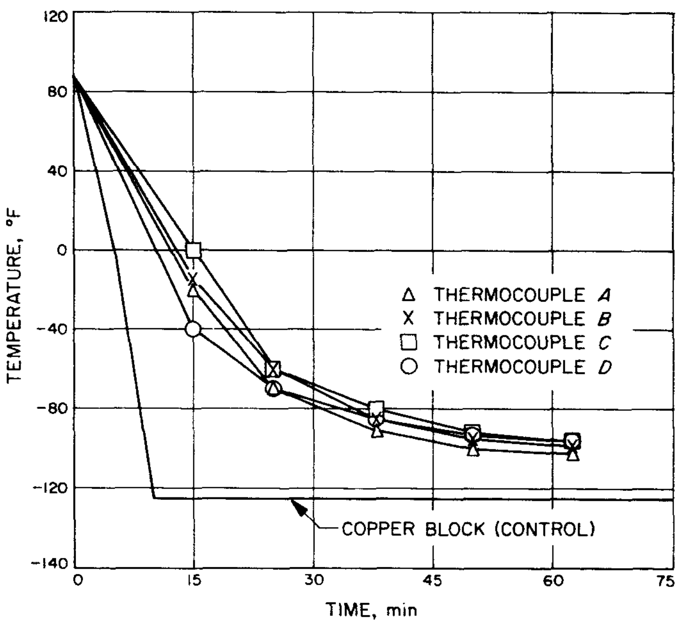

Fig. 5. Temperature-time history; specimen 6-65-4; series H

Finally, it was found that batch differences within a given test group caused no significant difference in thermal response. This was determined by performing temperature-time tests on specimens of different batches in the same manner and comparing the results.

E. Procedure

Since the program involved testing balsa-wood specimens under various environmental conditions, the detailed procedure employed was dependent on the test series. However, certain procedures were common to all test series. Immediately prior to insertion in the test chamber, each specimen was weighed and its dimensions measured. This operation served to establish the specimen density at the time of test. All tests were conducted at a plunger-penetration rate of 1 in. per minute. During the test a force-displacement record was obtained for subsequent data reduction and evaluation. After testing, each specimen was again weighed and measured, although the latter was not possible in some cases due to splitting during the test. These data provided a check against possible density changes during the test. A visual post-test inspection of the specimen was then made to determine its structural integrity.

1. Test Series 1

In this test series, unmoisturized, natural moisture content, and supermoisturized specimens were tested at atmospheric pressure and ambient temperature (approximately 75°F). Unmoisturized and natural moisture content specimens, respectively, were either preconditioned in the vacuum bell jar prior to testing or tested "as received." Supermoisturized specimens were preconditioned in the steel capsule prior to testing. Since all specimens were tested at ambient temperature, a temperature-time record was not required for this series.

After preconditioning, each test specimen was immediately weighed, measured, inserted in the test chamber, and tested. Specimens preconditioned in the steel capsule were allowed to cool to ambient temperature prior to removal from the capsule. After testing and inspection, all specimens, other than the unmoisturized specimens, were placed in the circulating air oven and dried at 250°F. The dry specimen weight and the weight at the time of the test then provided the means of computing the percent moisture content in the specimen.

2. Test Series 2

This test series involved testing specimens of natural moisture content at atmospheric pressure and temperatures equal to or less than ambient. Specimens used in this series were not preconditioned. In this series a temperature-time relation was developed for each test group, with the exception of ambient temperature test groups. For the temperature-time relation a specimen was instrumented and inserted in the copper cavity of the test chamber in the confined (spring-loaded side walls) condition. The specimen was then cooled through the use of the heat exchange unit until a steady-state temperature distribution approximating the desired mean temperature was achieved. The run was then terminated and the total elapsed time was noted. This time was then used as the "soaking" period prior to specimen testing. The temperature-time record established the rate of cooling (via the temperature control record) and the exact mean temperature of the specimen (via the imbedded thermocouples).

In performing the tests, each specimen was cooled at the proper rate and for the required time as established by the temperature-time relation for the particular test group. At the end of the "soaking" period, the specimen was tested. It was then removed from the test chamber, weighed, measured, inspected, and dried.

3. Test Series 3

In this test series, all specimens were tested in the unmoisturized condition at atmospheric pressure over a temperature range. All specimens were preconditioned in the vacuum bell jar. Prior to testing, a temperature-time relation was developed for each test group. The procedure was the same as for Test Series 2; however, the temperature-time specimen was preconditioned prior to instrumentation. After the temperature-time run, the test group was tested in the same manner as Test Series 2.

4. Test Series 4

This test series was identical to Test Series 3, except all specimens were tested in a vacuum rather than at atmospheric pressure. In conducting the temperature-time runs and tests, the vacuum pump system of the test chamber was activated at the same time as the heat exchange unit. Thus, simultaneous heating or cooling and vacuum conditioning of the test specimen occurred. In the cases where the heat exchange unit was not employed (ambient temperature tests), the vacuum pump system was activated upon insertion of the specimen in the test chamber. All tests were conducted at a chamber pressure of 4×10^{-4} torr, or less. Lower pressures generally required a considerably longer time to be attained.

V. ANALYSIS AND DISCUSSION OF TEST RESULTS

A. General

The program test results are presented in Tables A-1 through A-5 in the Appendix. In reviewing the results for each test series (Tables A-1 through A-4), it is evident that a scatter band of data exists for both the actual and normalized results of each test series. In most cases, normalizing the actual test results caused a slightly wider scatter band. The maximum deviation for both the actual and normalized test results was approximately ±15% of the average test results of similar specimens.

Also evident is the fact that the value of thickness efficiency is virtually constant for each test series. Thus, it is significant to note that thickness efficiency is relatively insensitive to the variables of wood density and test environment.

Finally, the test results indicate that the frequency of specimen splitting increased with increasing balsa density. In fact, of the 26 specimens of nominal 14 lb/ft^3 density tested in the program under various environmental conditions, only 5 specimens did not split. In general, unconfined specimens tested in a given environment showed a slightly higher frequency of splitting than their confined counterparts. The total number of split specimens, however, was quite low (excluding the nominal 14 lb/ft^3 specimens) in comparison to the number of specimens tested in the program. In all cases, the splitting was radial to the direction of load application and parallel to the grain of the wood.

B. Physical Properties

Pertinent average specimen physical properties for each test group are given in Table A-5. The data presented in this table indicate that there are definite changes in specimen physical properties between the original and the environmental test conditions. These changes, specifically in weight and volume, are significant since they must be considered in the design and fabrication of a balsa impact limiter. Changes in balsa weight and volume obviously affect the gross limiter weight and volume as well as the payload fraction and design envelope. In addition, volume changes, manifested by shrinkage or expansion, may result in splitting of the balsa.

Table A-5 indicates that maximum absolute changes in average specimen weight and volume were approximately 9% and 5%, respectively. The actual changes, however, are dependent on the environment at the time of test. As a matter of record, the average natural moisture content and growth ring radius are also presented for each test group.

C. Mechanical Properties

1. Effect of Moisture Content

The effect of moisture content on the response of balsa wood as an energy dissipator is shown in Fig. 6, 7, and 8. These Figures are derived from the data given in Table A-1.

As illustrated in Fig. 6, specific energy dissipation increases significantly with decreasing moisture content of the balsa. Specific energies equal to or exceeding 20,000 ft-lb/lb were obtained for both nominal 6 and 10 lb/ft^3 specimens at 0% moisture content. However, the variation in crushing stress as measured by the parameter, α, becomes more pronounced with decreasing moisture content. The specific energy dissipation of unconstrained specimens at 0% moisture content was

