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NATIONAL BUREAU OF STANDARDS REPORT

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GUIDELINES FOR SELECTION OF AND USE OF FOAM POLYURETHANE ROOFING SYSTEMS

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U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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NATIONAL BUREAU OF STANDARDS REPORT

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GUIDELINES FOR SELECTION OF AND USE OF FOAM POLYURETHANE ROOFING SYSTEMS

by
William C. Cullen
Walter J. Rossiter, Jr.
Structures, Materials & Life Safety Division
Center for Building Technology
Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

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Abstract

The use of spray-in-place polyurethane foam for roofing application in the United States is increasing at a rapid rate. Little unbiased information is available to guide the user in the specification, selection, application, and performance of this innovative roofing system. This report describes the current state-of-the-art of rigid polyurethane technology as applied to roofing systems. The performance parameters as observed during the field survey are discussed in terms of protective coatings, fire safety, durability and problem areas. Guidelines to assist the supplier and user alike in the use and selection of polyurethane foam roofing systems are given. Finally, a performance specification for spray-in-place polyurethane foam roofing system is suggested.

Key Words: Guidelines; durability; fire safety; performance; protective coatings; roofing; rigid polyurethane.

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1.0 Introduction

During the decade of the 1960's, spray polyurethane foam attained prominance as a roofing material in the United States. Basically, the roofing system consists of a sprayed-in-place polyurethane foam insulation combined with a protective cover. In some cases it has been recommended and specified for use over decks which, for one reason or another, cannot accommodate a conventional bituminous built-up roof. In other cases it has been recommended and specified for use in lieu of conventional membrane roofings and in still others it has been used as a repair covering over various and sundry roofing systems including built-up, metal and others. In brief, it is indeed unfortunate that the foamed-in-place urethane materials have been proposed, mostly by the uninformed, as a panacea for the many roofing problems which have plagued the industry for many decades. The number of contractors who have entered and departed the foam urethane roofing business during the past 10 years provides adequate testimony that foam urethane does not offer the universal solution to all roofing problems. On the other hand, when properly specified and applied, urethane has solved severe and costly roof problems which could not be easily solved by more conventional means. The user, including the construction agencies of the U. S. Government, is faced with a dilemma when a decision is necessary whether or not to select a urethane foam roofing system over the more conventional system for a particular use. Nevertheless, a decision must be made. In doing so the advantages and limitations of competitive systems must be considered in terms of utility, performance, durability and cost. In selecting his choice, the decision maker must recognize the possible trade-offs which will have to be made. Further, he must be willing to accept the consequences of the trade-offs. To assist in the decision process, valid data should be gathered and analyzed to obtain factual information. This can be expressed:

DATA + ANALYSIS ⟶ INFORMATION

The information then must be combined with sound engineering judgment to make the decision:

INFORMATION + JUDGMENT ⟶ DECISION

Several sources have been used to gather information including a survey of the current literature, personal contacts with suppliers and applicators of urethane foams and their protective coatings, and on-site observations of the performance, utility and durability of both new and aged foam urethane roof applications. We believe that it is the best information available at this point-in-time. To be useful, the information must be used in combination with sound engineering judgment to:

1. Determine whether or not foam urethane provides the solution. If the answer is positive,
2. Select the proper system to meet the requirements of the specific job.

In this report we have suggested guidelines and a performance specification for spray-in-place polyurethane used for roofing to assist the decision maker.

2.0 Purpose of the Report

Heretofore little unbiased information has been available regarding the choice, application, performance, advantages and limitations of the foamed-in-place urethane roofing systems to assist personnel charged with design, construction and maintenance responsibilities. Therefore, at the request of the Naval Facilities Engineering Command, U. S. Navy; the Directorate of Civil Engineering, U. S. Air Force; and the Office of Chief of Engineers, U. S. Army, a project was conducted to survey the state-of-the-art of polyurethane roofing technology. The purpose of this paper is to provide guidelines for the selection and use of foamed-in-place polyurethanes for roofing applications. A further purpose is to suggest a performance specification concerning the urethane foam system and its protective coating system.

3.0 Conduct of the Study

Initially, in formulating the project plan, it was decided not to perform laboratory research due to the magnitude of the problem and funding limitations. We believed that the better approach was to utilize in-use experience as the primary source of information. In this connection field inspections of almost a hundred roofs have been made in many areas of the United States. The roofs which were observed varied in size from a few squares 1/ to more than three acres 2/ in area. Several varieties of substrates used for the urethane systems, including weathered built-up roofing, were observed. The roofs surfaced with urethane ranged from flat to vertical. The urethane was exposed to climates varying from the relatively mild climates of California to those experiencing large temperature extremes such as Northern Alaska. The

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1/ One square of roofing is equal to 100 square feet.

2/ One acre is equal to 43,560 square feet.

performance of protective coverings of many different types and characteristics were observed. These observations were used in foaming the performance guidelines.

Several leading roofing contractors, including spray foam applicators, were contacted, interviewed and, in some cases, visited to obtain their views, experiences, and opinions on the use, application and performance of urethane roofing systems. These included successful and unsuccessful foam applicators and roofing contractors who have not been in the business directly but had definite opinions as expert "outside" observers. These contacts provided us with opportunities to hear and observe the "good and bad", the advantages and limitations, and the strengths and weaknesses of the foamed urethane systems in roof applications.

The opinions of owners and users were also solicited. The private as well as the public sector became involved and the opinion givers ranged from housewives to plant engineers who were responsible for urethane roofing systems of several acres in area. These opinions were also used in developing the performance guidelines.

Scientists experienced in the chemistry of polymers and in the chemistry and use of protective coatings were queried regarding chemical structure, reactions, chemical and physical properties, weathering and aging characteristics, compatibility, engineering properties and the like.

Further, the experience of personnel of the National Bureau of Standards familiar with the properties of materials and performance of all types of roofing systems over many years was called upon to condense the multifarious data obtained from the many and various sources into useful information to assist the decision maker.

Finally, a comprehensive survey of literature concerning polyurethane foams was completed to complement the information developed from in-service data sources.

4.0 Rigid or Structural Polyurethane Foams and Their Properties

4.1 Introduction - Polyurethane foams (often referred to as urethane foams) can be obtained in a broad variety of physical characteristics ranging from resilient and flexible to non-resilient and rigid. The formation of one type versus another is governed by the chemistry involved in their production. For the purpose of this report, we will be concerned only with the rigid polyurethane foams. However, even in this limited topic, there exists a very large variety of rigid foams and variations in formulating the foams which can result in changes in properties. Moreover, changing the proportions of reactants (without changing the reactants themselves) can also affect the resultant foam and its properties. Thus, it is difficult to generalize about the properties of rigid foams. Reactants can be chosen to give the desired product [1] [3]. Therefore, what is presented here is a synopsis of the properties of rigid polyurethane foams. Each property has been covered in considerably more detail in the literature.

Rigid polyurethane foams are often referred to as structural polyurethane foams. However, the term structural is used only to

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[3] Figures in brackets refer to literature reference at the end of the paper.

differentiate these foams from the flexible polyurethane foams. It does not mean that a rigid foam in a building has load-bearing capacity. On the contrary, a rigid or structural polyurethane foam should not be used in a building as a load-bearing member.

4.2 The Chemistry of Polyurethane Foams - The chemistry of polyurethane has been reviewed [2-4]. However, since the properties of polyurethane foams are so diversified and dependent upon the chemistry involved, some brief comments reviewing the chemistry would seem appropriate. This will be of value when discussing properties from a chemical viewpoint.

The most generally employed reaction for the formation of a urethane is that between a hydroxyl compound (alcohol) and an isocyanate (Equation I). Other reactions are known for the formation of urethanes but these are

$$\underset{\text{alcohol}}{R\text{-}OH} \quad + \quad \underset{\text{isocyanate}}{O{=}C{=}N{=}R} \quad \longrightarrow \quad \underset{\text{urethane}}{R\text{-}OOCNHR} \qquad \text{(Eq. I)}$$

seldom used in the production of rigid polyurethane foams. Modification of the reactants in the previous equation to di- or polyfunctional alcohols and di- or polyisocyanates results in the formation of a polyurethane (Equation II).

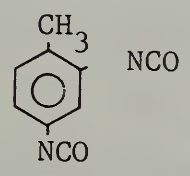
$$HO\text{-}R\text{-}OH \;+\; O{=}C{=}N\text{-}R\text{-}N{=}C{=}O \quad \longrightarrow \quad \left[O\text{-}R\text{-}OOCNH\text{-}R\text{-}NHCO \right]_n \qquad \text{(Eq. II)}$$

Equation II shows both the hydroxyl and isocyanate compounds as difunctional. This reaction produces linear polyurethanes. If the functionality of either is increased to three or more, then a crosslinked or chainbranched polyurethane is produced. The rigidity of a polyurethane foam is greatly dependent upon the degree of crosslinking. As the number of crosslinks increases, the foam becomes more rigid [5].

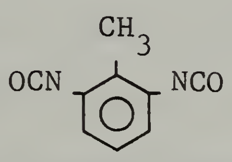
Besides the hydroxyl and isocyanate reactants, other components used in the production of polyurethane foams are blowing agents, catalysts, surfactants, fillers, and additives such as flame retardants and antioxidants [6].

4.3 Components of Foams

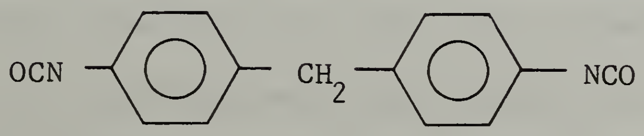
4.3.1 Isocyanates - For foams in general, these compounds may be either aliphatic or aromatic. However, rigid foams use aromatic di- or poly- isocyanates [7]. These isocyanates are toxic. The most common of these are tolylene diisocyanate (TDI) (IA + IB), 4,4' - diphenylmethane diisocyanate (MDI) (II) and the "crude" TDI and MDI. Which is not



IA



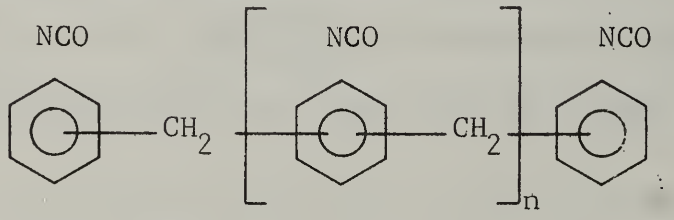
IB



II

generally used in spray applications is a mixture of two isomers, the 2,4 - (IA) and the 2,6 - (IB) isomers. TDI is a colorless liquid with a relatively high vapor pressure, a lachrymator, and respiratory irritant [3], and care should be used in spraying. Polymeric MDI is a solid with a low vapor pressure. Consequently, it is not as bad an irritant. However, in handling, care should again be taken that it is not spilled on the skin, and even more important, in spray applications caution should be exercised so that the fine spray is not inhaled.

