THE RELATIVE DURABILITY OF LOW-SLOPE ROOFING

CARL G. CASH
Simpson Gumpertz & Heger Inc.
Arlington, Massachusetts

This report on the durability, initial maintenance, and life cycle costs for many of the popular low-slope roof systems is based on a 1996 nationwide survey of the roofing industry. The paper discusses the idea of thermal load and deduces from the survey data the effect of temperature on the durability of these roof systems.

KEYWORDS

Durability, life cycle costs, low-slope roofing, roofing, thermal load.

INTRODUCTION

The author's last low-slope roofing survey was conducted in the winter of 1977-1978 and reported on in 1980.[1] This study did not include the now-popular glass-fiber-reinforced built-up roofing, single-ply, or polymer modified bitumen products because they were, at the time, relatively new or not yet in existence. Despite these obvious limitations, many people still use data from this early survey.

This paper reports the results of the author's extensive 1996 survey on the durability of low-slope roofing, discusses the idea of thermal loading, deduces the effect of temperature on product durability, and shows the estimated life cycle cost of each low-slope roof system. This report is based on the responses from this survey. These responses represent the opinion of the respondents; it is doubtful that any of them studied files or other data sources that might be more reliable than their memories.

THE SURVEY

Every member of the National Roofing Contractors Association (NRCA) received a survey (Appendix A). These members are principally roofing contractors and also include manufacturers, designers, consultants, and building owners. The NRCA members were asked to list, based on their experience, the average life, minimum life, installed cost, maintenance cost, and disposal cost for 14 generic low-slope roof systems.

Of the 4,200 questionnaires sent out, 430 responses from all over the United States were received; this is a ~10 percent response. Seventy-six of the responses were not usable for a variety of reasons (e.g., the responder did not feel qualified to present an opinion, was a steep-slope roofing contractor, or was a distributor or manufacturer of a related product, such as fasteners, and had no opinion about durability).

MAKE OR USE

Figure 1 shows the distribution of the responses to the "Make or Use" question and the percent of the total responses each roof system received.

Responses	Roof System (Symbol)	Percent Responses
283	Asphalt-Glass-Asphalt Built-Up Roofing (AGA-BUR) Styrene-Butadiene-Styrene Polymer Modified Asphalt	12.2
274	(SBS-PMB) 11.9	
252	Ethylene Propylene Diene (EPDM)	10.9
225	Atactic Polyethylene Polymer Modified Asphalt (APP-PMB)	9.7
187	Metal Panels (MP) 8.1	
180	Asphalt-Organic-Asphalt Built-Up Roofing (AOA-BUR)	7.8
155	Coal-Tar-Organic-Pitch Built-Up Roofing (CtOP-BUR)	6.7
148	Reinforced Poly[Vinyl Chloride] (PVC)	6.4
145	Hypalon, Chlorinated Polyethylene (CSPE, CPE)	6.3
115	Coal-Tar-Glass-Pitch Built-Up Roofing (CtGP-BUR)	5.0
113	Asphalt-Glass-Pitch Built-Up Roofing (AGP-BUR)	4.9
107	Polyurethane Foam (PUF)	4.8
82	Other Thermoplastic (EP, OT)	3.6
46	Polyisobutylene (PIB)	2.0

Figure 1. Make or use responses.

BUR systems had the largest percentage of responses (37 percent), followed by PMB systems (22 percent). PIB systems had the fewest responses (2 percent).

These numbers are interesting because they show the popularity of the systems listed. These percentages are not indicative of market volume; they are related to the number of categories of that type listed in the survey. For example, there were five built-up roofs, two polymer modified bitumen, two elastomeric, three thermoplastic, and two other categories in the survey. If a respondent checked all of the systems, built-up roofing would obtain five of 14, or 36 percent, of the responses.

