THE ECONOMIC FEASIBILITY OF THE POLYURETHANE FOAM ROOF SYSTEM

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In the summer of 1982, a year-long study was initiated at Arizona State University to determine if an economically feasible 20-year polyurethane foam (PUF) roof system could be specified, installed and maintained. Previous work in this area was limited to a few case studies conducted by government agencies.

The objectives of the study were to determine the following:

1. The existence of a "successful" PUF roofing system. A successful PUF roof system is defined as having a minimum 20-year service life without requiring more than 20 percent replacement of the PUF.
2. The existence of a "successful" applicator of PUF roof systems. A "successful" applicator was defined as having a 90 percent customer satisfaction rating and a 90 percent probablility of installing a potential 20-year PUF roof system, based on random sampling of past applications.
3. Required maintenance on "successful" PUF roof systems.
4. Potential of specifying and procuring a "successful" PUF roof system by defining the installation procedures of "successful" applications and establishing performance specifications based on quantitative measurements.
5. Equivalent uniform annual cost (EUAC) of a "successful" PUF roof system compared to the built-up roof (BUR) system.

OVERVIEW OF THE STUDY

The first requirement of the study was to locate potential 20-year PUF roof systems. The study was restricted to "successful" roof systems. "Unsuccessful" PUF roofs have been installed, but due to the lack of knowledge of why they failed, these roofs cannot be used to determine the potential service life of a properly installed PUF roof system. The model of a "successful" PUF roof used in this analysis has three major factors: the materials, the installation and the "in-place" roof system. The objective of this study is to first determine if the PUF roof system "in-place" can have a potential 20-year service life. To achieve this objective, the other two factors of the model must be held constant, therefore in the determination of the "successful" PUF roof system, it was assumed that the installation was "successful" and the materials were what was required for a "successful" PUF roof system. This was accomplished by considering only "successful" roof systems. If "unsuccessful" PUF roof systems were considered, the analysis would be invalid because of the failure to identify the cause for "failure." Once it was determined that PUF roof systems were successful "in-place", the required installation procedure and materials were reviewed, tested and validated.

As previously stated, one of the objectives of this study was to write a specification which can differentiate between "successful" and "unsuccessful," ensuring the installation (second factor of the model) of a "successful" PUF roof system. After the unbiased selection and inspection of the roofs, the results were analyzed for the consistency in the installation rate of "successful" PUF roof systems. The economic feasibility of the roof system then was determined. The concluding step was the writing and trial utilization of a specification that ensured the installation of the economically feasible "successful" PUF roof system identified in the study.

The project was broken into four stages. Questionnaires were used to select potential "successful" contractors in the continental United States. Five contractors and one using agency were selected for participation due to their longevity, availability of records, number of roofs they had installed, and the geographical location. Complete job listings of all roof installations were required of the participants. The second stage was to compile a data base of roof installations constructed from the job listings and select the roofs to be inspected and surveyed. All selections were made without any knowledge of existing roof conditions or customer satisfaction and emphasis was placed on older roofs. The third stage of the study included the inspection and survey of the roofs, and the analysis of the data collected. An economic analysis then was conducted using the data from the survey and inspections. The final task was to write a performance specification, use it in an engineering application, and compare the installation to the "successful" PUF roof system.

RATING SYSTEM

Each roof inspected (except for asphalt-coated PUF roofs which are listed under the AS column) was given a roof condition rating. A rating system devised by Alumbaugh, Humm, and Keeton,[2] slightly modified to allow for quantitative measurements, was utilized (*Table 1*). The roof condition ratings in Table 1 were used solely to classify the roof's condition in this report. Failure of a roof system is currently a subjective determination in the roofing industry. For example, a roof classified as "poor" would exhibit between 10 percent and 20 percent deterioration of its PUF and elastomeric coating. Deterioration was defined as areas containing coating or PUF requiring removal and replacement due to external influences (i.e., ultraviolet degradation, mechanical damage, etc.) to provide the PUF roof

system with a 20-year service life. The percentage of deterioration of a roof was determined by measuring areas of deterioration on a roof system. The minimum area of deterioration for the study was fixed at one square foot. Roofs which failed due to structural movement or "acts of God" were not counted as failures. Roofs are not designed to withstand structural movement of buildings or "acts of God." Thus for the purposes of this study, these influences were factored out. Asphalt-coated roofs were not rated because of the difficulty in determining what percentage of the roof required removal. A rating system for the asphalt-coated PUF roof is an area of future research. The owner of each roof inspected was asked the following questions to assist in determining the performance of the PUF roof system and the applicator:

