THE DEVELOPMENT OF AN EXPERT SYSTEM AND HISTORICAL DATA BASE FOR PUF ROOF SYSTEM SPECIFICATION, DESIGN AND ANALYSIS

DEAN T. KASHIWAGI, WILLIAM C. MOOR and TERRY G. BEAUMARIAGE
Arizona State University
Air Force Institute Technology
Tempe, Ariz.

From 1983 to 1989, the authors have collected performance data of polyurethane foam (PUF) roof systems in six geographical areas of the United States with varying environmental conditions. Roof systems included silicone, acrylic, urethane rubber and aggregate/asphalt coated systems. Failure mechanisms of PUF roof systems were identified and performance criteria for each system component specified.

In 1990, the authors reinspected 188 of these roof systems to confirm the following: failure mechanisms of various coating/form combinations, performance of 15- to 20-year PUF roof systems, similarities of successful PUF roof systems and optimal system specifications, and the economic feasibility of PUF roof systems in the various geographical areas. The authors also assessed the impact of new systems and robotic application on PUF roof systems. This data is now being organized into a user-friendly, computer-based expert system.

The computer-based expert system will include all available nonbiased data of installed PUF roof systems, and resulting capabilities and applications of the expert system, as well as an analysis of the knowledge base, and a complete discussion of the rules and conclusions and their derivations.

KEYWORDS

Acrylic-coated roofs, aggregate covered roofs, polyurethane foam (PUF), silicone-coated roofs.

INTRODUCTION

PUF roof systems have been installed since the late 1960s. Although it has been around for 20 years, when compared with the built-up roof system (BUR) and the single-ply roof system, it is a relatively new and unknown roofing system. It is a two-component, monolithic, closed-cell, sprayed-in-place system that historically has been installed in 1/8- to 1/4-inch lifts, to a total thickness of 1 inch of PUF on building roof decks. The PUF is protected by a thin film of elastomeric rubber coating. In the 1980s, with the arrival of spray machines with greater volume capacity, lifts could be installed in increments of ½ to 1 inch.

The credibility of PUF roof systems suffered in the 1970s due to a rash of roof failures. This led to the roof system being defined as an "experimental" or "specialty" roof system. Although installed since the early 1970s, the industry estimates that spray-applied PUF roofs make up only 3 percent of roofing installations.[3,6] Many architects, engineers and building owners were hesitant to use the system due to failures and a general lack of understanding of the PUF roof system. The following are basic PUF roof system misconceptions:

- PUF roof saturation was caused by liquid water penetration.
- The majority of PUF roof failures were coating related.
- Infiltration of ponded water causes saturation of closed-cell PUF.

In 1981, intrigued by the lack of information of the performance of PUF roof systems, Dean Kashiwagi selected eight locations to make an unbiased data base of installed PUF roof systems.[9] The original data base included roofs located in Colorado, Wyoming, New Mexico, Arizona, Wisconsin, New Jersey, Kentucky and Texas. The following criteria ensured the validity (representative sample of properly installed PUF roofs) of the data base:

- The contractor had a record of continuously installing PUF roofs for at least eight years.
- The contractor opened his entire job file for inspection.
- Roofs were selected with no previous knowledge of roof performance.

The authors developed a performance rating system for the PUF roof system which has since been modified.[7] The PUF and coating are now rated separately. The objective of the rating system was to classify the performance of a PUF roof and determine the most effective (waterproofing) and economical (cost) maintenance procedures. The rating system is for the PUF:

Rating	Description (percent of roof area with delamination, blistering, or substandard PUF)
Excellent	0 percent
Very Good	Less than 1 percent
Good	Less than 5 percent
Fair	Less than 10 precent
Poor	Less than 20 percent

The authors define blistering as the loss of structural cell integrity and delamination as the separation of PUF lifts. Roofs with less than 20 percent damage can be repaired due to the closed-cell nature of the PUF. Deteriorated portions can be removed and refoamed. Inspections showed that roofs with less than 15 years of service and over 20 percent damage were installed with less than optimal procedures and conditions (off-ratio PUF, inclement weather, excessive time periods between spraying of PUF lifts, and thin lifts of PUF). A similar rating is also given to elastomeric coating systems.

In the initial inspection, 246 roofs were selected from a listing of 1,125 roofs. The author conducted follow-up inspections in 1985, 1987, 1988 and 1989 on roofs in New Jersey, Kentucky, Arizona and Texas. Analysis of the data resulted in the following theorems:

- Sprayed-in-place PUF is a highly successful roofing material, and can be consistently and effectively installed in different geographical areas with the potential of a 20-year service period. Both customer satisfaction and successful roof performance exceeded 90 percent.
- PUF roof systems are an attractive, economic option when compared to alternative built-up and the single-ply roofing systems.
- The most critical component of the PUF system is the PUF.
- The requirements for an effective cover for PUF include protection against ultraviolet (UV) rays and mechanical traffic loads.
- Saturation of closed-cell PUF is caused by vapor drives, and not by penetration of standing water on the PUF roof system.
- Delamination and blistering of PUF is caused by repeated loading of thin lifts of PUF. It also can be caused by misapplication and substandard materials. Blistering that occurs in the first five years in areas other than traffic paths or maintenance areas is a result of misapplication or substandard materials.
- Asphalt and lightweight slag is an effective covering for PUF roofs. The purpose of the asphalt is to embed a large percentage of the aggregate and therefore restrain the aggregate from moving on the roof.

OBJECTIVES

The objectives of this study are to:

- Update the performance of silicone-coated roofs in Wisconsin. These roofs were last inspected in 1983.
- Inspect aggregate and PUF roofs in North and South Carolina for moisture, delamination and blisters. These roof systems are multiple-lift, 1 to 1-1/2 inch PUF covered with cold-applied cutback asphalt and ¾ to 1 inch of aggregate. Asphalt and aggregate covered roofs were first inspected in 1983[10] and again in 1985[9] and 1988.[8] Kashiwagi, Moor and Goertz were responsible for the original specification of the roof system.[9]
- Update the performance of previously inspected PUF roofs in Kentucky, Texas and Phoenix.
- Inspect and analyze the correlation between delamination and blistering of the PUF.
- Formulate guidelines for the proper identification of problems, solutions and specifications for PUF roof systems.
- Develop an expert system to do the above three tasks.
- Develop an expert systems to assist in the economic analyses and heat and vapor transfer analyses.

DATA COLLECTION AND ANALYSIS

Roofs were inspected in five major areas: Eau Clair, Wis., Louisville, Ky., College Station, Texas, Phoenix, Ariz. and Spartanburg, S.C. The results from each area will be discussed and analyzed. Except for a couple of cases, all inspected roofs were selected by the authors without any knowledge of roof application or performance. Due to a lack of information on aging acrylic-coated PUF roof systems, 20- and 16-year acrylic- coated PUF systems in Phoenix, Ariz. were added to the database.

All roofs were given ratings for PUF and coating (except the aggregate covered systems). Each roof was also checked for blisters, delamination, bird damage, mechanical damage and repairs. Aggregate covered roofs were also checked for moisture. The number of roofs with more than 1 percent of the total roof area with blisters (BL), bird damage (DB), mechanical damage (MD), and repair work (RP), is shown in Tables 1-6.

Eau Clair, Wisconsin

Fifty-six silicone-coated PUF roofs were inspected in Eau Clair, Wis. and the surrounding area. The average age of roofs inspected was 13 years, with 27 roofs over 14 years of age, the oldest being 21 years old (see Table 1). Eighty-seven percent of the roofs had less than 1 percent of damage, and only 4 percent had greater than 5 percent damage. Only one roof was removed in the last 7 years. Only two roofs had blisters on more than one percent of the roof area. Most of the damage observed was on roofs 14 and 15 years old. Fourteen percent of the roofs had repairs, and nine percent of the roofs had leaks. Half the roofs were sloped and half the roofs received traffic. The silicone coating was installed at 25-35 mils.

Eighteen percent of the roofs showed blisters in trafficking and localized areas. Upon examination, all blistered areas consisted of delaminated PUF that had lost structural strength (PUF cell wall structure was destroyed). Only 9 percent of the roofs had bird damage on more than 1 percent of the roof area. On these roofs, the contractor recoated with silicone and -11 granules. This corrective action eliminated all bird damage. Since 55 percent of the roofs were flat (ponding conditions), and Wisconsin is a snow and ice environment during the winter months, the performance of the roofs proves that silicone-coated roof systems can perform in ice and ponding environments.

