EFFECTS OF MOISTURE AND TEMPERATURE ON ROOFING MEMBRANES IN THERMALLY EFFICIENT ROOFING SYSTEMS

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INTRODUCTION

This paper presents the results of recent research on the destructive effects of temperature and moisture on builtup membranes, focusing on the aggravation of these effects by heavily insulated (i.e., thermally efficient) roof systems. Increased daily temperature ranges in membranes over thickened, more efficient thermal insulation may produce thermal and mechanical stress, plus accelerated bitumen oxidation and embrittlement, all tending to shorten membrane service life.

The deleterious effects of moisture and temperature are well documented, [Ref. 1-18], but more base-line data are needed for roofs in service.

Field and laboratory tests have been useful in establishing some parameters for predicting and modeling temperature and moisture effects on builtup bituminous membranes. Among this paper's highlights:

- A new NBS computerized model can predict cooling rate of hot-mopped bitumen, a critical factor in assuring good application of a sound builtup roof system under unfavorable conditions.
- This same NBS computerized model could predict the effect of thermal bridges – (e.g., insulation joint openings or mechanical fasteners) on heat flow through a roof system.
- Moisture changes probably play a greater role than temperature changes in promoting membrane splitting and other types of roofing failure, judged by research reviewed in this paper.

After discussing thermal effects on membranes, factors determining hot bitumen's cooling rate, and moisture effects, this paper cites research needs for a comprehensive roof research plan from an NBS workshop on thermally efficient roof systems.

THERMAL EFFECTS ON MEMBRANES

Increased insulation subjects roofs to slightly larger temperature differences in service [Ref. 19]. A black-surfaced membrane may be subjected to surface temperatures ranging from 180°F to -30°F. Daily surface temperature differences can sometimes range up to 110°F. Without sufficient strength, the cooling and contracting membrane could tear, especially if it is restrained intermittently or is otherwise flawed.

BITUMEN COOLING RATE

Heating temperature, bitumen quantities, and cooling rates of hot-mopped bitumen have long been recognized as critical factors affecting the quality and durability of field-manufactured bituminous, builtup roof systems. These critical factors have, however, only recently become the subject of scientific research. Bitumen quantities in three or four-ply membranes affect thermal expansion and initial temperature of the substrate and overlying felt. Field and laboratory studies by Rossiter and Mathey [Ref. 20] have correlated bitumen temperatures with viscosities. Other studies, by Dupuis [Ref. 21] and NBS researchers [Ref. 22] have focused on bitumen heating temperatures and cooling rates.

Too rapid cooling of hot-mopped asphalt can impair the strong, continuous adhesion required between roof-system components bonded by layers of hot asphalt. Poor adhesion at the deck-insulation interface increases the risk of wind blowoffs and membrane splitting. Poor adhesion at the insulation-membrane interface or in interply felt moppings heightens the risk of blisters originating in mopping voids.

The NBS study [Ref. 22] features a computerized model for predicting bitumen hot-mopped bitumen cooling rates.

Figure 1 shows the temperature profile of mopping asphalt on a plywood substrate one second after application. (Heat from the bitumen is dissipated through convection and radiation at the upper surface and through conduction of heat to the plywood substrate.)

As revealed by the computerized NBS model [Ref. 22], the factors affecting bitumen cooling rate collectively determine whether roofing mechanics have a leisurely 35 seconds or a frantic two seconds to place the insulation board or to unroll the felt in the hot layer of asphalt.

Critical factors studies in this recent research are:

- Asphalt mopping temperature
- Nature of the substrate
- Ambient air temperature
- Wind velocity
- Asphalt quantity
- Temperature and nature of felt or insulation board placed atop hot bitumen.

Asphalt mopping temperature is a major determinent of the time allowed for adhering compounds, as evidenced by the curves in Figures 2 and 3. Note that a drop in mopping asphalt temperature from 456°F to 350°F generally cuts the critical cooling time by half or more.

The nature of the substrate is also a basic determinant of asphalt cooling rate. A highly conductive concrete substrate of high heat capacity cools the hot asphalt down to 300°F from two to three times as fast as a less heat-conductive substrate of plywood (see Figures 2 and 3).

Ambient air temperatures also affects cooling rate, but not apparently to the same degree as a drastic change in substrate conductivity.

Wind velocity accelerates asphalt cooling rate. On a plywood substrate, at 400°F application temperature, air temperature 70°F, there is a loss of about 3 seconds, from 11 to 8 seconds, in the time required to cool the asphalt down to 300°F (minimum dependable bonding temperature) with a rise in wind velocity from 0 to 10 mph (see Figure 3).

