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DESIGN, FABRICATION, AND TESTS OF A METALLIC SHELL TILE THERMAL PROTECTION SYSTEM FOR SPACE TRANSPORTATION

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DESIGN, FABRICATION, AND TESTS OF A METALLIC SHELL TILE THERMAL PROTECTION SYSTEM FOR SPACE TRANSPORTATION

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SUMMARY

A new design of a thermal protection tile has been investigated as a possible alternative to some of the current Space Shuttle Orbiter tiles or as a system for future aerospace transports. The tiles differ from currently used reusable surface insulation (RSI) in that the proposed design consists of an outer load-carrying shell which is filled internally with low-density flexible insulations. One such tile has been fabricated from 0.004-in. superalloy for the top half of the tile and 0.004-in. titanium for the lower half and is filled with high-temperature ceramic flexible fibrous insulation. The tile has been tested in a radiant heat lamp facility up to 1600°F where it protected the underlying structure to 345°F. Each 2-3/8 in. x 6 in. x 6 in. test tile weighs 0.33 lb, with a unit weight of 1.328 lb/ft^2 for a four-tile array. The tiles appear to be competitive from the standpoint of insulating qualities and weight with current RSI. Further testing, however, would be required to verify the design for all aspects of the real flight environment.

INTRODUCTION

The Shuttle Orbiter employs an RSI over approximately 70 percent of the vehicle surface (ref. 1). This insulation (applied in small blocks) has proven to be one of the lightest, most insulative materials which could have been used for the current Space Shuttle. However, improvements in subsystems are constantly being sought, and alternate solutions for the surface insulations are being studied particularly with a view toward reducing initial cost and improving durability (ref. 2). In addition to the above goals for the current Shuttle, future aerospace transports may require a somewhat different type of thermal protection system. These systems will differ in entry environment, and therefore, the study of alternative systems is warranted. One notable area in which future transports differ is that of entry planform loading which, may be as little as 50 percent of the Shuttle values. This characteristic of future transports makes it possible to use lower heating rate trajectories (ref. 3) and, therefore, lower (than RSI) temperature capability materials (ref. 4).

In this paper, an alternate thermal protection system (TPS) is described in which a flexible insulation is encapsulated in a 6 in. x 6 in. semi-rigid shell (ref. 5). Radiant heat lamp test data for one such tile (having a metallic shell) are reported.

SHELL TILE CONCEPT

On the current Space Shuttle Orbiter, the RSI serves both as an insulator and structurally as a rigid outer surface to resist aerodynamic loads. In the proposed design, insulation and load-carrying functions are separated, that is, the outer shell carries loads, while the insulation package serves only for insulation.

The shell tile (shown in the cros section in figure 1) consists of a lower shell which is mechanically attached to the structural skin and an upper shell which is attached to the lower shell. The upper shell is stiffened with a dimpled sheet of material welded to the shell's inner surface. The dimpled sheet also acts as a radiation barrier. The top edge of the bottom shell is reinforced with a small rib to add stiffness. The bottom of the bottom shell is left open in the interest of weight saving with a flange provided to accommodate four mechanical fasteners.

A thermal isolation pad (TIP) is placed on the vehicle surface. The lower half of the shell tile is then fastened to the vehicle and filled with insulation, and the upper shell is attached with its insulation package already in place. In the baseline design, a self-locking mechanism is used to hold the upper and lower shells together (fig. 2). This locking system consists of pairs of thin wedges welded to the top and bottom shells at four locations at the midpoints of the sides of the shells. Stops are attached to the lower shell near each corner of the tile to insure proper locking action and correct tile height. To remove the tiles, four paddle shaped tools are inserted between the tiles and rotated 90° to disengage the four wedges (fig. 2).

As an alternate to the self-locking wedges, upper and lower shells can be fastened (by riveting). In fastening the upper and lower shells together prior to attachment to the vehicle, access to the inside of the tile is no longer possible; therefore, the tile must either be bonded or limited in use to structure that is accessible from the inside such that fasteners could be applied from the interior.

In addition to the mechanical design options described, many options are available in materials and internal insulations. For example, candidates for the outer shell include pyrolized composites, refractory metals, superalloys, stainless steels, and titanium alloys. In the two tiles shown in figure 3, the left-hand tile (upper shell) is fabricated from the refractory metal columbium while the right-hand tile is fabricated from the superalloy Rene 41. For the lower (unexposed) shells, stainless steels, titanium alloys, or more moderate temperature capability organic composites are likely candidates. Stainless steel and titanium were used for the left and right bottom shells, respectively, in figure 3.

For internal insulation, a wide variety of flexible refractory fibrous insulations or radiation shields can be used in multiple layers; each layer is selected for an optimum based on weight, insulating qualities, and temperature capabilities. Whereas rigidized ceramic fibrous materials used in making RSI typically have densities in the range of 9 to 22 lb/ft^3, suitable flexible insulations for a shell tile concept have densities in the range of 1 to 6 lb/ft^3. Since insulation qualities and insulation weight are both relevant to system efficiency, the density-conductivity ($\rho\kappa$) products are often compared (ref. 6). These values are shown for one rigidized (LI900) and two flexible insulations at sea level pressures (fig. 4). For example, the $\rho\kappa$ product for LI900 is over 2-1/2 times that of the material used in the shell tile design. (Compare RSI and microquartz in fig. 4 at 1600°F.) Since insulation in the shell tile can be stratified, even lower density and lower temperature capability insulations can be used in the lower stratified layers of the shell tile insulation such as the 1 lb/ft^3 material shown in figure 4. This material has a temperature capability of up to approximately 700°F.

Deterrents to extremely high efficiency for the current system are the weight and conductivity of the load carrying sidewalls. For example, 0.007-in-thick Rene 41 has a thermal conductivity of 14.6 Btu/(hr-ft-°F) compared with 0.704 Btu/(hr-ft-°F) for the 0.015-in. coating on the RSI. A carbon composite (also a likely candidate for the upper shell) has a conductivity of 2.5 Btu/(hr-ft-°F) (parallel to the graphite fibers). This value is still over 3 times greater than that for an RSI coating. What renders the shell tile competitive with RSI, however, are the extremely low $\rho\kappa$ products for the insulation materials which range from one third to one seventh of the values for the rigidized ceramic fiber blocks (i.e., RSI).

An additional deterrent to heat flow down the sides of the shell is the top-to-bottom shell juncture. In this regard, commercially available flexible high-temperature tapes can be placed in the juncture. Also, the use of lower conductivity materials such as titanium for the lower shell minimizes heat flow. Titanium has a conductivity of 6 Btu/(hr-ft-°F), or about 25 percent less than Rene 41 at the mean design operating temperature. In lower temperature (leeside) areas of the vehicle, titanium could also be used for upper shells and even lower temperature capability materials for lower shells.