The "crude" isocyanates have lower reactivities and lower vapor pressures. The lower reactivities mean that less heat is built up during the foaming process; the lower vapor pressures reduce the health hazard. "Crude" TDI is an undistilled grade of TDI. "Crude" MDI is prepared by the phosgenation of aniline-formaldehyde condensates and can be represented by the following structure:



This material is also referred to as polymethylene polyphenylisocyanate, and its functionality usually varies from two to three [3].

Other isocyanates are available for use in polyurethane production but these are not generally used.

4.3.2 Hydroxyl Components - The first hydroxyl components (polyols) used in the production of polyurethanes were hydroxyl-terminated polyesters. These commercial compounds were mainly formed by the reaction of adipic or phthalic acids with diols or triols. For rigid polyurethane foam production, polyesters have been largely replaced by hydroxyl-terminated polyethers [8]. These polyethers are prepared by the base catalyzed addition of an alkylene oxide to a polyfunctional alcohol. The alcohols may be diols, triols, tetrols, hexitols, or octols [3]. In rigid foams, the polyethers usually have a functionality of 4 or greater. Refined castor oil or deviatives have also been used for the production of rigid foams. It has been stated that the presence of castor oil in a polyurethane imparts water resistance and weathering resistance to it [3].

The properties of the foam are dependent upon the polyol chosen for its production [9]. Selection of the polyol is the major means of controlling the properties of the foam [10]. The reason is that there are a large variety of polyols available for rigid foam production, while only a few polyisocyanates are used.

4.3.3 Blowing Agents - The blowing or foaming agents are the gases trapped in the solid polyurethane polymer, producing the cellular character of the foam. There are two major methods of foaming polyurethanes. In the first method, a gas is produced <u>in situ</u> during the polymerization process. The major reaction in polyurethane technology is that between an isocyanate and water (Equation III). The resulting carbamic acid is unstable and it eliminates carbon dioxide, which becomes the foaming agent. In cases where the foam is to be used as insulation this technique is rarely used. Also, this type of foaming tends to be expensive since excess isocyanate must be used to react with the water.

$$\mathrm{R\text{-}N{=}C{=}O} + \mathrm{H_2O} \longrightarrow \underset{\substack{\text{carbamic acid}\\ \text{unstable}}}{\mathrm{RNHCOOH}} \longrightarrow \mathrm{RNH_2} + \underset{\text{gas}}{\mathrm{CO_2}} \qquad \text{(Eq. III)}$$

The second technique for foaming involves the incorporation of a volatile liquid in the formulation for polymer production. During the polymerization process which is highly exothermic, the heat of reaction is sufficient to vaporize the liquid and the resultant gas is entrapped in the polymeric solid producing the cellular structure. The most commonly used blowing agent for this type of foaming is monofluorotrichloromethane, CCl_3F, (Refrigerant 11), although others might be used depending upon the application. For example, in spraying in a hotter climate, a higher boiling blowing agent such as $C_2Cl_3F_3$ might be used instead of CCl_3F.

4.3.4 Catalysts - Catalysts are used to control the rate of reaction between the hydroxyl and isocyanate components. Also, the catalyst governs chain propagation, chain extension, and crosslinking [3]. Moreover, it is important in the "cure" of the foam. An incompletely cured foam will not achieve its maximum strength properties.

The two types of catalysts employed in foam production are tertiary amines and organotin compounds [6]. The choice of either is dependent upon the system being foamed and the properties desired in the resultant foam. In some cases, a combination of both may be used for synergistic effects among catalysts can be observed. For example, both types might be used in a spray application where a fast "cure" is desired [6].

Although the previously discussed components, isocyanate, hydroxyl, and blowing agent, have more influence on the properties of a foam, the catalyst can also influence the properties. One effect that should not be overlooked is that the catalyst in the foam can have an effect on the long term service properties of the foam. It is possible that a foam with good initial properties may not have good long term properties since the catalyst may enhance the rate of deterioration of the foam. For example, it has been stated that tin diethyl dicaprilate foams age to a greater extent than foams produced with other catalysts [11].

4.3.5 Surfactants - These compounds, usually silicon or silicon-polyether copolymers, are used to regulate cell size and cell wall rigidity in the foam [1].

4.3.6 Fillers - These are lightweight, bulky, inorganic materials added to extend the foam, either to lower its cost or to alter a physical property [12]. When using a filler, its compatibility with the polymer should be established. Also, if used to lower costs, it should be determined that an actual weight-to-cost reduction is achieved.

4.3.7 Additives - These are included to alter a property of the foam. Included here are flame retardants, antioxidants, and pigments. The effect of such additives on the properties of the foam should be determined.

4.4 Properties of Rigid or Structural Foams

Polyurethane foams possess many properties that make them attractive in the construction industry. Among these are the high strength-to-weight ratio, good thermal stability as compared to other organic polymers, low thermal conductivity and excellent adhesion to metals [6, 13]. Like other polymers, the properties of polyurethanes are dependent upon molecular weight, degree of crosslinking, effective intermolecular forces, stiffness of chain segments and crystallinity [3]. The preceding section describing the raw materials for foam production has been included here since the service properties of the foam can not be separated from the raw materials [1]. This section will now describe some of those properties that are important in roofing applications. The discussion will deal with each property independent of the other properties, although in many instances there is necessarily overlap between properties.

There are some general statements that may be made concerning polyurethane foams. Structural polyurethane foams obtained their rigidity from a high degree of crosslinking. Also rigid polyurethane foams contain a mostly closed-cell structure (as compared with the flexible polyurethane foams which are mostly open-celled). Rigid foams, as commonly used in construction, normally possess densities from 1 to 3 pounds per cubic foot (pcf) [13]. However, roof spray density ranges from 1.8 to 4 pcf.

Frisch has stated that the properties of rigid polyurethane foams are dependent upon three factors [10]:

1) the chemical structure of the foam components and of the the resulting polyurethane polymer,

2) the mode of preparation and the mechanical factors in the foam manufacture, and

3) the density and cell geometry of the foam.

4.4.1 Compressive Strength - The compressive strength of rigid polyurethane foams is dependent upon the density of the foam and the shape of the gas cells in the foam [14]. Of the two density is the property which most governs the strength of the foam. As the density increases, the strength of the foam increases [15]. Deverell prepared a number of rigid foams with densities ranging from 2 to 75 pcf [16]. He concluded that at room temperature there existed a parabolic relationship between compressive strength and density. These results have been observed by others (Figure I and Table I) [1,14]. Hilado states that in most applications of rigid polyurethane foams, the foam density ranges from 1.5 to 2.5 pcf [14]. If the density of the foam is below 1.5 pcf, then the foam does not possess adequate mechanical strength. If more strength is needed, then a higher density foam should be used. However, even though the lower density rigid foams have considerable strength, a foam with a density even as high as 20 pcf should not be used as a structural member [17].

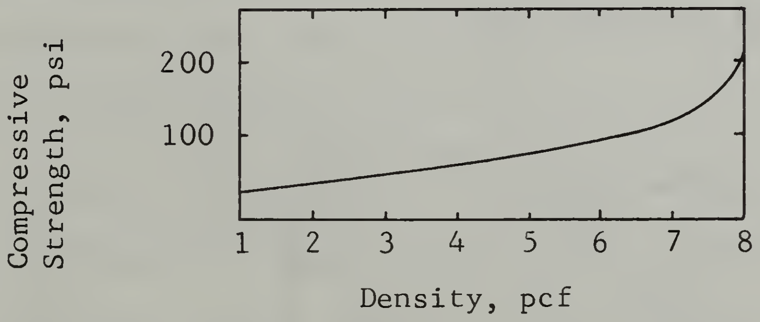


Figure I Compressive strength vs. density of rigid foam (according to Hilado [14]).

Density, pcf	Compressive Strength, psi
3	40-50
6	120-160
9	240-280
12	400-440

Table I Compressive strength vs. density of rigid foams (according to Gordon [1]).

The effect of temperature on the compressive strength of rigid foams has been studied [16,18]. As the temperature is increased above ambient, the compressive strength decreases until the foams become soft and flexible. This temperature is approximately 130-150°C (266-302°F) and is slightly dependent upon the blowing agent [17]. Above 150°C (302°F) most rigid polyurethane foams have no load bearing capacity but they can still possibly support their own weight. Figure II shows one example of the decrease of compressive strength with increasing temperature for a particular rigid foam. This figure shows that the decrease in strength is non-linear with increasing temperature. But, this is not always the case since a linear decrease for another foam has been reported [17]. As the temperature is decreased below room temperature, there is a slight increase in compressive strength [17].

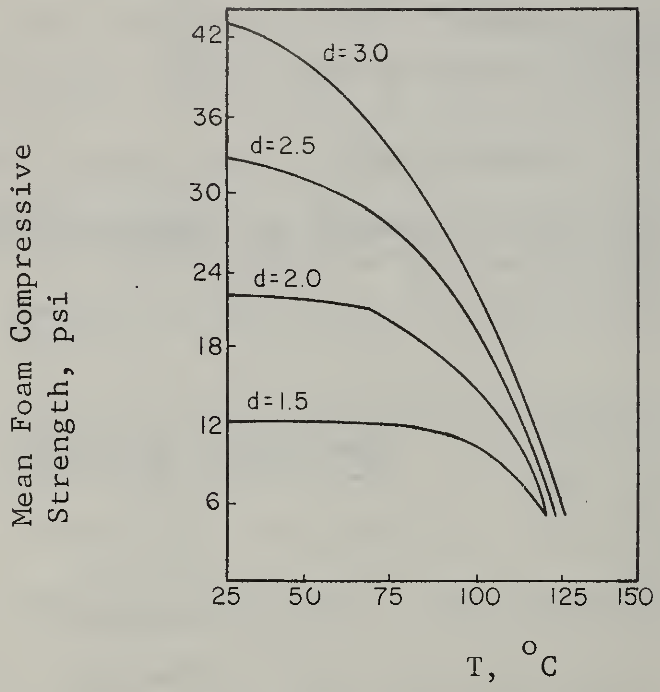


Figure II Compressive vs. Temperature for Various Densities (according to Harding and Hilado [18]).