Other factors affecting the hot-bitumen's cooling rate are substrate temperature (assumed at outside air temperature in Figures 2 and 3), mopping thickness (assumed at 25 lb./square in Figures 2 and 3) and temperature of the felt or insulation board atop the hot bitumen.

In addition to predicting bitumen cooling rates, the NBS computerized model can also predict thermal leaks through insulation board joints and mechancial fasteners. Heat energy losses through such "thermal bridges" are currently unquantified.

MOISTURE EFFECTS

Moisture intrusion into builtup membranes increases the risk of membrane splitting, wind blowoffs, and blistering. These hazards are aggravated by several moisture-produced effects:

- Reduction in membrane tensiles strength
- Dimensional changes
- Creation of interply mopping voids

Wetting-drying cycles reduce tensile strength of organic and asbestos-felt membranes to a minor fraction of their original strength. A roughly 20% reduction in tensile strength accompanied a single-wetting-drying cycle, according to Laaly [Ref. 26]. (This cycle consisted of 10-day wetting, followed by drying at room temperature to original weight, resulting in a 19% strength loss in both machine and cross-machine directions.) Additional wetting-drying cycles cut membrane tensile strength to approximately 10% of original strength. Laaly's study [Ref. 28] of the influence of moisture on stress-strain properties of Type 15 asphalt-saturated organic and asbestos felts (at room temperature, 50% relative humidity) resulted in strength reduction of asphalt-saturated organic felt by a factor of 6 for both machine and cross-machine directions. Asphalt-saturated organic felt that absorbed 60% (by weight) of distilled water during immersion at room temperature lost 84% of its original strength. Freeze-thaw cycles reduce strength even more drastically [Ref. 29].

Since felts absorb water rapidly, strength reduction is rapid, according to Laaly [Ref. 28] and Rissmiller [Ref. 15].

Dimensional changes from humidity changes are greater than temperature-produced dimensional changes, according to Long's study of roof felt laminates [Ref. 13]. Roof membranes expand or contract promptly with changes in relative humidity regardless of temperature, but total deformation depends upon the moisture history and the duration of the changed environment, according to Shuman [Ref. 7]. Shuman suggested that roofs that have withstood some severe cold waves without splitting may split when a very low relative humidity accompanies a less severe temperature drop.

Membrane splitting may be caused by a combination of mechanical temperature and moisture-induced stress. Laboratory studies corroborate field observations indicating increased frequency of splitting of older membranes.

Additional work is needed to evaluate moisture and thermal-related deformation of builtup membranes and the predictability of these deformations from physical properties of the constituent materials. Although the thermal expansion coefficients of constituent materials can be measured with some precision, membrane expansion/contraction also depends on the quantity, type, and distribution of interply bitumen, and the modulus of the materials. Other factors affecting strength and thermal expansion/contraction include substrate restraint, quantity and distribution of moisture in the felt plies, and previous history of the components.

Interply mopping voids, caused by moisture intrusion during construction or material storage, can shorten membrane service life in two ways: from blisters growing from the voids and from wind blowoffs attributable to weakened adhesion.

Blisters grow as roof temperature rises and evaporating water develops higher pressures under constant-volume conditions. The roof membrane is inherently impermeable, as noted by Joy [Ref. 8] and Stafford [Ref. 14]. Warden [Ref. 27] hypothesized that moisture can cause blistering in roof materials of low permeability. Vapor pressure can build up with increasing temperature within impermeable membranes and create blisters at points of weak interply adhesion. Low impermeabilities of roof plies decrease the potential for drying of trapped interply moisture. Temperature extremes and temperature changes in combination with moisture and use of thicker insulation may damage roof membranes.

Interply mopping voids may even contribute to membrane splitting. For membranes loaded by uniformly applied tensile forces, stresses in the vicinity of a small circular hole are approximately eight times larger than the average applied tensile stress, according to the theory of elasticity. The effect of repeated temperature cycling on the stress field and membrane durability is likewise unknown. Theories of cracking in other materials have produced some reliance on stress-vs-number of load cycle (S-N) diagrams, where the number of cycles of stress repetitions required to cause failure decreases as the stress increment is increased.

