THE RESPONSE OF MOLDED EXPANDED POLYSTYRENE (EPS) INSULATION BOARD TO VARIOUS ATTACHMENT METHODS

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Built-up and single-ply roofing membranes both utilize molded expanded polystyrene (EPS) insulation as part of a roof system. EPS insulation board may be loose-laid, mechanically attached or adhered to the substrate with asphalt. In many cases an overlayment board, such as wood fiberboard or perlite, is used between the roofing membrane and EPS insulation board. This research program investigated the effects of EPS insulation on the physical response of a roofing system.

The expansion and contraction of a typical built-up roofing membrane and many adhered single-ply systems must be restrained to some degree. The insulation system determines the amount of membrane restraint. A balanced insulation design, rigid enough to provide adequate membrane restraint but allowing some strain relief for the membrane, will increase the service life of a roof system. A roofing system expands or contracts with changes in temperature, moisture, aging and mechanical forces. Temperature change normally produces the largest effect.

This program studied the effects of a temperature change on a roof system. The physical properties of greatest importance for analyzing a roof system undergoing temperature change are the coefficient of expansion, temperature induced load, modulus of elasticity and modulus of rigidity (shear modulus of elasticity).

The design of an insulation system which will provide proper restraint of a built-up roofing membrane or adhered single-ply requires knowledge of:

1) The physical properties of the individual roofing system components;
2) The effect of substrate attachment on the physical properties;
3) The composite properties of the different system components.

This approach was used to investigate the effects of EPS insulation as a component in a roofing system.

PHYSICAL PROPERTIES OF THE INDIVIDUAL ROOFING SYSTEM COMPONENTS

The components tested in this part of the research program were:

1) A 2-inch-thick 0.7 pcf EPS insulation board;
2) A 2-inch-thick 1.25 pcf EPS insulation board;
3) A ½-inch-thick wood fiberboard;
4) A built-up roofing membrane composed of three plies of ASTM D2178 Type IV glass mat, 28 pound/square interply and 60 pound/square flood coat of ASTM D312 Type II asphalt.

The first series of tests determined the apparent coefficient of expansion of the samples from the temperature induced free contraction. A second test series measured the temperature induced load developed when all contraction of the sample was restrained. The modulus of elasticity was determined from the combined results of temperature induced load and temperature induced free contraction.

Testing of individual roof system component properties was conducted in a horizontal load frame. Each sample size was approximately 2 feet wide by 4 feet long. One end of the test sample was attached to a fixed support on the load frame. Measurements were taken on the top surface of the EPS and wood fiberboard insulation boards. EPS insulation samples were loose-laid on the substrate. Wood fiberboard and built-up roofing membrane samples were loose-laid on an EPS insulation board. An intermediate rib steel roof deck, used as the substrate, was anchored to the test table.

An environmental chamber was used to change sample temperature. The bottom of the substrate was exposed to room temperature (70F) while the top surface of the sample was cooled. Thus, the samples were tested under a temperature gradient similar to that which would occur in a roof system. The surface temperature of the top of the test samples was decreased from 70F to −30F at a rate of 40F per hour.

The apparent coefficient of expansion and modulus of elasticity results for individual system components were:

Sample	Coefficient of expansion (in/in/°F)	Modulus of elasticity (lb/in)
0.7 pcf EPS	19.4×10^{-6}	1300
1.25 pcf EPS	15.7×10^{-6}	1900
Wood Fiberboard	2.1×10^{-6}	18600
3-Ply Glass Built-Up Membrane	26.3×10^{-6} (@ 0F)	19300

The modulus of elasticity is an indication of sample stiffness. Elements of a roofing system with a relatively large modulus of elasticity, or stiffness, will have more control of the composite system than more flexible elements.

The apparent coefficient of expansion for the built-up membrane and wood fiberboard overlayment were significantly different. However, the relative stiffness of the two system elements were nearly equal. Thus, the built-up membrane and wood fiberboard overlayment have approximately equal effects on the assembled composite roof system. If the built-up membrane is adhered to the wood fiberboard overlayment, a lower apparent coefficient of membrane expansion would be expected.