Using the responses to the average life and the minimum life questions, the following values were calculated (the equations used are included):

- the mean

$$x=(\sum x)/n \qquad [1]$$

- the estimated standard deviation

$$s=[\sum x^2/(n-1)-(\sum x)^2/n(n-1)]^{0.5} \qquad [2]$$

- the estimated standard deviation of the mean

$$s_x=s/(n)^{0.5} \qquad [3]$$

- the average variance

$$V = s^2/n \qquad [4]$$

where $\bar{x}$ is the mean, x is the individual value, n is the number of responses, s is the estimated standard deviation, $s_{\bar{x}}$ is the estimated standard deviation of the mean, and V is the mean variance. The last statistic was used to gain an appreciation for the relative variability of these data and to test the statistical significance of the averages.

AVERAGE LIFE

The average life was defined as the number of years that half of all the roofs installed will perform satisfactorily, assuming proper design and installation. This is equivalent to "the mean time to failure" used in accelerated testing and durability analyses. One reviewer of this paper cautioned that many of the respondents may not have answered the question because some of the short "average life" data may be the result of unusual material problems, roof abuse, or exposure to storms beyond the design considerations.

The average life and minimum life responses form the backbone of this study. Average life data for each system are shown in Figure 2, ranked by their mean life. The range of the response averages is 10.6 to 25 years. The greatest variation was shown by the responses to the average life question for metal panels and for polyurethane foam systems.

Figure 3 shows the mean life of the systems after the individual averages were tested for statistical significance, using the null hypothesis at a 0.5 percent significance level.[2] The null hypothesis states that there is no statistically significant difference between data sets. The hypothesis is tested by standard statistical methods. If the hypothesis is accepted, the data are combined into a single set. If the hypothesis is rejected, the data sets are said to be statistically significant and are reported separately. This process reduced the 14 generic systems included in the study to six groups of systems with equivalent mean service lives.

These averages include many biases. For example, many "twenty year" responses were received for the built-up systems, and many "ten year" responses were received for the single-ply systems, showing that the time listed on the published warranties eventually affects the perception of durability. Thus, any opinion data of this sort must be examined critically. These data are opinions, and as such, are subject to a variety of influences, such as optimism or pessimism, but opinion more often determines the roof system selected than an objective study of the facts. One reviewer suggested that the relatively high number of respondents for PUF systems suggested that some of the respondents had never specified, applied, or used PUF systems and that, therefore, these respondents' opinions may be inaccurate. On the other hand, more negative comments were received from respondents who checked the PUF "Make or Use" column than from respondents who checked that column for any other system.

Roof System Symbol	Responses	Mean Life	Estimated Std. Dev.	Average Variance	Est. Std. Dev. of Mean
	n	$\bar{x}$	s	s^2/n	$s/n^{0.5}$
MP	187	25.0	12.13	0.787	0.887
CtOP-BUR	155	23.0	6.73	0.292	0.541
CtGP-BUR	115	21.9	7.02	0.429	0.655
AGP-BUR	113	17.7	6.01	0.320	0.565
AGA-BUR	283	16.7	4.79	0.081	0.285
SBS-PMB	274	15.9	4.63	0.078	0.280
AOA-BUR	180	14.7	5.04	0.141	0.376
EPDM	252	14.2	4.90	0.095	0.309
PVC	148	13.8	4.16	0.117	0.342
APP-PMB	225	13.7	4.56	0.092	0.304
CSPE,CPE	145	12.8	4.32	0.129	0.359
EP, OT	82	12.7	4.48	0.245	0.495
PUF	107	12.1	11.14	1.160	1.077
PIB	46	10.6	4.04	0.355	0.596

Figure 2. Mean life statistics, years.

Equivalent Systems	Mean Durability, Years
Metal Panels	25.0
Coal-Tar-Organic-Pitch or Glass Felts	22.5
Asphalt-Glass-Felt BUR, SBS Polymer Modified Asphalt, Asphalt-Glass Pitch	16.6
EPDM, Asphalt-Organic BUR APP Polymer Modified Asphalt, Poly[Vinyl Chloride],	14.1
Hypalon, CPE, other Thermoplastics	12.8
Polyurethane Foam, Polyisobutylene	11.6

Figure 3. Equivalent system.

