PERFORMANCE CRITERIA FOR THE PROTECTED MEMBRANE ROOF SYSTEM

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INSULATION NOMENCLATURE

Cut Cell Extruded Polystyrene—This polystyrene is continuously extruded into thick billets and then cut to desirable thickness.

Extruded Polystyrene Skinboard—This polystyrene is continuously extruded to the desired thickness. A high density polystyrene skin is formed on the top and bottom of this product during extrusion.

Cut Cell Moulded Bead Polystyrene - This polystyrene is moulded into thick billets and then cut to desired thickness.

Moulded Bead Polystyrene—This polystyrene is moulded to the desired thickness.

Polyurethane/Polyisocyanurate (without skins)—These products are made into thick billets and then cut to desired thickness.

Polyurethane/Polyisocyanurate Laminated with Paper or Aluminum Foil – These products are continuously made to desired thickness. The paper (or aluminum foil) facing on the top and bottom of these products is placed on the products as the products are being made.

Polyisocyanurate Laminated with Aluminum Foil and Containing Glass Fibers—This product is continuously made to desired thickness. The aluminum facing is placed on the product as the product is being made. The glass fibers are interspersed throughout the polyisocyanurate core as the product is made.

Cellular Glass—This inorganic product is made in billets and is cut to desired thickness.

Fiberglass—This rigid board contains glass fibers held together with a binder and topped with an asphalt saturated felt on one side.

Fiberboard—This product contains perlite, vermiculite or other inorganic particles held together with a binder.

I. INTRODUCTION & BACKGROUND

Prior to World War II the roof construction practice in the USA was to install a bitumen and felt roof membrane directly on the roof deck. Heat escaping from the building has a moderating effect on the BUR even though the top surface was exposed to the extremes of ambient outdoor temperature. The heat capacity of the deck allowed the BUR to react slowly to outdoor temperature changes. These roofs required very little maintenance in fact, some of them are still in service today. Figure I illustrates the temperature profile in an uninsulated roof system.

When insulation was added to the system, the BUR was isolated from the deck and exposed to the extremes of winter and summer temperatures. Temperature variations of as much as 100°F may occur during a typical day in summer or winter (see Fig. II). Membrane temperature changes with increasing amounts of insulation (see Fig. IV). The increased temperature during summer and thermal shock caused by changing weather conditions speeds the aging of the BUR, making it more susceptible to splitting, cracking, and alligatoring. Roof insulation improved the interior thermal environment and greatly reduced fuel consumption. At the same time it caused many more roof problems than occur on uninsulated roofs. Roofs have been second only to mechanical equipment as a source of problems to building owners, designers, and contractors. The General Services Administration has reported that 10 to 15% of all roofs fail prematurely (i.e. in less than five years).

Developed as a cure for the ills afflicting conventional BUR systems, the protected membrane or upside down (U.S.D.) roof system places the membrane back on the deck, as it had been in uninsulated roofs, with the insulation above the membrane. This arrangement keeps the membrane close to room temperature at all times (see Fig. III). Use of additional insulation in the USD system tends to stabilize the membrane temperature (see Fig. IV) and protect it from physical damage. The USD roof system originated with a test installation in 1951 and remained in the developmental stages until 1969. A careful analysis of these installations established the parameters for performance standards of the components and the system. The system was first marketed in Canada and Europe in 1969 and in the U.S. one year later. There are now over 3,000 installations in the U.S. and thousands more in Canada, Europe, Asia, and the Middle East, performing well in both severe heat and cold.

There has been no failure to date ("failure" defined as the degradation of a properly installed system to a point where replacement or major repair is necessary). The problems incurred have been minor "sins of omission," such as insufficient ballast causing floating insulation boards, flashings not completed, and new stacks or conduits installed without proper flashings.

Rearrangement of the components in the protected membrane concept drastically alters their performance criteria:

- The **membrane** function shrinks to the sole purpose of waterproofing. Unlike the membrane in a conventional BUR system, it no longer has to withstand extensive temperature change, foot traffic, and solar radiation.
- The **insulation** becomes the critical component. In addition to its primary function of conserving heating and cooling energy, it protects the membrane from temperature cycling, physical damage, and solar radiation. It must maintain longterm thermal efficiency despite perennial exposure to water, freeze-thaw cycles, and water-vapor pressure.
- The **top-covering** or **surfacing material,** provides ballast against flotation, shielding from u.v. radiation, hailstone impact resistance, and fire protection from small fire sources.

III. MEMBRANES

The U.S.D. roof has accelerated the growth of the currently small market for liquid-applied and sheet membrane systems. A protected membrane is similar to plaza and below-grade waterproofing, and many of the products formerly limited to those applications can now be used in roofing. Liquid-applied systems may be one or two component, hot or cold-applied. They are specified primarily for use over cast in place concrete decks.

Sheet membranes are more versatile than liquid-applied membranes. They may be installed loose, spot bonded, or solidly adhered to the substrate. Durability depends chiefly on the sheet materials' weather resistance. Materials in current use include:

- Heavy bitumen-coated felts from Europe, installed with propane torch.
- Bitumen elastomeric composites that are self-adhering.
- Elastomeric or thermoplastic sheets (films) fabricated with heat or adhesive.

Sheet and fluid-applied elastomeric membranes must be installed with meticulous care. Concrete substrates receiving fluid-applied membranes must be carefully prepared, since many liquid materials are subject to pinholing if the concrete surface is dusty or damp. Also important are proper storage and mixing of fluid materials and the design and installation of flashings at roof penetration and terminations.

Sheet membranes require careful sealing of every inch of every seam. (Some manufacturers recommend cap strips over seams for added insurance.) Penetrations and terminations are more easily made than on fluid-applied membranes.

The conventional BUR membrane, field-fabricated with alternating layers of felt and bitumen, is the predominant membrane used with the USD roof system. A review of the BUR membrane's physical and chemical behavior shows why it is well suited to the USD system.