Because the shell tile can be mechanically fastened, the permissible interface temperature is greatly increased, and therefore, a "warm or hot structure" approach to design could be utilized. For exampe, if the surface to which the tile is attached for the optimal design is titanium, temperature at the interface could be allowed to reach 750°F without detriment to the attachment system.

For added thermal protection, very thin foils (0.001-in. thick) can be added in alternate dimpled and flat sheets between the outer stiffened shell and the top shell insulation package. Because of their thin gauge and the absence of contact welds between sheets, they make an efficient deterrent to heat flow to the shell tile interior. (Note: The effectiveness of multi-layers of unbonded foil cannot be compared directly with a multi-wall construction, described in references 7 and 8, inasmuch as the latter are joined at the contact points and are fabricated from much thicker materials, namely, 8 to 14 thousandths versus 1 to 3 thousandths for the foil).

Currently used RSI tiles expand negligible amounts during peak heating, but gaps must be left between the mechanically weak tiles to prevent contact during flexure of the substructure to which they are attached. By the end of the peak heating period, the aluminum structure has heated up, and the gaps between the tile have increased.

With the shell tile design, the initial gaps can be sized so that the gaps essentially close during peak heating. Because the tiles are metallic, some contact interference is permissible and should cause no damage to the system. After peak heating and during atmospheric flight, because of their low thermal mass, the tiles quickly cool to match local flight conditions. In the contracted condition, the tile gaps are again rendered adequate to allow for deflections of the underlying structure such as those associated with subsonic maneuvers and higher dynamic pressures.

Tile sizes can be varied; the higher the predicted heating rate for a given location, the thicker the tile and the smaller the width dimensions needed to minimize the gap size changes between ambient temperature and peak heating at entry. In general, however, tile sizes should be kept small, since the whole design is predicated on small physical size to minimize weight, thermal distortions, and the initial tile gap width.

MANUFACTURING

All mechanical joints on the shell tile design were made using a capacitor discharge resistance welding device. In general, the tiles are easy to fabricate. Rene 41, however, is somewhat harder to form, and the dimpled stiffener sheets used in the top of the upper shells had to be formed in a two-step process with a 75-percent deformation followed by a 100 percent full-depth forming of the dimples. This was done to minimize cracking of the Rene 41.

Although different tooling would be used for mass production, the design and development costs are expected to be relatively low because of the simplicity of shell tile design. Further, there are no left- or right-hand tiles; therefore, tooling requirements are reduced. Fabrication of triangular or rectangular shell tiles should present no special problems. Shell tiles, having compound curvature, would be costly to manufacture, and special tooling would be required to form individual tiles. However, most of the tile dimensions are small relative to the large radii of curvature anticipated for the future vehicles, and therefore, flat tiles should suffice in most locations.

TEST TILE

The tile used in the radiant heat lamp tests was fabricated from 0.004-in. gauge Rene 41 for the upper shell and 6-Al-4V titanium for the lower (or inner) shell. As stated under the section on manufacturing, a 0.004-in. dimpled Rene 41 sheet was resistance welded to the inside surface of the upper shell in order to stiffen the surface. In this case, the lower shell was also stiffened by bending the titanium sidewall material 90° to form frames at the top and bottom of the lower shell (fig. 1). The upper and lower caps of the test tile were fastened with four 3/32-in-diameter blind rivets located in the overlap zone 3/8 in. from each of the four corners of the tile. A glass tape 3/32-in. thick by 1/2-in. wide was captured in the upper to lower shell overlap zone.

The tile was fastened from the back side of the simulated aluminum structure with 1/8-in. nut plates located inside and mounted on the lower flange of the lower shell. A 0.17-in. Nomex thermal insulation pad was placed beneath the shell tile assembly to reduce the heat flow down the sidewalls of the assembled tile into the structure beneath. The pad is of the same material as the strain isolation pad (SIP) used with RSI but is not required for strain isolation, since the floating nut-plate-fasteners (and clearance holes in the bottom shell) accommodate differential thermal expansion or mechanical strains between the shell tile and the structure. For the test, the entire upper and lower shells were filled with 3.5-lb/ft^3-density micro-quartz (because of availability). As mentioned earlier, lower density, lower temperature capability flexible insulations could be used for the lower layers. The upper insulations package used was 3/4-in. thick; the lower, 1-1/2-in. thick. Test tile component weights are given in table I and centerline properties, in table II. Various assumptions for boundary layer heat transfer coefficient can be made from adiabatic to $h = 30 \times 10^{-4}$ $Btu/(sec^2\text{-}ft^2\text{-}°F)$.

TEST APPARATUS AND PROCEDURE

For the tests described herein, a shell tile was mounted in a 6 in. x 6 in. cutout in a test frame which in turn was attached to a 1/4-in. aluminum plate to simulate structure (fig. 5). The test frame (mounted on four standoffs) was filled with the same insulation as the test tile. Four adjustable sheet metal angles were provided in the frame opening to simulate adjacent tiles and provide for adjustable tile gaps. The assembled tile and frame measured 20 in. x 30 in.

Six fixtures with eight infrared lamps in each were used. The lamps were rated at approximately 2500 watts each at voltages of 460 to 500 volts. Power to the lamps was regulated by a silicon-controlled rectifier. The lamps were provided with forced air for cooling and high-emissivity reflectors. A 12-channel printer recorder was used to record the tile temperatures every 30 seconds. Thermocouples of the chromel-alumel type were utilized. The top surface thermocouples were protected with 304 stainless sheathing. Thermocouple locations are described in table III and are shown on figures 6 and 7 as an inset. The principal objective in the selection of thermocouple locations was to measure the temperature drops across major components down the tile centerline and down the tile sidewalls.

To simulate an entry, the controller was programmed to raise the outer surface of the tile to the designated temperature linearly with time in 500 sec from room temperature. Peak temperature on the surface was held for three different time intervals, namely 500, 800, and 1100 sec to determine the effects of extended entry times on structure temperatures. Table IV shows the programmer inputs for the 500-sec hold time. At the end of the peak heating period, the panel was programmed to cool to room temperature in approximately 500 sec, but no active cooling systems were provided so that cooling periods were frequently longer, particularly for the high-peak-heating periods and temperatures.

TEST RESULTS

Sample test results obtained on the recorder are shown in table V and figures 6 and 7. In figure 6, a 500-sec-duration peak heating period at 900°F was used. The aluminum structure (thermocouple 8) reached a temperature of 107°F, or 37°F above ambient temperature. The second printout is shown for the same peak entry temperature, but the heating period was held for 1100 sec to simulate a higher heat load trajectory (i.e., longer entry time). Maximum aluminum structure temperature was 117°F for this case, or only 10°F higher than the 500-sec peak heating duration just cited. This suggests that the incremental increases in structural temperature resulting from extended entry times is extremely small.