The EPS insulation samples exhibited relatively low stiffness compared to the built-up membrane and wood fiberboard overlayment. The effects of the EPS insulation board properties on an adhered roofing membrane may be masked by the high stiffness of a wood fiberboard overlayment. This was investigated by testing the composite system.

ATTACHMENT OF THE INSULATION SYSTEM TO THE SUBSTRATE

The method of attaching an insulation board to the structural roof deck is critical to the service life of a roof system. The bond between the insulation board and roof deck must resist two types of forces:

1) Tension forces, caused by wind uplift, which are perpendicular to the roof surface.
2) Shear forces, caused by expansion and contraction of the roofing membrane, which are parallel to the roof surface.

Shear forces and the related lateral deflection parallel to the roof surface were examined in this portion of the research program.

An insulation board which is loose-laid on a substrate, partially restrains expansion and contraction of an adhered roofing membrane. The degree of membrane restraint depends on the coefficient of expansion and modulus of elasticity relative to that of the membrane. Restraint of membrane contraction results in tension forces in the membrane and approximately equal compression forces in the insulation board. Shear forces, other than friction, resulting from restraint of membrane contraction are not transferred to a loose insulation board's substrate.

If the insulation board is bonded to the roof deck, additional membrane restraint occurs because of shear forces in the insulation board. The level of membrane restraint due to shear forces depends on the modulus of rigidity (shear modulus of elasticity) and insulation board thickness. The additional restraining capability of the bonded insulation board will produce an increase in force and a decrease in lateral deflection of the membrane. Bonding the insulation board to the substrate transfers shear force between the bottom of the insulation board and the substrate.

Insulation board shear stiffness may also develop in a mechanically fastened system. Friction between the bottom of the insulation board and the roof deck forms the shear force. The compression force on the insulation board from a mechanical fastener increases the frictional force between the insulation board and the roof deck. Maintaining sufficient tension on the mechanical fastener is of primary importance in developing the shear stiffness of the insulation board.

Mechanical Fastener Force Decay

A series of tests conducted in the laboratory monitored the mechanical fastener tension force in an EPS insulation system using a mechanical fastener load measurement apparatus. A load frame supported the EPS insulation sample on a simulated roof deck, and a mechanical fastener was placed through the EPS insulation board. A load cell measured the load on the fastener. Rather than screwing the fastener into the roof deck, the fastener passed through the deck and into the load cell. The load was then transferred back to the bottom of the roof deck directly below the mechanical fastener. An environmental chamber cycled sample temperature.

For each density of EPS insulation a pilot study determined the initial tension force on the fastener at the time of installation. As expected, the higher the density of EPS insulation the greater the initial tension required to set the fastener plate to the proper depth. The approximate initial mechanical fastener tension at installation for 0.7 pcf EPS and 1.25 pcf EPS was 75 pounds and 130 pounds, respectively.

Samples were cycled through the following temperature sequence: 70F, 150F, 70F, 0F, 70F. The tension load on the mechanical fastener was allowed to stabilize at each temperature before continuing to the next temperature. Each sample was subjected to two temperature sequence cycles.

The results of the mechanical fastener load decay and fastener load level during the two temperature cycles are plotted on Figure 1. The most rapid mechanical fastener load decay occurred initially. After installation, the compression load on the insulation relaxed to approximately 40 percent to 50 percent of the initial load. The majority of load decay occurred within the first few hours.

A second significant period of mechanical fastener load relaxation occurred during the first 150F heating cycle. During this period the tension on the fastener dropped to 10 percent to 20 percent of initial installation load.

After initial mechanical fastener load relaxation during the first temperature cycle, fastener load fluctuated through a relatively narrow range during the remainder of the testing period. Apparently the EPS insulation under the mechanical fastener plate was permanently deformed. The insulation did not recover after the initial period of relaxation.

Figure 1 also plots the mechanical fastener load decay in a composite insulation system made up of 0.7 pcf EPS insulation with a ½-inch-thick wood fiberboard overlayment. The mechanical fastener load at installation in this system was more than twice that with EPS insulation board alone. Also, the magnitude of mechanical fastener tension remaining after two temperature cycles was significantly higher.