Louisville, Kentucky

Thirty-five roofs were inspected in Louisville, Ky. The majority of the roofs were silicone-coated PUF roofs. The oldest roofs were 16 years old, the average service period was 9.7 years and 11 roofs were older than 14 years (see Table 2). Two roofs were removed in the last two years. One of the roofs was removed due to non-roofing related reasons. Eighty-three percent of the roofs had less than 1 percent deterioration to the PUF, and there is no distinguishable pattern of deterioration as the roofs age. As in Eau Clair, the silicone coatings are performing very well. The percentage of roofs with blistering problems was higher at 11 percent, and mechanical damage was also higher at 11 percent. This could be attributed to more traffic on the roofs (60 percent vs. 41 percent).

Three roofs were inspected that were installed with a robotic spraying arm. The advantages of the robot are:

- The arm sprays at a 90 degree angle to the roof deck. It does not twist while spraying, which eliminates thinner pass edges.
- The robot can consistently install an inch and a half PUF pass. This eliminates the delamination/blistering problem of thin lifts.
- The robot does not perspire or get tired.

The shortcomings of the robot include the inability to operate on sloped roofs, and small roofs with a large number of penetrations. A reliability and feasibility study is being done on the robot.

College Station, Texas

Roofs at Texas A&M were urethane rubber coated systems. Although their current specification calls for 45 mils of urethane rubber coating and 2 inches of PUF, most of the older roofs have 1 to 1-1/2 inches of PUF and 20 to 35 mils of urethane rubber coating. Unlike the other locations, Texas A&M's roofs were installed by many different contractors. Thirty-two roofs were inspected. The oldest roof was 16 years old. The average age was 12 years (see Table 3). Eighty-eight percent of the roofs had less than 5 percent damage. When compared to the silicone coated systems, a larger percentage of roofs had blistering problems. As in the previous two locations, all blistered areas of PUF were first delaminated.

Phoenix, Arizona

The roofs in Phoenix, Ariz. were the oldest roofs inspected. Fourteen roofs were inspected. The majority of the roofs were granulated silicone roofs. The oldest roof was 20 years old. The average lifespan was 17 years. Eighty-six percent of the roofs had less than 1 percent damage. Many roofs were initially installed at 10 mils of silicone coating with granules over 1 inch of PUF. Seventy-one percent of the roofs have been recoated. One of the 18 year old roofs requires replacement. It was installed at ¾ inches of PUF over an existing BUR. The underlying BUR has since disbonded from the roof deck, causing the PUF to delaminate and blister in areas. The majority of the roofs had very little maintenance and were almost indistinguishable from new roofs.

Spartanburg, South Carolina

The aggregate covered asphalt coated PUF roofs in South Carolina were added to the database for the following reasons:

- To determine if having a totally permeable covering would reduce moisture accumulation from vapor drive in the PUF.
- To determine if the aggregate cover would adequately protect the PUF.
- To determine if the aggregate inflicts any noticeable damage on the PUF.

The aggregate and asphalt covered PUF roof systems inspected in North and South Carolina consisted of 1 to 1-1/2 inches of 3-pound density PUF with a tack coat of cold applied cutback asphalt and ¾ to 1 inch of #6 size aggregate. Historical development of the system is documented by the authors in a previous publication.[7,8]

Fifty roofs (all aggregate covered with asphalt coating) were randomly selected for inspection from a listing of 109 roofs. The oldest roof was four years old and the average age was 2.2 years. Ninety-six percent of the roofs had less than 1 percent damage. All fifty of the roofs were visually inspected and also checked with a Delmhorft moisture meter for moisture. No moisture was detected in the PUF on any of the roofs. Only two roofs had blisters in more than 1 percent of the roof area, and 88 percent of the roofs had no blisters. The aggregated covered roofs had 10 percent fewer roofs with blisters than the Wisconsin silicone roofs, 36 percent less than the Kentucky silicone coated roofs, 38 percent less than the Phoenix roofs and 66 percent less than the urethane coated Texas A&M roofs. Even though the PUF roofs in the other areas were older in age than the aggregated covered roofs, in general, the blisters were formed when the roofs were in the three- to five-year period. The aggregate covered PUF roofs showed no mechanical damage, bird damage or repairs. The effect of the gravel system on blistering will be monitored in longitudinal studies as the gravel roof systems become older.

The aggregate covered PUF roof system has some advantages over coated BUR roof systems:

- Blistered areas of multiple-lift installations are easier to repair. If the roof has been installed in multiple lifts, blisters can be carefully cut out and covered with aggregate. This is due to the lack of coating requirements of the repair and the monolithic closed-cell characteristics of the PUF.
- The system reduces the possibility of saturation of closed-cell PUF except over unique situations such as cold storage facilities. This is discussed in greater detail in the vapor drive analysis section.
- The covering does not have to be immediately installed after the PUF or replaced as the roof ages. With most elastomeric coating systems, the coating should be installed within 24 to 72 hours after the PUF is installed. This is to prevent the degradation and dusting of the PUF, and consequent disbonding between the PUF and the coating. The aggregate has no such time restrictions. The authors feel there is no problem with the PUF being left uncovered for a week. Some contractors extend this time period even longer. To do so may not impair the performance of the roof system, but it may open the door to unwise business practices.

The disadvantages of the aggregate covered system are:

- The authors recommend that it be installed only on slopes less than 1 inch per foot. The potential problem with steep roof applications is the problem with aggregate movement down the incline of a steep roof.
- It can only be installed where the structure can support the weight of the aggregate.
- It is much easier for an inexperienced roofing contractor to purchase PUF, incorrectly install the systems and cover his installation with slag. Historically, the industry (sprayed-on PUF roof system component manufacturers, suppliers and contractors) perceived that the coating and not the PUF was the most critical component. This resulted in the coating manufacturers burdened with the responsibility of regulating the industry, certifying the

contractors and issuing the warranties. Historically, the PUF manufacturers merely provided the PUF, accepting very little liability for the installed system. The PUF manufacturers are beginning to take over some of this responsibility, but until all PUF manufacturers and suppliers regulate the use of sprayed-on PUF for roof applications, this problem will continue.

- Whereas the coated system requires a minimum level of skill application of the PUF, the aggregate covered system lacks such a requirement. This is supported by the early applications of PUF roof systems installed by Goertz.[7] Many of the roofs contained PUF that was installed under less than optimum installation procedures. The coating covered systems with a minimum specified thickness of elastomeric coating require that the PUF be installed in a very smooth "orange peel" or "coarse orange peel" finish.[4] Unless this is accomplished, it is economically impossible to meet the minimum coating thickness requirements. This requirement implicitly requires that the applicator have a minimum skill level in applying the PUF. Therefore, by meeting the requirements of the coating manufacturer, the applicators were also correctly installing the PUF.

Overall Results

Table 6 summarizes the results. One hundred and eighty-eight roofs were inspected. Due to the method of selection of the inspected roofs, this is a representative sampling of successful PUF roof systems. Ninety-five percent of the roofs had less than 5 percent damage, and 88 percent had less than 1 percent damage. These are remarkable results when one realizes that 59 of the roofs were older than 14 years. The service of PUF roofs is extended when compared with the other roofing systems because the monolithic, closed-cell structure isolates damaged areas. Ninety-one percent of the roofs inspected had less than 1 percent of blistered roof area, 95 percent had no major mechanical damage and only 6 percent of the roofs had leaks. Most of the leaks were non-roofing related, due to air conditioners, open vents and problems with masonry wall and were correctable.

The insulated PUF roof systems are 20-year roof systems despite the fact that most of the roofs were underspecified and installed under less than optimum guidelines. Delamination and blistering is the primary cause of PUF roof failure. Installing the PUF in 1/2 inch lifts will decrease delamination and blistering. The optimum solution is to install the PUF using robotic application in one 1.5- to 2-inch pass, thus eliminating the possibility of delamination of lifts. The increased foam thickness may increase the moment of inertia of the PUF pass up to 27 times, greatly increasing the allowable compressive stresses and moment carrying capability of the PUF. The robotic PUF spray applicator has the potential to not only consistently spray thicker lifts of PUF, but also limit the feathering of pass line.