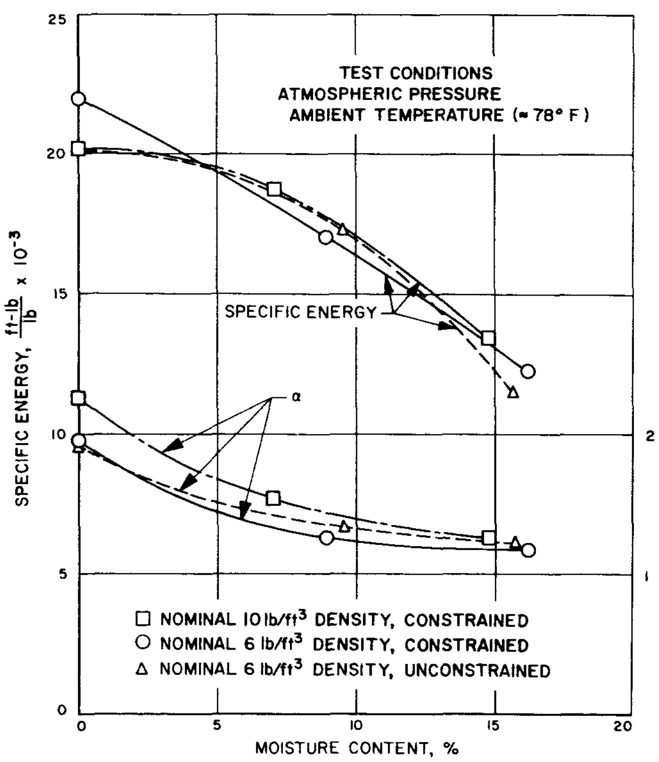

Fig. 6. Specific energy vs moisture content

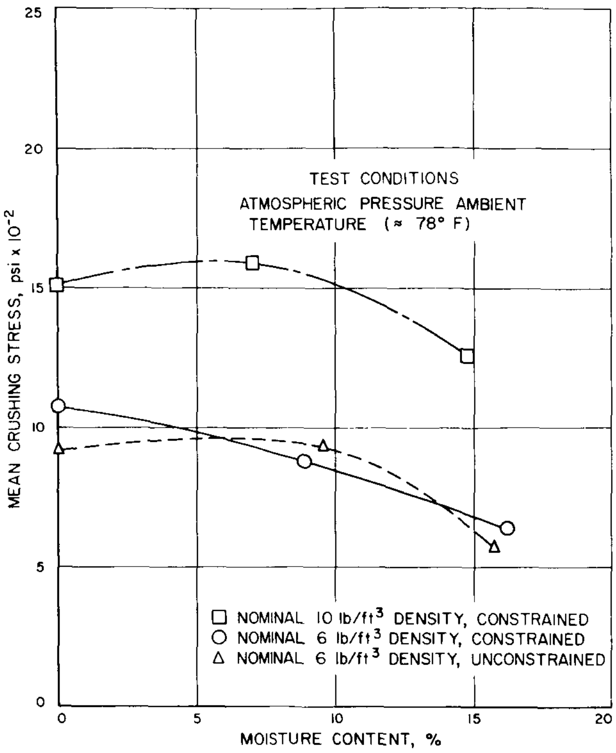

Fig. 7. Mean crushing stress vs moisture content

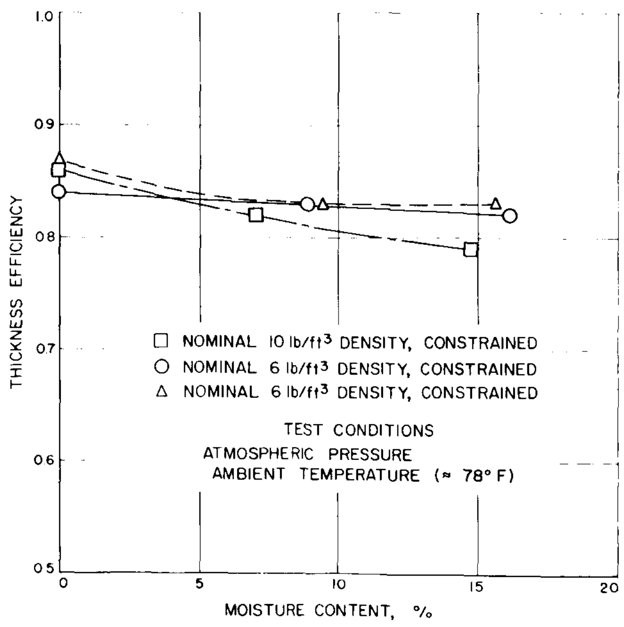

Fig. 8. Thickness efficiency vs moisture content

approximately 10% lower than that of the corresponding constrained specimens. As the moisture content of the specimens increased, however, the response was relatively insensitive to the small amount of lateral confinement.

By comparing the response of nominal 6 and 10 lb/ft^3 constrained specimens, it should be noted that a density dependence exists for the specific energy moisture content relationship in the low moisture content region. In fact, at 0% moisture content, the 10 lb/ft^3 balsa wood actually dissipated less energy than the 6 lb/ft^3 balsa wood. In this comparison it is also evident that increasing the balsa-wood density does not result in a significant increase in specific energy dissipation. This fact will be amplified and discussed later.

Increasing the balsa-wood density does, however, result in a significant increase in crushing stress as indicated in Fig. 7. The variation in crushing stress as a function of moisture content is not as pronounced as that of specific energy dissipation. Nevertheless, the crushing stress does increase with decreasing moisture content in the wood.

Finally, Fig. 8 shows that thickness efficiency increases slightly with decreasing moisture content. Values of thickness efficiency for the 10 lb/ft^3 specimens tended to be lower than the 6 lb/ft^3 specimens. For all practical purposes, however, thickness efficiency was insensitive to changes in moisture content and density of the specimens.

2. Effect of Temperature

The data presented in Tables A-2, A-3, and A-4 provide the basis for determining the effect of temperature on the energy dissipating response of balsa wood. This effect is graphically illustrated in Fig. 9 through 17. Figures

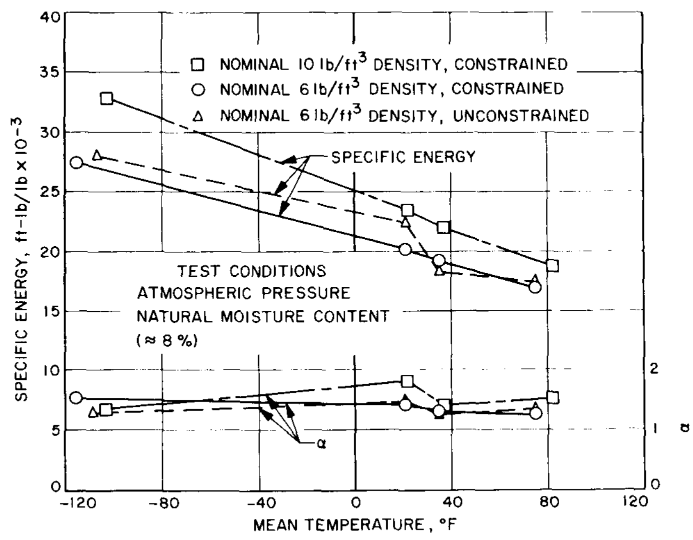

Fig. 9. Specific energy vs mean temperature; α vs mean temperature; moisture content $\approx$ 8%

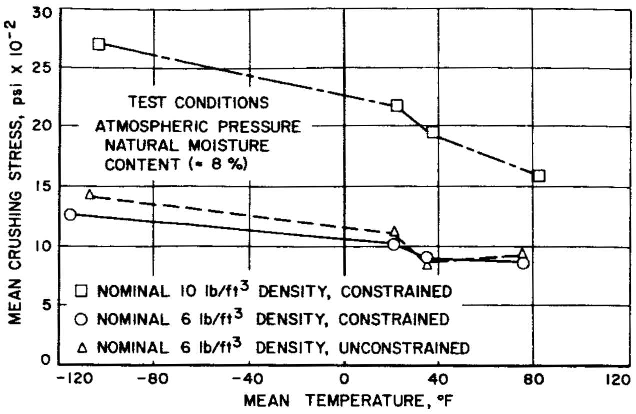

Fig. 10. Mean crushing stress vs mean temperature; moisture content ≈ 8%

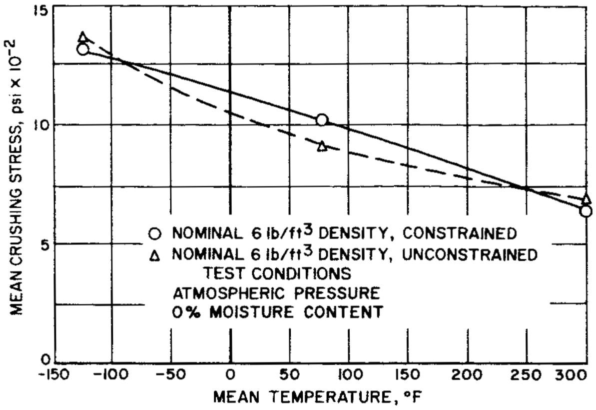

Fig. 13. Mean crushing stress vs mean temperature; moisture content, 0%

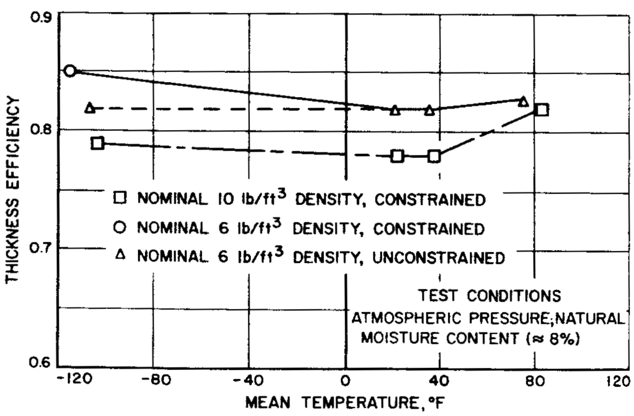

Fig. 11. Thickness efficiency vs mean temperature; moisture content ≈ 8%

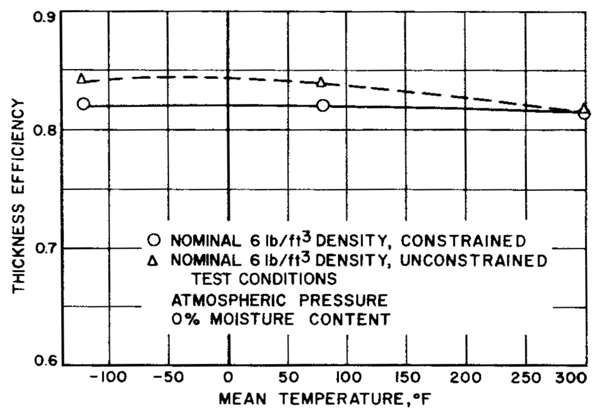

Fig. 14. Thickness efficiency vs mean temperature; moisture content, 0%

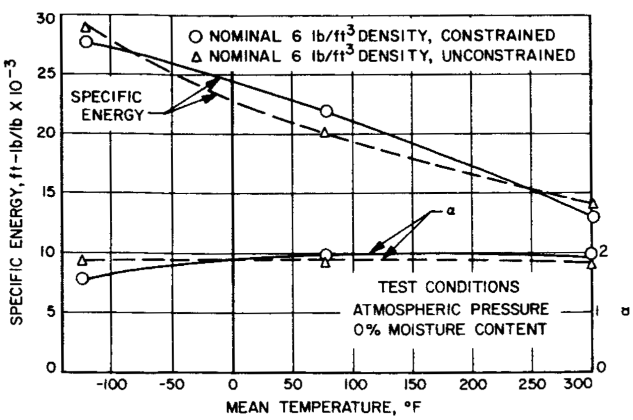

Fig. 12. Specific energy vs mean temperature; α vs mean temperature; moisture content, 0%

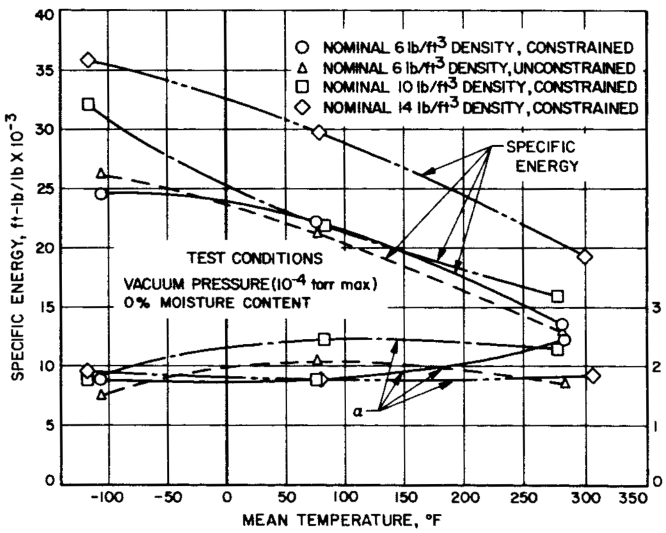

Fig. 15. Specific energy and α vs mean temperature; vacuum pressure (10^{-4} torr max)

