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ABSTRACT

The study describes the experimental procedure used to determine the static load-deflection characteristics of 3-inch (76.2-mm) cubes of redwood loaded parallel to the grain by a cylindrical plunger with a cross-sectional area of one square inch (645 mm^2). Tests were conducted over the temperature range of -40 to 230°F (-40 to 110°C). Specific energy and crushing stress as a function of temperature are given. Average values show an approximate 10 percent decrease in the specific energy and average crushing stress for a temperature rise from 70 to 230°F (21 to 110°C), while there is an approximate 30-percent increase in these quantities for a decrease from 70 to -40°F (21 to -40°C).

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SUMMARY

Redwood is used as an impact energy-absorbing material in the plutonium air transportable (PAT) package. To function properly the redwood must retain its properties over a wide temperature range. Since data were not available, an experimental program was conducted on 3-inch cubes of redwood over the temperature range of -40 to 230°F (-40 to 110°C). The specimens were loaded statically, parallel to the grain, by a steel cylindrical loading ram with a cross-sectional area of one square inch (645 mm^2) until bottoming occurred. Lateral restraint of the specimens was provided by a special test fixture. The specific energy and average crushing stress were determined from the experimental data. This and other information, such as percent compression at bottoming, are presented for the 22 specimens that were tested.

Average values show an approximate 10-percent decrease in the specific energy and average crushing stress for a temperature rise from 70 to 230°F (21 to 110°C); and an approximate 30-percent increase in these quantities for a decrease from 70 to -40°F (21 to -40°C). However, for a given set of conditions, there is up to 30-percent scatter in the experimental values.

THE EFFECTS OF TEMPERATURE ON THE ENERGY-ABSORBING CHARACTERISTICS OF REDWOOD

Introduction

This report describes tests conducted on redwood specimens to determine the effect of temperature on the energy-absorbing characteristics of the redwood. The study supports the program at Sandia Laboratories to develop and test a plutonium shipping container which can survive an aircraft crash and the resulting fire. This container, known as PAT,[1] uses redwood as a shock mitigator and fire insulator. Since the energy-absorbing characteristics of redwood as a function of temperature were unknown, a test program was initiated to determine these properties.

The PAT (Figure 1) is about 4 feet (1.08 m) high, 2 feet (0.62 m) in diameter, is constructed largely of stainless steel and redwood, and weighs about 500 pounds (227 kg). The capacity of the inner container is approximately 2 kilograms of plutonium dioxide in any solid form. The redwood is laminated so that its grain is generally oriented perpendicular to the outer surface of the package. It was chosen because of its high specific energy-absorbing characteristics and also because when it burns, the char actually becomes a carbon insulation layer. The package qualification criteria (essentially a test plan) include an impact test onto an unyielding surface at a velocity of 422 ft/s (128.6 m/s), and exposure to a jet fuel fire (approximately 2200°F [1204°C]) for 60 minutes. This program is being funded by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission.

The temperature of the redwood at impact depends on the ambient temperature and the amount of heat released by the contents of the inner container. It was determined that a temperature range of -40 to 230°F (-40 to 110°C) would encompass the extreme temperatures of the redwood.

Behavior of Energy-Absorbing Materials

To protect packages which are subject to impact on hard surfaces, sacrificial energy-dissipating materials may be used. Characteristic of these materials is a relatively low stress level at which crushing occurs, followed by a large displacement at an essentially constant stress level to a point where the material "bottoms out" (also called lockup--Figure 2). The elastic rebound is usually small and is commonly ignored. Enough volume and thickness of the material are used to limit the deceleration forces in the package and to prevent bottoming out of the crushable material. Some typical materials are different wood species, in particular, balsa and redwood, plastic foams, cellular concrete, and metal and paper honeycombs. For several of these materials the crushing behavior depends on the direction in which the load is applied; in other words, the materials are not isotropic.

The area under the load-displacement curve is the mechanical energy that is dissipated during crushing. To compare different materials, the specific energy dissipation, which is the amount of energy absorbed per pound of material being crushed, is usually calculated. The average crushing stress is defined as the area under the stress-deflection curve to the bottoming point divided by the deflection to this point (see Figure 2).