EXPERT SYSTEMS

There are five major engineering tasks in the design, specification, and maintenance of PUF roof systems:

- Determination of economic feasibility.
- Examination of the design for the effects of vapor drive.
- Specification of the right system.
- Identification of the cause of damage to the roof system.
- Selection of the most economical solution to maintain a roof.

The authors utilized two software packages: Quattro Pro, a spreadsheet developed by Borland International, and VP Expert, an expert systems shell developed by Paperback Software International. VP Expert is a production system composed of production rules. A production is a condition-action relationship. The inference engine or expert system processor identifies the condition of the "state of the world," and then prescribes the appropriate action or rule. The first two tasks, the economic analysis and the vapor drive analysis, are not yet integrated into the expert system shell.

Economic Analysis

The economic analysis expert system (computer program) was derived from a procedure documented in the National Roofing Contractors Association's publication "The Energy Manual."[2] It considers environmental conditions, energy costs for heating and cooling, inflation and interest rates, insulating qualities of building materials, building configuration, and roofing installation, tearoff and PUF recoating costs.

The spreadsheet program can produce a range of equivalent uniform annual costs (EUAC), and the number of years for the PUF roof system to payback, either against a "do nothing" alternative, or an alternative new roof system. For example, a silicone-coated PUF roof system is specified for a concrete building in Phoenix, Ariz. (see Figures 1 and 2).

The cost of the PUF roof system is $1.90/square foot for 1 inch of silicone-coated PUF and $.35 for an additional ½ inch of PUF. The system is compared to a single-ply system that costs $2.50/square foot. The spreadsheet produces the EUAC for the PUF system and for the single-ply system for variable service lives from 1 to 25 years (see Table 7). The spreadsheet also produces the required number of years of service for the PUF roof system to be equivalent to a 15-year single-ply system. In this example, it is 10 years. It is important to note that the PUF roof system used here is an 1-1/2 inch PUF thickness. From the survey data collected in this report, the expected lifetime of this system is at least 20 years.

The user can either read the number of years of payback of the PUF roof system off Figure 1 or Table 7 (both are a part of the same spreadsheet). For example, if the single-ply system's life is only 10 year instead of 15, the user would read the EUAC for the 10-year single-ply system as $.50/square foot. The payback in number of years for the silicone coated PUF system would be eight years. This is found by looking for $.50 in the silicone coated system (second) column and reading the corresponding year. It is interesting to note that the aggregate system has a payback of only five years when compared to a 15-year single-ply system.

The economic analysis was performed for both the metal deck and concrete deck configurations in a Phoenix, Ariz., environment. For a 100,000 square foot job, the difference in EUAC for the PUF system per square foot was only $.01 for comparable service lives. It also points out that the critical factors in selecting the most economical roof system are the installation costs and service periods of both systems. Ironically, the insulating capability of the PUF is rather insignificant when considering actual EUAC. This is very important when considering the phasing out of products using a chlorofluorocarbon (CFC) blowing agent. With the switchover to a blowing agent with a lower thermal resistance capability, the negative impact on the economic feasibility of the PUF roof system EUAC will be very small.

Vapor Drive Analysis

The vapor drive spreadsheet program calculates the temperatures, and vapor and saturation pressures through a roof system, and identifies where the saturation takes place. The inputs include the building components (including the presence of a vapor barrier), their vapor resistance factors, the inside and outside temperature and humidities. Different building configurations can be easily preset, requiring only the input of temperatures and humidities. The resulting saturation pressures and vapor pressures are listed in the two columns of the far right hand side. Anywhere that the vapor pressure exceeds the saturation pressure, saturation will take place. Using worst case conditions, three analyses were performed.

The first analysis is a summer environment to show the low probability of saturation in PUF when using a permeable cover for the PUF (see Table 8 and Figure 3). Saturation of the PUF can occur if there is a vapor barrier beneath the PUF, and if the temperature reaches 100 degrees with 77 percent humidity.

The second analysis uses a winter environment to show the effect on an impermeable coating on vapor drive as it passes through the roof system (see Table 9 and Figure 4). In this example, the upper inch of PUF will be saturated. Although a vapor barrier will generally eliminate this problem, the authors suggest that the PUF system with no vapor barrier and a permeable covering is more robust in handling vapor drive. The last example shows the effects of a totally permeable covering such as an aggregate covering in the same environment (see Table 10 and Figure 5). The potential for saturation is minimal. These results agree with the data collection of the aggregate covered roofs and explain the phenomena of why saturation will occur under ponded areas.[9]

Specification of the PUF Roof System

The objective of this expert system (Appendix 1) is to specify the most economical PUF roof system for any environment and roof configuration. The inputs required by the expert system include: load bearing capability of the structure, slope of the roof deck and potential loadings on the system (vapor drive, mechanical traffic, bird activity (bird pecks in the PUF), snow and ice, ponding, and high UV). After receiving the inputs, the expert system gives the most economical PUF roofing system.

The data and results of the analysis of the data were transformed into the following production rules:

- The PUF thickness should be a minimum of 1-1/2 inches.
- If a vapor drive exists in combination with any other loading (ponding, ice or mechanical traffic) on the PUF, the authors recommend 2 inches of PUF.
- If the slope of the roof is less than 1 inch per foot and the building structure has the necessary loadbearing capability, the most economical covering for the PUF is #6 aggregate (interlocking slag). This system can be used in most environments: snow and ice, bird activity, mechanical traffic and in vapor drive conditions. This can be verified using Table 8. The authors derive this result from the data in Table 7. If one compares a 20-year silicone roof system (which has been verified by inspection) with a seven-year aggregate covered PUF roof system, one can see they may be of comparable economic value. The authors have concluded that with the condition of the aggregate roofs inspected in South Carolina, and their knowledge of PUF failure mechanisms, that the aggregate covered PUF systems will perform for more than 10 years.
- Both urethane rubber coatings and silicone coatings with heavily embedded granules can be used to protect the PUF in environments with bird activity.
- If the roof has ice conditions, a urethane rubber or silicone coating can be used.
- If the roof has no ice, snow or bird attack, acrylic coatings are the most economical.
- Vapor barriers are to be used with impermeable urethane rubber coatings.

Identification of the Cause of PUF Roof Problems

If an engineer is required to identify the cause of damage on the PUF roof, he would use this portion of the expert system. The following inputs are required:

- Are blisters (PUF whose cell structure has lost it's structural capacity) on the roof?
- Is there delamination (separation of lifts) in the PUF?
- Are there full depth cracks in the PUF?
- Is there saturated PUF?
- What is the size of areas of each type of damage, and are they located in traffic areas?

The following production rules are used by the expert system to identify the cause of the damage:

- If delaminations and blisters occur in a roof in over 5 percent of the roof area in less than 10 years of service life, the cause is generally misapplication or substandard materials.
- Cracks of the PUF are generally caused by the lack of control joints.
- Saturation of closed-cell PUF is caused by a combination of a vapor drive and an impermeable covering.
- If blisters appear in more than 5 percent of the roof area, between the 10th and 20th years of service, generally the application of materials were suboptimal.
- After 20 years, delamination and blisters are due to the aging of the PUF roof system.
- Urethane coating that shows full depth cracks before the 10th year of service life was generally installed improperly or with substandard materials.
- Acrylic coating with full depth cracks before the 8th year of service is generally defective.
- Silicone coating that cracks or crazes before the 15th year of service is generally defective.

Maintenance Rules for PUF Roof Systems

The last task is the selection of the most economical maintenance procedure. The expert system can move from the identification of the cause to the selection of the most economical maintenance procedure without losing the description of damage. Additional inputs required include that status of the blisters and whether the roof can receive an aggregate cover. The production rules include:

- If blisters are localized and unbroken, do not break the blisters and avoid trafficking the blistered areas.
- If the coating is cracked, blistered areas are localized, the roof slope is less than 1 inch per foot and the structure can handle the weight of the aggregate (additional 8 to 10 pounds per square foot), the most economical solution is to cover the roof with #6 aggregate (ASTM D 1863).
- Unless in a couple of localized areas that may be economical to remove and replace, if over 20 percent of the roof area contains blistering, delamination or structural cracks, replace the roof system.
- If under 20 percent of the roof area is damaged, repair and recoat the damaged PUF. If the 20 percent of the roof area is in a couple of localized sections, the sections can be removed and replaced.
- If the PUF damage is less than 20 percent, the roof slope is less than 1 inch per foot and the building structure can receive the aggregate weight, repair the damaged PUF and cover with aggregate.