It appears that the overlayment board produces a greater tension force in the mechanical fastener. This was partially due to the larger distribution of load from the top plate of the fastener to the EPS insulation. The overlayment board spreads the load over a larger area. The reduced concentration of compression load on the EPS insulation produces less deformation and higher mechanical fastener tension forces. However, the expansion and contraction of the wood fiberboard overlayment, due to a moisture content change, may also contribute to mechanical fastener tension.

The Effect of Attachment on the Physical Properties of EPS Insulation

A series of tests compared the effects of three types of deck attachment on EPS insulation, and determined the physical properties of coefficient of expansion and stiffness of the top surface of 0.7 pcf and 1.25 pcf EPS insulation boards. The physical properties of the top of the insulation board are important because a membrane may be attached to this surface. Differences in EPS insulation board properties resulting from loose laying, mechanically fastening and adhering with asphalt were compared.

The test set-up was identical to that for determining individual system component properties. The same insulation board was used for each attachment technique. Strip mopped asphalt adhered the EPS insulation board to the steel roof deck for one part of the test. Four mechanical fasteners were used to attach the EPS insulation board to the substrate for another test series. Mechanical fastener tension force was allowed to relax for 24 hours at 70F and another 24 hours at 150F prior to testing. Surface temperature of the 0.7 pcf EPS insulation board sample was decreased from 70F to −30F. A decrease from 150F to −30F was used for the 1.25 pcf EPS insulation sample.

The effect of attachment on the dimensional stability and stiffness of 1.25 pcf EPS is shown in Figures 2 and 3, respectively. Figure 2 plots the dimensional change of the top surface of the insulation board caused by a temperature decrease. Figure 3 plots the temperature induced load as a function of contraction. The apparent coefficient of expansion and modulus of elasticity of the top surface of both 0.7 pcf and 1.25 pcf EPS insulation boards were calculater as:

EPS Insulation Density	Substrate attachment	Coefficient of expansion (in/in/°F)	Modulus of elasticity (lb/in)
0.7 pcf EPS	Loose Laid	19.4×10^{-6}	1300
0.7 pcf EPS	Mechanically Fastened	16.2×10^{-6}	1600
0.7 pcf EPS	Adhered with Asphalt	6.8×10^{-6}	4600
1.25 pcf EPS	Loose Laid	19.3×10^{-6}	1900
1.25 pcf EPS	Mechanically Fastened	14.4×10^{-6}	3000
1.25 pcf EPS	Adhered with Asphalt	8.4×10^{-6}	6200

Adhering an EPS insulation board to the substrate with asphalt significantly reduced the apparent coefficient of expansion and increased the stiffness of the board over that of a mechanically fastened or loose-laid board. This results from using the board's shear stiffness. Because EPS insulation is relatively flexible, increased stiffness is desirable if a membrane is to be adhered directly to the top surface. However, shear deflection is directly proportional to the thickness of the insulation board. Therefore, insulation thickness is a consideration when a membrane is directly attached to EPS insulation.

Mechanical fastening of an EPS insulation board produced the least change in the apparent coefficient expansion and stiffness. The mechanical fastener develops only a small portion of the potential shear stiffness and probably provides only uplift resistance for the EPS insulation board.

PHYSICAL PROPERTIES OF EPS INSULATION SYSTEMS WITH A BUILT-UP ROOFING MEMBRANE

Much past testing studied the tensile strength of built-up (BUR) membranes. However, membrane strength is only part of the information required to assemble a successful roof system. The more difficult question is: What strength is required? The insulation system and substrate attachment technique greatly affect the membrane strength required.

In an ideal roof system, the dimensional changes and forces generated in a roof membrane are symmetrical about the centerline of the roof. The center of the roof can be considered a fixed point. The greatest horizontal membrane deflection occurs at the edges of the roof. The test set-up for this part of the research program was designed to model the membrane/insulation system at the center of the roof. Figure 4 diagrams this location in an ideal roof system.