Figure 4 compares the mean durability data from the 1996 and 1977-1978 surveys, the author's 1995 survey on steep-slope roofing, and an independent survey[3] conducted at the Roofing Industry Educational Institute (RIEI). The correlations of these data are very high, and the differences have no statistical significance; they support and lend credence to the results of this study.

MINIMUM LIFE

For this survey, the minimum life was defined as the years of life typical of the worst 1 percent of the roofs installed. Figure 5 lists the statistics on the minimum life responses for each type of roofing. As with the average life responses, these averages were compared for statistical significance using the null hypothesis. This results in the five equivalent roof system groups shown in Figure 6.

As expected, there was a linear correlation between the average mean and the average minimum value data. The regression coefficient was 0.99; the minimum value responses averaged ~57 percent of the average mean life responses.

Survey: System	1977-1978 Survey	1996 Survey Survey	1995 Steep-Slope	RIEI Survey
AOA-BUR	17.0	14.7		
AG-BUR		16.7		16.0
CtGP-BUR		21.9		18.9
CtOP-BUR	18.8	23.0		21.0
EPDM		14.2		13.0
PVC		13.8		14.2
SBS-PMB		15.9		13.4
APP-PMB		13.7		11.1
CSPE		12.8		10.8
Metal Panels		25.0	28	
PIB		10.6		
PUF		12.1		

Figure 4. Mean durability, various surveys.

Roof System Symbol	Responses	Minimum Life	Estimated Std. Dev.	Average Variance	Est. Std. Dev. of Mean
	n	$\bar{x}$	s	s^2/n	$s/n^{0.5}$
MP	188	12.4	8.75	0.408	0.638
CtOP-BUR	158	12.2	6.54	0.271	0.521
CtGP-BUR	116	11.2	6.42	0.355	0.596
AGA-BUR	286	9.1	4.66	0.076	0.275
AGP-BUR	119	9.0	5.41	0.246	0.496
SBS-PMB	263	8.4	4.29	0.070	0.265
AOA-BUR	187	7.3	4.17	0.093	0.305
APP-PMB	221	7.1	4.01	0.073	0.270
EPDM	258	7.0	4.24	0.070	0.264
PVC	160	6.5	3.42	0.073	0.310
CPE	151	6.5	3.92	0.102	0.319
EP, OT	81	6.0	4.01	0.198	0.445
PIB	49	4.8	3.11	0.198	0.444
PUF	109	4.8	4.15	0.158	0.398

Figure 5. Minimum life.

Equivalent Systems	Minimum Durability, Years
MP; CtOP & CtGP- BUR	12.1
AGA & AGP-BUR; SBS-PMB	8.8
AOA-BUR; EPDM; APP-PMB	7.2
PVC; CSPE,CPE; EP, OT	6.4
PIB; PUF	4.8

Figure 6. Equivalent systems.

DURABILITY RANGES

Roof system durability is not a single number, but rather a range depending on the specific exposure, the specific type of system, the quality of the materials, the quality of the design, the care used in the installation, the presence or absence of natural disasters, and the diligence of the maintenance. Averages of the mean and minimum life responses permit the definition of the durability range of these low-slope systems. The durability of each system is assumed to be normally distributed. Therefore, the estimated standard deviation of the distribution is given by:

$$\sigma=(x_1-x_{50})/-2.326 \quad [5]$$

where σ is the estimated standard deviation of the durability distribution, and x_1 and x_{50} are the average minimum and mean durabilities, respectively. The durability range can then be calculated using:

$$F(y)=1-\phi[y-x_{50})/\sigma \quad [6]$$

where $F(y)$ is the survival fraction of the population by age y, and f is the standard normal cumulative distribution function.

Figure 7 shows the average calculated percent of the roof systems surviving after various years of outdoor exposure, based on survey data. Generally, the longer the mean durability, the broader the range (the longer the time) of the durability curve.

Figure 8 graphs the average durability range of the systems that the survey responses said were equivalent.

CLIMATOLOGICAL EFFECTS

It has long been assumed that the same roof system behaves differently when exposed to weather in different climates.