CONCLUSIONS AND RECOMMENDATIONS

This report includes the most current PUF roof system performance data, analysis of the data and the transformation of the data into production rules to specify economical PUF roof systems, and to identify causes of PUF roof system damage and its economical solutions. Spreadsheet programs were developed to assess the economic feasibility by sensitivity analysis, and aid in the preventing of saturation of the PUF.

Conclusions from the data collection and analysis include:

- The PUF roof system is a proven 20-year roofing system.
- The PUF is the critical component of the roofing system.
- Silicone is the most successful elastomeric coating.
- Acrylic and urethane rubber coatings are potential 20-year coatings if recoated in the 10- to 20-year period.
- Blistering is a result of delamination of lifts. It also can be caused by misapplication of substandard materials.
- Blistering problems can be generally eliminated by mechanically installing 1-1/2 to 2 inch lifts. This may increase the allowable compressive stresses by as much as 27 times. Installation of ½ inch minimum lifts with a minimum total thickness of 1/5 inches will also greatly reduce blistering and enhance the service life of the PUF.

FUTURE AREAS OF RESEARCH AND DEVELOPMENT

Additional areas of research and development include:

- Reliability and feasibility study of robotic spraying machine.
- Testing of repeated loadings on thin and thick lifts to determine optimum design.
- Testing and determination of the effects of spraying a 1-1/2 inch pass of PUF on built-up roofing.
- Integration and further development of the expert systems for the analysis of PUF roof systems. The expert system shell can be integrated with the spreadsheets to create a single user interface.
- Additional data on the percentage of blisters caused by trafficking, the amount of saturation in different coating systems and the service life of alternative roofing systems would enhance the current database.
- Long-term study of aggregate covered PUF roof systems.

FURTHER INFORMATION

Dean Kashiwagi and Dr. Moor in conjunction with Systems Analysis are working on a follow-up study on the reliability/feasibility of the PUF robot applicator. The study will include performance testing, economic feasibility and operational requirements. Also, additional roofing surveys have been scheduled for three additional states in 1991. Included in the surveys is a modified cementitious coating system that has an installation record dating back to 1970. The expert system is being modified to include the database of roofs and the economic analysis. Information on surveys and computer programs can be obtained by contacting Systems Analysis at (602)962-1320.

ACKNOWLEDGMENTS

The authors would like to acknowledge the cooperation and support of Irv Stumler of Urethane of Kentuckian, Rick Radobanko of Sprayform Southwest, Roger Morrison of North Carolina Foam Industries, Buddy Cubit of Southeastern Roofing, Samuel Cohen of Texas A&M University's Physical Plant Department and Tom Hagan of North Central Insulation.

REFERENCES

[1] Anon., "A Guide for Selection for Protective Coatings Over Sprayed Polyurethane Foam Roofing Systems," Society of the Plastics Industry, Inc., Washington, D.C., 1988.

[2] Anon. "The Energy Manual," NRCA, Rosemont, Ill., September 1989.

[3] Brzozowski, Kenneth. "PUF," *Contractors Guide*, Niles, Ill., pp. 16-22, January 1989.

[4] Coultrap, Keith H., Alumbaugh, R.L. and Humm, E.F., "Users Guide for Polyurethane Foam Roofing," Naval Facilities Engineering Command, UG-0011, April 1987.

[5] Friederich, Sylvia and Gargano, Michael, Expert Systems Design and Development, New York, John Wiles & Sons, 1989.

[6] Green, Tim, "Roofing Market Hits $17 Billion," *Professional Roofing*, Rosemont, Ill., pp. 40-41, February 1990.

[7] Jones, B.V., "Laboratory and Field Investigations of New Materials For Roof Construction," (Progress Report), Civil Engineering Laboratories Naval Construction Battalion Center, Port Hueneme, Calif., April 1976.

[8] Kashiwagi, D.T. and Moor, W.C., "Performance Criteria of Rigid Polyurethane Foam Roofing and Coatings Based on Random Sampling of Aged Roofs," 32nd Annual Polyurethane Technical/Marketing Conference, October 15-17, 1986.

[9] Kashiwagi, D.T. and Moor, W.C., "Performance and System Requirements For the Polyurethane Foam Roof System," 30th Annual Polyurethane Technical/Marketing Conference, October 15-17, 1986.

[10] Kashiwagi, D., "The Economical Feasibility of the Polyurethane Foam Roof System," Arizona State University, Tempe, Ariz., December 1983.

1 Location:	Phoenix Ariz.
2 Roof Area (SF):	100,000
3 Energy Calculations	
HEATING	
Cost/Gal Heating Oil:	$0.70
Cost/Mil BTU	5.00
Degree Days	1760
Diff U Values	0.0116
Efficiency of Heater	0.75
BUT Savings (Mil BTU)	2.7313
Annual Sav W/PUF	$13.66
COOLING	
Electric Cost/KWH	$0.065
A/C Efficiency (KHW/TON)	1.00
Equiv Oper Hrs	1460
ETD	52
Diff U Value	0.0115
Energy Savings (KWH/YR)	7261.3601
Savings Due to Cooling	$471.99
Total Energy Savings/YR	$485.64
4 Financial Rates	
Interest Rate	0.10
Inflation Rate	0.05
Combined Rate	0.15
5 Roofing Costs	
Tearoff	0
PUF Roof System	
Cost of PUF System (SF)	$2.00
Service Life	15
Additional PUF (IN)	0.5
Addition Cost of PUF	.035
Recoat (Cost/SF)	$1.00
(YR)	15
Present Cost (Total)	$244,449.70
(Cost/SF)	$2.44
EUAC (Cost/YR)	$41,319.42
(Cost/SF/YR)	0.41
Alternative Roof System	
Alt System Cost (SF)	$2.50
(Total $)	$250,000.000
Alt System Service Life	15
Alt EUAC (Cost/YR)	$42,754.26
(Cost/SF/YR)	$0.43
Payback Foam System (YRS)	14.0
Savings of PUF ($/YR)	$1,434.84
(Present $)	$8,213.71

Figure 1 *Silicone-coated PUF system vs. EPDM economic analysis for PUF roof system.*

R Values for Heating Calculations	
Alternative Roof System	R Values
External Air Film	0.17
Single-Ply Rubber Roof	0.1
One Inch Isocyanurate Bond	6.67
4 in. Concrete Deck	6.67
12 in. Air Space	0.94
5/8 in. Ceiling Tile	1.56
Inside Air Space	0.61
Total R Value	16.72
PUF Roof System	R Values
External Air Film	0.17
30 Mil Coating	0.1
PUF	10.71
4 in. concrete Deck	6.67
12 in. Air Space	0.94
5/8 in. Ceiling Tile	1.56
Inside Air Space	0.61
Total R Value	20.76
R Values for Cooling Calculations	
Alternative Roof System	R Values
External Air Film	0.25
Single-Ply Rubber Roof	0.1
One Inch Isocyanurate Board	6.67
4 in. Concrete Deck	6.67
12 in. Air Space	0.99
5/8 in. Ceiling Tile	1.56
Inside Air Space	0.61
Total R Value	16.85
PUF Roof System	R Values
External Air Film	0.25
30 Mil coating	0.1
PUF	10.71
4 in. Concrete Deck	6.67
12 in. Air Space	0.99
5/8 in. Ceiling Tile	1.56
Inside Air Space	0.61
Total R Value	20.89

Figure 2 *PUF vs. EPDM single-ply roof systems.*

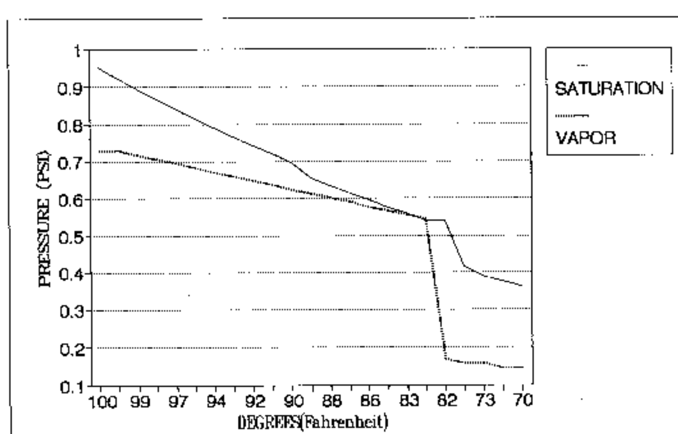

Figure 3 *Vapor pressure vs. saturation pressure (permeable covering case, summer).*