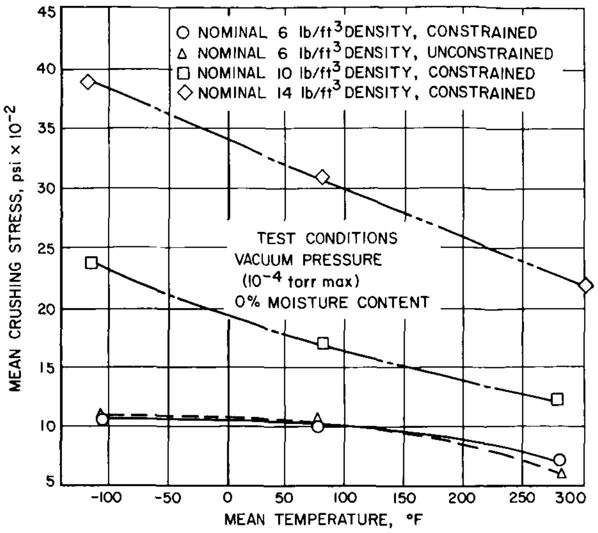

Fig. 16. Mean crushing stress vs mean temperature; vacuum pressure (10^{-4} torr max)

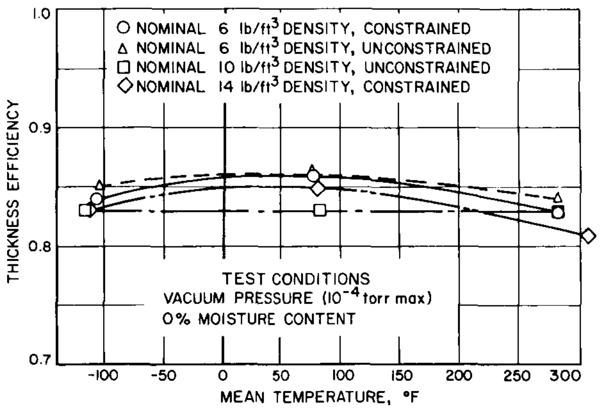

Fig. 17. Thickness efficiency vs mean temperature; vacuum pressure (10^{-4} torr max)

9, 10, 11 (Table A-2), and Fig. 12, 13, 14 (Table A-3) show temperature effects at atmospheric pressure when moisture is present and absent in the balsa, respectively. Figures 15, 16, and 17 show the effect of temperature on unmoisturized balsa when tested in a vacuum.

In analyzing the relationships shown in Fig. 9, it is immediately evident that specific energy dissipation increases with decreasing temperature. In fact, specific energies exceeding 27,000 ft-lb/lb were obtained for both 6 and 10 lb/ft^3 specimens at mean temperatures below −100°F. Closer examination of the specific energy curves reveals several significant facts. First, the relationships developed for 6 and 10 lb/ft^3 constrained balsa wood are linear functions of temperature. Thus, the change of state which occurs at 32°F, viz., freezing of the water in the balsa, has little effect on the response during crushing. Second, the specific energy-mean temperature relations are not density dependent. This fact is evident by comparing the relatively parallel slopes of the 6 and 10 lb/ft^3 constrained curves. Third, the results are virtually unaffected by small lateral confining forces, as evidenced by comparing the 6 lb/ft^3 constrained and unconstrained curves. It is interesting to note, however, that in the unconstrained condition, the state change at 32°F has a more significant effect on response. This behavior may be due to local differences between the constrained and corresponding unconstrained specimens since they were obtained from the same batch. Finally, the specific energy dissipation of 10 lb/ft^3 balsa wood was approximately 10% greater than the 6 lb/ft^3 balsa wood. This is evident by comparing ordinates of the curves at a given temperature. Thus, temperature tends to make density effects more pronounced.

The response during crushing (α curves) was relatively uniform and independent of temperature. In all cases, however, the variation in crushing stress was more pronounced slightly below 32°F than above it. Also the 10 lb/ft^3 balsa wood exhibited more variation in crushing stress than the 6 lb/ft^3 balsa wood.

As indicated in Fig. 10, the magnitude of mean crushing stress at a given temperature was considerably larger for 10 lb/ft^3 specimens than for the corresponding 6 lb/ft^3 specimens. In addition, the mean crushing stress levels increased with decreasing temperature. It should be noted that the state change occurring at 32°F had a noticeable effect on crushing stress levels. In all cases the values increased in a discontinuous manner as specimens were tested slightly below the freezing point of water.

Figure 11 shows that thickness efficiency is relatively insensitive to temperature changes for nominal 6 lb/ft^3 balsa wood. In the case of 10 lb/ft^3 balsa wood, however, a slight drop in thickness efficiency is discernible as the temperature decreases from ambient to the freezing point of water. In all cases the values for 10 lb/ft^3 balsa wood were slightly lower than the corresponding ones for 6 lb/ft^3 balsa wood.

Figure 12 shows the effect of temperature on the specific energy dissipation of nominal 6 lb/ft^3 unmoisturized balsa wood tested at atmospheric pressure. The primary objectives of the test series upon which this Figure is based were twofold: (1) to determine the response of specimens above the boiling point of water; and (2) to establish whether a temperature dependence exists for the specific energy-moisture content relationships presented in Fig. 6. In the process, the direct response of unmoisturized 6 lb/ft^3 balsa wood was established.

The results of this test series indicate that specific energy increases linearly with decreasing temperature, as shown in Fig. 12. It is evident that at 300°F the energy dissipating capacity of balsa wood is severely reduced. Also, a small amount of lateral confinement of the specimens has no appreciable effect on response. Finally, Fig. 12 shows that the variation between maximum and minimum crushing stress (α curves) was on the order of 2, and the response was relatively the same for all specimens tested.

Figures 13 and 14 show, respectively, a linear increase in crushing stress with decreasing temperature and a relatively constant value of thickness efficiency over the same temperature range. In both Figures it can be seen that the results are virtually unaffected by lateral confinement.

A comparison of the ordinates of Fig. 9 and 12 for 6 lb/ft^3 balsa wood at a given temperature indicates that at low temperatures, a temperature dependence exists for the relations presented in Fig. 6. For instance, at −100°F the specific energy values obtained for moisturized and unmoisturized 6 lb/ft^3 balsa wood were practically the same. This fact does not agree with the relationship of Fig. 6 which indicates that at ambient temperature, the specific energy of unmoisturized 6 lb/ft^3 balsa wood is approximately 25% greater than that of natural moisture content wood. This disagreement is attributable to the difference in test temperatures, thereby giving rise to a temperature effect on the specific energy-moisture content response.

Figure 15 indicates that the specific energy dissipation of unmoisturized balsa wood tested in a vacuum increases with decreasing temperature. A density dependence once again exists for these relationships, but only in the case of 10 lb/ft^3 wood. Also, there is little effect on response due to lateral confinement.

As indicated by the α curves, the variation in crushing stress was quite pronounced. The variation between maximum and minimum crushing stress, however, tended to decrease slightly with increasing temperature.

Figure 16 shows that crushing stress increased almost linearly with decreasing temperature for all densities. A significant increase in crushing stress level occurred with increasing density. This increase is consistent with that shown in Fig. 7 and 10.

As shown in Fig. 17, thickness efficiency is virtually independent of temperature. The magnitude of thickness efficiency, however, tended to decrease slightly with increasing density.

3. Effect of Pressure

The data presented in Tables A-3 and A-4 also serve to establish the effect of pressure on the energy-dissipating capacity of balsa wood. By comparing specimen response at atmospheric pressure (Table A-3) to the corresponding response in a vacuum (Table A-4), the effect of pressure was established. This effect is illustrated in Fig. 18 and 19. By comparing the ordinates of curves B and C in both Figures at a given temperature, it is

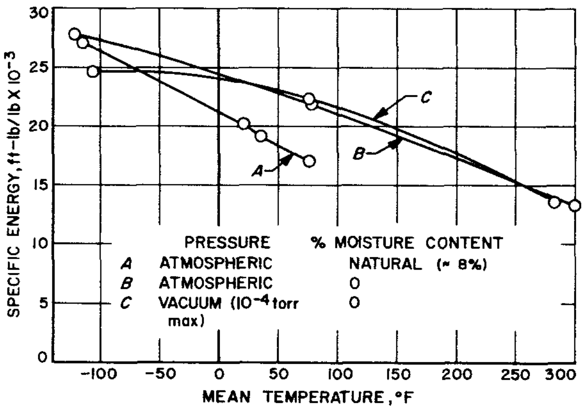

Fig. 18. Specific energy vs mean temperature for nominal 6 lb/ft^3 confined balsa wood

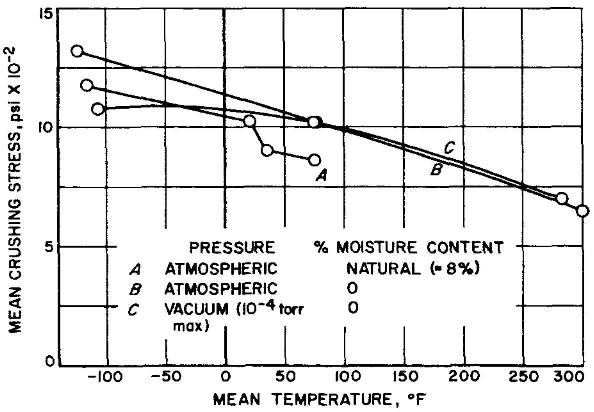

Fig. 19. Mean crushing stress vs mean temperature for nominal 6 lb/ft^3 confined balsa wood

evident that pressure has little effect on the response of balsa wood as an energy dissipator. A slight decrease in the specific energy dissipation and corresponding crushing stress of vacuum-tested balsa wood occurred, however, in the low temperature range as compared to the response of balsa wood tested at atmospheric pressure.

