Cork Thermal Protection Design Data for Aerospace Vehicle Ascent Flight

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Experimental testing has been completed for the purposes of obtaining design data on bonded sheet cork and qualifying it as an external insulation material for the ascent flight of Minuteman missiles. Considerations included the definition of heat flux and enthalpy ranges, the study of material thermal efficiency and material ablation characteristics, the evaluation of critical physical characteristics, the study of environmental effects, and the development of processing techniques. The program encompassed laboratory tests, large-scale-facility tests of components, experimental flight evaluations, and actual missile flights. The resulting test data and design criteria are summarized in tables. It is concluded that sheet cork is an efficient external insulation material for ascent flight conditions.

Introduction

DURING the launch of the Minuteman vehicle from its 12-ft-diam silo, 3000°F exhaust gases are expelled past the rising vehicle. During ascending flight, the following thermal environments result: 1) aerodynamic (convective) heating on the vehicle exterior, 2) convective and radiant heating from recirculating hot exhaust gases in the base areas during the operation of each of the four-nozzle-configuration motor stages, and 3) radiant heating during the operation of a single-nozzle motor configuration. A significant amount of design data has been obtained for the purpose of qualifying sheet cork as an external insulation material for a Minuteman weapon system aerospace vehicle. Testing has included laboratory tests, tests of Minuteman components in large-scale facilities (e.g., Arnold Engineering and Development Center test cells), NASA cork evaluation flight tests (Wallops Island) and Minuteman flight tests from the Atlantic Missile Range. The majority of the laboratory tests were conducted for the Air Force Ballistic Systems Division by The Boeing Company in accordance with a test program prepared by TRW Space Technology Laboratories. The test data support or supplement the design values as presented in this paper.

The purposes of this review are as follows: 1) to define the present status of sheet cork design information and make the data generally available for current and future designs, 2) to provide information on cork which may serve as a base for evaluating the physical properties of other proposed insulation materials for similar uses, and 3) to encourage the refinement of the design data as presented by making them available for comparison with future data from laboratory or flight testing.

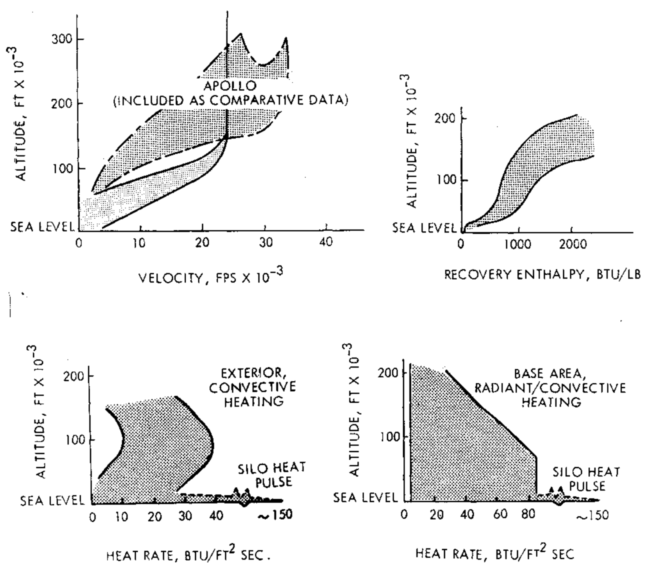

Fig. 1 ICBM altitude, velocity, heat rate, and enthalpy relationships.

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External Insulation Requirements

Flight Requirements (Thermal)

The initial Minuteman design concept recognized that the various thermal environments to be encountered during ascent would make external insulation of the primary structure a requirement. The general ranges of exterior and base-area heat flux, enthalpy, and altitude for ICBM's are indicated in Fig. 1. Apollo data[1] are included for comparison.

Two factors were determined to be important in selecting a thermal protection material: thermal efficiency and ablation characteristics. Initially, Fiberglas was studied extensively because of its desirable thermal characteristics and durability. Subsequently, tradeoff studies indicated that a number of

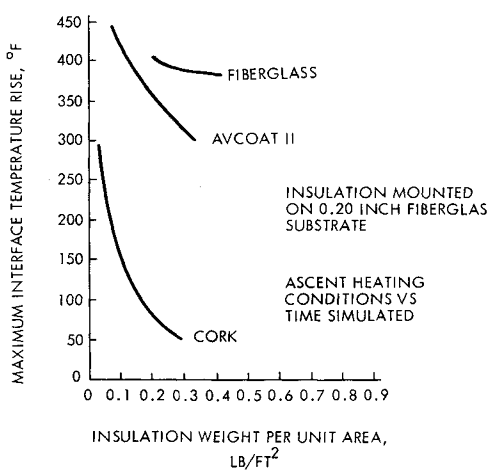

Fig. 2 Performance of insulation in nitrogen under ascent heat conditions (Lockheed hot flow facility test data).