In figure 8, temperature of the aluminum structure is plotted versus tile surface temperature. At 1600°F, structure temperatures reached 345°F for a 500-sec peak heating period, 5°F below the 350°F design limit used for the current Shuttle aluminum structure. (Also see table V data at 1600°F.)

For entry trajectories tailored for the longer peak heating periods (for example the 800 and 1100 sec shown), the amount of tile insulation would have to be increased if the 350°F structural temperature limit is to be maintained for a 1600°F surface temperature.

The weight of four test tiles in an array is 1.55 lb for a 1 ft^2 area of coverage. When the tile design is optimized and the insulation packages stratified with lower density insulation in the lower layers, the weight of a four-tile array is estimated to be 1.328 lb. This weight has been plotted in figure 9 from reference 9, in which several other metallic shell designs and Shuttle RSI are shown.

SUMMARY REMARKS

The concept appears to be weight competitive with other types of thermal protection systems. Advantages of the shell tile concept over other types are greater durability and flexibility than RSI in the substitution of materials, and greater ease of servicing and replacement. Even after the tiles are installed, the upper half of the tile could be removed and substitutions of other materials for the cap made that are nearly optimal for the local heating rate. Similarly, insulation types and thicknesses could be made that are more nearly optimal for the heat load. These changes could be made after the vehicle is in service since the changes in insulation would not result in any changes in the outer moldline.

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Table I

Test Tile Component Weights

Basic shell tile assembly	Wt, lb
Upper shell (0.004-in. René)	0.1272
Lower shell (0.004-in. Ti)	0.0463
Top insulation (microquartz)	0.0525
Bottom insulation package (microquartz)	0.1113*
Glass joint insulation	0.0020
	0.3393
Accessories	
Thermal insulation pad (0.16-in-thick Nomex)	0.0215
Fasteners	0.0269
	0.0484
Total weight per test tile	0.3877
4-tile array (3.54-lb/ft^3 insulation density)	1.551*
4-tile array (stratified insulation densities)	1.328

*Notes: Insulation with a density of 3.5 lb/ft^3 was used here in the test tile, but materials with a density as low as 1 lb/ft^3 are commercially available. These lower density insulations could be used in locations away from the outer surfaces of the tile.

Table II

Shell Centerline Properties

Temperature, °F	Specific Heat, C_p, Btu/(lb-°F)	Thermal Conductivity, K, Btu/(lb-sec-°F)
Layer 1 – René (tile outer shell) [t = 3×10^{-4} ft; ρ = 515 lb/ft^3; ε = 0.90]*		
540	0.11	1.7×10^{-3}
1040	0.12	2.9×10^{-3}
1540	0.13	4.0×10^{-3}
Layers 2 and 3 – microquartz insulation (in top and bottom shells) [t = 0.0625 ft (layer 2) and 0.125 ft (layer 3); ρ = 3.5 lb/ft^3]		
540	0.23	1.25×10^{-5}
1040	0.24	2.22×10^{-5}
1540	0.25	3.47×10^{-5}
Layer 4 – Nomex felt (thermal isolation pad) [t = 0.0133 ft ; ρ = 8 lb/ft^3]		
40	0.24	0.63×10^{-5}
540	0.45	1.32×10^{-5}
Layer 5 – Aluminum structure [t = 0.02 ft ; ρ = 173 lb/ft^3]		
70-350	0.22	0.03

*t = thickness, in.; ρ = density lb/ft^3; ε = emissivity

Table III

Thermocouple Locations

Thermocouple no.	Location
1	Tile surface centerline
2	Between dimpled stiffened sheet and top insulation pack
3	Between upper and lower insulation packages on tile centerline
4	On outside of top shell at upper-to-lower tile juncture
5	Inside surface of lower shell at upper-to-lower tile juncture
6	On bottom of lower tile sidewall above thermal isolation pad (TIP)
7	Underneath insulation pack on top of TIP at centerline of tile
8	On aluminum structure at centerline of tile

Table IV

Test Programmer Inputs for Time vs Temperature Tables
[500-sec hold time at maximum temperture]

Time, sec	Temperature, °F, for T_{max} of –			
	700°F	1320°F	1500°F	1600°F
0	60	60	60	60
100	185	310	250	370
200	320	570	440	680
300	450	810	630	990
400	570	1050	810	1290
500	700	1320	1500	1600
600	↓	↓	↓	↓
700				
800				
900				
1000				
1100	570	1050	810	1290
1200	450	810	630	990
1300	320	570	440	680
1400	185	310	250	370
1500	60	60	60	60

Table V

Maximum Thermocouple Temperature Readings

Peak Temp, °F	Lapsed Time at Peak Heating Rate, sec	Maximum Temperature, °F, at Thermocouple No. –							
		1	2	3	4	5	6	7	8
500	500	490	462	295	333	327	160	202	80
	800	490	465	333	360	355	185	121	90
	1100	495	477	360	370	365	190	130	90
700	500	683	650	450	465	462	213	140	93
	800	690	657	482	475	467	230	162	102
	1100	720	690	536	502	495	257	203	115
900	500	890	850	600	550	540	245	200	115
	800	875	845	641	573	562	272	227	117
	1100	885	850	675	596	585	285	245	120
1000	500	940	925	—	745	705	320	263	190
1300	500	1150	1180	—	860	820	363	340	225
	800	1290	1340	—	960	925	465	—	332
	1100	—	1300	—	960	925	490	—	366
1600	500	1600	1590	—	1133	1070	510	500	345