It is generally conceded that all bitumens oxidize when exposed to the weather and that heat, light, and water are the major contributors. Various conclusions regarding bituminous membranes, based on a survey of literature published over the past 60 years, are: 1) high temperatures will speed the oxidation of the bitumen and shorten the life of the membrane (see reference 1); 2) sunlight (U.V.) is extremely damaging to bitumens by making them soluble in water, causing cracking or alligatoring (see reference 2); 3) water alone plays a very small part in the oxidation of bitumens, because bitumens are almost totally insoluble in water (see reference 3); 4) water vapor transmission can be significant when high vapor pressure due to a temperature difference exists across a membrane (Fich's Law); 5) water absorption of bitumen is negligible (see reference 4). A careful analysis of these conclusions indicates that the performance criteria for BUR membranes has been with us for a long while but we have not taken advantage of the knowledge. A built up bituminous membrane will perform very well if the temperature is stabilized, a continuous coating of bitumen is used, and sunlight is excluded.

Since the USD roof system places the membrane on the deck under the insulation, the membrane remains very near room temperature at all times. Temperature measurements of actual buildings show that USD membrane temperature changes rarely exceed 30°F (17°C) while the top covering temperature may change as much as 175°F (97°C).

The stable membrane temperature of an USD roof is demonstrated by a Midland, Michigan school with steel deck, ½ in. fiber board, BUR, 1-¾ inch extruded polystyrene, and stone top covering. Temperature sensors were placed in the BUR and on top of the plastic foam insulation. At 8:00 a.m. on a hazy August day, both indicators read 70°F (21°C). At 1:15 p.m. the top side temperature was 160°F (71°C) while the BUR temperature was 82°F (28°C). Thus a solar induced temperature change of 90°F (50°C), caused only a 12°F (8°C) rise in the roof membrane. Data from other areas in the U.S., Canada, Europe, and the Mideast shows similar temperature differences.

The roof membrane is shielded from sunlight in the U.S.D. roof system by the insulation and top covering. Sunlight protection and lower temperatures substantially reduce oxidation and resultant hardening of bituminous membranes. Specimens taken from several 10 year old asphalt membranes in test installations show the 190°F (88°C) melt point essentially unchanged while the same asphalt on an adjacent conventional roof area had a melt point over 400°F (185°C). Specimens taken from other U.S.D. roof membranes also show little or no change in melt point of bitumen.

The importance of a continuous top coat of bitumen has been demonstrated. While investigating the source of a small leak on a U.S.D. roof it was determined that the top coat of bitumen was intermittent and separating from the underlaying felt. The felt was saturated with water. Another test cut was made in the same roof. In this case the top coat of bitumen was continuous and the membrane in perfect condition. The problem area has since been corrected.

Since the membrane's sole purpose in a USD roof is to provide waterproofing, it now appears that the most important requirement in built up bituminous membrane is a continuous top coat of bitumen. It is usually necessary to apply multiple coats to be assured of a continous coating.

IV. INSULATIONS

The ideal insulation for the U.S.D. roof system should be:

1) Ultraviolet (UV) stable;
2) nonbouyant;
3) noncombustible;
4) dimensionally stable;
5) water impermeable;
6) resistant to freeze/thaw action;
7) high in compressive strength.

Several insulations have some of the above properties, but none of the insulations available have all seven properties. The fibrous insulations meet the first four properties and some of the plastic foam insulations meat the last four properties.

Fortunately, the protected membrane concept makes this ideal insulation unnecessary. A protective surfacing atop the insulation can provide ballast against flotation and shielding from u.v. radiation. Moreover, no roof system with bitumen or petroleum-based products is noncombustible, but the U.S.D. roof system does meet the standard roofing fire requirements (see Total System section). The remaining four properties—dimensional stability, water resistance, freeze/thaw resistance and high compressive strength must be optimized because of the location of the insulation in this roof system. The high compressive strength is needed to protect the membrane from tools, equipment, roof traffic and other miscellaneous hazards. Dimensional stability is needed to maintain the insulation integrity when the insulation is directly exposed to extremes of temperature (up to 150°F in summer and down to -60°F in winter) and moisture (i.e. snow, rain, hail and ice).

However, the two major properties needed by the insulation are resistance to water and resistance to freeze/thaw action. The U.S.D. roof system has possibly the worst combination of water conditions: 1) a large temperature differential across the insulation; and 2) a constant source of high humidity at both the membrane level and above the insulation. Most building applications for insulations have either a temperature differential or a high humidity condition but not both conditions at the same time.

The temperature on one side of the insulation is at room temperature (70°F) and the other side of the insulation varies from ambient conditions (150 °F in summer to -60°F in winter). This temperature difference creates a large water vapor driving force. In the winter the water vapor or liquid water is driven from the membrane location up into the insulation. In the summer the water vapor or liquid water is driven from the top down into the insulation.

Water vapor or liquid is always available on a U.S.D. roof system because the roofs are usually low slope (less than ½ inch in 12 inches) and because a thin film of water usually remains at the membrane level. This water supply, along with the exposure of the insulation to the changing temperatures and seasons, makes the insulations susceptible to freeze/thaw action. These two conditions (permeability to water and freeze/thaw action) on insulation are usually synergistic in their detrimental effect on the insulation's longterm thermal efficiency.

There is no good single screening laboratory test to determine the best insulation with respect to long-term thermal performance in the U.S.D. roof system. However, by the combined use of several available laboratory tests for water absorption, we can determine the insulation best suited for the U.S.D. roof system.

A. Water Absorption Testing

The standard water absorption tests available for testing insulations in North America, submersion tests run for short durations such as 96 hours (ASTM D 2842), are inadequate for screening insulations for wet environmental applications such as the U.S.D. roof system, as insulations used in wet applications are subjected to long periods of immersion in water.