The effect of chemical structure on compressive strength has been studied [9,18]. It was concluded that for commercial applications the most practical method for changing the foam strength is to change the density and the cell structure [18]. The compressive strength is increased most effectively by using polyols of low equivalent weight, but this method is not always commercially practical [18].

Besides changing the chemical reactants to effect structural changes, one may also alter the stoichiometric ratio of the reacting isocyanate and polyol. This ratio, times 100, is called the isocyanate index ([NCO] /[OH] x 100). Results of changes in isocyanate index have been reported by Frisch [10]. In regards to compressive strength, it increases as the isocyanate ratio increases from 0.9 to 1.1. At the higher isocyanate ratio, however, the foams become more brittle.

The compressive strength of rigid polyurethane foams may be affected by water and water vapor. However, this only occures when water has penetrated into the interior of the foam [16]. In other words, the water must penetrate the closed cells. The open cells at the exterior of the foam may hold a large quantity of water but the foam properties will not generally be affected. In one case, exposure of a foam for 1000 hours at 100% relative humidity and $20^{\circ}C$ had a negligible effect on the strength properties of the foam. However, data describing longer exposures of foams to water were not found. For a roofing system which should last a minimum of 20 years, the effects of slow hydrolysis of the foam should be considered.

Besides density, the second major factor governing the compressive strength of foams is the shape of the cells holding the blowing agent. As previously mentioned, rigid polyurethane foams contain mostly closed cells. During the foaming process, these cells tend to elongate in the direction of the foam rise. This cell elongation gives an anisotropicity to the foam. The compressive strength of the foam is greatest in the direction of foam rise and minimum perpendicular to the foam rise [9,17]. For our area of interest, this has significance in the fact that a foam sprayed on a roof may not have uniform strength across the roof (even on a flat roof). This results because the direction of the flow of the rising foam may be either lateral or vertical in different spots. Thus, the possible variation in compressive strength in different areas depending upon the direction of foam rise.

4.4.2 Impact Resistance - This property of the foam is important since it prevents damage to the roof from falling objects. Such objects might include hail, tools, tree limbs, and the like. The review of the literature revealed little information in this area. In particular, nothing was found concerning hail damage to roofs. There was one recent report describing the impact resistance of uncoated rigid urethane foams [14]. The major conclusion is that the density is the main factor in controlling impact properties. As the density of the foam is increased, the impact resistance of the foam increases.

4.4.3 Dimensional Stability - Like all plastics, rigid polyurethane foams have a high linear coefficient of thermal expansion. These coefficients are higher than those of metals, for example 5-8 x $10^{-5}/^{o}C$ (28-44 x $10^{-6}/^{o}F$) for polyurethane vs. 2.3 x $10^{-5}/^{o}C$ (13 x $10^{-6}/^{o}F$) for aluminum [17]. However, the problem of dimensional stability of the polyurethane foam is caused primarily by changes in gas pressure within the cells and not by changes in the dimension of the solid plastic [9, 15-17]. As the temperature of the foam is raised, the gas pressure increases and the foam has a tendency to expand. Likewise, as the temperature is decreased, the gas pressure decreases and the foam has a tendency to contract. The better the foam can resist such gas pressure changes, the more dimensionally stable it is. The ability of the foam to resist these changes is governed by the foam density, the cell structure, and the polymer composition [15]. As the density is increased, the foam strength is increased allowing the foam to resist the increased pressure. Nearly round or uniform cells give better resistance to pressure changes. Foams that resist water vapor penetration are also more dimensionally stable since water infusion into the cells results in increased pressure. Water vapor transmission can be minimized by the choice of polymer since some polymers have less tendency to transmit water vapor than others. In general, hot and humid conditions are the worst climates for foams.

4.4.4 Thermal Stability - Polyurethane foams, as organic materials, are susceptible to thermal degradation. The chemistry involved in such decomposition has been studied and it is known that there are three major reaction pathways for decomposition [20]. This chemistry is important for it is through the use of such knowledge that the polymer chemist may modify the polymer to increase stability. Tilley and coworkers have reviewed the factors that govern the stability of the foam. These are the number of crosslinks, interchain forces, rigidity of the molecules, molecular fit, and molecular weight. Among these the number of crosslinks is most important, - the higher the crosslink density, the more thermally stable the polymer [5]. Increased crosslinking also increases the softening temperature [21]. Increased crosslinking is accomplished by increasing the functionality of either the component isocyanates and polyols, or by lowering the equivalent weight of these [5]. A more detailed discussion of the chemistry of thermal decomposition and stabilization does not seem appropriate here. Instead, some general observations about polyurethane foam thermal stability as obtained from the literature will be mentioned.

Methods such as heat aging, differential thermal analysis (DTA) and thermogravimetric analysis (TGA) have been used to study the thermal stability of foams. Although it would seem likely that foams may be synthesized that would not withstand temperatures encountered on a roof, all papers that discussed thermal stability and that were encountered in this study described foams that are capable of withstanding temperatures much higher than those on roofs. Smith reported the results of TGA and DTA on three different rigid polyurethane foams [22]. Even with the least stable foam, TGA showed no weight loss until 150°C (302°F) and on the same foam DTA also showed no major changes until 150°C (302°F). In a similar experiment Reegen and Frisch reported no weight loss until 260°C (500°F) as determined by TGA. This point corresponded to an exotherm on DTA. In this case, DTA showed a slight endothermic change at 110-115°C (230-239°F) which corresponded to the softening point of the foam.

In regards to heat aging and long term temperature stability, the type of information that was desired could not be found. Nothing appeared to be available describing the behavior of a polyurethane foam that had been heat aged at temperatures less than 100°C (212°F). Most experiments were designed to heat age at higher temperatures where changes might be expected. In one experiment, a number of foams were heated at 100°C but in an oxygen atmosphere [21].

In general, it can be stated that increased stability is imparted to polyurethane foams by:

1) increasing the crosslink density [5,21,23] and

2) using polyisocyanates of high aromaticity (i.e., MDI, PAPI) [5,21,24].

In regards to decreasing thermal stability, certain flame retardants are known to produce such an effect [24].

4.4.5 Photolytic Stability - In a paper written in 1966, Tarakanov and co-workers remarked that "The problem of change of polyurethane properties under the influence of ultraviolet radiation is given little attention in the literature....." [25]. We have made the same observation in our search of the literature. Data describing the behavior of polyurethane foams to ultraviolet light or sunlight was very scant.

The Tarakanov study was undertaken to elucidate the mechanism of photolytic destruction of polyurethanes. In one experiment, it was determined that a polyurethane formed from MDI was photolytically more stable than that from TDI. The same polyol was used in both foams. However, the formulations used were not of the type that would be encountered in rigid polyurethane foams.

Reegen and Frisch, in another experiment, exposed three different films, differing only in isocyanate reactant, to Fade-Ometer testing [21]. Their results showed that a TDI based polyurethane was more stable than a PAPI based polyurethane. This result is reversed from that of Tarakanov. These two reports show a good example of how formulation determines the properties of foams.

In general, polyurethanes based on aromatic isocyanates yellow after exposure to sunlight [3]. For outdoor applications such as roofing, foams must be protected from the weather by either covering with another material or painting [26].

4.4.6 Water and Water Vapor Transmission - The closed-cell structure of rigid polyurethane foams render them resistant to water penetration [17]. This property is an asset in roofing usage since even if the protective coating on the foam is broken, water still will not soak through the roof [27].

However, water vapor transmission, which should not be confused with water transmission, is possible through polyurethane foams [17,26]. It was previously pointed out that water vapor penetration into the foam can have an adverse effect on the strength and dimensional stability of the foam. Likewise, the insulation value of the foam can be considerably lowered. Since rigid foams are commonly applied for insulation, water vapor penetration should be minimized.

In order to minimize water vapor transmission, it has been suggested that in structures with high interior humidities, a vapor barrier be erected on the warm side of the insulated object [28]. In many applications in certain climates, the warm side of the insulation may be the low vapor pressure side. In such cases, a vapor barrier might then be necessary on the outside in the form of the protective coating. In any situation, if moisture does enter the foam, it should be allowed to get back out.

Hilado and Harding have reported on the relationship between water vapor permeability and chemical-physical structure in rigid polyurethane foams [29]. Water vapor permeability is lowered by higher functionality and aromaticity, and by lower equivalent weight and fewer polar elements in the polyol. Density and cell structure are also important. Permeability increases as density decreases and as cell size increases. Chemically to insure low water vapor permeability, the aromaticity should be kept as high as possible. Hilado and Harding also state that crosslink density higher than that required for rigidity is not a criterion for low water vapor penetration. Frisch states that crosslink density has a distinct effect [10]. As the crosslink density increases, the water vapor permeability decreases.

4.4.7 Insulation - The low thermal conductivity (K-value or K-factor) of polyurethane foam is one of its most important properties. In fact a good insulating foam will have a K-value that is at least twice as low as other insulations. However, the initial K-value does change with time, and it varies depending upon the aging conditions [30].

The mechanism of heat transfer through foams has been described by Levy [28]. It involves conduction, convection, and radiation. Radiation theory says that the large number of cells in foams minimizes radiation heat transfer. Cell size controls convection transfer, as the cells decrease in size, convection decreases. In foams with cells 0.2 in. (5.1 mm) or less in diameter, convection is essentially non-existent. Therefore, in closed-cell foams, heat transfer is mainly due to conduction through the foam materials.

In line with the theory of heat transfer, Varland has listed the factors which influence the initial and aged K-values of the foam [30,31]. These are: 1) the blowing agent used; 2) the open cell content of the foam; 3) the dimensions of the foam; 4) the temperature during aging;

5) orientation and size of the cells; and 6) the presence of natural or applied skins. Low thermal conductivity is one property of foam which is not directly related to density [32].

The most important of these factors is the blowing agent that is used. High molecular weight gases have lower thermal conductivities than low molecular weight gases [28]. Thus, the initial K-values of monofluorotrichloromethane blown foams are 0.10 to 0.15, while the initial K-values of carbon dioxide blown foams are about 0.22 to 0.24 [10]. Moreover, the K-values of carbon dioxide foams increase more than those from monofluorotrichloromethane as the foams age. Table III shows this effect. The increase in K-value is due to air permeating the foam and/or the other gases diffusing out [30,31]. Thus, for best insulation a foam blown with monofluorotrichloromethane should be used. It has been stated that with this gas, loss of insulation will only be significant if the foam is used at high temperatures (100°C), in thin sections (1 in.), and without a protective barrier [33].