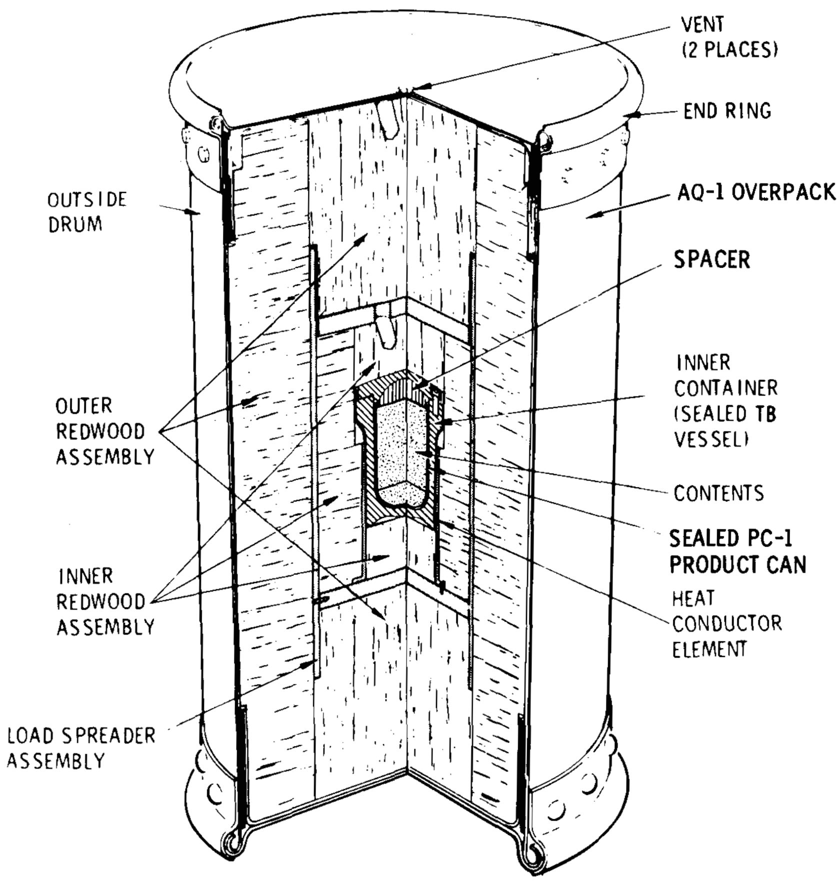

Figure 1. PAT (Plutonium Air Transportable) Package

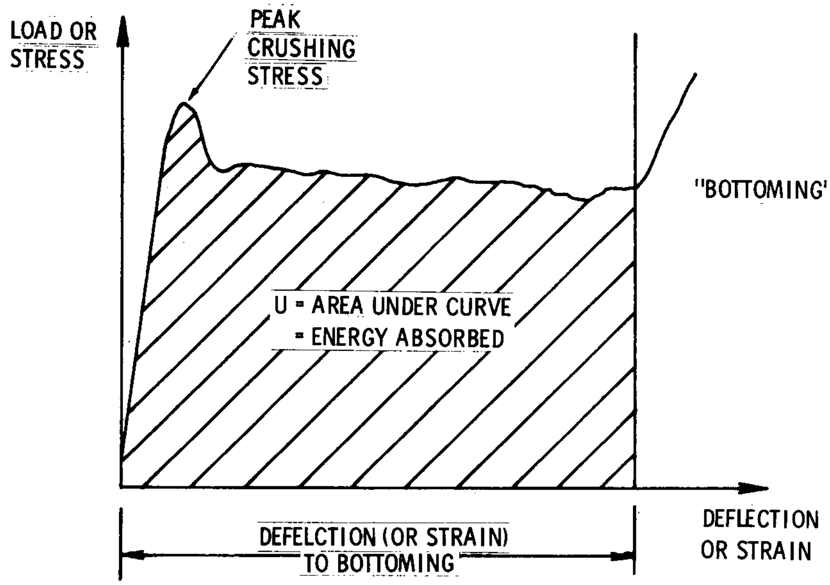

Figure 2. Typical Load-Deflection Curve for an Energy-Absorbing Material

Literature Investigation

Redwood Properties

Reference 2 reports the results of a series of static and dynamic crushing experiments on redwood and other woods, and also on foams. The static compression tests were performed on cylindrical specimens 5 inches (0.127 m) in diameter and 6, 7, and 8 inches (0.152, 0.178, and 0.203 m) long. The specimens were confined in a steel tube with an outside diameter of 5.5 inches (0.140 m) and a wall thickness of 3/16 inch (4.76 mm). The dynamic tests used only the 7-inch (0.178 m) long specimens and were impacted at a velocity of about 275 ft/s (83.8 m/s). The steel mass which impacted the specimen was instrumented with accelerometers. All tests were conducted at room temperature.

Five static and five dynamic tests were conducted in which the redwood was loaded parallel to the grain. The specific energy for the static tests ranged from 21,211 to 21,284 ft-lbf/lbm, (63350 to 63568 J/kg), while the range for the dynamic tests were from 21,644 to 26,465 ft-lbf/lbm (64643 to 79042 J/kg). The density of the specimens ranged from 17.4 to 22.4 lbm/ft^3 (278 to 359 kg/m^3).

Properties of Other Wood Species

No reports were found regarding the effect of temperature on the energy-absorbing capability of redwood. However, several reports do describe the effects of temperature on either woods in general or specific species other than redwood.

Reference 3 states:

> In general, the mechanical properties of wood decrease when heated and increase when cooled. This effect is immediate, but prolonged exposure at high temperature causes an irreversible decrease in properties.
>
> At a constant moisture content and below about 400°F (204°C) mechanical properties are essentially linearly related to temperature. (See comments regarding Reference 7 below.) The change in properties that occurs when wood is quickly heated or cooled and then tested at that temperature is termed an "immediate effect." At temperatures below 200°F (93°C) the immediate effect is essentially reversible; that is, the property will return to the value at the original temperature if the temperature change is rapid.