The best water absorption test for these end use applications for thermal insulations is where there is a water vapor driving force through the insulation from bottom to top. This test should have a temperature gradient, a water saturated environment, and a long-term exposure to water. If the insulation has a high water pickup, it should not be considered for wet environments with driving force conditions present (below grade perimeter, highway, or U.S.D. roof applications).

A water-diffusion test of this type is being developed in Germany. The test specimens are 20 inches (500mm) by 20 inches (500mm). The temperature gradient across the samples tested is 10°C per centimeter thickness. The specimens are turned daily in order to achieve a uniform moisture distribution. The water pickup is determined after 28 days and expressed in percent by volume. The performance of various insulations, under these test conditions, can be found in Figure VI. This test is officially specified by the German Research Association for Road Construction "Forschungsgesellschoff fur das Strassenwesen e.V.," Koln, under the recommendation for "Dammschichten als Frostschutz", paragraph 2.242. This test should be restricted to 70mm (max.) thickness at this time. Work is in progress to develop this test procedure to accommodate thicker samples (up to 200 mm).

The results of this test with various insulations are shown in Figure VI. The high density moulded bead polystyrenes tested (see Figure VI) were European and are not available in North America. The lower density moulded bead polystyrenes (1 lb and 1.5 lb/ft^3 density) that are available in North America would most likely perform worse than these high density moulded bead polystyrenes. The polyurethane with felt paper on the top and the bottom of the specimen would probably perform better in this test than is indicated in Figure VI if the paper on the polyurethane was waterproofed with wax or asphalt. The extruded polystyrene skinboard picked up the least amount of water.

B. Freeze/Thaw Action

Most of the United States has at least 30 freeze/thaw cycles a year with a freeze temperature defined as 28°F and a thaw temperature defined as 34°F (L. Williams, U.S. Army Natick Laboratories, "Regionalization of Freeze/Thaw Activity" [ref. #5]). A minumum criteria for a freeze/thaw cycle resistance test should be 500 to 700 freeze/thaw cycles (1000 cycles if one is conservative). This ten year freeze/thaw cycle band (500 to 700 cycles) on Figure VII covers geographical locations such as Philadelphia, Memphis, New York, Detroit, Chicago, Washington D.C., Cleveland, Indianapolis, Montreal, Toronto and Quebec City.

Four inch (100 mm) by four inch (100 mm) insulation samples were tested for 1041 freeze/thaw cycles following the ASTM C 666-73 test procedure (freeze in air, thaw in water) for concrete. The freeze/thaw results on various insulations are found in Figure VII. Extruded polystyrene skinboard was the best performer.

Fiberglass and fiberboard products were also tested for freeze/thaw but only 414 cycles before they started to break up. The 1" fiberglass board picked up 76% by volume water and the 1" fiberboard picked up 89% by volume water before breaking up. The polyisocyanurate with aluminum facings and glass reinforcing in the core had 88% by volume water before it began to break up after 458 freeze/thaw cycles. Cellular glass broke up after 97 freeze/thaw cycles. Freeze/thaw data on various insulations indicate that accelerated water pickup occurs after insulation samples exceed 10% by volume water (see Figure VII).

This freeze/thaw test does not simulate actual U.S.D. roof conditions; in fact, it does not appear as severe as some actual U.S.D. roof conditions. In this test, the four hour freeze/thaw cycle is controlled by using concrete cylinders. The freeze point in the concrete, not the insulation, is the determining factor for the cycle to switch; thus, the center of the insulations do not freeze. The test conditions do not allow one side of the insulation to retain water or remain at 70°F. When the freeze cycle begins, the water is allowed to drain away. Both sides of the insulation are at the same temperature, and no vapor pressure driving force exists.

C. The Effect of Moisture on Thermal Resistance of Insulation By Driving Force Conditions

An increase in an insulation's water content reduces its thermal resistance. The following equations were determined by laboratory experiments conducted at The Dow Chemical Company, the Swedish Institute (reference #6), and at Chalmers Technical Institute (reference #7) for 0 to 30% by volume water pickup. Similar equations, with slightly different coefficients, were obtained in studies by M. M. Levy (reference #8), H. Mittasch (reference #9), and J. Achteiger (reference #10). These equations do not indicate **how much** water a particular insulation will pick up in an actual end use applications, but do indicate what the effect of a certain water percentage (by volume) will be on the long-term thermal efficiency of the insulation in question.

The equations for the thermal conductivity (where V is the percent moisture by volume) are:

1. **Polyurethane/Polyisocyanurate (u)**

$K_{u\,wet} = k_{dry^*} + 0.008\,(V) = 0.16^* + 0.008(V)$

(0 to 10% by volume water)

$K_{u\,wet} = K_{dry^*} + 0.0055\,(V) + 0.00028\,(V^2) = 0.16^* + 0.0055\,(V) + 0.00028\,(V^2)$

(10 to 30% by volume water)

2. **Low Density Moulded Bead Polysytrene (bd bd)*****

$k_{bdbd\ wet} = K_{dry*} + 0.0122\,(V) = 0.28^{*} + 0.0122\,(V)$

(0 to 10% by volume water)

$k_{bdbd\ wet} =$ artificial factor** $+ 0.0167(V) = 0.225^{**} + 0.0167\,(V)$

(10% to 30% by volume water)

3. **High Density Moulded Bead Polysytrene (bd bd)******

$k_{bdbd\ wet} = k_{dry} + 0.015\,(V) = 0.24^{****} + 0.015\,(V)$

(0 to 30% by volume water)

4. **Fiberglass (FG)**

$k_{FG\ wet} = k_{dry*} + 0.082\,(V) = 0.25^{*} + 0.082\,(V)$

(0 to 2% by volume water)

$k_{FG\ wet} =$ artifical factor** $+ 0.006(V) = 0.41^{**} + 0.006\,(V)$

(3 to 10% by volume water)

$k_{FG\ wet} = k_{dry*} + 0.0217\,(V) = 0.25^{*} + 0.0217\,(V)$

(10 to 30% by volume water)

5. **Extruded Polystyrene (EP)**

$k_{EP\ wet} = k_{dry*} + 0.008\,(V) = 0.20^{*} + 0.008\,(V)$

(0 to 30% by volume water)

*Assumed aged value of at least one year using ASHRAE (1972).