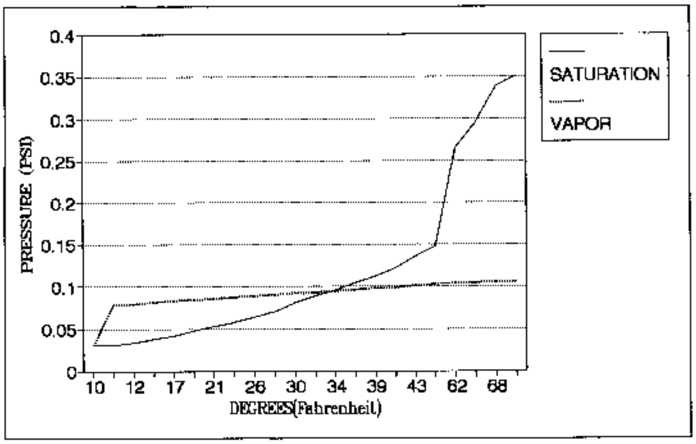

Figure 4 *Vapor pressure vs. saturation pressure (impermeable covering case, winter).*

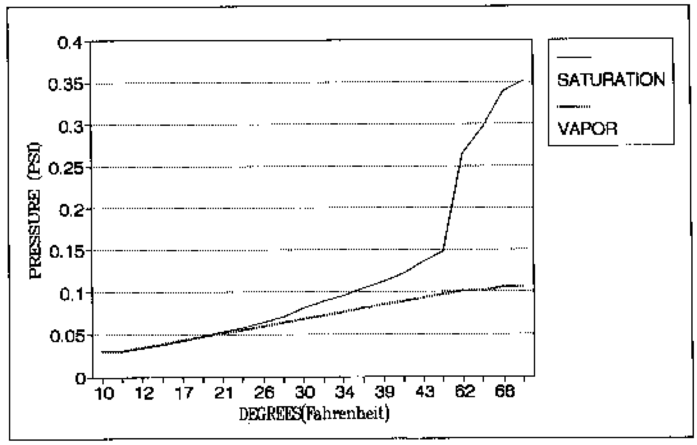

Figure 5 *Vapor pressure vs. saturation pressure (permeable covering case, winter).*

NOS = Number of roofs inspected
AGE = Age of roofs inspected
EX = Excellent condition (No deterioration)
VG = Very good condition (Less than 1% deterioration)
G = Good condition (Less than 5% deterioration)
FR = Fair condition (Less than 10% deterioration)
P = Poor condition (Less than 20% deterioration)
RM = Remove/replace or replaced
BL = Blisters
BD = Bird damage
TR = Traffic on roof
SL = Slope
LK = Leaks
MD = Mechanical damage
RP = Repairs

	NOS	AGE		PUF Condition				Coating Condition						BL	BD	MD	RP	TR	SL	LK
		EX	VG	G	FR	P	RM	EX	VG	G	FR	P	RC	(More than 1% of roof area)						
1	21	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	1
6	17	4	2	0	0	0	0	2	4	0	0	0	1	0	0	0	1	3	2	1
5	16	3	2	0	0	0	0	1	3	0	0	0	1	0	0	0	1	3	2	0
7	15	2	3	1	1	0	0	2	3	1	1	1	0	1	2	1	2	2	5	0
8	14	2	3	3	0	0	0	1	3	3	0	0	0	1	2	2	2	3	3	2
7	13	3	3	0	0	0	1	0	6	0	0	0	0	0	0	0	0	1	3	0
6	12	2	2	2	0	0	0	1	3	1	0	0	0	0	0	1	1	4	2	1
4	11	3	1	0	0	0	0	1	3	0	0	0	0	0	0	0	0	2	1	0
4	10	1	3	0	0	0	0	1	3	0	0	0	0	0	0	0	1	1	2	0
8	9	6	2	0	0	0	0	0	6	2	0	0	0	0	1	0	0	4	4	0
Avg age 13																				
Total																				
56		26	22	6	1	0	1	9	35	7	1	1	3	2	5	4	8	23	25	5
%		46	39	11	2	0	2	16	63	13	2	2	5	4	9	7	14	41	45	9

	NOS	% of total nos. of roofs
Roofs with no blister	43	78
Roofs with no mechanical damage	31	56
Roofs with no bird damage	30	55
Roof with no repairs	31	56

Table 1 *Data collection at Eau Clair, Wisconsin and surrounding areas.*

NOS = Number of roofs inspected
AGE = Age of roofs inspected
EX = Excellent condition (No deterioration)
VG = Very good condition (Less than 1% deterioration)
G = Good condition (Less than 5% deterioration)
FR = Fair condition (Less than 10% deterioration)
P = Poor condition (Less than 20% deterioration)
RM = Remove/replace or replaced
BL = Blisters
BD = Bird damage
TR = Traffic on roof
SL = Slope
LK = Leaks
MD = Mechanical damage
RP = Repairs

NOS	AGE	PUF Condition						Coating Condition						BL	BD	MD	RP	TR	SL	LK
		EX	VG	G	FR	P	RM	EX	VG	G	FR	P	RC	(MT 1% of RA)						
4	16	3	0	0	0	0	1	0	2	1	0	0	0	0	0	0	1	1	2	0
4	15	1	2	0	0	0	1	0	2	0	1	0	2	0	0	0	2	1	1	0
3	14	2	1	0	0	0	0	0	3	0	0	0	1	0	0	0	1	2	3	1
1	13	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
4	12	2	2	0	0	0	0	1	1	0	1	1	1	0	0	1	2	3	3	1
2	11	0	1	1	0	0	0	0	2	0	0	0	1	1	0	0	0	1	2	0
1	10	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
2	9	0	0	2	0	0	0	0	0	1	0	1	0	2	0	2	0	1	1	0
4	8	2	1	1	0	0	0	0	3	0	0	2	0	2	0	2	0	3	3	0
2	6	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	1	0
2	5	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	1	0
1	3	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
2	2	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	2	0	0
3	1	1	2	0	0	0	0	1	2	0	0	0	0	0	0	0	0	2	1	0
Avg age	9.7																			
Total																				
35		14	15	4	0	0	2	3	22	2	2	4	5	4	0	4	6	21	18	2
%		40	43	11	0	0	6	9	63	6	6	11	14	11	0	11	17	60	51	6

	NOS	% of total nos. of roofs
Roofs with no blisters	17	52
Roofs with no mechanical damage	12	36
Roofs with no bird damage	22	67
Roofs with no repairs	15	45

Table 2 Data collection at Louisville, Kentucky and surrounding areas.