Figures are given in Reference 3 which illustrate the change in modulus of rupture in bending, tensile strength perpendicular to grain, compressive strength parallel to grain, modulus as measured in bending, tension parallel to grain, and in compression parallel to grain. These figures show a decrease of 2 to 30 percent in the above values for a temperature change from 70 to 200°F (21 to 93°C).

In Reference 4, static tests on 3-inch (76.2-mm) cubes of balsa wood over the temperature range of -123 to 304°F (-86 to 151°C) are described. The blocks were loaded with a cylindrical one-square-inch plunger. Values presented in the report show an approximate 20-percent decrease in specific energy between room temperature and 200°F (93°C), and a similar increase between room temperature and -40°F (-40°C). These tests were conducted with zero percent moisture content. Tests were also conducted on samples with 8 percent natural moisture content between -115 and 86°F (-82 and 30°C). These tests showed that there was an approximate 40-percent increase in the specific energy between room temperature and -40°F (-40°C).

Reference 5 describes dynamic crush tests on balsa wood. All of the tests are at room temperature.

In Reference 6, the results of 1,241 crush tests on balsa wood in moist, dry, and sterilized conditions are reported. All of the testing was conducted at room temperature.

In Reference 7, six different woods are examined for the effect of temperature and moisture content on strength properties. One of these included toughness in both the radial and tangential directions, over the temperature range of -4 to 140°F (-20 to 60°C). The toughness was determined by a Denison toughness tester not described in the report. The results show that for some woods there was a decrease in toughness with an increase in temperature, while the reverse was true for some other woods. In addition, the change was linear only for two of the six woods examined.

Personnel contacted at the Forest Products Laboratory in Madison, Wisconsin, and the University of California Forest Products Laboratory in Richmond, California, were unable to supply any additional information.

Since there was no definite information available on the effects of temperature on the energy-absorbing properties of redwood, an experimental program was initiated. Due to both economic and time constraints, only the static properties at nominal moisture content were measured.

Experimental Procedure

The objectives of the experimental program were to measure, at quasi-static rates, the crush strength and energy-absorbing capacity of redwood as a function of temperature over the range of -40 to 230°F (-40 to 110°C).

Three-inch cubical redwood blocks, patterned after the test specimens described in Reference 4, were chosen as the specimen configuration. Thirty-eight specimens were fabricated by the Bendix Corporation, Kansas City, from a stock of 2- x 10-inch (51- x 254-mm) (nominal) redwood lumber being used in fabrication of PAT packages. It was necessary to bond two boards together to have sufficient thickness for cutting the test specimens. The specimens were cut and then sealed in plastic bags for shipment to Sandia Laboratories. Upon receipt of the specimens, dimensions and weights were taken to determine volume and density. While awaiting tests, the specimens were stored in a laboratory where the temperature was controlled at 70°F (21°C) and the relative humidity at 50 percent.

With the exception of loading direction with respect to the grain orientation and the amount of lateral confinement on the specimen, the experimental setup remained constant throughout the test program. Tests were conducted on a 20,000-pound (9070-kg) capacity screw-driven Instron machine. The redwood specimen and a steel cylindrical loading ram (1.0 in.^{2} [645 mm^2] loading area and 3.0 inches [76.2 mm] long) were placed between two loading platens of the Instron. The entire test volume was located inside a Missimer temperature chamber that has a -100 to 500°F (-73.3 to 260°C) operating temperature capability. The tests were performed by bringing the specimen to the desired temperature, allowing the temperature to stabilize, and then compressively loading the specimen at a crosshead deflection rate of 0.2 in./min (5.0 mm/min) while monitoring the load versus deflection response of the material (Figures 3 and 4).

The deflection or penetration of the loading ram into the redwood specimen was measured in two ways. The first 1.0 inch (25.4 mm) was determined by monitoring the relative displacement between the two loading platens with an Instron extensometer (Figure 5). One-inch displacement was the maximum range for the extensometers available. However, more deflection was required to bottom out the specimen; i.e., compress the redwood to the point where the load increases rapidly with little increase in deflection. To record data over the entire deflection range, the crosshead displacement was taken on the Instron chart. This displacement record is not as accurate a measure of ram penetration into the redwood as the extensometer data. However, the extensometer record was used to calculate a correction factor for the crosshead displacement record so that an accurate record of the load versus deflection data for the entire test was available.