The horizontal load frame and environmental chamber used for this testing are shown on Figure 5. Testing was accomplished by attaching one end of the 4 feet long by 2 feet wide built-up membrane to one end of the load frame to simulate the fixed point at the center of the roof. The other end of the BUR membrane was attached to a freely moving sled. The test procedure was the same as for determining the physical properties of individual system components. The apparent coefficient of expansion and modulus of elasticity were determined for the total roofing systems.

Built-Up Roofing Membrane Directly Attached to EPS Insulation

A series of temperature induced contraction and load tests were conducted on a BUR membrane/EPS insulation system. The system consisted of:

1) the same three-ply glass BUR membrane used in the determination of individual physical properties.
2) 2-inch-thick 1.0 pcf EPS insulation board.
3) intermediate ribbed steel roof deck.

The BUR membrane was mopped with hot asphalt and flopped on the EPS insulation board. The system was tested loose-laid, mechanically fastened and asphalt-adhered. The same membrane and insulation board was used for each test.

A summary of the results for the BUR membrane/EPS insulation system follows:

Sample type	Substrate attachment	Coefficient of expansion @ 0°F (in/in/°F)	Modulus of elasticity (lb/in)
BUR Membrane	Loose-Laid	26.3×10^{-6}	19,300
BUR Membrane/ EPS Insulation	Loose-Laid	27.3×10^{-6}	20,700
BUR Membrane/ EPS Insulation	Mechanically Fastened	24.6×10^{-6}	20,000
BUR Membrane/ EPS Insulation	Adhered with Asphalt	27.0×10^{-6}	22,600

The test results of the BUR membrane/EPS insulation system produced relatively small differences in physical properties when compared to those of the individual BUR membrane. The EPS insulation board did not significantly change the behavior of the BUR membrane over the 4-foot length of the sample. A small increase in BUR membrane/EPS insulation system stiffness was observed when the EPS insulation board was adhered to the substrate with asphalt. This system was observed to be performing satisfactorily in the field. The EPS insulation board apparently provides gradual restraint to expansion and contraction of the BUR membrane. An EPS insulation board adhered with asphalt to a rigid substrate is stiff enough to adequately restrain membrane dimensional changes.

BUR Membrane/Composite Insulation System

The physical properties of a BUR membrane attached to a composite insulation system were also studied. The composite system consisted of:

1) the same three-ply glass BUR membrane previously used.
2) ½-inch-thick wood fiberboard overlayment.
3) 2-inch-thick 1.0 pcf EPS insulation board.

4) ¾-inch-thick perlite underlayment.

5) intermediate ribbed steel roof deck.

The composite system was tested using the same three substrate attachment techniques. The BUR membrane was adhered to the overlayment board with asphalt for the mechanically fastened test series. The overlayment board was mopped with hot asphalt and flopped on the EPS insulation board for the loose-laid and asphalt adhered test series.

A summary of the BUR membrane/composite insulation system results follows:

Sample type	Substrate attachment	Coefficient of expansion @ 0°F (in/in/°F)	Modulus of elasticity (lb/in)
BUR Membrane	Loose-Laid	26.3×10^{-6}	19,300
BUR Membrane/ Composite	Loose-Laid	13.9×10^{-6}	42,000
BUR Membrane/ Composite	Mechanically Fastened	12.4×10^{-6}	42,300
BUR Membrane/ Composite	Adhered with Asphalt	13.4×10^{-6}	51,600

Changes in the BUR membrane/EPS insulation roof system properties with a wood fiberboard overlayment are significant. The coefficient of expansion of the system was reduced to a moderate level while the system's stiffness was greatly increased. The stiffness of the total system was approximately the sum of the stiffnesses of the individual system components.

The ½-inch-thick wood fiberboard overlayment performed as a substrate, restraining expansion and contraction of the BUR membrane. Apparently only a small portion of the contraction forces from the BUR membrane are transferred to the roof deck. Most of the forces remain internal in the BUR membrane and wood fiberboard overlayment.