Also presented in both Figures is the response of natural moisture content, 6 lb/ft^3 balsa wood tested at atmospheric pressure (curve A). Thus, Fig. 18 and 19 serve to provide a visual means of determining the effects of pressure, temperature, and moisture content on the energy-dissipating response of 6 lb/ft^3 balsa wood.

4. Effect of Density

The effect of density on the response of balsa wood as an energy dissipator is shown in Fig. 20 through 25. These relationships are based on the data presented in Tables A-1 through A-4. Figures 20, 21, and 22 show the effect of density on the response of balsa wood of three moisture contents when tested at atmospheric pressure and ambient temperature. Figures 23, 24, and 25 illustrate density effects when unmoisturized balsa wood is tested at three temperature levels in a vacuum.

Figure 20 indicates that the specific energy dissipation of moisturized balsa wood increases gradually with increasing density. However, the energy-dissipating capacity of unmoisturized balsa wood decreases with increasing density. It is significant to note that the relationship presented for natural-moisture-content balsa wood agrees reasonably well with that presented in

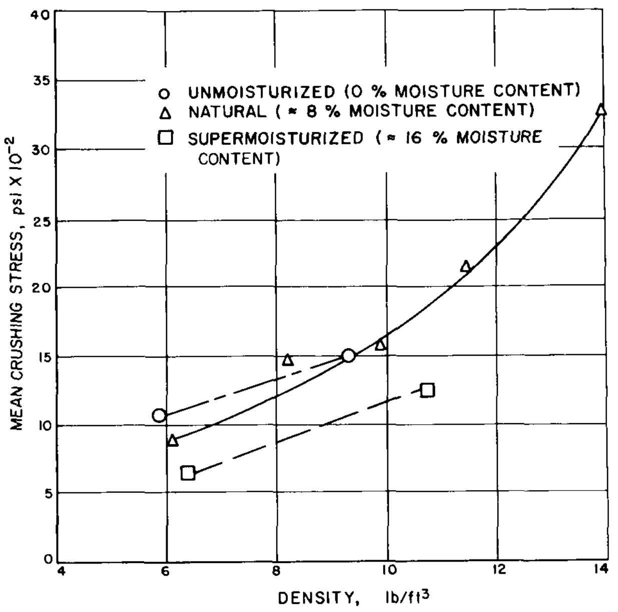

Fig. 21. Mean crushing stress vs density for constrained balsa wood at atm pressure and ambient temp (approx 78°F)

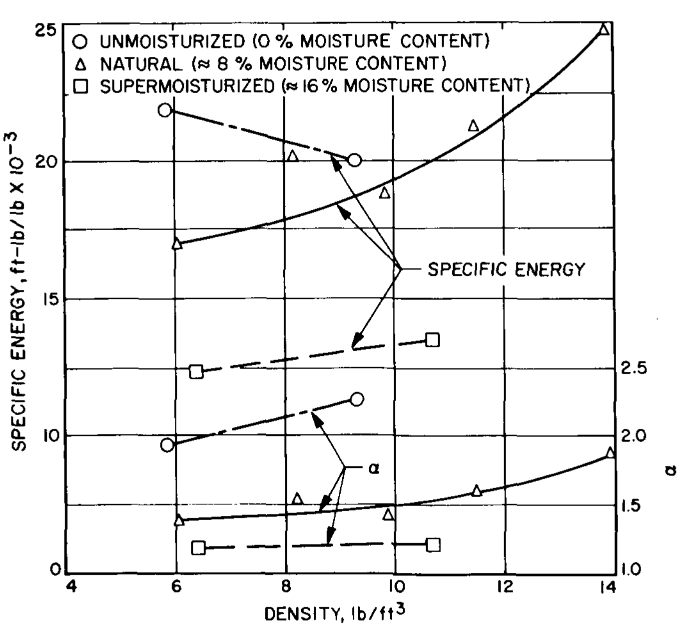

Fig. 20. Specific energy and α vs density for constrained balsa wood at atm pressure and ambient temp (approx 78°F)

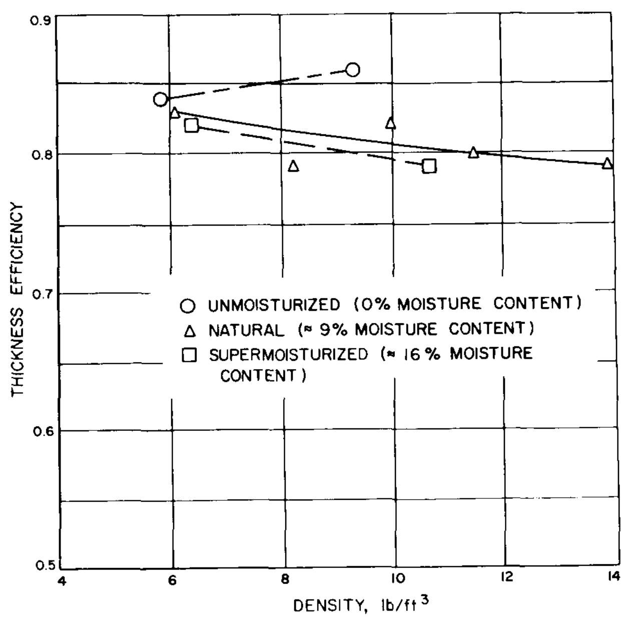

Fig. 22. Thickness efficiency vs density for constrained balsa wood at atm pressure and ambient temp (approx 78°F)

Ref. 1, 3. Regarding Ref. 1, this agreement is interestingly significant since the relationship is based primarily on data obtained by platen rather than penetration testing. This indicates that the amount of energy dissipated by shear and friction during penetration is small in comparison to the energy dissipated by mechanical crushing of the balsa wood. Also, the rank of the curves presented again indicates that the energy-dissipating capacity of balsa wood decreases with increasing moisture content. Finally, Fig. 20 indicates that the variation in crushing stress, as measured by the parameter, α, becomes more pronounced both with increasing density and decreasing moisture content.

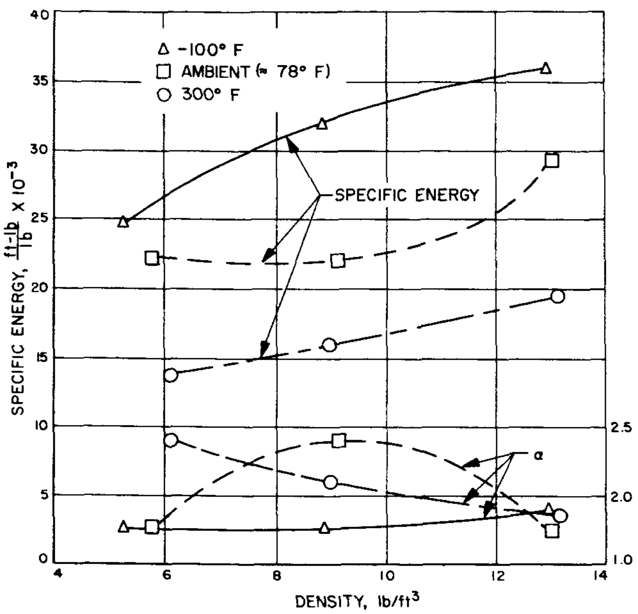

Fig. 23. Specific energy and α vs density for contrained balsa wood at vacuum pressure and 0% moisture content

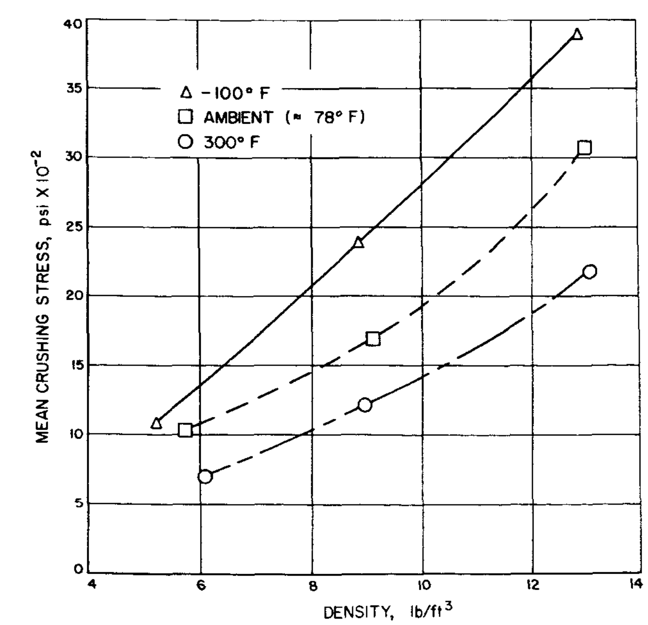

Fig. 24. Mean crushing stress vs density for constrained balsa wood at vacuum pressure and 0% moisture content

Figures 21 and 22 show, respectively, that crushing stress increases significantly with increasing balsa-wood density and that thickness efficiency values for moisturized balsa wood decrease slightly with increasing density. It is evident that increasing the moisture content of the wood results in lower values of both crushing stress and thickness efficiency.

The effect of density on the response of unmoisturized balsa wood tested in a vacuum is characteristically similar to that of balsa wood tested at atmospheric pressure and ambient temperature. Figure 23 illustrates that specific energy dissipation increases both with increasing density and decreasing temperature. Also the response during crushing (α curves) is quite erratic over the entire density range.

As shown in Fig. 24, the mean crushing stress of balsa wood increases somewhat linearly with increasing density. Again, the rate of increase of crushing stress as a function of density is significantly greater than that of specific energy over the same density range.

Figure 25 shows that thickness efficiency tends to decrease slightly with increasing density. Also, values of thickness efficiency appear relatively insensitive to temperature changes.