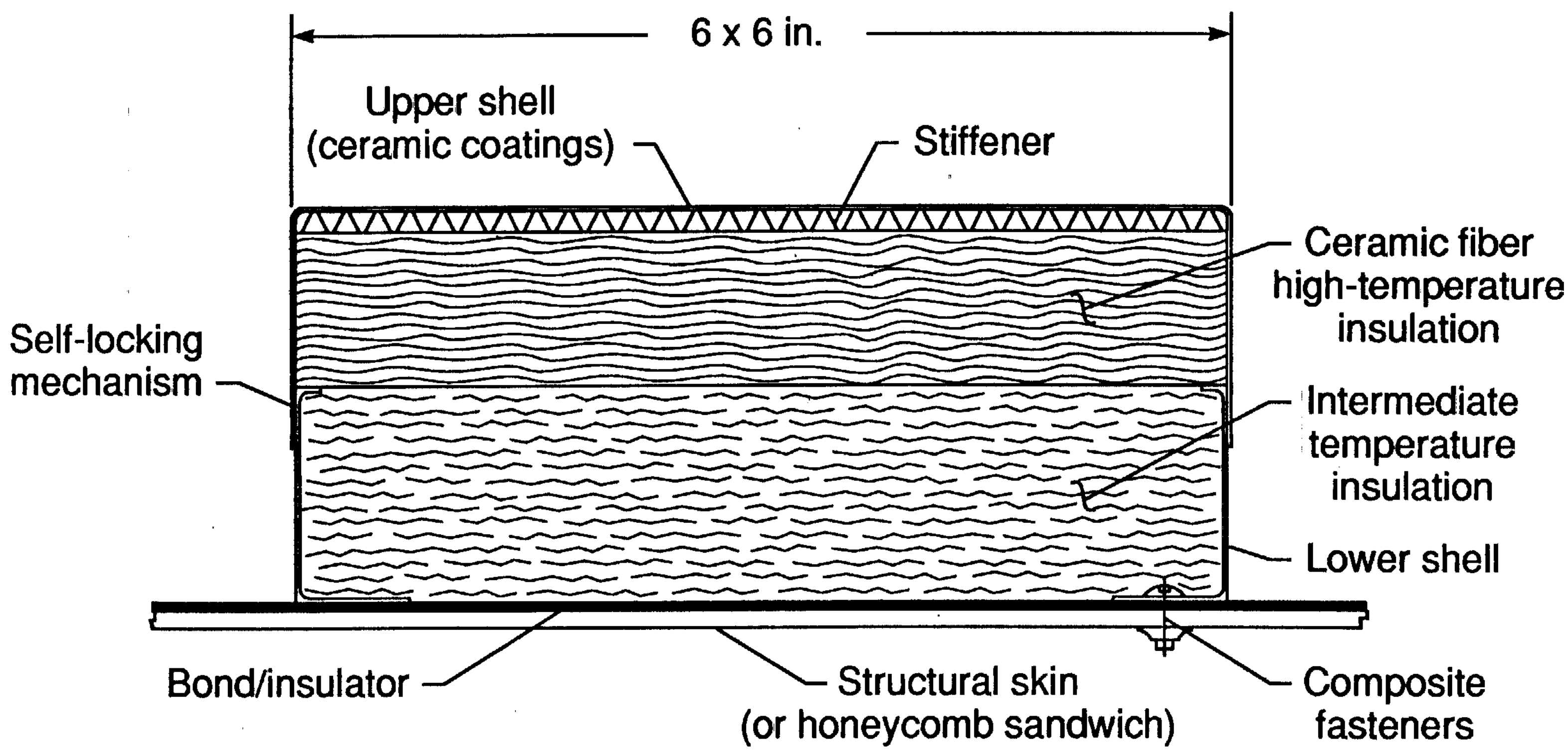
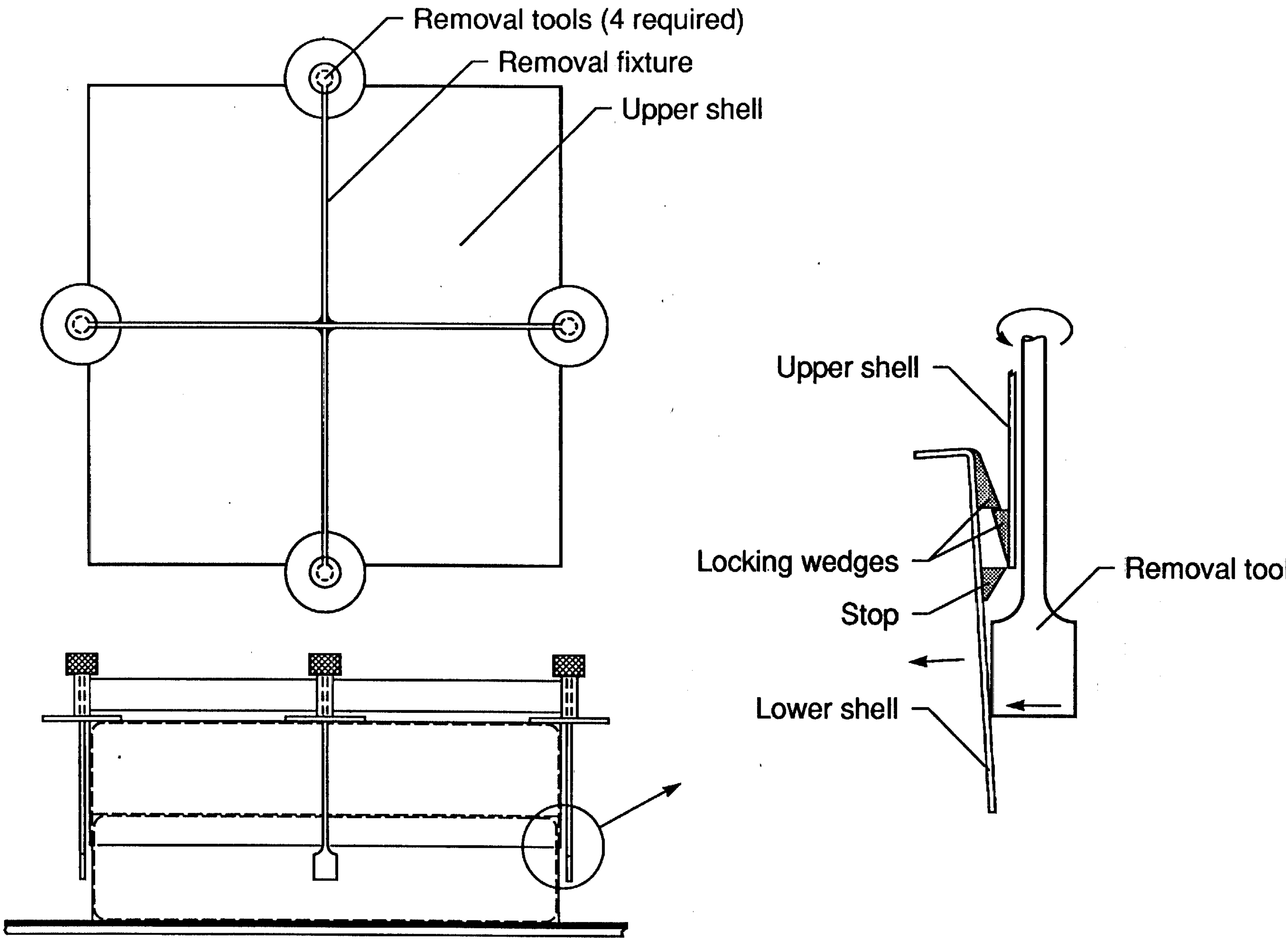


Figure 1. Shell tile concept.



(a) Removal fixture assembly.

(b) Removal method.

Figure 2. Tile locking and removal system.