RESEARCH NEEDS

The following outline of research needs emerged from an NBS workshop on thermally efficient roof systems:

A. Moisture

1) Determine quantity of moisture condensation in acceptable roof systems.
2) Develop tests to measure moisture accumulation in insulation and other components of roofing systems.
3) Survey moisture problems and determine their causes.
4) Evaluate non-destructive methods to determine moisture content.
5) Evaluate methods to dissipate moisture (e.g. venting).
6) Evaluate methods to prevent moisture entry (e.g. vapor retarders and systems design).
7) Develop a behavior theory for moisture migration in roofing systems.

B. Thermal Performance

1) Evaluate non-destructive methods (in place) to determine thermal characteristics of roofing systems and their moisture contents.
2) Identify "thermal leaks," such as insulation joints, penetrations and mechanical fasteners and determine their effect on thermal efficiency.
3) Conduct continual monitoring of thermal properties of various types of cooling systems (for various environmental conditions).
4) Determine by laboratory tests the effect of moisture on thermal conductivity and methods to measure conductivity of roofing components and systems containing moisture.
5) Develop models for heat and moisture transfer.

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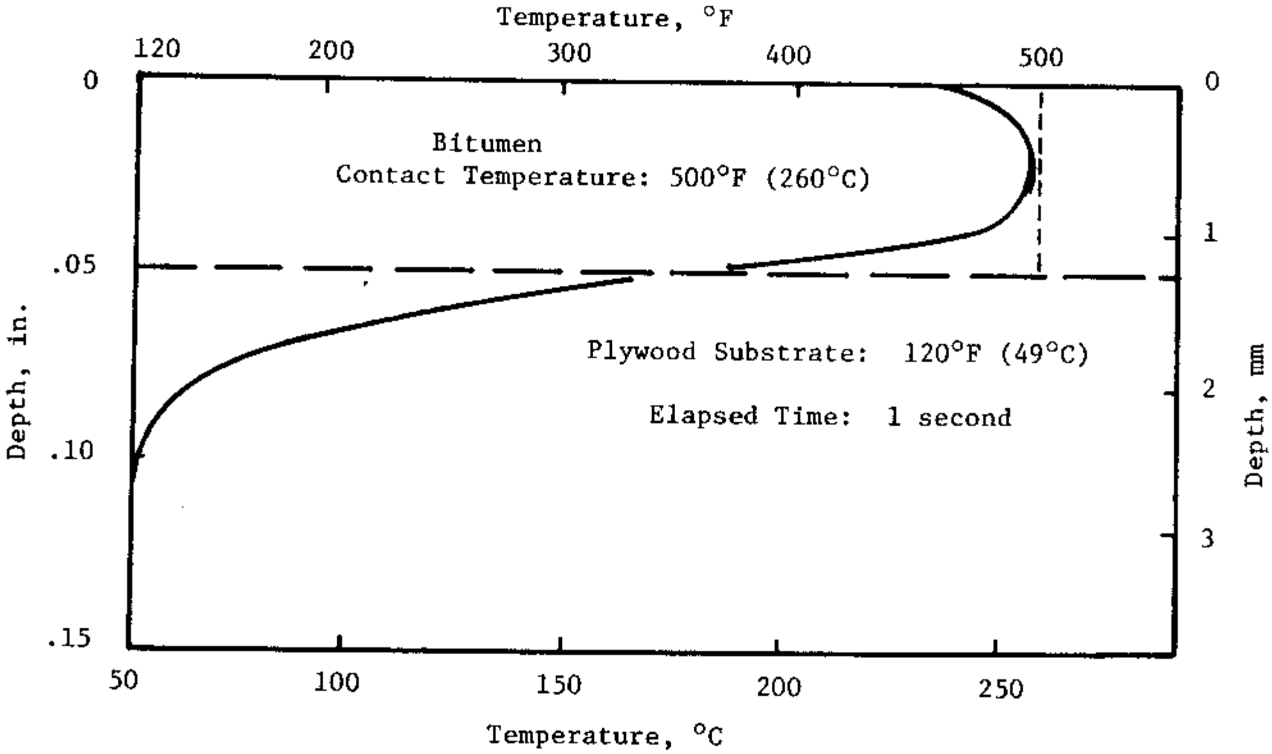

FIGURE 1 - EXAMPLE OF TEMPERATURES IN BITUMEN AND PLYWOOD SUBSTRATE ONE SECOND AFTER BITUMEN APPLICATION.