**Artificial factor determined by experimental data.

***These equations only apply to bead polystyrenes at or below 1.8 lb/ft^3 density.

****This equation only applies to bead polystyrenes with densities greater than or equal to 2.1 lbs/ft^3. Published k factor of European high density beadboards varies between 0.23 and 0.25.

D. Thermal Resistance Calculations of Wet Insulations

The **actual** change in thermal resistance of various insulations due to the presence of water is calculated as follows:

$$R_a = \frac{1}{C_a} = \frac{t}{k_{wet}}$$

where R_a = **actual** thermal resistance ($hr \cdot ft^2 \cdot {}^\circ F/BTU$) of insulations containing 0 to 30 % by volume water

C_a = actual thermal conductance ($Btu/hr \cdot {}^\circ F \cdot Ft^2$) of insulations

t = insulation thickness (inches)

k_{wet} = actual thermal conductivity ($Btu/hr \cdot {}^\circ F \cdot Ft^2/in$) of insulations (containing 0 to 30% by volume water) calculated by the formulas given earlier in this text.

E. Field Experience

U.S.D. roofs have been in use for the last 8 years. Data from some of these field installations can be found in Table I. Physical properties are shown for the following insulations: 1) moulded bead polystyrene; 2) extruded polystyrene skinboard; and 3) polyurethane (without skins). There is limited data on the performance of polyurethane insulation because of its limited use in U.S.D. roofs.

The data reported in Table I is restricted to roofs with slopes of less than or equal to ½ in. per foot. The top covering in all cases is stone. Data for samples taken from ponded areas are footnoted in Table I..

It has been discovered while testing insulation samples taken from U.S.D. roof that the moisture content of the sample varies with the time of year. This indicates that water vapor pressure driving force has a major effect on water pick up of the insulation. Insulation samples taken in spring will show higher water pick up than samples taken in late summer.

The overall performance of the U.S.D. roof insulations has been dependent on the type used. Compared with other materials, the extruded polystyrene skinboard is the most widely used and has demonstrated excellent thermal performance because of its resistance to water absorption in actual roof applications.

V. TOP COVERINGS

A. Function

The top covering in the Protected Membrane roof system usually provides the buoyancy resistance and the ultraviolet shield for the insulations. This UV protection is most important when using plastic foam insulation in the U.S.D. roof system.

The buoyancy resistance provided by the top covering is not easily understood. The insulations (plastic insulations weighing approximately 2 lbs/ft^3) used in the U.S.D. roof system are lighter than water which weighs 62.4 lbs/ft^3 (1 gm/cm^3). Thus, if a layer of water is present, there will be the potential of insulation flotation.

The insulations can be either bonded or laid loose over the various waterproofing membranes. However, even when the insulation is theoretically bonded in bitumen, the actual area of the bond will vary from 0 to 85%. The bond area depends on the flatness of the insulation and the roof deck, the temperature of the bitumen when the insulation is installed, and the longterm creep inherent in bitumen under buoyant force. The end result is that flotation is a potential problem that must be overcome.

For example, the approximate buoyancy uplift on plastic insulations is found by taking the difference in densitites of the insulations (2 lb/ft^3) and water (62.4 lbs/ft^3), their differences in specific gravities, and calculating the buoyancy per square foot for thickness of insulation. This calculation yields a buoyancy uplift force of approximately 5 lbs/ft^2/inch thickness $\frac{62.4\ lbs/ft^3 - 2\ lbs/ft^3}{12\ inches/ft}$. The difference in alternative materials' specific gravities is insignificant and was not considered in this calculation. This buoyancy uplift assumes 0% bond of the insulation to the membrane. As bond strength increases, the net buoyancy force decreases.

The top covering also provides fire protection for the U.S.D. roof system from potential burning brands blown onto the roof from a fire on another building or a flame spread or blown onto the roof from a window or adjacent roof section already on fire. Underwriters Laboratories, Incorporated (ULI), Northbrook, Illinois evaluates the entire roof system for such fire protection following ASTM procedure E108 (ULI procedure number 790). The U.S.D. roof systems with either stone, poured concrete or a concrete paver top covering are classified by ULI as "Class A" (resistance to the most severe fire exposure available under the specific test conditions).

Top coverings such as poured concrete and concrete paving blocks (in various sizes and shapes) can also be used where the U.S.D. roof system is the base for a parking deck, plaza area, walkway, picnic area, terrace, playground or even a tennis court. Sometimes a water-permeable separation layer is placed above the roof insulation. A sand or stone covering is then placed upon the insulation as a base for gardens, planters, etc. The need for the roof to be used for other purposes is another option that the U.S.D. roof system provides.

B. Precautions

1. U.S.D. Roofs

However, the top covering can also cause disadvantages with respect to the long-term thermal performance of insulations. Concrete paving blocks placed directly on top of an insulation in a U.S.D. roof system may retard the water vapor from escaping from the insulation in the winter, thus causing water pickup in the insulation. This block due to mass, thickness and surface tension also acts as a shield and reduces evaporative drying of the top surface of the insulation. The end result is some loss in thermal resistance of the insulation depending on the type and thickness of insulation used and the location (i.e., Montreal or Miami) of the roof application.

A recommended way to use concrete paving blocks to avoid any potential thermal resistance loss is the use of spacers or gravel between the insulation and the concrete paving blocks. Grooves or legs in the paving blocks which reduce the contact area of the block with the insulation to less than 50% may also be used.