1. Would you use the PUF roof system in the future? (Question 1 in *Table 2*)
2. Are you satisfied with your PUF roof system? (Question 2 in *Table 2*)
3. Are you satisfied with the applicator who installed your PUF roof system? (Question 3 in *Table 2*)
4. What type of maintenance do you conduct on your PUF roof system?
5. Has your roof leaked, and was it covered under warranty?

The various coatings and PUF roof systems then were analyzed by geographical area.

RESULTS OF SURVEY

A total of 246 roofs (22 percent of the 1,125 roofs listed in the data base) were selected and inspected. The PUF roof systems inspected were coated with silicone, acrylic, urethane rubber and asphalt coatings. Inspected roofs were located in Phoenix, Arizona; Boulder, Colorado; southern Wyoming; Eau Clair, Wisconsin, and surrounding areas; Cranford, New Jersey, and surrounding areas; Louisville, Kentucky; and College Station, Texas. The data collected in the survey and inspections resulted in all five participating contractors being classified by definition as "successful" applicators of PUF roof systems. The results show no decrease in customer satisfaction but an increase in the service life of the PUF roof systems (*Table 2*). The percentages shown are percentages of positive replies received for that particular question. The total number of roofs listed in Table 2 only includes those roofs wherein owners answered the survey questions. Some roofs were inspected, but the owner was unavailable for comment. Some owners refused to answer some of the questions. The lowest customer satisfaction was in the six- to nine-year-old roofs. The following reasons were recorded for dissatisfaction with the PUF roof system:

1. A silicone roof suffered heavy bird damage (pecking). The roof was not protected with a topcoat of granules. (This has been a solution to the bird problem).
2. A roof had a chronic leaking problem which the applicator had not been able to solve.
3. One customer had procured an asphalt-coated PUF roof six years ago for $1.50 per square foot (very inexpensive for a roof with a 10-year unconditional performance contract). She felt she had been cheated and gave a negative reply. Her roof had not leaked and was in excellent condition.
4. One customer was dissatisfied with the appearance of his asphalt-coated PUF roof. His roof was eight years old and had not leaked. He proceeded to have his PUF roof system recoated with another coating of asphalt and a layer of gravel for $.20 per square foot and a five-year "all inclusive" performance agreement.
5. Two customers did not know how to locate and fix a leak in their PUF roof. They did not contact the applicator to find the solution to their problem.
6. A roof leaked once at the nine-year service mark. The leak was repaired by the applicator at no cost to the owner. The building manager claimed that the PUF roof system was not a valid roof system, and gave a dissatisfied reply.
7. One owner had a leak in this building and claimed it was the roof that was leaking. When the applicator and the owner tested the roof with a hose, it was determined that the adjacent wall was leaking and not the roof. He gave a negative reply and would not explain his answer.
8. Another owner did not know how to repair three or four bird pecks in his roof. He was informed that repairs could be made with a tube of silicone caulking. His roof was years old, had not leaked, and was in "good" condition.

Only five (3 percent of all customers who answered this question) of the eight dissatisfied customers were dissatisfied because of the PUF roof-related problems. These were the customers (listed above as Numbers 1, 2, 5, and 8) who were dissatisfied because of a leaking problem or bird damage to their roof. The PUF roof systems inspected at Texas A&M University were all classified as "successful" PUF roof systems. These roofs did not receive customer satisfaction ratings because the author had had prior knowledge that the building systems engineer was satisfied with his urethane-coated PUF roof systems. The roofs were inspected for condition, required maintenance, and quantifiable physical properties of the installed systems.