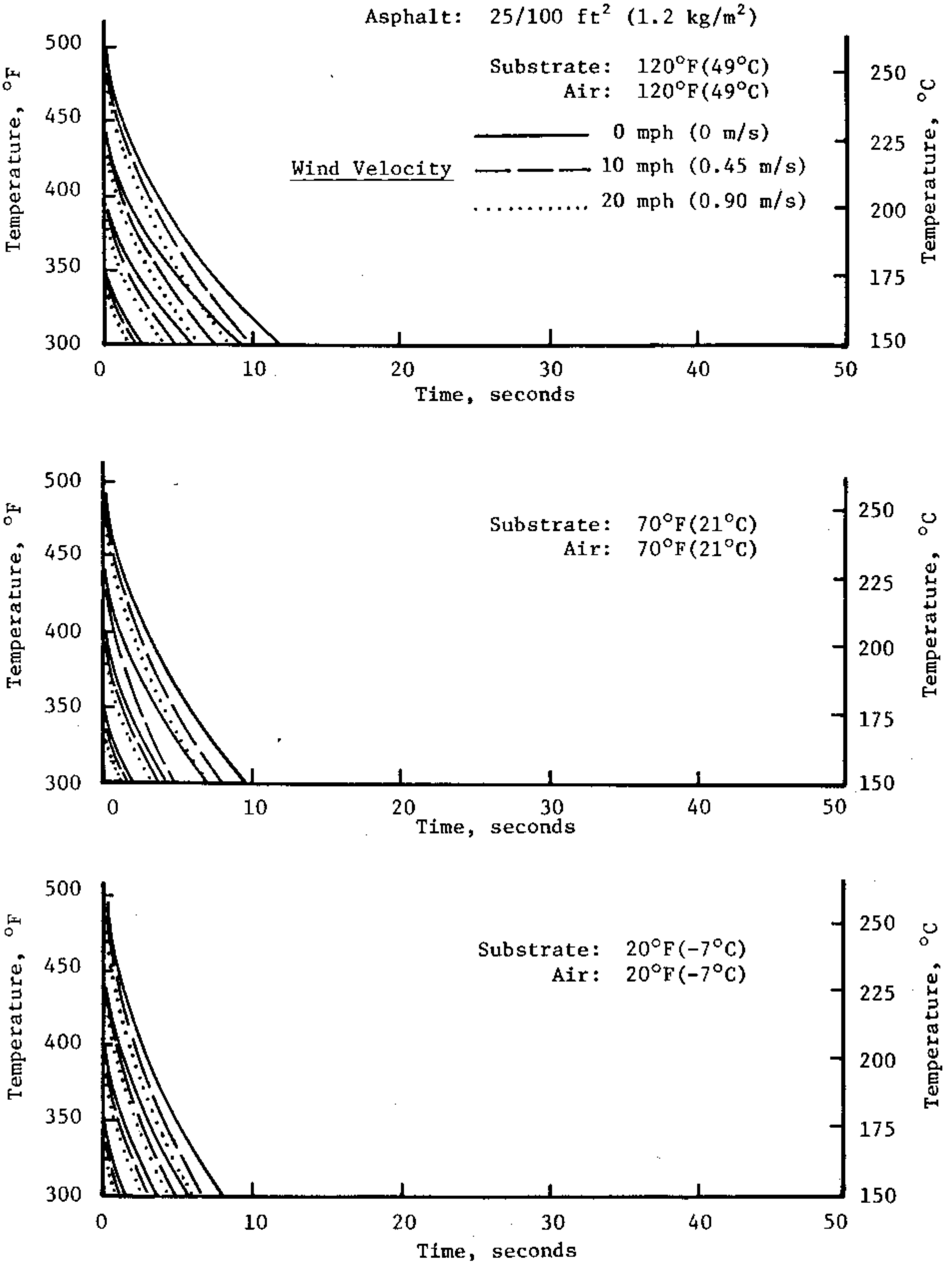

FIGURE 2 - EFFECT OF WIND VELOCITY AND CONTACT TEMPERATURE ON ASPHALT COOLING RATE - CONCRETE (142 lb/ft³, 2,272 kg/m³) SUBSTRATE [22].