Roof System	Percent Surviving After: 3 years	9 years	15 years	21 years	27 years	33 years	39 years	45 years
MP	100	99.9	97.1	77.6	35.2	6.4	0.4	0.0
CtOP-BUR	100	99.9	95.7	66.6	19.5	1.6	0.0	0.0
CtGP-BUR	100	99.7	93.2	57.5	13.6	0.8	0.0	0.0
AGP-BUR	100	99.0	76.4	18.9	0.7	0.0	0.0	0.0
AGA-BUR	100	99.0	69.9	9.5	0.1	0.0	0.0	0.0
SBS-PMB	100	98.3	61.0	5.7	0.0	0.0	0.0	0.0
AOA-BUR	100	96.4	46.4	2.3	0.0	0.0	0.0	0.0
PUF	100	83.7	17.9	0.2	0.0	0.0	0.0	0.0
PVC	100	93.7	35.2	1.2	0.0	0.0	0.0	0.0
EPDM	100	95.6	39.7	1.4	0.0	0.0	0.0	0.0
EP, OT	100	90.0	21.2	0.2	0.0	0.0	0.0	0.0
APP-PMB	100	95.3	32.3	0.5	0.0	0.0	0.0	0.0
CSPE,CPE	100	91.9	21.9	0.1	0.0	0.0	0.0	0.0
PIB	99.9	73.9	3.9	0.0	0.0	0.0	0.0	0.0

Figure 7. Average calculated percent surviving after outdoor exposure.

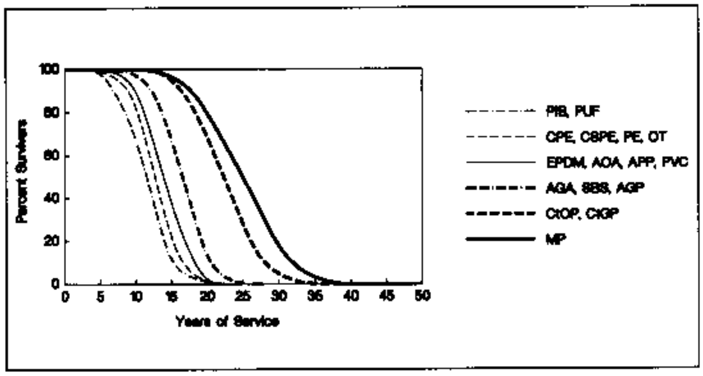

Figure 8. Mean durability of low-slope roof systems.

How each system can be expected to perform in each climate is of obvious practical interest. Less obvious is the importance of understanding the mechanisms that lead to failure and the insight that durability studies may provide to predict the performance of alternative systems.

Climate is a product of many forces, including temperature, precipitation, and wind. This paper explores only the effect of temperature on durability, with the full understanding that temperature alone is not the whole of climate. For example, in Dallas, Texas, the incidence of severe hailstorms may have a greater effect on performance than the thermal load.

The author's hypothesis is that increasing temperature decreases roof system durability in accord with the well-known Arrhenius life relationship.

Nelson[4] teaches that the Arrhenius life relationship is given by:

$$\tau=A\exp[E/(kT)] \quad [7]$$

where τ is the mean time to failure; A is the test statistic (it is empirical and depends on geometry, size, exposure, and other factors); E is the activation energy, usually in electron-volts; k is Boltzmann's constant, 8.6171 x 10^{-5} electron-volts per °C; and T is the absolute (i.e., Kelvin) temperature. The test statistic and activation energy were calculated from the survey data in this case, where values for these were not previously reported. The linear relationship between the mean durability and the absolute temperature (i.e., the thermal load) is logarithmic. The log of the nominal life is a linear function of the reciprocal of the absolute temperature; it is given by:

$$\log(\tau)=\gamma_0+(\gamma_1/T) \qquad [8]$$

where γ_0 is the intercept, and γ_1 is the slope of the curve. The slope is an index of thermal sensitivity.

A thermal load, for the purposes of this work, was defined as the calculated absolute temperature (Kelvin) of a horizontal surface at a specific location. The author's previous work developed the method for modeling the thermal climate[5] and the method of calculating the thermal load at a particular location.[6] These methods were used for this paper.