RESULTS OF THE ROOF INSPECTIONS

Twenty-eight percent of the roofs inspected exhibited no deterioration. Seventy-nine percent of the roofs had less than one percent of the total roof area showing deterioration. Table 3 lists the overall roof condition rating results. In Table 3, the asphalt-coated PUF roofs are listed separately under AS. Repair procedures such as "venting" saturated PUF, and recoating areas of ultraviolet "burned" PUF, made it difficult to determine a percentage of "deterioration" and a roof condition on the asphalt roofs with any degree of validity. Forty-nine of the roof systems (20 percent of the inspected roofs) were installed over nine years ago. Most of these roof systems were installed with a coating thickness less than that currently recommended for coatings. Considering the "state-of-the-art" practices,[5, 4, 3] the author concludes that PUF roof systems with the recommended coating thicknesses will outperform these older roof systems with the thinner coatings. Only two of the roof systems with over nine years service life (6 percent of those roofs receiving roof condition ratings), had more than 10 percent deterioration.

Only six roofs (3 percent of those receiving roof condition ratings) were classified as "failures." Of these, three were removed and replaced without the knowledge of the

contractor. Although they may have been repairable, they were classified as "failures." Another failure was located in Phoenix, Arizona. The owner had directed the contractor to install a 1-inch PUF roof system with an eight-mil thick acrylic coating. The applicator refused to warranty the roof system because of the inadequate coating thickness (the suggested thickness of acrylic coatings is 30 mils). After 10 years of service life, the coating was cracking and flaking, exposing the PUF, and causing leakage of water into the building. The owner had the damaged sections of the PUF replaced, and recoated with the proper thickness of coating. This application was classified a "failure" because over 20 percent of the PUF had to be removed and replaced. Another PUF roof application in Phoenix, Arizona, was on a water chiller tower. The clearance between the water chiller and the roof did not allow proper application around the numerous penetrations. After eight years, the water penetrated beneath the PUF and began to seep into the building. Due to the unique application, the owner decided to remove the existing PUF roof and replace it with another. The sixth failure was a low-density PUF application (approximately 1.5 pounds per cubic foot) in the heaviest hail environment in the continental United States. It was the only roof inspected in the area which failed due to hail damage.

The majority of the roofs inspected were "flat" roofs. Only 61 roofs (25 percent of those inspected) had slopes of more than ⅛-inch per lineal foot. Ninety-nine percent of the roofs were inspected two times a year or less, and 51 percent of the roofs had not been inspected at all until the study was conducted. Ninety-two percent of the roofs showed no problems. Bird damage was reported on three percent of the roofs. Eleven percent of the roofs had leaked at one time or another and were repaired at no cost or at owner's expense. Silicone, urethane rubber, acrylic, and asphalt-coated PUF roof systems were inspected. Each coating system requires a "successful" applicator or an applicator who uses the same technique of installation. More research is required on installed PUF and coating systems to more clearly define the limitations of each system.

SILICONE-COATED ROOF SYSTEMS

Data collected on silicone roofs in Phoenix, Ariz.; Boulder, Colo.; Eau Clair, Wis.; and Louisville, Ky. revealed the following:

1. If installed properly, silicone-coated PUF roof systems have a potential service life of 20 years. This conclusion was reached after 10-, 11-, and 12-year-old silicone-coated PUF systems showed no deterioration. Because silicone coatings maintain their elasticity and do not degrade from ultraviolet rays, it is safe to conclude that the roof system will reach a minimum service life of 20 years.[1]
2. Minimum thicknesses of 20 mils of silicones are sufficient for a "successful" roof system.
3. Granulation with Number 11 granules is successful in helping to provide protection against bird damage, hail damage and mechanical damage.
4. A minimum one-inch thick layer of three-pound density (one pound per cubic foot) PUF with silicone coatings (20 mils minimum) can resist mechanical damage, foot traffic and snow and ice loads. Silicone-coated PUF roof systems in hail areas also displayed resistance to hail.
5. Silicone-coated PUF roof systems do not have to be recoated during their service life. Maintenance can be performed by walking the roof and patching any punctures in the coating with a tube of silicone caulking. Coatings over 10 years old did not exhibit any noticeable deterioration due to ultraviolet degradation or trafficking.
6. Silicone-coated PUF roof systems are a solution to "flat" roofs.