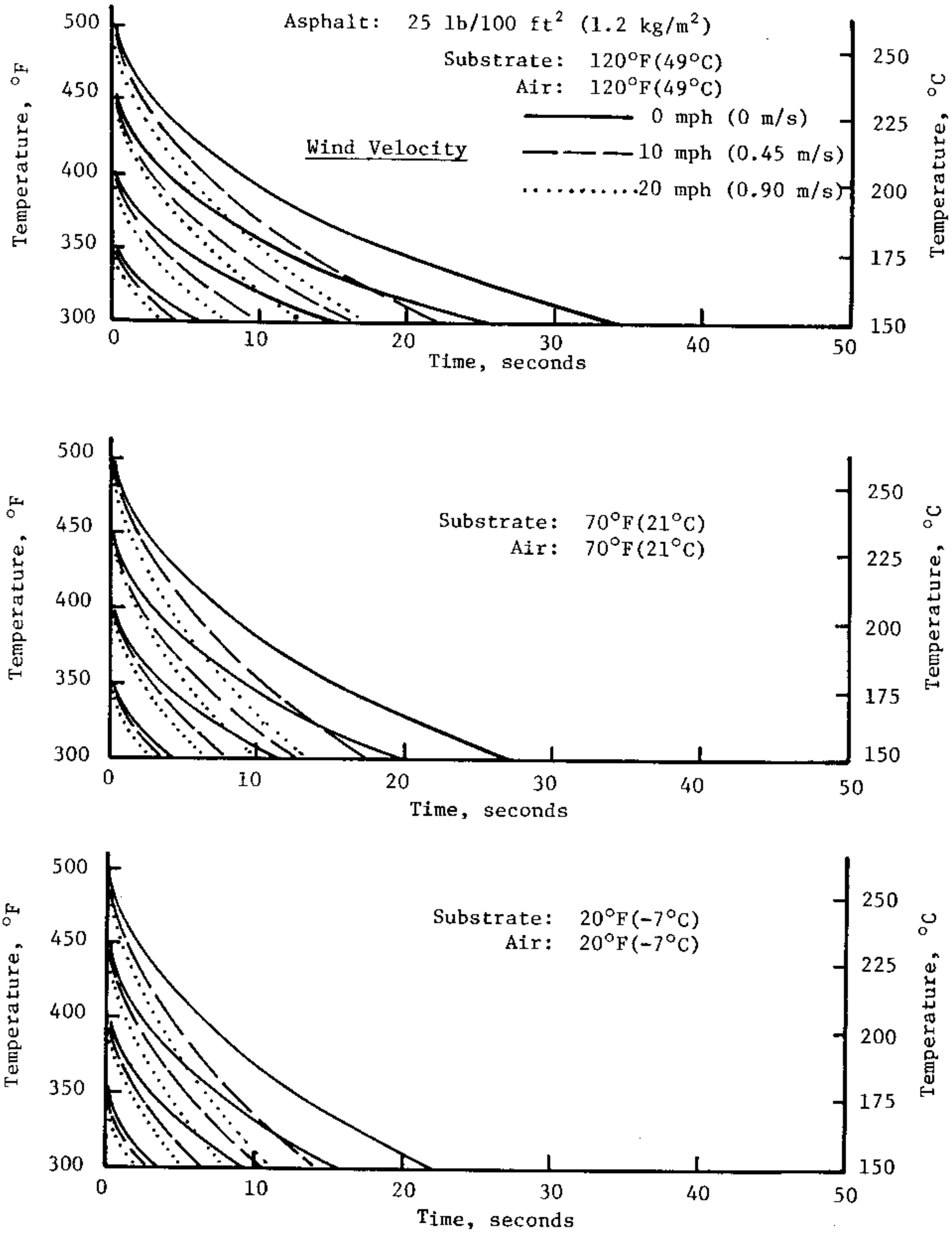

FIGURE 3 – EFFECT OF WIND VELOCITY AND CONTACT TEMPERATURE ON ASPHALT COOLING RATE – PLYWOOD SUBSTRATE [22].