Data generated by field testing, such as National Research Council of Canada study in Saskatoon, Saskatchewan (reference #11, #12) showed that spacers or gravel or reduced surface contact, reduced the loss in thermal resistance of the insulations significantly. The drainage space under the pavers made the water pickup (dependent on the insulation used) comparable to the stone covered U.S.D. roof system. Stone covered U.S.D. roofs have the minimum water pickup.

A stone covering embedded in an asphalt flood coat is also used as a top covering over some insulations in the U.S.D. roof system. The asphalt flood coat may retard escape of water vapor or liquid at the membrane level. This water pickup phenomenon would then follow the same scenario as the patio block situation with the end result being a loss in thermal resistance of the insulation under this covering. This type of top covering has not had enough exposure (years) to provide field data to correlate this theory.

2. Conventional Roof Comparison

This potential water pickup situation caused by the placement of patio block or an asphalt flood coat over the insulation is somewhat analogous to a conventional builtup roof system with the insulation under the membrane and asphalt. Historically, the water pick up of insulation in conventional roofs has been attributed to absorption. New data, however, indicate that water vapor pressure may be the prime force in the water pick up mechanism.

For example, if the roof deck is concrete or if there is a vapor barrier, and the membrane or flashing leaks, the water is trapped between the insulation and the deck. This water is driven into the insulation by the vapor pressure difference resulting from the temperature difference between the inside of the building and the ambient outside (in the winter). This water vapor or liquid is trapped within the insulation due to the relative impermeability of the built-up roof membrane and asphalt and the very low vapor driving force present in the top ¼ to ½ inch of insulation. Substantial water pickup, 30% or more by volume, and consequent loss in thermal resistance of various insulation has been measured.

VI. TOTAL SYSTEM

Although the individual components of the U.S.D. roof system have been analyzed in earlier sections, the merits of any system also depend on the performance of the individual components as an integrated system. Performance criteria for the U.S.D. roof system require

1) that the top covering stay in place,
2) that the entire system meet or exceed all existing fire requirements for roof systems,
3) that it provide long term thermal resistance (see Section IV), and
4) that it provide complete waterproofing (see Section III).

Additional maintenance cost saving may be obtained because: 1) the waterproofing membrane is physically protected by the insulation and the top covering from people and equipment; and 2) thermally protected by the insulation from large variations in temperature (normally less then ± 15°F change seasonally). Also, loss in volatiles due to membrane aging is reduced.

Wind and fire criteria are set by both insurance companies (for damage to building interiors) and building codes (for life-safety hazards). The U.S.D. roof systems available today meet the insurance requirements for fire and wind uplift on steel roof decks such as Class 1-60 and Class 1090 from Factory Mutual Research Corporation and Fire Acceptable and Class 30 and Class 60 wind uplift classifications from Underwriters Laboratories, Inc. These classifications were obtained by running large scale laboratory fire and wind tests at FM and ULI. Some of the U.S.D. roof systems are also classified in various roof/ceiling constructions for building code purposes. These roof/ceiling classifications are obtained by testing the entire roof structure including the roof deck and supports (and ceiling and lights if necessary) under large scale laboratory fire conditions for at least one hour. These classifications can be found in the Fire Resistance Index (Underwriters Laboratories, Inc.) and Factory Mutual Approval Guide.

Although all these wind uplift and fire classifications are obtained from large-scale laboratory tests, these results do not presuppose that all potential fire conditions have been simulated, nor do they indicate exactly how the classified systems will perform in an actual fire. All plastic foams used in U.S.D. roof systems are combustible (see insulation manufacturers literature for safe use instructions).

Wind blowoff is sometimes confused with wind uplift. Wind uplift measures the uplift resistance of the entire roof system. Wind blowoff usually refers only to the top covering resistance to pressures on the roof surface in high winds. Designing the appropriate top covering for the U.S.D. roof system for the specific wind conditions and needs in local building code areas may be quite complex. Some of the variables that must be considered are: 1) configuration of the building; 2) building location (i.e., Miami); 3) parapet height; 4) terrain surrounding the building (i.e., flat or hilltop); 5) actual mean wind speeds (not gust speeds) over the last 30 to 100 years. A good treastise on this subject is "Design of Rooftops Against Gravel Blowoff" by Kind and Wardlaw (reference #13).

VII. SUMMARY OF FIELD EXPERIENCE

A. Membranes

All types of roof membranes are performing well in the U.S.D. roof system. Several measured melt points of asphaltic membranes in U.S.D. roof show increases of less than 30°F in ten years. Surveys in Quebec, Canada of six 5 year old U.S.D. roofs showed no indication of any deterioration of the membranes nor rotting of felts.

Liquid membranes have ridden the U.S.D. roof concept into the waterproofing area of the roofing market, and sheet membranes installed within the last five years in U.S.D. roofs in Alaska and Europe have been performing well.

B. Insulation

Overall performance of the U.S.D. roof insulations has depended on the insulating materials used. Extruded polystyrene skinboard is the most widely used and has demonstrated excellent thermal performance because of its superior resistance to water absorption in actual roof applications. The specific long-term performance of the various insulations most commonly used in U.S.D. roofs can be found in Table I. The field performance of the insulations correlates well with laboratory studies described in this report.

C. Top Coverings

The predominant top covering for U.S.D. roofs over the last ten years has been stone. If the proper size and amount of stone covering is used, good long-term performance can be expected. Some flotation has resulted in those cases where inadequate quantities of stone have been installed. There had also been some minor scrubbing of stone observed in corners.