NOS = Number of roofs inspected
AGE = Age of roofs inspected
EX = Excellent condition (No deterioration)
VG = Very good condition (Less than 1% deterioration)
G = Good condition (Less than 5% deterioration)
FR = Fair condition (Less than 10% deterioration)
P = Poor condition (Less than 20% deterioration)
RM = Remove/replace or replaced
BL = Blisters
BD = Bird damage
TR = Traffic on roof
SL = Slope
LK = Leaks
MD = Mechanical damage
RP = Repairs

NOS	AGE		PUF Condition				Coating Condition						BL	BD	MD	RP	TR	SL	LK
		EX	VG	G	FR	P	RM	EX	VG	G	FR	P	RC	(MT 1% of RA)						
2	16	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	1	1
4	15	1	2	1	0	0	0	1	1	0	1	1	0	0	0	1	0	0	2	1
3	14	1	2	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
3	13	1	1	0	1	0	0	0	1	0	1	0	1	1	0	0	0	2	1	1
7	12	1	4	0	0	1	1	0	2	0	2	0	3	3	0	1	0	3	2	0
5	11	0	5	0	0	0	0	0	5	0	0	0	0	1	0	0	0	3	1	0
2	10	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	0	0
1	9	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2	8	0	1	1	0	0	0	0	1	0	0	1	0	1	0	0	0	2	0	0
1	7	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0
1	3	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0
Avg age 12																				
Total																				
32		5	21	2	1	1	2	2	19	0	4	3	4	6	0	2	2	14	8	3
%		0	16	66	6	3	3	6	6	59	13	9	13	19	0	6	6	44	25	9

	NOS	% of total nos. of roofs
Roofs with no blisters	7	22
Roofs with no mechanical damage	12	38
Roofs with no bird damage	32	100
Roofs with no repairs	15	47

Table 3 *Data collection at Texas A&M, College Station, Texas.*

NOS = Number of roofs inspected
AGE = Age of roofs inspected
EX = Excellent condition (No deterioration)
VG = Very good condition (Less than 1% deterioration)
G = Good condition (Less than 5% deterioration)
FR = Fair condition (Less than 10% deterioration)
P = Poor condition (Less than 20% deterioration)
RM = Remove/replace or replaced
BL = Blisters
BD = Bird damage
TR = Traffic on roof
SL = Slope
LK = Leaks
MD = Mechanical damage
RP = Repairs

NOS	AGE		PUF Condition				Coating Condition						BL	BD	MD	RP	TR	SL	LK
		EX	VG	G	FR	P	RM	EX	VG	G	FR	P	RC	(MT 1% of RA)						
1	20	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0
1	19	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0
5	18	2	2	0	0	0	1	1	2	0	2	0	2	1	0	0	2	2	3	2
3	17	1	1	1	0	0	0	1	1	0	1	0	2	1	0	0	1	2	1	0
1	16	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
1	14	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0
2	12	2	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0	2	2	0
Avg age 17																				
Total																				
14		7	5	1	0	0	1	7	4	0	3	0	10	2	0	0	3	8	8	2
%		50	36	7	0	0	7	50	29	0	21	0	71	14	0	0	21	57	57	14

	NOS	% of total nos. of roofs
Roofs with no blisters	7	50
Roofs with no mechanical damage	11	79
Roofs with no bird damage	11	79
Roofs with no repairs	7	50

Table 4 *Data collection at Phoenix, Arizona.*

NOS = Number of roofs inspected
AGE = Age of roofs inspected
EX = Excellent condition (No deterioration)
VG = Very good condition (Less than 1% deterioration)
G = Good condition (Less than 5% deterioration)
FR = Fair condition (Less than 10% deterioration)
P = Poor condition (Less than 20% deterioration)
RM = Remove/replace or replaced
BL = Blisters
BD = Bird damage
TR = Traffic on roof
SL = Slope
LK = Leaks
MD = Mechanical damage
RP = Repairs

NOS	AGE	PUF Condition						BL	BD	MD	RP	TR	SL	LK
		EX	VG	G	FR	P	RM	(MT 1% of RA)						
13	4	12	1	0	0	0	0	0	0	0	0	5	7	0
7	3	4	2	0	1	0	0	1	0	0	0	4	2	0
11	2	9	1	0	0	1	0	1	0	0	0	2	4	0
15	1	1	0	0	0	0	0	0	0	0	0	7	6	0
4	LT1	4	0	0	0	0	0	0	0	0	0	2	1	0
Avg age	2.2													
Total														
50		44	4	0	1	1	0	2	0	0	0	20	20	0
%		88	8	0	2	2	0	4	0	0	0	40	40	0

	NOS	% of total nos. of roofs
Roofs with no blisters	44	88
Roofs with no mechanical damage	50	100
Roofs with no bird damage	50	100
Roofs with no repairs	50	100

Table 5 Data collection at Spartanburg, South Carolina and surrounding areas.

NOS = Number of roofs inspected
AGE = Age of roofs inspected
EX = Excellent condition (No deterioration)
VG = Very good condition (Less than 1% deterioration)
G = Good condition (Less than 5% deterioration)
FR = Fair condition (Less than 10% deterioration)
P = Poor condition (Less than 20% deterioration)
RM = Remove/replace or replaced
BL = Blisters
BD = Bird damage
TR = Traffic on roof
SL = Slope
LK = Leaks
MD = Mechanical damage
RP = Repairs
RC = Recoated

NOS	AGE	PUF Condition						Coating Condition						BL	BD	MD	RP	TR	SL	LK
		EX	VG	G	FR	P	RM	EX	VG	G	FR	P	RC	(MT 1% of RA)						
1	21	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1
1	20	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
1	19	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
5	18	2	2	0	0	0	1	1	2	0	2	0	0	1	0	0	2	2	3	2
9	17	5	3	1	0	0	0	3	5	0	1	0	0	1	0	0	2	5	3	1
12	16	7	4	0	0	0	1	2	7	1	0	0	1	0	0	0	3	4	5	1
15	15	4	7	2	1	0	1	3	6	1	3	2	0	1	2	2	4	3	8	1
15	14	5	7	3	0	0	0	2	9	3	0	0	1	1	2	2	3	6	7	3
11	13	4	5	0	1	0	1	0	7	0	1	1	1	1	0	0	0	3	4	1
18	12	6	8	2	0	1	1	1	6	3	3	1	3	3	0	3	3	12	9	2
11	11	3	7	1	0	0	0	1	10	0	0	0	0	2	0	0	0	6	4	0
7	10	1	6	0	0	0	0	1	6	0	0	0	0	0	0	0	1	3	2	0
11	9	7	2	2	0	0	0	0	7	3	0	1	0	2	1	2	0	5	5	0
6	8	2	2	2	0	0	0	0	4	0	0	2	0	2	0	1	0	5	3	0
1	7	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0
2	6	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	1	0
2	5	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	1	0
13	4	12	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	7	0
9	3	4	4	0	1	0	0	0	2	0	0	0	0	1	0	0	0	7	2	0
13	2	10	2	0	0	1	0	1	1	0	0	0	0	1	0	0	0	4	4	0
19	1	16	3	0	0	0	0	3	1	0	0	0	0	0	0	0	0	10	7	0
4	LT1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0
Avg age	9.6																			
Total																				
186		95	67	13	3	2	6	19	79	11	10	8	6	16	5	10	19	87	79	72
		51	36	7	2	1	3	14	58	8	7	6	4	9	3	5	10	47	42	6

	NOS	% of total nos. of roofs
Roofs with no blisters	118	63
Roofs with no mechanical damage	116	62
Roofs with no bird damage	145	78
Roofs with no repairs	118	63

Table 6 1990 Data collection of PUF roofs.

Service Life	Silicone $2.25 EUAC $/SF/YR	Gravel $1.50 EUAC $/SF/YR	Acrylic $1.95 EUAC $/SF/YR	Urethane Rubber $2.35 EUAC $/SF/YR	EPDM Single-Ply $2.50 EUAC $/SF/YR
25	$0.34	$0.22	$0.33	$0.37	$0.39
24	$0.34	$0.22	$0.33	$0.38	$0.39
23	$0.34	0.23	$0.33	$0.38	$0.39
22	$0.34	$0.23	$0.34	$0.38	$0.39
21	$0.35	$0.23	$0.34	$0.38	$0.40
20	$0.35	$0.23	$0.34	$0.39	$0.40
19	$0.35	$0.23	$0.35	$0.39	$0.40
18	$0.36	$0.24	$0.35	$0.39	$0.41
17	$0.36	$0.24	$0.35	$0.40	$0.41
16	$0.37	$0.24	$0.36	$0.41	$0.42
15	$0.38	$0.25	$0.37	$0.41	$0.43
14	$0.38	$0.25	$0.37	$0.42	$0.44
13	$0.39	$0.26	$0.38	$0.43	$0.45
12	$0.40	$0.27	$0.40	$0.45	$0.46
11	$0.42	$0.28	$0.41	$0.46	$0.48
10	$0.44	$0.29	$0.43	$0.48	$0.50
9	$0.46	$0.30	$0.45	$0.51	$0.52
8	$0.49	$0.32	$0.48	$0.54	$0.56
7	$0.53	$0.35	$0.52	$0.58	$0.60
6	$0.58	$0.38	$0.57	$0.64	$0.66
5	$0.66	$0.43	$0.64	$0.72	$0.75
4	$0.77	$0.51	$0.75	$0.85	$0.88
3	$0.97	$0.64	$0.95	$1.07	$1.09
2	$1.36	$0.90	$1.33	$1.50	$1.54
1	$2.55	$1.69	$2.49	$2.81	$2.88

Table 7 Equivalent Uniform Annual Cost (EUAC)—concrete deck.