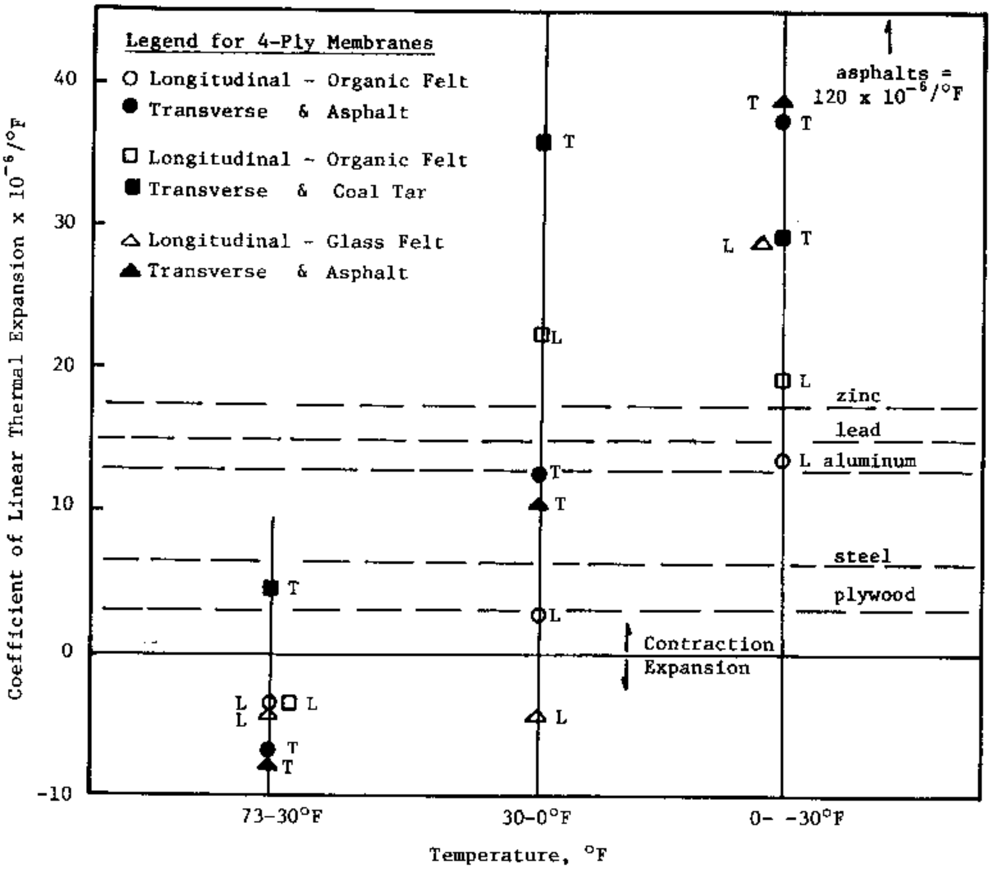

FIGURE 4 - TYPICAL VALUES OF THE COEFFICIENT OF LINEAR THERMAL EXPANSION FOR REPRESENTATIVE ROOFING MATERIALS [4].

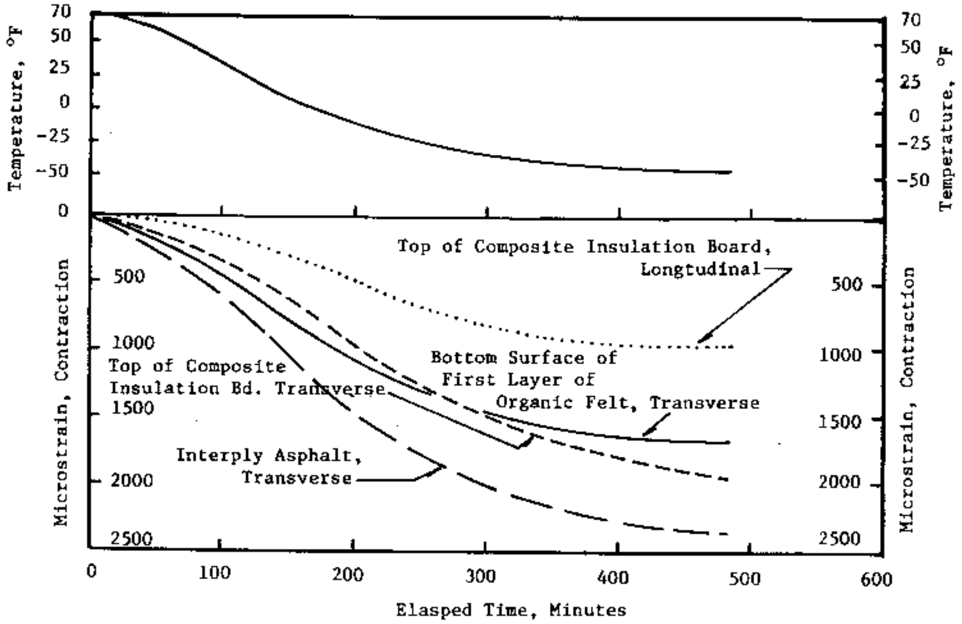

FIGURE 5 - TEMPERATURE-DEFORMATION TRAJECTORIES FOR SURFACE OF COMPOSITE INSULATION BOARD, INTERPLY ASPHALT AND OVERLYING ASPHALT SATURATED ORGANIC FELT [25].