The thermal load was calculated for a gray color at each respondent's location, and the response was placed in one of five groups that made up the full range of thermal loads in the United States

(Appendices B, C, and D are maps with thermal load isobars for white, gray, and black surfaces). This approach makes the following assumptions:

- Each respondent s business is local. This is not necessarily true; some respondents are national, or even international, companies. Nevertheless, "local" is probably more often the case because of the mass of the materials and the economics involved.
- The roof systems are gray. This is not always true, but more roofs most likely are in the mid-range of color than at the extremes of black or white. For example, the color of many PVC, CSPE, and PUF systems tend to be whiter, and EPDM systems tend to be blacker than gray. Even very white and dark black roofs tend to become the color of the ambient dirt; they tend to gray.

The durability data in each thermal load range was averaged, and regression analyses of these response averages were used to explore the fit of survey data to the Arrhenius equations.

These 0.90+ regression coefficients confirmed that the Arrhenius relationships apply to low-slope roof systems. Regression coefficients of ~0.75 for metal panel, asphalt-glass-pitch, and SBS polymer modified bitumen systems may suggest the presence of forces other than temperature that are important for these systems. For example, the metal panel data may reflect the performance of the coating on the panel, rather than the performance of the panel itself.

The slope of the linear regression line illustrates the sensitivity of the roof system to changes in temperature. These data show that the mean durability declines very dramatically with changes in the temperature for some systems, such as PUF, PVC, and PIB, and declines very little for other systems, such as SBS-PMB. Despite the assumption that all the roofs are gray, changing their color to white or black changes only the intercept; it does not change the slope of the curve. One reviewer of this paper believed that the steep slope of the PUF system data (i.e., its thermal sensitivity) was an artifact not supported by field data. The author must rely on the data from the survey; it suggests the reviewer is biased.

Each roof system has its own activation energy (E) and test statistic (A).[7] The system thermal stability increases as the activation energy declines and the test statistic increases.

Of course, both the mean and the minimum durability change with the thermal loading. Therefore, the durability range for each system also changes. Figure 10 shows the percent surviving for EPDM membranes at 280K (45°F) through 310K (99°F) thermal loadings.

The durability range decreases significantly as the thermal loading increases. Similar charts can be drawn for each of the roof systems covered by the survey.

LIFE CYCLE COSTS

The life cycle cost of each membrane system was calculated by adding the mean installed and disposal cost responses, dividing the sum by the mean durability, and adding the mean annual maintenance cost response. The polyurethane foam system cost is the only one that includes the insulation; for this reason, care should be used in comparing the PUF numbers with the other numbers for this survey.

This calculation assumes that the inflation rate equals the discount rate for the present value of future dollars. Figure 11 shows these computed life cycle costs.

The percent coefficient of variation p was calculated using:

$$p=100 \times s/(x \times n^{0.5}) \qquad [9]$$

It is good for these installed cost data, ranging from 3.5 to 7.1 percent. The disposal costs had a higher variability; p ranged from 6.7 to 14 percent of the mean, probably because of extremes in local costs. The maintenance costs showed the

Membrane Type	R Regression Coefficient	Mean Durability, years 280 K	290 K	300 K	310 K	γ_1 slope	E Activation Energy	A Test Statistic
PUF	0.99	31.8	13.9	6.5	3.2	2903	0.576	0.000000
PVC	0.95	26.8	16.4	10.3	6.7	1739	0.345	0.000016
PIB	0.95	14.8	10.9	8.2	6.3	1076	0.214	0.02118
EPDM	0.95	20.1	15.4	12.0	9.5	940	0.187	0.008789
APP-PMB	0.92	17.3	14.3	11.9	10.1	679	0.135	0.065139
CtGP-BUR	0.92	27.3	22.9	19.5	16.7	615	0.122	0.173
CSPE, CPE	0.99	16.4	11.9	11.9	10.2	611	0.121	0.1086
Metal	0.75	28.2	25.4	23.0	21.0	371	0.074	1.3343
AGP-BUR	0.75	20.7	18.7	17.0	15.6	359	0.071	1.0802
AOA-BUR	0.93	16.9	13.6	12.4	11.4	336	0.067	0.9557
EP, OT	0.93	14.0	12.8	11.8	10.2	314	0.062	1.0556
AGA-BUR	1.00	18.5	17.4	16.5	15.7	206	0.041	3.3915
CtOP-BUR	0.95	25.4	24.0	22.7	21.6	205	0.041	4.7269
SBS-PMB	0.74	16.3	15.9	15.5	15.2	92	0.018	7.7013