Aging in Days at 60°C (140°F)	K-Value CO_2 Blown	K-Value CCl_3F Blown
0	0.186	0.112
7	0.222	0.128
14	0.233	0.136
21	0.237	0.140
28	0.238	0.144
50	0.239	0.149
100	0.24	0.155
150	0.24	0.156
200	0.24	0.157
250	0.24	0.157

Table III The change in K-values of foam with time (according to Frisch [10]).

As previously mentioned water vapor penetration has an adverse effect on the insulating properties of rigid polyurethane foams. Used as insulation, the foam has a warm side and a cold side. Warm air normally contains more water than cold air and as the heat tends to migrate to the cold, water vapor is accompanied with it [29]. At the cold surface, the water can condense and liquid water has a thermal conductivity that is 10-40 times greater than that of the foam [29]. If the temperature is low enough, an ice barrier may even form which lowers the insulation value of the foam even further. Ice has a thermal conductivity about 100 times that of the foam [28]. Furthermore, such an ice barrier prevents the passage of water vapor and therefore, the ice barrier enlarges. To minimize such problems, a water vapor barrier should be used on the warm side.

4.4.8 Flammability - As organic materials rigid polyurethane foams are combustible. The degree of flammability is controlled by both physical and chemical flame retardant techniques. The important characteristics of flammability of cellular plastics have been described [34,35]. These are:

1) Ease of Ignition - The ease by which the plastic or its pyrolysis products can be ignited under given conditions of oxygen and temperature.
2) Flame Spread - The rate of spread of the flame once the fire begins under the conditions of burning. ASTM Standard E 176 defines this parameter as flaming combustion along a surface.
3) Fuel Contribution - Heat produced by the combustion of a given weight or volume of foam.

4) Smoke Density - Degree of light or sight obscuration produced by the smoke of the burning foam under the given conditions of combustion.

5) Products of Pyrolysis and Combustion - From foams, these are usually solid, carbonaceous char or residue, volatile gases, and entrained solid particles (smoke). Toxicity of combustion gases is included here.

Flammability tests are designed to evaluate these characteristics. A list of the most widely used and accepted flammability tests employed with polyurethane foams has been compiled by Hilado [36]. He states that in general there are two types of fires which these tests seek to simulate. The first is the small accidental fire with limited amounts of heat; the second is the large-scale fire with massive amounts of heat. He further states that tests for rigid foams tend to be large-scale since rigid foams, as used in construction, are used in large quantities, e.g., on a roof. Also, these tests for rigid polyurethane foams tend to be identical or related to tests for other construction materials. A single material may perform differently in different tests. For example, a plastic may be rated self-extinguishing in one test but yet it might burn vigorously in another [37]. This is quite significant. It means that foams should not be used that have not been completely evaluated for flammability. Using a foam because a particular fire test gives the foam a good rating could lead to a disaster. The fire rating could be completely meaningless under the service conditions. In the field, the foam might readily burn. Some tests are designed for standardization and comparison, and they do not necessarily represent field conditions. That is, the tests give relative ratings for burning but do not show the behavior of the material in an actual fire. This does not mean that flammability tests should not be used, but that tests used should be specific for the application and the conditions of application of the foam.

Of the various tests that have been employed for foams, the most common small-scale test is the ASTM D 1692. Another small-scale test is the ASTM E 162 (Radiant panel test). A large-scale test frequently conducted is the ASTM E 84 (tunnel test). The U. S. Bureau of Mines flame penetration test measures the foams ability to act as a flame barrier. For roofing purposes, ASTM Method E 108 is often used to evaluate the total system.

Besides being used to show how foams will behave in fire conditions, some flammability tests are also conducted to show how variations in foam formulation can alter the flame retardancy of a foam [27]. Flame retardancy is imparted to the foam by incorporating into the formulation compounds which contain halogen, either bromine or chlorine, phosphorus, or nitrogen [38]. These may be used either alone or in combination. Also, additives are used which have no or little flame retardancy in themselves but act synergistically with other compounds. The most well known example of this phenomenon is the use of antimony oxide with a chlorine containing compound.

There are two methods of incorporating these flame retardants into the foam. The first combines the retardant with the polymer molecule through chemical bonding; the second mixes or disperses the retardant in the foam only as an additive. The second method has drawbacks not associated with the first. The primary concern is that the retardant may not be permanent. If the additive is not compatible with the polyurethane polymer, it will diffuse from the polymer. Also, the additive may cause plasticization of the foam [38]. This leads to a reduction of the strength and dimensional stability of the foam.

Flame retardancy of the foam may also be governed by the chemistry of the polymer. For rigid polyurethane foams produced from polyether polyols, maximum flame retardancy is obtained from the following: 1) high functionality of the polyether; 2) high hydroxyl number polyether; 3) polyether with cyclic groups; 4) polycyclic isocyanate; and 5) polyfunctional isocyanate [39].

Another method for imparting flame retardancy to the foam is to cover the foam with a non-flammable or flame retardant covering such as an intumescent coating. A major difficulty here is that if the coating is damaged or destroyed, then the foam loses its protection from fire.

In one study involving flame retardant rigid polyurethane foams, it was concluded that such foams would not ignite when exposed to small flame sources [40]. They would burn rapidly when exposed to large sources of heat and flame. However, if flames did not strike the foam and air were excluded, the foam would not burn. This situation is encountered in sandwich panel construction where, for example, the panel is constructed with steel skins with a urethane core. A member of the NBS fire section concurred with the findings on sandwich panels [41]. However, in the same conversation it was mentioned that polyurethane foam slabs have cracks between them and the fire begins under the slabs. The cracks give a chimney type effect providing the fire with a means of burning into the foam.

Although foams are available that possess a high resistance to ignition and flame penetration, and a low rate of flame spread, these materials release a lot of smoke when burned [42]. Smoke is a problem since it obscures the vision of occupants of a building who are attempting to leave or the vision of firefighters attempting to put the fire out.

Even if the smoke does not obscure vision it is an eye irritant and many of the gases are toxic. In a roof-top fire where the fire is only on the exterior of the building, the problem of smoke generation is not as great as where the fire is in the interior of the building. A problem could arise if environmental conditions caused the smoke to be carried into the building.

4.4.9 Weathering - This is one area of polyurethane foam technology in which data is completely lacking in the literature. It is a recognized fact that polyurethane foam sprayed on a roof must be protechted from ultraviolet radiation by covering or coating. However, articles describing this could not be found. Also, no information was available comparing the outdoor behavior of foams covered with various materials.

4.4.10 Adhesion - It has been previously stated that rigid polyurethane foams have excellent adhesion to metals and other surfaces. To achieve good adhesion, the surface on which the polyurethane foam is applied must be clean, free from rust and corrosion, and dry.

5.0 Performance Parameters

There are several parameters which will affect the performance of a foam polyurethane roofing system. They include, among others which will be discussed later in this report:

- Substrates and Surface Preparation
- Slope
- Application Techniques
- Utilization of Vapor Flow Retarders
- Utilization of Expansion Joints.

5.1 Substrates and Surface Preparation

Sprayed urethane foams have been applied to several types of substrates in roofing applications. It has been estimated by one large applicator that probably 40% of urethane applications involve repairing or resurfacing existing bituminous built-up roofs. Other resurfacing applications involved the protection of weathered metal decks such as corrugated aluminum or steel.

In new work, urethane foam has been used over concrete, wood, and shredded wood fiber decks. As in the case of reroofing procedures, an overlayment over metal decks may be required before application of the urethane foam.

Structural concrete probably provides the better substrate for the urethane foam, followed closely by a firm plywood deck. However, before applying foam to a new concrete deck, the concrete must be dry! In short, the more stable the substrate and the fewer the joints between units of the substrate, the better will be the performance of the urethane. This statement applies equally to all types of roofing.

Although urethanes are noted for their good adhesive properties to clean, dry surfaces of many types, they may not adhere to oily, waxy, or extremely dirty or dusty surfaces. Therefore, it is generally suggested that surfaces of questionable characteristics be cleaned and primed before the application of the urethane foam. Asphalt primer conforming to Federal Specification SS-A-701 or ASTM Specification D-41 applied at a spreading rate of 33 to 50 square feet per gallon has been found to be satisfactory. The primer must be thoroughly dry before application of the urethane. Asphalt emulsions and hot applied asphalt have also been successfully used for this purpose.

Urethane foams are frequently applied in two layers. Therefore, the foam itself often becomes the substrate and the deterioration products (urethane foam surfaces degrade rather rapidly when exposed to ultraviolet radiation) may interfere with the proper adhesion of succeeding applications of foam. Inadequate adhesion between foam layers has resulted in bonding problems at the interface of the layers which can show up as severe blistering.

Previously, it was mentioned that probably 40% of the sprayed urethane foam for roofing applications is used over existing roofs. We believe that the reason is purely economical since it has been estimated that it is 35 to 40% cheaper to clean and prepare the old surface and apply urethane than it is to tear off and discard the old roof and apply a new one in kind.

In reroofing applications a prime requisite is that the old roof be in such a condition to receive the urethane system. In most cases special preparation of the old roof substrate is essential. The surfacing of slag or gravel, if present, should be spudded off. Defects as blisters, buckles, wrinkles, or splits should be repaired in accordance with accepted roofing practices. If wet insulation is part of the old roofing system, vents should be installed every 10-15 squares to relieve any potentially damaging vapor pressures due to moisture entrapped in the insulation. The surface should be cleaned of dust and dirt and, as in the case of new decks, the surface primed with asphalt primer at a spreading rate of 33 to 50 square feet per gallon. When the primer has dried, the urethane should be applied about one inch in thickness except in cases where gravel or slag particles are still present the thickness should be about 1 1/2 inches to compensate for thickness of any remaining gravel or slag.

In any substrate, be it old or new, areas where potential stresses can be transferred to the urethane foam such as cracks, joints, or splits should be provided with bond breakers so as to distribute stresses over larger areas of the urethane to avoid the cracking problem.

An acceptable criterion for adhesion of urethane to any substrate including itself is that it should be firmly adhered, a minimum of 95% of the surface area.