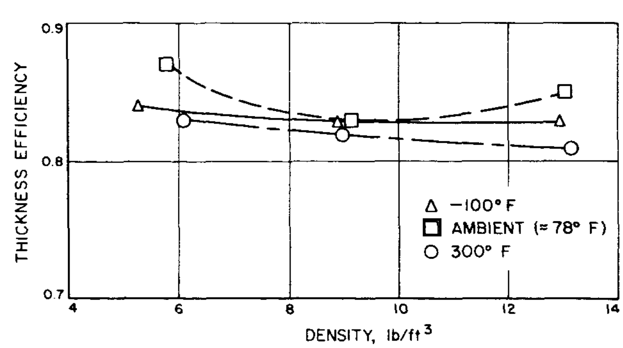

Fig. 25. Thickness efficiency vs density for constrained balsa wood at vacuum pressure and 0% moisture content

VI. CONCLUSIONS

The response of balsa wood as an energy dissipator is very dependent upon its physical and environmental conditions. It has been shown that certain combinations of these conditions have served to increase significantly the energy-dissipating capacity of the wood relative to its nominal capacity in an Earth environment. Specifically, it may be concluded that:

1. Specific energy dissipation and crushing stress increase with (a) decreasing moisture content, (b) decreasing temperature, and (c) increasing density.
2. Environmental pressure has little effect on response.
3. Thickness efficiency is insensitive to physical and environmental variables.
4. Specimen response is unaffected by a small amount of lateral confinement.
5. Crushing stress varies in magnitude during mechanical crushing of the balsa wood.
6. Frequency of balsa-wood splitting increases with increasing balsa-wood density.
7. Specimen response varies as much as $\pm 15\%$ of the average response of specimens tested under the same physical and environmental conditions. This indicates that proper care should be taken in the selection and inspection of balsa wood as an energy dissipator.

REFERENCES

1. "Impact Technology Document," Publication No. U-3031 (prepared for JPL under Contract No. 950996), Aeronutronic Division of Ford, Newport Beach, California, February, 1965.
2. *Rules for the Measurement and Inspection of Balsa Wood—U. S. War Production Board*, Balsa Ecuador Lumber Corporation, New York, 1944.
3. Daigle, D. L., and Lonborg, J. O., "Evaluation of Certain Crushable Materials," Technical Report No. 32-120, Jet Propulsion Laboratory, Pasadena, California, January 13, 1961.

APPENDIX

Tabulated Data for the Test Series

This Appendix comprises the supplemental tabulated data for the test series of this Report. The following pages include Tables A-1 through A-6.

Table A-1. Test series 1

Test group	Specimen No.	Specimen test condition: Mean temperature (°F)	Specimen test condition: Pressure	Specimen test condition: Moisture content (%)	Specimen test condition: Density (lb-ft^3)	Stresses (psi)—σ: Crushing: Initial peak	Stresses (psi)—σ: Crushing: Max	Stresses (psi)—σ: Crushing: Mean: Actual	Stresses (psi)—σ: Crushing: Mean: Normalized	Stresses (psi)—σ: Crushing: Min	α $\left(\frac{\sigma \text{ max crush}}{\sigma \text{ min crush}}\right)$	Specific energy $\left(\frac{\text{ft-lb}}{\text{lb}}\right)^*$: Actual	Specific energy $\left(\frac{\text{ft-lb}}{\text{lb}}\right)^*$: Normalized	β Thickness efficiency	Remarks
G1	6-2-1	75	atm	9.50	6.37	1230	1130	1000	950	910	1.28	18,540	17,650	0.82	
	6-1-1	75	atm	9.23	5.82	1020	950	830	790	750	1.27	17,250	16,430	0.84	
	6-23-2	75	atm	8.50	5.91	1125	1045	930	820	850	1.23	18,580	16,370	0.82	
	6-22-2	75	atm	8.50	6.35	1310	1260	1080	950	1020	1.24	20,080	17,710	0.82	
	average	75	atm	8.93	6.08			960	880		1.26	18,610	17,040	0.83	
G2	6-3-1	75	atm	10.40	6.49	1210	1110	970	920	890	1.25	17,650	16,810	0.82	
	6-4-1	75	atm	10.18	6.51	1290	1180	1000	950	870	1.36	18,360	17,480	0.83	
	6-54-3	75	atm	8.12	6.31	1260	1150	970	930	810	1.42	18,370	17,600	0.83	
	average	75	atm	9.57	6.44			980	930		1.34	18,130	17,300	0.83	
I1	6-16-2	75	atm	17.0	6.33	920	870	790	700	730	1.20	14,740	12,980	0.82	
	6-18-2	78	atm	15.4	6.09	810	730	690	610	570	1.27	13,380	11,790	0.82	
	6-37-3	78	atm	16.2	6.07	720	650	640	610	610	1.06	12,600	12,070	0.83	
	average	77	atm	16.2	6.39			710	640		1.18	13,570	12,280	0.82	
I2	6-17-2	75	atm	15.8	6.09	720	670	600	530	440	1.52	11,780	10,370	0.83	
	6-38-3	78	atm	15.7	6.04	710	650	640	610	600	1.08	12,660	12,130	0.83	
	6-46-3	85	atm	15.5	5.96	710	630	610	580	560	1.06	12,330	11,810	0.83	
	average	79	atm	15.7	6.02			620	570		1.22	12,260	11,440	0.83	
N1	10-9-1	81	atm	0	9.50	2590	2430	1620	1490	1320	1.84	22,100	20,280	0.90	split
	10-11-1	81	atm	0	9.62	2410	2280	1620	1490	1260	1.81	20,610	18,910	0.85	
	10-12-1	81	atm	0	9.46	2340	2300	1300	1190	540	4.26	18,010	16,520	0.91	split
	10-28-2	74	atm	0	9.05	2430	2200	1600	1600	1340	1.64	21,130	21,150	0.83	
	10-30-2	74	atm	0	9.28	2520	2550	1570	1570	1160	2.20	20,460	20,480	0.84	split
	10-31-2	75	atm	0	9.09	2710	2340	1730	1730	1320	1.77	22,750	22,770	0.83	
	average	78	atm	0	9.33			1570	1510		2.25	20,840	20,020	0.86	

$$\text{*Specific Energy} = \left[\frac{\text{Mean crushing stress (144)}}{\text{Test density}}\right]\beta$$

Table A-1. (Cont'd)

Test group	Specimen No.	Specimen test condition: Mean temperature (°F)	Pressure	Moisture content (%)	Density (lb-ft^3)	Stresses (psi)—σ: Crushing: Initial peak	Max	Mean: Actual	Mean: Normalized	Min	α $\left(\frac{\sigma \text{ max crush}}{\sigma \text{ min crush}}\right)$	Specific energy $\left(\frac{\text{ft-lb}}{\text{lb}}\right)^*$: Actual	Normalized	β Thickness efficiency	Remarks
O1	6-32-2	78	atm	0	5.59	1560	1470	1130	1000	810	1.82	24,450	21,540	0.84	
	6-34-2	78	atm	0	5.63	1680	1680	1200	1060	680	2.49	26,090	22,990	0.85	
	6-35-2	78	atm	0	5.65	1400	1400	1130	1000	860	1.63	23,900	21,060	0.83	
	6-82-5	73	atm	0	6.06	1250	1230	940	1020	600	2.05	18,760	20,310	0.84	
	6-84-5	75	atm	0	6.11	1430	1320	1180	1280	720	1.83	23,360	25,280	0.84	
	6-85-5	74	atm	0	6.06	1350	1350	960	1040	750	1.80	19,160	20,740	0.84	
	average	76	atm	0	5.85			1090	1070		1.94	22,620	21,990	0.84	
O2	6-42-3	78	atm	0	5.50	1180	1170	890	850	590	2.00	20,040	19,200	0.86	
	6-39-3	78	atm	0	5.92	1500	1480	1130	1080	770	1.92	24,570	23,540	0.89	split
	6-36-2	78	atm	0	5.85	1130	1230	940	830	690	1.78	19,670	17,330	0.85	
	average	78	atm	0	5.76			990	920		1.90	21,430	20,020	0.87	
P1	10-6-1	83	atm	7.03	10.03	2220	2100	1700	1560	1400	1.50	19,770	18,140	0.81	
	10-2-1	82	atm	7.02	9.96	2410	2300	1760	1610	1450	1.58	20,870	19,140	0.82	
	10-1-1	81	atm	7.02	9.99	2385	2280	1750	1610	1480	1.54	20,690	18,980	0.82	
	average	82	atm	7.02	9.99			1740	1590		1.54	20,440	18,750	0.82	
Q1	10-3-1	84	atm	14.50	10.56	1650	1510	1410	1290	1230	1.23	15,190	13,940	0.79	
	10-7-1	80	atm	14.92	10.82	1510	1450	1330	1220	1130	1.28	13,810	12,670	0.78	
	10-8-1	75	atm	14.80	10.70	1700	1580	1400	1280	1230	1.28	15,070	13,830	0.80	
	average	80	atm	14.77	10.69			1380	1260		1.26	14,690	13,480	0.79	

*Specific Energy = $\left[\frac{\text{Mean crushing stress (144)}}{\text{Test density}}\right] \beta$