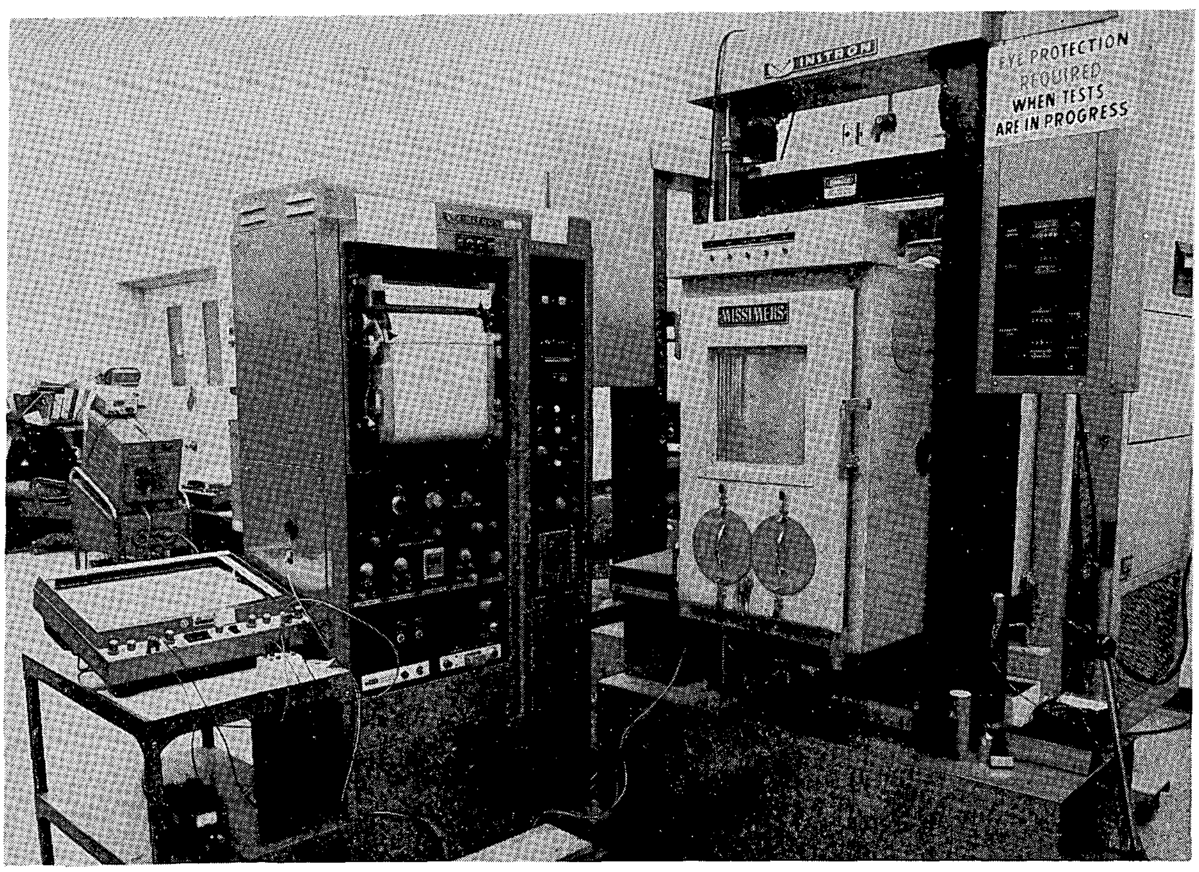

Figure 3. Test Equipment and Recording Devices

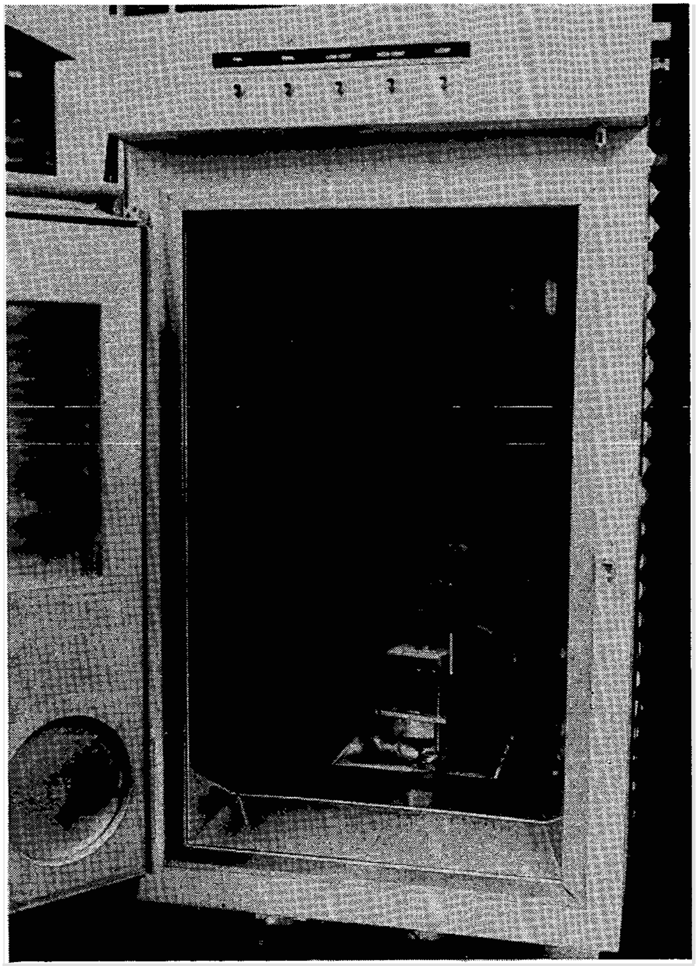

Figure 4. Redwood Specimen Constrained in One Axis in Temperature Chamber

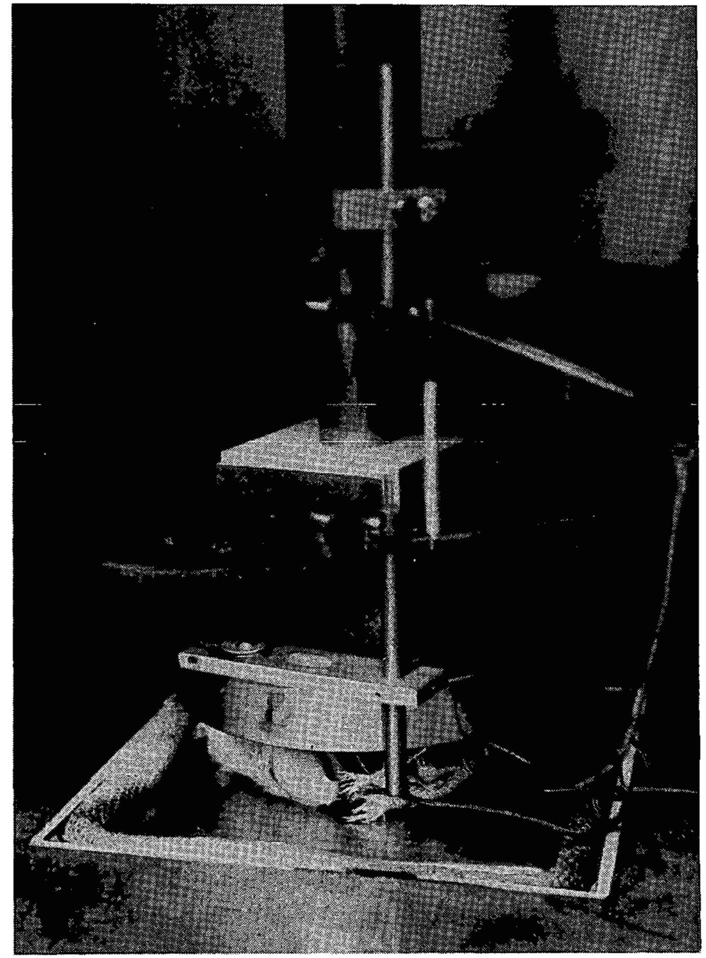

Figure 5. Closeup View of Specimen with Instron Extensometer

Prior to performing tests at other than room temperatures, knowledge of the time it would take for the specimen to stabilize at the test temperature was required. To obtain this information, Specimen No. 3, instrumented with two thermocouples in the locations shown in Figure 6, was placed in the temperature chamber which was being controlled at 100°F (37.8°C). Figure 6 shows the response of the temperature at the two thermocouple locations. Bear in mind that these results are dependent on the specimen size and characteristic of the Missimer temperature chamber. However, for this specimen/chamber combination, the specimen has essentially achieved chamber temperature within 4 hours throughout its volume. Therefore, in all tests at temperatures other than 70°F (21°C), the specimens were allowed to soak at test temperature for at least 4 hours prior to testing.