5.2 Slope

Roof decks with no slope (frequently and erroneously referred to as "dead level") are not acceptable aubstrates for any roofing system. The same criterion is even more valid for the sprayed urethane foam roofs. Generally, a minimum 1/4 inch fall per foot run is suggested, but frequently ignored, for most bituminous roofing membranes. In the case of urethane foams, due to surface irregularities and application practices a minimum of 1/2 inch per foot slope-to-drain appears to be desirable rather than the 1/4 inch guideline. Since water is among the greater enemies of urethane foam, it is desirable to get water away from the foam as quickly as possible, hence, the suggested 1/2 inch slope.

Frequently, varying thicknesses of foam have been specified to provide a positive slope to drain. In one case, foam as deep as 12 inches was proposed. This does not provide an economical solution to the slope problem. In fact, experience has shown that such a practice is detrimental. When a slope is required for urethane foam, it is the better practice to make provisions to slope the substrate to which it is to be applied.

5.3 Application Techniques

The successful application of a spray foam application depends on a number of factors including:

- the base chemical components (see Section 4)
- spray equipment
- surface preparation
- weather conditions, i.e. temperature, moisture, and wind
- skill of applicator

The skill of the spray man gained through experience is the most essential factor. Poor application techniques negate all other factors which might otherwise be adequate. The choice of base chemicals and spray equipment is generally left up to the contractor and, hopefully, is based on his experience with good application and performance characteristics and not on economics alone.

The surface preparation has been discussed in detail in Section 5.1. However, it might be well to reiterate here that foam will not bond to wet, oily, waxy or extremely dusty surfaces. A minimum of 95% adhesion of the foam to the substrate is a primary requirement. Any less is not acceptable.

Proper storage of the raw materials used in foam production is important. First, they must be kept sealed until used. The raw materials must be kept dry and the temperature should be controlled. A number of manufacturers suggest storage temperatures in the range of 50 to 85°F (10 to 29°C) as suitable.

As with all other roofing systems, the weather plays an important role in the application of foam urethane. In fact, since the foaming event on the roof depends on a chemical reaction the rate of which is temperature dependent, the importance of application and surface temperatures is obvious. It is the consensus of manufacturers and applicators alike that the temperature of the surface to be sprayed should be at least 40°F (4°C). Obviously, the temperature restrictions severely limit the application season in several parts of the United States. In most northern states urethane generally can be applied only from April to October. There is an inherent risk at other times of the winter season. The warmer climates present no such restrictions as far as temperature is concerned.

Moisture, in the form of rain or condensation, is another factor which determines the success or failure in a foam urethane roof. As previously pointed out, urethane will <u>not</u> adhere to a damp or wet surface. Therefore, it is a rule of thumb in the trade that the application of spray foam shall not commence during the inclement weather or when precipitation is imminent. This rule should <u>not</u> be waived under any circumstances. On clear, cool mornings, condensation is often present on the roof surface. This surface should be treated as a wet surface and allowed to dry before spraying is initiated.

In the foam application, wind becomes even a more important variable than it does in the application of other types of roofing. The surface texture of sprayed urethane is heavily dependent on wind velocity and the performance of a protective coating depends on surface texture. Wind velocities in excess of 15 mph make the spraying of urethane foam impracticable. Since urethane adheres rather tenaciously to most surfaces, caution should be taken to protect those areas not intended to receive foam. Provisions should also be made to protect areas and objects (automobiles and the like) from overspray.

In the spraying operation certain signs should be apparent to indicate the quality of the foaming operation. The two main ingredients of the plastic foam are sprayed simultaneously, usually in 1:1 ratio. Generally, if the ratio becomes out of balance, an immediate color change occures which alerts the spray applicators. Adjustments should be immediately made to obtain proper mixture.

The surface of the foam should be sufficiently smooth to receive the final protecting coating. "Popcorn" or "tree bark" like or rougher surfaces result from one or a combination of events as improper spraying techniques, improper mixing, or by application during windy periods. This type of surface is not acceptable.

Thickness of the urethane foam is important to its performance from a fire durability and performance aspect. The optimum thickness is one inch. The minimum thickness should be no less than one inch and the maximum no more than two and one quarter inches. When used as reroofing over a previously surfaced (gravel or slag) built-up roof, it is mandatory that all gravel or slag be first removed. A thickness of one and one half inches is suggested to compensate for the thickness of any individual gravel or slag particles which may remain after the spudding operation.

5.4 Utilization of Vapor Flow Retarders

A vapor flow retarder, often erroneously referred to as vapor barrier, has, in modern times, become an important element of the roofing system. So much so that a vapor retarder is frequently specified and applied when it is not required at all. In fact in some instances, the inclusion of the so-called vapor barrier is often detrimental to the performance of the roof. In the case of foam urethane roofing system as with other roofs, the question arises as to whether or not a vapor retarder is required. A general answer cannot be given. The ambient environment, the design and material aspects of the roofing system in question, and the interior environment of the building are factors which will influence the decision.

A further complication is that urethane foam cannot tolerate water for any prolonged length of time without being adversely affected. Therefore, the prudent designer should give special consideration in the selection of a vapor flow retarder. Certainly, it is the better practice to use vapor retarders in cases where the diffusion of moisture into the urethane is probable. For example, in roofing systems placed over high temperature-high humidity areas (swimming pools, laundries, bakeries, and the like) located in cold climates, the use of vapor retarders are mandatory. Frequently, the use of a continuous film of asphalt primer recommended for adhesive purposes will provide a suitable vapor retarder over concrete decks. The venting of insulation of old built-up roofs, as mentioned previously, assists in relieving vapor pressures generated at this origin. In cases over high temperature-high humidity areas, the application of an asphalt saturated and coated base sheet (ASTM Specification D 2626) with sealed side and end laps coated with hot asphalt will provide a sufficient vapor retarder for all practical purposes.

5.5 Flashings and Expansion Joints

Most urethane foams have a relatively high coefficient of linear thermal expansion. Although the measured and reported values fall in the 30 to 40 x 10^{-6} per °F or even much greater ranges, we have not been able to verify these values. They are at least 2 to 3 times the coefficients given for aluminum metal (13 x 10^{-6} per °F) which is considered quite high in the building trade. Therefore, provisions should be made to compensate for the thermal movements expected in on-the-roof applications by the use of expansion or control joints. A good guideline for placement of expansion or control joints is that one should be used for every 90 to 100 squares of roof area. Further, they should always be placed at reentrant corners to form square or rectangular roof areas.

In order to guard against future defects of urethane foam at vent pipes, vertical surfaces, fascia, gutters, and the like, fabric stripping reinforcement should be provided at these junctions. In addition cant strips to provide a 45° angle must be used under the urethane at all vertical surfaces which project above the plane of the roof.

6.0 Weather Protection of Foamed Urethane in Roofing Applications

Urethane foams possess certain inherent weaknesses which makes it mandatory to protect the foam from the weather with a coating or covering system. Since water is an enemy of the urethane foam, the foam must be kept dry. Further, polyurethane foam photooxidizes very rapidly when exposed to radiation in the ultraviolet region of the spectrum. This is characterized by the development of a yellowish or brownish color at the surface of the urethane usually within a matter of hours of exposure. Therefore, a protective coating is required. Urethane foam used for roofing purposes is generally of a low density. Therefore, it is susceptible to damage from abrasion, scuffing, and impact. Protection against abrasion, scuffing and impact is another reason why a protective coating is required. In summary, the purposes served by the protective coating are threefold and are listed in priority order:

1. Shield it from ultraviolet radiation.
2. Keep the foam dry.
3. Protect from abrasion and impact.

6.1 Properties

In order to fulfill its intended functions, a protective system must first be compatible with the foam urethane. Next, it must possess and retain upon exposure for some period of time, certain requirements as:

1. Adhesiveness to urethane in order to remain in place under conditions of exposure, e.g. wind, temperature, humidity and the like.
2. Impact resistance from hail, falling objects, and the like.
3. Adequate susceptibility to temperature change, e.g. good flexibility at low temperature, no flow at high temperatures.

4. Abrasion resistance to foot traffic, water and sand erosion, and the like.

5. Water resistance both in liquid and vapor states.

6. Weather resistance, e.g. sun, rain, dew, wind, and the like.

7. Maintainability, i.e. ease of repair if damaged and ability of weathered surface to accept and retain additional coating when recoating becomes necessary.

8. Durability, i.e. the ability of the coating or system to remain within acceptable performance levels over some period of time.

9. Strength and elasticity, i.e. strong enough and elastic enough to accommodate normal movements in the substrate without rupture.

Certain other characteristics which technically cannot be classed as performance characteristics are also important and are worthy of mention:

1. Appearance

2. Coverage

3. Drying time

4. Cost

6.2 Materials

Several coatings and other protective systems have been used to protect foam urethane roofing materials. Field experience varies from one to a few years and costs vary from as low as 10 cents per square foot up to about $1 per square foot for the coating system alone.

We have listed a number of materials and systems which have been used as protective coatings for foamed urethane. This listing is not necessarily complete but represents information developed from survey of literature as well as from field investigations. The opinions of the informed urethane producers, applicators and users vary considerably as to what constitutes an acceptable coating. There is certainly no consessus in the industry, although there has been considerable promotion of specific coatings for this use since the market is potentially large and apparently profitable. The materials which have been used as protective systems include:

1. Asphalt, clay-type, emulsion and asphalt aluminum paint
2. Asphalt roof coating
3. Aluminum roof coating
4. Hot-applied asphalt with gravel surfacing
5. Asphalt emulsion or asphalt roof coating surfaced with mineral granules
6. Latex paint with polyester coating
7. Several so-called elastomeric coatings based on polymeric resins as:
    - Butyl
    - Neoprene
    - Chlorosulfonated polyethylene
    - Vinyl
    - Acrylic
    - Vinyl acrylic
    - Polyurethane
    - Epoxy
    - Silicone

6.3 Application

It is extremely important from both a cost and performance viewpoint to understand application procedures. First, it must be established what application method, i.e. pour, brush, spray (air or airless), is to be used. Next, the number of coats required to obtain the specified thickness should be known. Is a primer required and, if so, is it of a different color than the specified top coat? The myriad of foams, spray equipment, surfacing materials which face the specifier make the decisions and judgments very difficult ones at best.