Table A-2. Test series 2

Test group	Specimen No.	Specimen test condition: Mean temperature (°F)	Specimen test condition: Pressure	Specimen test condition: Moisture content (%)	Specimen test condition: Density (lb-ft³)	Stresses (psi)—σ, Crushing: Initial peak	Stresses (psi)—σ, Crushing: Max	Stresses (psi)—σ, Crushing: Mean, Actual	Stresses (psi)—σ, Crushing: Mean, Normalized	Stresses (psi)—σ, Crushing: Min	α $\left(\frac{\sigma \text{ max crush}}{\sigma \text{ min crush}}\right)$	Specific energy $\left(\frac{\text{ft-lb}}{\text{lb}}\right)^*$: Actual	Specific energy $\left(\frac{\text{ft-lb}}{\text{lb}}\right)^*$: Normalized	β Thickness efficiency	Remarks
G1	6-2-1	75	atm	9.50	6.37	1230	1130	1000	950	910	1.28	18,540	17,650	0.82	
	6-1-1	75	atm	9.23	5.82	1020	950	830	790	750	1.27	17,250	16,430	0.84	
	6-23-2	75	atm	8.50	5.91	1130	1050	930	820	850	1.23	18,580	16,370	0.82	
	6-22-2	75	atm	8.50	6.35	1310	1260	1080	950	1020	1.24	20,080	17,710	0.82	
	average	75	atm	8.93	6.08			960	880		1.26	18,610	17,040	0.83	
G2	6-3-1	75	atm	10.40	6.49	1210	1110	970	920	890	1.25	17,650	16,810	0.82	
	6-4-1	75	atm	10.18	6.51	1290	1180	1000	950	870	1.36	18,360	17,480	0.83	
	6-54-3	75	atm	8.12	6.31	1260	1150	970	930	810	1.42	18,370	17,600	0.83	
	average	75	atm	9.57	6.44			980	930		1.34	18,130	17,300	0.83	
H1	6-41-3	−115	atm	8.17	5.75	1650	1530	1230	1180	990	1.55	26,180	25,080	0.85	
	6-50-3	−115	atm	7.88	5.70	1920	1740	1340	1280	1040	1.67	29,110	27,890	0.86	
	6-52-3	−115	atm	8.26	5.66	1770	1630	1400	1340	1150	1.42	29,920	28,660	0.84	split
	average	−115	atm	8.10	5.70			1320	1270		1.53	28,400	27,210	0.85	
H2	6-64-4	−107	atm	9.52	6.00	1480	1370	1220	1420	1030	1.32	24,010	28,050	0.82	split
	6-66-4	−107	atm	9.22	6.02	1470	1360	1220	1420	1090	1.26	23,640	27,610	0.81	
	6-69-4	−107	atm	9.81	5.91	1420	1370	1210	1410	1120	1.22	24,180	28,240	0.82	
	average	−107	atm	9.52	5.98			1220	1420		1.27	23,940	27,970	0.82	
J1	10-14-3	−103	atm	8.26	9.13	2960	2580	2380	2620	1810	1.43	29,650	32,580	0.79	split
	10-15-3	−103	atm	8.32	9.68	3390	2840	2560	2810	2070	1.37	30,080	33,060	0.79	split
	10-16-3	−103	atm	8.26	9.26	3010	2580	2420	2660	2070	1.25	29,730	32,620	0.79	split
	average	−103	atm	8.28	9.36			2450	2700		1.35	29,820	32,750	0.79	
P1	10-6-1	83	atm	7.03	10.03	2220	2100	1700	1560	1400	1.50	19,770	18,140	0.81	
	10-2-1	82	atm	7.02	9.96	2410	2300	1760	1610	1450	1.58	20,870	19,140	0.82	
	10-1-1	81	atm	7.02	9.99	2380	2280	1750	1610	1480	1.54	20,690	18,980	0.82	
	average	82	atm	7.02	9.99			1740	1590		1.54	20,440	18,750	0.82	

$$^*\text{Specific Energy} = \left[\frac{\text{Mean crushing stress (144)}}{\text{Test density}}\right]\beta$$

Table A-2. (Cont'd)

Test group	Specimen No.	Specimen test condition: Mean temperature (°F)	Pressure	Moisture content (%)	Density (lb-ft³)	Stresses (psi)—σ: Crushing: Initial peak	Max	Mean: Actual	Mean: Normalized	Min	α (σ max crush / σ min crush)	Specific energy (ft-lb / lb)*: Actual	Normalized	β Thickness efficiency	Remarks
R1	6-55-4	21	atm	8.70	6.13	1070	1030	890	1040	700	1.47	16,940	19,780	0.81	
	6-56-4	21	atm	8.92	5.89	1000	970	830	970	690	1.40	16,640	19,440	0.82	
	6-62-4	21	atm	9.16	5.84	1090	1030	890	1040	735	1.41	18,000	21,020	0.82	
	average	21	atm	8.93	5.95			870	1020		1.43	17,190	20,080	0.82	
R2	6-57-4	21	atm	8.75	6.21	1150	1110	950	1110	730	1.52	17,840	20,840	0.81	
	6-59-4	21	atm	7.81	5.75	1200	1150	1020	1190	810	1.42	21,200	24,770	0.83	
	6-60-4	21	atm	7.88	5.76	1090	1060	890	1040	690	1.54	18,250	21,310	0.82	
	average	21	atm	8.15	5.91			950	1110		1.49	19,100	22,310	0.82	
S1	6-88-7	35	atm	8.38	5.77	890	870	800	840	690	1.26	16,370	17,180	0.82	
	6-89-7	35	atm	8.67	5.47	1000	960	900	940	790	1.22	19,430	20,390	0.82	
	6-90-7	35	atm	8.76	5.56	1050	1030	870	910	700	1.47	18,700	19,620	0.83	
	average	35	atm	8.60	5.60			860	900		1.32	18,170	19,060	0.82	
S2	6-91-7	35	atm	9.42	5.59	960	950	850	890	730	1.30	18,170	19,070	0.83	
	6-92-7	35	atm	9.35	5.75	840	840	810	850	700	1.20	16,630	17,450	0.82	
	6-93-7	35	atm	8.76	5.62	930	910	830	870	660	1.38	17,650	18,520	0.83	
	average	35	atm	9.18	5.65			830	870		1.29	17,480	18,350	0.82	
T1	10-20-3	22	atm	8.93	10.65	2540	2560	2060	2260	1275	2.05	21,450	23,570	0.77	split
	10-21-3	22	atm	8.56	10.17	2450	2240	1830	2010	1395	1.60	20,210	22,210	0.78	split
	10-22-3	22	atm	8.58	10.22	2510	2510	2010	2210	1380	1.82	22,370	24,590	0.79	split
	average	22	atm	8.69	10.35			1970	2160		1.82	21,340	23,460	0.78	
U1	10-23-3	37	atm	8.59	9.26	2030	1950	1630	1790	1350	1.44	20,280	22,280	0.80	
	10-24-3	37	atm	9.58	10.35	2420	2200	1850	2030	1530	1.44	19,820	21,780	0.77	split
	10-25-3	37	atm	10.00	9.99	2150	2040	1800	1980	1480	1.38	19,980	21,950	0.77	
	average	37	atm	9.39	9.86			1760	1930		1.42	20,030	22,000	0.78	

$$\text{*Specific Energy} = \left[\frac{\text{Mean crushing stress (144)}}{\text{Test density}}\right]\beta$$

Table A-3. Test series 3

Test group	Specimen No.	Specimen test condition: Mean temperature (°F)	Pressure	Moisture content (%)	Density ($lb\text{-}ft^{-3}$)	Stresses (psi)—σ, Crushing: Initial peak	Max	Mean: Actual	Mean: Normalized	Min	α ($\frac{\sigma \text{ max crush}}{\sigma \text{ min crush}}$)	Specific energy ($\frac{ft\text{-}lb}{lb}$)*: Actual	Normalized	β Thickness efficiency	Remarks
M1	6-72-5	300	atm	0	5.83	770	770	590	640	360	2.14	12,100	13,090	0.83	
	6-73-5	300	atm	0	5.74	830	810	650	700	480	1.69	13,530	14,650	0.83	
	6-74-5	300	atm	0	5.79	740	710	550	600	370	1.92	11,350	12,290	0.83	
	average	300	atm	0	5.79			600	650		1.92	12,330	13,340	0.83	
M2	6-75-5	300	atm	0	5.88	790	750	580	630	360	2.08	11,790	12,760	0.83	
	6-76-5	300	atm	0	5.72	780	740	620	670	510	1.45	12,950	14,020	0.83	
	6-79-5	300	atm	0	5.93	920	900	720	780	450	2.00	14,510	15,710	0.83	
	average	300	atm	0	5.84			640	690		1.84	13,080	14,160	0.83	
O1	6-32-2	78	atm	0	5.59	1560	1470	1130	1000	810	1.82	24,450	21,540	0.84	
	6-34-2	78	atm	0	5.63	1680	1680	1200	1060	675	2.49	26,090	22,990	0.85	
	6-35-2	78	atm	0	5.65	1400	1400	1130	1000	860	1.63	23,900	21,060	0.83	
	6-82-5	73	atm	0	6.06	1250	1230	940	1020	600	2.05	18,760	20,310	0.84	
	6-84-5	75	atm	0	6.11	1430	1320	1180	1280	720	1.83	23,360	25,280	0.84	
	6-85-5	74	atm	0	6.06	1350	1350	960	1040	750	1.80	19,160	20,740	0.84	
	average	76	atm	0	5.85			1090	1070		1.94	22,620	21,990	0.84	
O2	6-42-3	78	atm	0	5.50	1180	1170	890	850	585	2.00	20,040	19,200	0.86	
	6-39-3	78	atm	0	5.92	1500	1480	1130	1080	770	1.92	24,570	23,540	0.89	split
	6-36-2	78	atm	0	5.85	1130	1230	940	830	690	1.78	19,670	17,330	0.85	
	average	78	atm	0	5.76			990	920		1.90	21,430	20,020	0.87	
V1	6-81-5	−123	atm	0	5.88	1560	1440	1290	1400	1020	1.41	27,170	29,400	0.86	
	6-78-5	−123	atm	0	5.70	1640	1310	1130	1220	810	1.62	23,690	25,640	0.83	
	6-77-5	−123	atm	0	5.73	1850	1710	1200	1300	980	1.74	26,240	28,400	0.87	
	average	−123	atm	0	5.77			1210	1310		1.59	25,700	27,810	0.85	
V2	6-80-5	−123	atm	0	5.90	1980	1590	1180	1280	800	1.99	24,480	26,490	0.85	
	6-83-5	−123	atm	0	6.06	2080	1950	1370	1480	920	2.12	28,320	30,650	0.87	
	6-86-5	−123	atm	0	5.65	1800	1620	1240	1340	1020	1.59	28,130	30,440	0.89	
	average	−123	atm	0	5.87			1260	1370		1.90	26,980	29,190	0.87	

$$\text{*Specific Energy} = \left[\frac{\text{Mean crushing stress (144)}}{\text{Test density}}\right]\beta$$