Outside Conditions		**Inside Conditions**	
Temperature	100	Temperature	70
Humidity (%)	77	Humidity (%)	40
Vapor Pressure	0.73118	Vapor Pressure	0.145216

Component	R-Value	Vapor Resistance	Temp (F)	Saturation Pressure	Vapor Pressure Saturation
Outside Air	0.170	0.000	100	0.950	0.731
Covering	0.100	0.000	100	0.921	0.731 O
PUF 1/8 in.	0.893	0.063	99	0.894	0.719 O
PUF 1/8 in.	0.893	0.063	98	0.867	0.708 O
PUF 1/8 in.	0.893	0.063	97	0.841	0.696 O
PUF 1/8 in.	0.893	0.063	96	0.816	0.684 O
PUF 1/8 in.	0.893	0.063	94	0.791	0.673 O
PUF 1/8 in.	0.893	0.063	93	0.767	0.661 O
PUF 1/8 in.	0.893	0.063	92	0.743	0.649 O
PUF 1/8 in.	0.893	0.063	91	0.721	0.637 O
PUF 1/8 in.	0.893	0.063	90	0.698	0.626 O
PUF 1/8 in.	0.893	0.063	89	0.656	0.614 O
PUF 1/8 in.	0.893	0.063	88	0.635	0.602 O
PUF 1/8 in.	0.893	0.063	87	0.615	0.590 O
PUF 1/8 in.	0.893	0.063	86	0.596	0.579 O
PUF 1/8 in.	0.893	.063	85	0.577	0.567 O
PUF 1/8 in.	0.893	0.063	83	0.559	0.555 O
PUF 1/8 in.	0.893	0.063	82	0.541	0.544 X
Waterproofing	0.100	2.000	82	0.541	0.168 O
Conc Deck 4 in.	6.670	0.056	74	0.416	0.158 O
Air Space 12 in.	0.990	0.000	73	0.389	0.158 O
Ceiling Tile	1.560	0.067	71	0.376	0.145 O
Inside Space	0.610	0.000	70	0.363	0.145 O
Total	24.48	3.122			

Table 8 Permeable covering case—summer vapor drive analysis.

Outside Conditions

Temperature	10
Humidity (%)	100
Vapor Pressure	0.03087

Inside Conditions

Temperature	70
Humidity (%)	30
Vapor Pressure	0.105252

Component	R-Value	Vapor Resistance	Temp (F)	Saturation Vapor Pressure	Vapor Pressure Saturation
Outside Air	0.170	0.000	10	0.031	0.031
Covering	0.100	2.000	10	0.031	0.079 X
PUF 1/8 in.	0.893	0.063	12	0.034	0.080 X
PUF 1/8 in.	0.983	0.063	15	0.038	0.081 X
PUF 1/8 in.	0.893	.063	17	0.042	0.083 X
PUF 1/8 in.	0.893	0.063	19	0.048	0.084 X
PUF 1/8 in.	0.893	0.063	21	0.053	0.086 X
PUF 1/8 in.	0.893	0.063	23	0.058	0.087 X
PUF 1/8 in.	0.893	0.063	26	0.064	0.089 X
PUF 1/8 in.	0.893	0.063	28	0.070	0.090 X
PUF 1/8 in.	0.893	0.063	30	0.081	0.092 X
PUF 1/8 in.	0.893	0.063	32	0.089	0.093 X
PUF 1/8 in.	0.893	0.063	34	0.096	0.095 O
PUF 1/8 in.	0.893	0.063	37	0.104	0.096 O
PUF 1/8 in.	0.893	0.063	39	0.112	0.098 O
PUF 1/8 in.	0.893	0.063	41	0.122	0.099 O
PUF 1/8 in.	0.893	0.063	43	0.137	0.101 O
PUF 1/8 in.	0.893	0.063	45	0.147	0.102 O
Conc Deck 4 in.	6.670	0.056	62	0.265	0.104 O
Air Space 12 in.	0.990	0.000	64	0.295	0.104 O
Ceiling Tile	1.560	0.067	68	0.339	0.105 O
Inside Space	0.610	0.000	70	0.351	0.105 O
Total	24.38	3.122			

Table 9 *Impermeable covering case—winter vapor drive analysis.*

Outside Conditions

Temperature	10
Humidity (%)	100
Vapor Pressure	0.03087

Inside Conditions

Temperature	70
Humidity (%)	30
Vapor Pressure	0.105252

Component	R-Value	Vapor Resistance	Temp (F)	Saturation Vapor Pressure	Vapor Pressure Saturation
Outside Air	0.170	0.000	10	0.031	0.031
Covering	0.100	0.000	10	0.031	0.031 O
PUF 1/8 in.	0.893	0.063	12	0.034	0.035 X
PUF 1/8 in.	0.893	0.063	15	0.038	0.039 X
PUF 1/8 in.	0.893	0.063	17	0.042	0.043 X
PUF 1/8 in.	0.893	0.063	19	0.048	0.047 O
PUF 1/8 in.	0.893	0.063	21	0.053	0.052 O
PUF 1/8 in.	0.893	0.063	23	0.058	0.056 O
PUF 1/8 in.	0.893	0.063	26	0.064	0.060 O
PUF 1/8 in.	0.893	0.063	28	0.070	0.064 O
PUF 1/8 in.	0.893	0.063	30	0.081	0.068 O
PUF 1/8 in.	0.893	0.063	32	0.089	0.072 O
PUF 1/8 in.	0.893	0.063	34	0.096	0.076 O
PUF 1/8 in.	0.893	0.063	37	0.104	0.081 O
PUF 1/8 in.	0.893	0.063	39	0.112	0.085 O
PUF 1/8 in.	0.893	0.063	41	0.122	0.089 O
PUF 1/8 in.	0.893	0.063	43	0.137	0.093 O
PUF 1/8 in.	0.893	0.063	45	0.147	0.097 O
Conc Deck 4 in.	6.670	0.056	62	0.265	0.101 O
Air Space 12 in.	0.990	0.000	64	0.295	0.101 O
Ceiling Tile	1.560	0.067	68	0.339	0.105 O
Inside Space	0.610	0.000	70	0.351	0.105 O
Total	24.38	1.122			

Table 10 *Permeable covering case—winter vapor drive analysis.*

APPENDIX 1
Expert System Part I
Specification of a PUF Roof System
September 21, 1990
Version 1.1