available materials had considerably better thermal efficiencies. A comparison for Fiberglas, Avcoat (epoxy polyamide), and cork is given in Fig. 2. For the test condition, cork is shown to be the thermally superior material. Studies also indicated that there are potential range advantages for materials that ablate but that Fiberglas was not to be expected to ablate appreciably for the Minuteman application; cork was found to have a significant weight advantage because of its ablation characteristics.

Predictions of the thermal performance of cork in flight are based upon "standardized" methods of computation which were developed for noncharring, ablating materials (e.g., the method defined by Ehrlich[2]). For such computations, thermal properties such as those given in Table 1 are required.

Table 1 Physical properties of sheet cork containing 78 ± 3% by weight of refined 16- to 50-mesh ground cork bonded with a thermosetting phenolic resin with a polyol plasticizer

Property	Value	Test method	Remarks
Thermal properties			
ρ, lb/ft^3	30 ± 2		"As received" cork under normal ambient conditions (see Table 3 for environmental effects)
k, Btu in/hr-ft^2-°F	0.512 (100°F) 0.532 (150°F) 0.540 (200°F)	American Society for Testing Materials (ASTM)C177-45	NOTE: With increasing moisture, k increases approx. proportional to the density (weight) increase. Specimen size: 8.2-in. diam, ½-in. thick
c_p, Btu/lb-°F	0.471 (80° to 360°F)	Wright Air Development Center (WADC)TR 57-374, Part 1	Specimen size: ½-in. diam, 2 in. long
T_a, °F	350–1000	Thermogravimetric	T_a = 500°F for aerodynamic heating T_a = 1000°F for convective/radiant heating of base area
T_s, °F	1000		Very approximate
Q^*, Btu/lb	1300 convection (aero) 2200 convection/rad (base) 1800 radiant (silo)		Approximate values (see Table 4 for alternate values)
Transmissivity, τ	0		
Absorptivity, α	0.9		
Emissivity, ϵ	0.9		
T_{bond}, °F	550		Radiant heating *through* cork
Thermal expansion, β, in/in-°F	5.10×10^{-5} (−65° to 130°F) 1.2×10^{-5} (130° to 425°F)	ASTM D 696-44	Specimen size: 0.35 × 0.35 × 2-in., transition temp. is 130°F
Mechanical properties			
σ_{ty}, psi (at temp.)/ elongation	720 (−65°F)/3.5% 350 (75°F)/16% 190 (200°F)/14%		Strain rate of 10 in./in./min Specimen thickness, 0.116 to 0.288 in.
Biax. strain, %	1.2 at 14.5 in./in./min (steel)	Cruciform/photoelastic	Tests completed indicate no biaxial strain problems for aluminum or steel substrates
Lap Shear, psi	157–220		
Compression deflection, %	50 (1010-psi load)	ASTM D 1056	At 0.10-in./min Specimen size: 1.129 in. diam., 0.50 in. thick
Creep compression Set, % (load)	6 (25 psi) 44 (300 psi)		Specimen thickness, 0.50 in. Returns within 18% within 48 hr
Hardness			
Shore A (5 sec)	72		
Rex	80		
Tear resistance, lb/in.	78		Specimen thickness, 0.20 in.
Abrasion vol. loss, cm^3	3.28	ASTM D 1242-52 OT sandpaper, 30-lb load	Results were determined after 62 rev
Impact resistance			
Charpy method, ft-lb/in.	1.8		
Gardner impact tester	77°F −65°F		Specimen thickness
Frontside, in.-lb	100 32		0.05
	88 38		0.125
	220 48		0.200
Backside, in.-lb	9 2		0.05
	11 3		0.125
	12 7		0.200
Flexibility (mandrel bend)	77°F −65°F		
Passing mandrel diam, in.	¾ 5		Specimen size: 1 × 6 × ⅛ in.
Failing mandrel diam, in.	⅝ 4		

The property values are considered to be useful as long as a reasonably conservative result is obtained. That disaster would result from design based upon nonconservative computations is obvious. It should be noted that cork does char under most of the heating conditions considered, and that a completely valid computational technique for performance of cork under char-forming conditions has not been developed. However, information and experience are being acquired which should result in refined prediction methods. Examples of the types of char obtained under simulated flight conditions are indicated by Table 2. Basic understanding of the char-forming process and char adhesion requires further study. The development of char layers and the effects of aerodynamic shear upon them must be well understood before the conservatism introduced into the thermal property values in Table 1 can be refined.