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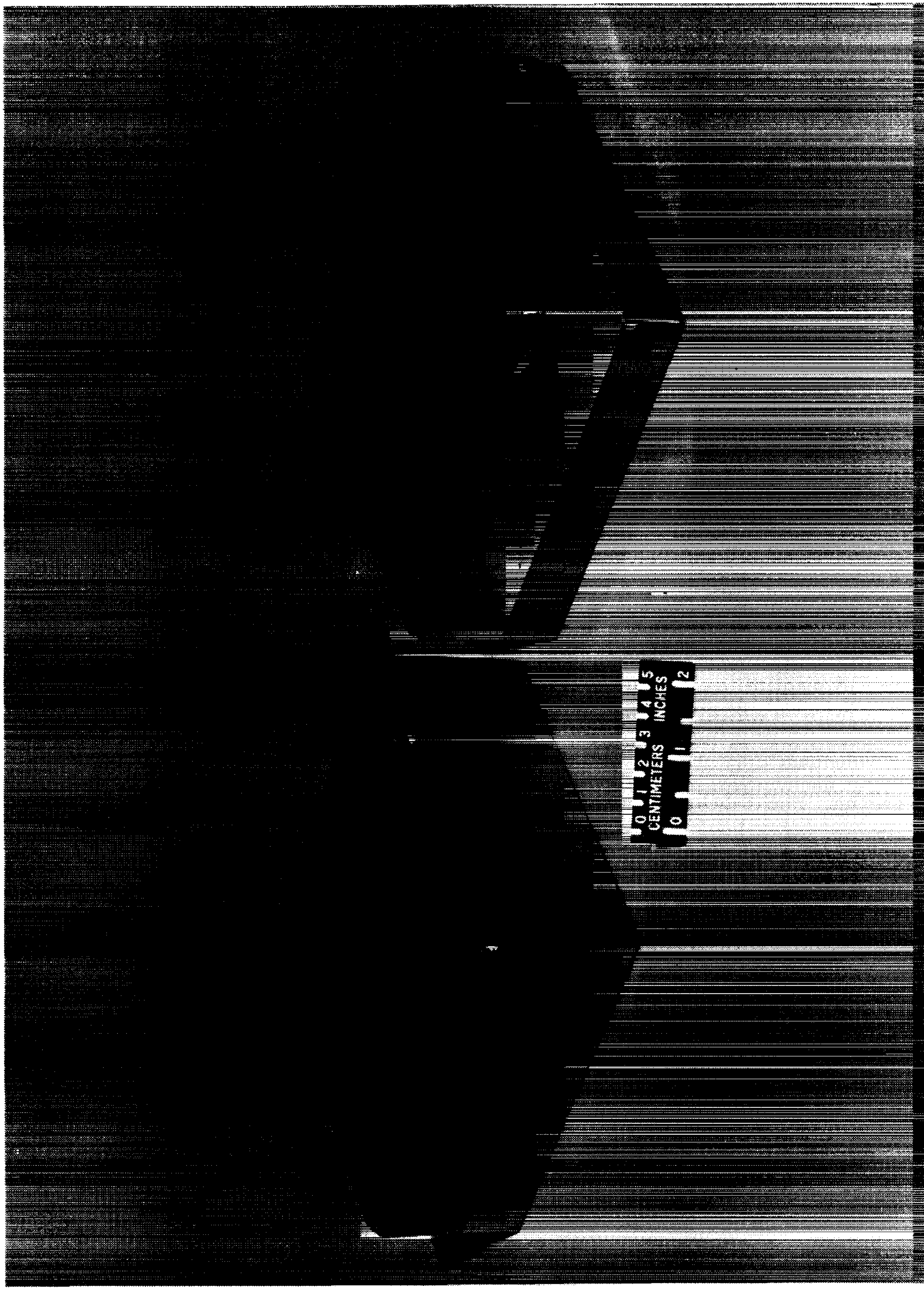

Figure 3. Demonstration tiles with columbium (left) and Rene caps.

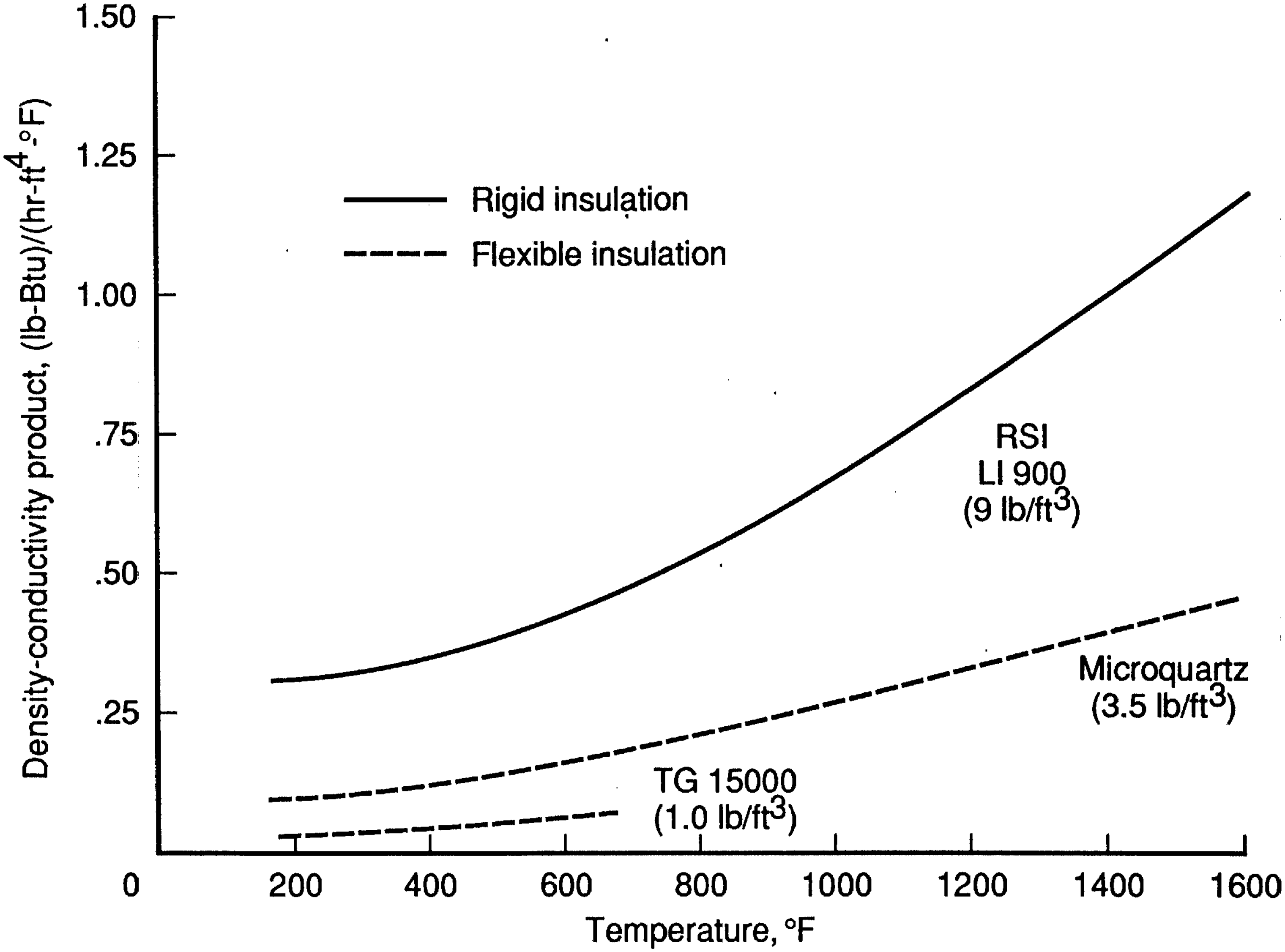

Figure 4. Density-conductivity product comparisons for three insulations.