URETHANE RUBBER-COATED PUF ROOF SYSTEMS

Urethane rubber coatings have not been around as long as the silicone coatings and their formulations recently have been approved. There is more of a variation in urethane coating formulations than with the silicone coatings. Only catalyzed urethane-coated PUF roof systems were inspected in the study. Data on the urethane rubber systems inspected in Louisville, Ken. and College Station, Texas led to the following conclusions:

1. Urethane rubber-coated PUF roof systems installed by "successful" contractors are potential 20-year systems. Eight- and nine-year-old urethane-coated PUF roof systems displayed no deterioration to the PUF. Although the coatings were showing cracking patterns in some areas, a recoating would produce an additional 10 years of service life.
2. Coating installed at 30 mils thicknesses requires recoating between the tenth and fifteenth years of service. This recoating should provide protection through the 20-year service life of the PUF roof system.
3. Urethane-coated PUF roof systems are a solution to "flat" roof problems.
4. Urethane rubber-coated PUF roof systems can be serviced by "in-house" maintenance personnel. Ninety-one percent of the 34 roofs inspected at Texas A&M had less than 1 percent deterioration.
5. Urethane-coated PUF roof systems do not require granulation due to their high tensile and shearing properties.

ACRYLIC-COATED PUF ROOF SYSTEMS

Very few acrylic coated PUF roof systems were inspected. They displayed an "in-the-field" proven service life of 10 years, and a potential 20-year service life with a recoating at the 10- to 13-year service period. Because of the wide spectrum of acrylic coating properties, it is of major importance to closely analyze the physical properties and proven service life of a particular acrylic coating in a specified environment."

ASPHALT-COATED PUF ROOF SYSTEMS

Asphalt-coated PUF roof systems were inspected in the New Jersey area. Asphalt coatings on PUF roof systems have not been well received in the roofing industry because of numerous failures.[1] For inspection, 69 roofs were selected from a listing of 175 roofs installed from 1970 to present. None were classified as "failures" and the contractor and asphalt system received a 98 percent customer satisfaction rating. The high customer satisfaction rating was partially

attributed to the maintenance service of the contractor. The data collected in the inspection and survey classify the asphalt-coated PUF roof system as "successful" in the New Jersey environment. More research is required to understand the mechanics of the asphalt-coated PUF roof system and to determine whether this system can be successfully installed by other applicators in other environments.

ECONOMIC ANALYSIS OF THE PUF ROOF SYSTEM

The results of the survey and inspection of 246 PUF roof systems have identified the PUF roof system as a low maintenance, 20-year roof system. The next task was to determine the economic feasibility of this roof system. Due to the numerous factors involved in monitoring energy consumption, simulation was the only feasible solution. An economic analysis was performed using a computer model which performed a one-at-a-time sensitivity analysis on the following parameters to determine their effect on the equivalent uniform annual cost (EUAC) of the PUF roof system in comparison with a 4-ply coal tar pitch built-up roof (BUR) system.

1. General inflation rate.
2. Interest rate.
3. Decreasing rate of insulative value of the PUF.
4. Service life of the PUF and BUR roof systems.
5. Thickness of the PUF.
6. Inflation rate of the cost of heating fuel and electricity to calculate the savings due to smaller power consumption.

Each of these factors was incremented for two simulated cases using the environments of Phoenix, Ariz. and Eau Clair, Wis. Both cases produced similar results. An analysis of the results showed that the most economic thickness of PUF depends upon the combination of factors, the most influential being the inflation rate of heating fuel and the environmental conditions.