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TABLE I

FIELD PERFORMANCE OF VARIOUS INSULATIONS USED IN STONE COVERED U.S.D. ROOFS (LOW SLOPE ≤ 1/2" PER FOOT)

Location	Thickness (inches)	Density	Time In Service (Yrs)	Properties of Insulations After Years in Service: Water Pickup (% by vol.)	Properties of Insulations After Years in Service: k Factor (Btu/hr-°F-Ft²/in)	Published k Factor (Btu/hr-°F-Ft²/in)
A. EXTRUDED POLYSTYRENE SKINBOARD						
1- Braunschweig, Germany	2	not measured	2	0.09%	0.20*	0.20
2- Stdhlton Frick, Switzerland	2	not measured	2.5	0.17%	0.20*	0.20
3- Neuheim, Switzerland	1.6	not measured	2.8	1.1%**	0.21*	0.20
	1.6	not measured	3	0.72%**	0.21*	0.20
4- Lausanne, Switzerland	1.6	2.25 lb/ft³	3.3	0.03%	0.20*	0.20
5- Montreal, Canada	1.5	not measured	3.8	not measured	0.20	0.20
6- Montreal, Canada	1.5	not measured	5	0.11%	0.22	0.20
7- Quebec, Canada	2	not measured	5	0.02%	0.21	0.20
8- Quebec, Canada	2	not measured	5	0.29%	0.22	0.20
9- Edmonton, Canada	1.5	not measured	5	0.01%	0.21	0.20
10- Midland, Michigan (USA)	1	not measured	6.4	0.13%	0.22	0.23
	1	2.43 lb/ft³	6.4	0.32%	0.22	0.23
	1	2.59 lb/ft³	6.4	0.24%	0.22	0.23
11- Mannheim, Germany	1.6	2.43 lb/ft³	7.2	0.62%	0.20	0.23
12- Hanau, Germany	not measured	not measured	7.7	0.15%	not measured	0.23
13- Mannheim, Germany	not measured	not measured	8	0.10%	not measured	0.23
B. MOULDED BEAD POLYSTYRENE						
1- Sarnia, Canada	1.25	1.76 lb/ft³	0.8	21.4%	0.52	0.24 to 0.26
2- Zug, Switzerland	2	2.31 lb/ft³	1	5.6%	0.32*	0.24 to 0.26
3- Toronto, Canada	3.5	1.95 lb/ft³	1	16.0%	0.53	0.24 to 0.26
4- Sarnia, Canada	2	1.52 lb/ft³	1.1	26.5%**	0.50	0.24 to 0.26
	2	1.52 lb/ft³	2.1	38.6%**	0.70	0.24 to 0.26
5- Quebec Province, Canada	2	1.82 lb/ft³	2	57.9%**	1.62	0.24 to 0.26
6- Heidelburg, Germany	2.4	1.75 lb/ft³	not known	18.7%	0.41	0.24 to 0.26
7- Zaandam, Holland	1.6	2.5 lb/ft³	3.5	17%	0.50*	0.24 to 0.26
8- Midland, Michigan (USA)	1	1.56 lb/ft³	7.3	8.6%	0.34	0.24 to 0.26
	1	1.57 lb/ft³	7.3	15.9%	0.43	0.24 to 0.26
	1	1.75 lb/ft³	7.3	17.2%	0.39	0.24 to 0.26
C. POLYURETHANE (Without skins)						
1- Braunschweig, Germany	2	2.09 lb/ft³	2	1.72%	0.17*	0.13 to 0.16
2- Saskatoon, Saskatchewan, Canada	2	2 lb/ft³	4	4.5%***	0.21*	0.13 to 0.16
	2	2 lb/ft³	4	12.0%****	0.27*	
3- Saskatoon, Saskatchewan, Canada	2	2 lb/ft³	5	5.1%***	0.22*	0.13 to 0.16
	2	2 lb/ft³	5	17.0%****	0.33*	0.13 to 0.16

*Not measured, but calculated by using formulas in Section IV-C of text
**Continuously ponded area
***Average of three samples (see reference 11)
****Maximum water pickup of samples (see reference 12)