Table A-4. Test series 4

Test group	Specimen No.	Specimen test condition: Mean temperature (°F)	Specimen test condition: Pressure (torr)	Specimen test condition: Moisture content (%)	Specimen test condition: Density (lb-ft³)	Stresses (psi)—σ: Crushing: Initial peak	Stresses (psi)—σ: Crushing: Max	Stresses (psi)—σ: Crushing: Mean: Actual	Stresses (psi)—σ: Crushing: Mean: Normalized	Stresses (psi)—σ: Crushing: Min	α $\left(\frac{\sigma \text{ max crush}}{\sigma \text{ min crush}}\right)$	Specific energy $\left(\frac{\text{ft-lb}}{\text{lb}}\right)$*: Actual	Specific energy $\left(\frac{\text{ft-lb}}{\text{lb}}\right)$*: Normalized	β Thickness efficiency	Remarks
A1	6-115-6	283	2×10^{-5}	0	6.39	1110	1030	800	770	360	2.86	14,960	14,460	0.83	
	6-116-6	283	3×10^{-5}	0	6.63	1160	1110	790	760	480	2.31	14,410	13,930	0.84	
	6-105-7	283	2×10^{-5}	0	5.28	620	620	530	560	400	1.55	12,000	12,580	0.83	
	average	283	2.3×10^{-5}	0	6.10			710	700		2.24	13,790	13,670	0.83	
A2	6-107-7	283	2×10^{-5}	0	4.95	570	570	460	480	330	1.73	11,370	11,920	0.85	
	6-108-7	283	2×10^{-5}	0	5.31	720	630	560	590	390	1.62	12,760	13,370	0.84	
	6-114-6	283	1.8×10^{-5}	0	6.49	1230	950	770	740	540	1.76	14,350	13,870	0.84	
	average	283	1.9×10^{-5}	0	5.58			600	600		1.70	12,830	13,050	0.84	
B1	6-8-1	75	8×10^{-6}	0	5.91	1650	1510	1080	1030	760	1.99	23,420	22,300	0.89	
	6-7-1	75	7×10^{-6}	0	5.46	1450	1370	930	890	730	1.86	21,340	20,320	0.87	
	6-40-3	75	6.5×10^{-6}	0	5.94	1650	1510	1210	1160	1040	1.47	25,230	24,160	0.86	split
	average	75	7.2×10^{-6}	0	5.77			1070	1030		1.77	23,330	22,260	0.87	
B2	6-5-1	75	9.5×10^{-6}	0	6.26	1800	1740	1100	1050	790	2.20	22,010	20,970	0.87	split
	6-6-1	75	1.2×10^{-5}	0	6.18	1920	1770	1200	1140	870	2.04	24,330	23,170	0.87	
	6-29-2	75	8.7×10^{-6}	0	6.06	1480	1450	1050	930	750	1.94	21,960	19,360	0.88	split
	average	75	1.0×10^{-5}	0	6.16			1120	1040		2.06	22,770	21,170	0.87	
C1	6-102-7	−106	4×10^{-4}	0	5.30	1500	1350	1110	1060	690	1.96	25,330	26,550	0.84	
	6-100-7	−106	3×10^{-4}	0	5.39	1470	1370	1130	1180	780	1.76	24,750	25,950	0.82	
	6-99-7	−106	6×10^{-4}	0	5.09	1160	1100	850	890	700	1.57	20,440	21,430	0.85	
	average	−106	4.3×10^{-4}	0	5.26			1030	1080		1.76	23,510	24,640	0.84	
C2	6-103-7	−106	4×10^{-4}	0	5.11	1440	1310	1160	1220	990	1.32	27,460	28,780	0.84	
	6-104-7	−106	4×10^{-4}	0	4.88	1170	1080	860	900	660	1.64	21,570	22,610	0.85	
	6-106-7	−106	3.8×10^{-4}	0	5.23	1170	1380	1110	1160	910	1.52	25,980	27,230	0.85	
	average	−106	3.9×10^{-4}	0	5.07			1040	1090		1.49	25,000	26,210	0.85	
D1	14-14-1	304	9.8×10^{-4}	0	13.23	3690	2650	2120	2180	1500	1.77	18,230	18,780	0.79	
	14-11-1	304	2.8×10^{-5}	0	12.99	3240	2640	2090	2150	1200	2.20	18,300	18,850	0.79	
	14-12-1	304	8×10^{-4}	0	13.17	3510	2640	2150	2210	1660	1.59	19,750	20,340	0.84	
	average	304	6.0×10^{-4}	0	13.13			2130	2180		1.85	18,760	19,320	0.81	

$$\text{*Specific Energy} = \left[\frac{\text{Mean crushing stress (144)}}{\text{Test density}}\right]\beta$$

Table A-4. (Cont'd)

Test group	Specimen No.	Specimen test condition: Mean temperature (°F)	Specimen test condition: Pressure (torr)	Specimen test condition: Moisture content (%)	Specimen test condition: Density (lb-ft^{-3})	Stresses (psi)—σ, Crushing: Initial peak	Crushing: Max	Crushing: Mean, Actual	Crushing: Mean, Normalized	Crushing: Min	α $\left(\frac{\sigma \text{ max crush}}{\sigma \text{ min crush}}\right)$	Specific energy $\left(\frac{\text{ft-lb}}{\text{lb}}\right)^*$: Actual	Specific energy: Normalized	β Thickness efficiency	Remarks
E1	14-5-1	75	1.2×10^{-5}	0	13.00	4980	4140	3320	3420	2590	1.60	30,890	31,820	0.84	split
	14-6-1	82	5×10^{-4}	0	13.09	4450	3360	2920	3010	2300	1.46	26,340	27,130	0.82	split
	14-9-1	76	3.3×10^{-4}	0	12.98	4640	3900	3160	3250	2040	1.91	29,450	30,330	0.84	split
	14-10-1	81	3×10^{-4}	0	13.06	4620	3440	2540	2620	1700	2.02	24,930	25,670	0.89	
	average	79	7.8×10^{-4}	0	13.03			2990	3080		1.75	27,900	29,240	0.85	
F1	14-3-1	−117	6×10^{-4}	0	12.80	4860	4740	3920	4040	3050	1.56	36,160	37,250	0.82	
	14-7-1	−117	3.8×10^{-4}	0	12.82	5190	4600	3560	3670	2420	1.90	32,790	33,770	0.82	split
	14-8-1	−117	4×10^{-4}	0	12.75	5360	5100	3810	3920	2520	2.02	36,150	37,230	0.84	split
	14-2-1	−117	3×10^{-4}	0	13.37	6150	5500	3870	3990	2640	2.08	34,600	35,630	0.83	split
	average	−117	4.2×10^{-4}	0	12.94			3790	3910		1.89	34,920	35,970	0.83	
K1	10-37-2	83	4×10^{-4}	0	9.08	2730	2450	1740	1740	1230	1.99	22,900	22,930	0.83	
	10-38-2	85	4×10^{-4}	0	9.22	2660	2420	1820	1820	1180	2.05	23,020	23,050	0.81	
	10-40-2	75	4×10^{-4}	0	9.12	2460	2100	1500	1500	780	2.69	19,900	19,920	0.84	split
	average	81	4×10^{-4}	0	9.14			1690	1690		2.24	21,940	21,970	0.83	
L1	10-32-2	−117	4×10^{-4}	0	9.03	2710	2680	2240	2240	1500	1.79	29,290	29,320	0.82	
	10-33-2	−117	4×10^{-4}	0	8.44	3480	3180	2610	2610	2160	1.47	36,960	37,000	0.83	
	10-39-2	−117	4×10^{-4}	0	9.17	2880	2840	2320	2320	1400	2.03	29,870	29,900	0.82	
	average	−117	4×10^{-4}	0	8.88			2390	2390		1.76	32,040	32,070	0.83	
W1	10-34-2	279	2×10^{-5}	0	8.98	2190	1640	1140	1140	660	2.48	15,170	15,190	0.83	
	10-35-2	279	1×10^{-4}	0	8.96	2130	1600	1340	1340	780	2.05	17,660	17,680	0.82	
	10-36-2	279	1×10^{-4}	0	8.99	1970	1500	1160	1160	850	1.77	15,240	15,250	0.82	
	average	279	0.7×10^{-4}	0	8.98			1210	1210		2.10	16,020	16,040	0.82	

$$\text{*Specific Energy} = \left[\frac{\text{Mean crushing stress (144)}}{\text{Test density}}\right]\beta$$

Table A-5. Test group average specimen physical properties

Test group	Wt (lb)			Vol (ft³)			Natural moisture content (%)	Growth ring radius (in.)
	Original	Test	% Change	Original	Test	% Change		
A1	0.10006	0.09311	−6.95	0.01556	0.01525	−2.03	6.91	5.57
A2	0.09035	0.08455	−6.43	0.01547	0.01515	−2.06	6.43	4.93
B1	0.09787	0.08968	−8.36	0.01564	0.01554	−0.68	7.99	5.20
B2	0.10437	0.09507	−8.91	0.01552	0.01542	−0.65	8.90	4.57
C1	0.08633	0.07932	−8.13	0.01558	0.01507	−3.27	8.14	3.50
C2	0.08377	0.07683	−8.29	0.01548	0.01526	−1.44	8.28	4.50
D1	0.21090	0.19856	−5.85	0.01546	0.01512	−2.16	5.87	3.90
E1	0.21163	0.19907	−5.93	0.01550	0.01518	−2.06	5.92	4.00
F1	0.20940	0.19520	−6.78	0.01552	0.01509	−2.80	6.80	4.58
G1	0.09317	0.09317	0	0.01544	0.01544	0	9.08	5.47
G2	0.10047	0.10047	0	0.01553	0.01553	0	9.57	4.83
H1	0.08932	0.08991	0.66	0.01573	0.01576	0.19	7.53	5.33
H2	0.09318	0.09386	0.73	0.01559	0.01557	−0.15	9.25	5.23
I1	0.09080	0.09933	9.40	0.01539	0.01614	4.89	10.38	5.00
I2	0.08967	0.09748	8.71	0.01560	0.01616	3.61	10.51	4.87
J1	0.14586	0.14586	0	0.01559	0.01559	0	8.29	4.50
K1	0.14761	0.13745	−6.89	0.01546	0.01509	−2.39	6.88	4.50
L1	0.14574	0.13441	−7.77	0.01538	0.01514	−1.61	7.80	4.00
M1	0.09711	0.08848	−8.89	0.01571	0.01529	−2.66	8.32	6.03
M2	0.09624	0.08896	−7.57	0.01553	0.01520	−2.14	6.82	5.67
N1	0.01589	0.01483	−6.66	0.01583	0.01549	−2.15	7.97	3.58
O1	0.09696	0.08906	−8.15	0.01553	0.01521	−2.08	7.90	5.10
O2	0.09664	0.08921	−7.69	0.01563	0.01543	−1.28	7.35	4.50
P1	0.15705	0.15695	−0.06	0.01587	0.01586	−0.04	8.02	3.76
Q1	0.16311	0.16987	4.14	0.01640	0.01681	2.49	6.92	2.92
R1	0.09288	0.09332	0.47	0.01560	0.01559	−0.10	8.92	5.07
R2	0.09183	0.09276	1.01	0.01555	0.01553	−0.07	8.14	5.27
S1	0.08660	0.08656	−0.04	0.01546	0.01545	−0.02	8.92	3.93
S2	0.08755	0.08715	−0.46	0.01551	0.01537	−0.86	9.24	4.50
T1	0.16197	0.16147	−0.31	0.01563	0.01561	−0.15	8.95	5.00
U1	0.15343	0.15347	0.03	0.01556	0.01541	−0.92	9.39	4.50
V1	0.09567	0.08803	−7.99	0.01559	0.01526	−2.14	8.01	4.93
V2	0.09426	0.08907	−5.51	0.01538	0.01517	−1.33	6.83	4.67
W1	0.14863	0.13538	−8.92	0.01538	0.01508	−1.91	7.67	4.00