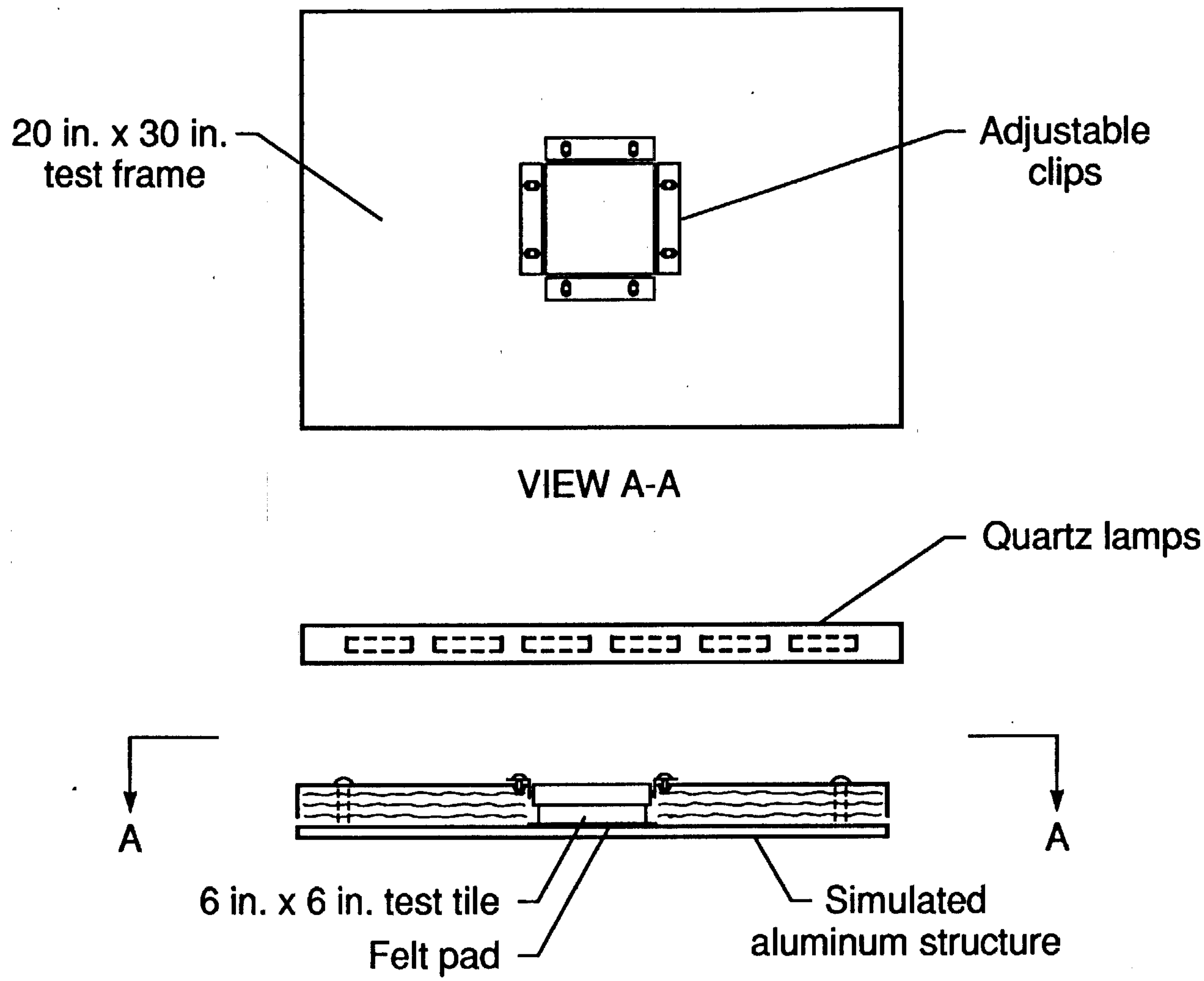

Figure 5. Radiant heat lamp test setup.