7.0 Discussion and Comments

The subject of the adequacy of the in-service performance of foamed urethane for roofing is a difficult one because of the many complex factors involved. First, the innovation of foamed urethane roofs has brought many factions unfamiliar with roofing materials, practices and performance into the roofing industry. As a result, the very basic rules of roofing technology have been often violated, hopefully through ignorance, with rather disastrous and costly results. Next, the customer's roof deck has often become a research facility to test the hypothesis of the manufacturer, contractor and owner alike concerning materials, equipment and application procedures. The scientific and engineering method of an ordered, intelligent approach through research and development techniques have virtually been ignored in the haste to share in the profits of protecting the billions of square feet of roof area in the United States. This is evident in many of the areas of the country and has been condoned by the private and public sector alike.

On the other hand, the intelligent use of foam urethane has resulted in the solution of very difficult roofing problems when solutions were not available from the more conventional sources. It becomes clear that urethane in roofing application has both merit and disadvantages. The advantages and disadvantages must be carefully weighted, the performance and economic trade-offs considered, and the choice made. It is worth repeating the word of caution that foam polyurethane is <u>not</u> a panacea for all roofing problems as many would like to believe.

It may be well to discuss some primary properties which affect performance and attempt to place them in perspective.

7.1 Durability

Durability as used here is the time-dimension of performance. In other words, the acceptable performance properties of the foam urethane system must remain below and above prescribed maxima and minima limits for some period of time under its conditions of exposure. Therefore, durability considers the many properties of urethane which determine its performance as a roofing system.

In brief, the long term durability of urethane foam roofing systems is still unknown. Four or five years of in-service experience, some good and some not so good, is hardly a criterion for urethane foam roofing when a useful life in excess of 20 years is expected from the more conventional bituminous, built-up roof.

It is well known that the urethane foam exhibits poor durability when exposed to ultraviolet radiation. Therefore, it must be protected. This poses another question - What is the durability of the protecting coating system?

At the state-of-the-art there is no way of predicting, with any amount of certainty, the long term, i.e. 20 years or more, performance of foamed urethane. The best that can be provided is a raw extrapolation of past experience into the future. The guidelines and suggested performance specification at the conclusion of this report are the best information available at this time which can be used in lieu of a valid extrapolation.

7.2 Fire Safety

From time immemorial the fire resistance of roofing materials as a part of the roof system has been of primary concern to building code officials, fire prevention personnel and, of course, the roofing industry itself. The roofing industry through the services of Underwriters Laboratories Incorporated has developed voluntary standards for roof covering materials which are generally accepted throughout the United States as a measure of fire resistance. The fire tests for roof coverings are conducted in accordance with Underwriters Standard UL 790 which is similar to ASTM Designation E-108, Fire Tests for Roof Coverings. According to these methods three different tests must be conducted to determine the fire retardant characteristics of roof coverings as follows:

(1) Intermittent Fire Exposure

(2) Spread of Flame Tests

(3) Burning Brand Tests

Depending on materials performance in the series of tests, the roofing systems are given a classification as follows: [4/]

Class A - Effective against severe fire exposure. Under such exposures roof coverings are not readily flammable and do not carry or communicate fire. They afford a fairly high degree of fire protection to the roof deck and do not slip from position. They do not possess a flying brand hazard and do not require frequent repairs to maintain their fire resistant characteristics.

[4/] Building Materials List, Underwriters Laboratories, Inc. January 1971, p. 667.

Class B - Effective against moderate fire exposure. They are not readily flammable and do not carry or communicate fire. They afford a moderate degree of fire protection to roof deck. They do not slip from position, and do not possess a flying brand hazard. However, they may require infrequent repairs to maintain their fire resisting properties.

Class C - Effective against light fire exposure. They are not readily flammable and do not readily carry or communicate fire. They afford some degree of protection to the roof deck and do not slip from position. They do not possess a flying brand hazard but may require occasional repairs or renewals to maintain their fire resisting properties.

We contend that the foam urethane roofing system (deck, foam and coating) should provide at least the same degree of fire resistance as is expected of the conventional roofing systems. The system should be tested exactly as it is to be applied in the field as to the type of deck (combustible or noncombustible), the vapor barrier, the fire barrier, the type and thickness of foam and the type and thickness of the protective coating system. In most cases, Class B ratings should be specified. However, a Class C rating may be specified when the roof is readily accessible for fire fighting. A listing by Underwriters Laboratories Inc. indicates that the products have been found to be in compliance with the Laboratories' requirements. It is interesting to note that the urethane systems of at least three manufacturers are listed in the Underwriters Laboratories, Inc. Building Materials Directory, January 1972.

For roofing purposes the flammability data from other tests such as ASTM E-84 or ASTM D-1692 can be and are often misleading. In fact, we believe that a SE (Self Extinguishing) rating or a flame spread of 25, as is often quoted in the industry, is meaningless as far as fire safety in roofing applications is concerned and should be ignored. The total system, i.e. the deck, the foam and the coating, must be considered.

7.3 Problem Areas

7.3.1 Performance of Protective Coating

One of the more common problems of the foamed urethane system which we have observed is the poor performance of the protective coating. Blistering, flaking, cracking, eroding, pinholing and sometimes complete loss of coatings have been observed. The most common failure is erosion or weathering off of the coating which exposes the urethane to the destructive forces of solar radiation and water. This deficiency frequently appears at "bird baths" where water collects and stands. We have observed that the aluminum pigmented coatings have been particularly susceptible to this type of failure. There are several factors which contribute to the failures. They include: (1) lack of compatibility between urethane surface and the protective coating; (2) failure to provide sufficient slope to drain which permits water to collect and stand; (3) application procedures not in accordance with acceptable practices; and (4) poor weatherability of the coating material.

The obvious solutions to eliminate or ameliorate these problems are: (1) to require a total urethane system, that is one that consists of foam and coating system supplied by a single manufacturer, applied to his specifications and the total system guaranteed by the single supplier; (2) to provide sufficient slope (greater than 1/4 in/ft) to allow quick and complete drainage; and (3) the single supplier to provide clear and proven application instructions to competent applicators under ample construction inspection.

7.3.2 Cracking

A frustrating and rather common type of deficiency we have observed has been cracking of the urethane foam and protective coating. The cracks often penetrate to the substrate and cause water problems. We have identified several conditions under which cracking occurs. The most common cracking failures were observed at reentrant corners where control joints were not provided. As a matter of fact, this problem is also associated with membrane roofing. We also observed cracking in the urethane system over joints between units of the substrate. Movement which occurs at these joints is translated to the urethane foam. The foam, being inelastic and weak in tension, fractures. Random type cracks which occur in foam urethane are thought to be associated with thermal movements which take place in urethane due to its rather large thermal expansion coefficient. Polyurethane may reach as high as 350°F on solidifying and the normal cooling produces significant thermal stress which may contribute to cracking.

Once the sources of the deficiencies are identified and understood, it becomes elementary to prevent them. For example, as a matter of practice, control joints should be placed at reentrant corners to provide square or rectangular roof areas. Further, slip sheets provided over joints or other substrate areas which may exhibit differential movement between units of the substrate will distribute stresses over larger areas of the urethane foam, thus tending to reduce tension breaks.

7.3.3 Adhesion and Blisters

Urethane foam adheres rather tenaciously to most surfaces with some exceptions. The exceptions are wet, dusty, dirty, oily, greasy, and waxy surfaces. Adhesion failures generally are evident as blisters or in rare cases as wind blow-offs. We have observed adhesion failures resulting in very large blisters, often several feet in diameter. The adhesion failures sometime occur at the urethane-urethane interface which again stresses the importance of an acceptable surface for urethane application even as the second application over urethane.

The prevention of this type of failure becomes obvious. Surfaces to be sprayed with foam urethane should be clean and dry. Experience has shown the urethane adheres well to an asphalt surface. Therefore, a thin coating of an asphalt primer, hot asphalt or asphalt emulsion, over questionable surfaces will usually provide a good base for the application of foam urethane.

7.3.4 Bird Damage

We have received several complaints and have observed several urethane applications which were subject to bird damage. Possibly the birds are seeking worms and insects in the foam which has the appearance of rotten wood. We hasten to add here that the damage we have observed has been superficial for the most part and more of a curiosity than a real problem area. The damage is readily repaired.

8.0 Guidelines for Selection and Use of Urethane Foam in Roofing Applications

Due to the lack of data on polyurethane roofing systems and to differences in climates where these roofing systems may be applied, it is not possible to provide a general set of guidelines to the designer to guide him in whether or not to select a urethane foam roofing system. In fact, it is extremely difficult to provide guidance about the selection of a roofing system or roof repair system without knowing the specifics involved in the particular roof under question. However, we can provide information based on the properties and performance experience of urethane and can describe properties which affect performance and attempt to place this knowledge in perspective as far as the performance of the roof is concerned. The designer, specifier or owner, as the case may be, can use this information in conjunction with the economics of his alternate choices and make a decision whether or not the use of foamed urethane is justified. While we have not made a study of the economics of various roofing systems, we would certainly suggest that this aspect should play an important role in the decision. Life cost must be considered and should take priority over first cost. This is especially true with the presently high cost of protective coatings and their questionable life span. The high life cost are readily apparent when a polyurethane roof must be recoated every 3-5 years at a cost of 50 cents to one dollar per square foot.

8.1 New Roofing Applications

First, let us discuss the application of urethane foam systems in new roofing work. Some guidelines are:

(1) In cases where the conventional surfaced built-up membrane

roofing can be specified, it should have a higher priority than the foam polyurethane system.

(2) In cases where there is no slope, i.e. less than 1/4 inch per foot run, the selection of urethane foam system should not be considered.

(3) In cases where industrial type roofings are concerned the fire resistance rating must meet the Class B requirement of Underwriters' Laboratories as listed by the Laboratories. SE (Self Extinguishing) classification or a flame spread of 25 or less when tested in accordance with ASTM procedures E-1692 or E-84 respectively should not be accepted as evidence that the system is acceptable or that it meets the UL Class B rating. In cases when the roof is readily accessible for fire fighting the UL C classification may be accepted. The remarks concerning SE and flame spread of 25 apply equally to residential roof construction.

(4) It is suggested that the complete system, i.e. the foam and the protective coating, be recommended, specified and guaranteed by a single foam supplier. Protective coating should be applied at the specified dry film thickness.

(5) The thickness of the urethane foam should be at least 1 inch and no more than 2 1/4 inches. Foam of varying thicknesses should not be used to provide slope to drain. However, low areas can be successfully leveled by the application of greater thickness of foam within reason. A good guideline is that it should not exceed 3 inches in depth.

(6) Fabric reinforcement of the polyurethane foam must be provided at all flashings including vents and stacks, gutters, edge flashing, skylight or expansion joints and vertical surfaces. Cant strips should be provided at junction of vertical and horizontal surfaces.