Ground Requirements (Mechanical)

An acceptable thermal protection material must survive manufacturing, handling, transportation, and storage environments. It should not be susceptible to damage and should be easy to repair. The physical characteristics of Fiberglas were considered to be generally known and acceptable, but for other materials the definition of critical physical properties and acceptable limits on them was difficult to establish because of inadequate use experience. Initial laboratory tests to evaluate cork performance indicated four potential problem areas. Although subsequent evaluations determined that these problems were not serious, they are noted here because questions about them recur frequently.

1) Under high-humidity conditions, cork absorbs considerable moisture, but it also casts off moisture rapidly with no apparent damage to the cork.

2) Cork will support fungus growth, but effective fungicides are available.

3) A significant compression set occurs in cork subjected to high loads for long periods, but this is not serious in the Minuteman design because the support strap loadings are quite low.

4) Protuberances or mismatches at joints create increased heating and material ablation, but local ramping of cork to increased thickness and use of cork potting compounds can handle this problem.

The general requirements for the resistance of cork insulation to ground environments and for its processing include 1) ability to withstand specified physical environments during processing, handling, transportation, assembly, and storage and 2) processing techniques for a) shop or field repair, b) contouring it in the vicinity of protuberances, c) materials and methods for insulating protruding boltheads, and d) assurance of an adequate bond to the base (metal) structure. Test results reported in the next section indicate that these requirements have been met with a sheet cork material.

Sheet Cork External Insulation Properties

Sheet cork as discussed herein is defined as a composition sheet material containing 78 ± 3% by weight of refined fine 16 to 50 mesh ground cork bonded with a thermosetting phenolic resin with a polyol plasticizer. Sheets are fine-sanded to a thickness tolerance of ±0.005 in. Splicing is permitted to produce sheets larger than 26 by 48 in. It must be stored at temperatures between 0° and 100°F and at relative humidities below 60% to reduce fungus and moisture problems. Nominal density is 30 lb/ft³. Natural cork, obtained from the outer, nonliving bark of the cork oak tree, is a cellular natural resin foam. Each cell is 14-sided, averages about 0.001 in. in diameter, and has tough, impervious walls enclosing trapped air. There are about 2×10^8 cells/in³. Cork's important physical properties stem from this unique cellular structure.

The thermal properties summarized in Table 1 are based upon analysis of both laboratory and flight-test data. As noted previously, consideration was given to performance factors, which are not well established (char formation and aerodynamic shear) so that the values given should provide for reasonably conservative design when used in currently available computing models[2] for ablating materials. Surface temperature (T_s) and ablation temperature (T_a) values require additional study; the T_a values quoted (500°F for aerodynamic heating conditions and 1000°F for base-area conditions that involve both convective and radiant heating) were judged to be consistent with test results.

The effective heat of ablation Q^* given in the tables is considered to be more an artifice than a fundamental parameter. Consistent with current usage, it is defined as the heat transferred to a nonablating surface at a defined surface temperature divided by the mass of material ablated. Studies of Q^* data from various test facilities indicate that variations in test technique lead to significant variations in the data reported. The Q^* values entered in the tables are consistent with the more conser‵‵ative of the data that were analyzed.

Mechanical properties are also summarized in Table 1. Specific criteria (other than quality control) for the acceptance/rejection of cork have not been developed, but Table 1 defines the properties of a demonstrated, successfully applied sheet cork insulation material for vehicle exterior and base-area application.

Three environments were used in the determination of environmental effects: 1) cycling temperature and humidity (MIL-E-5272)[3]; 2) constant temperature of 165°F and relative humidity of 95%; and 3) oven-aging at 160°F. Effects of these environments on tensile strength, lap-bond shear strength, hardness, and bond blistering were determined. Test results are summarized in Tables 3–5, together with comments on effects of fungus, rodent damage, and decompression, and the determination of dielectric constant and loss tangent for high-temperature, moist conditions.