Figure 6 plots the dimensional change versus temperature change of the loose-laid BUR membrane, BUR membrane/EPS insulation system and BUR membrane/composite insulation system when the latter two systems were adhered to the substrate with asphalt. Figure 7 plots the temperature induced load caused by dimensional change for the same three systems. The effect of using the wood fiberboard overlayment can be observed on Figures 6 and 7. The increase in stiffness of the composite insulation system results in larger temperature induced loads for the BUR membrane in that system. The gradual restraining effect of EPS insulation is masked by the wood fiberboard overlayment. A study of systems performing in the field, however, has shown that BUR membrane/composite insulation systems with mechanical or asphalt substrate attachment work equally as well as BUR membranes/EPS insulation systems with asphalt attachment to the substrate.

CONCLUSIONS

The following are some of the conclusions determined during this research program:

1) With time and temperature the compression force from a screw-type mechanical fastener, installed over a 2-inch-thick EPS insulation board, will relax to 10 percent to 20 percent of the initial installation force.
2) Wood fiberboard overlayment reduced the concentration of compression load on the EPS insulation board and resulted in less EPS deformation and higher mechanical fastener tension loads;
3) Adhering an EPS insulation board to a substrate with asphalt reduced the apparent coefficient of expansion and increased the stiffness at the top of the board.
4) An EPS insulation board, when adhered to a substrate with asphalt, provides a gradual restraining effect to expansion and contraction of a BUR membrane directly attached to the top of the board.
5) A ½-inch-thick wood fiberboard overlayment masks many of the effects of EPS insulation by providing most of the restraint to expansion and contraction of a BUR membrane.

REFERENCES

[1] Dupuis, Rene M., Haas, K. Alan and Leppo, Sheldon, "Temperature Induced Behavior of New and Aged Roof Membranes," Second International Symposium on Roofs and Roofing, Brighton, England, September, 1981.

[2] McCorkle, John E., Dupuis, Rene M., and LaCosse, R. A., "Membrane Integrity Depends on Characteristics of Entire Roof Assembly," Proceedings of 6th Conference on Roofing Technology, Gaithersburg, Maryland, April-May, 1981.

[3] "Dupuis, R. M. and Dees, Jerome G., "Expanded Polystyrene Insulation for Use in Built-Up and Single Ply Roofing Systems," Research Report, Structural Research, Inc., Madison, Wisconsin, August, 1984.

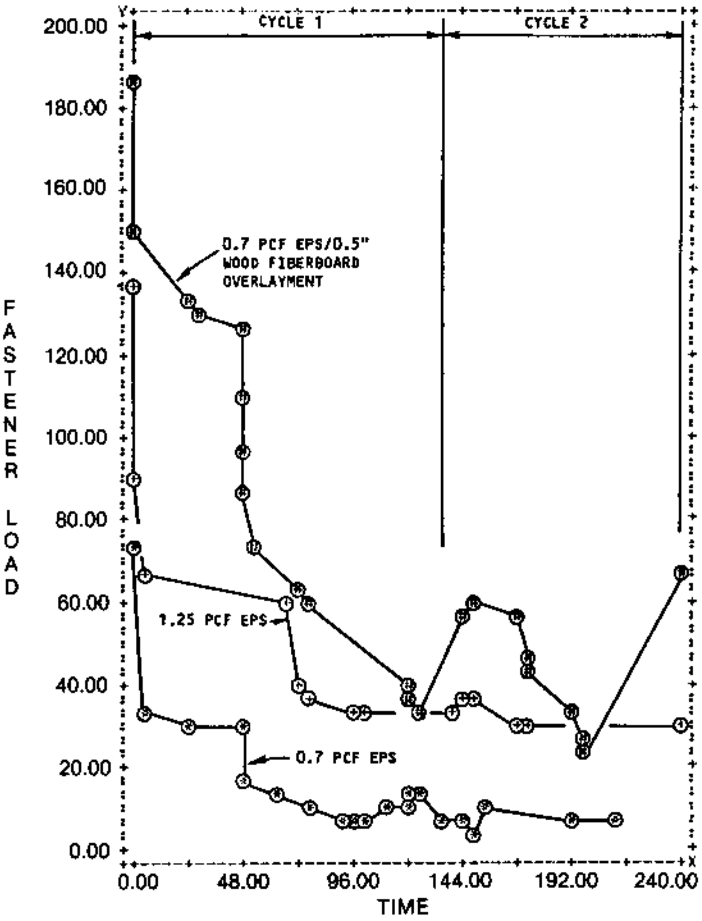

Figure 1 Mechanical fastener load decay

Y axis units are LB
X axis units are hours

Key
- * *2"—0.7 pcf EPS*
- + *2"—1.25 pcf EPS*
- # *2"—0.7 pcf EPS/.5" wood fiberboard overlayment*