(7) Control joints shall be provided at reentrant corners and other areas where stresses may occur in substrate which can be translated to the urethane.

(8) If concrete is completely dried, it provides the better deck for the applications of urethane in new work. However, urethane has been successfully applied to corrugated metal and plywood decks.

(9) Urethane foam should not be applied directly to the conventional, fluted metal deck. A minimum 1/8 inch plywood or equivalent board securely fastened to the metal deck with mechanical fasteners will provide a satisfactory surface or urethane application.

(10) Urethane will not adhere to a waxy, oily or wet surface. Cleaning and priming the surface with an asphalt primer (Federal Specification SS-A-701 or ASTM Specification D-41) or an asphalt emulsion (Mil. Spec. MIL-R-3472) and allowing it to dry provides an acceptable receiving surface for the polyurethane and is recommended.

(11) When applied over high humidity areas as swimming pools, laundries and the like, an asphalt saturated and coated base sheet, either nailed or adhered with hot asphalt depending on the deck, and coated with hot asphalt should be provided as the substrate for urethane foam.

(12) Slip sheets or bond breakers should be provided at joints in the substrate where stresses can occur which may be transferred to the urethane foam causing cracking.

(13) Application temperatures should be above 40°F (4°C) and below 120°F (49°C) at all times. In many situations these limits will be quite restrictive and may be extended providing measures are taken to compensate for application at lower or higher temperatures.

(14) The finished surface of urethane (before protective coating is applied) shall be free of bumps, lumps, and ridges and smooth enough to receive the coating. An orange peel effect is acceptable, however, a "popcorn" or "tree bark" type surface should be rejected.

(15) Applicators shall be required to follow instructions in the "Guide for the Safe Handling and Use of Urethane Foam Systems" as published by the Urethane Systems Manufacturers Committee, Cellular Plastics Division, Society of the Plastics Industry.

8.2 Reroofing Applications

The best estimate is that, at the present time, about 40% of the urethane foam used in roofing applications is for reroofing work. Probably the main reason for this use is because it is reportedly 35% to 40% cheaper to apply urethane over an old bituminous built-up roof than it is to remove and discard the old roof and replace it in kind. The question arises whether or not this is the more economical solution when one considers the cost per year. This question must remain unanswered until we have more information regarding the long-term durability of urethane foam systems.

A primary criterion concerning the choice of polyurethane vs. conventional systems in reroofing applications is whether or not funds are available. If they are available we believe that, at the present state-of-the-art, the better choice is conventional roofing. Our experience indicates that this is the more economical choice on a cost per year basis in spite of the reported 35% to 40% lower initial cost for polyurethane. We predict that this will continue until the <u>life</u> <u>span</u> to <u>cost</u> ratio of protective coating systems becomes considerably higher than it is at present. In certain situations a decision to use polyurethane will be made based on limited funding or on uncertainties concerning the future of the building in question. It is for use in these situations that we suggest the use of the following guidelines. We believe they will help insure the better chance of adequate performance from the polyurethane system.

(1) The slag or gravel surfacing, if present, must be removed. Do not attempt to foam over gravel or slag.

(2) The deficiencies of the old roof, such as blisters, buckles, wrinkles or cracks, must be repaired in accordance with good roofing practice before the application of the urethane.

(3) If insulation is a part of the existing roofing system, it must be vented with stack vents, preferably at the high points of the roof. One vent for not less than each 10 squares should be sufficient unless the insulation is wet. If the judgment is made that reroofing is still feasible then more vents will be required.

(4) Dust and dirt must be removed and the surface primed with an asphalt primer (SS-A-701 or ASTM D 41) at a spreading rate of 33 to 50 sq. ft./gallon or other suitable material. If the surface of the old roof is inherently damp, an asphalt emulsion (Military Specification MIL-R-3472) should be applied at a spreading rate of 33 to 50 sq. ft./gallon as primer.

(5) Any gravel or slag on the old roof must be removed as entirely as possible. The thickness of the urethane foam should be a minimum of 1 1/2 inches to compensate for any gravel or slag that remains.

(6) The guidelines set forth in new work (see 8.1) should also apply for reroofing work in addition to the guidelines stated herein.

9.0 Performance Specifications for Polyurethane Foam Roofing Systems

The complexity of the rigid urethane foams and their protective coating systems, the lack of technical data, and subsequent information about performance, durability, and long-term weatherability of foam urethane roofing systems are major constraints in developing adequate material specifications for urethane foams and protective coatings respectively. In the course of this study, we have attempted to set limiting values for specific properties in order to define acceptable service. However, we have been unsuccessful in these attempts since we have discovered large and uncomfortable gaps in the correlation of material property given by material suppliers and performance in service. We believe, at the current state-of-the-art, that these gaps are so large as to preclude the development of meaningful material specifications. The question now arises as to what steps can be taken to assist the designer, specifier, applicator, and owner in selecting a system which will insure acceptable performance.

We believe that the performance approach offers a valid means to this end. What it does is sets up what are believed to be acceptable performance levels for the complete foam urethane and protective coating system. We have attempted, as an innovative procedure, to develop a performance format to describe the complete system. We emphasize that the levels we have selected are based on the best information we have available. Therefore, they should be considered preliminary in nature and are subject to change as new data become available. We contend, however, that even at this embryonic stage, the document will be useful to guide the supplier and consumer alike, once the decision has been made to specify a urethane roofing system. Further, such a document will serve as a basis for a more comprehensive and perhaps a more valid performance standard for foam urethane roofing systems.

The performance format, as used here, consists of a stated requirement which is qualitative in nature. It is a statement of how we want the system to perform under specific exposure conditions. A criterion or criteria follow which express quantitatively the limiting value or values for performance in a specified test. Next in order to evaluate the criterion which is selected, a test method is identified. Finally, a commentary is added, where appropriate, to place in perspective the relation of the test procedure and the criteria to performance of the roofing system in service.

9.1 Suggested Performance Specification for Guidance in Selecting a Foam Urethane Protective Coating Roofing System

9.1.1 Fire Safety

°Requirement	The roofing system (deck, foam urethane, and protective coating) shall present no hazard either to the occupants or contents of the building nor to adjacent structures. The roofing shall not be susceptible to ignition from sparks or firebrands.
°Criterion	The roof system shall have an Underwriters' Laboratories Class B rating.

°Test	Underwriters' Laboratories Standard UL 790, ASTM E 108-58 (1970) Fire Tests of Roof Coverings.
°Commentary	For roofing purposes, flammability data from tests such as ASTM E 84 or ASTM D 1692 shall not be used for acceptance in lieu of the ASTM E 108 Test. A Class C rating may be substituted for the Class B rating where deemed appropriate.

9.1.2 Wind Resistance

°Requirement	The urethane foam roofing system shall withstand anticipated wind loads without damage to the system.
°Criterion	The urethane foam shall attain a minimum of 95% adhesion to the substrate.
°Test	Field experience and engineering judgment.
°Commentary	The above criterion is believed to be adequate for most locations. However, in high wind areas more rigid criteria may be required. Underwriters' Laboratories procedure (UL Bulletin of Research No. 52, 1962) may be accepted as evidence of wind resistance according to their classification of (30), (60), or (90).

Other tests as Factory Mutual and Owens-Corning Fiberglas Corporation methods may also be suitable for determining wind resistance.

9.1.3 Water Resistance

°Requirement The foamed urethane shall evidence no signs of deterioration or loss in value of essential performance properties, e.g. thermal conductivity, strength and the like, when exposed to water.

°Criteria a. The urethane foam shall have a closed cell content of not less than 90%.

b. The water absorption of urethane foam shall not be greater than 0.02 lb/ft^2.

c. The water vapor permeability of the urethane foam shall not exceed 3.0 perm-inches.

d. When the urethane roof system is used in cold storage applications or in high temperature-high humidity locations (tropical) the water vapor permeance of the protective coating system shall not exceed 0.5 perms.

°Tests a. ASTM D 2856-70 Open Cell Content of Rigid Cellular Plastics by Air Pycnometer.

b. ASTM D 2842-69 Water Absorption of Rigid Cellular Plastics.

c. ASTM C 355-64 desiccant method Water Vapor Transmission of Thick Materials.

d. ASTM E 96-66 Procedure A Water Vapor Transmission of Materials in Sheet Form.

°Commentary — Moisture is a prime enemy of urethane foam. It can enter the foam from interior sources (vapor flow and condensation) or from the exterior (rain, dew, snow). When the urethane system is used over high humidity areas, especially in cold climates, it is prudent to incorporate a vapor flow retarder on the high vapor pressure side.

9.1.4 Stress Resistance

°Requirement — The urethane foam shall possess sufficient strength to resist or withstand the normal stresses imposed from both internal and external sources.

°Criteria — a. The tensile breaking strength shall not be less than 25 p.s.i. when measured perpendicular to the direction of rise.

b. The shear strength of the foam shall not be less than 25 p.s.i. when measured parallel to the direction of rise.

°Test — a. ASTM D 1623-64 Tensile Properties of Rigid Cellular Plastics.

b. ASTM C-273-61 (1970) Shear Test in Flatwise Plane of Flat Sandwich Constructions or Sandwich Cores.

°Commentary Field experience has shown urethane foams are susceptible to fracture for both internally and externally produced stresses. The above stated values are absolute minimums based on products available at this point in time.

Urethane foam products exhibit anisotropic behavior due to the shape of cell formation during the foaming operation. The values given above are for the direction which is most appropriate for roofing application.

9.1.5 Resistance to Impact and Foot Traffic

°Requirement The urethane foam and its protective coating shall resist impact from foot traffic and falling objects.

°Criteria a. The density of the urethane foam shall not be less than 2 lb/ft^3.

b. The compressive strength of the urethane foam shall not be less than 30 p.s.i. when measured parallel to the direction of rise.

c. The protective coating over the urethane foam shall withstand the impact of an 1 1/4 inch ice sphere traveling at a velocity of 82 ft/sec without rupture or fracture of the protective coating.

°Test a. ASTM D 1622-63 (1970) Apparent Density of Rigid Cellular Plastics.

b. ASTM D 1621-64 Compressive Strength of Rigid Cellular Plastics.

c. NBS Hail Resistance Test [43]

°Commentary The criteria of core density and compressive strength are related to impact and foot traffic resistance. Common roofing systems such as asphalt shingles and built-up membranes meet the criterion for falling ice spheres and have performed satisfactorily under field conditions involving hail. We believe similar criteria are reasonable for urethane foam systems.