Table 2 Char observations

Test condition	Appearance after test
1) Convective tests	
a) Lockheed, $M \sim 2$, with movies	
Gas Temp (°F)	
0–1200	No evidence of burning or sparking; some swelling; firm "small bubble" char
1200–1500	Burning in O_2-rich atm, but not in N_2; powdery residue on surface
1500–2500	Broken char ("mud flats")
b) Boeing arc tests	
Heating rate (Btu/ft²-sec)	
0–7	0.002–0.003-in. char layer comprised of many small modules of approx. cork grain size
7–30	0.01–0.02-in. char layer; pebble-grained ("mud flat") with diam ~0.25 in.
2) Radiant tests	
Heating rate (Btu/ft²-sec)	
5–100	Dried "mud flat" with cracks down to unablated cork. Char thickness increases with q (5–30) for 60-sec test

Table 3 Environmental effects on sheet cork

Environmental aging. The three environments used in the aging tests:
(1) Cycling temperature and humidity: MIL-E-5272[3]
(2) Constant temperature of 165°F and relative humidity of 95%
(3) Oven-aging at 160°F
Density

Environment	3-day exposure	14-day exposure
(1) above	ρ = 47.2 lb/ft^3	ρ = 57.5 lb/ft^3
(2) above	ρ = 34.7 lb/ft^3	ρ = 32.8 lb/ft^3
(3) above	ρ = 29.6 lb/ft^3	ρ = 29.6 lb/ft^3

Tensile strength and elongation (see Table 1)
Environment (2) above reduced σ_{ty} by 40% after 3 days
Environments (1) and (3) increased σ_{ty} by 30%
Lap-bond shear strength
Environment (1) reduced it by 25%
Environment (2) reduced it by 35%
Environment (3) increased it by 30%
Hardness
Humidity effects reduced hardness indications
Oven-aging increased hardness indications
Bond blister
14-day exposure to environment (1) reduced the *backside* bond blister failure temperature from ~350° to 220°F
Temperature/altitude (see Table 5)

Fungus resistance. Fungus may grow for all of the conditions exceeding 60% relative humidity and 60°F. "As received" cork supports fungus growth per MIL-E-5272. Fungus preventative coatings (dip or spray) have been determined to be effective.

Rodent control. Test specimens (1 × 3 × 0.50 in.) are chewed 50 to 100% within one week by either starved or well-fed rats. Mice cause damage to a lesser extent.

Decompression. Tests were made to determine whether cavity volume and vent conditions in cork were such that cork could fracture and break away from a structure under rapid decompression. At initial pressures of 50 and 100 psia and decompression rates of 400 and 900 psi/sec., no damage occurred to the cork or the bond.

Dielectric constant and loss tangent at 9375 mc/sec

Cork condition	Dielectric constant	Loss tangent
Dry	1.7	0.01
5% moisture (as-received condition)	1.8	0.05
12% moisture	2.2	0.095
At 350°F	2.2	0.11

Process Considerations

Concurrent with the determination of its physical properties, a program was undertaken to determine processing techniques by which sheet cork may be properly bonded to a specified base material, optimum sheet-joining techniques, optimum shop and field repair techniques, optimum fabrication techniques for contoured insulation in the vicinity of protuberances, materials and techniques for the insulation of flush and protruding boltheads in the presence of surrounding cork insulation, and techniques for maintaining density to within 5% of the nominal value.

Armstrong J-1156 and several other adhesives will generally provide a satisfactory bond when applied to properly cleaned and primed surfaces. However, the bond strength varies with different substrate materials. Lap shear (Table 1), cure capabilities, bond blister temperature, low-temperature bond, and surface preparation tests were used in the evaluation (and qualification) of a number of adhesive materials.

For joining sheets, scarf joints of 30°, 45°, and 60° and notch-type joints are all acceptable. Butt-type joints lose tensile strength at 200°F; hence their use at joints critical in tension is not recommended.

Table 4 Alternate Q^* values for aerodynamic heating conditions

$Q^*/\Delta i^a$	$Q^*/\Delta i$	$Q^*/\Delta i$
15,000/0–220	2750/300	1820/2000 or greater
12,000/225	1480/350	
6300/250	980/700	

[a] Δ i = the difference between the air recovery enthalpy and the enthalpy of air at the boundary temperature.

For repair, both mechanical and chemical methods of cork removal have been evaluated. Methylene chloride can be used to strip cork from an isolated part but is not satisfactory for removing a section from an installed sheet of cork. Plastic or wood routing tools, similar to those used to repair adhesive-bonded aircraft structure, can be used in making cork repairs.