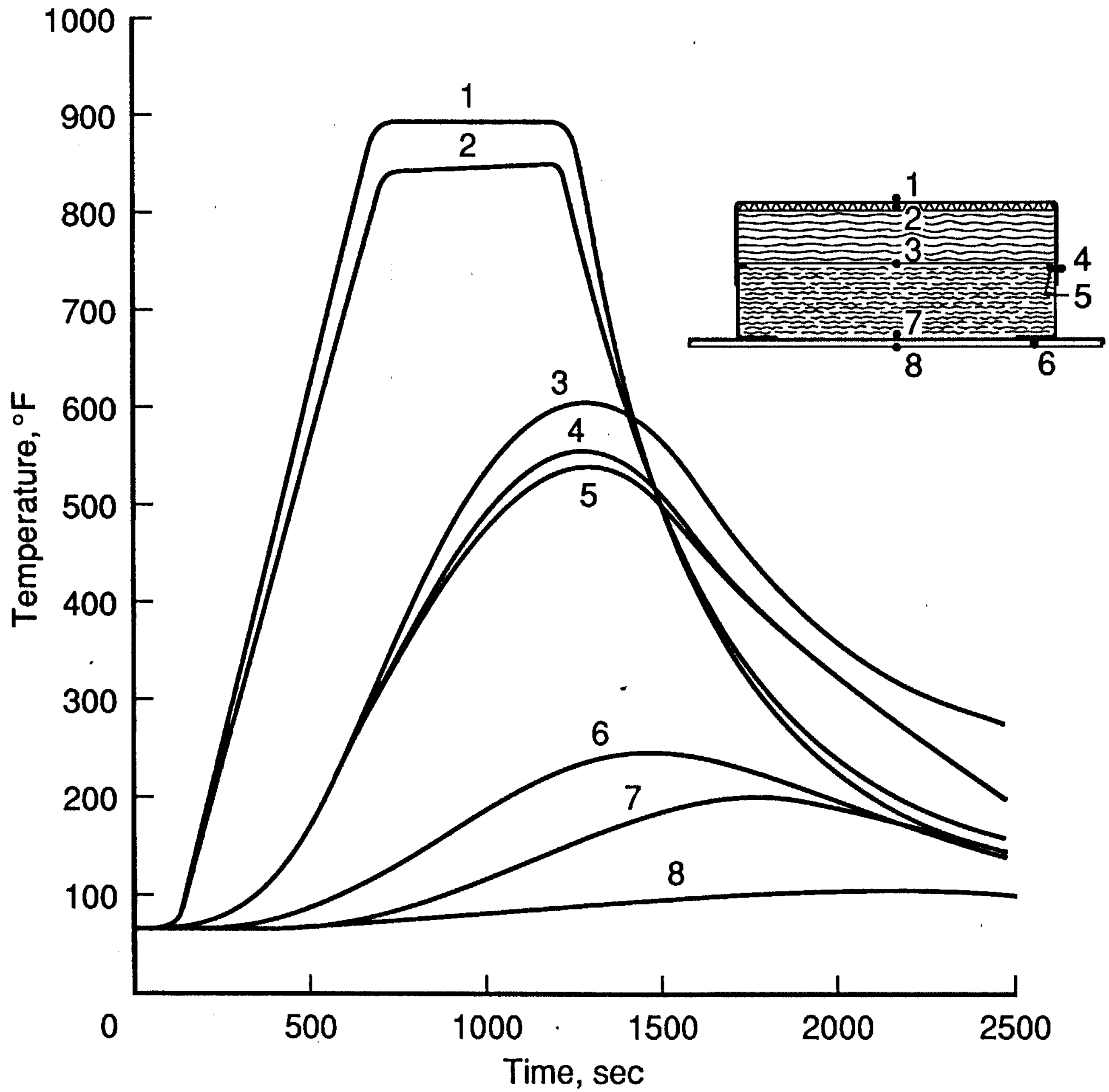

Figure 6. Temperature versus time for a 500-sec heating period at eight thermocouple locations.

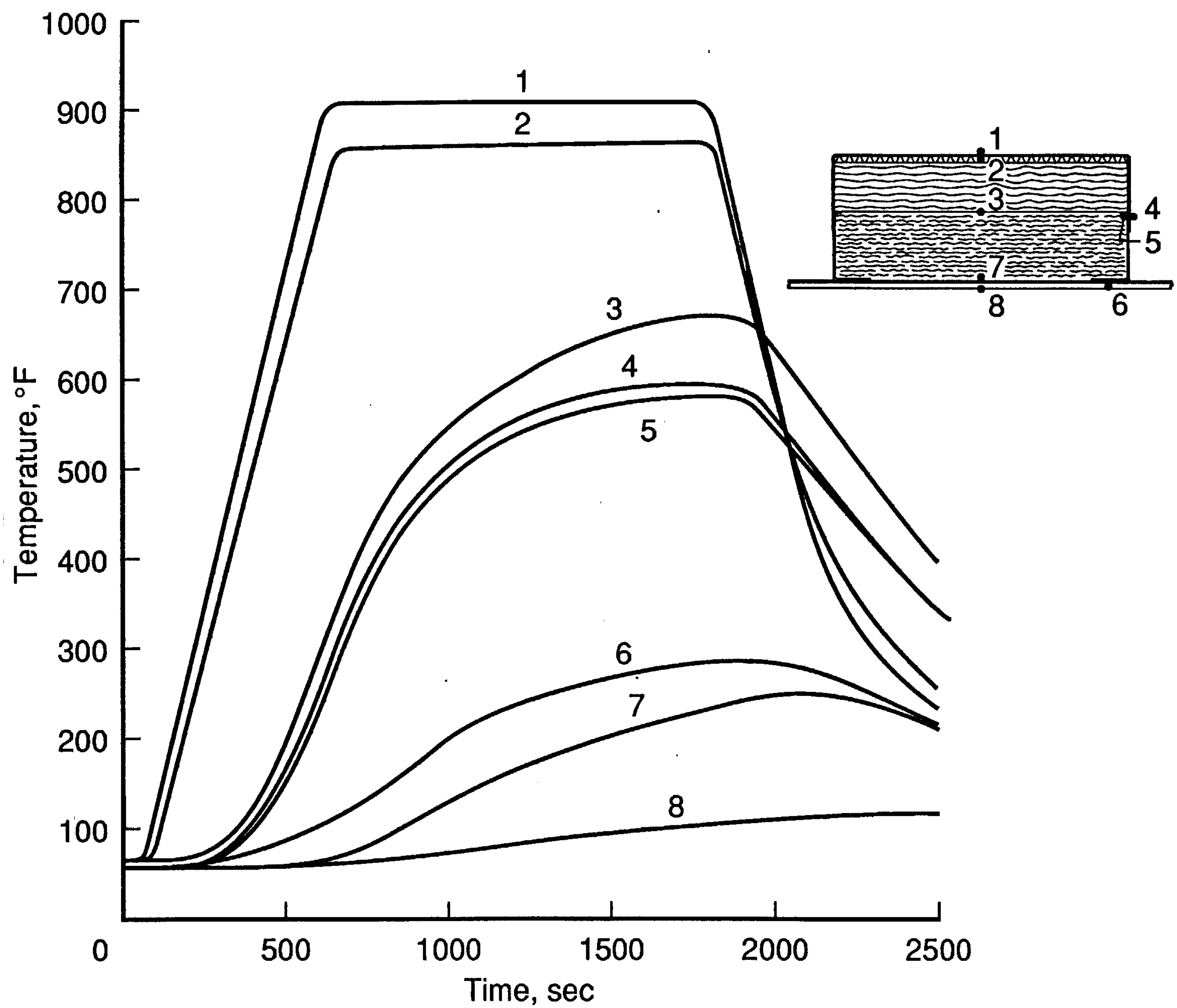

Figure 7. Temperature versus time for a 1100-sec peak heating period at eight thermocouple locations.