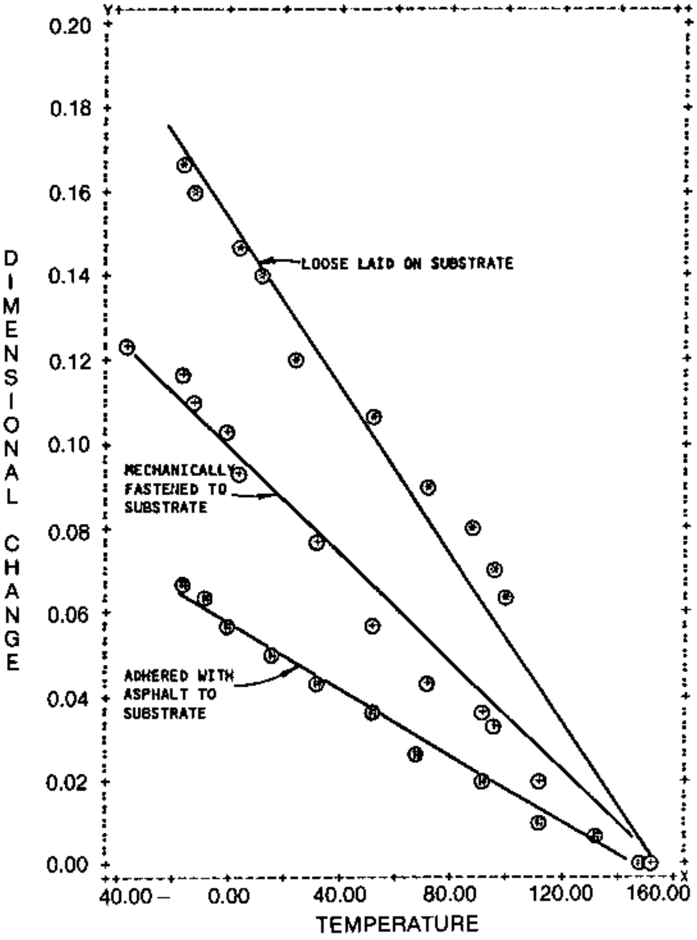

Figure 2 Temperature induced dimensional change

Y axis units are inches (over a 4' sample length)
X axis units are degrees F

Key
- * *1.25 pcf EPS loose-laid on substrate*
- + *1.25 pcf EPS mechanically fastened to substrate*
- # *1.25 pcf EPS adhered with asphalt to substrate*