9.1.6 Dimensional Stability

°Requirement The urethane foam roofing system shall not exhibit movements under service conditions of moisture and temperature changes so large as to inhibit the performance of the total system.

°Criteria a. The coefficient of linear thermal expansion of the urethane foam shall not exceed 40×10^{-6} per °F.

b. The volume change of the urethane foam shall not exceed the following values when exposed to the following conditions:

-40°F at ambient R.H. - ±3% for 1 week

140°F at ambient R.H. for 1 week - +5%

158°F at 100% R.H. for 1 week - +12%

°Test a. NBS Test Procedure for Built-Up Membranes [44] Temperature range 30°F to -30°F.

b. ASTM D 2126-66 Resistance of Rigid Cellular Plastics to Simulated Service Conditions.

°Commentary The value stated for the expansion coefficient may be too low. There are preliminary indications that polyurethanes for roofing applications may have considerably higher coefficients at the temperatures stated. Deficiencies observed in urethane roofing systems during the field survey have been attributed to lack of moisture and thermal stability. The above limits are based on a survey of literature and should be regarded as maximum. Lower values will decrease chances of adequate performance in service.

9.1.7 Durability of Protective Coating

°Requirement The protection system for the urethane foam shall withstand the environment of its exposure with regard to: (a) movements in the substrate (urethane foam), (b) moisture and temperature changes, (c) solar radiation, (d) atmospheric contaminants.

°Criterion	The protective coating shall not crack, blister, peel, pit, or erode to expose the urethane for a period of not less than <u>five</u> years. Further, during the same period there shall be no evidence of loss of adhesion between the protective coatings and urethane substrate.
°Test	Field observation and laboratory tests. Engineering and scientific judgment.
°Commentary	Performance data for many types of coatings used for the protection of urethane foam are incomplete. Experience based on performance in service should be used whenever possible. The durability of protective coatings is intimately connected with the performance of the total roofing system.

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11.0 References

1. Gordon, Joseph, "Watch Polyurethanes Bid for Big Time. II. Properties, Reaction, Additives, Control, Applications", Hydrocarbon Process: Petrol. Refined, 42, 123-34 (1963).

2. Saunders, J. L. and Frisch, K. C., "Polyurethanes, Chemistry and Technology", Part 1. Chemistry, High Polymers Vol. XVI, Interscience Publishers, New York, 1962.

3. Frisch, Kurt C. in "Polyurethane Technology", Bruins, Paul F., Ed., Interscience Publishers, New York, 1969, Chapter 1.

4. Lyman, Donald J., "Polyurethanes", Rev. Macromol. Chem., 1, 191-237 (1966).

5. Tilley, James N., Nadau, Herbert G., Reymore, Harold E., Waszeciak, Paul H., and Sayigh, Adman A. R., "Thermal Degradative Behavior of Selected Urethane Foams Related to Variations of Constituents. I. Thermal Stability and Test Methods", J. Cell. Plast., 4, 22-36 (1968).

6. Frisch, K. C. and Robertson, E. J., "Advances in Technology and Uses of Rigid Urethane Foams", Mod. Plastics, 40, 165-6, 168, 170, 172, 174, 212, 216 (1962).

7. Benning, Calvin J., "Plastic Foams: The Physics and Chemistry of Product Performance and Process Technology, Vol. II, Wiley-Interscience New York, 1969, p. 68.

8. Gordon, Joseph, "Watch Polyurethanes Go Big Time. I. Chemistry, Raw Materials, Diisocyanates, Polyethers, Polyesters", Hydrocarbon Process. Petrol. Refiner, 41, 191-9 (1962).

9. Hermansen, Ralph D., "Molded Rigid Urethane Foams: Dimensional and Physical Characteristics", J. Cell. Plast., 4, 459-73 (1968).

10. Frisch, Kurt C., "Relation of Chemical Structure and Properties of Rigid Urethane Foams", J. Cell. Plast., 1, 321-30 (1965).

11. Tarakanov, O. G., Orlov, V. A., and Belyakov, V. K., "Thermal Degradation and Thermal Oxidative Degradation of Polyurethanes", J. Polym. Sci., Part C 1966 (Pub. 1968), No. 23 (Pt. 1), 117-25.

12. "Cellular Plastics", Proc. Conf., Natick, Mass., April 13-15, 1966, Pub. 1462, Natl Acad. Sci., Natl Res. Council, Wash. D.C., 1967, pp 33-36, pp 66, 67.

13. Orefice, James D. and Pigott, Kenneth A., "Urethane Foam", Mod. Plastics Encycl. Vol. 48, No. 10A, 1971-1972, pp 152-154.

14. Hilado, Carlos J., "Getting the Most from Rigid Polyurethane Foams", *Chem. Eng.*, *74*, 190, 192, 194, 196 (1967).

15. Hull, G. K., "Formulating Principles of Rigid Polyurethan Foam Systems", *Rubber Plastics Age*, *47*, 773-774 (1966).

16. Deverell, D., "Applications of Some Novel Plastics Systems", *Brit. Plast.*, *39*, 707-13 (1966).

17. Doherty, D. J., Hurd, R., and Lester, G. R., "Physical Properties of Rigid Polyurethane Foams", *Chem. Ind.* (London), 1962, 1340-56.

18. Harding, R. H., and Hilado, C. J., "Relations among Strength, Temperature, and Chemical-Physical Structures in Rigid Urethan Foams", *J. Appl. Polymer Sci.*, *8*, 2445-60 (1964).

19. Harris, R. F., "Impact Testing of Rigid Urethane Foam", *J. Cell. Plast.*, *6*, 221-5 (1970).

20. Tilley, J. N., Nadeau, H. G., Reymore, H. E., Waszeciak, P. H., and Sayigh, A. A. R., "Thermal Degradative Behavior of Selection Urethane Foams Related to Variations of Constituents. II. Chemical Reactions in Urethane Decomposition", *J. Cell. Plast.*, *4*, 56-66 (1968).

21. Reegen, S. L. and Frisch, K. C., "The Effect of Chemical Structure on Thermal, Hydrolytic, and Solvent Resistance of Polyurethane Films", *J. Polym. Sci.*, *Part C*, No. 16 (Pt.5), 2733-49 (1967).

22. Smith, Clifford C., "Thermal Characteristics of Some Rigid Urethan Foams", *J. Appl. Polymer Sci.*, *9*, 3851-61 (1965).

23. Saunders, J. H., "Relations between Polymer Structure and Properties in Urethans", *Rubber Chem. and Technol.*, *33*, 1259-92 (1960).

24. Backus, J. L., Darr, W. C., Gemeinhardt, P. G., and Saunders, J. H., "Thermal Decomposition of Rigid Urethan Foams", *J. Cell. Plast.*, *1*, 178-86 (1965).

25. Tarakanov, O. G., Nevskii, L. V., and Belyakov, V. K., "Photodegradation and Photooxidative Degradation of Polyurethanes", *J. Polym. Sci.*, *Part C*, 1966 (pub. 1968), No. 23, (Pt.1), 193-9.

26. Mitchell, R.G.B., "Cellular Plastics in the Building Industry", *SPE Journal*, p. 21, March 1966.

27. Buist, J. M. and Wilson, J. W., "The Use of Urethanes in Building Applications. II.", *Rubber J.*, *149*, 16-17, 20,22-3, 25, 27 (1967).

28. Levy, Marshall M., "Moisture Vapor Transmission and Its Effect on Thermal Efficiency of Foam Plastics", *J. Cell. Plast.*, *2*, 37-45 (1966).

29. Hilado, C.J., and Harding, R.H., "Relations between Water Vapor Permeability and Chemical-Physical Structure in Rigid Urethane Foams", *J. Appl. Polymer Sci.*, *7*, 1775-90 (1963).

30. Varland, Robert H., "Long-term k-Factor Aging of Rigid Urethan Foam Insulation", *ASHRAE J.*, *8*, 84-7, 89 (1966).

31. Varland, Robert H., "Rigid Polyurethane Foams: Effect of Age on Heat Transfer", *SPE Journal*, p. 34, November (1966).

32. Eldib, I.A., "How to Make Polyurethanes", *Hydrocarbon Process. Petrol. Refiner*, *42*, 121-7 (1963).

33. Ball, George W., Hurd, R., and Walker, Maxwell G., "Thermal Conductivity of Rigid Urethane Foams", *J. Cell. Plast.*, *6*, 66-78 (1970).

34. Hilado, Carlos J., Burgess, Jr., Paul E., and Proops, William R., "Bromine, Chlorine, and Phosphorus Compounds as Flame Retardants in Rigid Urethane Foam", *J. Cell. Plast.*, *4*, 67-78 (1968).

35. Hildado, Carlos J., "Flammability Characteristics of Cellular Plastics", *Ind. Eng. Chem.*, *Prod. Res. Develop.*, *6*, 154-66 (1967).

36. Hilado, Carlos J., "Flame-Retardant Urethane Foams , *J. Cell. Plast.*, *4*, 339-44 (1968).

37. Anon., "Coping with Flammability", *Mod. Plastics*, *48*, 79-80 (1971).

38. Robitschek, Paul, "Flammability Characteristics of Cellular Plastics", *J. Cell. Plast.*, *1*, 395-9 (1965).

39. Dickert, E.A. and Toone, G.C., "Chemistry and Flame Retardancy of Rigid Urethan Foams", *Mod. Plastics*, *42*, 197-9, 201, 204, 264, 267 (1965).

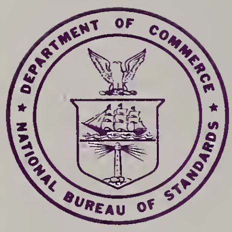
40. Doherty, D.J. and Wilson, W.J., "Protection of Rigid Urethane Foam from Fire Damage", *Bull. Inst. Int. Froid*, *Annexe*, *5*, 185-200 (1969).

41. Benjamin, Irwin A., personal communication

42. Martin, K.G., "Degradation of Rigid Cellular Plastics Under Fire Conditions in Buildings", *Rev. Pure Appl. Chem.*, *21*, 121-43 (1971).

43. Greenfeld, Sidney A., "Hail Resistance of Roofing Products", Nationsl Bureau of Standards (U. S.), Building Science Series 23, 11 pages (August 1969).

44. NBS Test Method for determining the coefficient of linear thermal expansion of built-up membranes (work in progress).



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