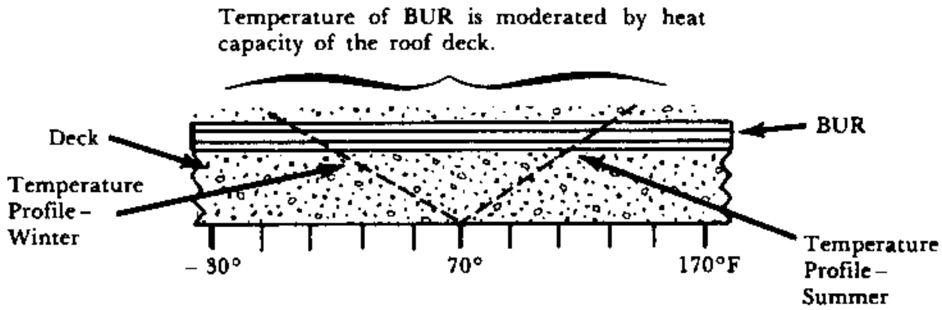

FIGURE 1 - TEMPERATURE PROFILE OF AN UNINSULATED ROOF SYSTEM

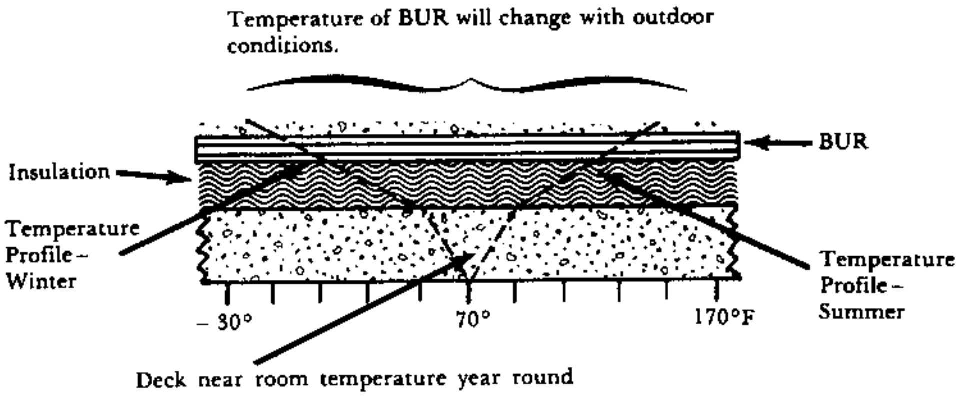

FIGURE 2 - TEMPERATURE PROFILE OF A CONVENTIONALLY INSULATED ROOF DECK

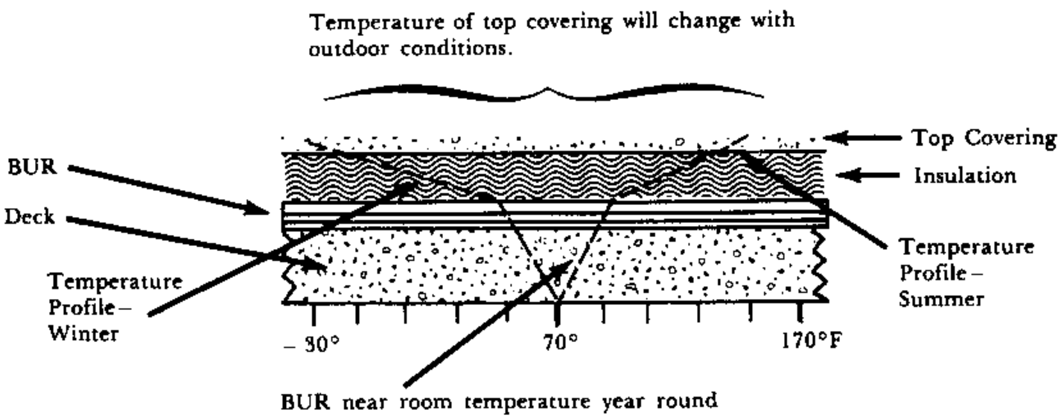

FIGURE 3 - TEMPERATURE PROFILE OF A PROTECTED MEMBRANE (USD) ROOF SYSTEM

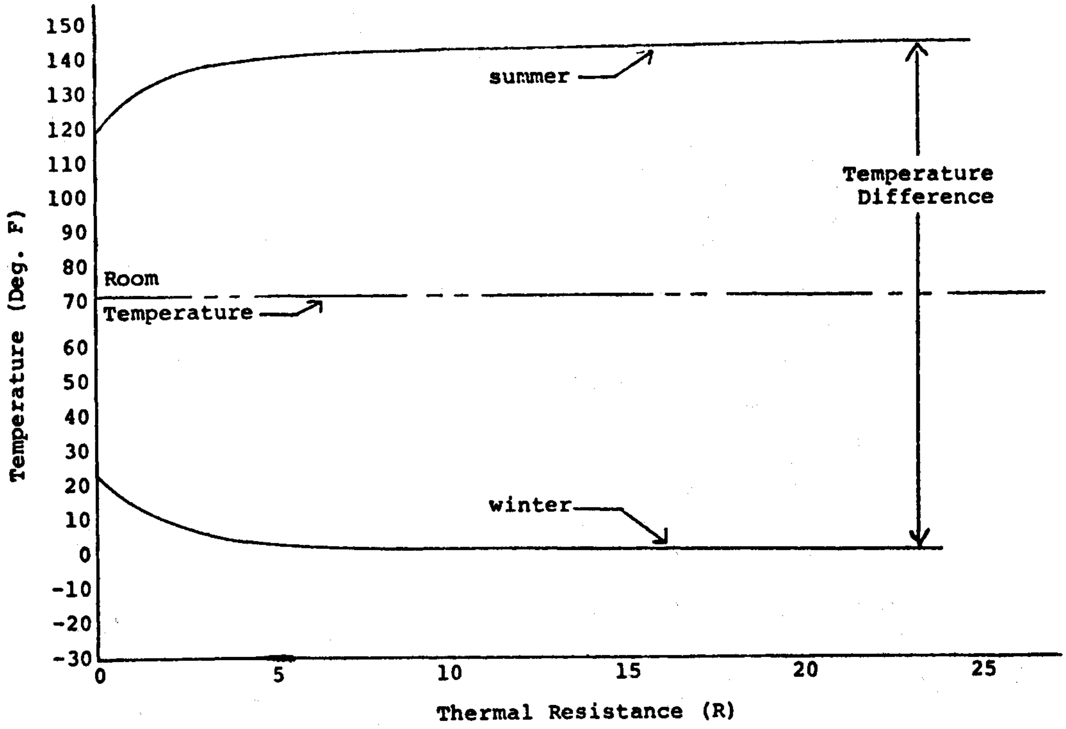

FIGURE 4 – TEMPERATURE OF MEMBRANE IN CONVENTIONAL ROOF SYSTEM WITH INCREASING AMOUNTS OF INSULATION

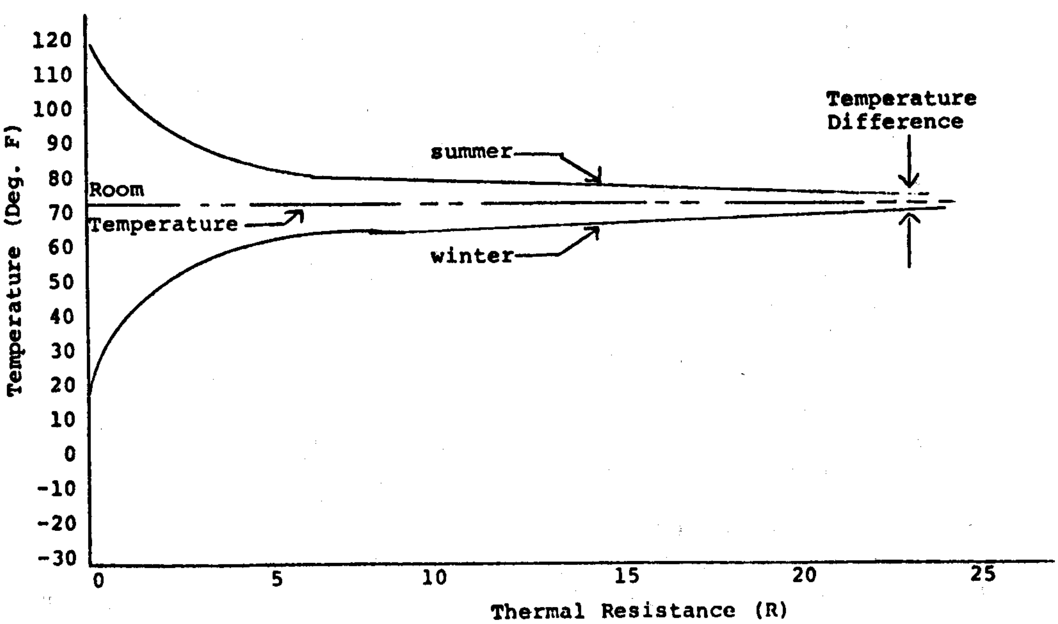

FIGURE 5 – TEMPERATURE OF MEMBRANE IN UPSIDE DOWN ROOF SYSTEM WITH INCREASING AMOUNTS OF INSULATION

A – 2.2" thick polyurethane laminated with paper (2.35 lb./ft.^{3})
B – 2" thick cut cell moulded bead polystyrene (2.68 lb./ft.^{3})
C – 2" thick cut cell moulded bead polystyrene (3.46 lb./ft.^{3})
D – 2" thick cut cell extruded polystyrene
E – 2" thick moulded bead polystyrene (2.10 lb./ft.^{3})