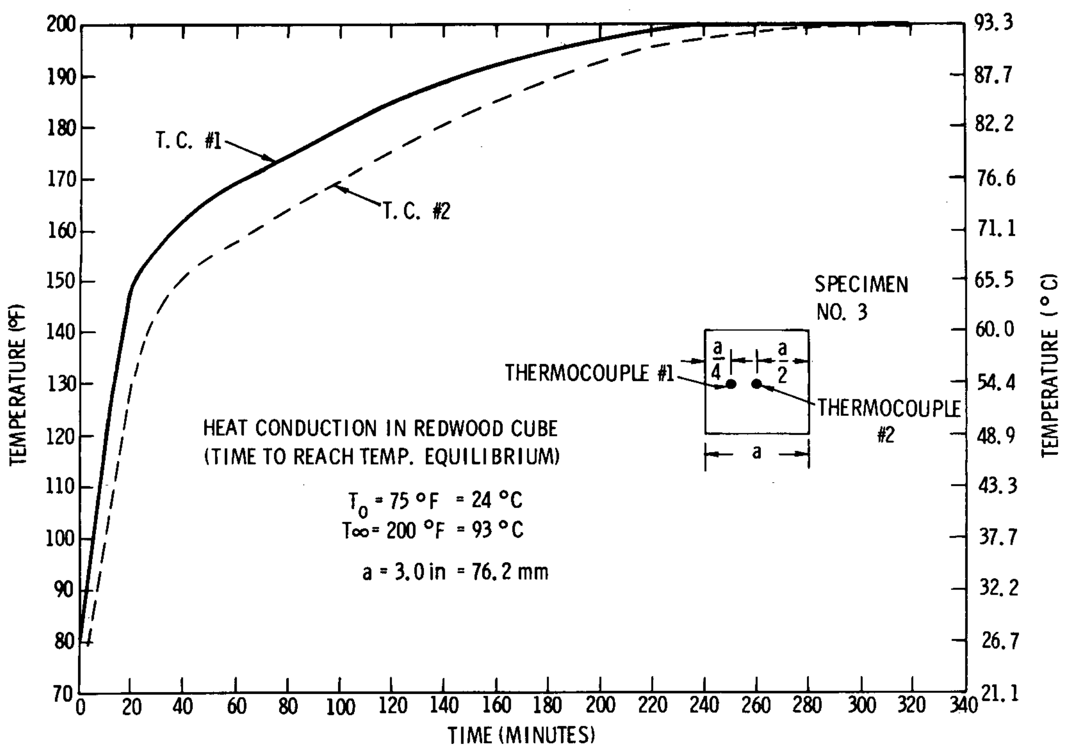

Figure 6. Thermal Response of Redwood

Unconfined Specimens

The first set of tests was performed at room temperature (70°F [21°C]) to check the experimental configuration and to evaluate the feasibility of testing the redwood, both parallel and perpendicular to the grain. In this set of tests the specimens were unconfined; i.e., there were no lateral constraints. The loading surface of the ram, which had a circular cross-section of one-square-inch (645-mm^2) area, was centered on the loading face of the specimen. In tests parallel to the grain, the specimen split along the glue line when the depth of penetration into the specimen was less than 1.0 inch (25.4 mm). These results yielded data for peak crushing stress but not for calculating the specific energy absorbed, because the material had not reached lockup. It was evident that some lateral confinement would be necessary in subsequent tests. The cylindrical ram punched out a clean cylindrical shape in the specimen. Therefore, in tests parallel to the grain, it is easy to measure the volume of material crushed during the tests.

On redwood specimens 5 and 9, tested perpendicular to the grain, the loading ram did not punch a clean hole. Instead, the wood tore and crushed unevenly so that it was not possible to measure accurately the volume of material being tested. For this reason, and because the grain is oriented perpendicular to the outer surface of the PAT package, it was decided that all additional tests would be restricted to loading parallel to the grain.

Partially Confined Specimens

A quick, simple solution for providing lateral confinement of the redwood specimens was evaluated. The approach consisted of using a large C-clamp to hold two 2.75- x 2.75- x 0.25-inch (70- x 70- x 6.4-mm) aluminum plates in such a manner as to restrict splitting along the glue bond (see Figure 5).

Room temperature tests using this partially confined clamping method revealed that the specimens exhibited greater crushup than previously observed, but still split before lockup. When all four sides were confined with two C-clamps and four aluminum plates, the material bottomed out prior to splitting. Comparison of the data from totally and partially confined specimens indicated the partially confined specimens were near lockup when splitting occurred. It was then possible to extrapolate the incomplete load versus deflection curves to total crushup, because the penetration depths in the completely confined specimens were essentially constant.

Since the temperature chamber was too small to house two of the C-clamps required for complete lateral confinement, tests were performed on partially confined specimens at 20, 70, 150 and 230°F (-7, 21, 66, and 110°C), while a smaller, fully confining fixture was being fabricated.

Fully Confined Specimens

A compact fixture to provide for complete lateral confinement of the test specimen was designed and fabricated (shown in the foreground of Figure 7). The specimen was inserted into the fixture and lateral pressure applied by tightening two bolts which pressed aluminum plates against the specimen. Initial tests using this fixture were performed at room temperature to obtain data for comparison with the data obtained from the previous clamping arrangements. The results indicated that the peak-crushing stress of the redwood tested parallel to the grain was not affected by the presence or absence of lateral confinement. Lateral confinement extends the useful range of deflection data by preventing splitting of the specimen until the material "bottoms out." Additional tests with the new fixture were conducted at 230°F (110°C) to check the deformation in the redwood when it has been completely crushed to the bottoming position. All tests at -40°F (-40°C) used the fully confining fixture.