Figure 9. Mean durability at various thermal loads, regression coefficients, thermal sensitivity, activation energy and test statistic.

Service Life, years	Thermal Loading			
	280K (45°F)	290K (63°F)	300K (81°F)	310K (99°F)
3	100	100	100	99.9
6	100	99.8	99.0	95.4
9	99.6	97.4	87.5	59.5
12	97.3	84.9	50.0	11.5
15	88.7	54.8	12.5	0.6
18	69.2	21.5	1.0	0.0
21	41.7	4.5	0.0	
24	17.6	0.4		
27	5.1	0.0		
30	0.9			
33	0.1			
36	0.0			

Figure 10. EPDM, calculated percent surviving at various ages and thermal loading.

highest variability; *p* varied from 8.1 to 27 percent, in part because of variations in local costs and, to some extent, survey responses that quoted dollars per 100 square feet instead of the dollars per square foot requested.

These cost data cannot be used as absolute values, because of the variation in these data. They are perhaps best used as indices of perception, because all data were treated uniformly.

CONCLUSIONS

These survey data speak for themselves. As useful as mean time to failure data may be to the industry, this study illustrates that durability is not one value, but a range of durabilities for each system, and that durability perceived by the respondents is greatly influenced by the thermal climate to which the system is exposed.

The activation energy and test statistic constants for the Arrehenius equations, which were reported as empirical values, may be the basis for additional research into the durability of roofing materials.

These data demonstrate that the reaction to temperature differs by material. Perhaps these data may be used to help design roof systems that are more durable. In any event, these data show that comparing roof systems composed of different types of materials, by exposing them to a uniform heat aging program, may be invalid, because the response of each system to heat differs.

Membrane Type	Installed Cost $/ft²	Disposal Cost $/ft²	Mean Durability Years	Maintenance Cost $/(ft² x yr.)	Life Cycle Cost $/(ft² x yr.)
CtGP-BUR	3.23	1.12	21.9	0.10	0.30
AGA-BUR	2.28	0.81	16.7	0.12	0.31
AGP-BUR	2.87	1.07	17.7	0.09	0.31
CtOP-BUR	2.97	1.10	23.0	0.14	0.32
EPDM	2.21	0.98	14.2	0.10	0.33
AOA-BUR	2.27	0.86	14.7	0.12	0.33
SBS-PMB	2.70	0.93	15.9	0.11	0.34
APP-PMB	2.35	0.72	13.7	0.12	0.34
PVC	2.54	0.84	13.8	0.11	0.36
Metal	4.94	1.27	25.0	0.11	0.36
EP, OT	2.61	0.73	12.7	0.11	0.37
CSPE, CPE	2.69	0.75	12.8	0.11	0.38
PIB	2.76	0.76	10.6	0.09	0.42
PUF*	2.57	1.27	12.1	0.15	0.47

* Includes insulation.

Figure 11. Low-slope roof membrane life cycle costs.

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ENDNOTES

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7. These terms are defined previously after Equation 7.

Appendix A

Simpson Gumpertz & Heger Inc.
1996 - Low Slope Roofing Questionnaire

❑ Check if you wish a summary of the data.