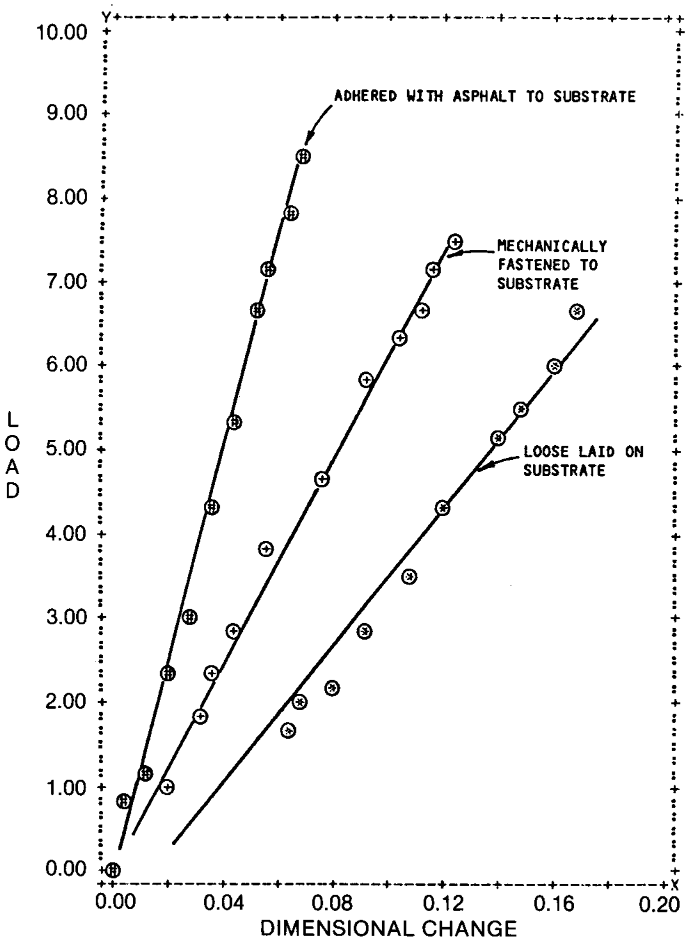

Figure 3 *Temperature induced—load vs dimensional change*

Y axis units are lb/in of sample width
X axis units are inches (over a 4' sample length)

Key

* *1.25 pcf EPS loose-laid on substrate*
\+ *1.25 pcf EPS mechanically fastened to substrate*
\# *1.25 pcf EPS adhered with asphalt to substrate*