Table A-6. Batch test results

Batch	Specimen No.	Specimen test condition: Mean temperature (°F)	Pressure	Moisture content (%)	Density (lb/ft³)	Stresses (psi)—σ, Crushing: Initial peak	Max	Mean, Actual	Min	α $\left(\frac{\sigma \text{ max crush}}{\sigma \text{ min crush}}\right)$	Specific energy $\left(\frac{\text{ft-lb}}{\text{lb}}\right)$*, Actual	β Thickness efficiency
1	6-1-1	75	atm	9.23	5.82	1020	950	830	750	1.27	17,250	0.84
	6-2-1	75	atm	9.50	6.38	1230	1130	1000	910	1.28	18,540	0.82
	average	75	atm	9.36	6.10			910	830	1.28	17,890	0.83
2	6-22-2	75	atm	8.50	6.35	1310	1260	1080	1020	1.24	20,080	0.82
	6-23-2	75	atm	8.50	5.91	1130	1050	930	850	1.23	18,580	0.82
	average	75	atm	8.50	6.13			1000		1.23	19,330	0.82
3	6-47-3	83	atm	7.97	5.70	1050	960	790	600	1.60	16,770	0.84
	6-49-3	82	atm	8.36	5.61	960	910	780	660	1.38	18,820	0.84
	average	82	atm	8.16	5.66			790		1.49	17,800	0.84
4	6-65-4	86	atm	9.08	5.85	890	830	730	600	1.38	14,740	0.82
	6-67-4	83	atm	8.28	5.95	910	900	730	590	1.52	14,490	0.82
	average	85	atm	8.68	5.90			730		1.45	14,620	0.82
5	6-A-5	82	atm	8.28	6.10	890	880	770	630	1.40	14,720	0.81
	6-B-5	83	atm	7.72	6.26	1060	1020	890	720	1.42	16,790	0.82
	average	83	atm	8.00	6.18			830		1.41	15,760	0.82
6	6-A-6	82	atm	7.81	6.68	1230	1200	990	840	1.43	17,710	0.83
	6-B-6	83	atm	8.52	6.67	1260	1200	980	810	1.48	17,560	0.83
	average	83	atm	8.17	6.67			980		1.45	17,640	0.83
7	6-A-7	83	atm	7.96	5.61	930	900	830	720	1.25	17,470	0.82
	6-B-7	84	atm	8.01	5.65	820	800	720	580	1.38	15,050	0.82
	average	83	atm	7.98	5.63			780		1.31	16,260	0.82
average	—	81	atm	8.41	6.04			860		1.38	17,040	0.82

$$\text{*Specific Energy} = \left[\frac{\text{Mean crushing stress (144)}}{\text{Test density}}\right]\beta$$

Table A-6. (Cont'd)

Batch	Specimen No.	Specimen test condition: Mean temperature (°F)	Pressure	Moisture content (%)	Density (lb/ft³)	Stresses (psi)—σ, Crushing: Initial peak	Max	Mean: Actual	Min	α $\left(\frac{\sigma \text{ max crush}}{\sigma \text{ min crush}}\right)$	Specific energy $\left(\frac{\text{ft-lb}}{\text{lb}}\right)$*: Actual	β Thickness efficiency
1	8-A-14	78	atm	7.2	8.34	1140	1140	900	700	1.63	12,600	0.81
	8-B-23	78	atm	8.4	8.89	1950	1910	1530	1280	1.50	19,300	0.78
	8-C-29	78	atm	9.5	7.48		1440	1200	1060	1.35	18,000	0.78
	average	78	atm	8.3	8.24			1210		1.49	16,630	0.79
2	8-A-43	78	atm	8.2	8.52	2020	2010	1710	1430	1.41	22,400	0.77
	8-B-45	78	atm	8.2	8.93	2000	1950	1720	1540	1.26	21,300	0.77
	average	78	atm	8.2	8.73			1710		1.34	21,850	0.77
3	8-A-84	78	atm	7.1	7.03		1840	1360	990	1.86	22,700	0.81
	8-B-94	78	atm	7.8	8.33	1980	1950	1550	1260	1.55	21,300	0.80
	average	78	atm	7.5	7.68			1460		1.76	22,000	0.81
average	—	78	atm	8.1	8.22			1420		1.51	19,660	0.79
1	10-1-1	81	atm	7.02	9.99	2380	2280	1750	1480	1.54	20,690	0.82
	10-2-1	82	atm	7.02	9.96	2410	2300	1760	1450	1.58	20,870	0.82
	10-6-1	83	atm	7.03	10.03	2220	2100	1700	1400	1.50	19,770	0.81
	average	82	atm	7.02	9.99			1740		1.54	20,440	0.82
2	10-26-2	82	atm	8.75	9.15	1680	1640	1450	1320	1.24	17,570	0.77
	10-27-2	82	atm	8.62	9.49	2040	1840	1680	1410	1.30	19,880	0.78
	average	82	atm	8.69	9.32			1570		1.27	18,730	0.78
3	10-18-3	82	atm	8.89	10.62	2130	2000	1630	1240	1.60	16,800	0.76
	10-19-3	82	atm	8.83	9.98	2020	1860	1560	1340	1.39	17,330	0.77
	average	82	atm	8.86	10.30			1600		1.49	17,070	0.76
average	—	82	atm	8.02	9.89			1650		1.45	18,990	0.79
1	11-5-1	78	atm	6.08	11.23	2840	2600	2090	1380	1.88	20,900	0.78
	11-6-1	78	atm	6.61	11.26	2830	2740	2150	1760	1.56	21,720	0.79
	11-7-1	78	atm	6.12	11.18	2710	2550	2180	1800	1.42	21,620	0.77
	average	78	atm	6.27	11.22			2140		1.62	21,410	0.78

*Specific Energy = $\left[\frac{\text{Mean crushing stress (144)}}{\text{Test density}}\right]\beta$

Table A-6. (Cont'd)

Batch	Specimen No.	Specimen test condition				Stresses (psi)—σ				α	Specific energy $\left(\frac{\text{ft-lb}}{\text{lb}}\right)$*	β
		Mean temperature (°F)	Pressure	Moisture content (%)	Density (lb/ft³)	Crushing: Initial peak	Max	Mean	Min	$\left(\frac{\sigma \text{ max crush}}{\sigma \text{ min crush}}\right)$		Thickness efficiency
								Actual			Actual	
2	11-1-2	78	atm	6.12	11.58	2700	2600	2300	2010	1.29	22,590	0.79
	11-2-2	78	atm	5.97	11.53	2730	2620	2220	1680	1.56	22,460	0.81
	11-7-2	78	atm	6.16	11.82	2720	2700	2190	1860	1.45	21,080	0.79
	average	78	atm	6.08	11.64			2240		1.43	22,040	0.80
3	11-8-3	78	atm	6.64	11.93	2550	2550	2160	1820	1.40	20,600	0.79
	11-9-3	78	atm	6.82	11.49	2460	2440	1940	1240	1.96	20,670	0.85
	11-11-3	78	atm	6.59	11.51	2840	2310	1900	1380	1.67	19,250	0.81
	average	78	atm	6.68	11.64			2000		1.68	20,170	0.82
average	—	78	atm	6.34	11.50			2130		1.58	21,210	0.80
1	14-13-1	78	atm	4.99	13.18	4200	3960	2710	1260	3.14	24,280	0.82
2	14-2-2	78	atm	7.52	15.59	4020	3780	3500	3300	1.15	25,860	0.80
	14-3-2	78	atm	7.77	14.65	3970	3660	3270	2960	1.24	23,780	0.74
	14-9-2	78	atm	8.50	14.74	4060	4060	3460	3200	1.27	26,700	0.79
	average	78	atm	7.93	15.00			3410		1.22	25,450	0.78
3	14-1-3	78	atm	8.34	13.20	3620	3600	3040	2800	1.29	26,200	0.79
	14-2-3	78	atm	8.22	14.03	4340	4200	3520	2700	1.55	28,900	0.80
	14-3-3	78	atm	7.73	15.23	3980	3980	3580	3260	1.22	27,420	0.81
	average	78	atm	8.10	14.15			3380		1.35	27,510	0.80
4	14-2-4	74	atm	6.67	13.43	3630	3480	2990	2100	1.66	24,360	0.76
	14-3-4	74	atm	6.83	13.50	3540	3540	3030	2340	1.51	24,240	0.75
	14-6-4	74	atm	6.67	13.30	2760	2760	2300	1440	1.92	19,420	0.78
	average	74	atm	6.72	13.41			2770		1.70	22,670	0.76
average	—	77	atm	7.32	14.08			3140		1.60	25,120	0.78

$$\text{*Specific Energy} = \left[\frac{\text{Mean crushing stress (144)}}{\text{Test density}}\right]\beta$$

ACKNOWLEDGMENT

The assistance of Messrs. Calvin Beylik, Eugene Bernett, and Harry Tracy, Engineering Mechanics Division, Jet Propulsion Laboratory, in the performance of the tests is gratefully acknowledged.