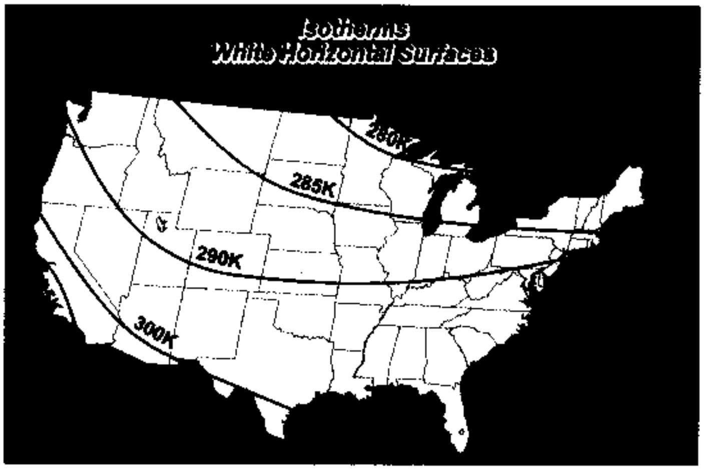
Please check the box in front of the types of roof your organization manufactures, applies, or investigates. Return the questionnaire unmarked if you are not involved in any of these types.

For each roof type with which you are involved, please write your estimate in the appropriate box of:

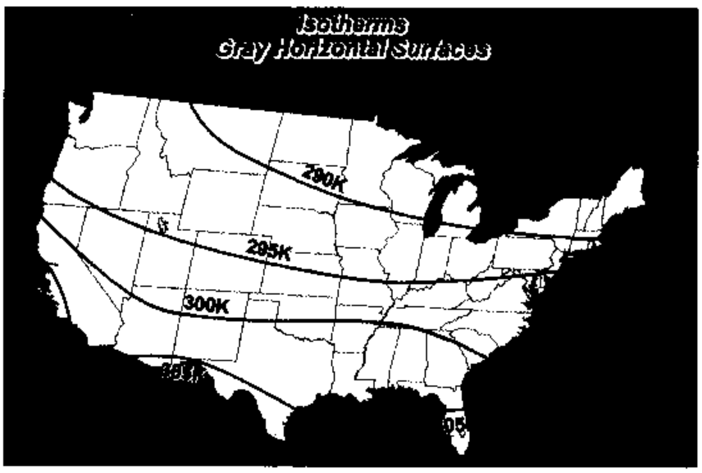
- the **average life** (the years that half of all of the roofs installed will perform satisfactorily, assuming proper design and installation),
- the **minimum life** (the years of life typical of the worst 1 percent of the roofs installed),
- the **installed cost** per square foot (materials, labor, profit and overhead, without insulation),
- the **maintenance cost** per square foot per year, and
- the **tear off and disposal cost** per square foot.

Make or Use	Low-Slope Roof Membrane	Average Life	Minimum Life	Installed Cost	Maint. Cost	Disposal Cost
180	Asphalt-organic felt & asphalt BUR	14.7	7.3	2.27	0.12	0.86
155	Coal-tar organic felt & pitch BUR	23.0	12.2	2.97	0.14	1.10
283	Asphalt-glass felt & asphalt BUR	16.7	9.1	2.28	0.12	0.81
113	Asphalt-glass felt & pitch BUR	17.7	9.0	2.87	0.09	1.07
115	Coal-tar-glass felt & pitch BUR	21.9	11.2	3.23	0.10	1.12
225	APP multiply modified bitumen	13.7	7.1	2.35	0.12	0.72
274	SBS multiply modified bitumen	15.9	8.4	2.70	0.11	0.93
46	Polyisobutylene	10.6	4.8	2.76	0.09	0.76
252	EPDM (ethylene-propylene- diamine)	14.2	7.0	2.21	0.10	0.98
148	Reinforced polyvinyl chloride	13.8	6.5	2.54	0.11	0.84
145	Reinforced Hypalon , CPE	12.8	6.5	2.69	0.11	0.75
82	Other thermoplastic single plies	12.7	6.0	2.61	0.11	0.73
107	Foamed in place urethane	12.1	4.8	2.57	0.15	1.27
187	Prefabricated sheet metal	25.0	12.4	4.94	0.11	1.27

Appendix B



Appendix C



Appendix D