Mismatches of the order of 0.050 in. are generally acceptable. Sheet cork ramps can be applied for small, local protuberances. Local heating effects may be significant, and, where a doubtful area exists, it is recommended that a thermal analysis based on conservative (i.e., high) heating rates be made to determine thickness requirements.

Although cork density increased up to 128% during temperature-humidity cycling tests, the results of constant-temperature-humidity tests (165°F, 95% relative humidity) indicated that the increase in cork density will not exceed 8 to 18% under actual conditions. Coatings slow down, but do not prevent, moisture absorption. Since the time to release moisture is also greatly increased by a coating, the use of a coating to retard moisture absorption is not necessary.

Table 5 Qualification boundaries for sheet cork for use as aerospace vehicle thermal insulation

Heat flux types	Convective/radiant
q (hot or cold wall), Btu/ft^2 sec	0 to 300
Enthalpy range, Btu/lb	0 to 3000
Aerodynamic shear stress, psf	0 to 8
Low velocity gas at temperatures, °F	0 to 3500
Pressure altitude, ft	0 to 300,000
Configurations	Structure exterior
	Stagnation areas (e.g., raceway caps)
	Base areas

However, a coating may perform a useful function by preventing the absorption of an accidently applied material (e.g., oil).

Conclusions and Recommendations

Sheet cork has been demonstrated to be an effective and efficient material for external thermal protection of aerospace vehicles such as Minuteman during launch and ascent both for the main vehicle surfaces and for base areas that are exposed to convective/radiant heating environments. Cork merits consideration for the external insulation of other current and future vehicles. The physical property data presented in this paper are believed to be valid for the design of presently conceived aerospace vehicles under boost-phase conditions. The potential for the use of cork in the high-shear environments experienced on re-entry also appears to be good for certain applications. Of course, the thermal environment for any new design must be carefully determined before one can judge the direct applicability of the data given herein.

References

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Measurement of Free-Air Properties from Onboard a Large Launch Vehicle

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An analysis is made of techniques to measure the pressure, density, temperature, and wind of the free atmosphere from onboard a large launch vehicle of the Saturn or Nova type. The flow field surrounding an accelerating launch vehicle of this size is so complex that it is impossible to make a measurement adjacent to the vehicle and convert it by shock and expansion theory to the free-air value. Consequently, attention was concentrated on remote measurement techniques wherein the instruments are located aboard the vehicle, but the actual measurement is made at a point outside the shock layer. All techniques used or proposed to be used to make aeronomical measurements with conventional sounding rockets or supersonic aircraft were evaluated. Measuring density by monitoring the change of differential absorption of solar radiation as the launch vehicle ascends is promising. The use of very short wavelength ultraviolet light to induce visible fluorescence is found to be very promising. Use of this more sophisticated technique will avoid the problem of backscatter from natural aerosols and meteoritic dust and will afford a much higher operation ceiling. A pitot-static tube is recommended for pressure, and a fixed cone with orthogonal static-pressure ports is recommended for wind.

Nomenclature

α = angle of attack
ρ = density
g = acceleration of gravity
h = altitude
H = scale height
I = intensity
k = mass absorption coefficient
$\bar{M}$ = mean molecular weight
R = gas constant
T = ambient temperature

Subscripts

0 = at the reference altitude (usually sea level)
1 = lower altitude
2 = upper altitude

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Introduction

A STUDY was recently completed at Electro-Optical Systems, Inc. (EOS) on techniques to measure the temperature, pressure, density, and wind above 30 km from onboard a large launch vehicle.[1] It was not the characteristics of the shock layer that were sought, but rather the characteristics of the free atmosphere, undisturbed by the passage of the launch vehicle. The purpose of the measurement is to obtain a more complete picture of the environment during the flight test of Apollo and Gemini launch vehicles than is possible with measurements made within the shock layer. This may appear at first to be an insignificant problem, since the making of aeronomical measurements from rockets is an everyday occurrence, but the problem is more difficult than is encountered with aeronomical soundings. The flow field surrounding an accelerating launch vehicle of the Saturn or Nova type is so complex that it is very difficult to make a measurement adjacent to the vehicle and convert it by shock and expansion theory to the free air value.

Vehicle and Measurement Location

Figure 1 illustrates the complicated, nonisentropic flow field around a Saturn at Mach 1.93, and probably is typical of