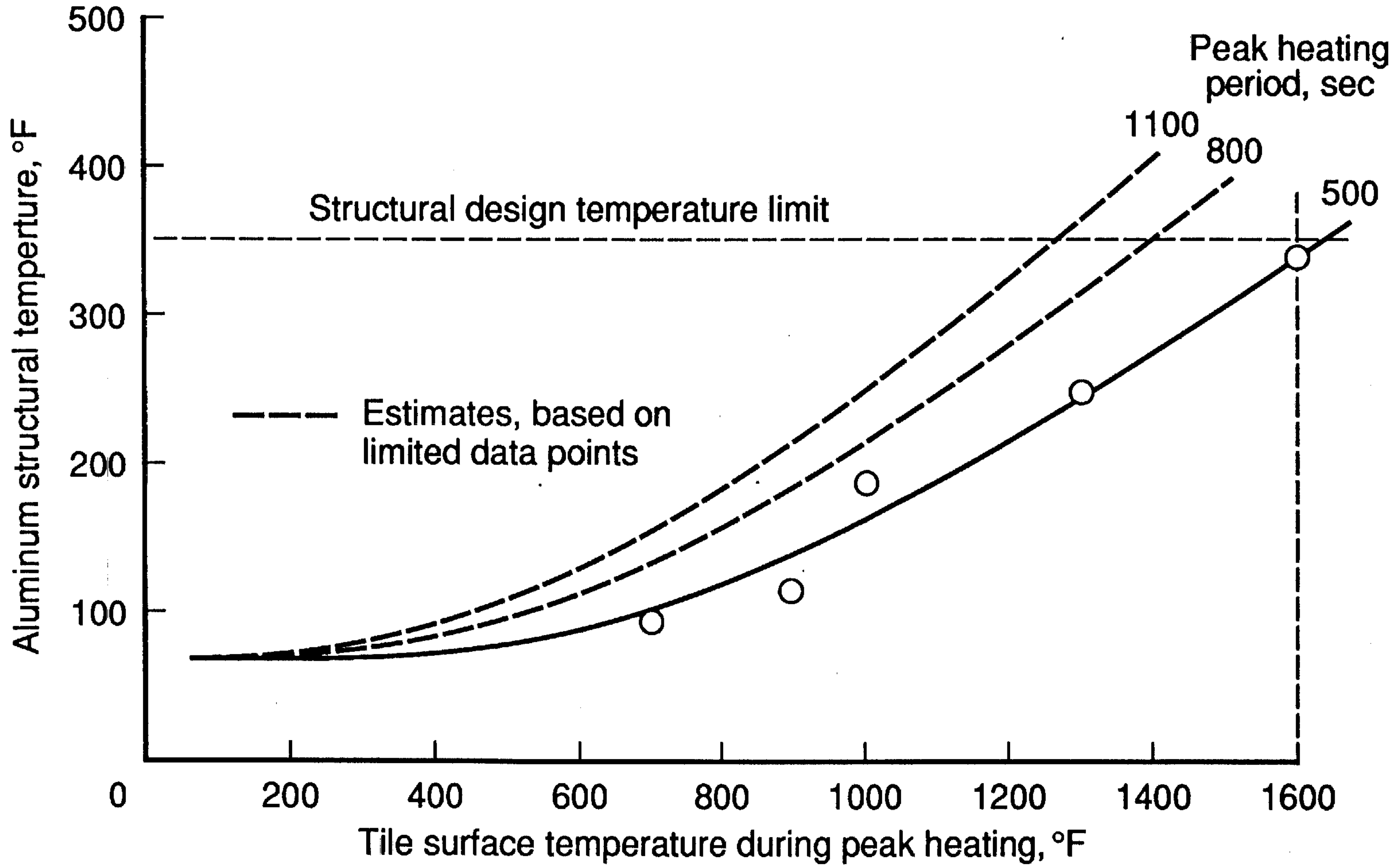

Figure 8. Vehicle temperature for various peak surface temperatures and peak heating periods.

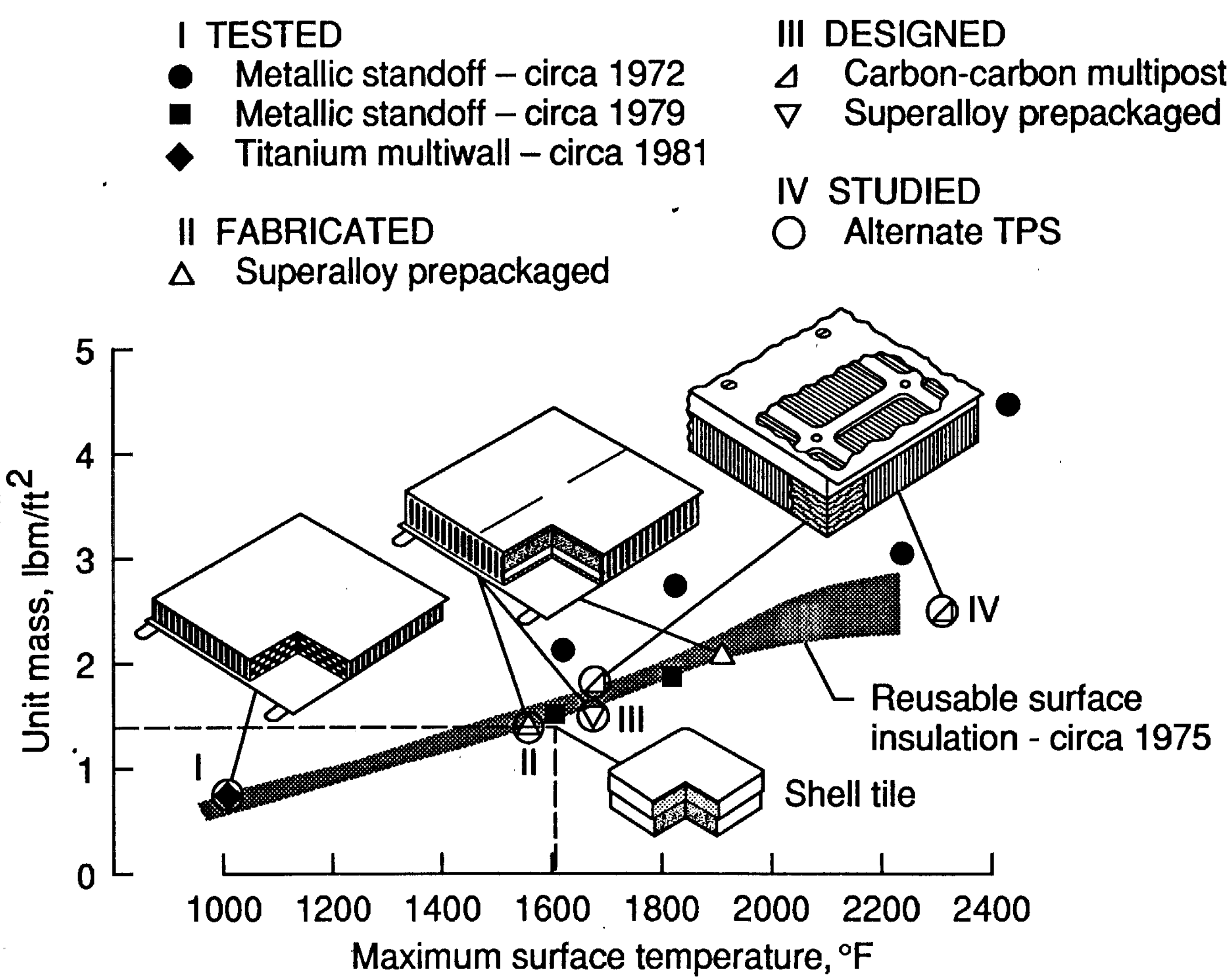

Figure 9. Shell tile weight comparison with other tiles.

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16. Abstract

A thermal protection title for Earth-to-orbit transports is described. The tiles consist of a rigid external shell filled with a flexible insulation. The tiles tend to be thicker than the current Shuttle rigidized silica tiles for the same entry heat load but are projected to be more durable and lighter. The tiles have been thermally tested for several similated entry trajectories.

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