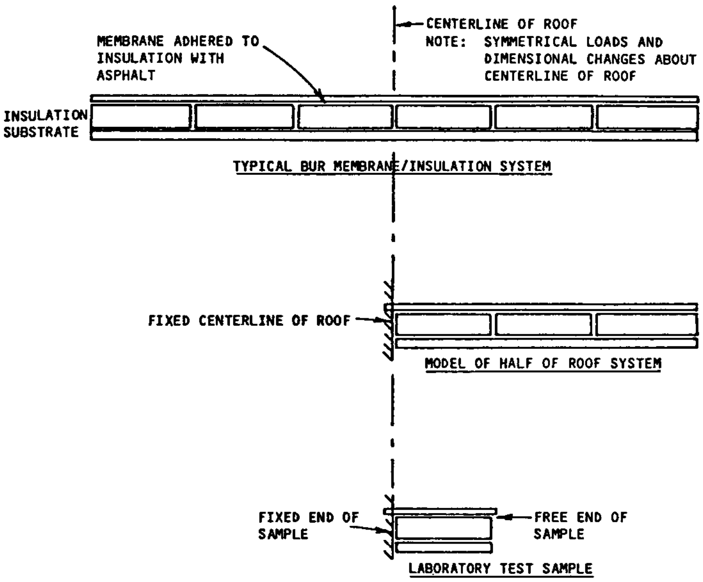

Figure 4 *Location of test sample in roof system*

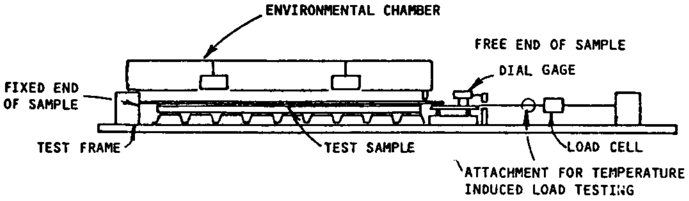

Figure 5 *BUR membrane/insulation system test apparatus*

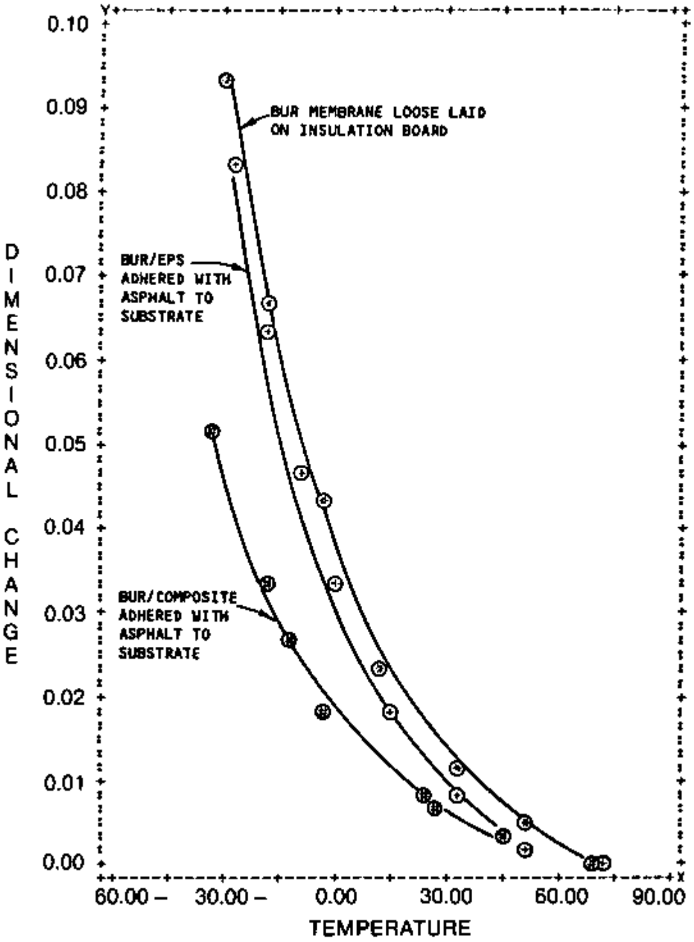

Figure 6 *Temperature induced dimensional change*

Y axis units are inches (over a 4' sample length)
X axis units are degrees F

Key

- * *BUR membrane, loose-laid*
- \+ *BUR membrane/1.0 pcf EPS, EPS adhered with asphalt*
- \# *BUR membrane/composite, adhered with asphalt*

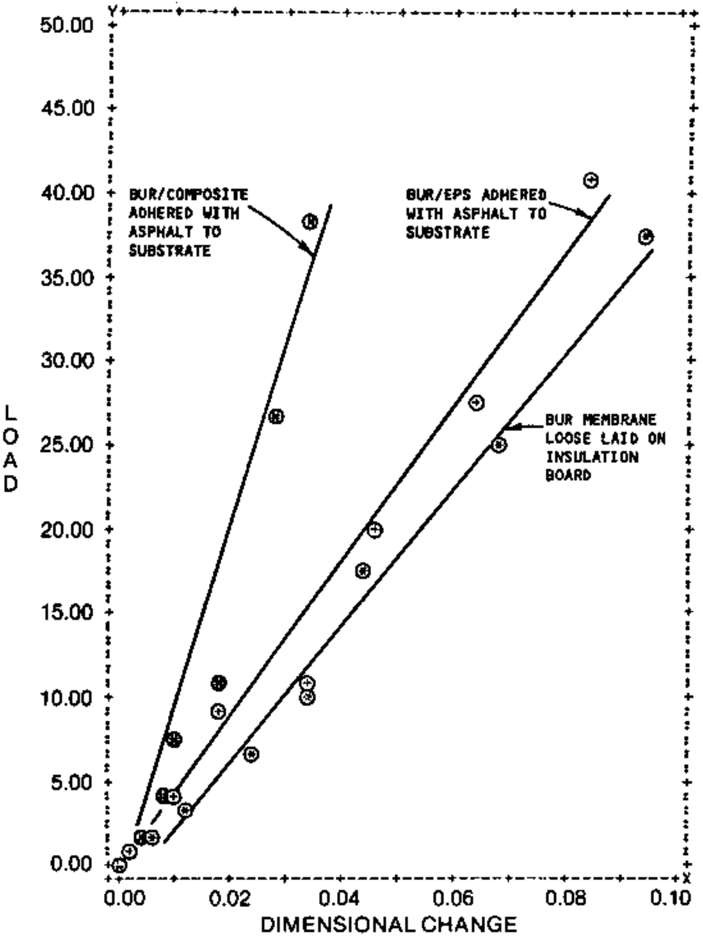

Figure 7 *Temperature induced—load vs dimensional change*

Y axis units are lb/in of sample width
X axis units are inches (over a 4' sample length)

Key

- * *BUR membrane, loose-laid*
- \+ *BUR membrane/1.0 pcf EPS, EPS adhered with asphalt*
- \# *BUR membrane/composite, adhered with asphalt*