Author: Dean T. Kashiwagi

```
EXECUTE;
ENDOFF;
BKCOLOR = 1;
ACTIONS MOUSEOFF;
COLOR = 7
DISPLAY "This expert system advises you on the optimal and most
economical PUF roofing system you can install on a roof deck.
This system is not sponsored by a manufacturer of a particular
coating or roof system, and all proposals are based on study of
PUF roof systems in the field. If the economical system and the
optimal system are the same, only the most economical system
will be listed.
  DISPLAY "To enter in the values, hit the return key. To move
the highlight from one choice to another, use the arrow keys.
  FIND economical—cover
  CHAIN part2; !PART 1 CHAINS TO PART 2 WHICH IN-
CLUDES CAUSES/SOLUTIONS
  RULE O
IF
  design = no
THEN
  economical—cover = not—interested;
  RULE 1 !Aggregate w/no vapor drive
IF
  loadbearing = yes AND
  vapor—drive = no AND
  ice—and—snow = yes OR
  ice—and—snow = no AND
  bird—attack = yes OR
  bird—attack = no AND
  mechanical—traffic = yes OR
  mechanical—traffic = no AND
  slope ◄ = 1.0
THEN
  economical—cover = #6—lightweight—aggregate
  economical—depth = 1.5
  DISPLAY "The most economical system is 1.5 inches of PUF
with a covering of #6 lightweight aggregate.";

RULE 2 !Aggregate w/vapor drive and no ponding or ice
IF
  loadbearing = yes AND
  vapor—drive = yes AND
  ponding = no AND
  ice—and—snow = no AND
  bird—attack = yes OR
  bird—attack = no AND
  mechanical—traffic = yes OR
  mechanical—traffic = no AND
  slope ◄ = 1.0
THEN
  economical—cover = #6—lightweight—aggregate
  economical—depth = 1.5
  DISPLAY "The most economical system is 1.5 inches of PUF
with a covering of #6 lightweight aggregate.";

RULE 3 !Aggregate w/vapor drive and ponding
IF
  loadbearing = yes AND
  vapor—drive = yes AND
  ponding = yes AND
  ice—and—snow = no OR
  ice—and—snow = yes AND
  bird—attack = yes OR
  bird—attack = no AND
  mechanical—traffic = yes OR
  mechanical—traffic = no AND
  slope ◄ = 1.0
THEN
  economical—cover = #6—lightweight—aggregate
  economical—depth = 2.0
  DISPLAY "The most economical system is 2 inches of PUF with
a covering of lightweight aggregate.";

RULE 4 !Aggregate w/vapor drive and ice
IF
  loadbearing = yes AND
  vapor—drive = yes AND
  ponding = yes OR
  ponding = no AND
  ice—and—snow = yes AND
  bird—attack = yes OR
  bird—attack = no AND
  mechanical—traffic = yes OR
  mechanical—traffic = no AND
  slope ◄ = 1.0
THEN
  economical—cover = #6—lightweight—aggregate
  economical—depth = 2.0
DISPLAY "The most economical system is 2 inches of PUF with
a covering of lightweight aggregate.";

RULE 5 !Bird attack w/O vapor drive
IF
  bird—attack = yes AND
  vapor—drive = no AND
  ponding = yes OR
  ponding = no AND
  ice—and—snow = yes OR
  ice—and—snow = no AND
  mechanical—traffic = yes OR
  mechanical—traffic = no
THEN
  economical—cover = urethane—rubber
  economical—depth = 1.5
  DISPLAY "The most economical system is 1.5 inches of PUF
with a urethane rubber coating.";

RULE 6 !Bird attack w/vapor drive
IF
  bird—attack = yes AND
  vapor—drive = yes AND
  ponding = yes OR
  ice—and—snow = yes AND
  mechanical—traffic = yes OR
  mechanical—traffic = no
THEN
  economical—cover = urethane—rubber
  economical—depth = 2.0
  DISPLAY "The most economical system is 1.5 inches of PUF
with a urethane rubber coating.";

RULE 7 !Bird attack w/vapor drive, no ice/ponding
IF
  bird—attack = yes AND
  vapor—drive = yes AND
  ponding = no OR
  ice—and—snow = no AND
  mechanical—traffic = yes OR
  mechanical—traffic = no
```

```
THEN
  economical—cover = urethane—rubber
  economical—depth = 1.5
  DISPLAY "The most economical system is 1.5 inches of PUF
with a urethane rubber coating.";

RULE 8 !Bird attack w/vapor drive
IF
  bird—attack = yes AND
  vapor—drive = no AND
  ponding = no AND
  ice—and—snow = no AND
  mechanical—traffic = yes OR
  mechanical—traffic = no
THEN
  economical—cover = urethane—rubber
  economical—depth = 1.0
  DISPLAY "The most economical system is 1.5 inch of PUF with
a urethane rubber coating.";

RULE 9 !Snow/Ice, traffic, and vapor drive
IF
  ice—and—snow = yes AND
  mechanical—traffic = yes AND
  vapor—drive = yes AND
  bird—attack = no AND
  ponding = yes OR
  ponding = no
THEN
  economical—cover = urethane—rubber
  economical—depth = 2.0
  DISPLAY "The most economical system is 2 inches of PUF with
a silicone coating with granules or a urethane rubber coating.";

RULE 10 !Snow/Ice, traffic, and no vapor drive
IF
  ice—and—snow = yes AND
  mechanical—traffic = yes AND
  vapor—drive = no AND
  bird—attack = no AND
  ponding = yes OR
  ponding = no
THEN
  economical—cover = urethane—rubber
  economical—depth = 1.5
  DISPLAY "The most economical system is 1.5 inches of PUF
with a silicone coating with granules or a urethan rubber coating.";

RULE 11 !Snow/ice, no traffic, and vapor drive
IF
  ice—and—snow = yes AND
  mechanical—traffic = no AND
  vapor—drive = yes AND
  ponding = yes OR
  ponding = NO
THEN
  economical—cover = silicone—coating
  economical—depth = 2.0
  DISPLAY "The most economical system is 2 inches of PUF with
a silicone coating with granules.";

RULE 12 !Snow/ice, no traffic and no vapor drive
IF
  ice—and—snow = yes AND
  mechanical—traffic = no AND
  vapor—drive = no AND
  bird—attack = no AND
  ponding = yes OR
  ponding = no
THEN
  economical—cover = silicone—coating
  economical—depth = 1.5
  DISPLAY "The most economical system is 1.5 inches of PUF
with a silicone coating with granules.";

RULE 13 !No bird attack, ice, traffic, and vapor drive, with
ponding
IF
  bird—attack = no AND
  ice—and—snow = no AND
  mechanical—traffic = yes AND
  vapor—drive = yes AND
  ponding = yes
THEN
  economical—cover = acrylic—rubber
  economical—depth = 2.0
  optimal—coating = silicone—coating—with—granules
  DISPLAY "The most economical system is 2 inches of PUF with
an acrylic coating with granules. More optimal coatings are sili-
cone with granules and urethane rubber coatings.";

RULE 14 !No bird attack, ice, traffic, vapor drive, no ponding
IF
  ice—and—snow = no AND
  bird—attack = no AND
  mechanical—traffic = yes AND
  vapor—drive = yes AND
  ponding = no
THEN
  economical—cover = acrylic—coating
  economical—depth = 2.0
  optimal—coating = silicone—coating—with—granules
  DISPLAY "The most economical system is 2 inches of PUF with
an acrylic coating with granules.";

RULE 15 !No bird attack/ice, no traffic, vapor drive, ponding
IF
  bird—attack = no AND
  ice—and—snow = no AND
  mechanical—traffic = no AND
  vapor—drive = yes AND
  ponding = yes
THEN
  economical—cover = acrylic—rubber
  economical—depth = 2.0
  optimal—coating = silicone—coating—with—granules
  DISPLAY "The most economical system is 2 inches of PUF with
an acrylic coating with granules. A more optimal coating is sili-
cone coating with granules.";

RULE 16 !No bird attack/ice, no traffic, vapor drive, no ponding
IF
  bird—attack = no AND
  ice—and—snow = no AND
  mechanical—traffic = no AND
  vapor—drive = yes AND
  ponding = no
THEN
  economical—cover = acrylic—rubber
  economical—depth = 1.5
  optimal—coating = silicone—coating—with—granules
  DISPLAY "The most economical system is 1.5 inches of PUF
with an acrylic coating with granules. A more optimal coating is
a silicone coating with granules.";

RULE 17 !No bird attack/ice, no traffic, no vapor drive
IF
```

bird—attack = no AND
ice—and—snow = no AND
mechanical—traffic = no AND
vapor—drive = no AND
ponding = no OR
ponding = yes
THEN
economical—cover = acrylic—rubber
economical—depth = 1.5
optimal—coating = silicone—coating—with—granules
DISPLAY "The most economical system is 1.5 inches of PUF with an acrylic coating with granules. A more optimal coating is a silicone coating with granules.";

INPUT QUESTIONS
Ask design: "Do you want to do a specification of a PUF system?"
Choices design: yes, no;

Ask loadbearing: "Is the roof capable of receiving 40 psf of lightweight aggregate?";
Choices loadbearing: yes, no;

Ask slope: "What is the slope of the roof? Enter the slope in inches per foot. Example if 1 inch/foot, enter 1.";

Ask ponding: "Is there a potential of ponding on the roof?";
Choices ponding: yes, no;

Ask mechanical—traffic: "Will there be mechanical traffic on the roof?";
Choices mechanical—traffic: yes, no;

Ask high—uv: "Is there high uv in the area?";
Choices high—uv: yes, no;

Ask ice—and—snow: "Does the roof collect snow/ice?";
Choices ice—and—snow: yes, no;

Ask vapor—drive: "Will there be vapor drive from the inside to the outside?";
Choices vapor—drive: yes, no;

Ask bird—attack: "Is there incidents of birds attacking PUF in the area?";
Choices bird—attack: yes, no;