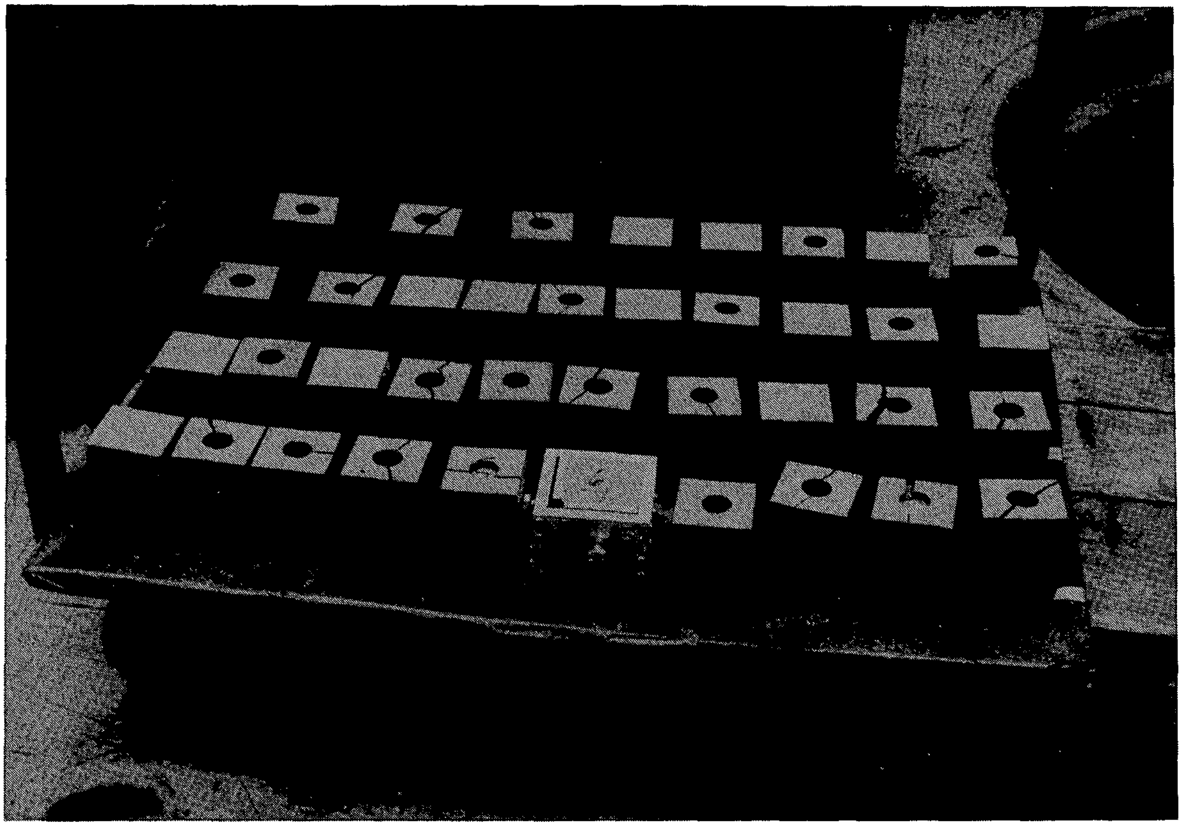

Figure 7. Redwood Specimens and Lateral Confinement Fixture

Results

Typical load versus deflection curves for the redwood loaded parallel to the grain at four different temperatures are shown in Figure 8. The area under the load versus deflection curves to bottoming out were measured with a planimeter and normalized with respect to the density of the specimen to obtain the specific energy-absorbing characteristics of the redwood. These data for the 22 redwood specimens loaded parallel to the grain are listed in Table I.

Table I also shows the values for the peak crushing stress and the average values to one-inch deflection (i.e., 33-1/3 percent compression) and to bottoming out point. An examination of these values indicates the variation in the stress during crushing. An "X" in the deflection column indicates that splitting of the wood due to lack of full confinement occurred before bottoming.

Figure 9 is a plot of the specific energy versus temperature for the 22 tests. Also shown in Figure 9 are the experimental values from Reference 1, and an average value curve of all of the tests.

TABLE I

Experimental Results of Redwood Crushing Tests, Parallel to Grain

Temperature °F	Temperature (°C)	Specimen No.	Density (lbm/ft^3)	Deflection to Bottoming (in.)	Compression (%)	Crushing Stress (psi) Peak	Crushing Stress (psi) Average To 1 in. Deflection	Crushing Stress (psi) Average To Bottoming	Specific Energy (ft-lbf/lbm)
-41	(-40.6)	10	20.6	2.00	67	8,500	6,890	6,620	30,800
-32	(-35.6)	38	20.6	1.85	62	8,150	6,920	6,610	28,600
16	(-8.9)	8	20.6	X		6,550	6,210	5,900±	26,100±
		33	20.6	X		7,500	6,740	5,320±	23,500±
		4	23.1	X		8,400	7,690	7,170±	28,300±
70	(21.1)	19	21.2	X		6,300	5,670	5,360±	23,000±
		25	20.6	X		6,050	5,550	5,290±	23,400±
		18	23.1	X		7,700	6,950	6,080±	24,000±
		12	21.2	1.90	63	5,800	-	5,130	22,000
		29	23.1	1.91	64	6,800	-	6,110	24,300
		7	20.6	1.88	63	5,500	-	5,000	21,900
		15	20.0	1.85	62	5,250	4,810	4,770	21,200
		21	20.6	1.88	63	5,550	5,330	5,300	22,500
152	(66.7)	16	23.7	1.88	67	7,300	5,840	5,400	20,300
		22	23.7	X		7,050	5,600	5,320±	20,500±
		32	21.2	X		5,600	4,740	4,390±	18,900±
231	(110.6)	14	21.8	X		5,500	4,900	4,130±	17,200±
		20	23.7	X		6,600	5,550	4,720±	18,100±
		2	21.2	X		5,300	4,630	3,860±	16,600±
		31	23.1	2.18	73	6,850	5,420	5,920	24,600
		27	20.6	2.05	68	5,150	4,260	4,540	20,400
		36	24.3	2.10	70	7,200	6,050	5,360	22,200

X -- Specimen was not fully constrained and lockup did not occur.

1.0 lbm/ft^3 x 16.019 = kg/mm^3; 1.0 ft-lbf/lbm x 2.99 = J/kg; 1.0 psi x 6.895 x 10^3 = Pa.