The analysis of the Phoenix, Ariz. case study shall be briefly discussed. The two roof systems used in the comparison were a silicone-coated, one-inch PUF system and a four-ply, coal tar BUR system. Both were installed over metal decks. Tables 4 through 7 list the components and R-values of each roof system. The heating power source was Number 2 fuel oil and the cooling power source was electricity. A general inflation rate of 5.5 percent and an inflation rate of the cost of fuel of 3.3 percent was used. A loss of insulative quality of the PUF of 2 percent a year for 20 years was implemented, in accordance with Alumbaugh's findings on the deterioration of PUF's insulative qualities.[6] A maintenance cost of $0.01 per square foot per year was used for the BUR system. The analysis provided the following results:

1. A six-year $1.90 per square foot PUF roof system is an economical alternative to a 20-year, $2.96 per square foot BUR system.
2. A 10-year, $1.90 per square foot PUF roof system is an economical alternative to a 20-year, $1.50 per square foot BUR system. It would be highly unlikely that a 20-year BUR could be purchased for $1.50 per square foot, but it is used here to show how economically feasible the PUF roof system can be if it has a 10-year service life.
3. The cost of the BUR systems increased at a slightly higher rate than the cost of the PUF roof system as the interest rate and the inflation rate were increased.
4. The most economical thickness of PUF in this analysis was one inch. In the Eau Clair, Wis. case study, the most economical thickness of PUF in this analysis was 1.25 inches. This increased dramatically when the fuel inflation rate was increased.

PERFORMANCE SPECIFICATION

The results of the study show that the PUF roof system is an economical alternative to the BUR system. As with all other roofing systems, it is a product installed "in-place," requiring the combination of good engineering design, appropriate materials and proper installation. A properly specified "successful" PUF roof system installation required the following:

1. Prequalification of the contractor by his experience with the specified PUF roof system, by the successful performance of previous installations in similar environments.
2. Prequalification of the applicator or "man at the gun" by previous experience with the PUF roof system to be installed.
3. Manufacturer's warranty of the performance of the composite PUF and coating roof system.
4. Quantitative performance criteria which can be measured and verified by inspection or laboratory tests.
5. A full-time quality control monitor hired by the contractor to ensure the installed roof will meet the requirements of the specification.
6. Testing of random "in-field" samples.

A trial specification incorporating the above requirements was used on a barrel-shaped hanger at Williams AFB, Arizona. The award was made on the basis of competitive bids, with the award going to the low bidder. This resulted in a superior application of a silicone-coated PUF roof system.

SUMMARY

The study identified the existence of "successful" 20-year PUF roof systems that can be specified, installed and maintained. The data from the surveys and inspections of the randomly selected PUF roof systems classified the PUF system as a "low-maintenance," potential 20-year roof system which can be installed on sloped or "flat" roofs, located in varying environmental conditions. The inspected PUF roof systems had a proven life that exceeded what is required to be considered economically feasible when compared to a BUR system. The "successful" PUF roof system is an economical alternative to the BUR system, and can be specified to ensure its installation in a low-bid award situation.

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ROOF CONDITION RATINGS

	RATING	% OF DETERIORATED ROOF (D)
E	EXCELLENT	D = 0
VG	VERY GOOD	D < 1
G	GOOD	1 ≤ D < 5
F	FAIR	5 ≤ D < 10
P	POOR	10 ≤ D < 20
F	FAILURE	D ≥ 20

Table 1

RESULTS OF CUSTOMER SATISFACTION OF THE PUF ROOFS SURVEYED

AGE OF ROOFS	NO. OF ROOFS	NO. OF POSITIVE RESPONSES Q1	%	Q2	%	Q3	%
16	1	1	100	1	100	1	100
13	2	2	100	2	100	2	100
12	6	5	100	6	100	5	100
11	9	7	100	6	100	6	100
10	15	12	92	12	100	11	92
9	13	9	82	9	82	9	82
8	18	12	86	12	93	12	86
7	23	19	87	22	92	20	95
6	22	17	94	19	95	18	95
5	28	23	100	25	100	22	96
4	18	14	100	15	100	14	100
3	13	11	91	11	91	11	100
2	22	20	100	20	100	20	100
1	14	11	100	11	100	11	100
TOTALS	204	163	94	171	97	162	95