F – 2" thick extruded polystyrene skinboard

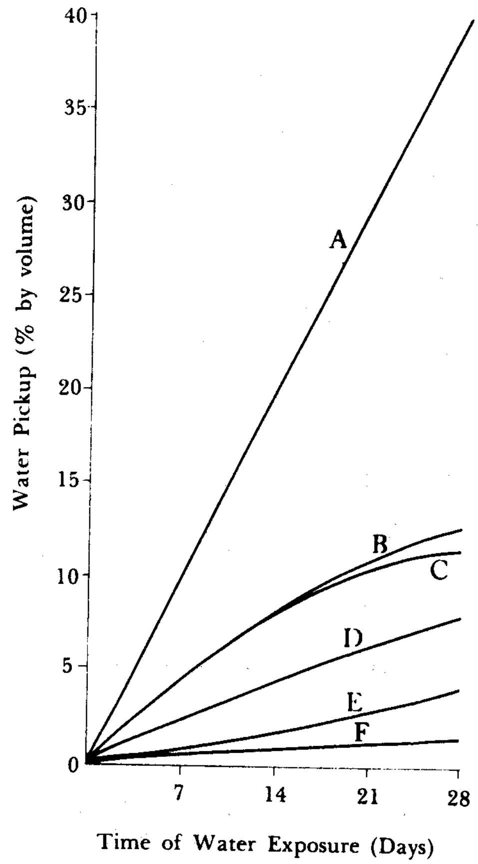

FIGURE 6 – WATER PICKUP (% BY VOLUME) VERSUS TIME (DAYS). GERMAN WATER ABSORPTION TEST BY DIFFUSION (TEMPERATURE GRADIENT OF 10°C PER CENTIMETER THICKNESS). THE DOW CHEMICAL COMPANY, HORGEN, SWITZERLAND (1976)

A – 1½" thick cellular glass (9 lb./ft.^{3})
B – 1" thick polyisocyanurate, glass reinforced with aluminum facings (2.6 lb./ft.^{3})
C – 1" thick moulded bead polystyrene (1 lb./ft.^{3})
D – 2" thick moulded bead polystyrene (1.7 lb./ft.^{3})
E – 2" thick polyurethane with aluminum skins (3.1 lb./ft.^{3})
F – 2" thick German moulded bead polystyrene (2.2 lb./ft.^{3})
G – 1" and 2" thick extruded polystyrene skinboard

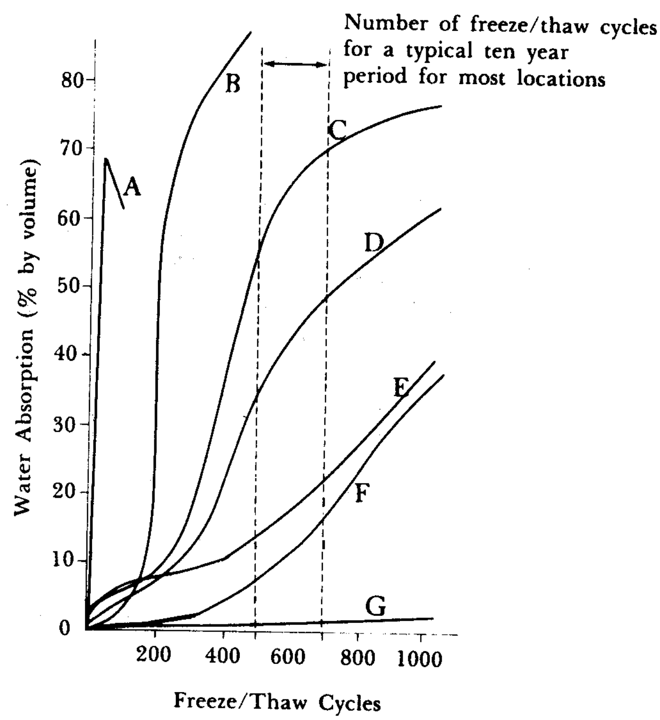

FIGURE 7 – THE WATER ABSORPTION OF VARIOUS INSULATIONS AFTER FREEZE/THAW EXPOSURE FOLLOWING ASTM C 666-73 (FREEZE IN AIR, THAW IN WATER). THE DOW CHEMICAL COMPANY, MIDLAND, MI. 1976.