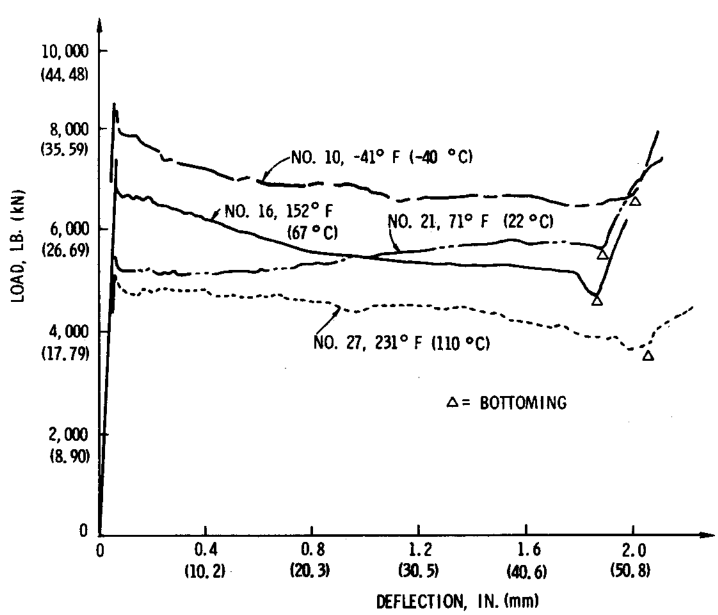

Figure 8. Typical Load-Deflection Curves for Redwood

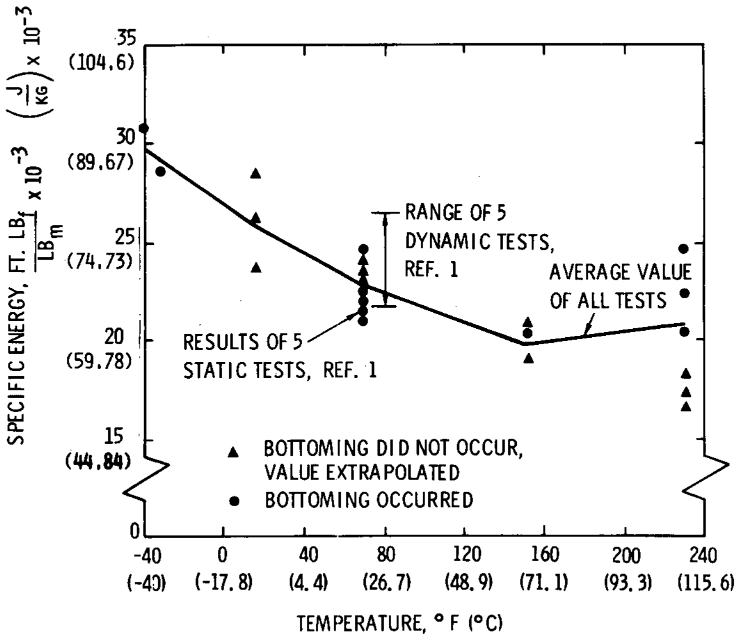

Figure 9. Specific Energy vs Temperature

Figure 10 is a plot of the average crushing stress versus temperature for the 22 tests on the redwood specimens loaded parallel to the grain. Also shown is an average-value curve for all of the tests.

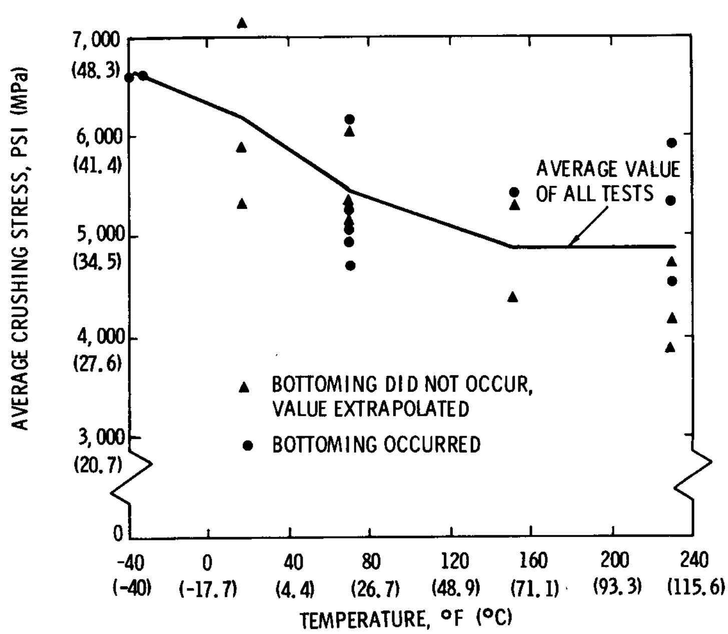

Figure 10. Average Crushing Stress vs Temperature

Conclusions

As expected, there is considerable scatter in the results. Since additional testing would not reduce the scatter, it was not undertaken even though a better determination of average values could have been obtained. It was determined that, for a temperature rise from 70 to 230°F (21.1 to 110°C), there is an approximate 10-percent decrease in the specific energy and average crushing stress; for a decrease from 70 to -40°F (21.1 to -40°C), there is an approximate 30-percent increase in the specific energy and average crushing stress.

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