Table 2

ROOF CONDITION RATINGS OF PUF ROOFS INSPECTED

AGE (YRS)	AS	E	%	VG	%	G	%	FR	%	P	%	F	%
16	-	-	-	-	-	1	100	-	-	-	-	-	-
13	2	-	-	-	-	-	-	-	-	-	-	-	-
12	5	-	-	-	-	-	-	1	100	-	-	-	-
11	1	1	13	4	50	2	25	-	-	-	-	1	12
10	4	1	9	5	46	3	27	1	9	-	-	1	9
9	1	3	21	6	42	5	30	1	7	-	-	-	-
8	5	1	6	13	71	3	17	-	-	-	-	1	6
7	4	3	13	15	62	3	13	2	8	-	-	1	4
6	6	5	22	12	52	5	22	1	4	-	-	-	-
5	7	8	28	16	55	5	17	-	-	-	-	-	-
4	6	8	50	8	50	-	-	-	-	-	-	-	-
3	9	2	40	4	60	-	-	-	-	-	-	-	-
2	9	10	71	4	29	-	-	-	-	-	-	-	-
1	7	8	100	-	-	-	-	-	-	-	-	-	-
1	3	-	-	-	-	-	-	-	-	-	-	-	-
?	-	-	-	-	-	-	-	-	-	-	-	2	100
TOT.	69	50	28	87	51	27	15	5	3	0	0	6	3

Table 3

SIMULATED BUR SYSTEM IN ECONOMIC ANALYSIS

• ROOF COMPONENT	R-VALUE (COOLING)	
• OUTSIDE AIR FILM:	0.25	
• BUR:	0.33	
• ONE INCH PERLITE INSULATION:	2.78	
• VAPOR RETARDER:	0.12	
• STEEL DECK:	0.00	
• FOUR INCH REINFORCED CONCRETE DECK:		0.33
• AIR SPACE:	0.99	
• 5/8 INCH CEILING TILE:	1.56	
• INSIDE AIR FILM:	0.92	
• TOTAL:	6.95	7.28

Table 4

SIMULATED BUR SYSTEM IN ECONOMIC ANALYSIS

• ROOF COMPONENT	R-VALUE (HEATING)	
• OUTSIDE AIR FILM:	0.17	
• BUR:	0.33	
• ONE INCH PERLITE INSULATION:	2.78	
• VAPOR RETARDER:	0.12	
• STEEL DECK:	0.00	
• FOUR INCH REINFORCED CONCRETE DECK:		0.33
• AIR SPACE:	0.94	
• 5/8 INCH CEILING TILE:	1.56	
• INSIDE AIR FILM:	0.61	
• TOTAL:	6.51	6.84

Table 5

SIMULATED PUF SYSTEM IN ECONOMIC ANALYSIS

• ROOF COMPONENT	R-VALUE (COOLING)	
• OUTSIDE AIR FILM:	0.25	
• PUF:	6.25	
• VAPOR RETARDER:	0.12	
• STEEL DECK:	0.00	
• FOUR INCH REINFORCED CONCRETE DECK:		0.33
• AIR SPACE:	0.99	
• 5/8 INCH CEILING TILE:	1.56	
• INSIDE AIR FILM:	0.92	
• TOTAL:	10.09	10.42

Table 6

SIMULATED PUF SYSTEM IN ECONOMIC ANALYSIS

• ROOF COMPONENT	R-VALUE (HEATING)	
• OUTSIDE AIR FILM:	0.17	
• PUF:	6.25	
• VAPOR RETARDER:	0.12	
• STEEL DECK:	0.00	
• FOUR INCH REINFORCED CONCRETE DECK:		0.33
• AIR SPACE:	0.94	
• 5/8 INCH CEILING TILE:	1.56	
• INSIDE AIR FILM:	0.61	
• TOTAL:	9.65	9.98

Table 7